A Summary Note on Household and Living Arrangement Projections for Informed Decision-Making

-- Background materials for "International Training Workshop on Household and Living Arrangement Projections Using the ProFamy Method/software",
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(Prepared by the ProFamy Research Group)

In this summary note, we first briefly review the significant utility of and the main types of methods for household projections; we then summarize the basic ideas, assessments and applications of the ProFamy extended cohort-component method for household and living arrangement projections. Finally, we present our recommendations to strengthen household and living arrangement projections for informed decision-making.

Significant Utility of Household and Living Arrangement Projections for Informed Decision-Making

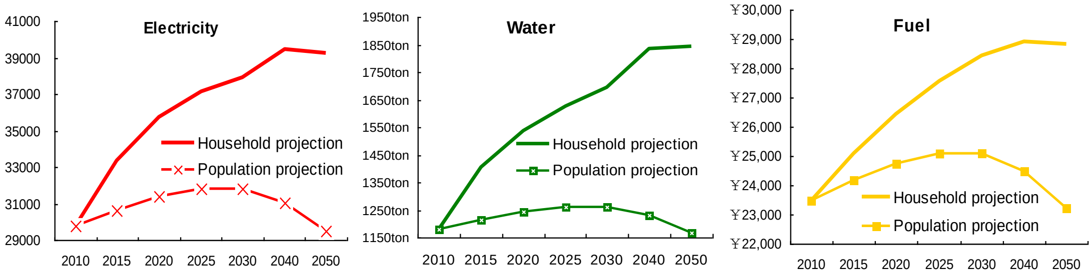
Household and living arrangement projections are useful in socioeconomic and welfare planning. For example, several welfare programs in the Europe and the United States restrict eligibility to single-parent (especially single-mother) households (Maldonado & Nieuwenhuis 2015). As a result, projecting the needs and costs of such programs depends heavily upon projections of the numbers, types, and sizes of single-parent households and children living in these households in the future (Moffitt 2000; Casey & Maldonado 2012).

Past research has established that, in addition to disability status, households and living arrangements are the major determinants of the amounts, types and use of long-term care for the elderly (Freedman, 1996; FIFARS 2010; Li et al., 2013; Francesca et al., 2011). Clearly, projections of households and living arrangements that include elderly's marital/union statuses and co-residence with children are significantly useful to face the challenges of rapid population aging in the decades to come in almost all countries in the world.

Compared with growth of the population of individuals, changes in numbers, sizes and structures of households are more important in analyses on energy-related consumption, human impacts on the environment, and sustainable development (Lutz and Prinz, 1994; Mackellar et al., 1995; Keilman 2003; Ryszawaka-Grzeszczak 2010; Knight and Rosa, 2012; Bradbury et al., 2014). This is because energy-related commodities such as water, electricity, gas and vehicles are often purchased and consumed by households rather than individuals. In the United States, for instance, household vehicles account for 68% of all energy consumed by road vehicles (UN 2007); in the Republic of Korea, the household sector was responsible for about 52% of the national energy consumption in 1980-2000 (Park & Heo 2007). Air pollution, both indoors and outdoors, is closely related to household energy consumption, especially in developing countries where clean fuels are not widely available (IEA 2004).

Changing demographic factors (including higher divorce rates, more migrations, and the vanishing social norms that prescribe co-residence of old parents and adult children) contribute to smaller household size, and continuously and quickly increasing numbers of households all over the world (Gu et al., 2015). Consequently, it would seriously underestimate future years' energy consumption and mislead the policy makers, if the energy-use forecasting is based on population growth, which has slowed down greatly and will become negative soon in many countries. For example, Figure 1 shows that the projection based on population changes seriously under-estimates the future residential energy demand in the Hebei province of China. This is because population growth is very slow now and will become negative around 2035, but the number of households which truly determines home-based energy demands will continue to substantially increase in the next four decades. Clearly, conducting household projections by types and sizes is crucially important in forecasting energy demands and strategic planning of environmental protections, and considering population changes only would seriously under-estimate future energy demands and mislead policy makers (Keilman 2003; Liu et al., 2003; Cohen et al., 2010; UNEP, 2011; Bradbury et al., 2014).

Figure 1. Comparisons of the energy demand forecasting between projections based on household changes and population changes, Hebei province of China, 2010-2050



Source: Zeng et al. (2017).

Business market analyses of various home-based goods and services heavily rely on household and living arrangement projections. An obvious example is that planning for housing needs and estate market studies depend on projected numbers, types, and sizes of households in future years. The demand for banking/financing, consumer durables such as appliances, furniture and vehicles are also determined by projected changes in household size and structure (e.g., Myers et al., 2002; Prskawetz et al., 2004).

Since the late 1990s, more researchers and policymakers have demanded household projections at sub-national levels such as provinces (or states), counties and cities, and other small areas (Smith et al., 2001; Rao 2003; Zeng, Land et al., 2013; Feng, Choi et al., 2018). Household and living arrangement projections at sub-national and county/city levels are useful for distributing government funds, allocating various types of resources, planning the development of infrastructure and public facilities, market research, production planning for household-related goods and services, and decisions on the expansion or reduction of local businesses (Smith et al. 2001; Swanson and Pol 2009; Yamagata, Murakami and Seya 2015).

A Brief Review of the Major Types of Methods for Household Projections

Demographers conduct household projections based primarily on three major types of methods: headship-rate, microsimulation, and macrosimulation (Willekens 2010), which will be briefly reviewed here. Microsimulation models simulate life course events and keep detailed records of demographic status transitions for each individual of the sample population (Wachter 1987; Ruggles 1993; Wolf 1988; Hammel et al., 1981; 1991; Hammel 2005). Macrosimulation models deal with individuals grouped by specified attributes (e.g. with the same race, sex, age, and marital status) and the calculations proceed iteratively, group-by-group and time-period-by-time-period. A prominent example of the macrosimulation model is the

LIPRO two-sex multistate model that projects numbers of individuals by age, sex, and family or household position (Van Imhoff and Keilman 1991, 1992; Keilman, 2018: 8). The data needed to run LIPRO model consist of numbers of individuals by household types and living arrangements in the reference year and rates or probabilities of transitions between household positions by age and sex, collected in surveys, censuses and population (Van Imhoff & Keilman 1992; Keilman 1988, 2018). Note that the LIPRO model cannot directly link changes in household positions and living arrangements to demographic rates and it is therefore difficult to identify the impacts of marriage/union formation and dissolution, fertility, mortality, migration on changes in household structure. The LIPRO model has been used by Statistics Netherlands for their official household forecasts, by The Office of National Statistics of England and Wales for their marital status projections, and in several other countries (Keilman, 2018).

Comparisons between microsimulation and macrosimulation approaches for household projections can be found in the literature (e.g., Van Imhoff 1999; Van Imhoff & Post 1998; Keilman, 2018). The choice between a micro or macro model depends on the complexity of the user's task. For detailed analyses of behavioral patterns and complex family kinship relationships, a microsimulation approach may be preferable. For relatively straightforward demographic and household projections based on commonly available data for the purposes of policy analyses, market trends studies, and socioeconomic planning, especially projections used by non-experts, a macrosimulation approach may well be satisfactory.

Headship-rate is computed by dividing the number of persons who are heads (or householders) of households by the total number of persons of the same age and sex. The numbers of households in future years are projected by extrapolating the headship-rates. Household projections at the national and sub-national levels by statistical offices and market analysts mostly employ the traditional headship-rate method (or occasionally use its extension such as the propensity method). However, the headship-rate method suffers several serious shortcomings and has been criticized widely by demographers for about three decades (Bell & Cooper 1990; Budlender 2003; Christiansen and Keilman 2013; Wilson 2013; Berard-Chagnon 2015). Many demographers' criticisms of the headship-rate method can be summarized into four main points. First, the designation of a household head is a vague, ill-defined, and arbitrary choice that is not easy to model, making projections difficult (Murphy 1991; Mason and Racelis 1992). Second, no direct link exists between headship rates and demographic rates. This makes it impossible to incorporate projected or assumed changes in marriage, divorce, fertility, leaving home, migration, and deaths, which are the main drivers of household changes (Mason and Racelis 1992; Spicer et al. 1992). Third, headship rates cannot handle the consistency issues between marital/union couples and between parents and children (Keilman, 2018). Fourth, the information on households produced by headship-rate projections is very limited and inadequate for detailed planning and analysis (Bell and Cooper 1990; Wilson, 2013). The propensity method, which is the extension of the headship-rate, avoids the first drawback but it still suffers the other three drawbacks of the headship-rate method (Wilson 2013).

A Summary of ProFamy Extended Cohort-Component Method and its Input Data

Benefiting from methodological advances in multistate demography (Schoen 1988; Land & Rogers 1982; Willekens et al., 1982; Rogers 1975), Bongaarts (1987) innovatively developed a nuclear-family-status life table model. Zeng (1986; 1988; 1991) extended Bongaarts's nuclear-family-status life table model into a general-family-status life table model that includes both nuclear and three-generation family households. Based on Bongaarts's and Zeng's one-sex life table models, Zeng, Vaupel, and Wang (1997, 1998) initially proposed and Zeng, Land, Wang and Gu (2006, 2013) further developed the ProFamy model, which is a two-sex multistate cohort-component method that projects numbers of individuals by sex, age and statuses of marriage/union, numbers of co-residing children and parents, and derives household types/sizes from these projected individuals' statuses. The ProFamy model projects simultaneously the households of various types and sizes (ref. Table 2 in Zeng, Land et al., 2006), and sex, age and living arrangements distributions of all individual members of the population under study.

Both the ProFamy model LIPRO model apply the harmonic mean (Keilman, 1985) to ensure consistencies between the two sexes and between children and parents. More specifically, the numbers of new marriages and cohabiting union formations each year among males are ensured to equal those among females, and numbers of children who leave (or return to) the parental homes each year are ensured to be equal to the corresponding numbers of parents who experience the changes in the number of co-residing children (Zeng, Vaupel and Wang, 1997, 1998).

As commented by Willekens (2010:11), a major strength of ProFamy model is that the family and household dynamics are derived from demographic events, and consequently, it requires conventional demographic data that are readily available from ordinary surveys, population registers, vital statistics and censuses (see Table 1). Because its reliance on demographic rates, ProFamy provides a tool to quantitatively assess the effects of demographic changes in marriages/unions, divorces, fertility, mortality, migrations, etc., on family household and living arrangement dynamics (Willekens, 2010).

Note that the needed sex-age-specific net rates of leaving the parental home and the summary measures (e)~(j) listed in section (3) of Table 1 will be estimated by the ProFamy software using the commonly available census micro file (or population register data) (see (a) of section (1) in Table 1). In fact, as demonstrated in Table 1, in addition to the basic data for standard population projections, the major work of data preparation for household and living arrangement projections using the ProFamy extended cohort-component method/software is to estimate the age-parity-specific o/e rates of marital and non-marital fertility and the sex-age-specific o/e rates of marriage/union formation and dissolution, which will be discussed in more details later in this note.

As Keyfitz (1972) pointed out, demographic projections based on trend extrapolation of each age-sex-specific rate could result in an excessive concession to flexibility and readily produce erratic results. Accordingly, analysts should use the fixed sex-age-specific standard schedules (section (2) of Table 1) and concentrate on projecting future changing demographic summary parameters (section (2) of Table 1) in population, household and living arrangement projections. Numerous studies have demonstrated that the fixed sex-age-specific standard schedules and a few changing summary parameters offer an efficient and realistic approach for demographic projections (Brass 1974; Coale et al., 1983; Booth 1984; Paget and Timaeus 1994; Zeng et al., 1994). The theoretical foundation of this practice is that the changing demographic summary parameters are crucial to determine dynamics in level and age pattern of the age-specific rates which affect the projections. At the same time, the projection results typically are not highly sensitive to the fixed sex-age-specific standard schedules. Thus, the national sex-age-specific standard schedules can be readily employed for household and living arrangement projections at the sub-national and county/city levels using the ProFamy method/software, as empirically tested in various studies (Smith et al., 2012; Zeng, Land et al., 2013; 2014; Feng, Choi, 2018), or even be used for projections or estimations in other countries with similar demographic patterns, as corroborated in Zeng et al. (2000).

Table 1. Data needs to project households and living arrangements using the ProFamy extended cohort-component method, with a comparison to standard population projections

Contents of the needed data for the projections	ProFamy household projection	Standard population projection
(1) Baseline population of starting year of projection at national or sub-national level		
(a) A census micro sample or population register or an exceptionally large survey data file with only a few needed demographic variables, including sex, age, marital/union status, relationship to the householder, and whether living in a private or institutional household; (b) Published 100% census tabulations of age-sex-specific (and marital status-specific if possible) distributions of the entire population, and aggregated numbers of households.	√ (& a few more var. from census data)	√
(2) Sex-age-specific standard schedules at the national level (can be used for projections at sub-national and county/city levels)		
(a) Sex-age-(and marital-status if possible)-specific mortality rates;	√	√
(b) Sex-age-specific rates of international immigration and emigration, or sex-age-specific rates of international net-migration;	√	√
(c) Sex-age-specific rates of domestic in-migration and out-migration if the projections are for the sub-national regions;	√	√
(d) Age-specific fertility rates; (e) Age-parity-specific o/e rates of marital and non-marital fertility; (f) Sex-age-specific o/e rates of marriage/union formation and dissolution;	√ √ √	√
(g) Sex-age-specific net rates of leaving the parental home, estimated based on two adjacent census micro data files and the intra-cohort iterative method (Coale1984; 1985; Stupp 1988; Zeng, Coale et al. 1994), using the ProFamy software.	√	
(3) Demographic summary parameters for the nation or sub-national regions or counties in the baseline and selected future projection years		
(a) Total Fertility Rates (TFR) by parity; (b) Sex-specific life expectancies at birth; (c) Sex-specific general rates of migration; (d) Sex-specific mean ages at first marriage and mean age at births;	√ √ √ √	√ √ √
The summary measures (e)~(j) listed below for the baseline year will be automatically estimated by ProFamy software using the census (or population register) micro data file (see section (1)), users will decide whether they keep constant or change in future years: (e) General rates of marriage and divorce (need total # of marriages and divorces at the baseline year of the projection); (f) General rates of cohabitation union formation and dissolution; (g) Proportion of those aged 45-49 who do not live with parents; (h) Sex-age-specific proportion of elderly living with child(ren); (i) Household size-specific average number of other relatives (than spouse/partner, parents and children) and non-relatives living in the same household; (j) Sex-age-specific proportion of persons living in group quarters (collective households).	√ (estimated by ProFamy software using the census or population register micro data)	

Notes: The data categories of race or rural/urban are optional based on the actual demographic situation and data availability of the country or region or county/city under study. If the categories of race or rural/urban are adopted in the application, all data listed in this table will need to be race-specific or rural/urban-specific.

Assessments and Applications of the ProFamy Extended Cohort-component Method

Assessments validated the accuracy of projections using the ProFamy model for the United States and China from 1990 to 2000, namely, the forecast errors, measured by discrepancies between the projected values and the 2000 census observations, are reasonably small (Zeng, Land et al., 2006; Zeng et al., 2008). The test comparisons of the ProFamy projections from 1990 to 2000 with census counts in 2000 for each of the 50 U.S. states and DC showed that 63.0, 17.4, 12.9, and 6.7 percent of the absolute percentage errors were <3.0%, 3.0-4.99%, 5.0-9.99% and ≧ 10.0%, respectively, among 306 pairs of comparisons of the main indices of household projections between forecasts and the census observations (Zeng, Land et al., 2013). Similar assessments for each of the 31 Chinese provinces show that the ProFamy method/software works well. Tests of projections of households and living arrangements in 2000-2010 and comparing the results with the 2010 census counts for the six counties of Southern California validated the applications of ProFamy approach at county/city level (Feng, Choi et al., 2018). Another assessment compares average forecast errors between the ProFamy approach and the classic headship-rate method, by projecting the number-of-bedrooms-specific housing demands from 1990 to 2000 and then comparing them with census counts in 2000 for each of the U.S. 50 states and DC. The results demonstrate that, as compared to the ProFamy approach, the headship-rate method produces much more serious forecast errors, because it projects household types only but not by sizes (Zeng, Land et al., 2013).

The ProFamy model and the user-friendly free software have been used to generate: U.S. household and living arrangement projections by race (Jiang and O'Neill, 2007); implications of changes in U.S. households and living arrangements for the housing industry and policy-making (Smith et al., 2008); U.S. household projections and home-based energy consumption and future carbon emissions (Dalton et al., 2008; O'Neill and Chen 2002; O'Neill and Jiang 2007); household automobile consumption in the United States (Feng et al., 2011) and Austria (Prskawetz et al., 2004); fertility policy analyses, retirement ages and elderly care needs/costs studies in China (Zeng, 2007, 2011; Zeng et al., 2008; Zeng et al., 2013; 2014; Feng et al., 2018); German household and living arrangement projections (Hullen 2000; 2003); household and living arrangement projections in South Korea (Kye 2014), Brazil (Tirza 2017) and Mexico (Landy 2017). The ProFamy model/software has also been used to produce household projections at sub-national and county/city levels, including socioeconomic planning and housing demand analyses, in the United States, Germany, Brazil, mainland and the Taiwan province of China (e.g., Jiang and Kuijsten 1999a, 1999b; Yang and Zeng 2000; Hullen 2001; Smith et al., 2012; Zeng, Land et al., 2013; Zeng, Li et al., 2013; Tirza, 2017; Feng, Choi et al., 2018). A notable example is that the local governmental office employed ProFamy method/software, the U.S. national race-sex-age-specific standard schedules and the demographic summary parameters at the county level to successfully project households and living arrangements for six counties in Southern California since 2009, with projections renewed every two years. The six counties' governments have effectively used these detailed biennial projections for their socio-economic planning, budget allocations, and policy analyses on housing, traffic, energy consumption, elderly care and other home-base social services (Feng, Choi et al., 2018).

We would like to indicate that similar to all other simulation/projection models, ProFamy is a simplification of reality - it builds on model assumptions that were described and discussed in previous publications (Zeng, Vaupel, Wang 1997, 1998; Zeng, Land et al, 2006, 2013) but not detailed here due to space constraint. Limitations of the ProFamy extended cohort component model/software for household and living arrangement projections remain; thus, further strengthened research is needed (Zeng, Land, 2014: 330-332), such as those recommended below. The ProFamy method, including user-friendly and free software, have been further developed with support of the "China National Health Safeguard Information System," which is hosted at China Population and Development Research Center and Digit China Health.

Recommendations to Strengthen Household and Living Arrangement Projections for Informed Decision-Making

(1) Estimate the sex-age-specific standard schedules of the demographic rates

As reviewed earlier, it is now time to replace the widely-criticized headship-rate by a method that considers how household structures are produced by demographic events of marriage/union, fertility, migration and mortality in the life course. As demonstrated in Table 1, in addition to the same basic input data as the standard population projections require, the additionally needed sex-age-specific net rates of leaving the parental home and the summary measures (e)~(j) listed in section (3) of Table 1 are estimated by the ProFamy software using the census micro data (or population register data). Thus, the main task of data preparation to use ProFamy extended cohort-component method/software for household and living arrangement projections is to estimate the sex-age-specific standard schedules of the occurrence/exposure (o/e) rates of marriage/union formation and dissolutions and the age-parity- specific o/e rates of marital and non-marital fertility. Note that lack of these o/e rates of sex-age-specific standard schedules in many countries is the main barrier of broader applications of detailed and useful projections of households and living arrangements. However, as shown in the technical note in the Appendix of this note, these needed o/e rates of sex-age-specific standard schedules can in fact be relatively easily estimated, using event history analysis (Allison, 1995) and standard statistical software, based on fertility and marriage histories data collected in the ordinary fertility/family surveys in most countries (Zeng, Morgen et al. 2012: 214-215).

We recommend that demographers and statistical offices may take the lead to estimate the sex-age-specific standard schedules of o/e rates of marriage/union formation and dissolution, and age-parity-specific o/e rates of marital and non-marital fertility, based on mostly available marriage/union and fertility history data in demographic surveys or population registers. Using the sex-age-specific standard schedules at the national level estimated by the researchers themselves or someone else and projected or assumed summary parameters in the future years, researchers and statistical offices can conveniently perform the forecasts of households and living arrangements at national, sub-national and county/city levels through employing the user-friendly & free ProFamy software (www.profamy.com.cn). Clearly, this action would effectively strengthen household and living arrangement projections for informed decision making, and also to enhance other types of multistate macro- and micro models for family and life course analyses.

(2) Research on living arrangements of children and single-parent (especially single mother)

One could use the ProFamy method/software to address research questions such as: how many children will live in single-parent households, and how many teenage and adult single mothers will have to care for their 1, 2, 3 or more children with no spouse or partner present in the future years? Applications to address these research questions, which are overlooked so far, are practically feasible using the ProFamy method/software, as it already includes children's status of co-residence with two or one parent(s), and adults' statuses of marital/union and number of co-residing children.

(3) Strengthen analyses and projections on family households, elderly living arrangements, caregivers and home-based care needs/costs for elders who

have cognitive impairments and are disabled in daily living

Populations are aging, societies are greying quickly, and the age-specific prevalence of cognitive impairments and disability in daily living will increase sharply for older persons in almost all countries around the world. It is imperative to conduct analyses and projections on family households, elderly living arrangements, caregivers and home-based care needs/costs for elders who have cognitive impairments (including dementia and Alzheimer's disease) and are disabled in daily living; and the ProFamy extended cohort/component method/software can make useful contributions to these topics (Zeng, Chen et al. 2013; Zeng, Land et al. 2014: 167-188). It also will be useful to extend the ProFamy model/software for addressing interesting research questions on, in the future years, how many elderly will have 0, 1, 2, 3 or more surviving adult children, and how many young and middle-age adults will have to take care of surviving old parent(s) plus 0, 1, 2, 3 or more young kids, namely, the so-called "over-load" middle-generation (Zeng, Land et al., 2014: 330).

(4) Household and home-based energy demands forecasting for sustainable development planning

As discussed earlier, it would seriously underestimate future years' energy demands and mislead policy makers, if energy-use forecasting is based on population growth, which has slowed down greatly and will soon become negative in many countries. We recommend conducting household types/sizes and home-based energy demand forecasts, which are crucially important for strategic planning of energy use, environment protection and sustainable development (Keilman 2003; UNEP 2011; Bradbury et al., 2014).

(5) Probabilistic household and living arrangement projections

While probabilistic household and living arrangement projections are needed to address future uncertainties (Bijsk et al., 2015), they are much more complicated than probabilistic population projections (Alho and Keilman 2010; Christiansen and Keilman, 2013). The ProFamy extended cohort-component model/software, using fixed sex-age-specific standard schedules of the demographic rates and a few changing summary parameters, may provide a modeling framework and tool for research on probabilistic household and living arrangement projections, such as following the cohort-component book-keeping methods developed by Alho and Spencer (2005) and the pioneering approach of probabilistic household projection described in Christiansen and Keilman (2013).

(6) Combine microsimulation and macrosimulation models

Note that ProFamy and other macrosimulation models for household and living arrangement projections (such as LIPRO) do not have the possibility to link parents in a given age group to children of a certain age (Keilman, 2018: 13), and future research on the MicMac model (Willekens 2009) to combine microsimulation and macrosimulation (such as LIPRO and ProFamy) may make very useful contributions.

(The user-friendly & free ProFamy software can be downloaded from our Website: www.profamy.com.cn).

Appendix: A Two-step Procedure to Estimate the Sex-age-specific Standard Schedules of Sex-age-specific o/e Rates of Marriage/union Formation and Dissolutions and Age-parity-specific o/e Rates of Marital and Non-marital Fertility

As reviewed earlier in this note, the race (or rural/urban)-sex-age-specific occurrence/exposure (o/e) rates of marriage/union formation and dissolutions and the age-parity-specific o/e rates of marital and non-marital fertility are crucially important for the household and living arrangement projections. But directly computed race (or rural/urban)-sex-age-specific schedules of the o/e rates (defined as number of demographic events that occurred in the age interval divided by the number of person-years at risk of experiencing the event) may not be reliable, because of small sub-sample sizes for some ages cross-classified by race (or rural/urban), marital/union and parity statuses in the survey datasets. Note that classic multivariate regression models, which complete the regression in “one-step” without first calculating the baseline 5-year-age-sex-specific o/e rates of the model schedule for all other covariates combined, are powerful in explanatory analysis of associations with the socio-economic and demographic covariates. When the primary purpose is, however, to estimate the age-specific schedules/trajectories and propensities of the occurrence of the events rather than explanatory analysis, the classic multivariate regression “one-step” approach may not be ideal. This is because the estimates of the age covariate coefficients in the “one-step” regression model may not accurately represent the age trajectory, unless the age trajectory follows precisely linear or log-linear or another kind of analytical distribution and all sources of individual-level variations are explained by the covariates that enter the regression, which are very unlikely (Land, Guralnik, and Blazer 1994: 304).

We have empirically tested the “one-step” approach of the multivariate regression model to directly estimate the sex-age-covariate-status-specific o/e rates, without first estimating the 5-year-age-specific o/e rates of the model schedule. The results are out of an empirically plausible range for some age groups. Even after correcting the logic errors by introducing some constraints to the regression, the estimates are still unreasonable. Thus, we apply a “two-step” approach, which was proposed based on careful investigations and empirical tests (Zeng, Land et al., 2006; 2013; 2014: 171, 186), to estimate the single-year-age-sex-covariates status-specific o/e rates. We present below the two-step procedure for estimating the race (or rural/urban)-age-parity-marital/union status-specific o/e rates as an example. The two-step procedure illustrated by this example can be readily applied to estimate the race (or rural/urban)-sex-age-specific o/e rates of marriage/union formation and dissolutions.

Step one: Directly calculate the baseline 5-year-age-parity-specific o/e rates of the fertility model schedule with all of the other covariates of race (or rural/urban) and marital/union statuses combined, denoted as $p^b(x)$ (where b is parity, x is 5-year-age group), based on fertility event history data from the demographic survey (or population register). We may define parity index b=1, 2, 3+ (or 4+ or 5+), depending on the fertility level in the population under study. To have enough numbers of births by parity and women with different ages, race (or rural/urban) and marital/union statuses who are at risk of giving the parity-specific births from the survey, one needs to merge the retrospective event history data of past 10 years (or at least 5 years).

Step two: Estimate the 5-year-age-parity-race (or rural/urban)-marital/union status-specific o/e rates of fertility, using the event history analysis method (Allison, 1995; 2014) and standard statistical software, based on fertility and marriage history data collected in the demographic surveys or population registers.

(1) For each of the parities, we employ the Cox proportional hazard regression model as follows for the event history analysis (Lagakos, 1981; Fox, 2002):

$$h^b(t|X^b, R^b, M^b) = h_0^b(t) \times \exp[\sum_i \alpha_i^b X_i^b + \sum_j \beta_j^b R_j^b + \sum_k \gamma_k^b M_k^b] \qquad (1)$$

Where, h^b_0 (t) is the baseline hazard; $h^b(t|X^b,R^b,M^b)$ is the age-parity-specific fertility hazard rate at T=t for women with covariates X^b_i, R^b_j and M^b_k; X^b_i represents 5-year age groups from age 15 to age 49 for women who are at risk of giving births of parity b, i=1, 2, 3,…,7, referring to ages 15-19, 20-24, 25-29,…, 45-49. R^b_j represents race groups, j = 1, 2, 3, 4, referring to White and non-Hispanic, Black and non-Hispanic, Hispanic, Asian/Others and non-Hispanic, respectively, for the U.S. applications. For the other applications, one may have 3, 2 or 1 race group(s); or j = 1, 2, referring to rural/urban residence. M^b_k represents marital/union statuses, k = 1, 2, 3, 4, 5, 6, 7, referring to Never married and not-cohabiting, Never married and cohabiting, Married, Divorced and not-cohabiting, Divorced and cohabiting, Widowed and not-cohabiting, Widowed and cohabiting, respectively, for the U.S applications. One may combine three cohabiting statuses with different marital statuses into one status of “cohabiting & not-married”, as the differences in fertility levels among the cohabiting statuses are usually very small. One may also identify four marital statuses only (Never-married, Married, Divorced and Widowed), if cohabitation is negligible in the population.

The Cox proportional hazard model expressed in Equ. (1) is based on the assumption that the effects of races (R^b_j) and marital/union statuses (M^b_k) on the age-parity-specific o/e rates of fertility are proportional across different 5-year-age groups, which is usually met in the reality. If the proportionality assumption is not met in an exceptional case, one will need to revise the model into non-proportional hazards model, such as the Cox stratified regression model or an extended Cox model with time-dependent variables (Ata & Sözer, 2007; Babińska et al, 2015). The coefficients of the Cox hazard model are estimated by the standard statistical software such as STATA, SAS, and SPSS, while appropriately handling the possible left truncating and right censoring problems in the retrospective survey data (Guo, 1993; Allison, 2014).

(2) For each of the parities b, we multiply the baseline 5-year-age-parity-specific o/e rates of fertility $p^b(x)$ calculated in Step One by the odds ratios of R^b_j and M^b_k, namely the exponentials of β^b_j and γ^b_j, estimated based on the event history analysis regression model expressed in Equation (1), to get the initially estimated race-marital/union-5-year-age-specific o/e rates of fertility:

$$p^b(X_i^b, R_j^b, M_k^b) = p^b(x) * \exp(\beta_j^b) * \exp(\gamma_k^b) \qquad (2)$$

We need to further adjust the initially estimated $p^b(X^b_i, R^b_j, M^b_k)$ as follows, to ensure that the weighted average of race-marital/union-5-year-age-specific o/e rates of fertility, denoted as $pp^b(X^b_i, R^b_j, M^b_k)$, is equal to the baseline 5-year-age-parity- specific o/e rates of fertility $p^b(x)$ for all other covariates combined calculated in Step One:

$$pp^b(X_i^b, R_j^b, M_k^b) = p^b(X_i^b, R_j^b, M_k^b) * \frac{p^b(x)}{\sum_j \sum_k W^b(X_i^b, R_j^b, M_k^b) * p^b(X_i^b, R_j^b, M_k^b)} \qquad (3)$$

where, $W^b(X^b_i,R^b_j,M^b_k)$ are the weights, which are the proportion of women aged x with the covariates of R^b_j and M^b_k among all women who are aged x and at risk of giving births of parity b ($\sum_j \sum_k W^b(X_i^b, R_j^b, M_k^b) = 1.0$); the weights $W^b(X^b_i,R^b_j,M^b_k)$ are estimated based on the survey data.

(3) We finally interpolate the 5-year-age-race-marital/union-parity-specific o/e rates of fertility into single-year-age-race-marital/union status-specific o/e rates of fertility by the curve-fitting or other interpolating method, which are available in the standard statistical software such as STATA, SAS and SPSS.

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