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Research Article

Modelling the age and sex profiles of net international migration

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Abstract

BACKGROUND
Many national statistical offices and international agencies use age and sex profiles of net migration as inputs into demographic accounting models for population estimation and projection. Commonly used residual methods for inferring these profiles have proven inadequate due to errors in the measures of populations, births, and deaths.

OBJECTIVE
We test and apply a new methodology to infer the age and sex profiles of net international migration.

METHODS
Our strategy focuses on estimating flows of immigration and emigration by age and sex. Differences from these flow estimates are then used to represent estimates of net international migration.

RESULTS
Based on promising results from empirical tests that used data from Sweden and the Republic of Korea, the methodology is extended to estimate age–sex patterns of net international migration for countries lacking migration data.

CONCLUSIONS
We develop a relatively simple yet powerful model for estimating the age and sex profiles of net international migration from estimated immigration and emigration age–sex profiles. The model is flexible such that it can be applied to any country situation, with or without data, and can be modified to incorporate new data or assumptions.

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CONTRIBUTIONS
This research contributes towards overcoming data limitations and improving understanding of migration processes, as well as the estimation and projection of populations.

1. Introduction

International migration is an increasingly important driver of population change in many countries (White 2016; United Nations 2017a). Particularly for those in the advanced stages of the demographic transition with low fertility and mortality rates, the future levels of net international migration will determine whether the population grows or declines during the coming decades (United Nations 2024). Unfortunately, empirical data on international migration remain sparse, because they are either not collected or made accessible to users (Iredale, Guo, and Rozario 2003; Hugo 2005; Skeldon 2006). For the migration data that are available, there are many issues concerning measurement, coverage, and quality (see, e.g., Poulain 1993; Nowok, Kupiszewska, and Poulain 2006; Raymer et al. 2013; Wiśniowski et al. 2016).

The absence of international migration data is associated with issues concerning the "registration of foreign workers, estimates of unauthorized migration, measurement of return migration, estimating the number of nationals abroad, the public availability of migration statistics and institutional cooperation" (Huguet 2008: 231). For example, data on emigration and irregular migration are particularly problematic because individuals rarely have incentives to report their departures in comparison to their arrivals, and those who migrate irregularly may have weak legal status and are thus less likely to engage with administrative authorities (Asis and Battistella 2018). The stark differences in migration policies and management across regions in the world further complicate the measurement of international migration, resulting in government authorities focusing on particular types of foreign citizenship migration associated with reasons for entry, such as labour, education, and family reunification. These authorities may not have the capacity, interest, or official channels to communicate their data with other agencies to form a comprehensive picture of migration. Parts of Asia, for example, are characterized by "strict control of foreign workers, prohibition of settlement and family reunion, and denial of worker rights (especially for less-skilled personnel)" (Castles 2009: 451). By contrast, no restrictions are in place in the European Union for migrants who have citizenship from member countries.

Determining levels of international migration for most countries is difficult due to the absence of data. Instead, national statistical offices and international agencies rely on indirect estimation methods that infer the total levels of net migration and patterns by sex and age based on information about changes in overall population size and age structure over time. For example, to produce estimates of net international migration for all countries in the world, the United Nations (2022) uses a combination of residual methods, which compared populations enumerated in successive censuses, and model migration age schedules, which apply an assumed age distribution based on flows observed in a small number of countries with available data. This approach has limitations however. Residual methods are hampered by errors in the measurement of populations and vital rates. Model schedules are intended to describe flows and are not well suited to represent net migration patterns, which are the difference between levels of immigration and emigration that are often highly correlated (Rogers 1990). In light of these challenges, further efforts are needed to improve the estimation of net migration profiles by age and sex.

In this paper, we propose a model framework to distribute the age and sex profiles of net international migration. We focus on estimating net international migration because of its widespread use in population estimation and projection and because, for most countries in the world, there is no way to validate estimates of immigration and emigration. The framework focuses on approximating levels of (1) immigration by age and sex and (2) emigration by age and sex. The differences between these two approximations then yields the estimates of net international migration by age and sex. The method was developed specifically to support the Population Division of the United Nations Department of Economic and Social Affairs (UNDESA) efforts to produce its biannual official population estimates and projections for all countries in the world in the World Population Prospects (WPP).

In the following sections, we describe the age, sex, and compositional regularities of international migration that are fundamental to our model design, which is followed by a review and evaluation of previous approaches used to estimate net international migration by sex and age. We then propose a method to model the age and sex profiles of international migrants that can be used for both population estimation and projection. The model parameters of the new method are evaluated by assessing how closely the results replicate empirically observed patterns of net international migration by age and sex in Sweden and the Republic of Korea. Finally, we apply the methodology to situations in which there are assumed to be no migration data. The paper ends with a conclusion and recommendations for future research in this area.

2. Background

The aim of this research is to improve the modelling of age and sex patterns of net international migration, where sex refers to males and females and age to single-year age groups. Ideally, net international migration totals are calculated by subtracting emigration from immigration that have occurred during a calendar year for a particular country.

2.1 Age patterns of migration

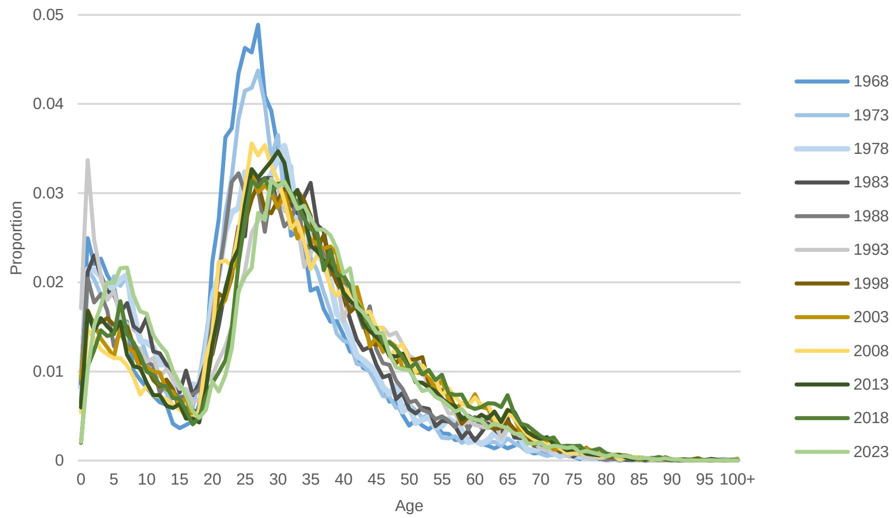
Similar to mortality, fertility, marriage, divorce, and remarriage, age profiles of both internal and international migration exhibit remarkably persistent regularities when measured as directional movements (Rogers and Castro 1981a, 1981b; Raymer and Rogers 2008; Wiśniowski et al. 2016; Raymer and Wiśniowski 2018). The most prominent regularity in age-specific profiles of migration flows is the high concentration of migration among young adults. Levels of migration can also be high among children, starting with a peak during the first year of life and dropping to a low point around ages 12 to 16 years. Although relatively rare for international migration, some domestic (internal) migration flows exhibit humps at the onset of retirement and upward slopes at the oldest ages associated with migration to live closer to (adult) children or to seek care (Rogers 1988).

Regularities in the age patterns of migration include many underlying causes of migration that also have specific age patterns (Rogers and Castro 1981b; Plane and Heins 2003; Raymer, Liu, and Bai 2019). For example, migration for tertiary educational purposes is concentrated in the young adult age groups. Employment-related migration exhibits broader young adult age profiles that often include relatively high rates of young children migrating with their parents. Retirement-related migration exhibits a peak centred around the age of 65 years that is most likely to occur in movements from cities where housing costs are high towards areas with good climate, an abundance of natural amenities, and low housing costs. The causes of different age profiles of migration may be interpreted from a life course perspective. The life course perspective explains how a series of individual life status transitions (e.g., from living with parents to living alone) or life events (e.g., completing education) results in distinct forms of spatial movement (Elder 1985; Plane and Heins 2003; Kulu and Milewski 2007). Moreover, migration is more than a collection of independent movements; it also includes those who are dependent on others – for example, children migrating with their parents, spouses with their partners, and elderly with their children.

Migration is also influenced by the compositional aspects of the population ‘at risk’ of migration. To understand these influences, Castro and Rogers (1983a, 1983b) illustrate a number of ways in which the age profile of migration is sensitive to relative changes in the population age profile by disaggregating migrant populations according to age, sex, and whether the migrants were independent or dependent. Viewing the migration process within a framework of dependency allows one to predict the shape of the age profile. For example, if the migration process largely comprises individual movements, one might expect relatively few children and older migrants. On the other hand, if the migration process consists primarily of family migration, then the share of dependent children may become a very important component of the age pattern. In other words, population age compositions have the potential for use in inferring age profiles of migration (Little and Rogers 2007).

To illustrate how migration varies by age and sex, we present in Figure 1 the patterns of emigration from Sweden every five years from 1968 to 2023. These data were obtained from a population register that maintains a continuous and accurate accounting of population change, including entries and exits. In the figure, we see that the age profiles are dominated by young children and young adults. Also, when expressed as proportions, the age patterns are remarkably similar each year. The situation for immigration (not shown) is similar, except that the levels tended to be higher and somewhat less stable throughout the 55-year period. Also, males aged 15 to 16 years exhibited increasing immigration levels after 2006, which were linked to increases in unaccompanied minors seeking asylum (Çelikaksoy and Wadensjö 2015).

Figure 1: Proportionate age distribution of male emigration from Sweden, 1968–2023

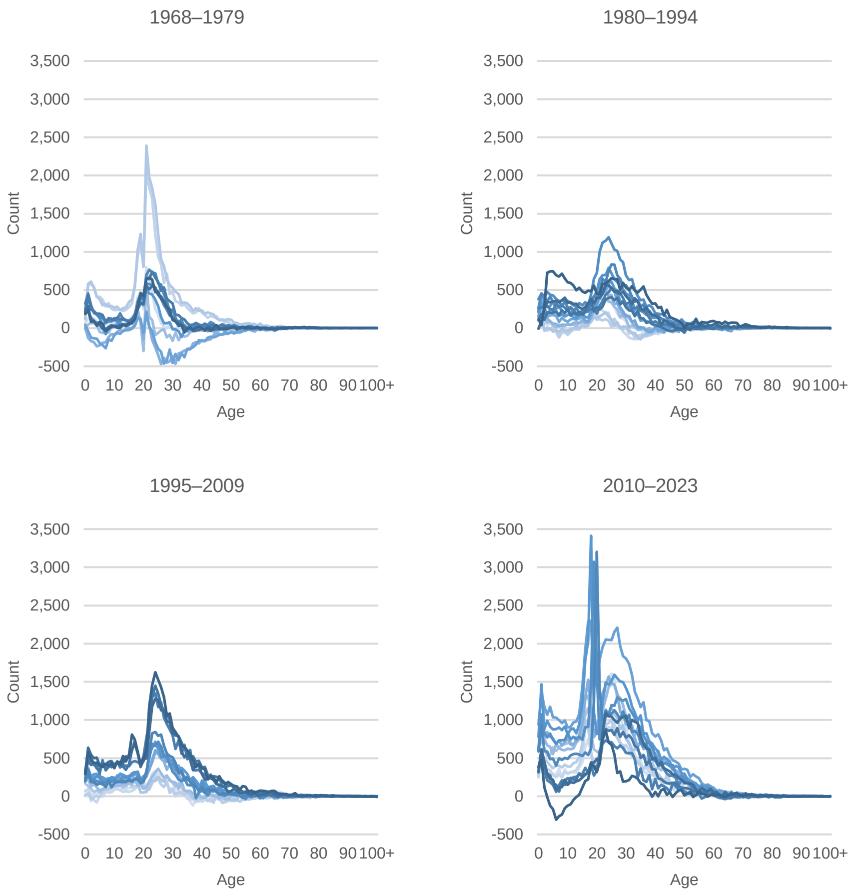


Source: Statistics Sweden Statistical Database (https://www.statistikdatabasen.scb.se/pxweb/en/ssd/).

In Figure 2, we present the age patterns of net migration for males in Sweden, separated into the following four periods: 1968–1979, 1980–1994, 1995–2009, and 2010–2023. The late 1960s and 1970s were a relatively volatile period with considerable positive and negative values for young adults. The net migration patterns for the 1980s to early 2000s appeared relatively stable.[3] After 2004, net migration increased across all ages due to the expansion of the European Union (EU).[4] In comparison to the emigration age profiles, the net age profiles of international migration were much less stable over time.

[3] Sweden joined the European Union on 1 January 1995 with Austria and Finland.
[4] In 2004, Cyprus, Chechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, and Slovenia joined the European Union. In 2007 Bulgaria and Romania joined the European Union.

Figure 2: Male net international migration by age for Sweden, 1968–2023 (persons)



Source: Statistics Sweden Statistical Database (https://www.statistikdatabasen.scb.se/pxweb/en/ssd/).
Note: Lines are shaded by year with darker lines representing recent years.

2.2 Sex patterns of migration

Similar to age profiles of international migration, sex patterns of international migration are influenced by different types of migration (Schoorl 2012). For example, in Western Europe between 1950 and 1970, low-skilled labour migration was dominated by young adult men who were recruited to work in construction, factories, harbours, mining, agriculture, and sanitation (De Haas, Castles, and Miller 2020: Chapter 6). In the 1970s and 1980s, family reunification became a major cause of migration, which consisted predominately of women and children. In 2019, migrant worker populations were 59% male and 41% female, representing a slight shift towards more equal gender distribution than previously estimated (McAuliffe and Triandafyllidou 2021: 37–38).

Low-skilled female migrants tend to work in agriculture, manufacturing, textiles, food processing, healthcare, restaurants, and hotels (UNDESA 2006: 30–32). Domestic service and caring for children, elderly, and disabled persons are also common occupations for low-skilled migrant women. Skilled women, on the other hand, tend to seek employment in health and social fields, such as education, social work, and nursing (Jolly and Reeves 2005; UNDESA 2006).

Worldwide, refugees are 48% women and 52% men (UNHCR 2021). Some refugees arrive in a country of destination under formal resettlement schemes. They may be young people with high employment qualifications or families with single mothers. Of the asylum seekers who arrive in Europe, men are more numerous than women. Women account for about one-third of the asylum applications in Europe. Part of this is due to the way data are collected: Women are more likely to be seeking asylum as part of a family group or to be married (UNHCR 2010; United Nations 2011; IOM 2022), and women are usually not the primary applicants (UNFPA 2006).

Females represented 58% of foreign tertiary education graduates in OECD countries in 2021 (OECD 2023: Table B5.2). However, the type of degrees being sought can change the percentage, with male students typically having much higher proportions in the information and communication technologies and engineering, manufacturing, and construction fields of study.

2.3 Family patterns of migration

Family-related migration can be categorized into three distinct types (Schoorl 2012): (1) family reunification, whereby family members join someone, often a husband or father, who migrated earlier; (2) marriage migration, where the bride or bridegroom migrates to the new spouse's country of residence; and (3) joint family migration, when the members of a family migrate together at the same time. Family reunification refers to the process of bringing in immediate family members – usually a spouse and under-age dependent children, sometimes also parents and other dependent family members – by the primary migrant. Typically, a waiting period applies, and the primary migrant has to satisfy a number of conditions regarding income and housing before dependents are admitted to the country. Women form a clear majority of those admitted for family reunification (EMN 2008). Joint family migration implies a sex-balanced composition of migration flows. This category is less common as many countries do not allow temporary permit holders to be accompanied by family members, except for highly skilled migrants. Some refugees, especially those entering on settlement schemes or quotas, are admitted jointly with their family (IOM 2008).

There are several types of marriage migration. The first concerns second-generation migrants who bring in a spouse from their parents' country of birth. The second type of marriage migration involves native citizens who bring in a partner they have met while abroad for work, study, or holiday. In this case, the marriage is a secondary effect of the reason for going abroad. The third type of marriage migration involves the recruitment of mostly women from other countries (Hwang and Parreñas 2018). In exchange for marriage, the migrants may gain economic benefits or be able to send remittances back home. There is also the potential for exploitation or human trafficking with migrants not having equal rights to their spouses.

2.4 Return migration

Return migration occurs in nearly all situations of international migration. Return migrants are those who leave a country to reside in another and then, after a period of time, migrate back to the country of origin. The reasons for return migration are numerous, including, for example, completion of study or fixed-term position, loss of a job, to form a family, and a general desire to be closer to family or friends. With regard to age patterns of migration, migrants are obviously older when they return. For countries that experience more emigration than immigration, we would expect immigration to have a slightly older age profile than emigration. The opposite is the case for countries that experience higher levels of immigration than emigration.

3. Methods for estimating patterns of migration

To overcome the problems associated with inadequate and missing data, there are numerous examples of research on estimating both net international migration and international migration flows (see, e.g., Poulain 1993; Raymer 2008; De Beer et al. 2010; Raymer et al. 2013; Wiśniowski et al. 2016; Abel 2018; Fiorio et al. 2021). Below, we review a number of methods that have been used to estimate the patterns of migration, including the approach used by the United Nations (2022).

3.1 Residual methods for estimating net migration totals

In situations where neither immigration nor emigration data are available, net international migration may be inferred by using the vital statistics method or the survival ratio method (Bogue 1969: 758–759). These methods use population, mortality, and fertility data to infer totals of net migration and can be applied at any level of disaggregation, including across age cohorts.

The vital statistics method for obtaining net migration relies on reported births and deaths between censuses and uses the demographic accounting equation. That is, in simplified form, annual net migration $N_i^{t-1,t}$ is equal to a population in a country *i* at a particular time, P_i^t, minus the population one year earlier, P_i^{t-1}, minus births that occurred during the year, $B_i^{t-1,t}$, plus deaths that occurred during the year, $D_i^{t-1,t}$:

$$N_i^{t-1,t} = P_i^t - P_i^{t-1} - B_i^{t-1,t} + D_i^{t-1,t}. \quad (1)$$

The survival ratio method compares an estimated number of people at age *x* surviving and living in the same place from time *t*–1 to *t* with an observed population at time *t*. To estimate the number of survivors, this method uses a life table to apply age-specific mortality and assumes no migration occurred during the time interval. The difference between the observed number of persons at age *x* and time *t* and the corresponding estimated number of survivors (S) is attributed to net migration:

$$N_i^{t-1,t}(x) = P_i^t(x) - S_i^t(x), \quad (2)$$

where $N_i^{t-1,t}(x)$ denotes net migration for country *i* at age *x* between time *t*–1 and *t*, and $P_i^t(x)$ and $S_i^t(x)$ denote the corresponding number of persons and survivors, respectively.

Both the vital statistics method and the cohort survival method assume that the available age and sex data on populations, births, and deaths are accurate and complete. In reality, the inferred net migration totals often include measurement errors in the populations and vital events (Edmonston and Michalowski 2004: 471). Moreover, small errors in the population counts may result in large errors in the estimation of net international migration. Also, population measurement errors can vary substantially by age, which can produce distorted age distributions via residual methods. Further, the methods do not provide information about the relative numbers of immigration and emigration or countries of origin or destination. For a given net migration total, there may be infinite combinations of immigrants and emigrants. This makes net migration difficult to explain and may result in biased predictions of population change (Rogers 1990).

Despite the problems of measurement, indirectly estimated net migration numbers can be very useful, particularly in cases for which no migration flow data are available (Smith and Swanson 1998). Net migration provides important information on how much the population grows or declines due to migration during a specified period of time. The figures are also easy to incorporate into cohort component projection models.

3.2 Model age schedules

In the 1970s, Pittenger (1974, 1978) developed a typology of net internal migration age schedules for use in population projections. The typology was based on directional flow patterns of internal migration in the United States and Canada, where areas were distinguished according to rural, exurban, central city, suburban, and metropolitan characteristics. Each area was assumed to have low or high levels of migration and corresponding early or late peaks in the young adult age groups with, for example, unattractive areas exhibiting early age peaks. In the 1978 paper, Pittenger proposed a parameterized migration rate model for the age patterns of the directional flows, which could then be used to determine age patterns of net migration.

Around the same time that Pittenger was developing a typology of net internal migration age schedules, Rogers and colleagues developed a model schedule for migration flow data (Rogers, Raquillet, and Castro 1978; Rogers and Castro 1981a). The model migration schedule is a parameter-based approach for smoothing and representing age patterns of migration based on combinations of exponential and double-exponential curves. Rogers and Castro (1981a) analyse 524 age profiles of interregional migration gathered from 17 countries to demonstrate the regularities present in the age patterns of migration. A key component of the report is the specification of model migration families. In particular, four families of multiexponential model migration schedules were put forward: (1) a standard seven-parameter model, (2) a nine-parameter elderly postretirement migration model, (3) an eleven-parameter elderly retirement peak model, and (4) a thirteen-parameter elderly retirement peak and postretirement model. The standard migration schedule is the most commonly found in empirical data settings. Its basic form is specified as

$$m_{ix} = a_0 + a_1\exp(-\alpha_1 x) + a_2\exp\{-\alpha_2(x-\mu_2) - \exp[-\lambda_2(x-\mu_2)]\}, \qquad (3)$$

where m_{ix} is the predicted out-migration rate from origin i and age x, a_0 is a constant (i.e., minimum level), $a_1\exp(-\alpha_1 x)$ is a negative exponential curve representing the ages prior to joining the labour force, and $a_2\exp\{-\alpha_2(x-\mu_2) - \exp[-\lambda_2(x-\mu_2)]\}$ is a double-exponential (unimodal) curve representing the labour force ages. This multiexponential model migration schedule is useful for describing or inferring age-specific migration patterns when data are incomplete or missing. It has been demonstrated to effectively capture most age profiles of migration with a high level of accuracy and has been used for a wide variety of situations that require age patterns of migration.

As argued by Rogers and Castro (1981a), the relatively stable shape of the age-specific migration curve provides analysts and researchers with the possibility of simplifying their underlying assumptions and estimation models. Indeed, many predictions of migration focus on indicator variables, such as net migration, total immigration, or total emigration, which are then distributed into assumed age-specific migration profiles for producing age-specific population projections (e.g., Azose, Ševčíková, and Raftery 2016).

3.3 Other methods

Multiplicative component models have been used to estimate origin–destination–age counts of internal and international migration (Willekens and Baydar 1986; Raymer, Bonaguidi, and Valentini 2006; Raymer, Biddle, and Campbell 2017; Raymer, Bai, and Smith 2020; Shen et al. 2024), from which net migration can be derived. This approach is particularly useful when aggregate information on migration flows are available, such as total immigration or total emigration. However, in the context of international migration, data are hardly available for countries outside Europe.

When good quality data are available, time series and probabilistic methods, including Bayesian, may be used to produce estimates and forecasts of international migration (Bijak 2011, 2012; Azose and Raftery 2015). For example, Hyndman and Booth (2008) forecast age patterns of net migration using functional data analysis, a statistical approach for analysing data that are in the form of curves (see also Shang et al. 2016). Also, Wiśniowski et al. (2015) and Raymer and Wiśniowski (2018) develop a

Bayesian model to forecast age-specific immigration and emigration counts using annual time series data on immigration and emigration by age and sex. This model was motivated by the Lee–Carter (1992) model, designed originally for forecasting age patterns of mortality.

3.4 The United Nations' approach

Every two years, the United Nations' Population Division publishes its WPP, which contains estimates and projections of demographic change for all countries in the world. An important component underlying this work is estimates and projections of net international migration by sex and age, which vary according to each country's context and time period. In the 2022 WPP (United Nations 2022), model migration schedules are used to estimate net international migration for many countries over time. Specifically, the `mig_un_fam()` function of the *DemoTools* R package (Riffe et al. 2019) is used, which includes a family model characterized by fairly even proportions of male and female migrants. The corresponding age-specific curve concentrates migrants in the young adult age groups with the male labour model dominated by migration of males of working age and the female labour model dominated by migration of females of working age. In some cases, a population distribution pattern is applied, in which the age–sex distribution of net migration is assumed identical to the age–sex distribution of the population. In cases where countries have reliable census or population register data or other high-quality population estimates, residual methods are used to estimate both the total level of net international migration and the patterns by age and sex.

4. Methodology

In this section, we propose and test a new methodology to estimate net international migration by age and sex for the WPP. As there are no known systematic regularities of net migration across age and sex, the focus is on approximating the age and sex patterns of immigration and emigration, from which net migration totals may be calculated.

4.1 Model

To illustrate the age pattern effects on net migration by different levels of immigration and emigration, we present some hypothetical model migration schedules and the corresponding net migration schedules in Figure 3. The positive red line represents immigration, the negative blue line represents emigration, and the green line represents net migration. The first graph (Figure 3a) shows how net migration is zero across all ages when both the levels and age compositions of immigration and emigration are the same. The second graph (Figure 3b) shows how age-specific net migration increases when the overall level is increased consistently across all ages. The remaining four illustrations (3c–3f) show how age-specific net migration changes when parameters associated child migration and young adult migration levels are changed while still holding the emigration level and age composition fixed.

The procedure for estimating how net migration should be distributed by age and sex is presented below. First, assuming annual net migration totals are known and true, we approximate the levels of immigration and emigration by age and sex. This involves (a) crudely estimating the aggregate totals of immigration and emigration and then (b) distributing these totals across age and sex. Second, we calculate the difference of these patterns to obtain estimates of net international migration by age and sex.

The overall model is specified as

$$\widehat{N}_{xy} = (\hat{I})(i_{x|y})(i_y) - (\hat{E})(e_{x|y})(e_y), \tag{4}$$

where $\widehat{N}_{xy}$ denotes estimated net international migration by age x and sex y; $\hat{I}$ and $\hat{E}$ are crude estimates of total immigration and emigration, respectively; $i_{x|y}$ and $e_{x|y}$ are the corresponding immigration and emigration age compositions (proportions) for males and females; and i_y and e_y are the overall proportions of immigration and emigration by sex. Further, let

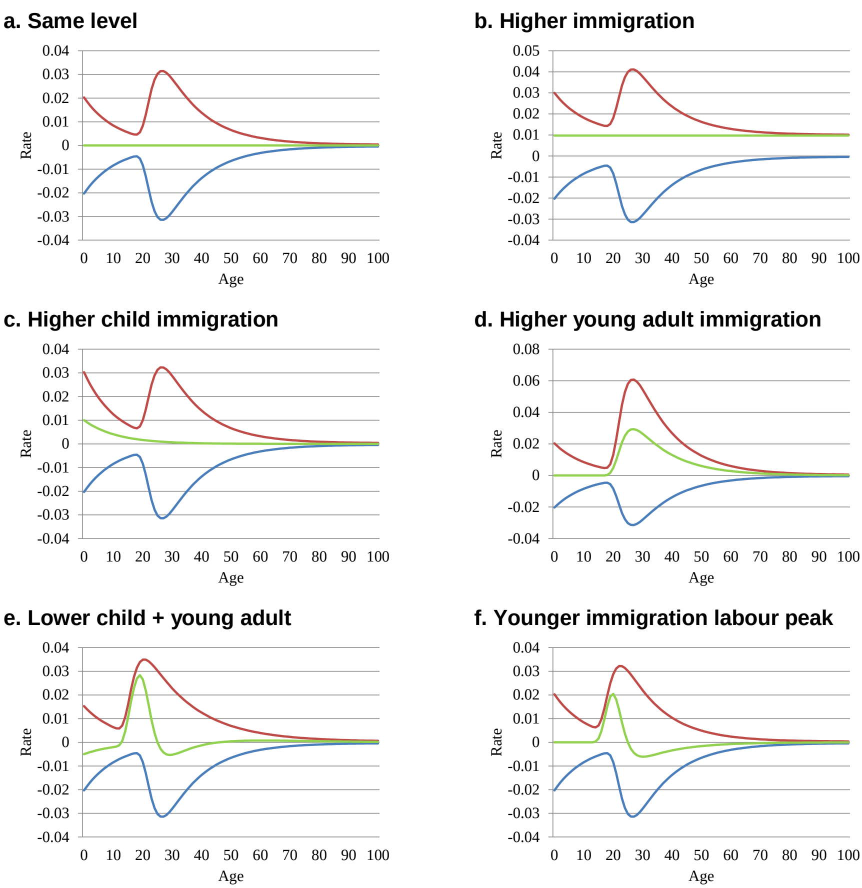
$$\hat{I} = P * m + \tfrac{1}{2}N \tag{5}$$

and

$$\hat{E} = P * m - \tfrac{1}{2}N, \tag{6}$$

where P is the mid-year population size of a country, N is the reported or estimated net migration total (assumed to be true), and m is a migration rate specified to be somewhere between 0.003 and 0.015 used to approximate both immigration and emigration. Since it is necessary that the estimated immigration and emigration numbers are both positive, we must choose $m > |N| / 2P$. The above specifications of immigration and emigration also ensure that whatever migration rate is used to estimate the flows, the result will match the specified net migration total. This is important because in the WPP procedures, net migration totals are first estimated independently of the age and sex patterns. It also ensures that immigration and emigration flows are highly correlated and proportional to the population of interest. For Equations 4, 5, and 6, it is assumed the numbers are specific to a single country and for a given year. Finally, the range of *m* was guided by Raymer et al. (2022: 652), who states that emigration rates estimated "among 53 Asia-Pacific countries range from 0.1% to 3.4% over the 20-year period, compared to 0.2% to 3.5% among 30 European countries," noting that the highest rates were for very small countries.

Figure 3: Hypothetical age patterns of immigration (red lines), emigration (blue lines), and net migration (green lines)



Once immigration and emigration levels are approximated, the next step is to decompose them by age and sex. This requires inferring the proportions of immigration and emigration by sex, i_y and e_y, and age profiles for male immigration, female immigration, male emigration, and female emigration, denoted by $i_{x|male}$, $i_{x|female}$, $e_{x|male}$, and $e_{x|female}$, respectively. These proportions may be obtained in a number of ways. They can be based on historical data, auxiliary data, or expert judgements. In the next subsection, we provide a proof of concept based on empirical data from Sweden and South Korea. Second, in Section 5, we combine available data from the WPP, estimates of sex-specific flows from migrant stock data, and hypothetical model migration schedules to produce age- and sex-specific estimates of net migration total for countries without data. Here, for a small number of countries with reliable residual estimates of age-specific net migration, procedures were added to optimize the calculation of m and to adjust the position of the peak age in the modelled age patterns. This extension to the model framework demonstrates its ability to incorporate additional information where available.

4.2 Tests with empirical data

To test the model for estimating net migration totals by age and sex, we use data from Sweden and South Korea – two countries known to have reliable single-year age and sex flow data for both immigration and emigration. In the tests, the parameter values represent averages of observed data over time.

4.2.1 Sweden 1968–2023

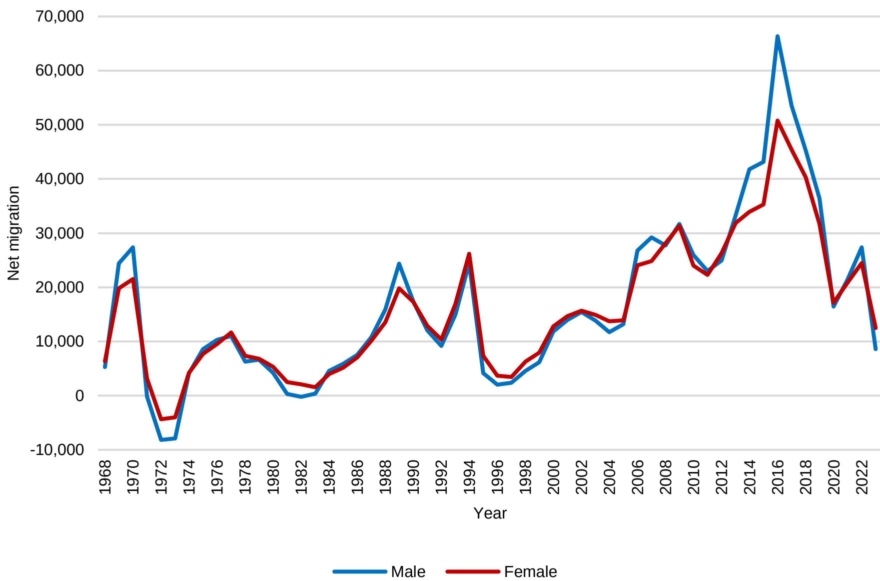
Annual immigration and emigration flow data by age and sex for Sweden were obtained from Statistics Sweden[5] for a 55-year time period from 1968 to 2023. The flows are defined according to a twelve-month duration-of-stay criterion.

In Figure 4, we see that net international migration totals for Sweden vary greatly over time but that male and female patterns are largely parallel. According to the Swedish Institute,[6] migration was first characterized by those primarily seeking employment from countries such as Finland, Italy, Greece, the former Yugoslavia, Turkey, and other Balkan countries. In the 1970s, the Swedish government tightened its immigration policies, and flows subsequently decreased, alongside increased return migration of foreigners.

[5] Visit http://www.scb.se/en/ for more information.
[6] Visit https://sweden.se/culture/history/sweden-and-migration for more information.

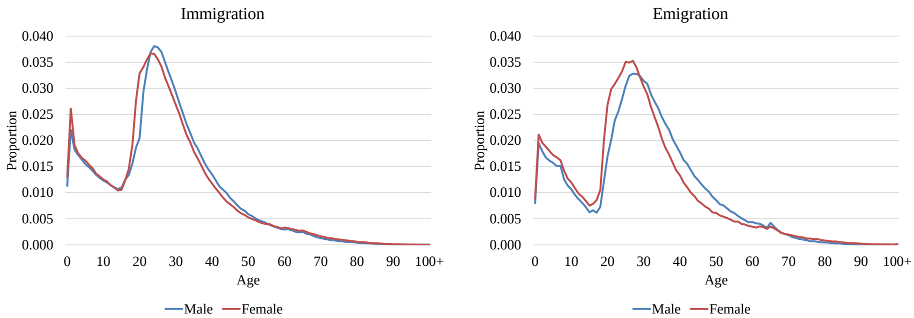
Between 1980 and 1999, there was a rise in asylum seekers, particularly from Iran, Iraq, Lebanon, Syria, Turkey, Eritrea, and Somalia, as well as from some South American countries. Sweden joined the Schengen Agreement in 2001, which resulted in increased flows from EU member states. Net migration levels reached their highest point for both males (66,000) and females (51,000) in 2016 before dropping to around 10,000 in 2023.

Figure 4: Net migration totals by sex, Sweden 1968–2023



For the empirical data tests, the time series is shortened to 2003–2012 to better reflect current patterns. The age profiles of migration, averaged over the 2003–2012 period, are presented for immigration and emigration by sex in Figure 5. Here we see that the age profiles of immigration are similar, but females exhibit slightly younger age patterns in the young adult years. For the corresponding emigration patterns, females have higher rates before 30 years, whereas males exhibit higher rates in ages between 30 and 60 years.

Figure 5: Average age profiles of immigration and emigration by sex, Sweden 2003–2012

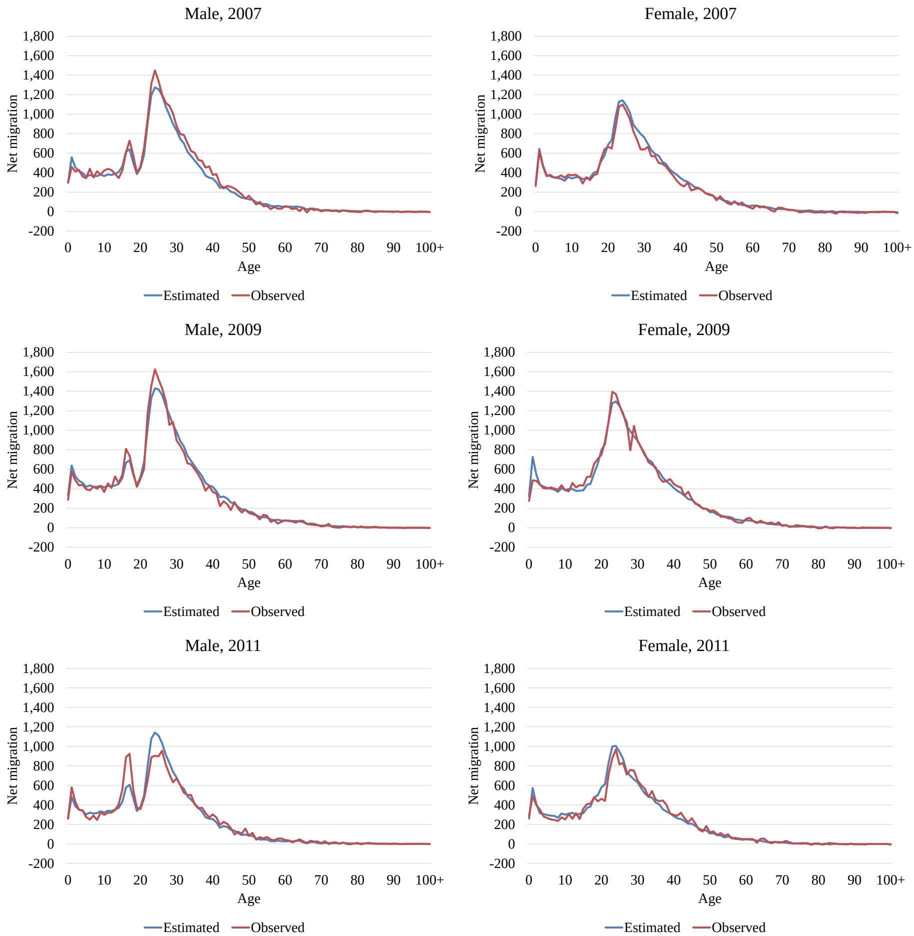


Annual levels of immigration and emigration are approximated by multiplying the population in each year by 0.007, which is the observed average rate of migration (m) from 2003–2012. Note, we tested the model using rates ranging from 0.003 to 0.015 and found the value of m did not greatly influence the resulting age–sex patterns of net migration.

For distributing $\hat{I}$ and $\hat{E}$ by age and sex, two sets of proportions are used. The first captures the proportion of total immigration and emigration by sex (i_y and e_y, respectively). For male immigration, we used the observed average proportion of 0.5210. For male emigration, it was 0.5373. The second set of proportions captures the average age proportions of immigration and emigration by sex ($i_{x|y}$ and $e_{x|y}$, respectively). Here, we used the proportions presented in Figure 5.

Using Equation 4 and the parameter inputs described above, the net migration totals by age and sex for Sweden were estimated from 2003 to 2012. A selection of the results for males and females are presented in Figure 6 for the years 2007, 2009, and 2011. As can be seen, the model produced estimates that were very close to the observed values in each year.

Figure 6: Comparison between observed and estimated net migration by age and sex for Sweden, 2007, 2009, and 2011



4.2.2 Republic of Korea 2000–2021

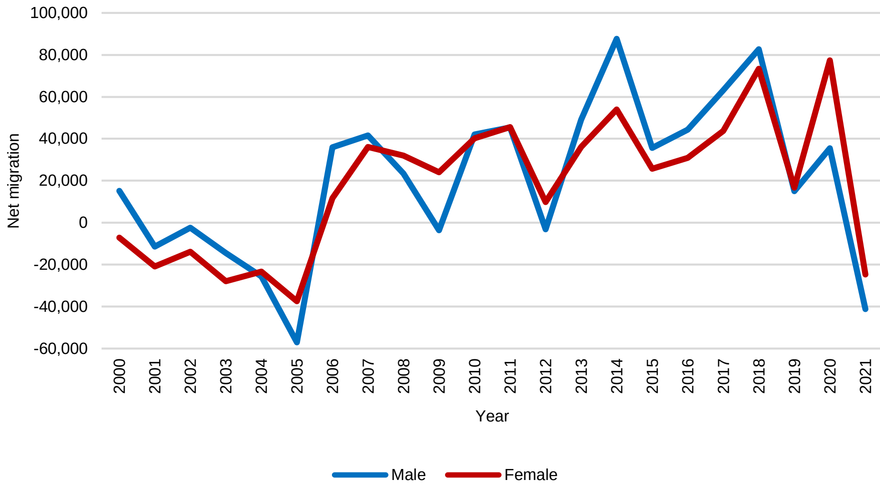
Migration data for the Republic of Korea were obtained from the Korean Statistical Information Service, operated by Statistics Korea. [7] The data represent annual immigration and emigration, measured using a twelve-month definition, by age and sex from 2000 to 2021.

Compared with Sweden, immigration to the Republic of Korea is relatively recent. Previously a net sender of migrants, the Republic of Korea has been a net receiver of migrants since the late 1980s (Oh et al. 2012). In 1990, there were 43,000 international migrants living in the Republic of Korea, increasing to 244,000 in 2000 and 1.1 million by 2015 (United Nations 2017b: Table 1). According to Oh et al. (2012), migration between 1990 and 2003 largely consisted of two groups: those involved in the technical training system and marriage migrants from other Asian countries. From 2004 onwards, migration was regulated through a work permit system, and immigration both for marriage and for high-skilled work increased. Between 2000 and 2015, flows of immigration and emigration steadily increased from 371,000 (47% foreign) and 363,000 (25% foreign), respectively, to 684,000 (55% foreign) and 622,000 (48% foreign) (Statistics Korea 2016). Today, immigrants consist largely of low-skilled temporary workers, foreign brides, and returning South Korean nationals.

In Figure 7, we see that the levels of net international migration for the Republic of Korea increased after 2005. While largely parallel, the male and female net migration totals deviated from each other in some years. For example, net migration was higher for males in 2006 and 2014 and higher for females in 2005, 2009, and 2020.

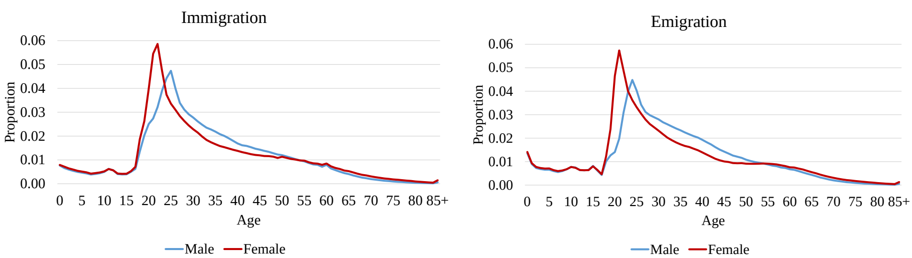
[7] Visit http://kosis.kr/eng/ for more information.

Figure 7: Net migration totals by sex, Republic of Korea 2000–2021 (persons)



Age profiles of immigration and emigration, averaged over the 2000–2021 period, are presented by sex in Figure 8. In both cases, female proportions are higher between ages 19 years and 22/23 years and male proportions are higher between ages 22/23 years and 49/51 years. In comparison to Sweden, the age patterns for the Republic of Korea are more focused in the young adult years and do not contain many child migrants.

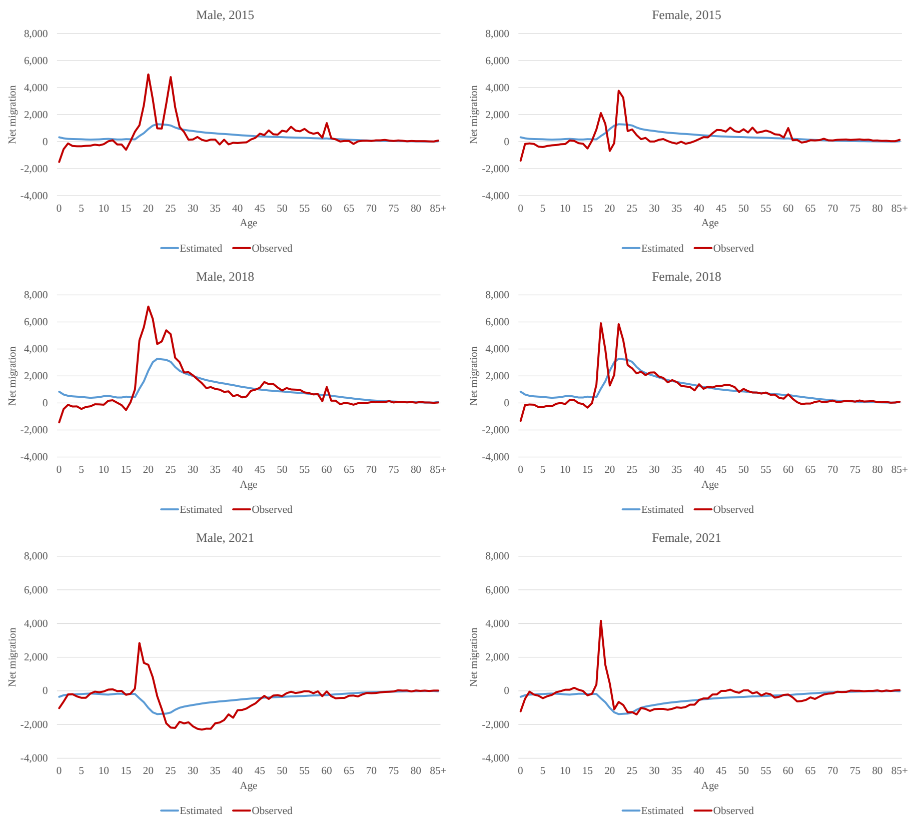
Figure 8: Average age profiles of immigration and emigration by sex for Republic of Korea, 2000–2021



For the empirical test of the age–sex distribution model for the Republic of Korea, annual levels of immigration and emigration were approximated by multiplying the population in each year by 0.012, which is the average proportion observed from 2000 to

2021. The average observed proportions of immigration and emigration for males were 0.5333 and 0.5321, respectively. We used the average age proportions of immigration and emigration by sex presented in Figure 8. As with Sweden, the model reproduced the patterns of observed age- and sex-specific net migration, albeit with some differences in the young adult years. In Figure 9, we present a selection of results by sex for the years 2015, 2018, and 2021. Here, we see that the observed and estimated net age profiles exhibited two positive labour force peaks in 2015 and 2018 while in 2021 the patterns changed to a positive and then negative peak.

Figure 9: Comparison between observed and estimated net migration by age and sex for the Republic of Korea, 2015, 2018, and 2021



4.2.3 Summary

Based on empirical tests using data from Sweden and the Republic of Korea, the model expressed in Equation 4 performs well. These two countries were chosen because they provide detailed and reliable information on migration flows and because the patterns by age and sex are very different. Although not shown, we also applied the above procedure to estimate age and sex patterns of net migration for Australia, Canada, and New Zealand and obtained similar results. The empirical tests, as described in this section, provide some confidence that we can proceed to estimate a time series of age and sex patterns of net international migration for countries without data, assuming that information for each of the parameters in the model can be obtained or inferred. In the next section, we demonstrate how the model can be applied for all countries in the world in the absence of empirical data on flows and describe some of the results.

5. Application to all countries

In this section, we show how we used Equations 4, 5, and 6 to estimate age and sex patterns of net international migration for countries in the WPP from 1950 to 2022. For approximating the total levels of immigration ($\hat{I}$) and emigration ($\hat{E}$), we used the total population and aggregate net migration totals from the 2022 WPP as inputs. Rates of migration (m) were initially set at 0.005 but, in the R code, this parameter is adjustable.[8]

For distributing the crude levels of immigration and emigration by sex, we averaged the proportions from the estimates of sex-specific migration flow from stock data provided by Abel and Cohen (2022) and proportions that assumed equal shares of migration by sex. This had the effect of reducing sex-specific proportions that were considered extreme. The Abel and Cohen estimates include five-year migration transitions by origin, destination, and sex from 1990–1995 and 2015–2020 based on six different methods. We used the pseudo-Bayesian estimates from the method that applied a closed demographic accounting system (Abel and Cohen 2022; Azose and Raftery 2019) as it showed the highest correlation with reported data.

For distributing the immigration and emigration totals by single-year age groups, we created a series of model migration schedules based on two age profiles: Western standard and low dependency. Both schedules were adapted from a United Nations (1992) manual for internal migration. The Western standard schedule exhibits a broad labour force peak and has a downward sloping child migration curve. The low dependency schedule is dominated by a young adult peak. We adjusted these schedules

[8] The R code can be found at https://osf.io/5wvmc/.

depending on (1) direction of the flow and (2) sex. For direction of flow, we assumed receiving countries (i.e., countries that exhibited positive net migration values) would receive younger immigrants than emigrants on average. The opposite was assumed for sending countries (i.e., countries that exhibited negative net migration values). Similarly, we adjusted the model migration schedule parameters to estimate younger male patterns, younger female patterns, or neutral patterns (i.e., same age profiles by sex).

The parameters for the Western standard and low dependency model migration schedules are presented in Table 1, Panel A (see also Equation 3). Here we see the parameter values are the same between the two schedules, except the low dependency schedule has a lower value for a_1 to represent a lower curve for child migration, a higher value for a_2 to represent a higher labour migration peak, and a lower value for μ_2 to represent a younger labour force peak. Further the μ_2 parameter values were adjusted +/– 1 to produce slightly younger or older age profiles in each schedule. The resulting Western standard and low dependency schedules are presented in Figure 10 for receiving countries. The model migration schedule parameters for the neutral, younger male, and younger female assumptions are the same as the Western standard and low dependency model schedules, except for the μ_2 parameters, as shown in Table 1, Panel B. As the sex-specific profiles closely resemble the sending and receiving profiles presented in Figure 10, they are not shown.

Table 1: Model migration schedule parameters for representing age patterns of immigration and emigration and by sex

A. Receiving and sending

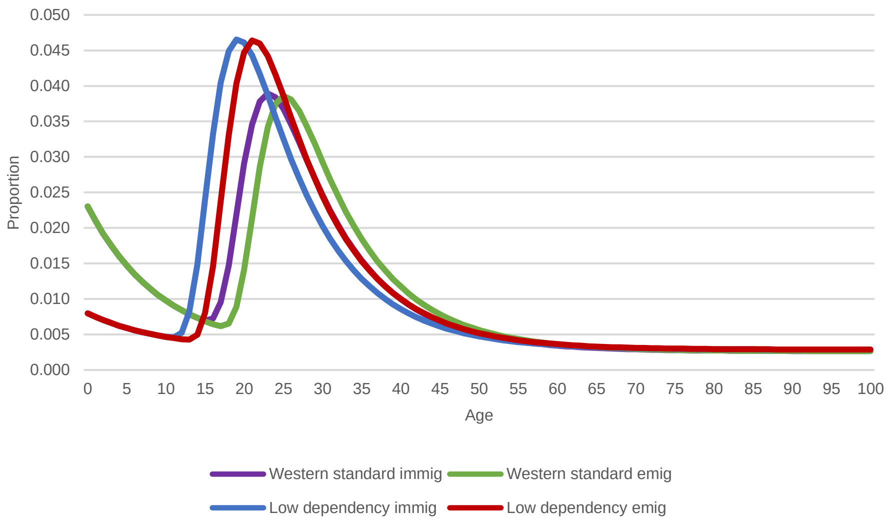
	Western standard: Receiving		Western standard: Sending		Low dependency: Receiving		Low dependency: Sending	
	Immig.	Emig.	Immig.	Emig.	Immig.	Emig.	Immig.	Emig.
a_1	0.0215	0.0215	0.0215	0.0215	0.0050	0.0050	0.0050	0.0050
α_1	0.1050	0.1050	0.1050	0.1050	0.1050	0.1050	0.1050	0.1050
a_2	0.0694	0.0694	0.0694	0.0694	0.0800	0.0800	0.0800	0.0800
α_2	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120	0.1120
μ_2	20.0400	22.0400	22.0400	20.0400	16.0900	18.0900	18.0900	16.0900
λ_2	0.3910	0.3910	0.3910	0.3910	0.3910	0.3910	0.3910	0.3910
a_0	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028

B. Sex*

		Western standard		Low dependency	
		Male	Female	Male	Female
Neutral	μ_2	21.0400	21.0400	17.0900	17.0900
Male	μ_2	20.0400	22.0400	16.0900	18.0900
Female	μ_2	22.0400	20.0400	18.0900	16.0900

* Aside from µ2, parameters are the same for Western standard and low dependency schedules as presented Table 1, Panel A.

Figure 10: Western standard and low dependency model migration schedules for receiving countries



The final step involved combining the age assumptions for migration by direction and migration by sex. We did this to simplify the estimation of the four age profiles of migration. These two sets of age profiles can be averaged to provide reasonable estimates of the four age profiles. For example, the proportion in the first age group for male immigration would be equal to the proportion in the first age group of immigration plus the proportion in the first age group for males divided by two (i.e., average). This makes the process simpler in the sense that one does not have to think about how, say, male emigration is different from female immigration. One just has to think about how migration age patterns differ in terms of direction and how they differ by sex. For example, a receiving country with a Western standard (referred to below as WS) schedule and with assumed gender-neutral migration would have the following age–sex schedules of migration:

$i_{x|\text{male}}$ = [WS(immigration) + WS(neutral)]/2
$i_{x|\text{female}}$ = [WS(immigration) + WS(neutral)]/2
$e_{x|\text{male}}$ = [WS(emigration) + WS(neutral)]/2
$e_{x|\text{female}}$ = [WS(emigration) + WS(neutral)]/2

The model design is flexible to incorporate different sets of assumptions for the age schedules. For each country, three questions are used to add assumptions to the age schedules for migration by direction and sex:

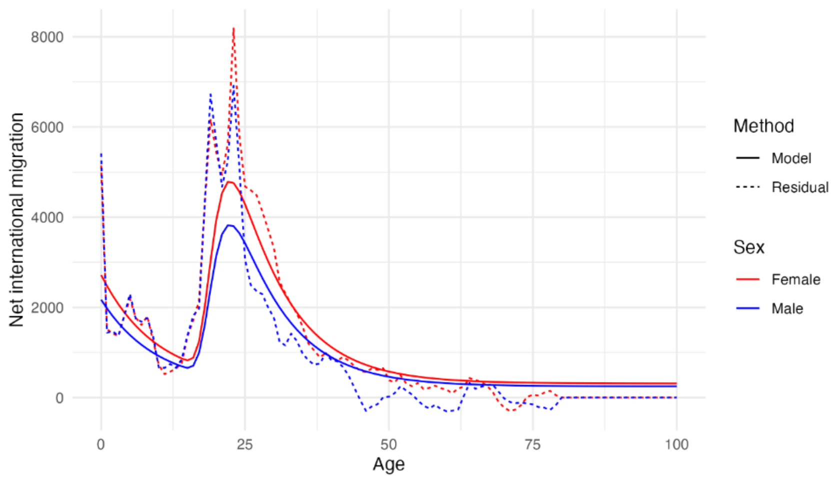
1. Does the country's migration age profile follow the Western standard or low dependency model migration schedule?
2. Is the country a net receiver or a net sender of migrants?
3. Comparing the sex composition of migrants for the country, are male or female migrants younger or about the same?

For the 2024 revision of the WPP, the new method was applied to estimate the net migration sex-age profiles for all countries over the projection horizon 2024–2100. During the course of this work, some adjustments were made to the default parameters in order to more closely represent the age patterns inferred by residual methods for a small number of countries with high-quality data. Specifically, for all country-years with high-quality residual estimates of sex- and age-specific net international migration, we used the `optim()` function of the stats package for R to optimize the values of the migration rate *m* and the peak ages of immigration and emigration represented by the μ_2 model migration schedule parameter while maintaining the default values of the other parameters described in Table 1. Two sets of optimized parameters were identified for each country-year: one for the Western standard profile and the other for the low dependency profile. Further, when implementing the model for the WPP, we found that the estimated net migration at older ages was too high (see Australia example presented in Figure 11). To deal with this, we set net migration above age 75 years to zero and redistributed those counts proportionally below age 75 years.

Figure 11 plots the residual estimates of net migration by sex and age for Australia in 2015 against the model estimates with the default Western standard parameter values on the top and against the model estimates with the optimized migration rate and peak ages on the bottom. The female proportion of immigration and emigration are both set to 0.556 to match net migration estimates by sex obtained from using the residual method. The optimized value of the migration rate of 0.008 is very similar to the default rate of 0.007. But the optimized values of the peak ages of immigration and emigration differ substantially for the defaults. Australia is a receiving country, with immigrants being younger than emigrants. The optimized peak age of immigration is 18.4 years, which is slightly younger than the default value of 20.04 years, while the optimized peak age of emigration is 28.9 years, which is nearly seven years older than the default value of 22.04. The results indicate that while the default parameter values produce a reasonable approximation of the net international migration profile estimated via residual methods, the optimized parameter values yield a closer representation. Note, in Appendix Part D, comparisons of the final model results of net international migration by age and sex for 2010 with corresponding reported values are presented for Australia, Canada, South Korea, New Zealand, and Sweden.

Figure 11: Model and residual estimates of net international migration by age and sex for Australia, 2015

A. Default parameters



B. Optimized parameters

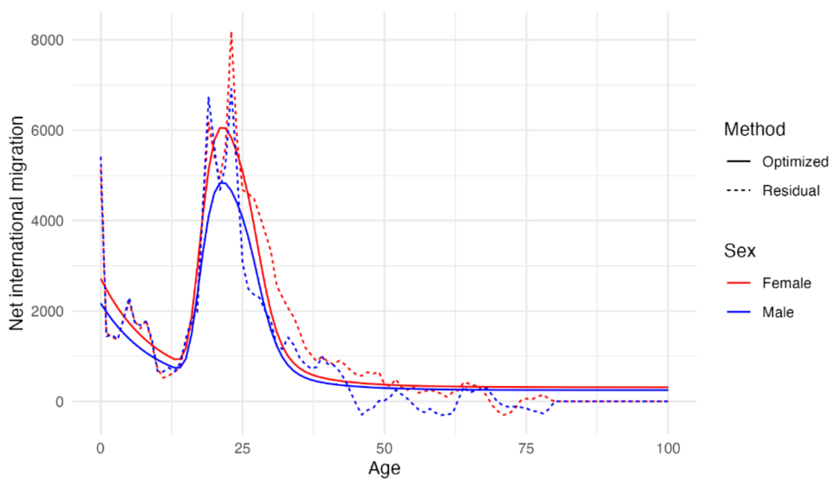
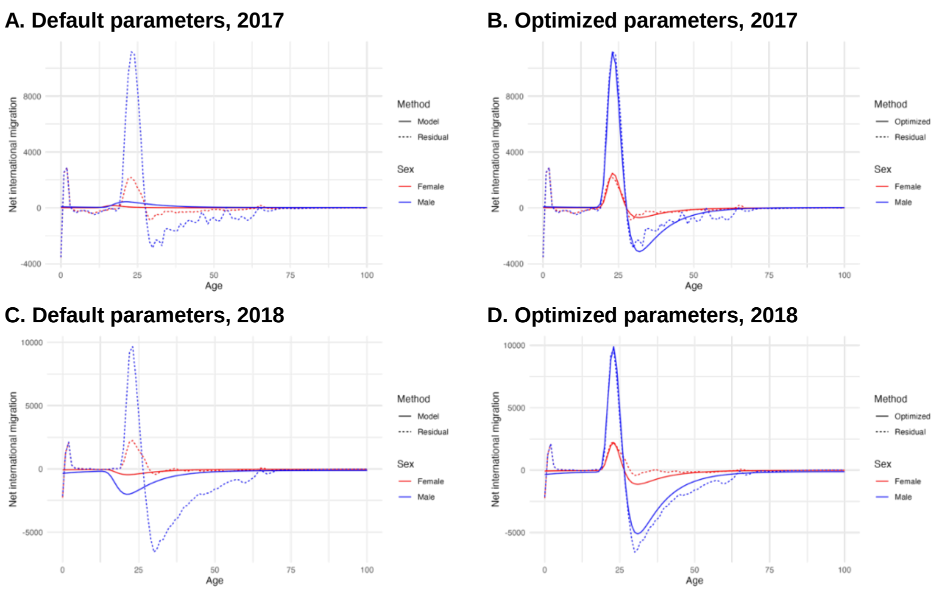


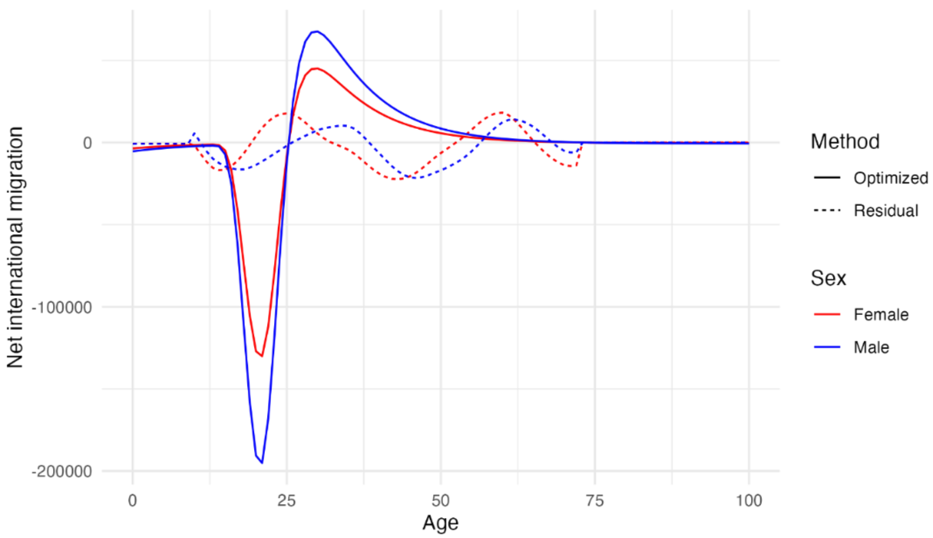
Figure 12 gives another example, this time for Oman (low dependency), a country that hosts large flows of temporary labour migration that can change in magnitude and direction from one year to the next. In 2017, residual estimation based on population register for the WPP indicates that immigration to Oman exceeded emigration by around 12,000. In 2018, residual estimates indicate that the level of net international migration for Oman turned negative, amounting to around –52,000. The female proportions of immigration and emigration are set to 0.182 to match the net migration estimates by sex obtained from the residual method. The optimized peak age parameter values for 2018 (i.e., 23.3 and 24.8 for immigration and emigration, respectively) are essentially the same as for 2017 (i.e., 23.8 and 24.7, respectively) but the optimized migration rate for 2018 is 0.214, compared to 0.340 for 2017. The optimized parameters for both the peak migration ages and migration rates were considerably larger than the default parameters: 0.007 migration rate, 16.1 for peak age of immigration, and 18.1 for peak age of emigration.

Figure 12: Model and residual estimates of net international migration by age and sex for Oman, 2017 and 2018



For countries with high-quality estimates of population and vital rates, the optimized parameter values over the most recent 15 years of the estimation period were used to define the migration age–sex profiles over the projection period. For countries that lack sufficient data to produce reliable estimates of net international migration by age and sex using residual methods, the average values computed across countries with high-quality data were used to inform the parameters applied in the projection period. Figure 13 shows the resulting sex-age profile of net international migration projected for India in 2030 (solid lines), compared to the profile implied by the residual migration pattern estimated on the basis of the 2001 and 2011 population censuses (dashed lines). The female proportion is set to 0.4. Both series presented in the figure correspond to a total level of net international migration of approximately –388,000. Applying the intercensal residual pattern to that total yields an age profile with multiple pronounced peaks and valleys, which likely reflect inconsistencies in the age distributions of the populations enumerated in the two censuses and not the true patterns of net international migration to and from India. Using model profiles corresponding to the average parameter values across countries with good data, however, yields a much more plausible age pattern, with the largest net outflows occurring among young adults and some net return migration reflected in positive net values at older adult ages.

Figure 13: Model and residual estimates of net international migration by age and sex for India, projected for 2030



6. Conclusion

Age and sex profiles of net international migration are required in population estimation and projection, yet the direct measures are often absent from reported migration data. Instead, population scientists and policymakers rely largely on model-based estimates that are derived from residual methods as inputs into demographic accounting models and use them to understand population changes. Given the known irregularities in net migration age schedule and errors in population and vital statistics measures, in this paper we have developed a relatively simple yet powerful model for estimating the age and sex profiles of net international migration from approximated levels of immigration and emigration by age and sex. The model is flexible such that it can be applied to any country situation, with or without data, and can be modified to incorporate new data or assumptions. The model has been coded in R, which makes it possible to estimate (or project) the age and sex patterns of net international migration for any country in the United Nations' WPP dataset.

The work presented in this paper should be considered a starting point to estimate net migration age and sex patterns. Continued analyses of model outputs and implications for population estimation and projection are needed. If required, the model framework may need further refinement and potential expansion of model migration age profiles. For example, small island countries or countries that have very high levels of temporary migrants (e.g., Gulf Cooperation Council countries) may require specific models. Also, the Western standard and low dependency model migration schedules could be further tested to determine the appropriateness of these schedules. A relational model approach could be developed whereby one starts with a general model migration schedule and then adjusts it depending on a set of covariate relationships. One might expect a highly developed population with a large proportion of migrants to have emigration flows with a wide labour force peak. The width of this peak could depend on how relatively old the population is in comparison to other migrant populations. Similarly, the immigration level of child migrants could depend on whether the country has high levels of temporary migration or not, where temporary visa regimes are generally assumed to exclude children of migrants.

While future efforts on refining the model are being made, we believe we have made an important contribution to overcoming data limitations, and this work will greatly help improve both the understanding of migration processes as well as the estimation and projection of populations. Further, while the method was designed with net international migration in mind, the procedure is general enough to be applied towards any geographic classification where migration data are missing, including local or regional areas and those involving domestic movements.

References

Abel, G.J. (2018). Estimates of global bilateral migration flows by gender between 1960 and 2015. *International Migration Review* 52(3): 809–852. doi:10.1177/0197918318781842.

Abel, G.J. and Cohen, J.E. (2022). Bilateral international migration flow estimates updated and refined by sex. *Scientific Data* 9(1): 173. doi:10.1038/s41597-022-01271-z.

Asis, M.M.B. and Battistella, G. (2018). Irregular migration in Asia: Are new solutions in sight? In: Liu-Farrer, G. and Yeoh, B.S.A. (eds.). *Routledge handbook of Asian migrations*. London: Routledge: 277–287. doi:10.4324/9781315660493-21.

Azose, J.J. and Raftery, A.E. (2015). Bayesian probabilistic projection of international migration. *Demography* 52(5): 1627–1650. doi:10.1007/s13524-015-0415-0.

Azose, J.J. and Raftery, A.E. (2019). Estimation of emigration, return migration, and transit migration between all pairs of countries. *Proceedings of the National Academy of Sciences* 116(1): 116–122. doi:10.1073/pnas.1722334116.

Azose, J.J., Ševčíková, H., and Raftery, A.E. (2016). Probabilistic population projections with migration uncertainty. *Proceedings of the National Academy of Sciences* 116(1): 116–122.

Bijak, J. (2011). *Forecasting international migration in Europe: A Bayesian view*. Dordrecht: Springer. doi:10.1007/978-90-481-8897-0.

Bijak, J. (2012). Migration assumptions in the UK national population projections: Methodology review. Titchfield: Office for National Statistics (Commissioned report). Available at: http://www.ons.gov.uk/ons/guide-method/method-quality/specific/population-and-migration/population-projections/npp-migration-assumptions-methodology-review/index.html.

Bogue, D.J. (1969). *Principles of demography*. New York: Wiley.

Çelikaksoy, A. and Wadensjö, E. (2015). Unaccompanied minors and separated refugee children in Sweden: An outlook on demography, education and employment. Bonn: Institute for the Study of Labor (IZA Discussion Paper 8963). doi:10.2139/ssrn.2593253.

Castles, S. (2009). Development and migration or migration and development: What comes first? *Asian and Pacific Migration Journal* 18(4): 441–471. doi:10.1177/011719680901800401.

Castro, L.J. and Rogers, A. (1983a). What the age composition of migrants can tell us. *Population Bulletin of the United Nations* 15: 63–79.

Castro, L.J. and Rogers, A. (1983b). Patterns of family migration: Two methodological approaches. *Environment and Planning A* 15(2): 237–254. doi:10.1068/a150237.

De Beer, J., Raymer, J., Van der Erf, R., and Van Wissen, L. (2010). Overcoming the problems of inconsistent international migration data: A new method applied to flows in Europe. *European Journal of Population* 26(4): 459–481. doi:10.1007/s10680-010-9220-z.

De Haas, H., Castles, S., and Miller, M.J. (2020). *The age of migration: International population movements in the modern world*, 6th Edition. London: Red Globe Press.

Edmonston, B. and Michalowski, M. (2004). International migration. In: Siegel, J.S. and Swanson, D.A. (eds.). *The methods and materials of demography*, 2nd Edition. Amsterdam: Elsevier Academic Press: 455–492. doi:10.1016/B978-012641955-9/50052-7.

Elder, G.H. Jr. (1985). Perspectives on the life course. In: Elder, G.H. Jr. (ed.). *Life course dynamics: Trajectories and transitions, 1968–1980*. Ithaca: Cornell University Press: 23–49.

EMN (2008). Family reunification. Brussels: European Migration Network, European Commission. Available at https://www.emn.at/wp-content/uploads/2017/01/EMN_Family-Reunification_Synthesis-Report_Jan08.pdf.

Fiorio, L., Zagheni, E., Abel, G.J., Hill, J., Pestre, G., Letouzé, E., and Cai, J. (2021). Analyzing the effect of time in migration measurement using georeferenced digital trace data. *Demography* 58(1): 51–74. doi:10.1215/00703370-8917630.

Huguet, J.W. (2008). Towards a migration information system in Asia: Statistics and the public discourse on international migration. *Asia and Pacific Migration Journal* 17(3–4): 231–255. doi:10.1177/011719680801700301.

Hugo, G. (2005). Migration in the Asia-Pacific region. Geneva: Policy Analysis and Research Programme, Global Commission on International Migration.

Hwang, M.C. and Parreñas, R.S. (2018). Intimate migrations: The case of marriage migrants and sex workers in Asia. In: Liu-Farrer, G. and Yeoh, B.S.A. (eds.). *Routledge handbook of Asian migrations*. London: Routledge: 64–74. doi:10.4324/9781315660493-4.

Hyndman, R.J. and Booth, H. (2008). Stochastic population forecasts using functional data models for mortality, fertility and migration. *International Journal of Forecasting* 24: 323–342. doi:10.1016/j.ijforecast.2008.02.009.

IOM (2008). World migration 2008: Managing labour mobility in the evolving global economy. Geneva: International Organization for Migration. Available at https://publications.iom.int/books/world-migration-report-2008-managing-labour-mobility-evolving-global-economy.

IOM (2022). Women and girls account for the majority of migrants in East and Horn of Africa: Geneva: International Organization for Migration. Available at https://www.iom.int/news/women-and-girls-account-majority-migrants-east-and-horn-africa-iom-report#:~:text=Women%20account%20for%20the%20highest,in%20search%20for%20employment%20opportunities.

Iredale, R., Guo, F., and Rozario, S. (2003). Introduction. In: Iredale, R., Guo, F., and Rozario, S. (eds.). *Return migration in the Asia-Pacific*. Cheltenham: Edward Elgar: 1–25. doi:10.4337/9781781957431.00008.

Jolly, S. and Reeves, H. (2005). Gender and migration: Overview report. Brighton: BRIDGE, Institute of Development Studies. Available at https://www.ssatp.org/sites/ssatp/files/publications/HTML/Gender-RG/Source%20%20documents/Technical%20Reports/Gender%20Research/TEGEN7%20BRIDGE%20Gender%20and%20Migration%20Overview.pdf.

Kulu, H. and Milewski, N. (2007). Family change and migration in the life course: An introduction. *Demographic Research* 17(19): 567–590. doi:10.4054/DemRes.2007.17.19.

Lee, R.D. and Carter, L.R. (1992). Modeling and forecasting US mortality. *Journal of the American Statistical Association* 87(419): 659–671. doi:10.1080/01621459.1992.10475265.

Little, J.S. and Rogers, A. (2007). What can the age composition of a population tell us about the age composition of its out-migrants? *Population, Space and Place* 13(1): 23–39. doi:10.1002/psp.440.

McAuliffe, M. and Triandafyllidou, A. (eds.) (2021). World migration report 2022. Geneva: International Organization for Migration. Available at doi:10.1002/wom3.25.

Nowok, B., Kupiszewska, D., and Poulain, M. (2006). Statistics on international migration flows. In: Poulain, M., Perrin, N., and Singleton, A. (eds.). *THESIM: Towards Harmonised European Statistics on International Migration*. Louvain-la-Neuve: UCL Presses: 203–231.

OECD (2023). *Education at a glance 2023: OECD indicators*. Paris: Organization for Economic Cooperation and Development. doi:10.1787/e13bef63-en.

Oh, J.-E., Kang, D.K., Shin, J.J., Lee, S.-L., Lee, S.B., and Chung, K. (2012). Migration profile of the Republic of Korea. Gyeonggi-do: Migration Research and Training Centre, International Organization for Migration (IOM MRTC Research Report Series 2011-01).

Pittenger, D.B. (1974). A typology of age-specific net migration rate distributions. *Journal of the American Institute of Planners* 40(4): 278–283. doi:10.1080/01944367408977480.

Pittenger, D.B. (1978). On making flexible projections of age-specific net migration. *Environment and Planning A* 10: 1253–1272. doi:10.1068/a101253.

Plane, D.A. and Heins, F. (2003). Age articulation of U.S. inter-metropolitan migration flows. *The Annuals of Regional Science* 37: 107–130. doi:10.1007/s001680200114.

Poulain, M. (1993). Confrontation des statistiques de migrations intra-Européennes: Vers plus d'harmonisation? *European Journal of Population* 9: 353–381. doi:10.1007/BF01265643.

Raymer, J. (2008). Obtaining an overall picture of population movement in the European Union. In: Raymer, J. and Willekens, F. (eds.). *International migration in Europe: Data, models and estimates*. Chichester: Wiley: 209–234. doi:10.1002/9780470985557.ch10.

Raymer, J., Bai, X., and Smith, P.W.F. (2020). Forecasting origin-destination-age-sex migration flow tables with multiplicative components. In: Mazzuco, S. and Keilman, N. (eds.). *Developments in demographic forecasting*. Dordrecht: Springer: 217–242. doi:10.1007/978-3-030-42472-5_11.

Raymer, J., Biddle, N., and Campbell, P. (2017). Analysing and projecting Indigenous migration in Australia, *Applied Spatial Analysis and Policy* 10: 211–232. doi:10.1007/s12061-015-9179-6.

Raymer, J., Bonaguidi, A., and Valentini, A. (2006). Describing and projecting the age and spatial structures of interregional migration in Italy, *Population, Space and Place* 12(5): 371–388. doi:10.1002/psp.414.

Raymer, J., Guan, Q., Shen, T., Wiśniowski, A., and Pietsch, J. (2022). Estimating international migration flows for the Asia-Pacific region: Application of a generation–distribution model. *Migration Studies* 10(4): 631–669. doi:10.1093/migration/mnac023.

Raymer, J., Liu, N., and Bai, X. (2019). Age articulation of Australia's international migration flows. In: Franklin, R.S. (ed.). *Population, place, and spatial interaction: Essays in honor of David Plane*. Singapore: Springer Nature: 171–200. doi:10.1007/978-981-13-9231-3_10.

Raymer, J. and Rogers, A. (2008). Applying model migration schedules to represent age-specific migration flows. In: Raymer, J. and Willekens, F. (eds.). *International migration in Europe*: *Data, models and estimates*. Chichester: John Wiley & Sons: 175–192. doi:10.1002/9780470985557.ch8.

Raymer, J. and Wiśniowski, A. (2018). Applying and testing a forecasting model for age and sex patterns of immigration and emigration. *Population Studies* 72(3): 339–355. doi:10.1080/00324728.2018.1469784.

Raymer, J., Wiśniowski, A., Forster, J.J., Smith, P.W.F., and Bijak, J. (2013). Integrated modeling of European migration. *Journal of the American Statistical Association* 108(503): 801–819. doi:10.1080/01621459.2013.789435.

Riffe, T., Aburto, J.M., Alexander, M., Fennell, S., Kashnitsky, I., Pascariu, M., and Gerland, P. (2019). *DemoTools: An R package of tools for aggregate demographic analysis*. https://github.com/timriffe/DemoTools/.

Rogers, A. (1988). Age patterns of elderly migration: An international comparison. *Demography* 25(3): 355–370. doi:10.2307/2061537.

Rogers, A. (1990). Requiem for the net migrant. *Geographical Analysis* 22(4): 283–300. doi:10.1111/j.1538-4632.1990.tb00212.x.

Rogers, A. and Castro, L.J. (1981a). Model migration schedules. Laxenburg: International Institute for Applied Systems Analysis (Research Report 81-30). Available at https://pure.iiasa.ac.at/id/eprint/1543/1/RR-81-030.pdf.

Rogers, A. and Castro, L.J. (1981b). Age patterns of migration: Cause-specific profiles. In Rogers, A. (ed.). *Advances in multiregional demography*. Laxenburg: International Institute for Applied Systems Analysis: 125–159. (Research Report 81-6). Available at https://pure.iiasa.ac.at/id/eprint/1556/1/RR-81-006.pdf.

Rogers, A., Raquillet, R., and Castro, L.J. (1978). Model migration schedules and their applications. *Environment and Planning* A 10: 475–502. doi:10.1068/a100475.

Schoorl, J. (2012). Sex-specific migration flows. Oslo: Norface Research Programme on Migration (Unpublished report prepared for Integrated Modeling of European Migration meeting (https://www.norface-migration.org/).

Shang, H., Smith, P.W.F., Bijak, J., and Wiśniowski, A. (2016). A multilevel functional data method for forecasting population: With an application to the United Kingdom. *International Journal of Forecasting* 32(3): 629–649. doi:10.1016/j.ijforecast.2015.10.002.

Shen, T., Raymer, J., Guan, Q., and Wiśniowski, A. (2024). The estimation of age and sex profiles for international migration amongst countries in the Asia-Pacific region. *Population, Space and Place* 30(1): e2716. doi:10.1002/psp.2716.

Skeldon, R. (2006). Recent trends in migration in East and Southeast Asia. *Asian and Pacific Migration Journal* 15(2): 277–293. doi:10.1177/011719680601500206.

Smith, S.K. and Swanson, D.A. (1998). In defence of the net migrant. *Journal of Economic and Social Measurement* 24(3): 249–264. doi:10.3233/JEM-1998-0150.

Statistics Korea (2016). International migration statistics in 2015. Daejeon: Statistics Korea (Press Release). Available at: www.kostat.go.kr/portal/eng/pressReleases/8/5/index.board.

United Nations (1992). Preparing migration data for subnational population projections. New York: Department of International Economic and Social Affairs, United Nations (ST/ESASER.A/127).

United Nations (2011). International migration in a globalizing world: The role of youth. New York: Population Division, Department of Economic and Social Affairs, United Nations (Technical Paper 2011/1).

United Nations (2017a). Migration and population change: Drivers and impacts. New York: Population Division, Department of Economic and Social Affairs, United Nations, (Population Facts No. 2017). Available at: https://www.un.org/en/development/desa/population/migration/publications/populationfacts/docs/MigrationPopFacts20178.pdf.

United Nations (2017b). Trends in international migrant stock: The 2017 revision. New York: Population Division, Department of Economic and Social Affairs, United Nations (POP/DB/MIG/Stock/ Rev.2017).

United Nations (2022). Methodology report: World population prospects 2022. New York: Department of International Economic and Social Affairs, United Nations (UN DESA/POP/2022/DC/NO.6).

United Nations (2024). World population prospects: Summary of results. New York: Department of International Economic and Social Affairs, United Nations (UN DESA/POP/2024/TR/NO. 9).

UNDESA (2006). 2004 World Survey on the role of women in development: Women and international migration. New York: Division for the Advancement of Women, Department of Economic and Social Affairs, United Nations (A/59/287/Add.1, ST/ESA/294). Available at https://www.unwomen.org/sites/default/files/Headquarters/Attachments/Sections/Library/Publications/2005/World-survey-2004-Women-and-international-migration-en.pdf.

UNFPA (2006). State of the world population 2006 – A passage to hope: Women and International Migration. New York: United Nations Population Fund, United Nations. Available at: http://www.unfpa.org/upload/lib_pub_file/650_filename_sowp06-en.pdf.

UNHCR (2010). UNHCR statistical yearbook 2009. Geneva: United Nations High Commissioner for Refugees.

UNHCR (2021). Global trends: Forced displacement in 2021. Geneva: United Nations High Commissioner for Refugees. Available at: https://www.unhcr.org/media/global-trends-report-2021.

White, M.J. (2016). Introduction: Contemporary insights on migration and population distribution. In: White, M.J. (ed.). *International handbook of migration and population distribution*. Dordrecht: Springer: 1–8. doi:10.1007/978-94-017-7282-2_1.

Willekens, F. and Baydar, N. (1986). Forecasting place-to-place migration with generalized linear models. In: Woods, R. and Rees, P. (eds.). *Population structures and models: Developments in spatial demography*. London: Allen & Unwin: 203–244. doi:10.4324/9781003430346-11.

Wiśniowski, A., Forster, J.J., Smith, P.W.F., Bijak, J., and Raymer, J. (2016). Integrated modelling of age and sex patterns of European migration. *Journal of the Royal Statistical Society Series A* (*Statistics in Society*) 179(4): 1007–1024. doi:10.1111/rssa.12177.

Wiśniowski, A., Smith, P.W.F., Bijak, J., Raymer, J., and Forster, J.J. (2015). Bayesian population forecasting: Extending the Lee-Carter method. *Demography* 52(3): 1035–1059. doi:10.1007/s13524-015-0389-y.

Appendix: Description for input data and R code

Part A: Input data

There are three main sources of data underlying the estimation model:

1. Empirical migration data, including annual immigration and emigration flow data by sex, is provided for Sweden 1968–2023 from Statistics Sweden and for South Korea (Republic of Korea) 2000–2021 from Korean Statistical Information Service. We also include data for Australia 1981–2021 from the Australian Bureau of Statistics, Canada 2000–2020 from Statistics Canada, and New Zealand 2001–2019 from Statistics New Zealand. Note, the age-specific data for Australia and New Zealand are five-year age groups, whereas for the other countries, they are single-year age groups.

2. Net migration totals and mid-year population data in the WPP (2022) are used for model testing (mid-year population) and application to all countries in the world.

3. Estimated immigration and emigration flows by sex are provided by Abel and Cohen (2022) for 2000–2005. We used the estimates produced using the pseudo-Bayesian method. These estimates are used to construct sex profiles in the full model.

Part B: Code for model testing

The input files and R code for estimating the age–sex profiles of net international migration for Sweden and South Korea are available at https://osf.io/5wvmc/. The code can also be applied to the other countries in our dataset (i.e., Australia, Canada, and New Zealand).

To run the code, we first need to process the immigration and emigration data from one of the countries above and obtain the following information:

a) age profile of immigration and emigration by sex (averaged across years);

b) total female proportion of immigration and emigration (averaged across years); and

c) total net migration for each year.

We then need to obtain the total population for each year for same particular country (from the United Nations' WPP). After obtaining this information, we can then generate the model estimates:

Step 1: Generate initial immigration and emigration total.
Step 2: Combine age and sex profile with immigration and emigration totals.
Step 3: Calculate net migration by age and sex.

Part C: Code for model estimation

There are five steps in the R code to estimate the age–sex profile of net international migration for a country in the WPP. In the first step, the script requires the user to select a country and make assumptions about migration patterns through three prompts:

(i) Does the country's migration age profile follow the Western standard or low dependency model migration schedule?
(ii) Is the country a net receiver or a net sender of migrants?
(iii) Comparing the sex composition of migrants for the country, are male or female migrants younger or about the same?

In the second step, five sets of input data are loaded and filtered based on the selected country. These include the following:

(i) The Western standard and low dependency age schedules by direction of the flow (receiving or sending country) and by sex (younger male migrants, younger female migration, or neutral) adapted from the United Nations (1992) manual for internal migration. The average of the two types of age patterns is used to generate model age schedules ($i_{x|y}$ and $e_{x|y}$) and applied to the selected country based on the user's answers to the three prompts.
(ii) Sex profiles for immigration and emigration (i_y and e_y) representing a balance between equal shares of migration by two sexes (i.e., half male migrants and half female migrants) and the pseudo-Bayesian estimates produced by Abel and Cohen (2022) for 2000–2005. If the selected country has no data in Abel and Cohen (2022), 0.5 is used.
(iii) Total net migration from WPP.
(iv) Total mid-year population data from WPP.
(v) An arbitrary migration rate (m), such as 0.007.

In the third step, crude estimates of total immigration $\hat{I}$ and emigration $\hat{E}$ for the selected country are generated using the relationships between mid-year population *P*, net migration *N*, and the rate *m*, as specified in Equations 5 and 6 in the paper.

In the final two steps, the age compositions ($i_{x|y}$ and $e_{x|y}$) and sex profiles (i_y and e_y) identified in the second step are applied to the crude estimates of total immigration and emigration for the selected country to generate age- and sex-specific immigration and emigration levels. The age- and sex-specific net migration levels $\hat{N}_{xy}$ for the selected country are calculated as the difference between age-specific immigration and emigration levels, as specified in Equation 4 in the paper.

Note: Models are coded in R and RStudio with the `tidyverse` library installed. The R code can be found at https://osf.io/5wvmc/.

Part D: Model results

The following graphs compare reported statistics of net international migration by age and sex in 2010 with corresponding predicted values.

Figure A-1: Comparison of observed and predicted net international migration totals by age and sex in 2010 for Australia (AUS), Canada (CAN), South Korea (KOR), New Zealand (NZL), and Sweden (SWE)