Economic & Social Affairs

World Population Prospects

United Nations

Methodology of the United Nations Population Estimates and Projections

2017 REVISION

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ESA/P/WP.250

Department of Economic and Social Affairs
Population Division

World Population Prospects
The 2017 Revision

Methodology of the United Nations Population Estimates and Projections

United Nations
New York, 2017

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.

The Population Division of the Department of Economic and Social Affairs provides the international community with timely and accessible population data and analysis of population trends and development outcomes for all countries and areas of the world. To this end, the Division undertakes regular studies of population size and characteristics and of all three components of population change (fertility, mortality and migration). Founded in 1946, the Population Division provides substantive support on population and development issues to the United Nations General Assembly, the Economic and Social Council and the Commission on Population and Development. It also leads or participates in various interagency coordination mechanisms of the United Nations system. The work of the Division also contributes to strengthening the capacity of Member States to monitor population trends and to address current and emerging population issues.

Notes

The designations employed in this report and the material presented in it do not imply the expression of any opinions whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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PREFACE

This report provides a detailed overview of the methodology used to produce the *2017 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 *2017 Revision* is the twenty-fifth 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 uncertainty bounds for different components at the country level is available on the website of the Population Division, *www.unpopulation.org* (see also: https://esa.un.org/unpd/wpp/Graphs/Probabilistic/).

The *2017 Revision* of the *World Population Prospects* was prepared by a team led by François Pelletier, including Lina Bassarsky, Helena Cruz Castanheira, Danan Gu, John Kanakos, Neena Koshy, Igor Ribeiro, Cheryl Sawyer, Thomas Spoorenberg and 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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EXPLANATORY NOTES

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 countries, territories and areas:

The designations employed and the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

The designation "more developed" and "less developed" regions are intended for statistical purposes and do not express a judgment about the stage reached by a particular country, territory or area in the development process. The term "country" as used in this publication also refers, as appropriate, to territories or areas.

More developed regions comprise all subregions of Europe plus Northern America, Australia/New Zealand and Japan. Less developed regions comprise all subregions of Africa, Asia (excluding Japan), and Latin America and the Caribbean as well as Melanesia, Micronesia and Polynesia. Countries or areas in the more developed regions are designated as "developed countries". Countries or areas in the less developed regions are designated as "developing countries".

The group of least developed countries, as defined by the United Nations General Assembly in its resolutions (59/209, 59/210, 60/33, 62/97, 64/L.55, 67/L.43, 64/295 and 68/18) included 47 countries in June 2017: 33 in Africa, 9 in Asia, 4 in Oceania and one in Latin America and the Caribbean. Those 47 countries are: Afghanistan, Angola, Bangladesh, Benin, Bhutan, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kiribati, Lao People's Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Myanmar, Nepal, Niger, Rwanda, São Tomé and Príncipe, Senegal, Sierra Leone, Solomon Islands, Somalia, South Sudan, Sudan, Timor-Leste, Togo, Tuvalu, Uganda, United Republic of Tanzania, Vanuatu, Yemen and Zambia. These countries are also included in the less developed regions.

The group denominated "other less developed countries" comprises all countries in the less developed regions minus the least developed countries.

The country classification by income level is based on 2016 GNI per capita from the World Bank.

The term "sub-Saharan Africa" is used to designate the countries of Africa excluding those of Northern Africa.

Countries and areas are grouped geographically into six regions designated as: Africa; Asia; Europe; Latin America and the Caribbean; Northern America, and Oceania. These regions are further divided into 21 geographical subregions.

The names and composition of geographical areas follow those presented in "Standard country or area codes for statistical use" (ST/ESA/STAT/SER.M/49/Rev.4), available at http://unstats.un.org/unsd/methods/m49/m49.htm.

The following abbreviations have been used:

AIDS	Acquired immunodeficiency syndrome
DESA	Department of Economic and Social Affairs
DHS	Demographic and Health Surveys
GHS	General Household Survey
HIV	Human immunodeficiency virus
HMD	Human Mortality Database
IGME	Inter-agency Group for Child Mortality Estimation
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)
TFR	Total fertility rate
UNAIDS	Joint United Nations Programme on HIV/AIDS
UNHCR	Office of the United Nations High Commissioner for Refugees
WFS	World Fertility Survey
WHO	World Health Organization

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 (1950-2015) and projections (2015-2100). 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 1950-2015 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 2015, separating the past estimates from the projections, is called the base year of the projections. The projection period of this revision covers 85 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 (prediction intervals or PIs). Population estimates and projections were carried out for a total of 233 countries or areas. Detailed results have been published for 201 countries or areas with 90,000 inhabitants or more in 2017; for the remaining 32 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 subjected to quality analyses 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, as well as for countries where the prevalence of HIV/AIDS was still relatively high in recent years. Details of these procedures are provided in the body of this report.

The report first describes the way that the estimates were revised during the preparation of the *2017 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.

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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 *2017 Revision*.

Estimates and projections of total population are provided in this revision for 233 countries or areas, comprising the entire population of the world. Information on other demographic components refers to 201 countries or areas with at least 90,000 inhabitants in 2017, for which the *2017 Revision* contains full time series of population size by age and sex and of the components of population change. 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[1].

Population

Recent population count data 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, 2008 and 2017 - Statistics Division), 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 changes. 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 170 countries or areas, representing 73 per cent of the 233 countries or areas included in this analysis. For 54 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 (1943), Afghanistan (1979), Democratic Republic of the Congo (1984), Eritrea (1984), Somalia (1987), Uzbekistan (1989), Madagascar (1993), Iraq (1997) and Pakistan (1998).

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. 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 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)[2]. In addition, some countries field national demographic surveys, and a few have established sample

[1] Data sources and related meta-information for the *2017 Revision* of the *World Population Prospects* are available for each country or area from the following web page: http://esa.un.org/unpd/wpp/DataSources/.

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

vital registration systems. Numerous countries ask summary questions in the census on the number of children ever born. The *2017 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 2017, all but nine had available data on fertility collected in 2010 or later. For those nine countries, the most recent data were collected between 2000-2009.

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 2017, only nine did not have available child mortality data collected in 2010 or later; in another six countries, the data available since 2010 were considered but then excluded from the analysis for reasons of data quality. 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 1950-2015 varied greatly across countries. In preparing estimates of child mortality for the 2017 Revision, the Population Division coordinated closely with the United Nations Inter-agency Group for Child Mortality Estimation[3] (IGME) led by UNICEF.

b) Mortality above age 5

Compared to information on fertility and child mortality, information on adult mortality was more sparse, 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. 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 prevalence, the demographic impact of the AIDS epidemic was explicitly incorporated using a multi-state epidemiological model (for further details, see p. 27). 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 this *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, and to data about refugee stocks and flows prepared by the Office of the United Nations High Commissioner for Refugees (UNHCR). It should be noted that such information is not provided by most countries and even by combining these various data sources, it was difficult to produce comprehensive and consistent estimates of net migration over time. Therefore, in several cases, net international migration was estimated as the residual not accounted for by natural increase between successive census enumerations. The paucity of reliable and comprehensive data on international migration is an important limitation to producing more accurate population estimates.

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[3] 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.

B. GENERAL ANALYTICAL STRATEGY AND MAJOR STEPS FOR PRODUCING POPULATION ESTIMATES

With each revision of the *World Population Prospects*, the Population Division of the United Nations 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 often 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. Nevertheless, for several countries with inadequate migration data, estimates of net international migration 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 (Moultrie et al., 2013; United Nations, 1983, 2002).

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 (Gerland, 2014; Heilig et al., 2009; Spoorenberg and Schwekendiek, 2012).

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. 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 population and its distribution by age and sex. The overall analytical approach used in the *2017 Revision* 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[4]. 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.

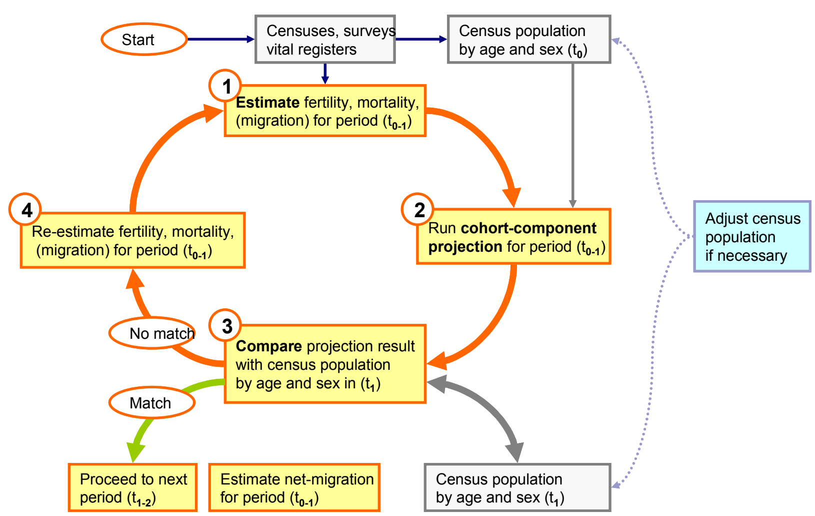
[4] Traditionally, the data are obtained from the United Nations Statistics Division (Demographic Yearbook), national statistical offices, United Nations Regional Commissions (e.g., ECLAC), other United Nations entities (e.g., WHO, UNICEF, UNAIDS), international databases (e.g., Human Mortality Database, Human Fertility Database), microdata archives (e.g., DHS, MICS, IPUMS-International).

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 of the United Nations Population Division using standard demographic techniques, such as accounting for under-enumeration of young children or smoothing age distributions characterized by age-heaping.

   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 of the *World Population Prospects* were carefully reviewed and, if necessary, were revised based on the new data.

3. *Country-specific consistency checking and cross-validation*: The previous steps provided initial sets of independent estimates for each demographic component (population, fertility, mortality, and migration). However, the methods used focus on only one demographic component (such as fertility or mortality) 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, Heuveline and Guillot, 2001; Whelpton, 1936). This is known as the demographic balancing relationship.

Figure I.1. Process used to ensure intercensal consistency between demographic components and populations



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 (fertility, mortality, migration) 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 overall intercensal cohort consistency.

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 net international migration, which for each 5-year period must sum to zero at the world level.

C. Addressing challenges arising from data quality issues

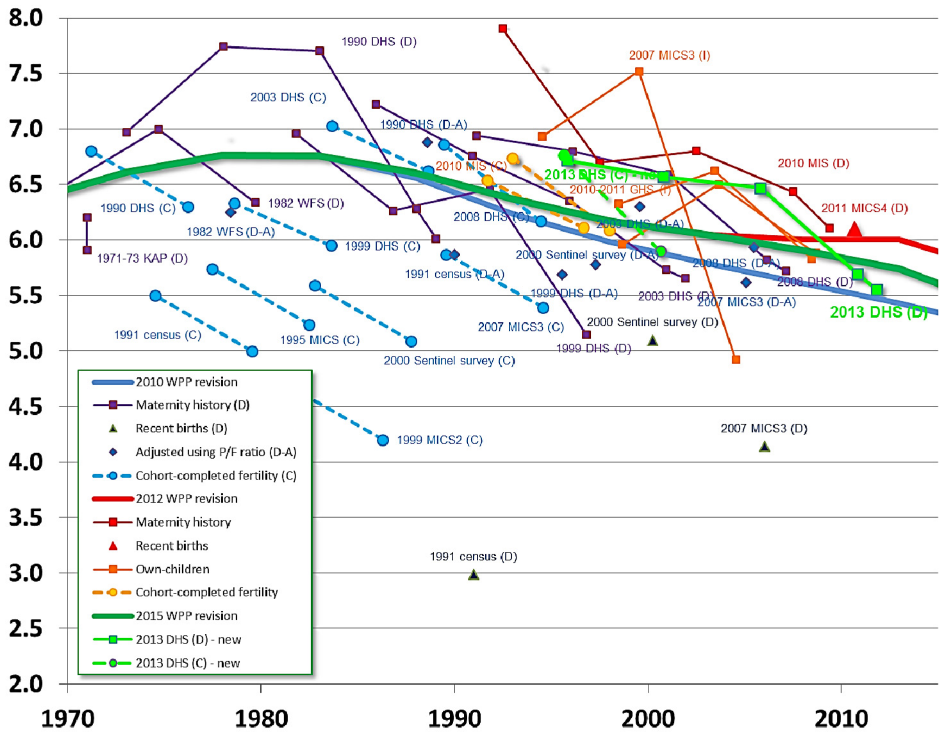
In updating estimates of populations and related demographic components for each country, a major challenge was to address encountered inconsistencies across various empirical data sets. This was predominantly the case in countries with deficient demographic data, where different data sources often provide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

The first example focuses on the data available at different points in time for updating fertility estimates for Nigeria, comparing the results across three recent *Revisions*. In figure I.2, the data shown in blue and purple represent the empirical evidence considered in deriving total fertility estimates for the period 1970-1975 to 2010-2015 that were available at the time of the *2010 Revision*. Multiple data sources were considered, and one or multiple estimation methods were used to derive fertility estimates from each source. These sources and methods included: (a) direct estimates based on maternity-history data adjusted for underreporting from the 1981-1982 Nigeria World Fertility Survey (WFS), 1990, 1999, 2003 and 2008 DHS, (b) recent births in the preceding 12 months (or 36 months) by age of mother, from these surveys and from the 1971-1973 National Fertility, Family Planning and Knowledge, Attitudes and Practices survey, 1991 census, 2000 Nigeria Sentinel Survey, 2007 MICS 3; (c) adjusted fertility using Brass P/F ratio (United Nations, 1983) and data on children ever born from these sources; and, (d) cohort-completed fertility[5] from these surveys and censuses, as well as from the 1995 MICS and 1999 MICS2 surveys. The blue line in figure I.2 represents the final trend estimates produced after evaluation of these disparate and conflicting sources.

In the *2012 Revision*, results from several new surveys became available and were considered in addition to those previously used. Specifically, the 2010 Malaria Indicator Survey (MIS) provided maternity-history data covering the retrospective period 1990-2010, the 2011 MICS4 provided fertility for the 12-months preceding the survey, and microdata available for the MICS4 survey as well as the previous 2007 MICS3 and 2010-2011 General Household Survey (GHS) enabled the computation of indirect fertility estimates using the own-children method. These additional data points, shown in red and orange in figure I.2, were the basis for increasing estimated fertility levels in the *2012 Revision*. When the *2015 Revision* was prepared, new data had become available from the 2013 DHS providing retrospective fertility information for the previous 25 years, and it was deemed necessary to revise downward the estimates of fertility for more recent periods (green line). These modifications in the more recent fertility levels also had implications for the projected fertility trends and associated projected populations.

[5] Using Ryder's (1964, 1983) correspondence between period and cohort measures, the mean number of children ever born (CEB) to a cohort is used to approximate the period total fertility rate at the time this cohort was at its mean age at childbearing. See Feeney (1995, 1996) for further details about time translation of mean CEB for women age 40 and over.

Figure I.2. Total fertility estimates (in live births per woman) based on various data sources and estimation methods, and WPP estimates for the *2010*, *2012* and *2015 Revisions,* Nigeria, 1970-2015



NOTE: This figure illustrates the "cloud" of empirical estimates of total fertility (number of live births per woman) derived from different data sources in Nigeria. The thick solid lines – in blue, red and green - represent the assessments from the *2010, 2012 and 2015 Revisions*, respectively. Overall, as new information became available, the more recent estimates of fertility were revised. With the incorporation of the results of the 2013 DHS, the fertility levels in Nigeria were estimated to be lower in the *2015 Revision*, as compared to the *2012 Revision*, throughout the more recent years. No additional data became available before the *2017 Revision*, and therefore the fertility estimates of the *2017 Revision* remained unchanged from the *2015 Revision*.

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 $_{45}q_{15}$[6] when time series of age-specific mortality rate were unavailable) were generated either through expert-based opinion reviewing and weighting each observation analytically, or using automated statistical methods (for example, pooled analysis using Loess (local regression) or cubic splines with analytical weights (Obermeyer et al., 2010; Rajaratnam et al., 2010; Wang et al., 2012), or by using a bias-adjusted data model to control for systematic biases between different types of data (Alkema and New, 2013; Alkema et al., 2012)).

The overall analytical approach used to measure under-five mortality in the *2017 Revision* followed that of the United Nations IGME (Hill et al., 2012; You et al., 2015), which fitted a robust trend through the various data sources. 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. 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 were excluded from the analysis due to their lack of reliability or national representativity.

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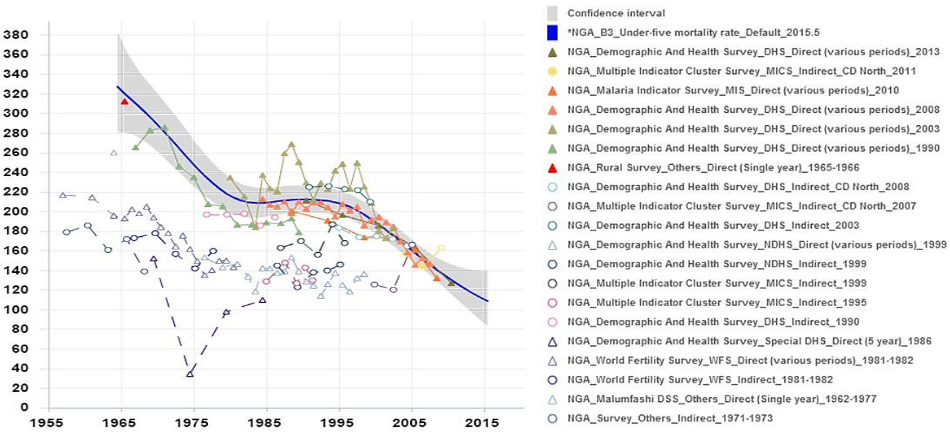
[6] $_5q_0$ refers to under-five mortality, that is, the probability of dying between birth and age 5. $_{35}q_{15}$ *and* $_{45}q_{15}$ are the probabilities of dying between age 15 and 50 and 15 and age 60, respectively, conditional on survival to age 15. These are commonly used summary indices of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

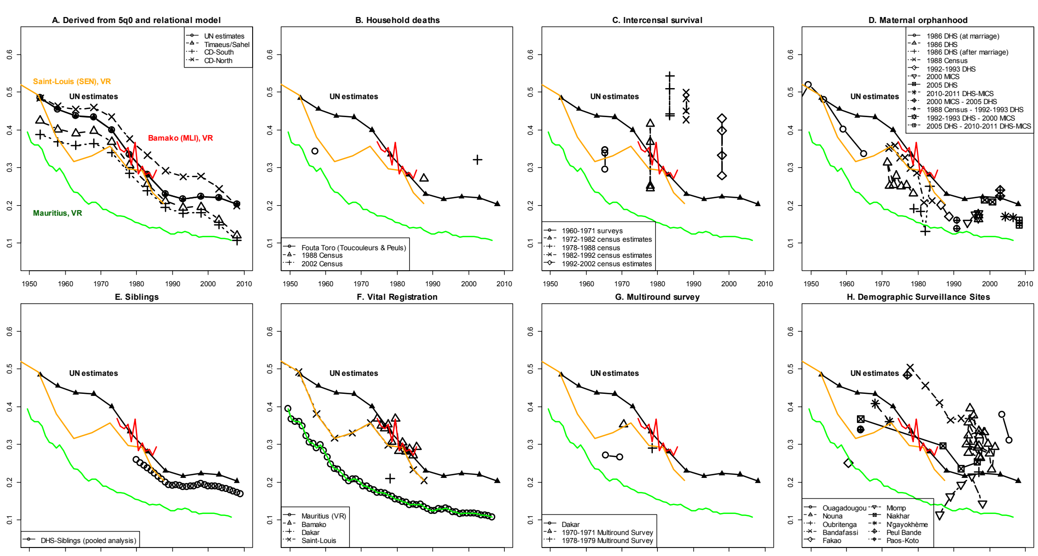
Figure I.3. Estimates of under-five mortality (deaths under age five per 1,000 live births) derived by using various data sources and estimation methods, with IGME fitted trend, Nigeria, 1955-2015



Source: www.childmortality.org.

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 (Hill, Choi and Timaeus, 2005; Masquelier, 2012; Moultrie et al., 2013; Obermeyer et al., 2010; Rogers and Crimmins, 2011; United Nations, 1983, 2002). 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 as seen through the plots in figure I.4, the reality is quite complex and estimates are often biased.

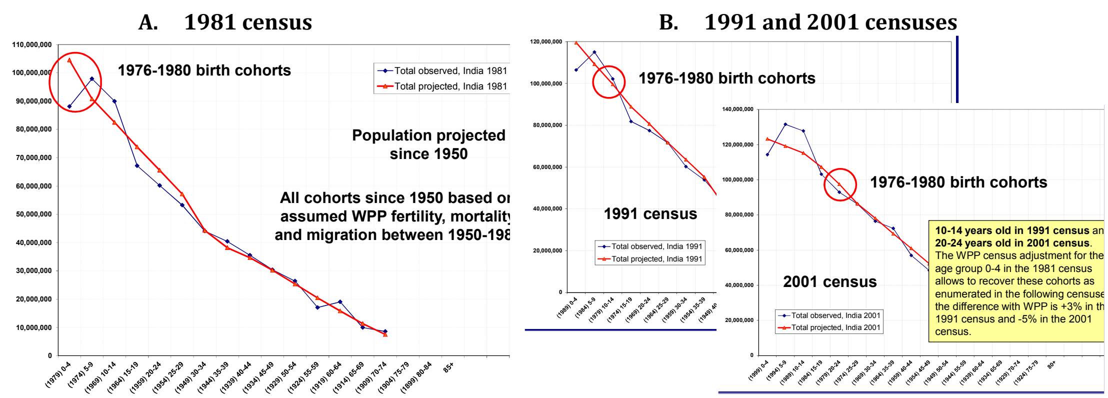
Figure I.4. Estimates of female adult mortality (deaths under age 5 per 1,000 alive at age 15) derived by using various data sources and estimation methods, Senegal, 1950-2010



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). 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.

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.

In producing population and demographic estimates for all country 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 evaluate, analyse and reconcile 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 migration indicators within many countries.

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. 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 migration on a population at some given point in the future (see Preston et al., 2001).

In the *2017 Revision*, the future population of each country was projected from 1 July 2015. The base population starts from 2015 rather than 2017 because the Population Division makes projections of future populations by 5-year age group over a 5-year time period. Compared to the *2015 Revision*, the base population estimates of the *2017 Revision* were updated using the most recent demographic data available. 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. Fertility assumptions: convergence towards low fertility

Consistent with previous revisions, the *2017 Revision* of the *World Population Prospects* 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. In addition, a new momentum variant was introduced, 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.

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.

1. Medium-fertility assumption

a. Stages of fertility transition and Bayesian projection methods

The *2017 Revision* of the *World Population Prospects* used probabilistic methods for projecting total fertility, first employed in the *2010 Revision* and updated in subsequent revisions (Alkema et al., 2011; Raftery et al., 2009; Raftery, Alkema and Gerland, 2013; United Nations, 2015a). The method utilizes the fertility levels and trends estimated for the *2017 Revision* for all countries[7] of the world for the period 1950 to 2015.

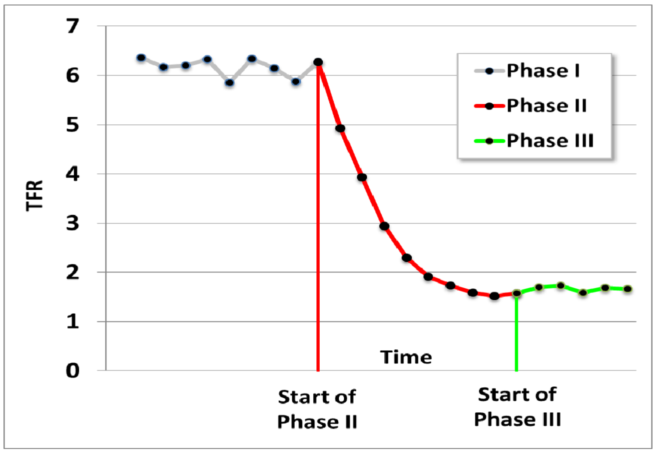
The demographic transition theory is the basis for projections of future country-specific fertility levels. Overall, there is a consensus that the historical evolution of fertility includes three broad phases: (i) a high-fertility, pre-transition phase, (ii) a fertility transition phase, and, (iii) a low-fertility, post-transition phase. Figure II.1 illustrates the three phases of fertility transition. During the observation period from 1950 to 2015, 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

[7] Only countries or areas with 90,000 inhabitants or more in 2017 are considered.

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 *2017 Revision*.

Figure II.1. Schematic phases of the fertility transition (in 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 et al. (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 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).

Starting from the *2004 Revision*, the United Nations Population Division developed three models of fertility decline, using a double logistic function defined by six deterministic parameters (United Nations, 2006). These models were intended to capture a variety of pathways from high to low fertility and were used for country-specific projections. For countries that had completed the fertility transition, simple assumptions about long term convergence in total fertility were used.

The probabilistic framework introduced in the *2010 Revision* for projecting total fertility consisted 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 decomposed 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 results 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 one to take into account the historical experience of each country, but also to reflect the uncertainty about future fertility decline based upon 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 (namely, the world's experience through the information 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 as to their speed of decline. Thus, their future potential trajectories (and speed of decline) 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 (see figure II.1), the second component of the projection procedure implemented a time series model to project further fertility change, on the assumption that fertility in the long run would approach and fluctuate around country-specific ultimate levels based on a Bayesian hierarchical model (Raftery et al., 2014). 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 *2017 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. 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[8].

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 (Bongaarts and Sobotka, 2012; Caltabiano, Castiglioni, and Rosina, 2009; Goldstein, Sobotka and Jasilioniene, 2009; Myrskylä, Goldstein and Cheng, 2013; Myrskyla, Kohler and Billari, 2009; Sobotka, 2011), the modelling approach additionally 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. This assumption is supported by research on the “low fertility trap hypothesis” for some low-fertility countries of Europe (Lutz, 2007; Lutz, Skirbekk and Testa, 2006) and East Asia (Basten, 2013; Frejka, Jones and Sardon, 2010; Jones, Straughan and Chan, 2008).

In recent revisions, an increasing amount of evidence on Phase III recoveries has become available. The number of countries having already entered Phase III increased from 25 in the *2012 Revision*, to 36 in the *2017 Revision*.

To construct projections for all countries still in Phase II, the Bayesian hierarchical model was used to generate 600,000[9] double-logistic curves for all countries that have experienced a fertility decline (see example in figure II.2), representing the uncertainty in the double-logistic decline function of those countries[10]. This sample of double-logistic curves was then used to calculate 600,000 total fertility projections for all countries that had not reached Phase III by 2010-2015. 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.

The assumption of a long-run fertility level of 1.85 children per woman has not been used for several 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 (in Phase III). The pace of fertility change, as well as the level and timing when Phase II stops and Phase III starts, varies for each of the 600,000 projected fertility

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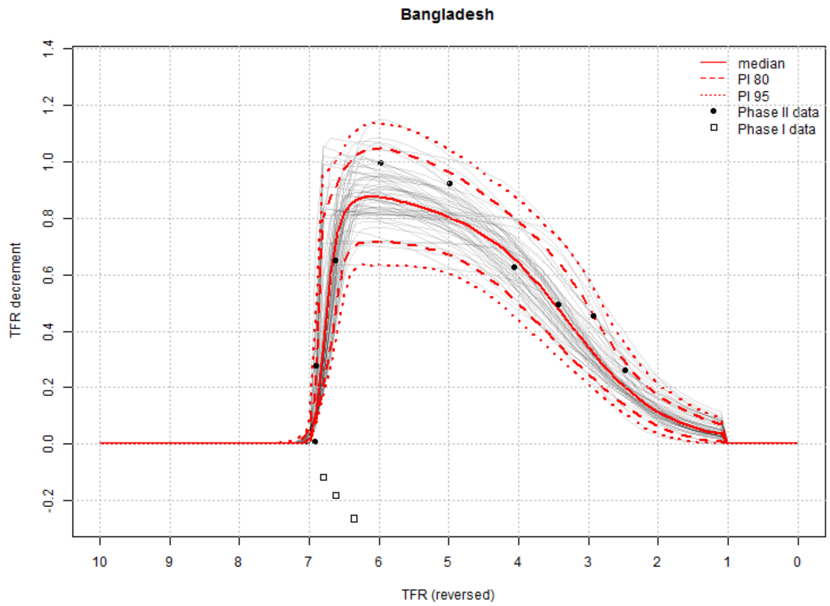
[8] While the asymptote does not have an explicit lower bound, it does implicitly because any given total fertility trajectory is restricted not to be smaller than 0.5 child.
[9] Actually, ten simulations are run in parallel with 62,000 iterations performed for each simulation, and the first 2,000 are discarded.
[10] Graphs of this double-logistic curve are available online at: http://esa.un.org/unpd/wpp/Graphs/Probabilistic/FERT/CHG/.

trajectories for a country that has not reached Phase III by 2010-2015. 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 2010-2015, the time series model for that phase is used directly.

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



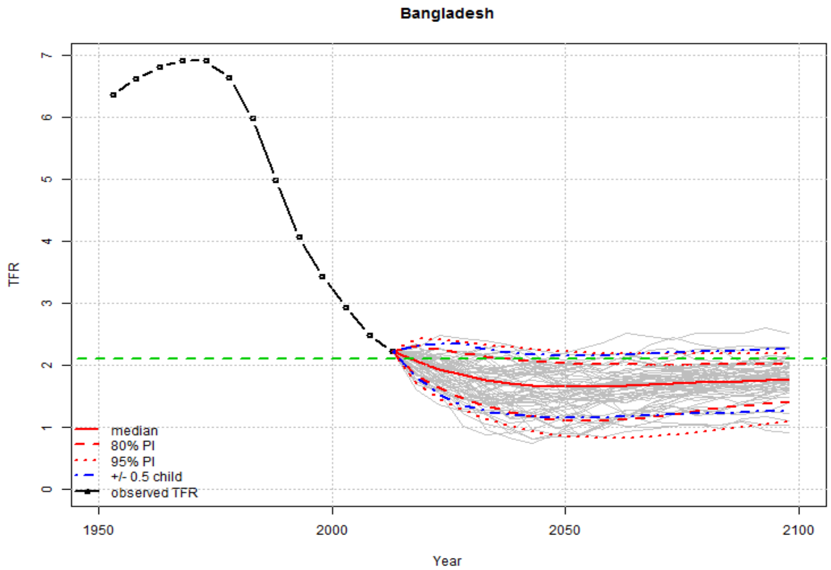
NOTE: Observed five-year decrements by level of total fertility are shown as black dots. For clarity, only 60 trajectories of the 600,000 calculated are shown here. The median projection is the solid red line, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

By systematically sampling one in ten of the 600,000 simulated trajectories produced by this process, the end result was 60,000 projected trajectories of total fertility for each country. The median of these 60,000 trajectories was used as the medium-fertility variant projection in the *World Population Prospects*. To express the uncertainty surrounding future trends in fertility, 80 and 95 per cent prediction intervals were also calculated (see figure II.3 for Bangladesh; additional tables[11] and graphs[12] are available online for all countries). For countries that had not reached Phase III by 2010-2015, the projected median trajectory reflects the uncertainty as to when the fertility transition will end and at what level.

[11] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online tables of stochastic projections of total fertility: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/.

[12] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online plots of projections of total fertility: median, 80% and 95% prediction intervals, high and low WPP fertility variants; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/FERT/TOT/.

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



NOTE: For clarity, only 60 trajectories of the 60,000 calculated are shown here for 2015 to 2100. The median projection is 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 *2017 Revision* correspond to +/- 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 only for reference.

The fertility projections produced in the *2017 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. Projection of the age pattern of fertility

Once the path of future total fertility was determined, age-specific fertility rates by five-year age group consistent with the total fertility for each quinquennium were calculated. In the *2017 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[13] (Ševčíková et al., 2016). The projection method was implemented on the proportionate age-specific fertility rates (PASFR) with seven age groups from 15-19 to 45-49.

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

(a) A first preliminary projection, assuming that the PASFRs converge to the global model pattern; and
(b) A second preliminary projection, assuming that the observed national trend in PASFRs continues into the indefinite future.

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[13] The global model pattern in this revision is based on an unweighted average of PASFRs for selected low fertility countries that have already reached their Phase III, and represent later childbearing patterns with mean age at childbearing close to or above 30 years in 2010–2015: Austria, Czech Republic, Denmark, France, Germany, Japan, Netherlands, Norway, and Republic of Korea.

The method was applied to each of the trajectories that made up the probabilistic projection of the total fertility rate of each country, based on the estimated PASFRs for 1950-2015 used in the *2017 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 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 whether the projected fertility for a given period is higher than the ultimate TFR (2095-2100) in the medium variant projection (Ševčíková et al., 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).

2. High-fertility assumption

The *2017 Revision* retains a number of standard 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 (2010-2015) 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 (2015-2020) compared to the baseline, 0.4 births higher in the second projection period (2020-2025), and 0.5 births higher thereafter. Thus, starting in 2025-2030, fertility in the high variant was assumed to be 0.5 births higher than that of the medium variant. For example, 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 insure a smoother transition between the baseline period (2010-2015) and the low variant, fertility in the low variant is initially -0.25 births in the first projection period (2015-2020), -0.4 births in the second projection period (2020-2025), and -0.5 births thereafter. By 2025-2030, 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 2010-2015. 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 2015-2020. Fertility varies over the remainder of the projection period in such a way that the net reproduction rate always remains equal to one thus ensuring, over the long-run, the replacement of the population[14]. Mortality and migration assumptions are the same as those in the medium fertility variant.

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

6. Momentum assumption

A new variant, the momentum variant, was introduced in the *2017 Revision*. This 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 2015-2020, while the mortality is kept constant as of 2010-2015 and the net international migration is set to zero as of 2015-2020.

B. MORTALITY ASSUMPTIONS: INCREASING LIFE EXPECTANCY FOR ALL COUNTRIES

1. Normal-mortality assumption

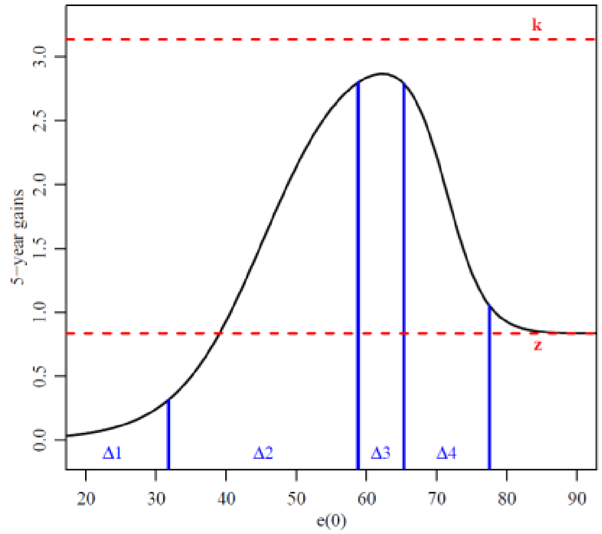
Assumptions for the projection of mortality are specified in terms of life expectancy at birth by sex. As in previous revisions, life expectancy was generally assumed to rise over the projection period, and only one variant of future mortality trends was used for each country as part of the traditional "high", "medium" and "low" projection variants, which reflect variation in fertility alone. However, as part of the probabilistic population projections, the Population Division also 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. For countries where this model was used, the median trajectory provides the mortality trend used in the high-, medium- and low-fertility variants.

The *2017 Revision* of *World Population Prospects* used probabilistic methods for projecting life expectancy at birth. Following further analysis of the results of the *2015 Revision,* several modifications were made in the implementation of the models used in the previous revision. These changes involved modifying some model parameters that are specified *a priori* and some assumptions regarding outliers (see section b), as well as expanding the dataset used for estimating the model of the female-male gap in life expectancy at birth (see section c).

a. ***Projection of female life expectancy***

The probabilistic methods used in the *2017 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 et al., 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 gains in life expectancy (figure II.4). The first phase consists of the initial slow growth in life expectancy associated with the diffusion of improved hygiene and nutrition, followed by a period of accelerated improvements, especially in the mortality of infants and children, associated with social and economic development accompanied by interventions in public health and basic medical care (for example, infant feeding, water and sanitation, and childhood immunization programmes). The second phase begins once the easiest gains, mainly against infectious diseases that often strike in childhood, have been achieved. The second phase is characterized by continuing gains against infectious diseases across the age range and also against 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 an older person (compared to saving a child), the rise of life expectancy is slower in the second phase (Fogel, 2004; Riley, 2001; Wilmoth, 1998).

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



Source: Raftery et al. (2013).

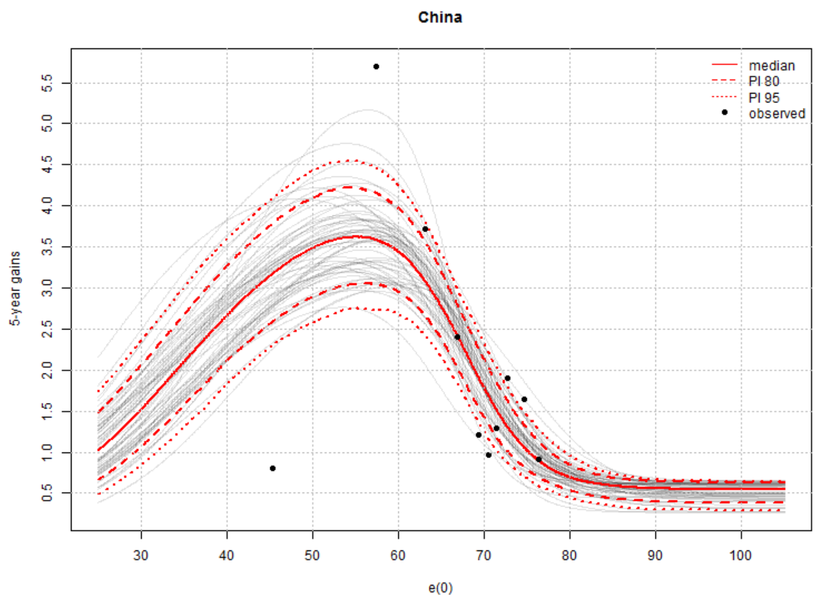
NOTE: The deltas (Δ) in the figure represent changes in the magnitude of 5-year gains against increases in life expectancy at birth.

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. 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 2015 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. 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 et al. 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, Deegan, Lundstrom and Horiuchi, 2000; Wilmoth and Ouellette, 2012; Wilmoth and Robine, 2003). 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 a model parameter that helps to determine the asymptotic average rate of increase in female life expectancy[15].

To construct projections of female life expectancy at birth for all countries without generalized HIV/AIDS epidemics, the Bayesian hierarchical model was used to generate 1,100,000[16] double-logistic curves for each country or area (see example in 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[17]).

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



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 1,100,000 simulated trajectories are shown here. The median projection is the solid red line, and the 80% and 95% prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

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. The median of these 100,000 trajectories was used as the standard mortality projection of the *2017 Revision*. To evaluate the uncertainty of future trends in female life expectancy at birth, 80- and 95-per cent prediction intervals were also calculated (see figure II.6 for China; additional tables[18] and graphs[19] are available online for other countries).

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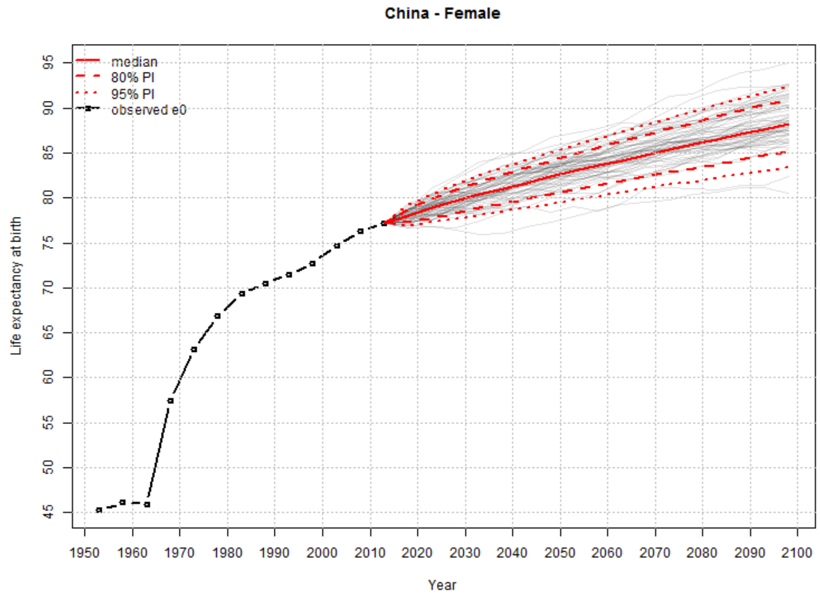
[15] Following the notation used in Raftery et al. (2013), to obtain a posterior median of the annual gain in life expectancy of around 0.125 year (or 5-year gain of 0.625), the parameter constraining the maximal value of the asymptote of the double-logistic curve at high levels of life expectancy was 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.

[16] Actually, ten simulations were run in parallel with 160,000 iterations performed for each simulation, and the first 50,000 were discarded.

[17] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. 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 http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/CHGFEM/.

[18] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online tables of probabilistic projections of female life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/.

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



NOTE: For ease of viewing, only 60 simulated trajectories of the 100,000 sampled trajectories are shown here for 2015 to 2100. The median trajectory is the solid red line, and the 80% and 95% prediction intervals (PI) are shown as dashed and dotted red lines respectively.

b. Changes in the implementation of the life expectancy projection model

The Bayesian hierarchical model for projecting female life expectancy at birth described above was used by the United Nations Population Division in the *2012* and *2015 Revisions* of the *World Population Prospects* (United Nations 2013, 2015a). In the current revision, the Population Division has continued to refine the specifications of the model based on previous experience with its application. In the *2015 Revision*, prior distributions were adjusted for close to 30 per cent of all countries or areas for which the model was being used, because the unadjusted trajectories of future life expectancy at birth were deemed too high or too low compared to the projections generated for other countries with similar levels of life expectancy in recent years (United Nations 2015a). A subsequent analysis of uncertainty bounds suggested that model performance could be improved by revising certain aspects of the model. An analysis of the sensitivity of results derived from the model to changes in specific priors and the use of expanded datasets guided choices that were made while updating the model to generate projected trends of life expectancy at birth in the *2017 Revision*[20]. These changes have improved the model fit and the internal consistency and plausibility of the results, yielding a substantial decrease in the number of countries or areas for which adjustments were deemed necessary in the current revision as compared to the previous one. The main changes are described below.

[19] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York. Online plots of probabilistic projections of female life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/Female/.

[20] For further details, please see Castanheira, Pelletier and Ribeiro (2017).

i) The sum of the "deltas" (Δ)

In the *2017 Revision,* an analysis of the role of the maximum sum of deltas on the projected levels of life expectancy at birth and associated uncertainty bounds was conducted. The results of the analysis showed that reducing the maximum limit for the sum of deltas from 110 years to 86 years provided more coherent results for several countries, both in terms of the projected median trajectory and the upper prediction bounds. This reduction in the sum of the deltas affected considerably the upper prediction bounds of several countries, mainly countries with lower levels of life expectancy in 2010-2015 that were in early phases of the mortality transition. Consequently, cross-country comparisons of these bounds are now more coherent; overall, fewer countries that currently have low levels of life expectancy have projected trajectories of life expectancy surpassing those of countries that currently have the highest longevity on record (e.g., see figure II.7 below). Furthermore, within this revision, the number of countries that were adjusted because their projected life expectancy levels were deemed too high was reduced as compare to the *2015 Revision* (see table II.1, p. 26). Restricting the maximum sum of deltas to 86, meant that the mortality transition of countries was completed as female life expectancy reached 86 years, after which the increments in life expectancy were mainly driven by the asymptotic average rate of increase.

ii) Re-estimation of model priors and definition of outlier observations

Furthermore, the Bayesian approach requires specifying the distributions of certain model parameters *a priori*. In this revision, the five models that had been used to develop the priors for previous revisions were updated to incorporate more recent life expectancy data.

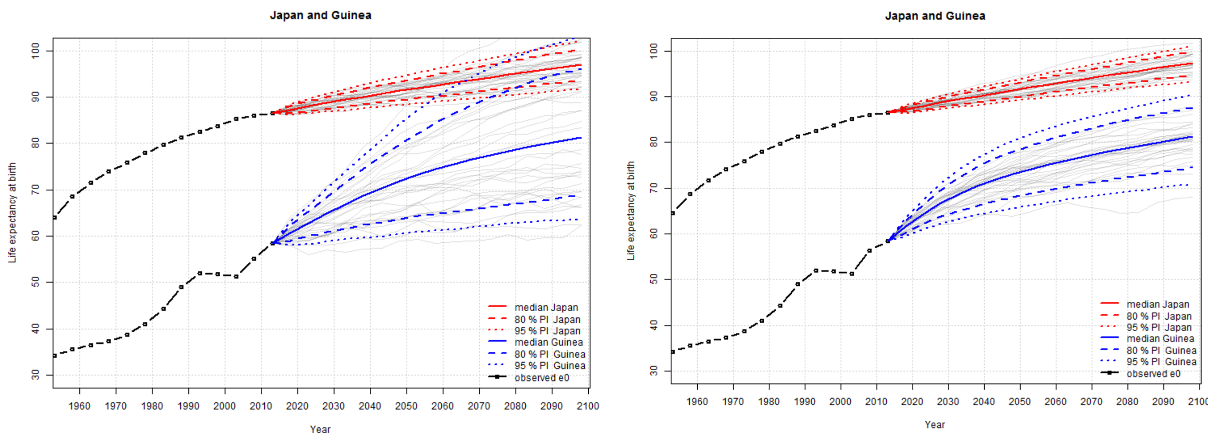
The updated database for the Bayesian model consisted of 2,502 five-year gains in female life expectancy ($g(e_{c,t}) = e_{c,t+1} - e_{c,t}$) for 182 countries[21] from 1950-1955 until 2010-2015 and historical supplemental data for 29 countries with reliable life expectancy estimates before 1950. The data contained a total of 111 country-periods with negative gains in life expectancy, resultant of mortality crises or exceptional mortality conditions. These negative gains influenced the predicted parameters of countries, especially the ones with no supplemental historical data, and, consequently, were influencing their trajectories in the future. Given that these negative gains were mostly observed for countries that by 2010-2015 had already reached or surpassed the life expectancy experienced in the period before the loss[22], the database was truncated at zero (i.e., all negative gains were removed) so that the loss in life expectancy would not influence the mortality trajectories of countries in the future. In addition, observations with life expectancy gains greater than three standard deviations from the mean, that is, seven years of life expectancy (a total of 20 country-period observations), were also considered outliers and removed from the database. The final number of country-period observations for which the Bayesian hierarchical model was estimated was 2,371.

To illustrate the impact of some of the changes in the model that were described above, figure II.7 shows a comparison of probabilistic female life expectancy trajectories for Japan and Guinea in the *2015* and *2017 Revisions*. The upper 95-per cent prediction intervals for both Japan and Guinea reached levels of about 100 years by the end of the century in the *2015 Revision*, while that of Guinea is much lower in the *2017 Revision*. Generally, future trajectories of countries that had lower levels of life expectancy in 2010-2015 were more impacted by the changes made in the model. For several countries, the estimated uncertainty bounds are highly dependent on the values or assumptions made in specifying the model.

[21] Out of a total of 233 countries or areas in the world, the database consisted of 182 countries, excluding 32 countries with less than 90,000 inhabitants, Syria, currently in a mortality crisis, and 18 countries with a maximum HIV prevalence of 5% or above between 1980 and 2015 among persons aged 15 to 49 years (see table II.2, p.28).
[22] Negative gains were observed in the data for 66 out of 182 countries. Among these 66 countries, only Belize, Côte d'Ivoire, and Iraq had not achieved in 2010-2015 the life expectancy levels prevailing before the loss.

Figure II.7. Female life expectancy at birth and prediction intervals, *2015* and *2017 Revisions*
Japan and Guinea, 1950-2100

2015 Revision ***2017 Revision***



Data Sources: United Nations, Department of Economic and Social Affairs, Population Division (2017c, d), *World Population Prospects: The 2017 Revision*; United Nations, Department of Economic and Social Affairs, Population Division (2015b, c), *World Population Prospects: The 2015 Revision.*

c) 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 obtain 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, Lalic and Gerland, 2014).

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 et al., 2008; Rogers et al., 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 et al., 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 countries with emerging economies, was assumed to apply in the future to other countries as well. Such a trend does not seem implausible given the diffusion of effective public health and safety measures and medical interventions (Bongaarts, 2009; Vallin, 2006). 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 exist 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 (see example in figure II.8), representing the uncertainty in the projected future gap (graphs of the sex gap trajectories for other countries are available online[23]). 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.

For the *2017 Revision,* historical data for periods prior to 1950 for several countries were included in the dataset used to estimate the coefficients of the sex gap model. The inclusion of these historical data provided more plausible combinations of results from the two models (for female life expectancy and for the sex gap) across the relevant range of life expectancy at birth. For many countries, this expansion of the dataset used for estimating the sex gap model produced a slower (and seemingly more plausible) decline of the female-male gap in life expectancy at birth over the projection period, or allowed for the gap to continue to increase for a longer period before starting to decline. An additional modification for the *2017 Revision* was that the minimum and maximum bounds of the gap were set at 0 and 18; in the previous revision, the lower bound had been set at -1. This change also contributed to a slightly slower decline in the projected sex gap for some countries.

Figure II.8 shows for selected countries the effects of the revisions to the sex gap model with respect to the historical data. As seen in the cases of China and India, the median trajectory of the female-male gap in life expectancy at birth decreased more slowly in China or continued to increase for a longer period in India, when the historical data were included in the estimation (red lines). Similar effects were observed for many countries after the inclusion of the historical data. For countries more advanced in the mortality transition, such as Japan or Switzerland, shown in the lower panels of figure II.8, although the projection intervals changed slightly in some cases, the median trajectory barely changed. Overall, for countries with life expectancies closer to 86 years in 2010-2015, the inclusion of the historical data in the estimation had almost no effect. The observed difference for countries at lower levels of life expectancy was driven by the assumption of a constant sex gap once countries reach a female life expectancy of 86 years. At this level, the gap no longer drifts upward or downward but rather tends to remain at approximately the same value, with only small random changes over time that follow the normal distribution.

The sample of gender gap trajectories was then used to calculate over 100,000 male life expectancy projections for each country. The median of these projections was used as the standard mortality projection in the *World Population Prospects*. To evaluate the uncertainty of future trends in male life expectancy at birth, 80- and 95-per cent prediction intervals were also calculated (see figure II.9 for China, additional tables[24] and graphs[25] are available online for all countries).

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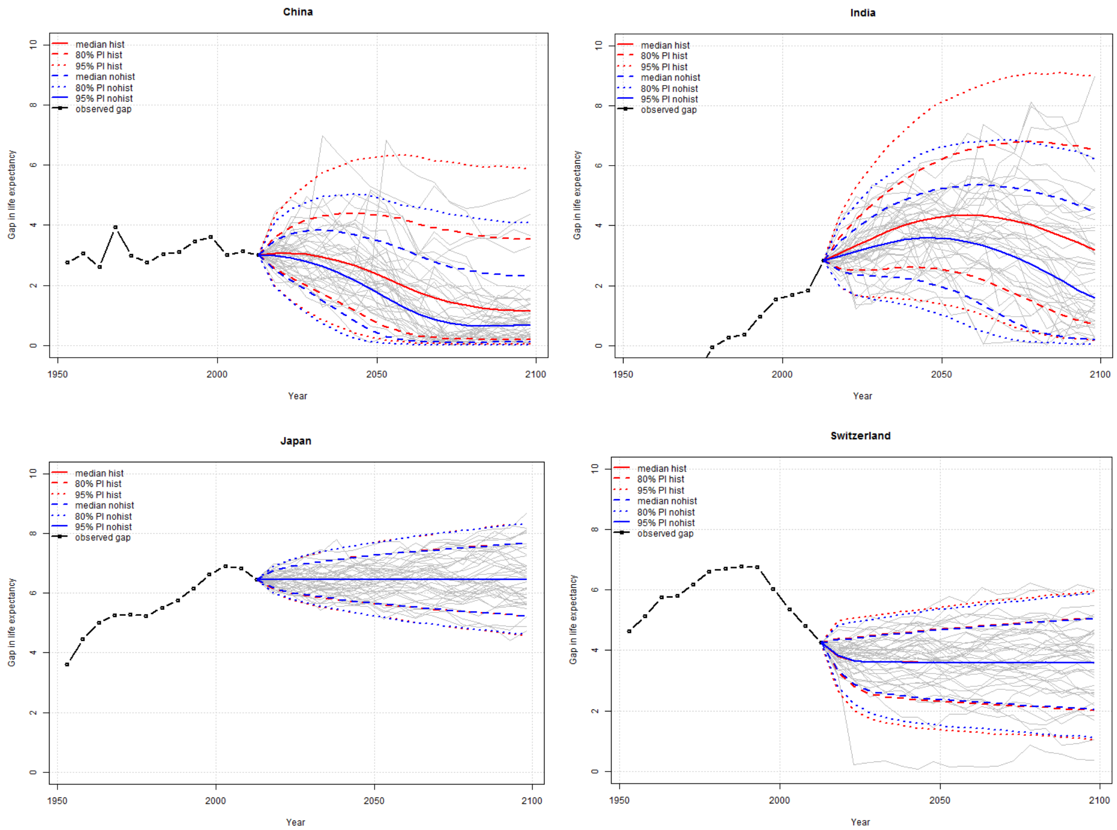
[23] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online plots of female-male gap in life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/FMGAP/.

[24] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online tables of probabilistic projections of male life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/.

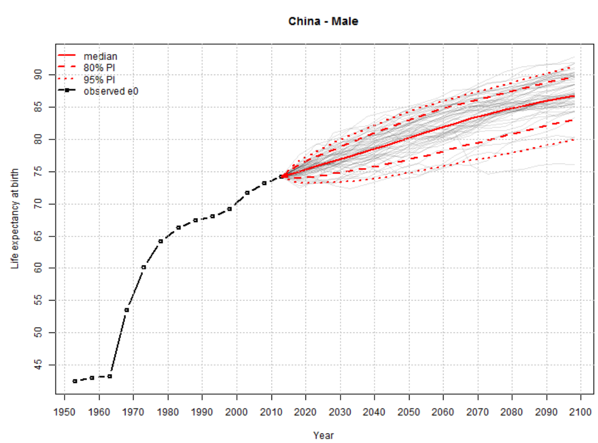
[25] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. New York: United Nations. Online plots of probabilistic projections of male life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/Male/.

Figure II.8. Female-male gap in life expectancy at birth (in years) and projected prediction intervals, with and without the inclusion of the historical mortality data, China, India, Japan and Switzerland, 1950-2100



NOTE: The observed gap between female and male life expectancy at birth are shown by black dots and solid line. For clarity, only a limited number of trajectories out of the 100,000 calculated are shown here for 2015 to 2100. The median projections are the solid red and blue lines, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted lines respectively. The red lines show the results when historical data were included in the model; the blue lines show the results without inclusion of historical data.

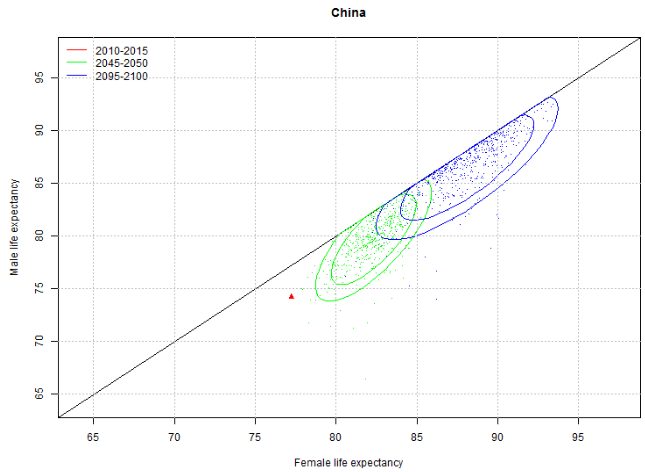
Figure II.9. Estimates and projected probabilistic trajectories of male life expectancy at birth (in years), China, 1950-2100



NOTE: For clarity, only 60 trajectories of the 100,000 calculated are shown here for 2015 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.

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 (see example in figure II.10 comparing the distributions for China in 2045-50 and 2095-2100). The 80- and 95-per cent prediction intervals are shown as ellipses. The relationship if both male and female life expectancies are equal is displayed with a diagonal line. Graphs of the joint distributions of life expectancy by sex for other countries are available online.[26]

Figure II.10. Comparison of probabilistic projections of female and male life expectancies at birth (in years), selected periods, China



NOTE: The figure shows the relationship between probabilistic projections of male and female life expectancies at birth for 2010-2015, 2045-2050 and 2095-2100 that has been carried out with estimates from the *2017 Revision* of the *World Population Prospects*. For ease of viewing, only 500 of the 100,000 projected trajectories are shown here for each sex.

Adjustments

The approach to life expectancy projection 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 typically 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 double logistic function responsible for future gains for each country were informed by the experience of the leading countries in its respective region[27]. In the first case, this approach was used to temper large gains for some countries

[26] United Nations, Department of Economic and Social Affairs, Population Division (2017). *World Population Prospects: The 2017 Revision*. 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% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/FMCOMP/.

[27] Following Raftery et al. (2013) formal notation, 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.

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, 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). The countries to which adjustments were applied are listed in table II.1. Changes made to the model in the *2017 Revision*, as described above, reduced the number of countries requiring adjustments from 52 in the *2015 Revision* to 14 in the current revision, indicating an improvement in the performance of the model. Overall, the results are more in line with what would be expected in future survival prospects based on our knowledge of current levels of life expectancy at birth and socio-economic and health conditions of individual countries.

TABLE II.1. COUNTRIES FOR WHICH ADJUSTMENTS WERE MADE TO THE DEFAULT PROJECTION TRAJECTORY IN THE 2017 REVISION

	Country or area		*Country or area*
A. Countries with projected life expectancies that were deemed too high			
1	Angola	6	Niger
2	Bolivia (Plurinational State of)	7	Sierra Leone
3	Cambodia	8	Solomon Islands
4	Ethiopia	9	Timor-Leste
5	Lao People's Democratic Republic		
B. Countries with projected life expectancies that were deemed too low			
1	Côte d'Ivoire	4	Pakistan
2	Djibouti	5	Yemen
3	Guyana		

d. Projection of the age pattern of mortality

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 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, Lee, and Gerland, 2013)[28], or (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, Gu, and Gerland, 2013)[29], or (c) from extended model life tables (Li and Gerland, 2011). With each method, additional constraints were sometimes used at younger or older ages to ensure greater consistency in sex differentials, especially at very high levels of projected life expectancies. 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. 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 [30].

[28] 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.
[29] 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.
[30] For further details, please see Gu, Pelletier and Sawyer (2017).

For countries lacking recent or reliable information on age patterns of mortality, mortality rates were directly obtained from an underlying model life table. 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 (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[31,32].

2. The impact of HIV/AIDS on mortality

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 *2017 Revision* made explicit modelling assumptions to incorporate the demographic impact of the HIV/AIDS epidemic for 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 (table II.2). In countries most highly 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. The model developed by the UNAIDS Reference Group on Estimates, Modelling and Projections (Stanecki, Garnett, and Ghys, 2012; Stover, Brown, and Marston, 2012), and all epidemiological parameters (including treatment data) used by UNAIDS were made available to the Population Division in 2016[33] and were used to derive the mortality impact of HIV/AIDS. The model was not used for all countries with prevalence above 5 percent to generate mortality estimates. In a few cases where sufficient empirical evidence on adult mortality was available, and HIV prevalence was at one point above 5 per cent, estimates of adult mortality by age and sex were derived from empirical observations in conjunction with estimates of under-five mortality (see online listing of data sources[34] for country-specific details).

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[31] United Nations Population Division (2011). *Extended Model Life Tables Version 1.3*. New York: United Nations. Available online at: http://esa.un.org/unpd/wpp/Download/Other/MLT/.

[32] 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.

[33] 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.

[34] Data sources and related meta-information for the *2017 Revision* of the *World Population Prospects* are available for each country from the following web page: http://esa.un.org/unpd/wpp/DataSources/.

TABLE II.2. HIV PREVALENCE RATE AMONG ADULTS AGED 15-49 YEARS IN THE COUNTRIES FOR WHICH EXPLICIT MODELLING OF HIV/AIDS WAS EMPLOYED IN THE *2017 REVISION*

Country	*Adult HIV prevalence rate (%) in 2015*	*Maximum HIV rate (%) between 1980 and 2015*	*Country*	*Adult HIV prevalence rate (%) in 2015*	*Maximum HIV rate (%) between 1980 and 2015*
Botswana	23.1	28.5	Mozambique	11.2	11.6
Cameroon	4.6	5.4	Namibia	14.0	18.1
Central African Rep.	4.2	9.2	Rwanda	2.7	6.1
Congo	2.7	5.5	South Africa	19.9	22.1
Equatorial Guinea	5.3	6.9	Swaziland	27.2	27.3
Gabon	4.1	5.7	Uganda	7.7	13.5
Kenya	5.4	12.2	UR of Tanzania	5.5	8.3
Lesotho	23.2	23.8	Zambia	13.5	16.8
Malawi	10.5	17.4	Zimbabwe	15.7	25.9

Source: UNAIDS (2016). *Prevention Gap Report*. Geneva, and 2016 set of UNAIDS/WHO estimates (unpublished tabulations made available in September 2016).
Also see: http://www.unaids.org/sites/default/files/media_asset/2016-prevention-gap-report_en.pdf.

In the *2017 Revision*, in order to address concerns related to the sex ratio of all-cause mortality in specific age groups, the ratio of female to male HIV incidence for ages 15-49 was modified for a number of countries in the process of estimating the demographic impact of the HIV/AIDS epidemic. The sex ratio of HIV incidence was modified in the countries that had a prevalence of 8 per cent or more between 1980 and 2015, namely Botswana, Central African Republic, Lesotho, Malawi, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe, using lower levels in line with those estimated for Mozambique. It was still assumed that more women than men were being infected by HIV, but to a lesser degree than assumed in the default time-series included in the SPECTRUM files. These changes had implications for the all-cause mortality levels for both men and women. Overall, it implied higher mortality levels for men and lower ones for women, which is, on the whole, more consistent with empirical evidence. The default sex ratios in Congo, Gabon and Rwanda were modified as well, though they were assumed to be higher than for the countries with higher prevalence listed above.

The projection assumptions used in the *2017 Revision* assumed that the HIV prevalence rate observed in 2015 would decline by 2100 to about 1/10 of its value following an exponential decay function. The sex ratio of HIV incidence (female to male incidence for age 15-49) was assumed to follow a linear trend from its 2015 value to reach 1.1 in 2050 and to remain constant thereafter. Proportions of HIV-positive children and adults receiving treatment in each country were taken from estimates prepared by the World Health Organization and UNAIDS. For adults, 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. A similar approach was used for the treatment of children while coverage of interventions to prevent mother-to-child transmission of HIV was assumed to reach 90 per cent in almost all countries by 2050, and remain constant thereafter until 2100.

3. Constant-mortality assumption

Under the constant-mortality assumption, mortality over the projection period is maintained constant for each country at the level estimated for 2010-2015.

C. 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 volatile process. Not only has international migration shown drastic changes in absolute numbers, but the direction of the flows has changed as well. As a result, some countries that historically have been primarily countries of origin have become countries of destination, and vice versa. Therefore, formulating assumptions about future trends in international migration is extremely challenging. Where migration flows have historically been small and have had little net impact on the demography of a country, adopting the assumption that migration will remain constant throughout most of the projection period is usually acceptable. In situations where migration flows are a dominant factor in demographic change, more attention is needed.

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. Because immigration and emigration flows affect countries differently, international migration is ideally studied as the flow of people moving between countries. In practice, data on international migration flows only exist for a small number of countries. Therefore, international migration in this revision, as in previous ones, has been incorporated as net migration. Net migration—the difference between the number of immigrants and the number of emigrants for a particular country and period of time—shows the net effect of international migration on the respective population. It does not provide an indication about the number of immigrants and emigrants involved. In an extreme case, immigration and emigration for a country could be significant, but if the number of immigrants were equal to the number of emigrants, net migration would amount to zero.

In preparing assumptions about future trends in international migration, several pieces of information were taken into account: (1) information on net international migration or its components (immigration and emigration) as recorded by countries; (2) data on labour migration flows; (3) estimates of undocumented or irregular migration; (4) and data on refugee movements in recent periods.

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 5 to 10 years. If a country was projected to experience both international migration and refugee movements, the two processes were added in order to capture the overall net migration during a given period.

Usually, migration assumptions are expressed in terms of the net number of international migrants. The distribution of 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 frequent lack of suitable 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 assumed (for example, labour migration or family migration). The age and sex profiles of the net migration flows were then used as input for the cohort-component projection model (Castro and Rogers, 1983; United Nations, 1989). In the instances where it was possible to estimate the age and sex distribution of international migrants, those distributions were used to determine the most suitable model or, in some cases, those data were 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 labour migrants accounting for the ageing of the migrants involved. The same practice was applied to refugee flows.

International migration has become a nearly universal phenomenon affecting virtually all countries of the world. For the few countries that were known neither to admit international migrants nor to supply a sizeable number of 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 sending countries as receiving countries.

As a final step, it was necessary to ensure that the sum of all international migration added to zero at the global level for each 5-year estimation and projection period. This was achieved by an iterative process in which individual country estimates and projections were revisited and altered accordingly.

1. Normal migration assumption

Under the normal migration assumption, the future path of international migration is set on the basis of past international migration estimates and consideration of 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 circumstances noted above, such as large recent fluctuations in migration numbers, refugee flows, or temporary labour flows. After 2050, it is assumed that net migration would gradually decline and reach 50 per cent of the projected level of 2045-2050 by 2095-2100. This assumption is unlikely to be realized but 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.

2. Zero-migration assumption

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

D. Nine projection variants

The *2017 Revision* includes nine different projection variants (see table II.3). Five of those variants differ only with respect to the level of fertility, that is, they share the same assumptions made 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 2010-2015. 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 2015-2020. 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 (i.e., both fertility and mortality are kept constant) have been prepared. The constant-mortality variant and the zero-migration variant both used the same fertility assumption (medium fertility). 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 various population quantities. 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 an assessment of the effect that non-zero net migration has on various population quantities. 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.

In the *2017 Revision,* a new momentum variant was added to illustrate the impact of age structure on long-term population change. The variant combines elements of three existing 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	Normal	Normal
High fertility	High	Normal	Normal
Constant-fertility	Constant as of 2010-2015	Normal	Normal
Instant-replacement-fertility	Instant-replacement as of 2015-2020	Normal	Normal
Momentum	Instant-replacement as of 2015-2020	Constant as of 2010-2015	Zero as of 2015-2020
Constant-mortality	Medium	Constant as of 2010-2015	Normal
No change	Constant as of 2010-2015	Constant as of 2010-2015	Normal
Zero-migration	Medium	Normal	Zero as of 2015-2020

Furthermore, the outputs from the *2017 Revision* also include the 80 and 95 per cent prediction intervals from the probabilistic projections of fertility and mortality levels, as well as the associated prediction intervals for total population and selected broad age groups.

E. INTERPOLATION PROCEDURES

The cohort-component method used in the *2017 Revision* 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 *2017 Revision* are also 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) (the next 5-year projection period) centred on 1 January year (t+3). For example, the estimate for life expectancy at birth for 2000-2005 refers to the period from mid-2000 to mid-2005 (i.e., 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.

a. 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, p. 728). The second 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, p. 727) 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 *2017 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.

b. 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, p. 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 this 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.

F. TABULATIONS

After preparing the projections for individual countries, the results were aggregated for the world, regions, subregions, development groups and other aggregates. For a list of aggregation units, see the explanatory notes at the beginning of this report[35].

The aggregation of populations by age and sex and vital events by age and sex is performed by simply adding the variables according to lists that assign individual countries to the aggregates. For synthetic variables, like life expectancy, total fertility, median age or net reproduction rates, proper population weighted averages are calculated.

G. SUMMARY OF METHODOLOGICAL CHANGES INTRODUCED IN THE *2017 REVISION*

The following summarizes the major changes made in the *2017 Revision* compared to procedures followed in the *2015 Revision*.

- In the *2017 Revision,* a momentum variant was added to illustrate the impact of the current age structure on future population change. The new variant combines the defining elements of three existing variants: instant replacement-level fertility, constant mortality, and net migration equal to zero.

[35] Also see: https://esa.un.org/unpd/wpp/General/Files/Definition_of_Regions.pdf

- During the *2017 Revision*, several parameters within the probabilistic models used for projecting life expectancy at birth (both level and sex gap) were modified, changing the projected trends for many countries, for both the median trajectory and associated uncertainty bounds. These changes improved both the model's goodness-of-fit based on empirical data and the internal consistency and plausibility of projected trends, reducing the number of countries for which adjustments to the model-based projections were deemed necessary in the *2017 Revision* as compare to the previous one. In addition, the use of historical data from before 1950 in fitting the sex gap model contributed to the improved projections of the sex gap, especially for countries at less advanced stages of the mortality transition.
- The *2017 Revision* made explicit modelling assumptions to incorporate the demographic impact of the HIV/AIDS epidemic for 18 countries where HIV prevalence among persons aged 15 to 49 was at least 5 per cent at some point between 1980 and 2015. In order to address concerns related to the sex ratio of all-cause mortality in specific age groups, the ratio of female to male HIV incidence for ages 15-49 was modified for a number of countries in the process of estimating the demographic impact of the HIV/AIDS epidemic.

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