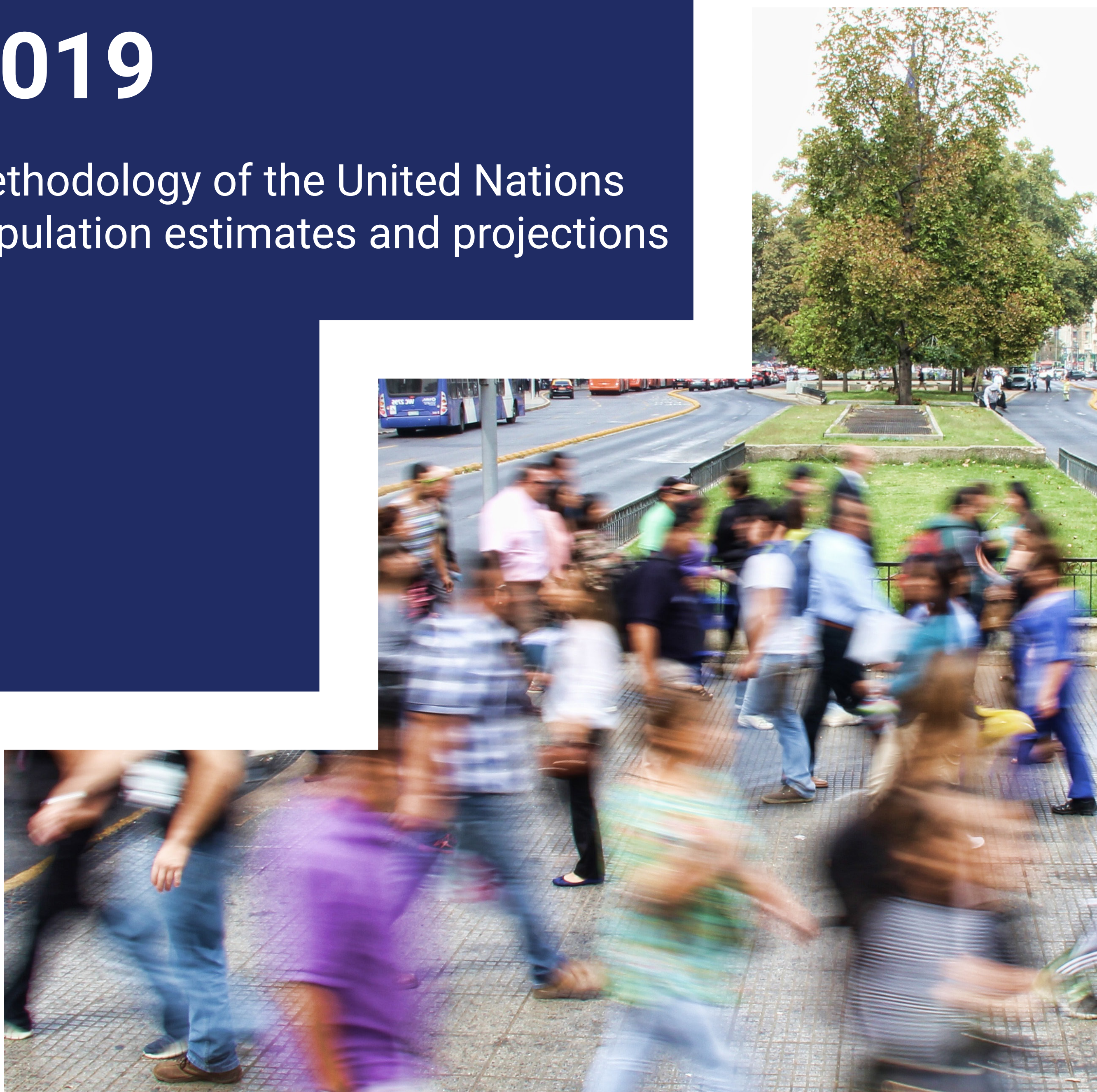
United Nations | Department of Economic and Social Affairs

World Population Prospects 2019

Methodology of the United Nations population estimates and projections



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Department of Economic and Social Affairs
Population Division

World Population Prospects 2019

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United Nations
New York, 2019

The Department of Economic and Social Affairs of the United Nations Secretariat is a vital interface between global policies in the economic, social and environmental spheres and national action. The Department works in three main interlinked areas: (i) it compiles, generates and analyses a wide range of economic, social and environmental data and information on which States Members of the United Nations draw to review common problems and take stock of policy options; (ii) it facilitates the negotiations of Member States in many intergovernmental bodies on joint courses of action to address ongoing or emerging global challenges; and (iii) it advises interested Governments on the ways and means of translating policy frameworks developed in United Nations conferences and summits into programmes at the country level and, through technical assistance, helps build national capacities.

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Notes

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The term “country” as used in this report also refers, as appropriate, to territories or areas.

This report is available in electronic format on the Division’s website at www.unpopulation.org. For further information about this report, please contact the Office of the Director, Population Division, Department of Economic and Social Affairs, United Nations, New York, 10017, USA, by fax: 1 212 963 2147 or by e-mail at population@un.org.

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PREFACE

This report provides a detailed overview of the methodology used to produce the 2019 revision of the official United Nations population estimates and projections, prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. The 2019 revision is the twenty-sixth round of global population estimates and projections produced by the Population Division since 1951.

The report first describes the way that country estimates have been prepared and then explains the approaches and assumptions that were used to project fertility, mortality and international migration up to the year 2100. The report also provides an overview of the variants used in generating the different sets of population projections as well as information on the recently developed probabilistic projection methods, which depict the uncertainty of future demographic trends, with results presented for all countries and areas of the world up to the year 2100. The Population Division has continued to refine the methods used for these probabilistic projections. It should be noted, however, that making projections to 2100 is subject to a high degree of uncertainty, especially at the country level. In that regard, users are encouraged to focus not only on the medium variant, which corresponds to the median of several thousand projected trajectories of specific demographic components, but also on the associated prediction intervals, which provide an assessment of the uncertainty inherent in such projections. Detailed information on the 80 and 95 per cent uncertainty bounds for different components at the country level and major geographic aggregates is available on the website of the Population Division, *www.unpopulation.org*.

The 2019 revision of the *World Population Prospects* was prepared by a team led by Patrick Gerland, including Kirill Andreev, Lina Bassarsky, Guiomar Bay, Helena Cruz Castanheira, Victor Gaigbe-Togbe, Danan Gu, Sara Hertog, Nan Li, Igor Ribeiro, Thomas Spoorenberg, Philipp Ueffing, Mark Wheldon, Lubov Zeifman and benefited of the support of Bela Hovy, Kyaw Kyaw Lay, Frank Swiaczny, Guangyu Zhang. The team is grateful to other colleagues in the Population Division for the support they have provided, including to John Wilmoth for reviewing this report.

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The following symbols have been used in the tables throughout this report:

A full stop (.) is used to indicate decimals.

Years given refer to 1 July.

Use of a hyphen (-) between years, for example, 1995-2000, signifies the full period involved, from 1 July of the first year to 30 June of the second year.

References to regions, development groups, countries or areas:

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In this table, data for countries or areas have been aggregated in six continental regions: Africa, Asia, Europe, Latin America and the Caribbean, Northern America, and Oceania. Further information on continental regions is available from https://unstats.un.org/unsd/methodology/m49/. Countries or areas are also grouped into geographic regions based on the classification being used to track progress towards the Sustainable Development Goals of the United Nations (see: https://unstats.un.org/sdgs/indicators/regional-groups/).

The designation of "more developed" and "less developed" regions is intended for statistical purposes and does not express a judgment about the stage reached by a particular country or area in the development process. More developed regions comprise all regions of Europe plus Northern America, Australia and New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (excluding Japan), and Latin America and the Caribbean as well as Oceania (excluding Australia and New Zealand).

The group of least developed countries includes 47 countries located in sub-Saharan Africa (32), Northern Africa and Western Asia (2), Central and Southern Asia (4), Eastern and South-Eastern Asia (4), Latin America and the Caribbean (1), and Oceania (4). Further information is available at http://unohrlls.org/about-ldcs/.

The group of Landlocked Developing Countries (LLDCs) includes 32 countries or territories located in sub-Saharan Africa (16), Northern Africa and Western Asia (2), Central and Southern Asia (8), Eastern and South-Eastern Asia (2), Latin America and the Caribbean (2), and Europe and Northern America (2). Further information is available at http://unohrlls.org/about-lldcs/.

The group of Small Island Developing States (SIDS) includes 58 countries or territories located in the Caribbean (29), the Pacific (20), and the Atlantic, Indian Ocean, Mediterranean and South China Sea (9). Further information is available at http://unohrlls.org/about-sids/.

The classification of countries or areas by income level is based on the gross national income (GNI) per capita as reported by the World Bank (June 2018). These income groups are not available for all countries or areas.

The following abbreviations have been used:

AIDS	Acquired immunodeficiency syndrome
AIM	Aids Impact Model
ART	Antiretroviral therapy
BHM	Bayesian hierarchical model
CPS	Contraceptive Prevalence Surveys
DHS	Demographic and Health Surveys
GBD	Global Burden of Disease
GHS	General Household Survey
HFD	Human Fertility Database
HIV	Human immunodeficiency virus
HMD	Human Mortality Database
IGME	Inter-agency Group for Child Mortality Estimation
IPUMS	Integrated Public Use Microdata Series
LAMBdA	Latin American Mortality Database
MAC	Mean age at childbearing
MICS	Multiple Indicator Cluster Survey
MIS	Malaria Indicator Survey
PAPFAM	Pan-Arab Project for Family Health
PASFR	Proportionate age-specific fertility rate
PI(s)	Prediction interval(s)
PMA	Performance Monitoring and Accountability
RHS	Reproductive Health Surveys
SAR	Special Administrative Region
TFR	Total fertility rate
UN	United Nations
UNAIDS	Joint United Nations Programme on HIV/AIDS
UNDESA	United Nations Department of Economic and Social Affairs
UNFPA	United Nations Population Fund
UNHCR	Office of the United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
WFS	World Fertility Survey
WHO	World Health Organization
WPP	World Population Prospects

INTRODUCTION

The preparation of each new revision of the official population estimates and projections of the United Nations involves two distinct processes: (a) the incorporation of new information about the demography of each country or area of the world, involving in some cases a reassessment of past estimates; and (b) the formulation of detailed assumptions about the future paths of fertility, mortality and international migration, again for every country or area of the world.

The population estimates and projections contained in this revision cover a 150-year time horizon, which can be subdivided into estimates (1950-2020) and projections (2020-2100). The estimates were produced by starting with a base population by age and sex for 1 July 1950 and advancing the population through successive 5-year time intervals using the cohort-component method, based on age-specific estimates of the components of population change (fertility, mortality, and international migration). Population counts by age and sex from periodic censuses were used as benchmarks. The relevant estimates of demographic components for 1950-2020 were taken directly from national statistical sources, or were estimated by staff of the Population Division when only partial or poor-quality data were available. Necessary adjustments were made for deficiencies in age reporting, under-enumeration in censuses, or underreporting of vital events.

The year 2020, separating the past estimates from the projections, is called the base year of the projections. The projection period of this revision covers 80 years and ends in 2100.

Population projections prepared by the United Nations Population Division have traditionally been produced for a number of variants to highlight, for instance, the effect of changes in the assumptions about different trajectories of fertility on the projected size and structure of the population. More recently a probabilistic approach was adopted for the projection of certain components, such as total fertility and life expectancy at birth by sex, to determine the median trajectory of these components and also provide statistical bounds of uncertainty[1] (prediction intervals or PIs). Population estimates and projections were carried out for a total of 235 countries or areas. Detailed results have been published for 201 countries or areas with 90,000 inhabitants or more in 2019; for the remaining 34 countries or areas that fell below that threshold, only total population and growth rates have been made available.

A key aim within each revision of the *World Population Prospects* is to ensure the consistency and comparability of estimates and projections within countries over time and across countries. Accordingly, for the estimation period, newly available demographic information was assessed through various data quality checks and was also evaluated by analysing the impact of its incorporation on recent trends in fertility, mortality, or migration, and by comparing the simulated outcome with existing estimates of the population structure by age and sex at successive time intervals. With respect to the projection period, probabilistic statistical techniques or general guidelines were used to determine the paths that fertility, mortality and international migration are expected to follow in the future. In some cases, deviations from these guidelines or default median probabilistic trajectories were required. This was mainly the case for the projection of net international migration and life expectancy at birth for selected countries. Details of these procedures are provided in the body of this report.

1 For further discussion about uncertainty in future population projections, see also United Nations (2019a).

The report first describes the way that the estimates were revised during the preparation of the 2019 revision. It then examines the approaches and assumptions used to project fertility, mortality and international migration up to the year 2100. The report contains information on the probabilistic projection methods as well as an overview of the different deterministic variants used in generating the multiple sets of population projections.

I. THE PREPARATION OF POPULATION ESTIMATES

A. DATA AVAILABILITY

Recent data on the population size and age structure of each country, as well as data on fertility, mortality, and international migration, are needed for the preparation of updated population estimates. In the absence of recent data, estimates for recent years were obtained by projecting forward from the last available data point, based on assumptions about trends in the demographic components of population change (fertility, mortality and migration). The following section summarizes the availability of recent data on population and the components of change used in preparing the 2019 revision.

Estimates and projections of total population are provided in this revision for 235 countries or areas, comprising the entire population of the world. Information on demographic components refers to 201 countries or areas with at least 90,000 inhabitants in 2019, for which the 2019 revision contains full time series of population size by age and sex and of the components of population change. For the 2019 revision, 1,690 population censuses conducted between 1950 and 2018, as well as information on births and deaths from vital registration systems for 163 countries and demographic indicators from 2,700 surveys were considered. A listing of the data sources used, and the methods applied in revising past estimates of demographic indicators, for each country or area, is available online[2].

Population

Recent population counts are critical for obtaining accurate estimates of population size and its composition by age and sex. The principal data source used for this purpose is the population census. Following the *UN Principles and Recommendations on Population and Housing Censuses* (United Nations, 2017b) most countries conduct a census about once per decade. Altogether, more than 1,600 censuses have been conducted worldwide since the 1950s, providing a wealth of data for the analysis and monitoring of population change. In some countries, population registers based on administrative data systems are sufficiently well developed to serve as a basis for population estimates.

At the global level, population data from censuses or registers referring to 2010 or later were available for 188 countries or areas, representing 80 per cent of the 235 countries or areas included in this analysis. For 39 countries, the most recent population count data available were from the period 2000-2009. For the remaining nine countries, the most recent available census data were from before the year 2000. These nine countries (with date of last census) were Lebanon (1932), Afghanistan (1979), Democratic Republic of the Congo (1984), Eritrea (1984), Somalia (1987), Uzbekistan (1989), Madagascar (1993), Iraq (1997), and Turkmenistan (1995).

Fertility

The preferred source of data on fertility is counts of live births, by age of mother, from a system of civil registration with national coverage and a high level of completeness (United Nations, 2014a). In cases where the registration of births is deficient or lacking, fertility estimates are typically obtained through sample surveys. Demographic sample surveys may provide estimates of fertility by asking

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[2] Data sources and related meta-information for the *World Population Prospects 2019* are available for each country or area from the following web page in textual format from: https://population.un.org/wpp2019/DataSources/. and can be downloaded in structured tabular format from: https://population.un.org/wpp/Download/Metadata/Documentation/.

women detailed questions to obtain their complete childbearing histories, or just summary information about the total number of children ever born. Current global survey programmes collecting detailed birth histories include the Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS)[3]. In addition, some countries field national demographic surveys, and a few have established sample vital registration systems. Numerous countries ask summary questions in the census on the number of children ever born. The 2019 revision incorporates, in most cases, relatively recent direct or indirect information on fertility. Among the 201 countries or areas with 90,000 inhabitants or more in 2019, all but 34 had available data on fertility collected in 2015 or later. For 33 countries, the most recent data were collected between 2010-2014, and only for Somalia the most recent national data were from 2006.

Mortality

a. Mortality at ages under 5

Similar to estimates of fertility, estimates of child mortality, measured by the probability of dying between birth and age five, can be derived from direct or indirect questions in surveys or censuses when reliable data from civil registration are not available. For child mortality, the available information is largely up to date. For countries or areas with 90,000 inhabitants or more in 2019, 164 countries had available child mortality data collected in 2015 or later, for another 35 countries the most recent data were collected between 2010-2014. Only two (Somalia and Western Sahara) did not collect child mortality since 2006. However, despite the availability of recent data in the vast majority of countries, the quantity and consistency of data available to cover the entire estimation period from 1950 to 2020 varied greatly across countries. In preparing estimates of child mortality for the 2019 revision, the Population Division coordinated closely with the United Nations Inter-agency Group for Child Mortality Estimation[4] (IGME), which is led by UNICEF.

b. Mortality above age 5

Compared to information on fertility and child mortality, information on adult mortality was sparser, more likely to be outdated, or, for a few countries, lacking altogether. Estimates of adult mortality were derived from complete data on registered deaths by age and sex whenever possible. In other cases, analysts evaluated data from incomplete registration; from questions on household deaths by age and sex, usually for a 12-month period before a census or survey; or from questions on the survival of the siblings of respondents in demographic surveys. Among the 201 countries or areas with 90,000 inhabitants or more in 2019, 137 countries had available adult mortality data collected in 2015 or later, for the remaining 64 countries the most recent data were collected between 2010 and 2014 in 51 countries, and between 1998 and 2009 for another ten countries. No empirical data on adult mortality are available for Djibouti (since 1991), Somalia, and Western Sahara. Model-based estimates of adult mortality from the 2017 revision of the Global Burden of Disease project (IHME, University of Washington) were also considered for countries lacking reliable vital registration data. In cases where available data on adult mortality were too sparse or inconsistent, life expectancy at birth was derived by using recent information about infant and child mortality together with model life tables. Furthermore, in countries with high levels of HIV

[3] Fertility estimates from some other international survey programs were also considered, for example the Performance Monitoring and Accountability (PMA) surveys. Other international survey programs that provided fertility estimates in decades prior to 2010 included the World Fertility Survey (WFS), the Contraceptive Prevalence Surveys (CPS), the Reproductive Health Surveys (RHS), and the Pan-Arab Project for Family Health (PAPFAM).

[4] The IGME database, including the complete set of available empirical data used to construct the latest global estimates of under-five mortality, is available at www.childmortality.org.

prevalence among persons aged 15 to 49 (i.e., at least 4 per cent at some point between 1980 and 2018), age-specific mortality patterns up to the period 2015-2020 were estimated as a function of adult HIV prevalence, child mortality, adult mortality, and coverage of antiretroviral treatment (ART) of both children and adults, based on model life tables accounting for the effect of HIV on mortality (Sharrow and others, 2014) recalibrated using the latest epidemiological data (UNAIDS, 2019). For many countries, empirical adult mortality estimates were considered "post-facto" to validate modelled estimates but were not used as direct inputs.

Net international migration

A final consideration in the revision of past estimates of population dynamics concerns the sources of information regarding international migration. In preparing the 2019 revision, attention was given to official estimates of net international migration or its components (immigration and emigration), to information on labour migration or on international migration flows recorded by receiving countries, to data about refugee (and asylum-seeker) stocks and flows prepared by the Office of the United Nations High Commissioner for Refugees (UNHCR)[5], and to estimates of stocks of foreign-born persons prepared by the Population Division of UN DESA[6]. Given the absence of empirical data on inflows and outflows of international migrants, it was difficult to produce comprehensive and consistent estimates of net migration over time. Therefore, in many cases, net international migration was estimated as the residual not accounted for by natural increase between successive census enumerations (after adjustment for net coverage errors and data quality issues). The paucity of reliable and comprehensive data on international migration is an important limitation to producing more accurate population estimates.

5 For refugee statistics from the Office of the United Nations High Commissioner for Refugees (UNHCR), see http://popstats.unhcr.org/en/overview

6 For estimates of international migration flows and stocks of foreign-born from the United Nations, see https://www.un.org/en/development/desa/population/migration/data/index.asp

B. General analytical strategy and major steps for producing population estimates

With each revision of the *World Population Prospects*, the Population Division of UN DESA carries out a "re-estimation" of recent or historical demographic trends for many countries and areas of the world. These demographic estimates are based on the most recently available data sources, such as censuses, demographic surveys, registries of vital events, population registers and various other sources (e.g., refugee statistics). With each new data collection, the time series of fertility, mortality and migration, as well as population trends by age and sex, can be extended and, if necessary, corrected retrospectively. For countries with highly deficient demographic data, or many years without a census or demographic survey, the availability of new data can lead to a reassessment of historical demographic trends.

For most countries in the more developed regions, the availability of detailed information on fertility and mortality trends over time and of regular periodic censuses of the population has greatly facilitated the task of producing reliable estimates of past population dynamics (United Nations, 2004). In any interval of time, births and immigration add to the initial population, and deaths and emigration subtract from it. Such basic demographic accounting (and balancing equation relationship[7]) allows to generate intercensal and post-censal population estimates if vital statistics from civil registration and international migration statistics are available and accurate (United Nations, 1955). Nevertheless, for various countries with inadequate migration data (at least for some time periods), estimates of net international migration (i.e., number of immigrants minus number of emigrants during the same time period) were obtained by computing the difference between the growth in population as recorded in successive censuses (total increase) and the growth implied by estimated levels of fertility and mortality (natural increase).

The estimation of past trends is usually more complex for most countries or areas of the less developed regions, for which demographic information may be limited or lacking, and available data are often unreliable. In such cases, more reliable estimates can be obtained by making use of model-based methods of indirect estimation (United Nations, 1983, 2002; Moultrie and others, 2013).

One of the major tasks in revising the demographic estimates for each country or area of the world is to obtain and evaluate the most recent information available on each of the three components of population change: fertility, mortality and international migration. In addition, newly available census information or other data providing information on the age distribution of the population should also be evaluated. When countries have conducted several censuses, the results can be analysed not only for each census independently but also by following cohorts as they age through time and are counted in successive censuses (Heilig and others, 2009; Spoorenberg and Schwekendiek, 2012; Gerland, 2014).

However, this process of updating and revising population estimates typically entails not only the separate evaluation of the quality of the different estimates available, but also the search for consistency among them to insure that the demographic balancing equation is preserved, including by age and sex, as birth cohorts are surviving or migrating over time. A key task therefore is to ensure that for each country past trends of fertility, mortality and international migration are consistent with changes in the size of the

[7] The demographic balancing equation states that between two dates (t_0 and t_1), the population at the end of this time period (t_1-t_0) denoted (P_1) is equal to the population at the start of the time period (P_0), plus the number of live births during this time period (B), plus the number of immigrants during this time period (I), minus the number of deaths during this time period (D), minus the number of emigrants during this time period (E) which can be noted as: $P_1 = P_0 + B + I – D – E$

population and its distribution by age and sex. The overall analytical approach used in the 2019 revision as well as in previous ones consisted of four major steps:

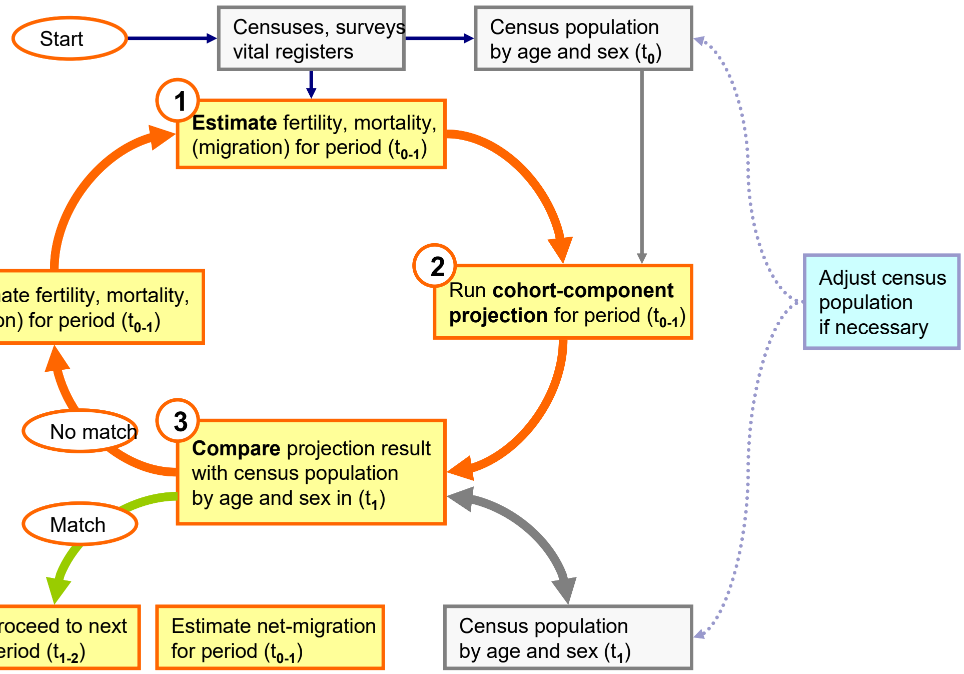
1. *Data collection, evaluation and estimation*: Analysts collected available data from censuses, surveys, vital and population registers, analytical reports and other sources for a given country[8]. Typically, analysts assembled a collection of estimates from various sources for each component. In many cases, estimates derived from different sources or based on different modelling techniques varied significantly, and all available empirical data sources and estimation methods were compared. Various techniques were used to identify the most likely time-series of fertility, mortality and international migration data.

2. *Further evaluation and adjustments*: After the initial compilation and trend line determination, the data were evaluated for geographical completeness and demographic plausibility. Post-enumeration surveys were used if available to evaluate the quality of census data. If necessary, adjusted data were obtained from national statistical offices or adjustments were applied by analysts using standard demographic techniques, such as accounting for under-enumeration of young children or smoothing age distributions characterized by age-heaping (Ewbank, 1981; Moultrie and others, 2013).

   For countries where no, or only minimal, demographic information was available, demographic models were used to estimate fertility, mortality and migration. For all countries, estimates contained in the previous revision(s) of the *World Population Prospects* were carefully reviewed and, if necessary, were revised based on the new data.

[8] Traditionally, the data are obtained from the United Nations Statistics Division (Demographic Yearbook), national statistical offices, United Nations Regional Commissions, other United Nations entities (e.g., UNAIDS, UNFPA, UNICEF, WHO, World Bank), and complemented using international databases (e.g., the Human Mortality Database (University of California at Berkeley (USA) and Max Planck Institute for Demographic Research (Germany), 2018) and Human Life Table Database (Max Planck Institute for Demographic Research (Germany) and others, 2018), the Human Fertility Database (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2018b) and Human Fertility Collection (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2018a), the Latin American Mortality Database–LAMBdA (Palloni and others, 2014), the International Data Base (U.S. Bureau of the Census, 2018), the Global Burden of Disease project (Institute for Health Metrics and Evaluation, 2018) and the Developing Countries Mortality Database (Mi, 2018)), and public use microdata archives (e.g., DHS, MICS, IPUMS-International).

Figure I.1. Process used to ensure intercensal consistency between demographic components and the total population



NOTE: The diagram above illustrates how individual estimates of fertility, mortality and net-migration were subjected to tests of internal consistency using a cohort-component projection framework for the period between t_0 and t_1. This procedure has been applied in each new revision of the *World Population Prospects*. Past estimates are re-evaluated when new information becomes available; therefore, with every revision past demographic trends may be adjusted.

The estimates obtained from steps 1 and 2 were subjected to a series of checks whereby the relationship between the enumerated populations and their estimated intercensal demographic components was tested for internal consistency. For countries where several censuses were available, intercensal consistency was analysed by projecting the population between census years using the initial estimates for fertility, mortality and migration obtained in steps 1 and 2. If the population by age and sex of the subsequent censuses could not be matched by the projection, adjustments to one or more demographic components were made (figure I.1). In some cases, the initial starting population itself was revised; consistency was achieved through an iterative step-by-step "project-and-adjust" process from one census to the next to insure optimal consistency of the intercensal cohorts.

3. *Country-specific consistency checking and cross-validation*: The previous steps provided initial sets of independent estimates for the total population and for each demographic component (fertility, mortality, and international migration). However, the methods used focus on only one demographic component without taking into account the interaction with the other demographic components. A further check on the estimates occurs when the separate estimates for fertility, mortality and migration are integrated into a cohort-component projection framework where these demographic rates are simultaneously applied to a base population in order to compute subsequent populations by age and sex. Typically, population projection uses vital rates and migration to project populations by age and sex from a baseline year, denoted t_0, forward in time. In its simplest form, the population in year t+n, $t_0 \leq t \leq t+n$, equals the population in year t plus the intervening births and net migration, minus the intervening deaths (Preston and others, 2001; Whelpton, 1936). This is known as the demographic balancing relationship (see footnote 7).

4. *Checking consistency across countries*: Once all the components of each country's estimates were calculated, the results were aggregated by geographical region and a final round of consistency checking took place, which involved comparing the preliminary estimates against those from other countries in the same region or at similar levels of fertility or mortality. When inconsistencies were identified, necessary adjustments were made. An important component of the work at this stage was ensuring the consistency of information on the net number of international migrants, which for each 5-year period must sum to zero at the world level.

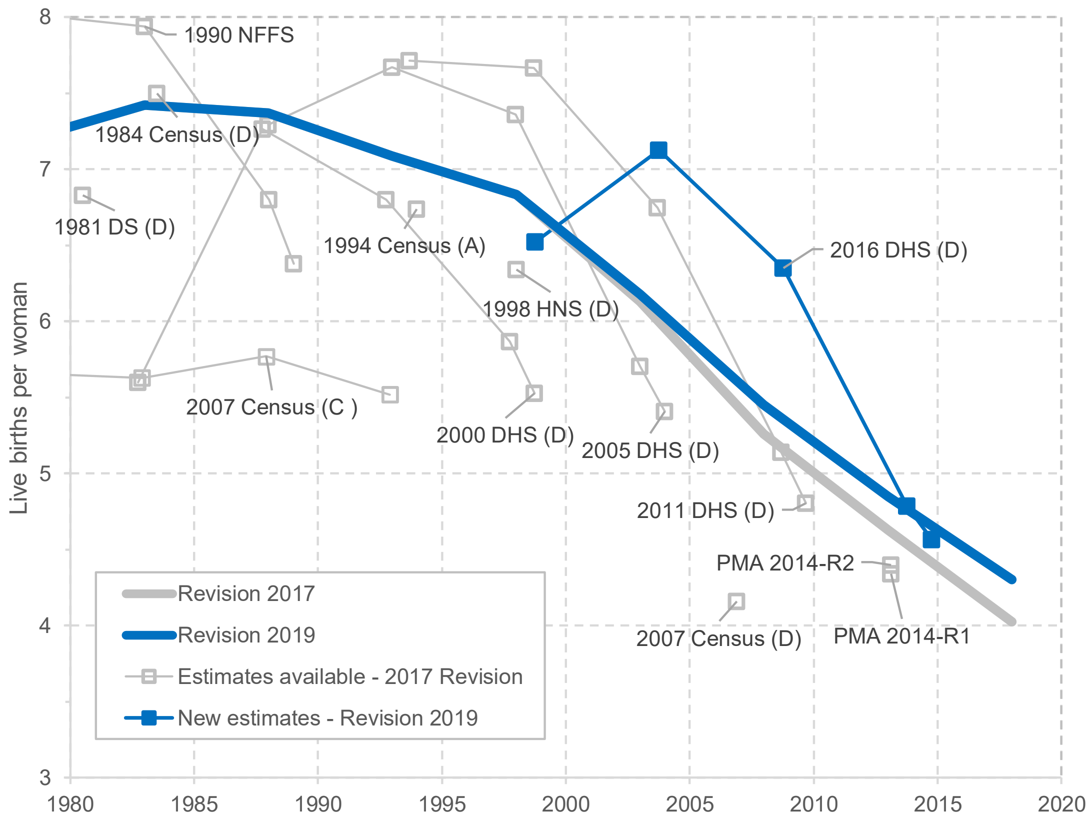
C. Addressing challenges arising from data quality issues

In updating estimates of populations and related demographic components for each country, a major challenge was to address inconsistencies across various empirical data sets. This was predominantly the case in countries with deficient demographic data, where different data sources often provide different estimates even for the same reference point of time or period. This section provides several country-specific examples to illustrate the challenges and how they were addressed.

The first example focuses on the data available at different points in time for updating fertility estimates for Ethiopia, comparing the results across the most two recent revisions. In figure I.2, the data shown in grey represent the empirical evidence considered in deriving total fertility estimates for the period 1980-1985 to 2010-2015 that were available at the time of the 2017 revision. Multiple data sources were considered, and one or multiple estimation methods were used to derive fertility estimates from each source (for details about the data sources and estimation methods used, see https://population.un.org/wpp2019/DataSources/). The grey line "Revision 2017" in figure I.2 represents the final trend estimates produced after evaluation of these disparate and conflicting sources, and that allow to reproduce the birth cohorts across successive censuses best.

When preparing the 2019 revision, estimates from a new survey had become available and were considered in addition to those used in the 2017 revision. The addition of the fertility estimates from the 2016 Demographic and Health Survey (DHS), shown in blue in figure I.2, were the basis for revising slightly upward the estimated fertility levels, depicted by the thick blue line "Revision 2019". These modifications in the more recent fertility levels (e.g. slower fertility decline) have implications for the projected fertility trends, as well as for the associated projected populations.

Figure I.2. Total fertility estimates based on various data sources and estimation methods, and WPP estimates for the 2017 and 2019 revisions, Ethiopia, 1980-2020



Note: This figure illustrates the "cloud" of empirical estimates of total fertility (number of live births per woman) derived from different data sources in Ethiopia. The thick solid lines – in grey and blue – represent the assessments from the 2017 and 2019 revisions, respectively. The empirical estimates available for the 2017 revision are indicated in grey; the ones that became available for the 2019 revision are indicated in blue. As new information became available between revisions, the more recent estimates of fertility were revised. With the incorporation of the estimates from the 2016 DHS (blue series), the fertility levels in Ethiopia were estimated to be slightly higher in the more recent years in the 2019 revision, as compared to the 2017 revision.

DHS = Demographic and Health Survey; DS = Demographic Survey; NFFS = National Fertility and Family Survey; HNS = Health and Nutrition Survey. (A) refers to adjusted figure. (C) refers to cohort completed fertility (i.e. average number of children ever born) for women aged 40-44 or above at the date of the census or survey and backdated using their mean age of childbearing. (D) refers to direct fertility estimates based on maternity histories or recent births in the 12 or 24 months preceding the census or survey.

Similar challenges were encountered in estimating mortality. Different data sources as well as different analytical methods can produce substantially different estimates of underlying rates. Moreover, non-sampling errors can bias series in systematic ways. To address these various challenges, trends by age and sex (or overall summary indices like ${}_5q_0$ and ${}_{35}q_{15}$ or ${}_{45}q_{15}$[9] when time series of age-specific mortality rate were unavailable) were generated either through expert-based opinion reviewing and weighting each observation analytically, or by using automated statistical methods[10].

The overall analytical approach used to measure under-five mortality in the 2019 revision followed that of the United Nations IGME (Hill and others, 2012; Alkema and others, 2014; Hug and others, 2019),

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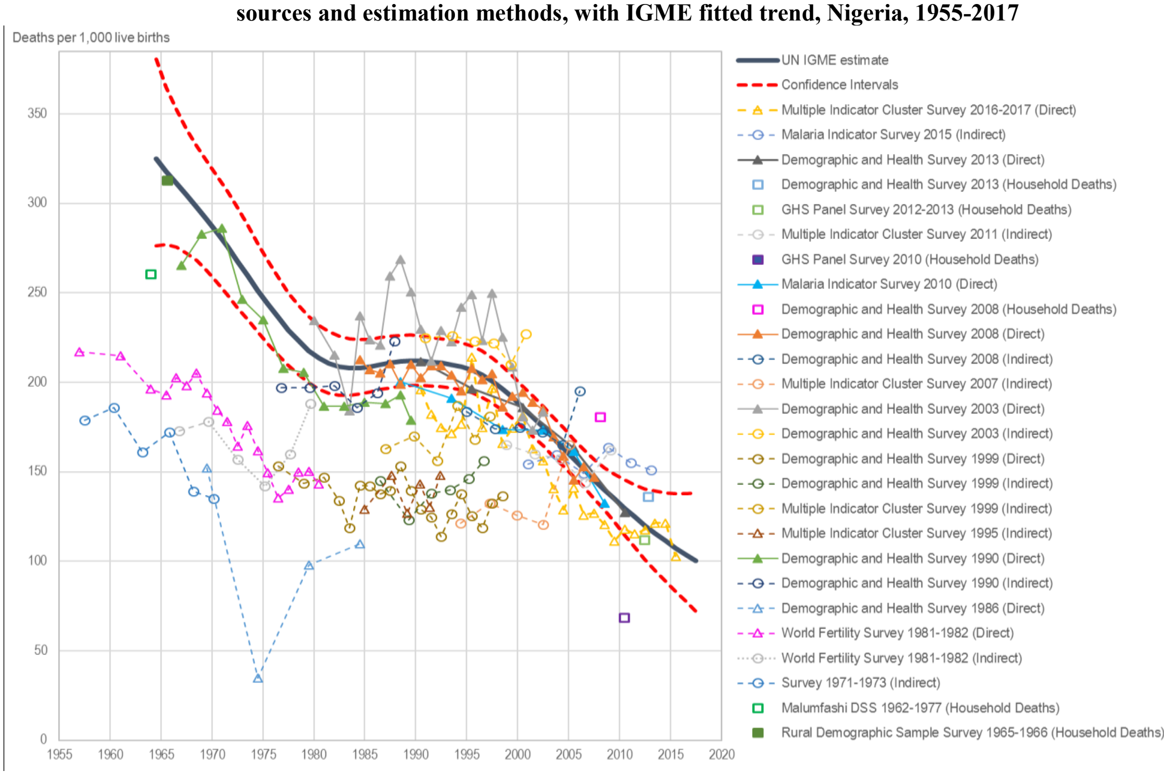
[9] ${}_5q_0$ refers to under-five mortality, that is, the probability of dying between birth and age 5. ${}_{35}q_{15}$ *and* ${}_{45}q_{15}$ are the probabilities of dying between age 15 and 50 and 15 and age 60, respectively, conditional on survival to age 15. These are commonly used summary indices of adult mortality.

[10] For example, pooled analysis using Loess (local regression) or cubic splines with analytical weights (Obermeyer and others, 2010; Rajaratnam and others, 2010), spatiotemporal Gaussian process regression using covariates (Dicker and others, 2018) or by using a bias-adjusted data model to control for systematic biases between different types of data (Alkema and others, 2012; Alkema and others, 2014; Masquelier and others, 2018).

which fitted a robust trend through the various data sources. As an example, figure I.3 provides an overview of the underlying empirical estimates for Nigeria, which were used to derive child mortality ($_5q_0$) estimates for both sexes combined. Note that the various series represented by dashed lines and non-filled markers were excluded from the analysis due to their lack of reliability or national representativity.[11]

Figure I.3. Estimates of under-five mortality (deaths under age five per 1,000 live births) derived by using various data sources and estimation methods, with IGME fitted trend, Nigeria, 1955-2017

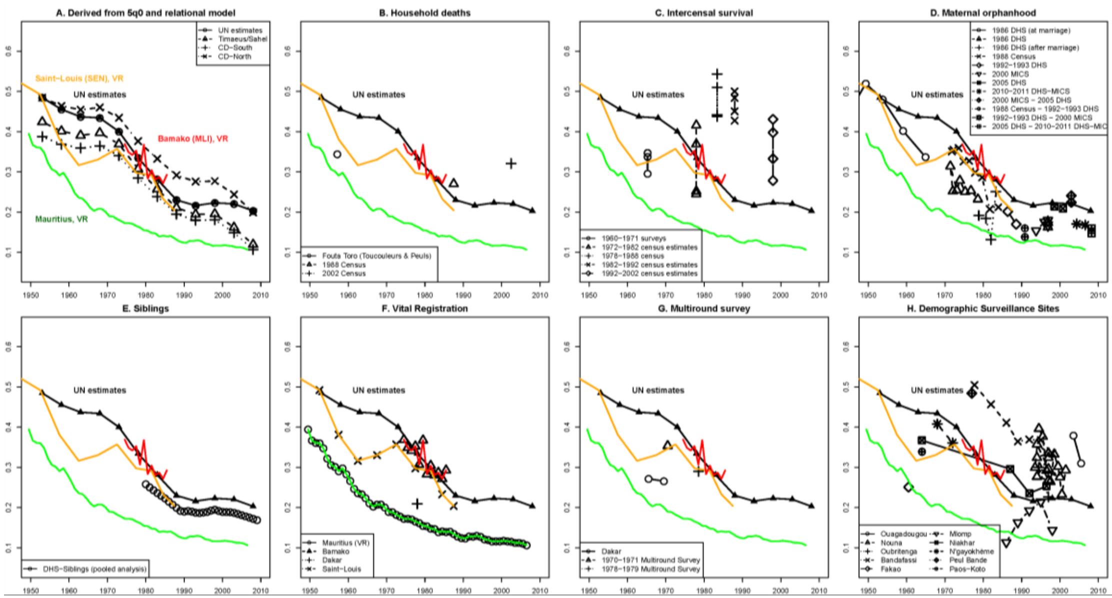


Source: www.childmortality.org (accessed 1 July 2018).

For adult ages, age and sex-specific mortality rates (or summary indices of adult mortality such as $_{35}q_{15}$ or $_{45}q_{15}$) were analysed using a variety of data sources and estimation methods based on data availability and reliability (United Nations, 1983, 2002; Moultrie and others, 2013; Hill and others, 2005; Obermeyer and others, 2010; Rogers and Crimmins, 2011; Masquelier, 2013; Dicker and others, 2018). For example, figure I.4 shows estimates of female adult mortality in Senegal based on various data sources and estimation methods. These various sets of estimates can be roughly categorized into four types: (a) model-based, (b) direct estimates (e.g., household deaths, survival from sibling histories), (c) indirect estimates (e.g., paternal and maternal orphanhood methods) and (d) small area estimates from demographic surveillance sites. If all estimation methods and data sources were internally consistent, all estimates should agree but indicated by the plots in figure I.4, the reality is quite complex, and some of the empirical estimates can be biased and provide very different assessments of levels and trends that are difficult to reconcile.

[11] Further details about the methodology for estimating child mortality and detailed set of series included in the analysis are publicly available for all countries at http://www.childmortality.org/.

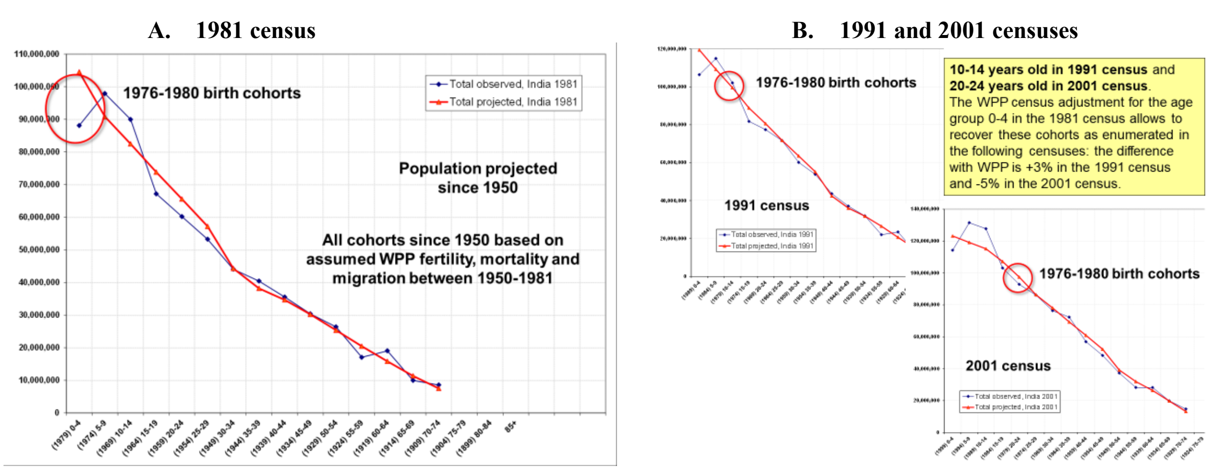
Figure I.4. Estimates of female adult mortality (deaths under age 60 per 1,000 alive at age 15) derived by using various data sources and estimation methods, Senegal, 1950-2010



Note: Estimates of female adult mortality ($_{45}q_{15}$) for Senegal were derived using the implied relationship between child mortality and adult mortality of the North model of the Coale-Demeny Model Life Tables in the 1950s, but were assumed to converge over time towards the South model of Coale and Demeny by the 1990s (panel A). In addition, recent data on household deaths from the 1988 and 2002 censuses (panel B) and the 1978-1979 Multiround Survey (panel G) were also considered, together with estimates from data on parental orphanhood from these censuses and surveys (panel D) and estimates from DHS siblings survival (panel E). Intercensal survivorship from successive census age distributions (smoothed and unsmoothed) for periods 1976-1988 and 1988-2002 (panel C) was reviewed but excluded from the analysis due to lack of reliability. Data from urban vital registration (panel F) and West African rural demographic surveillance sites (Panel H) were also considered. Vital registration data from Mauritius are shown in green in each panel to represent a plausible lower bound for female adult mortality.

When multiple successive censuses are available, it is possible to track cohorts over time. This information can be used to assess the degree to which an apparent under-enumeration of children under the age of five reflected a real reduction in the size of the birth cohort or whether it was the result of age misreporting or date omission problems (Gerland, 2014).

Figure I.5. Comparison of 1976-1980 birth cohorts enumerated in the 1981, 1991 and 2001 censuses of India, and WPP estimates based on a 1950 population reconstruction



Note: India 1976-1980 birth cohorts (circled) enumerated in 1981, 1991 and 2001 censuses (line with diamond) compared to projected cohorts based on WPP reconstruction (line with triangles) using an initial 1950 base population and subsequent trends in fertility, mortality and international migration.

As seen in figure I.5, the size of the 1976-1980 birth cohorts in India as enumerated in 1981 census (panel A) was compared with the number of 10-14 year olds in the 1991 as well as the number of 20-24 year olds in the 2001 census (panel B). Based on the UN adjusted estimates for the age group 0-4 (as compared to the 1981 census), the subsequent "projected" sizes of these adjusted cohorts are fairly close to the enumerated populations in corresponding age groups in the 1991 and 2001 censuses. This suggests that the systematic under-enumeration of children under the age of 5, together with some over-reporting of children age 5-9 and 10-14, is a reporting artefact that disappears once children reach older ages.

In producing population and demographic estimates for all countries or areas of the world, the Population Division has gathered and taken into account multiple data sources. As illustrated in above examples, considerable effort has been devoted to evaluating, analysing and reconciling empirical evidence to produce consistent and reliable estimates. However, in the absence of perfect demographic data, it should be noted that there is still a degree of uncertainty associated with the estimates of the population and related fertility, mortality and international migration indicators within many countries, especially in earlier decades.

II. THE PREPARATION OF POPULATION PROJECTIONS

The Population Division has employed the cohort-component projection method for producing individual country projections since the *1963 Revision*. This method, the most common projection method used by demographers, provides an accounting framework for the three demographic components of change — fertility, mortality and international migration — and applies it to the population in question (United Nations, 1956). Technically, it is not a complete projection method on its own, as it requires that the components of change be projected in advance. Rather, it is an application of matrix algebra that enables demographers to calculate the effect of assumed future patterns of fertility, mortality, and international migration on a population at some given point in the future (Preston and others, 2001; Whelpton, 1936) .

In the 2019 revision, the future population of each country was projected from 1 July 2020. The base population starts from 2020 rather than 2015 because the Population Division makes projections of future populations by 5-year age group over a 5-year time period. Compared to the 2017 revision, the base population estimates of the 2019 revision were updated using empirical data for each demographic components up to the most recent year upon data availability, and short term extrapolation methods were used, as applicable, to estimate the population for mid-2020 and components of demographic change for the period from mid-2015 to mid-2020. To project the population forward until 2100, various assumptions were made regarding future trends in fertility, mortality and international migration. Probabilistic methods were used to project future fertility and mortality levels, specifically to derive trajectories of total fertility and life expectancy at birth. In addition, a number of different projection variants were produced to convey the sensitivity of the projections to changes in the underlying assumptions. The following sections summarize the assumptions used for each variant and the associated projection methods.

A. LEVELS AND TRENDS OF FUTURE FERTILITY: CONVERGENCE TOWARDS LOW FERTILITY

As part of its work on probabilistic projections, the Population Division has also published the 80 and 95 per cent prediction intervals of future fertility levels, along with the median trajectory. It should be noted that the median trajectory constitutes the medium-fertility assumption.

Consistent with previous revisions, the 2019 revision of the *World Population Prospects* also includes several variants with different fertility assumptions: (1) medium-fertility assumption; (2) high-fertility assumption; (3) low-fertility assumption; (4) constant-fertility assumption; (5) instant-replacement assumption, and (6) a momentum variant which has a different treatment of the mortality and migration assumptions as compared to the instant-replacement-fertility variant. In preparing the different variants, making the medium-fertility assumption is the most significant first step.

1. Medium-fertility assumption

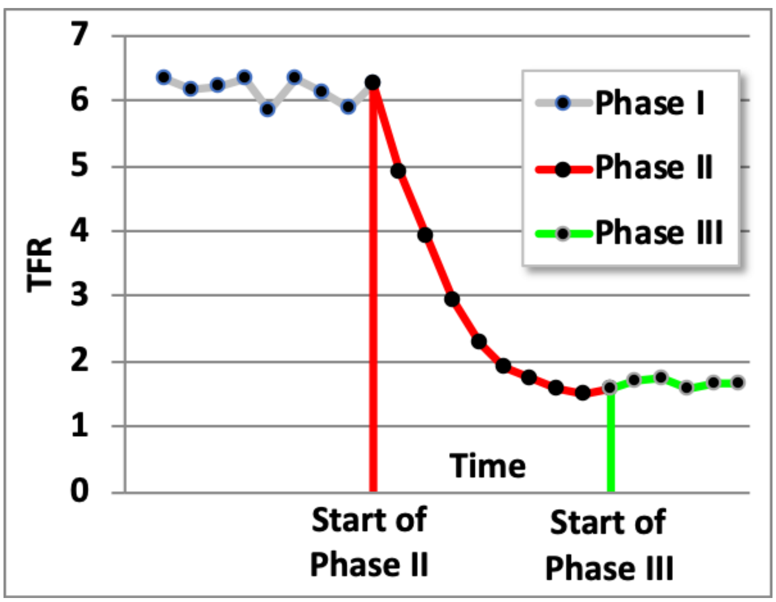
a) Stages of fertility transition and Bayesian projection methods

The 2019 revision of the *World Population Prospects* used probabilistic methods for projecting total fertility, first employed in the 2010 revision (Alkema and others, 2011; Raftery and others, 2009) and updated in subsequent revisions (Raftery and others, 2014a; United Nations, 2014b, 2015, 2017c). The method utilizes the fertility levels and trends estimated for the 2019 revision for all countries[12] of the world for the period 1950 to 2020.

The demographic transition theory is the basis for projections of future country-specific fertility levels. Overall, there is a consensus that the historical evolution of fertility includes three broad phases: (i) a high-fertility, pre-transition phase (phase I), (ii) a fertility transition phase (phase II), and, (iii) a low-fertility, post-transition phase (phase III). Figure II.1 illustrates the three phases of fertility transition. During the observation period from 1950 to 2020, the start of phase II was determined by examining the maximum total fertility. The start of phase II was deemed to have occurred before 1950 for countries where this maximum was less than 5.5 births per woman, and in the period of the local maximum for all other countries. The end of phase II was defined as the midpoint of the time periods when the first two successive increases were observed, after the level of total fertility had fallen below 2 births per woman. If no such increase was observed, a country was treated as still being in phase II.

Based on the most recent population and demographic data available, it was determined that all countries had begun or already completed their fertility transition, being in either phase II or phase III. Thus, fertility transition in these two phases were modelled separately, while phase I was not modelled in the 2019 revision.

Figure II.1. Schematic phases of the fertility transition (live births per woman)



Phase I: High-fertility, pre-transition phase. Not modelled.

Phase II. Fertility-transition phase, modelled by double-logistic function using a Bayesian hierarchical model.

Phase III. Low-fertility, post-transition phase, modelled with a first-order auto-regressive time series model, AR(1), in a Bayesian hierarchical framework.

Source: (Alkema and others, 2011).

The process of fertility decline differs across countries. However, a pattern has been observed in many countries. Overall, the pace or speed of fertility decline is usually faster after the onset of the decline. When fertility is at ‘intermediate” levels, and when fertility approaches the replacement level, the pace usually becomes slower again. It was also found that some variations of this general pattern are associated with the pace of fertility decline at the beginning and at the end of the fertility transition. This empirical evidence made it feasible to first predict the pace of fertility decline over a certain period at

[12] Only countries or areas with 90,000 inhabitants or more in 2019 are considered.

different fertility levels, which subsequently was used to project future levels of fertility, rather than to directly predict the future level of fertility (United Nations, 2006).

The probabilistic framework for projecting total fertility, first applied in the 2010 revision consists of two separate processes:

The first process models the sequence of change from high to low fertility (phase II of the fertility transition). For countries that are undergoing a fertility transition, the pace of the fertility decline is divided into a systematic decline and various random distortion terms. The pace of the systematic decline in total fertility is modelled as a function of its level, based on a double-logistic decline function. The parameters of the double-logistic function were estimated using a Bayesian hierarchical model (BHM), which resulted in country-specific distributions for the parameters of the decline. These distributions are informed by historical trends within the country as well as the variability in historical fertility trends of all countries that have already experienced a fertility decline. This approach not only allows taking into account the historical experience of each country, but also to reflect the uncertainty about future fertility decline based on the past experience of other countries at similar levels of fertility. Under the model, the pace of decline and the limit to which fertility was able to decline in the future varied for each projected trajectory. The model is hierarchical because in addition to the information available at the country level, a second level that is the global experience of all countries is also used to inform the statistical distributions of the parameters of the double-logistic function. This is particularly important for countries at the beginning of their fertility transition, because limited information exists on their speed of decline. To conclude, the future potential trajectories as well as the speed of decline in fertility of countries at the beginning of the fertility transition are mainly informed by the world's experience and the variability in trends experienced in other countries at similar levels of fertility in the past.

Once projected fertility reached phase III (figure II.1), the second component of the projection procedure implemented a time series model to project further fertility change based on the assumption that fertility would approach and fluctuate around country-specific ultimate levels based on a Bayesian hierarchical model, in the long run (Raftery and others, 2014a). The time series model used the empirical evidence from low-fertility countries that have experienced fertility increases from a sub-replacement level following a historic fertility decline. Thus, future long-run fertility levels in the 2019 revision are country-specific, accounting for the country’s own historical experience and also informed by statistical distributions that incorporate the empirical experience of all low-fertility countries that have already experienced a recovery from sub-replacement fertility levels. The world mean parameter for the country-specific asymptotes was restricted to be no greater than a fertility level of 2.1 births per woman.[13]

While for low-fertility countries the long-term assumption of a fertility increase (phase III) is supported by the experience of many countries in Europe and East Asia (Goldstein and others, 2009; Caltabiano and others, 2009; Myrskyla and others, 2009; Sobotka, 2011; Bongaarts and Sobotka, 2012; Myrskylä and others, 2013) the modelling approach also draws upon the specific experience of each country. With this method, countries that have experienced extended periods of low fertility with no empirical indication of an increase in fertility were projected to continue at low fertility levels in the near future (Billari, 2018). This assumption is supported by research on the “low fertility trap hypothesis” for some low-fertility countries in Europe (Lutz, 2007; Lutz and others, 2006) and East Asia (Jones and others, 2008; Frejka and others, 2010; Basten, 2013).

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[13] While the asymptote does not have an explicit lower bound, it does implicitly because any given total fertility trajectory is restricted not to be smaller than 0.5 child.

More recent revisions of WPP have been informed by increasing evidence on recoveries from sub-replacement fertility levels. In total, the number of countries or areas having already entered phase III increased from 25 during the 2012 revision, to 40 during the 2019 revision.[14]

To construct projections for all countries still in phase II, the Bayesian hierarchical model was used to generate 186,000[15] double-logistic curves for all countries that have experienced a fertility decline (figure II.2), representing the uncertainty in the double-logistic decline function of those countries[16]. This sample of double-logistic curves was then used to calculate 100,000 total fertility projections for all countries that had not reached phase III by 2015-2020. For each trajectory at any given time, the double-logistic function provides the expected decrement in total fertility in relation to its current level. A distortion term was added to the expected decrement to reflect the uncertainty inherent in the estimated model of fertility decline.

Up to the 2010 revision an assumption of a long-run fertility level of 1.85 children per woman has been used. In subsequent revisions, the projected level of total fertility has been allowed to fall below that threshold, reflecting uncertainty with regard to the historic minimum level of fertility at the end of phase II before the start of a recovery as part of phase III. The pace of fertility change, the level of fertility, as well as the timing of the end of phase II and the start of phase III, varies for each of the 100,000 projected fertility trajectories for a country that had not reached phase III by 2015-2020. Future trajectories consist of a combination of cases with total fertility in phase II or III, until eventually all trajectories are in phase III. For countries that were already in phase III by 2015-2020, the time series model for that phase was used directly. The unweighted mean value for the world distribution based on the 40 countries or areas that have entered phase III is 1.78 children per woman in 2095-2100 while the 95 per cent prediction interval ranges between 1.66 and 1.94.

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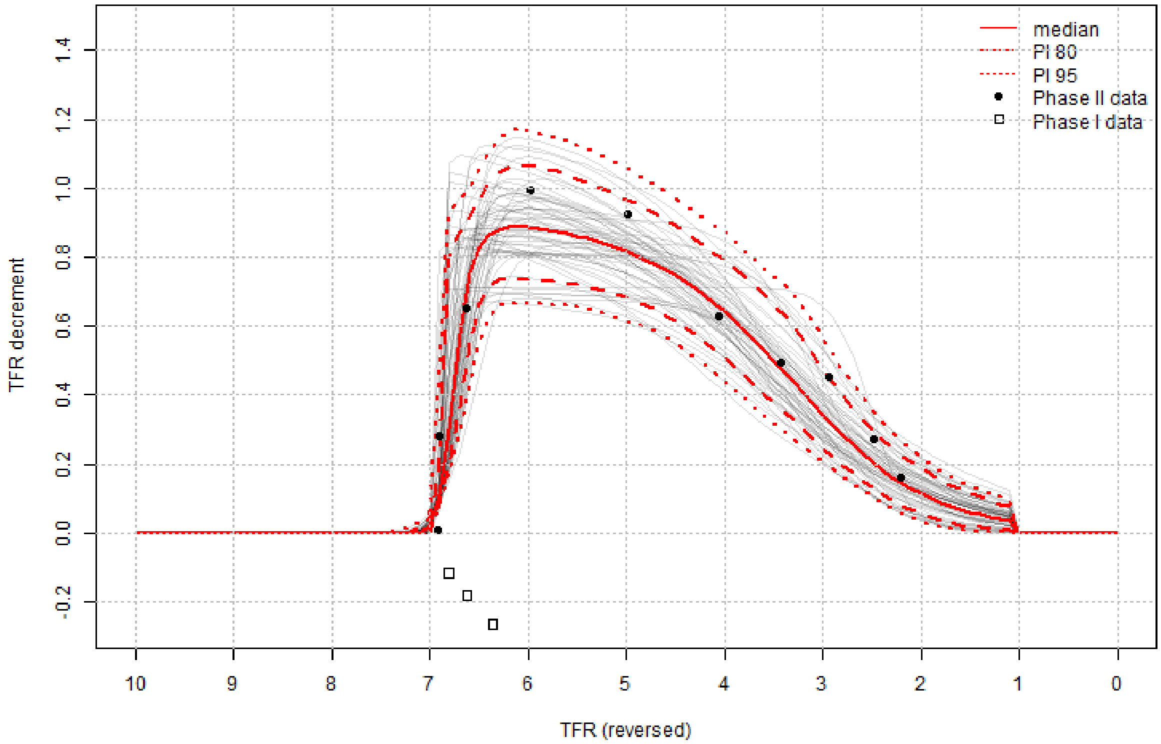
14 The 2019 revision of WPP was informed by the experience of 40 countries or territories that had entered phase III in Eastern and South-Eastern Asia (China, China - Hong Kong SAR, China - Macao SAR, China - Taiwan Province of China, Japan, Singapore, Viet Nam), Latin America and the Caribbean (Aruba, Barbados), and in Europe and Northern America (Armenia, Austria, Belarus, Belgium, Bulgaria, Channel Islands, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States of America).

15 Actually, ten Markov chain Monte Carlo (MCMC) simulations are run in parallel to find the various combinations of parameters with 18,600 iterations performed for each simulation, and the first 2,000 iterations for each simulation are discarded as burn-in trials so that the effect of initial values on the final results is minimized.

16 Graphs of this double-logistic curve are available online at: https://population.un.org/wpp2019/Graphs/Probabilistic/FERT/CHG/50.

Figure II.2. Total fertility decrements by level of fertility and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part) (live births per woman)



Note: Observed five-year decrements by level of total fertility (TFR) are shown as black dots. For clarity, only 60 of the 100,000 calculated trajectories are shown here. The median projection is depicted by the solid red line, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

The probabilistic projections of total fertility have been computed using “bayesTFR” (Ševčíková and others, 2019a; Ševčíková and others, 2011) an open-source and portable software implementation based on the R statistical language with the graphical user interface “bayesDem” (Ševčíková, 2013), and the full dataset used for the 2019 revision (United Nations, 2019b).

The median of these 100,000 trajectories was used as the medium-fertility variant projection in the 2019 revision of WPP. To express the uncertainty surrounding future trends in fertility, 80 and 95 per cent prediction intervals were also calculated (figure II.3). Additional tables[17] and graphs[18] are available online for all countries. For countries that had not reached phase III by 2015-2020, the projected median trajectory reflects the uncertainty as to when the fertility transition will end and at what level.

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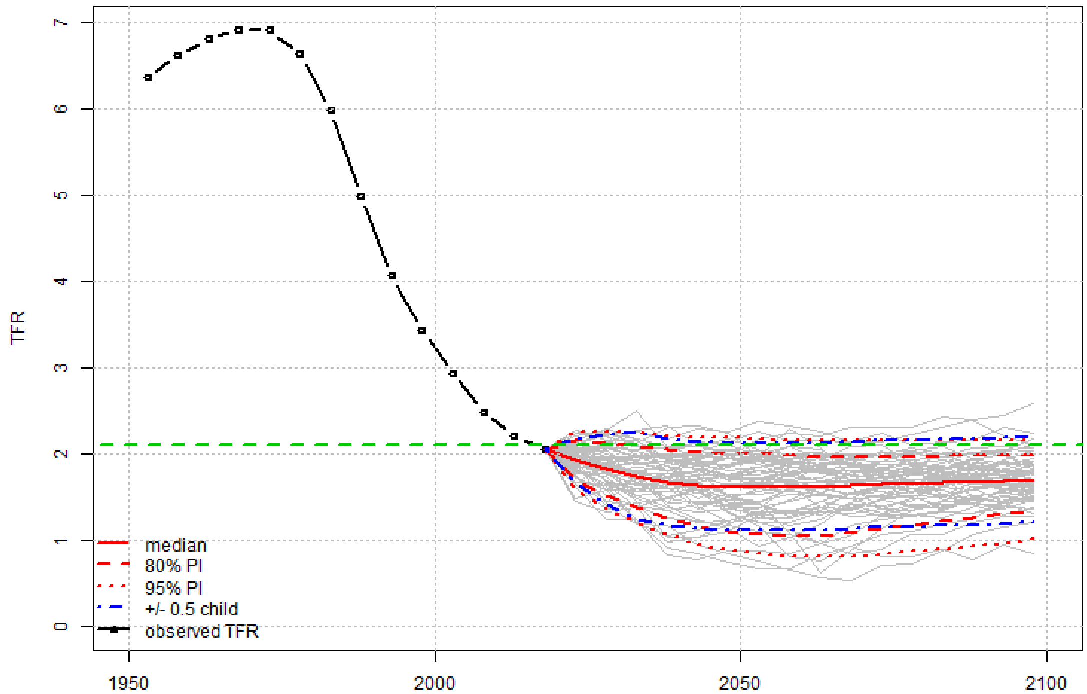
[17] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online tables of stochastic projections of total fertility: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Download/Probabilistic/Input/.

[18] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online plots of projections of total fertility: median, 80 and 95 per cent prediction intervals, high and low WPP fertility variants; see https://population.un.org/wpp2019/Graphs/Probabilistic/FERT/TOT/50.

Figure II.3. Estimates and projected probabilistic trajectories of total fertility, Bangladesh, 1950-2100 (live births per woman)



Note: For clarity, only 60 of the 100,000 calculated trajectories are shown here for the period 2020 to 2100. The median projection is depicted by the solid red line, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively. The high- and low-fertility variants of the 2019 revision correspond to the plus or minus 0.5 births around the median trajectory, shown here as blue dashed lines. The replacement-level of 2.1 births per woman is plotted as green horizontal dashed line for reference purposes only.

The fertility projections produced in the 2019 revision have been informed by historical trends in fertility and reflect an implicit assumption that the conditions facilitating fertility decline will persist in the future. Should massive efforts to scale up family planning information, supplies and services be realized, then the median fertility projections may be too high. On the other hand, should prevailing conditions underlying fertility decline deteriorate (for example, if there is a slowdown in modern contraceptive method uptake or a persistent or resurgent desire for early marriage and large families), then the median projected levels of fertility in this revision may be too low.

b) Short-term adjustments for selected countries or areas with fertility below replacement level

Some countries with fertility below replacement level (phase III) have experienced recent downward trends in total fertility after a period of sustained increase. This trend implies a rupture between the estimated and the projected trajectories. To assure a smoother transition between the last estimation periods and the first projection intervals, the level of fertility projected for 2020-2025 and 2025-2030 was adjusted by blending the most recent observed trend with the unadjusted model prediction respectively by 2/3 in 2020-2025 and 1/3 in 2025-2030 weights given to the most recent country trend, and the complement used for the model prediction. Such post-adjustment was applied to five countries in the

2019 revision (Finland, Italy, Japan, Luxembourg and Ukraine)[19], and all probabilistic trajectories were proportionately adjusted based on these adjustment factors for the median trajectory of each country.[20]

2. *High-fertility assumption*

The 2019 revision of WPP retains a number of standard projection variants that are used to illustrate the effects of certain fertility assumptions when applied to all countries simultaneously. Under the high variant, fertility is projected to remain 0.5 births above the fertility in the medium variant over the entire projection period except for the initial years. To create a smooth transition between levels observed for the baseline period (2015-2020) and future levels within the high variant, fertility for the high variant was assumed to be 0.25 births higher in the first projection period (2020-2025) compared to the baseline, 0.4 births higher in the second projection period (2025-2030), and 0.5 births higher thereafter. Thus, starting in 2030-2035, fertility in the high variant was assumed to be 0.5 births higher than that of the medium variant. In other words, a country with a total fertility rate of 2.1 births per woman in some time period under the medium variant would have a total fertility of 2.6 births per woman in the high variant.

3. *Low-fertility assumption*

Under the low variant, fertility is projected to remain 0.5 births below the fertility in the medium variant over most of the projection period. To ensure a smoother transition between the baseline period (2015-2020) and the low variant, fertility in the low variant is initially 0.25 births lower in the first projection period (2020-2025), 0.4 births lower in the second projection period (2025-2030), and 0.5 births lower thereafter. By 2030-2035, fertility in the low variant is therefore half a child lower than that of the medium variant. That is, countries reaching a total fertility rate of 2.1 births per woman in the medium variant have a total fertility rate of 1.6 births per woman in the low variant.

4. *Constant-fertility assumption*

As the name implies, under the constant-fertility variant, fertility in all countries remains constant at the level estimated for 2015-2020. Meanwhile, mortality and migration assumptions are the same as those in the medium fertility variant.

5. *Instant-replacement assumption*

Under the instant-replacement variant, for each country, fertility is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2020-2025. Fertility varies over the remainder of the projection period in such a way that the net reproduction rate always remains equal to one ensuring, over the long run, the replacement of the population[21]. Mortality and migration assumptions are the same as those in the medium fertility variant.

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[19] The list of countries is based on the following three criteria: (1) TFR is below 2.1 children per woman in 2015-2020 and (2) the TFR between 2010-2015 and 2015-2020 periods decline by 2.5% or more, and (3) the unadjusted median TFR between 2015-2020 and 2020-2025 periods is projected to increase by 2.5% or more.

[20] The adjustment for a country and time period corresponds to the ratio between the unadjusted median TFR and adjusted median TFR, and is applied to each TFR probabilistic trajectory for the corresponding country and period.

[21] Mortality levels are also taken into account while measuring the replacement level.

6. *Momentum assumption*

The momentum variant combines elements of three existing variants (the instant-replacement-fertility variant, the constant-mortality variant, and the zero-migration variant) that were routinely produced in previous revisions. Under this variant, for each country, fertility is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2020-2025, while the mortality is kept constant as of 2015-2020 and net international migration is set to zero from 2020-2025 onwards (United Nations, 2017a).

B. PROJECTION OF THE AGE PATTERNS OF FERTILITY

Once the path of future total fertility was determined, age-specific fertility rates by five-year age group were calculated, which were consistent with the total fertility for each quinquennium. In the 2019 revision, a standard approach was used to project age-specific patterns of fertility for all countries. Beginning from the most recent observation of the age pattern of fertility in the base period of projection, the projected age patterns of fertility were based on past national trends combined with a trend leading towards a global model age pattern of fertility[22] (Ševčíková and others, 2016). The projection method was implemented on the proportionate age-specific fertility rates (PASFR) with seven age groups, ranging from 15-19 to 45-49.

The final projection of the PASFR for each age group is a weighted average of two preliminary projections:

1. first preliminary projection, assuming that the PASFRs converge to the global model pattern, and
2. second preliminary projection, assuming that the observed national trend in PASFRs continues indefinitely.

The method was applied to each of the trajectories that constituted the probabilistic projection of the total fertility rate of each country, based on the estimated PASFRs for 1950-2020 used in the 2019 revision. In examining the resultant mean age at childbearing (MAC), it was found that the mean values, rather than the median values, of generated PASFRs produced a smoother trend line for most countries.

It was assumed that the transition in each trajectory from the observed national trend to the global model age pattern of fertility was dependent on (a) the timing of when the total fertility rate (TFR) entered phase III, i.e. when the fertility transition was completed and a given country trajectory reached its lowest level of fertility, and on (b) whether the projected fertility for a given period is higher than the ultimate TFR (2095-2100) in the medium variant projection (Ševčíková and others, 2016). For some countries with low fertility that already have later mean age at childbearing than the global model age pattern, the fertility pattern was held constant when the highest mean age was reached in the convergence period (phase III).

[22] The global model pattern in the 2019 revision is based on the unweighted average of the proportionate distribution of the age-specific fertility rates by five-year age group for the following low fertility countries or areas that (a) have reached phase III, and (b) display childbearing patterns with a mean age at childbearing of 30 years or above in 2015-2020: Austria, Belgium, Channel Islands, China - Hong Kong SAR, China - Macao SAR, China - Taiwan Province of China, Czechia, Denmark, Estonia, Finland, France, Germany, Italy, Japan, Luxembourg, Malta, Netherlands, Norway, Singapore, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Out of 20 major methods to project fertility by age, this overall approach has been confirmed to be one of the four best performing methods (Bohk-Ewald and others, 2018) with the greatest accuracy to predict completed cohort fertility (i.e., how many children will be born on average by women over their entire reproductive lifetime).

C. MORTALITY ASSUMPTIONS: INCREASING LIFE EXPECTANCY FOR ALL COUNTRIES

1. Normal mortality conditions

a) Assumptions for future levels and trends of life expectancy at birth

Assumptions for the projection of mortality are specified in terms of life expectancy at birth by sex. As part of the probabilistic population projections, the Population Division publishes 80 and 95 per cent prediction intervals for future levels of life expectancy at birth, along with the median trajectory derived from a statistical model describing mortality change over time. The median trajectory provides the mortality trend used in the high-, medium- and low-, instant-replacement-fertility, and zero-migration variants. Only one variant of future mortality trends for each country was used for these variants, which reflect variation in fertility alone. As in previous revisions, life expectancy was generally assumed to rise over the projection period.

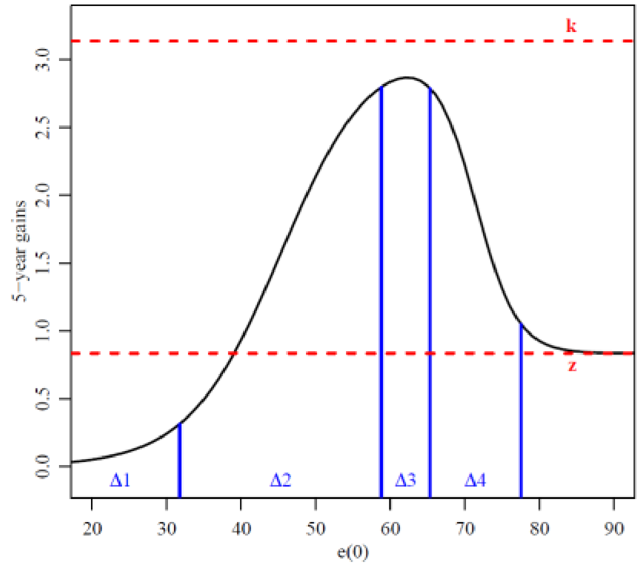
The 2019 revision of *World Population Prospects* used probabilistic methods for projecting life expectancy at birth, including the modifications that were made in the implementation of the models in the 2017 revision (Castanheira and others, 2017; United Nations, 2017c). It also uses a new extension to account for past and expected levels and trends in HIV prevalence and adult antiretroviral therapy (ART) coverage for countries affected by the HIV/AIDS epidemic.

b) Projection of female life expectancy

The probabilistic methods used in the 2019 revision for projecting life expectancy at birth comprise two separate models. The first model depicts the gradual increase over time in female life expectancy at birth (Raftery and others, 2013). In this model, the transition from high to low levels of mortality is divided into two phases, each of which are approximated by a logistic function that models the gains in life expectancy (figure II.4).

The first phase, modelled through the first two delta terms in figure II.4, consists of the initial slow growth in life expectancy associated with the diffusion of improved hygiene and nutrition, followed by a period of accelerated improvement, especially in the mortality of infants and children, associated with social and economic development accompanied by interventions in public health and basic medical care, including infant feeding, water and sanitation, and childhood immunization programmes. The second phase, modelled through the third and fourth delta terms in figure II.4, begins once the easiest gains, mainly from fighting infectious diseases that often strike in childhood, have been achieved. The second phase is characterized by a combination of continued gains from defeating infectious diseases across the age range and from combating non-communicable diseases that strike primarily at older ages. Given the greater challenges in preventing deaths from non-communicable diseases and the lower payoff in years of life expectancy gained that result from saving the life of an older person as compared to that of a child, the rise of life expectancy is slower in the second phase (Fogel, 2004; Riley, 2001).

Figure II.4. Phases of the mortality transition: gains in life expectancy at birth by level of life expectancy at birth (years)



Source: Raftery and others (2013).
Note: The deltas (Δ) in the figure represent changes in the magnitude of 5-year gains against increases in life expectancy at birth.

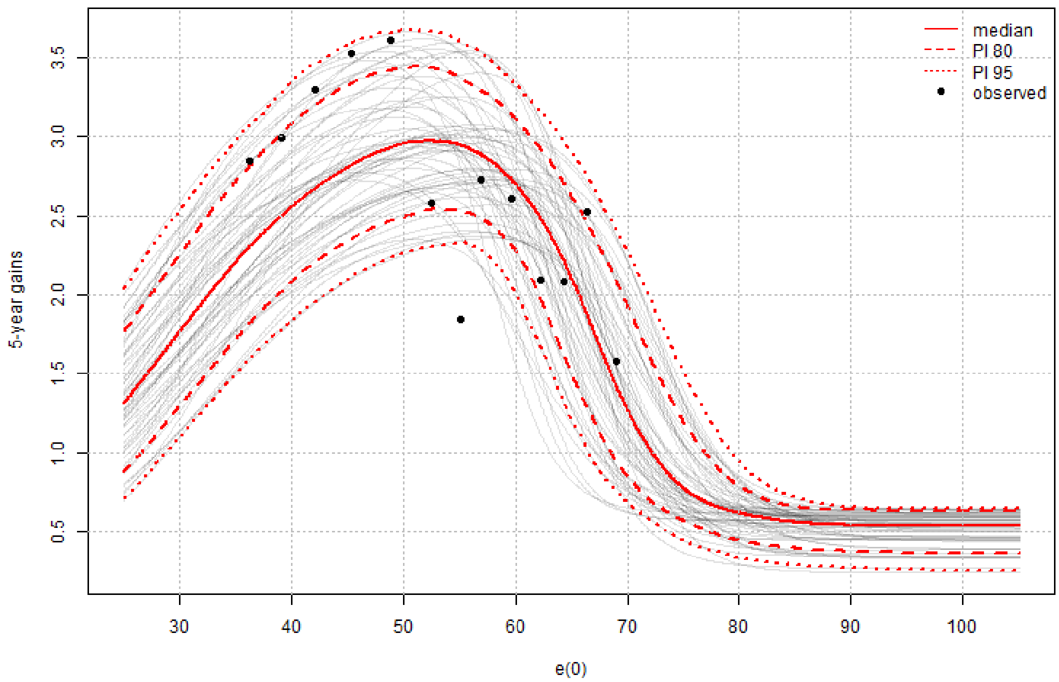
For all countries undergoing a mortality transition, the pace of improvement in life expectancy at birth described by the model is composed of two parts, which are depicted by a systematic decline term and a random distortion term:

1. The pace of the systematic gains in life expectancy at birth is modelled as a function of the level of life expectancy, based on a double-logistic improvement function developed in earlier revisions of *World Population Prospects* (United Nations, 2006). The parameters of the double-logistic function were estimated on the basis of the observed gains in female life expectancy from 1950 until 2020 for each country, using a Bayesian hierarchical model that yields country-specific distributions for all estimated parameters and for future trends in life expectancy. The model is hierarchical because, in addition to the information available for a particular country, a second level of information derived from the average global experience is used to inform the estimation of each country-specific double-logistic curve.

2. Given the estimated double-logistic curve for a particular country or area, each projected value of life expectancy at time t+5, the next 5-year projection period, was derived using a random walk with drift (Raftery and others, 2013), where the drift parameter, which specifies the pace of change over time, was taken from the estimated country-specific double-logistic function.

Under these conditions, the pace of improvement and the asymptotic limit to future gains in female life expectancy vary for each projected trajectory, but ultimately are informed and constrained by the finding that the rate of increase of maximum female life expectancy over the past 150 years has been approximately linear (Oeppen and Vaupel, 2002; Vaupel and Kistowski, 2005), albeit at a slower pace after female life expectancy at birth in the vanguard countries started to exceed 75 years in the 1960s (Vallin and Meslé, 2009). Additional evidence used to guide decisions about the future rate of increase of life expectancy at birth included information on the historic increase of the maximum recorded age at death for women, or the maximum observed female lifespan, among countries with high life expectancies and reliable data on mortality at very old ages. Maximum recorded female age at death in countries such as Sweden and Norway has been increasing at a steady pace of about 1.25 years per decade since around 1970 (Wilmoth and others, 2000; Wilmoth and Robine, 2003; Wilmoth and Ouellette, 2012). Since the increase in average lifespan cannot exceed the increase in maximum lifespan indefinitely, the historic pace of increase in the observed maximum lifespan of women from selected countries was used to set the value of the model parameter that helps to determine the asymptotic average rate of increase in female life expectancy.[23]

Figure II.5. Female gains in life expectancy at birth by level of life expectancy at birth and prediction intervals of estimated double-logistic curve, India (years)



Note: The observed five-year gains by level of life expectancy at birth (e(0)) are shown by black dots. For ease of viewing, only 60 of the 1,380,000 simulated trajectories are shown here. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

To construct projections of female life expectancy at birth for all countries, the Bayesian hierarchical model was used to generate 1,380,000[24] double-logistic curves for each country or area (figure II.5), representing the uncertainty in the estimated curve describing the country-specific relationship between the current value of life expectancy and the pace of increase in life expectancy[25].

A systematic sampling of double-logistic curves was then used to calculate over 100,000 projected values of life expectancy at birth for each country or area in each time period. All the probabilistic

[23] Following the notation used in Raftery and others (2013), to obtain a posterior median of the annual gain in life expectancy of around 0.125 year (or 5-year gain of 0.625), the parameter constraining the maximal value of the asymptote of the double-logistic curve at high levels of life expectancy was set to 0.653, both for the global parameter (z) and for each country-specific parameter (z^c), during both the estimation and subsequent use of the collection of country-specific double-logistic curves.

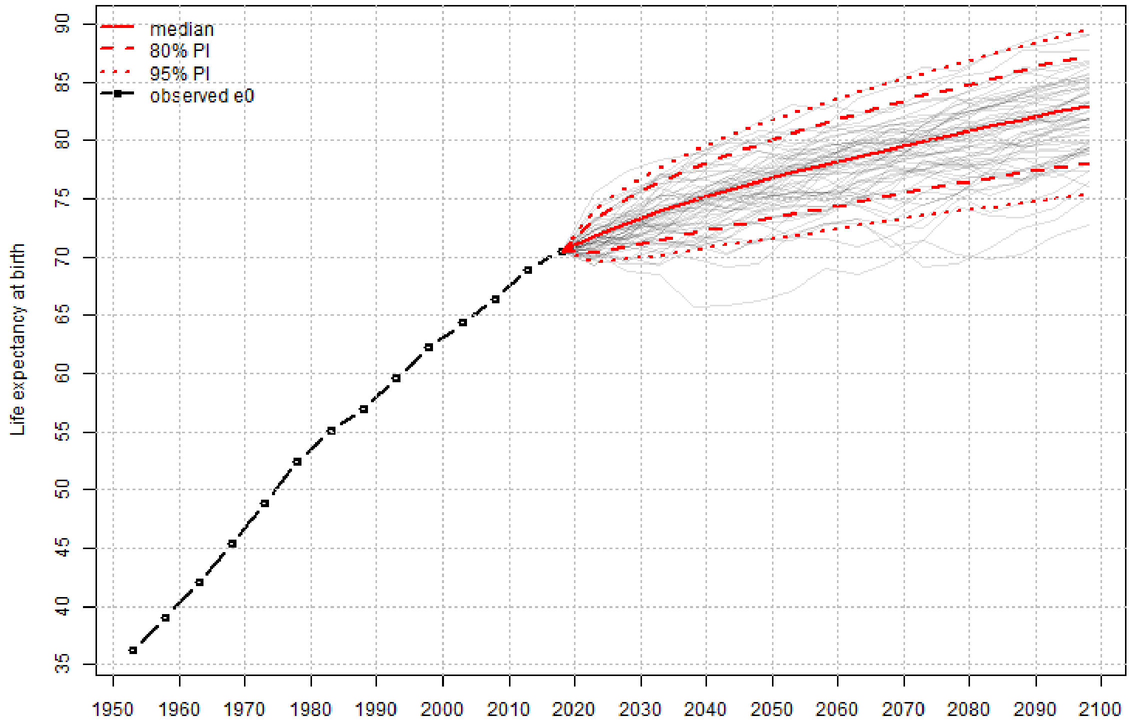
[24] Actually, ten Markov chain Monte Carlo (MCMC) simulations were run in parallel to find the various combinations of parameters with 138,000 iterations performed for each simulation, and the first 10,000 for each simulation were discarded as burn-in trials so that the effect of initial values on the final results is minimized.

[25] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York. Online plots of double-logistic curves depicting 5-year gains in female life expectancy at birth, estimated using a Bayesian hierarchical model (BHM): median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Graphs/Probabilistic/EX/CHGFEM/356.

projections of female life expectancy at birth were computed using "bayesLife" (Ševčíková and others, 2014), an open-source and portable software implementation based on the R statistical language together with the graphical user interface "bayesDem" (Ševčíková, 2013), and the full dataset used for the 2019 revision (United Nations, 2019b).

The median of these 100,000 trajectories was used as the standard mortality projection of the 2019 revision. To evaluate the uncertainty of future trends in female life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.6). Additional tables[26] and graphs[27] for all countries are available online.

Figure II.6. Estimates and projected probabilistic trajectories of female life expectancy at birth, India, 1950-2100 (years)



NOTE: For ease of viewing, only 60 trajectories of the 100,000 simulated trajectories are shown here for 2020 to 2100. The median trajectory is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines respectively.

2. *Projections of life expectancy at birth for HIV/AIDS countries*

The 2019 revision took a different approach compared to the 2017 revision to project the life expectancy at birth of countries affected by the HIV/AIDS epidemic. For the 58 countries or areas having ever experienced adult HIV prevalence of one per cent or more among males or females during the period 1980 and 2017, the levels of life expectancy at birth were projected using the existing Bayesian probabilistic life expectancy projection methods (United Nations, 2017c) extended to account for past and expected levels and trends in HIV prevalence and adult antiretroviral therapy (ART) coverage (Godwin

[26] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. Online tables of probabilistic projections of female life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Download/Probabilistic/Input/.

[27] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York. Online plots of probabilistic projections of female life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Graphs/Probabilistic/EX/Female/356.

and Raftery, 2017). The latest epidemiological data for these countries were used for the 1980-2017 period (UNAIDS, 2019). The projection assumptions for the future course of the HIV/AIDS epidemic were similar as in previous revisions: the 2019 revision assumed that the HIV prevalence rate observed in 2017 would decline by 2100 to about one-tenth of its value following an exponential decay function. Coverage of ART was projected to reach 90 per cent in 2050 if it was below 85 per cent in 2017 or to reach 95 per cent if it was above 85 per cent in 2017; it remained constant thereafter until 2100. All computations for the probabilistic projections of life expectancy at birth for HIV/AIDS countries were performed using the open source "bayesLifeHIV" R package (Ševčíková and others, 2019b).

3. Modelling of the gap between female and male life expectancy

The second model used for projecting future mortality trends addresses the gap between female and male life expectancy at birth. Results obtained using the model of the sex-gap in life expectancy were combined with those from the model of female life expectancy in order to derive projections of male life expectancy. In other words, projected values of male life expectancy were obtained by subtracting the projected gap from the projected value of female life expectancy. The application of this approach took into account the correlation between female and male life expectancies, and the existence of outlying data points during periods of crisis or conflict (Raftery and others, 2014b).

The gap in life expectancy at birth between females and males was modelled using an autoregressive model with female life expectancy serving as a covariate. A large body of literature exists on biological, behavioural and socioeconomic factors underlying the gap in life expectancy between women and men (Oksuzyan and others, 2008; Rogers and others, 2010; Trovato and Heyen, 2006; Trovato and Lalu, 1996, 1998). Recent trends provide evidence of a narrowing in the sex gap for almost all high-income countries (Glei and Horiuchi, 2007; Meslé, 2004; Oksuzyan and others, 2008; Pampel, 2005). The pattern of decline in the sex gap at high levels of life expectancy, which has been observed for high-income countries and for some emerging economies, was assumed to apply in the future to other countries as well. Such trend does not seem implausible given the diffusion of effective public health and safety measures and medical interventions (Vallin, 2006; Bongaarts, 2009). In effect, the projection model used by the United Nations implies, on the basis of past experience in countries from across the world, that the future sex gap is expected to widen when life expectancy is low but will tend to narrow once female life expectancy reaches about 75 years. In the current implementation of the model, this narrowing is assumed to continue until female life expectancy attains a threshold value set equal to 86 years. This specification brought about some convergence in male and female values of life expectancy at birth within the projection interval for some countries. For projected levels of female life expectancy at or above the highest values observed to date (about 86 years), the sex gap was modelled as constant with normally distributed distortions because little information on the determinants of changes in the gap exists at these high ages and beyond.

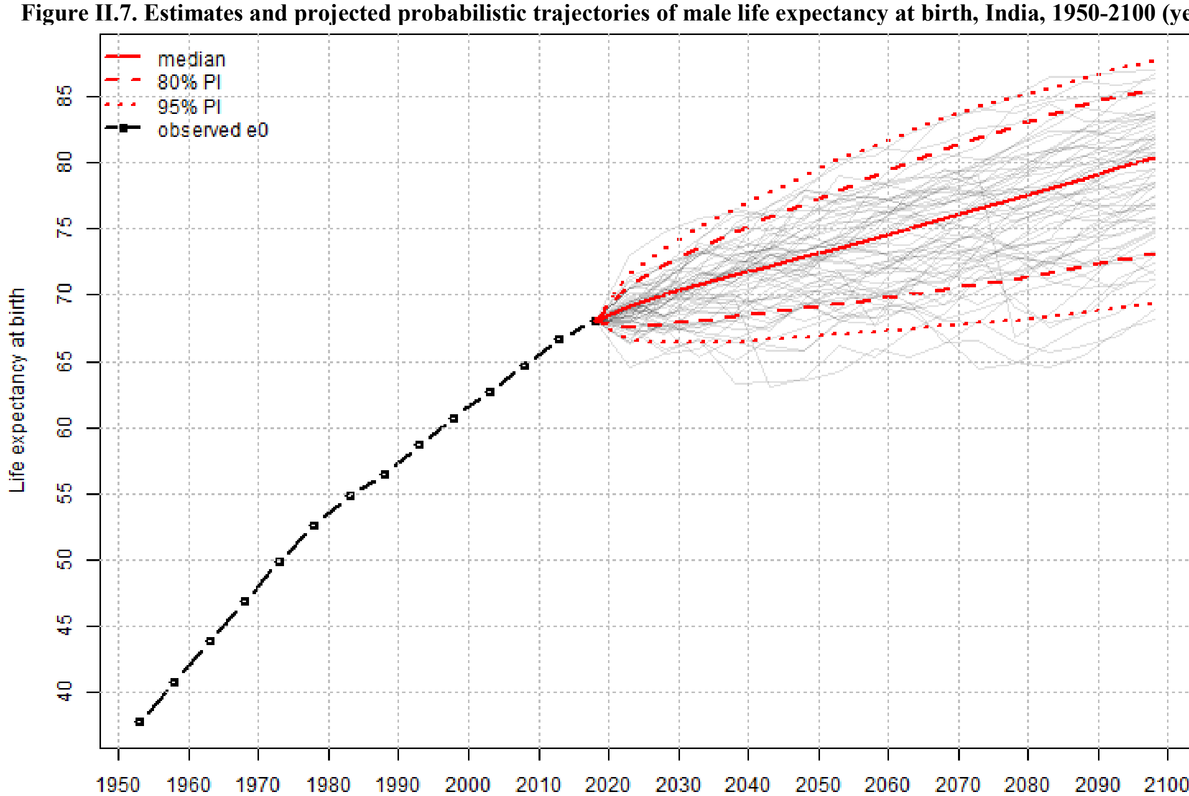
To systematically produce joint probabilistic projections of female and male life expectancy, a large number of future trajectories for the gap in life expectancy was simulated. To construct projections of male life expectancy at birth, the autoregressive model of the sex gap in life expectancy was used to generate 100,000 trajectories of the gap for each country (figure II.8), representing the uncertainty in the projected future gap. Then, each simulated value of the sex gap was subtracted from its paired value of female life expectancy to generate the corresponding projected value of male life expectancy. Graphs of the sex gap trajectories for all countries are available online[28].

As in the 2017 revision (United Nations, 2017c), the 2019 revision includes historical data for periods prior to 1950 for several countries in the dataset used to estimate the coefficients of the sex gap model. The minimum and maximum bounds of the gap were set at 0.5 and 18, respectively.

The sample of gender gap trajectories was then used to calculate over 100,000 male life expectancy projections for each country. All the computation for the probabilistic projections of male life expectancy at birth were performed using the open source "bayesLife" R package (Ševčíková and others, 2014).

The median of these projections was used as the standard mortality projection in the 2019 revision of WPP. To evaluate the uncertainty of future trends in male life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.7). Additional tables[29] and graphs[30] for all countries are available online.

Figure II.7. Estimates and projected probabilistic trajectories of male life expectancy at birth, India, 1950-2100 (years)



NOTE: For clarity, only 60 trajectories of the 100,000 calculated are shown here for 2020 to 2100. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively.

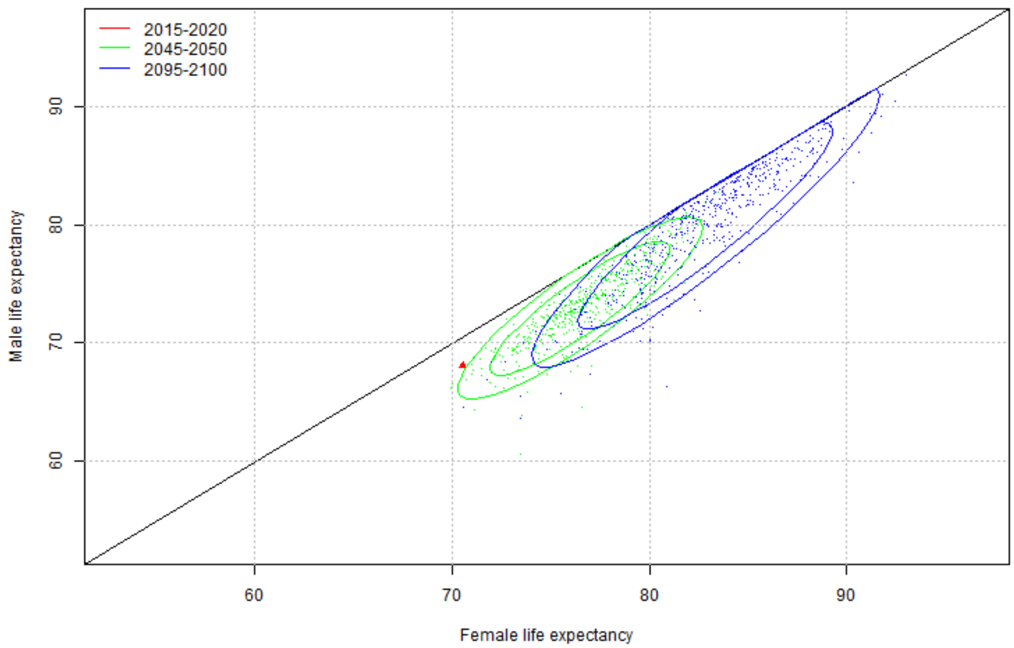
28 United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online plots of female-male gap in life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Graphs/Probabilistic/EX/356.

29 United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online tables of probabilistic projections of male life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Download/Probabilistic/Input/.

30 United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online plots of probabilistic projections of male life expectancy at birth: median, 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Graphs/Probabilistic/EX/Male/356.

The relationship between probabilistic projections of male and female life expectancy at birth for selected projection periods can be summarized through scatter plots showing a subsample of 500 probabilistic trajectories of life expectancy at birth for males and females (figure II.8). The 80 and 95 per cent prediction intervals are shown as ellipses. The diagonal line represents equal male and female life expectancies. Graphs of the distributions of life expectancy by sex for all countries are available online.[31]

Figure II.8. Comparison of probabilistic projections of female and male life expectancies at birth, selected periods, India (years)



NOTE: The figure shows the relationship between probabilistic projections of male and female life expectancies at birth for 2015-2020, 2045-2050 and 2095-2100, computed on the basis of estimates from the 2019 revision of the *World Population Prospects*. For ease of viewing, only 500 of the 100,000 projected trajectories are shown here for each sex.

4. Adjustments for future mortality improvements for selected countries or areas

The approach to life expectancy projections described above worked well for the majority of countries that have experienced normal or typical improvements in survival since the 1950s. But some countries stood out either because of much faster or much slower improvements than experienced by other countries. Countries that have experienced much faster gains in life expectancy since the 1950s, or over segments of the estimation period, are often countries that still have relatively low life expectancy even though they may have made substantially faster progress than that historically observed in other countries. A relatively fast decline in child mortality in the latter part of the observation period may have contributed to a strong increase in the projected life expectancy based on the current model application in some of these countries. On the other hand, several countries that experienced periods of stagnating mortality in the observation period tended to have unusually small projected increments in life expectancy with the standard approach. In both cases, adjustments were made such that the four parameters of the

[31] United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. Online plots of Comparison between probabilistic projections of male and female life expectancies at birth for selected projection periods: 80 and 95 per cent prediction intervals; see https://population.un.org/wpp2019/Graphs/Probabilistic/EX/FMCOMP/356.

double logistic function responsible for future gains for each country were informed by the experience of the leading countries in its respective region.

The countries to which adjustments were applied are listed in table II.1 together with the respective values used as priors for each adjusted parameter[32]. In the first case (A), this approach was used to temper large gains for some countries in the distant future that lead in some cases to implausible outcomes or crossovers in long-term projections (i.e., countries that were lagging in the recent observation period becoming leaders by 2100). In the second case (B), this approach was used to provide further guidance on the trajectory of long-term potential gains for countries that have experienced mortality stagnation or worsening (i.e., it is assumed that, in the long run, these countries will gradually catch up with the more advanced countries in their region).

TABLE II.1. COUNTRIES FOR WHICH ADJUSTMENTS WERE MADE TO THE DEFAULT MORTALITY PROJECTION TRAJECTORY IN THE 2019 REVISION

A. Countries with projected life expectancies that were deemed too high		Upper bound for country-specific priors of the double-logistic parameters			
Country or area		Δ_{c3}	Δ_{c4}	k^c	z^c
1.	Angola	12.00	16.00	2.8959	0.5750
2.	Bolivia (Plurinational State of)	8.00	16.00	3.1649	0.5774
3.	Cambodia	12.00	17.00	2.9743	0.5983
4.	Central African Republic	12.00	17.00	2.6909	0.5945
5.	Chad	12.00	17.00	2.2299	0.5946
6.	Democratic Republic of the Congo	12.00	17.00	2.5214	0.5948
7.	Equatorial Guinea	12.00	17.00	2.6909	0.5946
8.	Eswatini	12.00	16.00	3.1206	0.5752
9.	Guinea	12.00	17.00	2.8068	0.5948
10.	Guinea-Bissau	12.00	17.00	2.5944	0.5940
11.	Lao People's Democratic Republic	12.00	16.00	2.6896	0.5778
12.	Liberia	12.00	17.00	2.8068	0.5948
13.	Mali	12.00	16.00	3.2477	0.5749
14.	Niger	12.00	16.00	2.6674	0.5756
15.	Nigeria	12.00	16.00	2.4551	0.5749
16.	Sierra Leone	12.00	16.00	2.6674	0.5756
17.	Somalia	13.89	18.46	1.9808	0.5951
18.	South Sudan	13.89	18.46	1.9808	0.5951
19.	Tajikistan	12.00	17.00	2.2715	0.5832
20.	Timor-Leste	13.00	17.00	3.1603	0.5962

B. Countries with projected life expectancies that were deemed too low		Lower bound for country-specific priors of the double-logistic parameters			
Country or area		Δ_{c3}	Δ_{c4}	k^c	z^c
1.	Cote d'Ivoire	9.89	16.10	4.0155	0.4857
2.	Fiji	12.00	18.00	3.5829	0.4819

[32] Following the formal notation of Raftery and others (2013), country-specific priors were specified for the first set of countries for the upper bound of the Δ_{c3}, Δ_{c4}, k^c and z^c double-logistic parameters while for the second set of countries, the lower bound were used for these parameters. In general, the upper quartile of the distribution of these parameters for the best performers in each region was used to inform other countries.

A. Countries with projected life expectancies that were deemed too high	Upper bound for country-specific priors of the double-logistic parameters			
Country or area	Δ_{c3}	Δ_{c4}	k^c	z^c
3. Kenya	9.65	14.05	2.6872	0.4515
4. Pakistan	11.00	18.00	3.7196	0.4971
5. Togo	8.20	13.86	2.8044	0.4477

The expanded modelling in the 2019 revision to take into account past and expected levels and trends in HIV prevalence and adult antiretroviral therapy (ART) coverage when projecting life expectancy at birth leads to imposing such adjustments to 25 countries[33]. These adjustments insure that the results are more consistent with evidence from past experiences of countries in similar situations.

In another twenty countries,[34] recent trends and levels in life expectancy at birth for one or both sexes have been affected negatively by crises, including political upheaval, armed conflict, public health issues and environmental disasters. In those contexts, the default projected trajectory of life expectancy at birth assumed too optimistic values for the next two projection intervals. The 2019 revision assumed that these countries would experience slower progress for the next 5-10 years, after which they would resume a 'normal' trajectory of progress in life expectancy. For these countries, the values of life expectancy at birth projected for 2020-2025 and 2025-2030 were adjusted by blending the most recent observed trend for the 2010-2015 and 2015-2020 periods with the unadjusted model prediction for 2030-2035 using a spline interpolation constrained on these three periods to predict the values for 2020-2025, reflecting a slowdown in the most recent country trend, and 2025-2030, reflecting a gradual recovery toward the model prediction of a continuous progress in life expectancy, respectively. [35] All probabilistic trajectories were proportionately adjusted based on this adjustment approach for the median trajectory of each country.[36]

5. *Constant-mortality assumption*

Under the constant-mortality assumption, mortality over the projection period is kept constant for each country at the level estimated for 2015-2020.

D. Assumptions on the age patterns of mortality

1. *Normal mortality conditions*

Once the path of future life expectancy was determined, mortality rates by five-year age group and sex, consistent with the life expectancy at birth for each quinquennium, were calculated. For countries with recent empirical information on the age patterns of mortality, mortality rates for the projection period

[33] Adjustments were limited to 14 countries in the 2017 revision, but no-AIDS mortality assumptions were required for 18 countries most affected by the HIV/AIDS epidemic.

[34] Albania, Austria, Barbados, Canada, Chile, Cuba, France, Fiji, French Guyana, Grenada, Jamaica, Lebanon, Mayotte, Mexico, Seychelles, United Kingdom, United States of America, Venezuela (Bolivarian Republic of), Viet Nam, and Yemen. The list of countries is based on the following three criteria: (1) the life expectancy at birth between 2005-2010 and 2010-2015 periods increased by less than 2.5 per cent, (2) the life expectancy at birth between 2010-2015 and 2015-2020 periods increased by 0.05 per cent or less, and (3) the unadjusted median life expectancy between 2015-2020 and 2020-2025 periods is projected to increase by more than 0.05 per cent.

[35] For Venezuela (Bolivarian Republic of), the adjustment was performed only for the 2020-2025 period and the model prediction was assumed for 2025-2030.

[36] The adjustment for a country and time period corresponds to the ratio between the unadjusted median life expectancy at birth and adjusted median life expectancy at birth. It is applied to each life expectancy at birth probabilistic trajectory for the corresponding country and period.

were obtained by extrapolating the most recent set of mortality rates by the rates of change from (a) country-specific historical trends using the modified Lee-Carter method (Li and others, 2013)[37], (b) a model of typical age-specific patterns of mortality improvement by level of mortality estimated from individual country experiences included in the Human Mortality Database (HMD) (Andreev and others, 2013)[38] or (c) from extended model life tables (Li and Gerland, 2011). An open source implementation of these three projection methods is available through the "MortCast" R package (Ševčíková and others, 2019c; Ševčíková and others, 2016) which is used for the probabilistic population projections in the 2019 revision.

Application of the modified Lee-Carter was restricted to countries with good quality data, that is, to a subset of 25 of the countries included in the HMD[39]. For the remainder of the HMD countries as well as all other countries, the Lee-Carter method produced less stable results overall and the second approach of typical age-specific patterns of mortality decline was used instead (Gu and others, 2017).

For 14 countries or areas lacking recent or reliable information on age patterns of mortality, mortality rates were directly obtained from an underlying model life table[40]. A choice could be made among nine model life table systems, four proposed by Coale and Demeny (1966); Coale, Demeny and Vaughn (1983); and Coale and Guo (1989), and five model systems for developing countries produced by the United Nations (United Nations, 1982). These nine model life tables have been updated and extended by the Population Division in order to cover the whole age range up to 130 years, and a range of life expectancies from 20 to 100 years (United Nations, 2011)[41].

For the remaining 161 countries or areas as well as an additional 9 countries or areas with less than 90,000 inhabitants in 2019 the age patterns of mortality for the period 2015-2020 were projected using the rates of change from the model of typical age-specific patterns of mortality improvement by level of mortality (Andreev and others, 2013) blended with an underlying model life table associated to the projected life expectancy for a given period[42]. Additional constraints on sex-specific mortality rates under age 60[43] were used for over 100 of these countries or areas to ensure greater consistency in the sex differentials of the projected age patterns of mortality and to avoid implausible cross-over between male and female mortality patterns, especially at very high levels of projected life expectancies.

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[37] In this case, the modified Lee-Carter method is constrained to the projected median UN life expectancy at birth by selecting appropriate increases in the level parameter (k_t) for each of the projection periods with the age pattern (a_x) based on the most recent period or the average 1950-2010 period, and the age pattern of mortality improvement (b_x) gradually changes by level of mortality to reflect the fact that mortality decline is decelerating at younger ages and accelerating at old ages.

[38] Available demographic data have permitted reliable estimation of the patterns of mortality improvement only up to 75-80 years of e0 for males, and 80-85 years for females. For extrapolating patterns of mortality improvement into higher levels of life expectancy at birth, smoothed linear trends were extrapolated for levels of life expectancy at birth up to 105-110 years of age.

[39] The countries for which the modified Lee-carter method was used are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, United Kingdom of Great Britain and Northern Ireland and the United States of America.

[40] The countries for which model life tables were used are Afghanistan, Aruba, Channel Islands, Comoros, Democratic Republic of the Congo, French Guiana, Guam, Lao People's Democratic Republic, Lebanon, Nepal, New Caledonia, State of Palestine, United States Virgin Islands, Western Sahara and 25 more countries or areas with less than 90,000 inhabitants in 2019.

[41] It must be noted that the last available entry in the revised system of model life tables of 100.0 years of life expectancy, for both males and females, are not meant to represent a ceiling for human longevity.

[42] The blending of the two methods is done using linear weights varying from 1 in 2020-2025 to 0.5 in 2095-2100 for the model of typical age-specific patterns of mortality improvement, and the complement used for the underlying model life table.

[43] Under normal mortality conditions, male mortality is expected to exceed female mortality, and the sex ratio between male and female mortality rates exceeds 1. In general, the male to female sex ratio of the mortality rates for a given age group in the projection period was projected to follow its own historical trajectory. However, if the sex ratio was projected to be below 1 a constraint was applied as follows. In cases where the sex ratio was above 1 at the most recent estimation period (i.e., 2015-2020), the ratio was adjusted by using its ratio from the preceding period so that the ratio at a given age would not go below 1. In cases where the sex ratio was already below 1 at the most recent estimation period, the ratio was assumed to be constant in the projection period.

2. *The impact of HIV/AIDS on mortality age patterns*

The general approach described above for deriving estimates and projections of mortality is not appropriate for countries whose recent mortality patterns have been significantly affected by the HIV/AIDS epidemic. The particular dynamic of HIV/AIDS and the severity of its outcome require explicit modelling of the epidemic. Unlike other infectious diseases, HIV/AIDS has a very long incubation period during which an infected person is mostly symptom-free but still infectious. Also unlike many other infectious diseases, individuals do not develop immunity, but, in the absence of treatment, almost always die as a consequence of their compromised immune system. Another reason for an explicit modelling of the HIV/AIDS is the avalanche-like process of the infection spreading through a population and the particular age pattern of infection exhibited by HIV/AIDS. The additional deaths due to HIV/AIDS, predominantly occurring among adults in their reproductive age, consequently distort the usual U-shaped age profile of mortality; this distorted atypical pattern cannot be found in the model life tables that are available to demographers (Heuveline, 2003).

As a consequence, instead of an overall mortality process that can be captured by standard age patterns of mortality and smooth trends of changing life expectancy, for countries highly affected by HIV/AIDS, two separate mortality processes must be modelled: the mortality due to the HIV/AIDS epidemic itself and the mortality that prevails among the non-infected population. The latter is often called the level of "background mortality".

The 2019 revision made explicit modelling assumptions to incorporate the demographic impact of the HIV/AIDS epidemic on the mortality age patterns for 21 countries where HIV prevalence among persons aged 15 to 49 was ever equal to or greater than 4 per cent between 1980 and 2018 (table II.2).

In countries most affected by the HIV/AIDS epidemic, mortality was projected by modelling explicitly the course of the epidemic and projecting the yearly incidence of HIV infection. To achieve this, the 2019 revision took a different approach than in previous revisions by using model life tables that were calibrated to account for the effect of HIV on mortality (Sharrow and others, 2014). The original model life tables were recalibrated based on a set of simulated life tables computed using the model developed by the UNAIDS Reference Group on Estimates, Modelling and Projections (Stanecki and others, 2012; Stover and others, 2012; Stover and others, 2014), and all epidemiological parameters, including coverage of antiretroviral treatment data, provided to the Population Division by UNAIDS. After some corrections for the time series of sex ratio of infection (Pelletier, 2019), this information, together with the Spectrum[44] software and AIM module (AIDS Impact Model), was used in the 2017 revision to derive the mortality impact of the HIV/AIDS epidemic in 18 countries where HIV prevalence among persons aged 15 to 49 was ever equal to or greater than 5 per cent between 1980 and 2015 (United Nations, 2017c).

[44] For accessing the official versions of Spectrum, please see: www.avenirhealth.org/software-spectrum.php. A special release of Spectrum (UNPOP100, December 2014), specifically extended to handle higher life expectancy projections up to age 100 was used for the *2017 Revision*. Different versions of Spectrum are available at: http://spectrumbeta.futuresinstitute.org/. Spectrum is an analytical tool developed to support policy decisions concerning public health. Spectrum includes modules for examining health intervention impact and costing along with underlying demographics.

TABLE II.2. HIV PREVALENCE RATES AMONG ADULTS AGED 15-49 YEARS IN COUNTRIES FOR WHICH EXPLICIT MODELLING OF HIV/AIDS WAS EMPLOYED IN THE 2019 REVISION (PERCENTAGES)

Country	*Adult HIV prevalence rate (%) in 2017*	*Maximum HIV rate (%) between 1980 and 2017*	*Country*	*Adult HIV prevalence rate (%) in 2017*	*Maximum HIV rate (%) between 1980 and 2017*
Botswana	22.8	27.0	Liberia	1.4	5.3
Cameroon	3.7	5.1	Malawi	9.6	14.9
Central African Republic	4.0	9.9	Mozambique	12.5	13.3
Congo	3.1	4.8	Namibia	12.1	14.6
Côte d'Ivoire	2.8	8.3	Rwanda	2.7	6.0
Equatorial Guinea	6.5	6.5	South Africa	18.8	18.9
Eswatini	27.4	28.4	Uganda	5.9	10.7
Gabon	4.2	4.3	U.R. of Tanzania	4.5	8.4
Guinea-Bissau	3.4	4.1	Zambia	11.5	15.9
Kenya	4.8	10.2	Zimbabwe	13.3	27.3
Lesotho	23.8	23.9			

Source: UNAIDS (2019) (unpublished tabulations made available in September 2018).
See also: https://population.un.org/wpp/Download/Files/4_Metadata/WPP2019_F01_LOCATIONS.XLSX

For the 2019 revision, a simulated set of life tables was created for each of these 18 countries using the Spectrum software covering the period 1970-2100 with the standard set of projection assumptions for the period 2015-2100[45]. An additional four scenarios were created, without changing any of the demographic indicators, in which the incidence rate of HIV was increased by 10 per cent and 20 per cent and decreased by 10 per cent and 20 per cent, respectively. The resulting five sets of age-specific mortality rates with their associated time series of adult HIV prevalence, child mortality, adult mortality, and coverage of antiretroviral treatment (ART) of both children and adults were used in the 2019 revision to recalibrate the open source "HIV.LifeTables" R package (Sharrow, 2019) to derive model life tables accounting for the effect of HIV on mortality. This new set of model life tables was used for all countries with prevalence above four percent to generate mortality estimates using the latest set of adult HIV prevalence, child mortality, adult mortality, and coverage rates for antiretroviral treatment (ART) of both children and adults (UNAIDS, 2019).

In order to address concerns related to the sex ratio of all-cause mortality in specific age groups in the 2019 revision, the ratio of female to male HIV incidence for ages 15-49 was modified for two countries in the process of estimating the demographic impact of the HIV/AIDS epidemic. The sex ratio of HIV incidence in Congo and Gabon was modified using the unweighted average sex ratio of HIV incidence observed in the other countries affected by the HIV/AIDS epidemic.

Lastly, for the projection period 2020-2100, the mortality age patterns of all countries affected by the HIV/AIDS epidemic were projected from 2015-2020 onward using the model of typical age-specific patterns of mortality improvement by level of mortality (Andreev and others, 2013) blended with the

[45] The HIV prevalence rate for 2015 is assumed to decline by 2100 to about 1/10 of its value following an exponential decay function, and coverage of treatment was projected to reach 90 per cent in 2050 if it was below 85 per cent in 2015 or to reach 95 per cent if it was above 85 per cent in 2015; it remained constant thereafter until 2100.

North model of the Coale-Demeny model life table[46]. This choice assures a better consistency between the estimated and projected trajectories of each age group.

E. International migration assumptions

International migration is the component of population change that is most difficult to project. Data on past trends are often sparse or incomplete. Moreover, the movement of people across international borders, which is often a response to rapidly changing economic, social, political and environmental factors, is a very erratic process. In some instances, both the volume and direction of international migration have changed significantly within a short timeframe. As a result, some countries that historically have been primarily countries of origin have become countries of destination of international migrants, and vice versa. Therefore, formulating assumptions about future trends in international migration is extremely challenging. Because migration flows have historically been small and have had little impact on the size and composition of national populations, adopting the assumption that migration will remain constant throughout most of the projection period is a plausible scenario. For countries where migration flows have historically, or have become more recently, a dominant factor in demographic change, a different approach is called for.

When a person moves from one country to another, that person is an emigrant when leaving the country of origin and becomes an immigrant when entering the country of destination. International migration is ideally studied as the flow of people moving between countries. In practice, however, data on international migration flows only exist for a small number of countries. Therefore, international migration in the 2019 revision, as well as in previous ones, has been incorporated as net migration only. Net migration—the difference between the number of immigrants arriving in and the number of emigrants leaving from a particular country during a certain period of time—shows the net effect of international migration on the size and composition of the population in both country of origin and destination. In other words, the net international migration indicator in WPP is not based on, and neither does it allow for, a disaggregation between the volume of arriving immigrants and of departing emigrants. In countries where the number of immigrants equals the number of emigrants, net migration will amount to zero even if immigration and emigration levels for that country are significant.

In preparing assumptions about future trends in international migration, the following four pieces of information were taken into account: (1) information on net international migration flows or its components (immigration and emigration) as recorded by countries, (2) data on labour migration flows, (3) estimates of flows of undocumented or irregular migration, (4) data on refugee (and asylum-seeker) movements, and (5) changes in the stock of foreign-born persons.

The basic approach for formulating future net international migration assumptions is straight-forward for most countries. For any given country, a distinction was made between international migration flows and the movement of refugees. For international migration, it was assumed that recent levels, if stable, would continue until 2045-2050. The government's views on international migration as well as estimates of undocumented and irregular migration flows affecting a country were also considered. Regarding the movements of refugees, it was assumed in general that refugees would return to their country of origin within one or two projection periods, i.e., within five to ten years. If a country was projected to

[46] The blending of the two methods is done using linear weights varying from 1 in 2020-2025 to 0.5 in 2095-2100 for the model of typical age-specific patterns of mortality improvement, and the complement used for the underlying model life table.

experience movements of both refugees and other international migrants, the figures of both processes were added up in order to capture total net migration during a given period, except for those countries where refugee movements were already included in international migration data.

Usually, migration assumptions are expressed in terms of the net number of international migrants. The distribution of international migrants by sex was established on the basis of what was known about the participation of men and women in different types of flows for any given country (*i.e.*, labour migration, family reunification, etc.). Given the lack of information on the age distribution of migrant flows, models were often used to distribute the overall net number of male and female migrants by age group according to the dominant type of migration flow a. The age and sex profiles of the net migration flows were then used as input for the cohort-component projection model (United Nations, 1989; Castro and Rogers, 1983). In those instances where it was possible to estimate the age and sex distribution of international migrants, the distributions were used to determine the most suitable model or, in some cases, used directly as input. The distribution of net migrants by age and sex was generally kept constant over the projection period. However, if a country was known to attract temporary labour migrants, an effort was made to model the return flow of those migrants, taking into account their ageing. The same method was applied to refugee flows.

International migration has become a universal phenomenon affecting virtually all countries of the world. For the few countries that were known neither to admit nor to supply a sizeable number of international migrants, net migration was assumed to be zero, or to become zero shortly after the start of the projection. However, the vast majority of countries were projected to experience non-zero net international migration during most of the projection period. Among these, almost twice as many were projected to be net sending countries as net receiving countries.

As a final step, to ensure consistency at the global level, the sum of all net international migration flows had to be zero at the global level for each five-year estimation and projection period. This was achieved by an iterative process in which individual country estimates and projections were revisited and altered accordingly, with a focus in each period on the top twelve countries with the largest net positive number of international migrants (i.e., net receiving countries), and the top twelve countries with the largest net negative number of international migrants (i.e., net sending countries).

1. Normal migration assumption

Under the normal migration assumption, the future path of net international migration is set on the basis of past international migration estimates, while also taking into account the policy stance of each country with regard to future international migration flows. Overall, projected levels of net migration were generally kept constant until 2045-2050, with the exception of the specific circumstances noted above, such as large and recent fluctuations in total migration, refugee movements or temporary labour flows. After 2050, it is assumed that net migration would continue to remain constant until 2095-2100 at the projected level of 2045-2050. This assumption, while unrealistic, represents a compromise between the difficulty of predicting the levels of immigration or emigration for each country of the world over such a far horizon, and the recognition that net migration is unlikely to reach zero in individual countries.

In sum, and as indicated by the 2019 revision of WPP, international migration has become a major component of population change in some parts of the world. Yet, as discussed above, projecting future migration levels is highly speculative, because such flows tend to fluctuate significantly in response to labour market needs, changes in national migration policy, armed conflict and environmental disasters. Predicting the occurrence of these events is nearly impossible.

2. *Zero-migration assumption*

Under this assumption, for each country, international migration is set to zero starting in 2015-2020.

F. NINE PROJECTION VARIANTS

The outputs from the 2019 revision include the 80 and 95 per cent prediction intervals from probabilistic projections of fertility and mortality levels, as well as the associated prediction intervals for total population and selected broad age groups. The 2019 revision also includes nine different projection variants (table II.3). Five of those variants differ only with respect to the level of fertility, that is, they share the same assumptions with respect to mortality and international migration. The five fertility variants are: low, medium, high, constant-fertility and instant-replacement-fertility. A comparison of the results from these five variants allows an assessment of the effects that different fertility assumptions have on other demographic parameters. The high, low, constant-fertility and instant-replacement variants differ from the medium variant only in the projected level of total fertility. In the high variant, total fertility is projected to reach a fertility level that is 0.5 births above the total fertility in the medium variant. In the low variant, total fertility is projected to remain 0.5 births below the total fertility in the medium variant. In the constant-fertility variant, total fertility remains constant at the level estimated for 2015-2020. In the instant-replacement variant, fertility for each country is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2020-2025. In this variant, fertility varies slightly over the projection period in such a way that the net reproduction rate always remains equal to one, thus ensuring the replacement of the population over the long run.

In addition to the five fertility variants, a constant-mortality variant, a zero-migration variant and a "no change" variant, that is, both fertility and mortality are kept constant, have been computed. The constant-mortality variant and the zero-migration variant both use the medium-fertility assumption. Furthermore, the constant-mortality variant has the same international migration assumption as the medium variant. Consequently, the results of the constant-mortality variant can be compared with those of the medium variant to assess the effect that changing mortality has on population size and composition. Similarly, the zero-migration variant differs from the medium variant only with respect to the underlying assumption regarding international migration. Therefore, the zero-migration variant allows for an assessment of the effect that non-zero net migration has on various population size and composition. The "no change" variant has the same assumption about international migration as the medium variant but differs from the latter by having constant fertility and mortality. When compared to the medium variant, therefore, its results shed light on the effects that changing fertility and mortality have on the results obtained. The momentum variant illustrates the impact of age structure on long-term population change (United Nations, 2017a). This variant combines elements of three variants: the instant-replacement-fertility variant, the constant-mortality variant, and the zero-migration variant.

Table II.3. PROJECTION VARIANTS IN TERMS OF ASSUMPTIONS FOR FERTILITY, MORTALITY AND INTERNATIONAL MIGRATION

	Assumptions		
Projection variants	*Fertility*	*Mortality*	*International migration*
Low fertility	Low	Normal	Normal
Medium fertility	Medium (based on median probabilistic fertility)	Normal (based on median probabilistic mortality)	Normal
High fertility	High	Normal	Normal
Constant-fertility	Constant as of 2015-2020	Normal	Normal
Instant-replacement-fertility	Instant-replacement as of 2020-2025	Normal	Normal
Momentum	Instant-replacement as of 2020-2025	Constant as of 2015-2020	Zero from 2020-2025
Constant-mortality	Medium	Constant as of 2015-2020	Normal
No change	Constant as of 2010-2015	Constant as of 2015-2020	Normal
Zero-migration	Medium	Normal	Zero from 2020-2025

Note: “normal” assumptions for mortality and international migrations refer to the default projection assumptions presented in the previous sections, and used for the medium-fertility variant.

G. POPULATION PROJECTION METHOD

The Population Division uses the cohort-component method (United Nations, 1956) to reconstruct the population dynamics, including its size and composition, between 1950 and 2020 and to project the future population of each country or area to 2100. The cohort-component method ensures internal consistency by age and sex and over time, and between the three demographic components of change (fertility, mortality and net migration) and the projected population.

Using a cohort-component approach, the population by five-year age groups and by sex for each country or area was projected from mid-2020, the base year, up to mid-2100 by five-year periods using future survival probabilities by sex and five-year age groups, future net migration by age and sex, and future numbers of births distributed by sex. The population in year t+5 is equal to the population in year t plus the intervening births and net migration, which can be positive or negative, minus the intervening deaths, with the computations carried out by sex and age along cohort lines over the time interval.

The Population Division releases two types of population projections: a probabilistic version and a deterministic version.

a) The probabilistic version extends the deterministic version by incorporating uncertainty about future changes in fertility and mortality. For each country, 10,000 population projections are computed from 2020 to 2100, each one using a projected trajectory of total fertility rates and a projected trajectory of life expectancy in the country sampled from the predictive distribution of these quantities (Raftery and others, 2012; Gerland and others, 2014). The various population and demographic indicators, including vital events and vital rates, are computed for each trajectory, and summarized through 80 and 95 per cent prediction intervals (Raftery and others, 2014a). All computations are done using the open source “bayesPop” R package (Ševčíková and others, 2019d; Ševčíková and Raftery, 2016) with the graphical user interface “bayesDem” (Ševčíková, 2013). These probabilistic projections do not incorporate uncertainty about future net international migration, for reasons outlined above, nor do they take into account the uncertainty in the baseline population or demographic rates.

b) In the deterministic version, the population is projected using the median trajectory of the total fertility rate and life expectancy at birth and the assumptions discussed in the previous section.

H. Aggregation procedures

After preparing the projections for individual countries and areas, the results were aggregated for 50 major aggregates[47] (e.g., world, geographic regions, development groups, income groups, etc.) and an additional 200 special aggregates (e.g., regional economic communities, political units, United Nations related groupings)[48].

Whereas the aggregation of populations and of vital events by age and sex is performed by simple summation, vital rates are recomputed using the aggregated numerators and denominators. For summary indicators, such as life expectancy, total fertility, median age or net reproduction rates, averages are calculated, weighted by the size of the respective population.

The same principles are also used for aggregating the probabilistic results. Aggregations are first performed at the trajectory level, and the aggregated results of the 10,000 trajectories of population and vital events used to derive summary statistics. Between-country correlations not captured by the Bayesian hierarchical projection model for total fertility are incorporated into the final projected trajectories for each country using the method described in Fosdick and Raftery (2014) through a set of time invariant covariates, that is, whether the countries are contiguous, whether they were colonized by the same country after 1945, and whether they are located in the same continental region. For mortality, the modelling approach used (Raftery and others, 2013; Raftery and others, 2014b; Godwin and Raftery, 2017) does not require additional provisions for between-country correlations in life expectancy.

I. Interpolation procedures

The cohort-component method requires a uniform age format for the estimation of the size and structure of a population and the measurement of vital events. For the purpose of global population estimates and projections, most empirical data are only available in five-year age groups. As a consequence, all results produced by the cohort-component method in the 2019 revision are in five-year age groups and, for vital events, represent five-year periods. All vital rates are given as the average over the five-year period from mid-year (t) to mid-year (t+5), that is, the next five-year projection period, centred on 1 January (t+3). For example, the estimate for life expectancy at birth for 2000-2005 refers to the period from mid-2000 to mid-2005, or 2000.5 to 2005.5 in decimal dates, with 1 January 2003 as the mid-point (i.e., 2003.0 using a decimal date). Special interpolation routines were then used to produce estimates and projections for single calendar years and for single-year age groups. It must be noted, however, that interpolation procedures cannot recover the true series of events or the true composition of an aggregated age group.

1. Interpolation of populations by age and sex

The basis for the calculation of interpolated population figures by single year of age and for calendar years ending with either 0 or 5 were the estimated and projected quinquennial population figures by five-year age groups for each sex. In a first step, the quinquennial population figures were interpolated into annual population figures by applying Beers' ordinary formula (Swanson and Siegel, 2004). The second

47 See also https://population.un.org/wpp/DefinitionOfRegions/.
48 Available from https://population.un.org/wpp/Download/SpecialAggregates/.

step of this interpolation was to generate the population by single year of age for each year by applying Sprague's fifth-difference osculatory formula (Swanson and Siegel, 2004) for subdivision of groups into fifths. This interpolation procedure generated a smooth interpolated series of figures while maintaining the original values. It should be noted that for ages above 80 or under five, the stability and reliability of the interpolation procedure was not always satisfactory.

In order to maintain consistency along cohort lines, a third step was added to the interpolation procedures for the 2019 revision, in which the populations by single year of age were linearly interpolated for each calendar year between those ending with 0 or 5, along the cohort survival line. For example, the populations at ages 1, 2, 3, and 4, in years 1951, 1952, 1953, and 1954 respectively, were produced as linear interpolations between the population aged 0 in 1950 and the population aged 5 in 1955. The last such linear interpolation was carried out between age 94 at time t and age 99 at time t+5. Because of the last age group being open-ended, a linear interpolation was not possible beyond age 94. As a last step, the interpolation results were prorated such that the sum of all age groups between ages 0 and 99, before and after the linear interpolation, is the same.

2. *Interpolation of vital events and summary statistics*

For the interpolation of vital events, their rates and other measures into annualized times series, the modified Beers formula was used (Swanson and Siegel, 2004, 729). This formula combines interpolation with some smoothing. The Beers modified method was preferred over the Beers "ordinary" formula as it avoided fluctuations at the beginning and the end of the series that were atypical for the variables concerned.

The time periods in the estimates and projections of the 2019 revision are anchored to mid-year. Each observation or projection period starts at 1 July of a particular year and ends at mid-year five years later. Therefore, the annualized interpolated indicators refer to the period between the mid-year points of two consecutive calendar years. In order to provide annualized variables that refer to calendar years, an adjustment was made that simply assumed that the arithmetic average between two such periods would be a good representation of the calendar year-based indicator.

J. SUMMARY OF MAIN UPDATES INTRODUCED IN THE 2019 REVISION

In comparison with previous revisions, the 2019 revision includes the following updates:

Fertility

- In the 2019 revision, the projection of fertility in countries with fertility levels below 2.1 live births per woman was based on the experience of 40 countries or areas[49] that have had levels of fertility below 2.1 and that have experienced an increase in the level of fertility over at least two consecutive five-year periods after reaching their lowest level. The number of low-fertility countries that experienced such a recovery in the level of fertility has risen since the 2017 revision, when 36 countries or areas met both criteria, and the 2012 revision, when 25 met both criteria.

[49] These are 50 countries or areas are located in Eastern and South-Eastern Asia (China, China - Hong Kong SAR, China - Macao SAR, China - Taiwan Province of China, Japan, Singapore and Viet Nam), in Latin America and the Caribbean (Aruba and Barbados), and in Europe and Northern America (Armenia, Austria, Belarus, Belgium, Bulgaria, Channel Islands, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom and United States of America).

- The model used to project the age patterns of fertility was also updated to include new empirical evidence. The projection model combines past national trends of the age pattern of fertility with a trend leading towards a global model age pattern of fertility. The global model pattern is an unweighted average of the proportionate age-specific fertility rates with seven five-year age groups, ranging from 15-19 to 45-49. This global model pattern was updated to include a larger number of countries with fertility below 2.1 live births per woman that have experienced a recovery over at least two consecutive five-year periods after having reached their lowest level and where the mean age at childbearing reaches 30 years or above in 2015-2020. In the 2019 revision, 24 countries[50] were used to compute the global model pattern, compared to only nine in the 2017 revision.

- In five countries with fertility below 2.1 live births per woman, that is, Finland, Italy, Japan, Luxembourg and Ukraine, the level of fertility projected for 2020-2025 and 2025-2030 was adjusted to smooth the transition between a recent downward trend in fertility and an expected future increase. For each of these countries, where a recent downward trend in total fertility followed a period of sustained increase, the recent decline in fertility during the estimation period contrasted with an immediate increase in the first projection period.

Mortality

- Due to political upheaval, armed conflict, public health concerns and similar events, twenty countries[51] have experienced a recent slow-down or reversal in progress in life expectancy at birth for one or both sexes. In the projection of life expectancy at birth, the 2019 revision assumed that these countries would experience slower progress for the next 5 to 10 years, after which they would resume a 'normal' trajectory of progress in life expectancy.
- As in previous revisions, the 2019 revision made explicit modelling assumptions to incorporate the demographic impact of the HIV/AIDS epidemic on mortality for 21 countries where HIV prevalence among persons aged 15 to 49 was at least four per cent at some point between 1980 and 2018. The 2019 revision took, however, a different approach than in previous revisions by using model life tables accounting for the effect of HIV on mortality (Sharrow and others, 2014), which were recalibrated using the latest UNAIDS epidemiological data. The age-specific mortality patterns up to 2015-2020 were estimated as a function of adult HIV prevalence, child mortality, adult mortality and coverage of antiretroviral treatment (ART) of both children and adults.
- For the projection of the levels of mortality for the 58 countries or areas having ever experienced adult HIV prevalence of one per cent or more among males or females during the period 1980 to 2018, the 2019 revision used a different approach compared to the 2017 revision. In the latest revision, the levels of life expectancy at birth were projected using the existing Bayesian probabilistic life expectancy projection methods (United Nations, 2017c) extended to account for past and expected levels and trends in HIV prevalence and adult ART coverage (Godwin and Raftery, 2017).
- For the countries that have experienced adult HIV prevalence of four per cent or more at any point between 1980 and 2018, the age patterns of mortality were projected using a model of

[50] Austria, Belgium, Channel Islands, China - Hong Kong SAR, China - Macao SAR, China - Taiwan Province of China, Czechia, Denmark, Estonia, Finland, France, Germany, Italy, Japan, Luxembourg, Malta, Netherlands, Norway, Singapore, Slovenia, Spain, Sweden, Switzerland, and United Kingdom.

[51] Albania, Austria, Barbados, Canada, Chile, Cuba, France, Fiji, French Guyana, Grenada, Jamaica, Lebanon, Mayotte, Mexico, Seychelles, United Kingdom, United States of America, Venezuela (Bolivarian Republic of), Viet Nam, and Yemen.

typical age-specific patterns of mortality improvement by level of mortality estimated from individual country experiences included in the Human Mortality Database (HMD) (Andreev and others, 2013).

International migration

- The 2019 revision assumed that net international migration from 2050 to the end of the 21st century would remain constant at the level projected in 2045-2050. In the previous revision, it was assumed that net international migration would, by 2095-2100, reach half the level projected for 2045-2050.

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