ACCSCIENCE PUBLISHING

International Journal of Population Studies

RESEARCH ARTICLE

# Estimates and probabilistic projections of total marriage rates and total divorce rates for probabilistic household and living arrangement projections to inform healthy aging and sustainable development in Singapore and Indonesia

**Minhui Liu[1†], Yi Sun[1†], Qiushi Feng[1†], Zhenglian Wang[2†], Ying Lu[3], Zhuoru Ma[3], Wei Tang[4], Yan Mo[1], Zuqi Cai[1], Evi Nurvidya Arifin[5], Kenneth Land[6*], Aris Ananta[5,7*], and Yi Zeng[3,8*]**

[1]Department of Sociology and Centre for Family and Population Research, Faculty of Arts and Social Sciences, National University of Singapore, Singapore

[2]China Population and Development Research Center, Beijing, China

[3]National School of Development, Faculty of Economics and Management, Peking University, Beijing, China

[4]School of Politics and Public Administration, Southern China Normal University, Guangzhou, Guangdong, China

[5]Centre for Advanced Research, Universiti Brunei Darussalam, Bandar Seri Begawan, Brunei-Muara District, Brunei Darussalam

[6]Department of Sociology and Population Research Institute, Trinity College of Arts and Sciences, Duke University, Durham, North Carolina, United States of America

[7]Faculty of Economics and Business, Universitas Indonesia, Depok, West Java, Indonesia

[8]Geriatrics Division, Center for the Study of Aging and Human Development, School of Medicine, Duke University, Durham, North Carolina, United States of America

[†]*These authors contributed equally to this work.*

***Corresponding authors:**
Kenneth Land
(kland@duke.edu);
Aris Ananta
(arisananta@ui.ac.id);
Yi Zeng
(zengyi@nsd.pku.edu.cn)

**Citation:** Liu, M., Sun, Y., Feng, Q., Wang, Z., Lu, Y., Ma, Z., Tang, W., Mo, Y., Cai, Z., Arifin, EN., Land, K., Ananta, A., & Zeng, Y. (2026). Estimates and probabilistic projections of total marriage rates and total divorce rates for probabilistic household and living arrangement projections to inform healthy aging and sustainable development in Singapore and Indonesia. *International Journal of Population Studies*. 12(6):026190107. https://doi.org/10.36922/IJPS026190107

**Received:** May 8, 2026

**Revised:** August 4, 2026

**Accepted:** August 5, 2026

**Published online:** September 9, 2026

**Copyright:** © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.

**Publisher's Note:** AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

## Abstract

Household and living arrangement projections are very important for socioeconomic planning and policy-making. In this article, we present time-series estimates of total marriage rates (TMR[t]) and total divorce rates (TDR[t]) for Singapore and Indonesia, using conventionally available demographic datasets. We also present probabilistic projections of TMR(t) and TDR(t) in 2021–2060 for Singapore and Indonesia. In addition to probabilistically projected total fertility rates (TFR[t]) and sex-specific life expectations at birth (e0[s,t]) publicly released by the United Nations Population Division, the probabilistically projected TMR(t) and TDR(t) were used for probabilistic household and living arrangement projections (PHPs) in future years. This is crucial for PHPs using the ProFamy approach, because PHPs largely depend on the projected summary measures TMR(t), TDR(t), TFR(t), and e0(s,t). Finally, we discuss our ongoing research on optimized random combinations of TMR(t), TDR(t), TFR(t), e0(s,t), and other further research needed for PHPs.

***Keywords:*** Total marriage rate; Total divorce rate; Bayesian AR1 model; DemoRates R package; ProFamy probabilistic household and living arrangement projection; Socioeconomic planning; Informed policy-making

## 1. Introduction

Household and living arrangement projections are useful in many aspects of socioeconomic planning and sustainable development. First, allocations of health care resources, welfare programs, and estimates of care needs and costs for older adults with disability depend heavily upon projections of numbers, types, and sizes of households and ages, marital/union statuses, co-residence statuses between older parents and adult children, and other statuses of living arrangements (Zeng *et al*., 2015). Previous studies have found that disabled older adults with disability living alone have much higher needs for paid services (Dreyer *et al*., 2018; Grundy, 2001) and faster cognitive decline (Mazzuco *et al*., 2017) than those who live with children and/or a spouse. Second, compared with population growth, changes in household numbers, sizes, and structures are more important for forecasting residential energy demand (Bradbury *et al*., 2014; Keilman, 2003). This is because residential energy commodities, such as water, electricity, and gas, are often purchased and consumed by households rather than individuals. Lower fertility, higher divorce rates, more migration, reduction in co-residence between older parents and adult children, and population aging contribute to smaller household sizes, continuously and rapidly increasing the number of households in many countries all over the world; population growth has slowed down greatly and is negative or will soon become negative in many countries (Gu *et al*., 2015). Consequently, if residential energy demand forecasting is based on population growth, it will drastically underestimate future demand and mislead policymakers (Zeng *et al*., 2021). Third, business market analyses of various home-based goods and services, as well as government planning to meet housing and associated infrastructure (reservoirs, etc.) needs, rely heavily on household and living arrangements projections. For example, planning for consumer durables, such as appliances, furniture, and household vehicles, must take into account projected changes in household numbers, sizes, and structures (Feng *et al*., 2011; Prskawetz *et al*., 2004). Meanwhile, planning for housing and real estate markets depends on projected household types, sizes, and numbers (Smith *et al*., 2008, 2012).

The United Nations Population Division (UNPD) has released probabilistic population projections (PPPs) for each country since 2014, based on probabilistic projections of total fertility rate (TFR[t]) and sex-specific life expectancy at birth in year t (e0[s,t]; s represents sex) (Gerland *et al*., 2014; Raftery *et al*., 2013). Although this is a great historical breakthrough, PPPs do not include projections of households and living arrangements. As outlined above, household and living arrangement projections are crucial for the socioeconomic planning of housing, critical infrastructures, social and home-based services for older adults, household vehicles, home-based energy demands, and market analyses. Thus, research on the methodology and software development of probabilistic household and living arrangement projections (PHPs), as well as on their applications in healthy aging and sustainable development, is of great significance.

As discussed in Zeng *et al*. (2024), it is ideal and highly feasible to substantially extend the internationally widely applied ProFamy cohort-component method for PHPs, and it is crucial for conducting PHPs to probabilistically project total marriage rates (TMR[t]) and total divorce rates (TDR[t]) as summary measures in future years based on time series estimates, in addition to the UNPD-released probabilistically projected TFR(t) and e0(s,t) (see **Section 3.1**).

In **Section 2**, we outline the data sources used to estimate time-series and probabilistic projections of TMR(t) and TDR(t) for Singapore and Indonesia, and discuss the measures and methods. We present time-series estimates of TMR(t) and TDR(t) using available demographic datasets from Singapore and Indonesia in **Section 3**. The probabilistically projected TMR(t) and TDR(t) for 2021–2060 in both Singapore and Indonesia are also discussed. Finally, in **Section 4**, we discuss our conclusions and the perspectives of our ongoing PHPs research project.

## 2. Methods

### 2.1. Data sources for Singapore estimates

The data sources used for Singapore estimates of the single-year-period-specific time series of TMR(t) and TDR(t) for 1980–2020 were:

(1) Vital Statistics of Marriages (1980–2020) in Singapore (https://tablebuilder.singstat.gov.sg/table/TS/M830163), released by the Department of Statistics Singapore.
(2) Vital Statistics of Divorces (1980–2020) in Singapore (https://tablebuilder.singstat.gov.sg/table/TS/M830251), released by the Department of Statistics Singapore.

### 2.2. Data sources for Indonesia estimates

Since the official statistics from Indonesia are unavailable, the estimates of the time series of TMR(t) and TDR(t) were obtained from the Indonesian Family Life Surveys (IFLSs) conducted in 1993, 1997, 2000, and 2007, as well as the two most recently published Indonesia Demographic and Health Surveys (DHSs) conducted in 2012 and 2017. Because earlier DHSs (1987, 1991, 1994, 1997, 2002–2003, and 2007) only interviewed currently married women,

which were insufficient for estimating TMR(t) and TDR(t), we used only the 2012 and 2017 DHSs. As these sample sizes were limited, we estimated the two-year-period-specific TMR(t) and TDR(t) for 1981–2020.

### 2.3. Definitions, interpretations, and the methods to estimate time-series data of TMR(t) and TDR(t)

Similar to the definition of TFR(t), TMR(t) and TDR(t) are the summations of age-specific frequencies of marriages (including first marriages and remarriages) and divorces, respectively, in year t. The age-specific frequencies of marriages and divorces are defined as the numbers of marriages and divorces that occurred to persons of age x in year t, respectively, divided by the total number of persons aged x in year t. The equations for calculating TMR(t) and TDR(t) in Singapore using five-year-age-group-specific vital statistics data are presented in **Section S1**, while those for calculating TMR(t) and TDR(t) in Indonesia, based on single-year-age-specific survey data, are presented in **Section S2**. TMR(t) and TDR(t) are age-structure-standardized estimates. TFR(t) is conventionally interpreted as the average number of births a synthetic cohort of women would have if they experienced the age-specific fertility rates observed in year t throughout their reproductive lifespan (Preston *et al.*, 2001). Similarly, TMR(t) and TDR(t) are demographically interpreted as the average numbers of marriages and divorces that a hypothetical cohort would have for the whole life if they experienced the age-specific rates of marriages and divorces observed in year *t*, respectively, throughout their life course.

Notably, direct calculations of TMR(t) and TDR(t) might not be accurate due to sample size constraints, especially when using survey datasets. Thus, in addition to the direct calculations, we applied the Bayesian AR1 (first-order autoregressive) model in the BayesRates R package, part of the DemoRates R software (Version 3.0, Joint Rsearch Group of National School of Development at Peking University and Center for Family and Population Studies at National University of Singapore, Singapore), to estimate the time-series data of TMR(t) and TDR(t) in Singapore and Indonesia.

### 2.4. Probabilistic projections of the trajectories of TMR(t) and TDR(t)

Inspired by the pioneering studies on probabilistic projections of TFR(t) and e0(s,t) in the PPPs using Bayesian hierarchical models (Alkema *et al.*, 2011; Gerland *et al.*, 2014; Raftery *et al.*, 2013), we developed and applied the Bayesian hierarchical model in the BayesRates R package, and the DemoRates R package, which is part of ProFamy-PHPs software (Version 6.0, Rsearch Group of National School of Development at Peking University, China) for PHPs (Feng *et al.*, 2024; Wang *et al.*, 2024).

We applied the Bayesian AR1 (first-order autoregressive) and Bayesian damped linear trend (DT) models for probabilistic projections of TMR(t) and TDR(t), and found that the Bayesian AR1 model performs better than the Bayesian DT model in terms of projection appropriateness. Although both models were fitted to the same historical series, they yielded notably different long-term trajectories because they made different assumptions about the evolution of the underlying process.

The Bayesian AR1 model assumed that the time series is a stationary process fluctuating around a fixed long-run mean, so its projections eventually revert to that mean. Singapore's historical TMR(t) declined from 0.891 in 1980 to 0.520 in 2020, and the model estimated the long-run mean over this period to be around 0.700. Although the most recent observed value was only 0.520, the projection gradually moved upward toward the estimated long-run mean of about 0.700 and then stabilized.

The Bayesian DT model, by contrast, did not assume any mean. Instead, it followed the most recent level and local slope, with the slope damping to zero over time. Since Singapore's TMR(t) has remained relatively stable in recent years, the model extrapolated forward at approximately the last observed level of around 0.500.

The two models also produce differently shaped prediction intervals. Because the Bayesian AR1 was a stationary process, its forecast variance had an upper bound, and the predictive interval first widened and then stabilized at a fixed width (**Figure S2A**). The Bayesian DT model, however, contained a non-stationary component; hence, its forecast variance kept growing without bound as the horizon lengthened, and the predictive interval kept widening throughout the projection period, even becoming negative after year 2040 (**Figure S2B**).

We employed the Bayesian AR1 model to probabilistically project TMR(t) and TDR(t) for 2021–2060 using the BayesProj R package, which is part of the ProFamy-PHPs software. For each of the 2,000 estimated trajectories of single-year-period-specific TMR(t) and TDR(t) for 1980–2020 in Singapore and two-year-period-specific TMR(t) and TDR(t) for 1981–2020 in Indonesia, we fitted a Bayesian AR1 time-series model and used the fitted model to obtain probabilistic projections. To ensure the plausibility of the probabilistic projections, we incorporated appropriate expert judgments. We finally obtained 2,000 probabilistically projected trajectories of single-year-period-specific TMR(t) and TDR(t) for 2021–2060 in Singapore and two-year-period-specific TMR(t)

and TDR(t) for 2021–2060 in Indonesia. For details of the Bayesian AR1 model, please refer to **Section S4**.

### 2.5. Decomposition of the probabilistically projected four marital statuses into seven marital/union statuses

When using the ProFamy method/software to deterministically project households and living arrangements, users can choose either a multistate transition model with four marital statuses (never married, currently married, widowed, and divorced) or a model with seven marital/union statuses (never married and not cohabiting, currently married, widowed and not cohabiting, divorced and not cohabiting, never married and cohabiting, widowed and cohabiting, and divorced and cohabiting) (Zeng *et al.*, 2014). However, if the seven-status marital/union transition model were adopted in the PHPs (**Figure S1A and S1B**), it would be necessary to estimate the time series and probabilistically project the summary measures for transitions among the 13 marital/union statuses, in addition to estimating the 13 sets of rural/urban- (or ethnic group/race-), sex-, and age-specific standard schedules.

However, we could not probabilistically project summary measures of cohabitation-status transitions because most countries worldwide, including Singapore and Indonesia, lack sufficiently long time-series data to estimate and probabilistically project these measures. Additionally, it is difficult to estimate the 13 sets of rural/urban- (or ethnic group/race-), sex-, and single-age-specific standard schedules because cohabitation has become widely popular worldwide in recent years. Thus, we adopted the multistate transition model with four marital statuses in our PHPs and applied the Sullivan proportional distribution approach to decompose the probabilistically projected three non-married statuses (never-married, widowed, and divorced) in future years into six statuses: never-married and cohabiting, never-married and not cohabiting, widowed and cohabiting, widowed and not cohabiting, divorced and cohabiting, and divorced and not cohabiting. This decomposition was performed using straightforward equations (**Section S3**).

## 3. Results and discussion

### 3.1. Estimates of time series of TMR(t) and TDR(t) in Singapore and Indonesia

The observed marriage and divorce data in 2020 were distorted by the effects of the COVID-19 pandemic, which began in Singapore and Indonesia at the start of 2020. During that period, it was almost impossible to have marriage ceremonies, dinner parties, and official registrations. As a result, many couples might actually get married without those formalities, leading to a large drop in the number of marriages in 2020. Similarly, the process of officially registering divorces was challenging, while couples might have actually ended their marriages during the COVID-19 pandemic in 2020. Therefore, we did not use the 2020 marriage and divorce data. Instead, for each trajectory of estimated TMR(t) and TDR(t) in Singapore and Indonesia, we assumed that TMR(t) and TDR(t) in 2020 equal the averages of the estimated TMR(t) and TDR(t) in 2018 and 2019, respectively, for both Singapore and Indonesia.

#### *3.1.1. Estimates of single-year-period-specific time series of TMR(t) and TDR(t) for 1980–2020 in Singapore*

Tables 1 and 2 present comparisons between direct calculations and Bayesian model estimates of rural/urban-combined, male/female-combined single-year-period-specific time series of TMR(t) and TDR(t) for 1980–2020 in Singapore. The differences were generally small, primarily due to the large sample sizes.

**Table 1. Comparison between direct calculations and Bayesian AR1 model estimates of rural/urban-combined, male/female-combined total marriage rates for 1980–2020 in Singapore**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1980 | 0.892 | 0.891 | −0.1 |
| 1981 | 0.917 | 0.916 | −0.1 |
| 1982 | 0.811 | 0.810 | −0.1 |
| 1983 | 0.741 | 0.741 | 0.1 |
| 1984 | 0.820 | 0.821 | 0.2 |
| 1985 | 0.774 | 0.776 | 0.3 |
| 1986 | 0.680 | 0.680 | 0.0 |
| 1987 | 0.790 | 0.789 | −0.1 |
| 1988 | 0.828 | 0.827 | −0.2 |
| 1989 | 0.774 | 0.774 | 0.0 |
| 1990 | 0.773 | 0.774 | 0.1 |
| 1991 | 0.784 | 0.783 | −0.2 |
| 1992 | 0.798 | 0.798 | 0.1 |
| 1993 | 0.772 | 0.771 | −0.1 |
| 1994 | 0.738 | 0.738 | 0.0 |
| 1995 | 0.727 | 0.727 | 0.0 |
| 1996 | 0.682 | 0.681 | −0.1 |
| 1997 | 0.700 | 0.700 | 0.1 |

(*Cont'd...*)

**Table 1. (*Continued*)**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1998 | 0.619 | 0.620 | 0.1 |
| 1999 | 0.684 | 0.683 | −0.1 |
| 2000 | 0.600 | 0.599 | −0.1 |
| 2001 | 0.587 | 0.585 | −0.3 |
| 2002 | 0.609 | 0.609 | 0.0 |
| 2003 | 0.585 | 0.588 | 0.5 |
| 2004 | 0.599 | 0.599 | 0.0 |
| 2005 | 0.614 | 0.614 | −0.1 |
| 2006 | 0.608 | 0.608 | −0.1 |
| 2007 | 0.581 | 0.582 | 0.2 |
| 2008 | 0.563 | 0.563 | 0.1 |
| 2009 | 0.575 | 0.574 | −0.1 |
| 2010 | 0.526 | 0.527 | 0.1 |
| 2011 | 0.580 | 0.580 | −0.1 |
| 2012 | 0.583 | 0.582 | −0.2 |
| 2013 | 0.537 | 0.537 | 0.1 |
| 2014 | 0.570 | 0.571 | 0.3 |
| 2015 | 0.566 | 0.565 | −0.1 |
| 2016 | 0.554 | 0.553 | −0.2 |
| 2017 | 0.555 | 0.556 | 0.2 |
| 2018 | 0.534 | 0.534 | 0.0 |
| 2019 | 0.507 | 0.506 | −0.1 |
| 2020 | 0.520 | 0.520 | −0.1 |

**Table 2. Comparison between direct calculations and Bayesian AR1 model estimates of rural/urban-combined, male/female-combined total divorce rates for 1980–2020 in Singapore**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1980 | 0.085 | 0.086 | 1.4 |
| 1981 | 0.094 | 0.094 | 0.1 |
| 1982 | 0.093 | 0.093 | −0.2 |
| 1983 | 0.100 | 0.100 | −0.4 |
| 1984 | 0.097 | 0.096 | −1.0 |
| 1985 | 0.098 | 0.097 | −0.7 |
| 1986 | 0.108 | 0.106 | −1.5 |

(*Cont'd...*)

**Table 2. (*Continued*)**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1987 | 0.104 | 0.106 | 2.3 |
| 1988 | 0.114 | 0.112 | −1.4 |
| 1989 | 0.108 | 0.109 | 1.0 |
| 1990 | 0.128 | 0.129 | 0.8 |
| 1991 | 0.151 | 0.151 | −0.3 |
| 1992 | 0.142 | 0.141 | −0.4 |
| 1993 | 0.145 | 0.145 | 0.3 |
| 1994 | 0.131 | 0.133 | 1.3 |
| 1995 | 0.146 | 0.147 | 0.9 |
| 1996 | 0.152 | 0.154 | 1.2 |
| 1997 | 0.159 | 0.157 | −1.5 |
| 1998 | 0.177 | 0.177 | −0.2 |
| 1999 | 0.163 | 0.163 | 0.2 |
| 2000 | 0.157 | 0.156 | −0.6 |
| 2001 | 0.152 | 0.152 | 0.2 |
| 2002 | 0.169 | 0.170 | 0.4 |
| 2003 | 0.190 | 0.191 | 0.5 |
| 2004 | 0.184 | 0.184 | −0.1 |
| 2005 | 0.204 | 0.203 | −0.5 |
| 2006 | 0.201 | 0.202 | 0.3 |
| 2007 | 0.203 | 0.202 | −0.6 |
| 2008 | 0.195 | 0.195 | 0.2 |
| 2009 | 0.196 | 0.197 | 0.7 |
| 2010 | 0.198 | 0.197 | −0.3 |
| 2011 | 0.204 | 0.203 | −0.7 |
| 2012 | 0.193 | 0.192 | −0.5 |
| 2013 | 0.198 | 0.198 | 0.2 |
| 2014 | 0.187 | 0.189 | 0.9 |
| 2015 | 0.198 | 0.197 | −0.7 |
| 2016 | 0.199 | 0.199 | 0.2 |
| 2017 | 0.203 | 0.202 | −0.3 |
| 2018 | 0.194 | 0.194 | 0.1 |
| 2019 | 0.205 | 0.204 | −0.4 |
| 2020 | 0.199 | 0.199 | −0.2 |

#### *3.1.2. Estimates of the two-year-period-specific time series of TMR(t) and TDR(t) in Indonesia*

Unlike the Singapore datasets, which have large sample sizes to estimate single-year-period-specific time series of TMR(t) and TDR(t), Indonesia lacks the necessary statistics, necessitating the use of survey data. Because the Indonesian survey datasets have limited sample sizes, we estimated the two-year-period-specific time series of TMR(t) and TDR(t).

Tables 3 and 4 present comparisons between direct calculations and Bayesian AR1 model estimates of rural/urban-combined, male/female-combined two-year-period-specific time series of TMR(t) and TDR(t) for 1981–2020 in Indonesia. The differences were small in general, with some exceptions when the survey sample size was extremely small, while the Bayesian AR1 model estimates were smoother than the direct calculations.

**Table 3. Comparison between direct calculations and Bayesian AR1 model estimates of rural/urban-combined, male/female-combined total marriage rates for 1981–2020 in Indonesia**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1981–1982 | 1.053 | 1.007 | −4.4 |
| 1983–1984 | 0.854 | 0.902 | 5.6 |
| 1985–1986 | 0.855 | 0.881 | 3.0 |
| 1987–1988 | 0.839 | 0.852 | 1.5 |
| 1989–1990 | 0.940 | 0.924 | −1.7 |
| 1991–1992 | 0.787 | 0.827 | 5.1 |
| 1993–1994 | 0.884 | 0.915 | 3.5 |
| 1995–1996 | 1.162 | 1.132 | −2.6 |
| 1997–1998 | 1.290 | 1.292 | 0.2 |
| 1999–2000 | 1.404 | 1.379 | −1.8 |
| 2001–2002 | 1.201 | 1.232 | 2.6 |
| 2003–2004 | 1.220 | 1.187 | −2.7 |
| 2005–2006 | 1.044 | 1.061 | 1.6 |
| 2007–2008 | 1.139 | 1.130 | −0.8 |
| 2009–2010 | 1.164 | 1.156 | −0.7 |
| 2011–2012 | 1.134 | 1.131 | −0.3 |
| 2013–2014 | 1.014 | 1.031 | 1.7 |
| 2015–2016 | 1.005 | 1.009 | 0.4 |
| 2017–2018 | 0.820 | 0.854 | 4.1 |
| 2019–2020 | 0.913 | 0.932 | 2.1 |

**Table 4. Comparison between direct calculations and Bayesian AR1 model estimates of rural/urban-combined, male/female-combined total divorce rates for 1981–2020 in Indonesia**

| Year | Direct calculation | Bayesian AR1 model estimation | Difference (%) |
|---|---|---|---|
| 1981–1982 | 0.117 | 0.115 | −2.0 |
| 1983–1984 | 0.101 | 0.110 | 8.9 |
| 1985–1986 | 0.087 | 0.102 | 16.7 |
| 1987–1988 | 0.120 | 0.114 | −5.0 |
| 1989–1990 | 0.127 | 0.117 | −7.9 |
| 1991–1992 | 0.093 | 0.108 | 16.3 |
| 1993–1994 | 0.128 | 0.133 | 3.9 |
| 1995–1996 | 0.157 | 0.157 | 0.0 |
| 1997–1998 | 0.189 | 0.169 | −10.6 |
| 1999–2000 | 0.161 | 0.180 | 11.8 |
| 2001–2002 | 0.158 | 0.142 | −10.1 |
| 2003–2004 | 0.130 | 0.148 | 13.8 |
| 2005–2006 | 0.150 | 0.134 | −10.7 |
| 2007–2008 | 0.127 | 0.144 | 13.4 |
| 2009–2010 | 0.157 | 0.150 | −4.5 |
| 2011–2012 | 0.150 | 0.160 | 6.7 |
| 2013–2014 | 0.181 | 0.193 | 6.6 |
| 2015–2016 | 0.180 | 0.189 | 5.0 |
| 2017–2018 | 0.147 | 0.160 | 8.8 |
| 2019–2020 | 0.164 | 0.175 | 6.7 |

### 3.2. Probabilistic projections of TMR(t) and TDR(t) for household and living arrangement projections in Singapore and Indonesia

#### *3.2.1. Total marriage rate*

When employing the Bayesian AR1 model to probabilistically project TMR(t) without incorporating expert judgments, the differences between the probabilistically projected U80 and median of TMR(t) were extremely wide relative to those observed/estimated in the historical time series of TMR(t) in Singapore and Indonesia (**Figures S2A & S10**). Therefore, we examined three possible expert-judgment scenarios in which the differences between the probabilistically projected U80 and median of TMR(t) for 2021–2060 were set to 90%, 45%, and 22.5%, respectively, of the corresponding differences between the U80 and median of TMR(t) in the historical period in Singapore

 https://doi.org/10.36922/IJPS026190107

and Indonesia. We compared the resulting differences between the probabilistically projected U80 and median of TMR(t) and selected the most appropriate scenario. The three expert-judgment scenarios for the probabilistically projected U80 of TMR(t) were denoted U80(I) of TMR(t), U80(II) of TMR(t), and U80(III) of TMR(t), respectively, and they were calculated using **Equations 1–3**:

$$\text{U80(I) of TMR(t)} = \text{Median of TMR(t)} + (\text{U80 of TMR[t]} - \text{Median of TMR[t]}) \times 0.90 \quad (1)$$

$$\text{U80(II) of TMR(t)} = \text{Median of TMR(t)} + (\text{U80 of TMR[t]} - \text{Median of TMR[t]}) \times 0.45 \quad (2)$$

$$\text{U80(III) of TMR(t)} = \text{Median of TMR(t)} + (\text{U80 of TMR[t]} - \text{Median of TMR[t]}) \times 0.225 \quad (3)$$

where all $t > 2020$.

The probabilistically projected U80 without expert judgment, and the expert-judgment scenarios U80(I), U80(II), and U80(III) of TMR(t) in Singapore and Indonesia are presented in **Tables S1 and S3**, respectively. The numerical values of the lower and upper bounds of the 95% confidence interval (L95 and U95, respectively), the lower and upper bounds of the 80% confidence interval (L80 and U80, respectively), and the median of the probabilistically projected TMR(t) for PHPs for 2021–2060 (without expert judgment, with U80[I] of TMR[t] expert judgments, U80[II] of TMR[t] expert judgments, and U80[III] of TMR[t] expert judgments) in Singapore and Indonesia are presented in **Tables S5–S8**, and **Tables S9–S12**, respectively.

Employing the Bayesian AR1 model and the estimated time series of TMR(t) in the past decades (**Section 3.1.1**), with the expert judgments of U80(I), U80(II) and U80(III) and without expert judgments, we produced 2,000 sets of probabilistically projected trajectories of TMR(t) for 2021–2060 in Singapore and Indonesia. As demonstrated in **Figures S2–S17**, we found that U80(II) expert judgments were most appropriate compared with those of U80(I) and U80(III) for 2021–2060 in both Singapore and Indonesia. This is because the predictive intervals of TMR(t) and TDR(t) in the future years with U80(II) expert judgments were moderate (Figures 1–4), but those with U80(I) expert judgments were extremely large, while those with U80(III) expert judgments were extremely narrow (**Figures S2–S17**).

#### *3.2.2. Total divorce rate*

Similarly, employing the Bayesian AR1 model to probabilistically project TDR(t), the differences between the probabilistically projected U80 and the median of TDR(t) for 2021–2060, without expert judgments, in Singapore and Indonesia were extremely wide (**Figures S6 and S14**). Thus, we examined three possible expert-judgment scenarios in which the differences between the probabilistically projected U80 and median of TDR(t) for 2021–2060 were set to 90%, 45%, and 22.5%, respectively, of the corresponding differences between the U80 and median of TDR(t) in the historical period in Singapore and Indonesia. We compared the resulting differences between the probabilistic projections U80 and median of TDR(t) and selected the most appropriate scenario. The three expert-judgment scenarios for the probabilistically projected U80 of TDR(t) were denoted U80(I) of TDR(t), U80(II) of TDR(t), and U80(III) of TDR(t), respectively, and they were calculated using **Equations 4–6**:

$$\text{U80(I) of TDR(t)} = \text{Median of TDR(t)} + (\text{U80 of TDR[t]} - \text{Median of TDR[t]}) \times 0.90 \quad (4)$$

$$\text{U80(II) of TDR(t)} = \text{Median of TDR(t)} + (\text{U80 of TDR[t]} - \text{Median of TDR[t]}) \times 0.45 \quad (5)$$

$$\text{U80(III) of TDR(t)} = \text{Median of TDR(t)} + (\text{U80 of TDR[t]} - \text{Median of TDR[t]}) \times 0.225 \quad (6)$$

where all $t > 2020$.

The probabilistically projected U80 without expert judgments and the expert-judgment scenarios U80(I), U80(II), and U80(III) of TDR(t) in Singapore and Indonesia are presented in **Tables S2 and S4**, respectively. The numerical values of the L95, L80, median, U80 and U95 of the probabilistically projected TDR(t) for PHPs for 2021–2060 (without expert judgment, with U80[I] of TDR[t] expert judgment, U80[II] of TDR[t] expert judgment, and U80[III] of TDR[t] expert judgment) in Singapore and Indonesia are presented in **Tables S13–S16**, and **Tables S17–S20**, respectively.

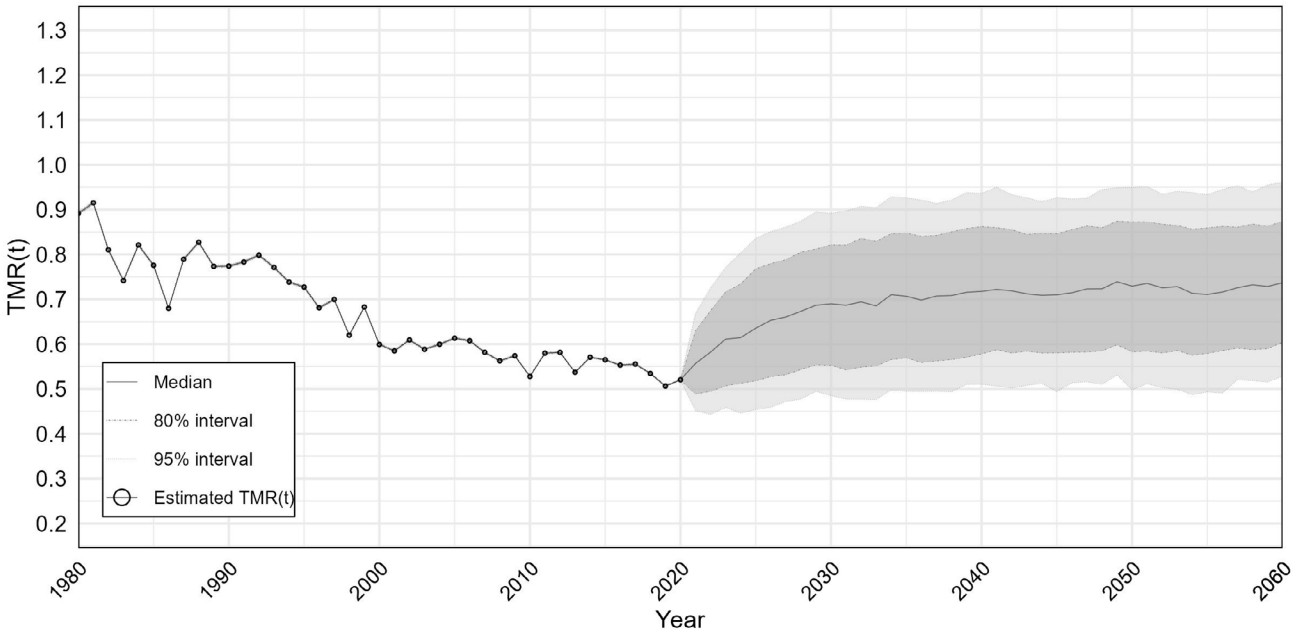



**Figure 1.** Estimates of total marriage rate (TMR[t]) for 1980–2020 and the probabilistically projected TMR(t) from the Bayesian AR1 model with U80(II) of TMR(t) expert judgments for probabilistic household and living arrangement projections for 2021–2060 in Singapore

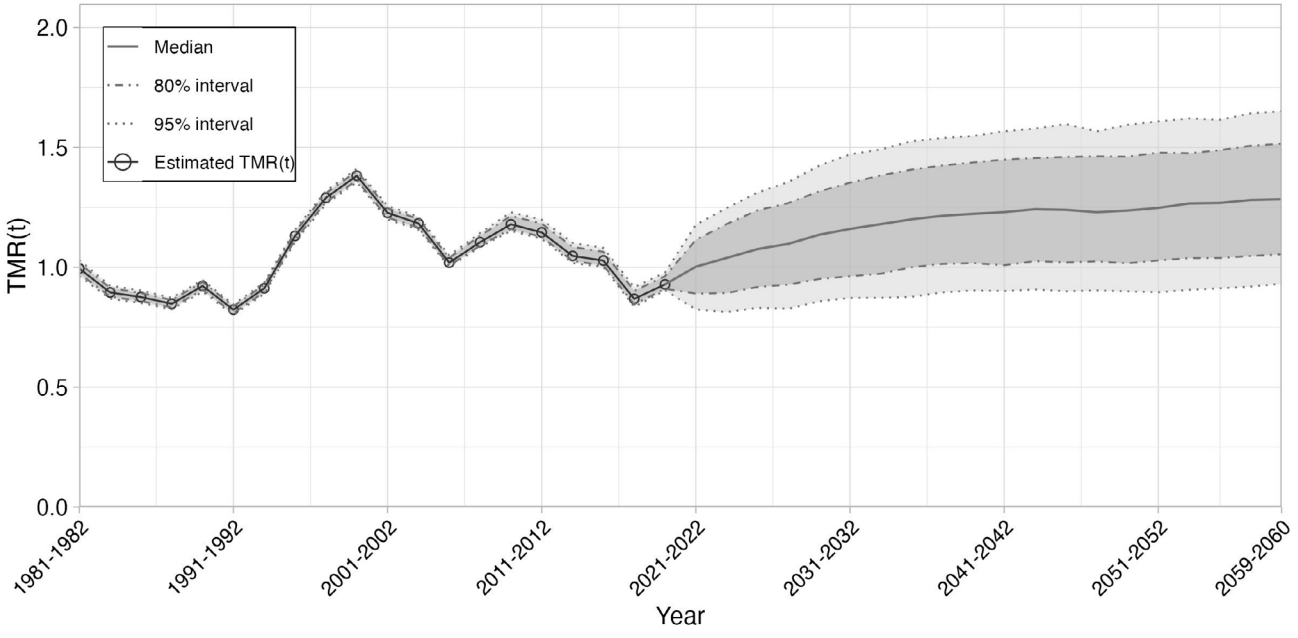



**Figure 2.** Estimates of total marriage rate (TMR[t]) for 1980–2020 and the probabilistically projected TMR(t) from the Bayesian AR1 model with U80(II) of TMR(t) expert judgments for probabilistic household and living arrangement projections for 2021–2060 in Indonesia

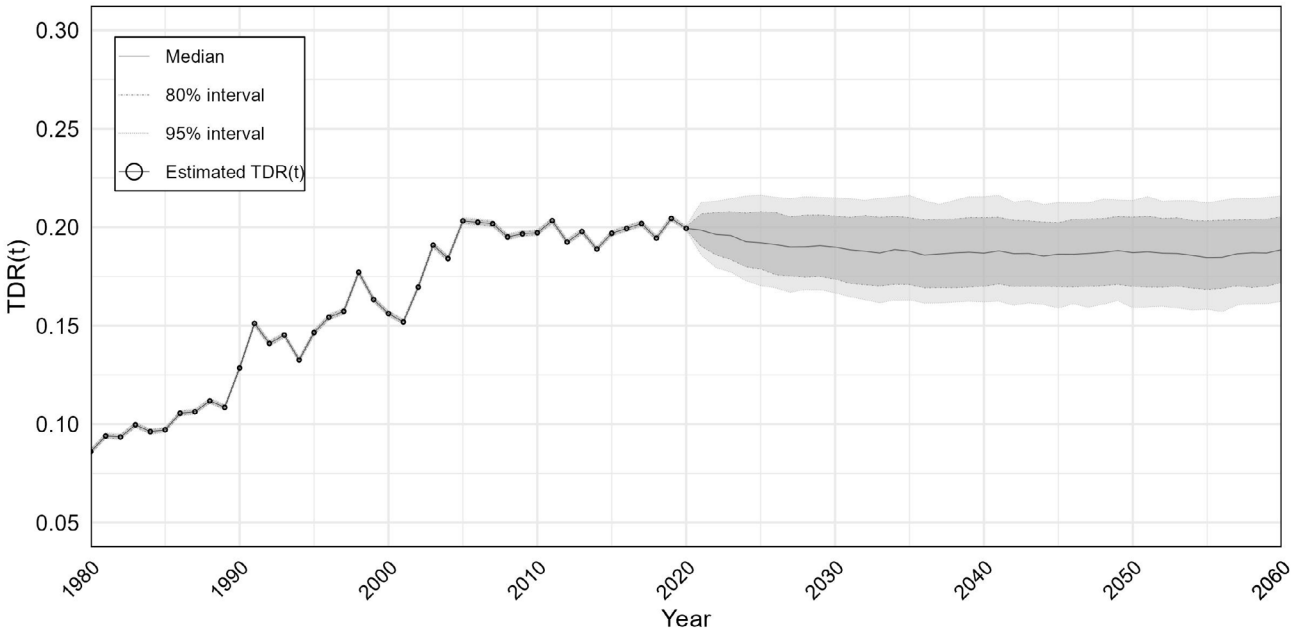



**Figure 3.** Estimates of total divorce rate (TDR[t]) for 1980–2020 and the probabilistically projected TDR(t) from the Bayesian AR1 model with U80(II) of TDR(t) expert judgments for probabilistic household and living arrangement projections for 2021–2060 in Singapore

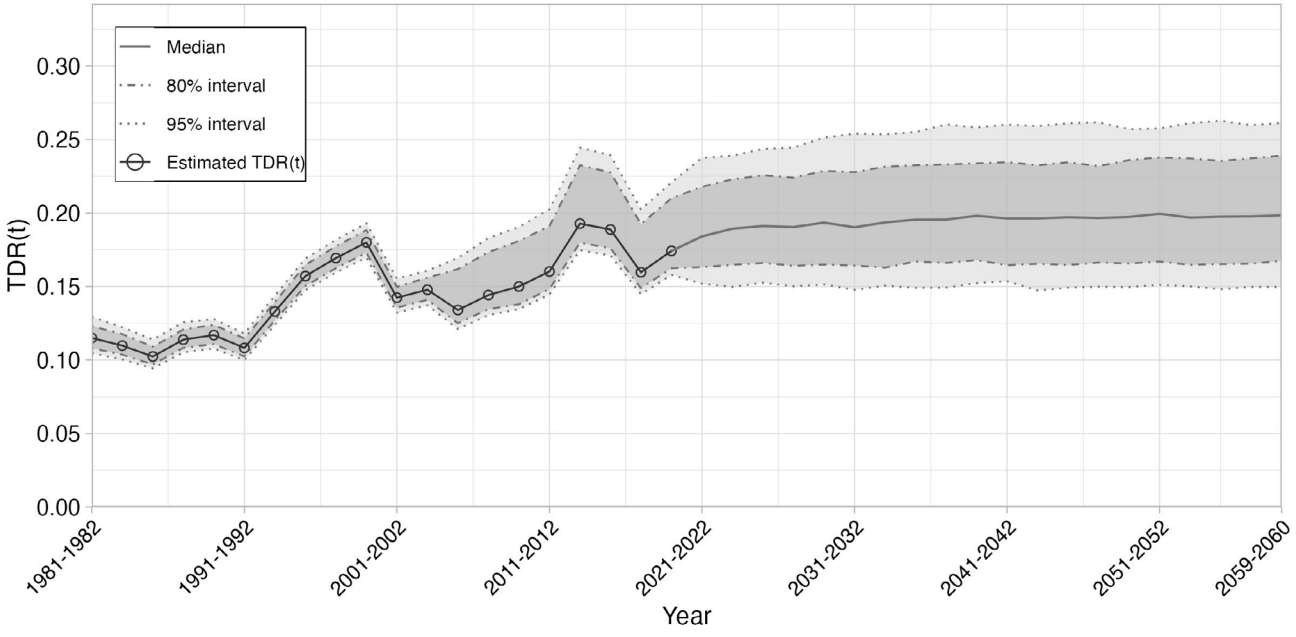



**Figure 4.** Estimates of total divorce rate (TDR[t]) for 1980–2020 and the probabilistically projected TDR(t) from the Bayesian AR1 model with U80(II) of TDR(t) expert judgments for probabilistic household and living arrangement projections for 2021–2060 in Indonesia

## 4. Conclusion

In this study, we estimated time series of TMR(t) and TDR(t) over the past four decades using statistics from Singapore and survey datasets from Indonesia. To examine the accuracy of the estimates, we compared direct calculations with estimates obtained using the Bayesian AR1 model. We found that if the statistics of sex- and age-specific numbers of newly married persons and newly divorced persons, and sex- and age-specific total numbers of persons in each of the years are available, it is better to use the statistics, instead of survey data, and the Bayesian model to estimate the time series of TMR(t) and TDR(t). We recommend that countries collect statistics on sex- and age-specific numbers of newly married and newly divorced persons, and on sex- and age-specific total numbers of persons, all of which constitute large sample sizes, to estimate the time series of TMR(t) and TDR(t) using the Bayesian AR1 model.

We conducted probabilistic projections of TMR(t) and TDR(t) for 2021–2060 as summary measures of marriages and divorces for PHPs, based on Bayesian estimates of the time series of TMR(t) and TDR(t) in Singapore and Indonesia. These works are crucial for PHPs because changes in households and living arrangements in future years largely depend on the projected summary measures of TMR(t) and TDR(t), as well as the probabilistically projected TFR(t) and e0(s,t) released by the UNPD.

We also recognize that this study has some limitations. For example, we did not use the observed/estimated differences between the U80 and median of TMR(t) over the past decades to verify whether the probabilistically projected differences between the U80 and median of TMR(t) for future decades would be excessively wide without expert judgments.

In addition to the research presented in this article, we have made substantial progress in our ongoing international collaborative project on PHP research (Li *et al.*, 2025; Zeng *et al.*, 2024). Nonetheless, more research is required for our PHP study. First, in addition to our recently published research on optimized random combinations of TFR(t) and e0(s,t) for PPPs (Li *et al.*, 2025), we need to employ the optimized random combinations of the probabilistically projected TMR(t), TDR(t), TFR(t), and e0(s,t) for 2021–2060 for PHPs. Second, we need to continue developing new methods and the user-friendly software (ProFamy-PHPs) so that researchers, including us, can conduct PHPs relatively easily using conventionally available demographic rates for Singapore, Indonesia, and other countries.

Overall, the methods and findings presented in this study provide a foundation for advancing PHPs and underscore the importance of continued methodological development, improved demographic data, and user-friendly software to facilitate PHPs in Singapore, Indonesia, and other countries.

## Acknowledgments

The authors appreciate Associate Prof. Junni Zhang for her advice and comments on the applications of the Bayesian AR1 model to estimate and probabilistically project TMR(t) and TDR(t).

## Funding

This study was funded by the International Collaborative Research Program of the Ministry of Finance and the Ministry of Foreign Affairs of China, and the Ministry of Education of Singapore (grant number MOE-T2EP40222-0002). The study funders provided financial support for the scientific research but had no role in the writing of the paper, interpretation of the results, and submission for consideration of publication.

## Conflict of interest

The authors declare that there are no potential conflicts of financial or non-financial interests relevant to this work.

## Author contributions

*Conceptualization:* Minhui Liu, Yi Sun, Qiushi Feng, Zhenglian Wang, Yi Zeng
*Formal analysis:* Minhui Liu, Yi Sun, Kenneth Land, Yi Zeng
*Investigation:* Kenneth Land, Yi Zeng
*Methodology:* Zhenglian Wang, Kenneth Land, Yi Zeng
*Supervision:* Zhenglian Wang, Yi Zeng
*Writing–original draft:* Minhui Liu, Yi Sun, Yi Zeng
*Writing–review & editing:* Minhui Liu, Yi Sun, Qiushi Feng, Zhenglian Wang, Ying Lu, Zhuoru Ma, Wei Tang, Yan Mo, Zuqi Cai, Evi Nurvidya Arifin, Aris Ananta, Yi Zeng

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

The data produced in this study are available from the corresponding authors upon reasonable request.

## References

Alkema, L., Raftery, A. E., Gerland, P., Clark, S. J., Pelletier, F., Buettner, T., & Heilig, G. K. (2011). Probabilistic projections of the total fertility rate for all countries. *Demography, 48*(3), 815–839.

https://doi.org/10.1007/s13524-011-0040-5

Bradbury, M., Peterson, M. N., & Liu, J. (2014). Long-term dynamics of household size and their environmental implications. *Population and Environment, 36*(1), 73–84.

https://doi.org/10.1007/s11111-014-0203-6

Dreyer, K., Steventon, A., Fisher, R., & Deeny, S. R. (2018). The association between living alone and health care utilisation in older adults: A retrospective cohort study of electronic health records from a London general practice. *BMC Geriatrics, 18*, 269.

https://doi.org/10.1186/s12877-018-0939-4

Feng, Q., Wang, Z., Gu, D., & Zeng, Y. (2011). Household vehicle consumption forecasts in the United States, 2000 to 2025. *International Journal of Market Research, 53*(5), 593–618.

https://doi.org/10.2501/IJMR-53-5-593-618

Feng, Q., Wang, Z., Tang, W., Mo, Y., Lu, Y., Cai, Z., & Zeng, Y. (2024). *Usefulness, illustrative applications and methodology of DemoRates R packages: A user-friendly R program of data preparation for household and living arrangement projections using the ProFamy method/software and for other demographic analyses (Version 3.0)* [Software documentation]. http://www.profamy.com.cn/#/download

Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B. K., Chunn, J. L., Lalic, N., Bay, G., Buettner, T., Heilig, G. K., & Wilmoth, J. (2014). World population stabilization unlikely this century. *Science, 346*(6206), 234–237.

https://doi.org/10.1126/science.1257469

Grundy, E. (2001). Living arrangements and the health of older persons in developed countries. In United Nations (Ed.), *Living arrangements of older persons: Critical issues and policy responses* (Population Bulletin of the United Nations, Special Issue Nos. 42/43, pp. 311–329). United Nations. https://digitallibrary.un.org/record/464936

Gu, D., Feng, Q., Wang, Z., & Zeng, Y. (2015). *Recommendation to consider the crucial impacts of changes in smaller household size and its structure on sustainable development goals* [Scientific brief]. United Nations Sustainable Development Knowledge Platform. https://sdgs.un.org/documents/brief-gsdr-2015-recommendation-consider-t-20857

Keilman, N. (2003). Biodiversity: The threat of small households. *Nature, 421*(6922), 489–490.

https://doi.org/10.1038/421489a

Li, M., Zhu, S., Wang, Z., Feng, Q., Zhang, J., Chao, F., Tang, W., George, L. K., Grundy, E., Murphy, M., Lutz, M., Dobra, A., Land, K. C., & Zeng, Y. (2025). Optimized random-combinations of total fertility rates and life expectancies at birth for probabilistic population projections. *Population Research and Policy Review, 44*, 7.

https://doi.org/10.1007/s11113-024-09926-y

Mazzuco, S., Meggiolaro, S., Ongaro, F., & Toffolutti, V. (2017). Living arrangement and cognitive decline among older people in Europe. *Ageing & Society, 37*(6), 1111–1133.

https://doi.org/10.1017/S0144686X16000374

Prskawetz, A., Jiang, L., & O'Neill, B. C. (2004). Demographic composition and projections of car use in Austria. *Vienna Yearbook of Population Research, 1*(2004), 175–202.

https://doi.org/10.1553/populationyearbook2004s175

Raftery, A. E., Chunn, J. L., Gerland, P., & Ševčíková, H. (2013). Bayesian probabilistic projections of life expectancy for all countries. *Demography, 50*(3), 777–801.

https://doi.org/10.1007/s13524-012-0193-x

Smith, S. K., Rayer, S., & Smith, E. A. (2008). Aging and disability: Implications for the housing industry and housing policy in the United States. *Journal of the American Planning Association, 74*(3), 289–306.

https://doi.org/10.1080/01944360802197132

Smith, S. K., Rayer, S., Smith, E. A., Wang, Z., & Zeng, Y. (2012). Population aging, disability, and housing accessibility: Implications for sub-national areas in the United States. *Housing Studies, 27*(2), 252–266.

https://doi.org/10.1080/02673037.2012.649468

Wang, Z., Feng, Q., Mo, Y., Tang, W., Lu, Y., Cai, Z., & Zeng, Y. (2026). *User guide of DemoRates: A user-friendly R program of data preparation for household and living arrangement projections using the ProFamy extended method/software and for other demographic analyses (Version 3.0)* [User manual]. http://www.profamy.com.cn/#/download

Yang, G., & Zhang, L. (2023). Relationship between aging population, birth rate, and disposable income per capita in the context of COVID-19. *PLoS ONE, 18*(8), e0289781.

https://doi.org/10.1371/journal.pone.0289781

Zeng, Y., Chen, H., Wang, Z., & Land, K. C. (2015). Implications of changes in households and living arrangements on future home-based care costs for disabled elders in China. *Journal of Aging and Health, 27*(3), 519–550.

https://doi.org/10.1177/0898264314552690

Zeng, Y., Land, K. C., Gu, D., & Wang, Z. (2014). *Household and living arrangement projections: The extended cohort-component method and applications to the U.S. and China*. Springer.

https://doi.org/10.1007/978-90-481-8906-9

Zeng, Y., Wang, Z., Feng, Q., Gu, D., Zhang, J., Tang, W., & Land,

K. (2024). Extend the ProFamy cohort-component method to conduct probabilistic households and living arrangement projections. *China Population and Development Studies*, 8(4), 378–403.

https://doi.org/10.1007/s42379-024-00171-6

Zeng, Y., Yang, H., Wang, Z., & Li, L. (2021). Impacts of family household dynamics on residential energy demands in Hebei Province of China. *Genus, 77*, 35.

https://doi.org/10.1186/s41118-021-00148-0