The reversal of the gender gap in education and relative divorce risks: A matter of alternatives in partner choice?

Model description V4 – September 2017

This document describes the model presented in Grow, Schnor, and Van Bavel (2017), following the ODD+D standard (Müller et al. 2013). The model has been implemented in NetLogo 5.2.0 (Wilensky 1999), but this description is intended to be independent of the specific modelling language used. Auxiliary variables and procedures that were needed to implement the model in NetLogo are therefore described only in the code itself. Wherever possible, our ODD+D description is identical to the description in Grow, Schnor, and Van Bavel (2017).

1 Overview

1.1 Purpose

The model explores a new mechanism that might generate the link between (1) the reversal of the gender gap in educational attainment, (2) changing patterns of assortative mating, and (3) changing patterns of divorce, which has been observed in empirical research.

Over the last few decades, Europe, North America, and many other parts of the world have experienced dramatic changes in the educational attainment of women relative to that of men. Until the 1970s, university education was mostly a domain of males, but participation of females has steadily increased since then. From about the 1990s, women have been surpassing men in terms of participation and success in higher education (Schofer and Meyer 2005). One consequence of this reversal is that longstanding patterns of educational assortative mating have changed. In most marriages, the wife and husband have similar levels of educational attainment (homogamy). But, in the past, if there was a difference in educational attainment, the wife tended to be less educated than the husband (hypergamy). Today, if there is a difference, the wife tends to be more educated than the husband (hypogamy) (Esteve et al. 2012, 2016; Grow and Van Bavel 2015; De Hauw et al. 2017).

Earlier studies have shown that marriages in which the wife was more educated than the husband were less stable, giving rise to the concern that the increasing prevalence of hypogamy might increase the divorce rate (see Schwartz and Han 2014 for a review). However, Schwartz and Han (2014) showed that among recent cohorts in the United States (US), hypogamous marriages no longer exhibit a higher divorce risk than other marriage types. The authors suggested that this convergence might be the result of changing norms and family values. Hypogamy used to be uncommon and violated the norm that a husband should have a higher socioeconomic status than his wife, in line with the male breadwinner family model. In recent years, as women's educational attainment has increased and their market participation has continued to expand, family values have become more egalitarian. This may have rendered hypogamy less non-normative and may have reduced the threat that a more educated spouse posed to a man's male identity.

The model explores a different mechanism that may also lead to a convergence in the divorce risks of hypogamous and hypergamous marriages, without the need to assume that norms and family values change. The mechanism builds on the assumption that educational attainment is an important factor in mate selection and holds that the reversal of the gender gap in education has affected the remarriage opportunities of highly educated men and women, thereby decreasing the divorce risk of hypogamous marriages and increasing the divorce risk of hypergamous marriages over time.

The model is based on the work of Grow and Van Bavel (2015), who studied the link between the reversal of the gender gap in educational attainment and assortative mating for the period 1921–2012 in 12 European countries: Belgium (BE), Denmark (DK), Finland (FI), France (FR), Germany (DE), Greece (GR), Ireland (IE), the Netherlands (NL), Portugal (PT), Spain (ES), Sweden (SE), and the United Kingdom (UK). We have adjusted their model in a number of technical aspects to make the detailed study of divorce possible (see Sect. '3.1 Implementation Details').

1.2 Entities, state variables, and scales

Individuals (i.e., agents) are the focal entities and represent men and women who are looking for a spouse based on certain partner preferences (see details in Sect.s '2.1 Theoretical and empirical principles' and '2.2 Individual decision-making'). Each agent, i, can be described by the following state variables (see Table 1 for an overview): gender, g_i (1 = male or 2 = female); age, a_i (measured in time steps); the highest educational level that they will ever attain, s_i (1 = no education, 2 = primary education, 3 = secondary education, or 4 = tertiary education); earnings prospects, y_i (expressed in five ordered categories); educational enrolment status, r_i (1 = not in the educational system yet, 2 = in primary education, 3 = in secondary education, 4 = in tertiary education, or 5 = finished education); relationship status, l_i (1 = single, 2 = dating, 3 = married, or 4 = divorced); the time they have already been in a relationship with their current partner, c_i (measured in time steps); and the ideal age they prefer in a partner, u_i (expressed in time steps). The exact role that each state variable plays during the simulation process is described in the section '3.4 Submodels'.

Next to agents' state variables, there are a number of run-time settable parameters that govern the overall behaviour of the model (see Table 2 for an overview; these parameters are also called factors/drivers in the ODD+D terminology): the number of agents in the initial population, I; the age at which agents enter the marriage market, A_{marr}; agents' maximal educational attainment, S_{max}; the age at which agents enter/exit a given educational level, $A_{en,r}/A_{ex,r}$; agents' maximal earnings prospects, Y_{max}; the maximal age that agents can reach, A_{max}; the importance that male (m) and female (f) agents attach to the educational attainment, w_s, earnings prospects, w_y, and age, w_a, of prospective partners; the rate at which they become commitment to their current partner, β; the age pressure that they experience during mate search, σ; and the effect that the educational system has on meeting opportunities among agents who are looking for a partner, δ. Table 3, finally, shows the ages at which agents transition between educational levels as they grow older. The exact role that each parameter plays during the simulation process and the substantive meaning of the values shown in Tables 2 and 3 is described in Sect. '3.4 Submodels'.

Variable	Description	Possible states
g_i	Gender	1 = male 2 = female
a_i	Age	Time steps: $\in \{0, 1, \cdots, A_{max}\}$
s_i	Educational attainment	1 = no education 2 = primary education 3 = secondary education 4 = tertiary education
r_i	School enrolment status	1 = not in the educational system yet 2 = in primary education 3 = in secondary education 4 = in tertiary education 5 = finished education
l_i	Relationship status	1 = single 2 = dating 3 = married 4 = divorced
c_i	Duration of current relationship	Time steps: $\in \{0, 1, \cdots, A_{max} - 160\}$
u_i	Ideal age that agent i prefers in a partner	Time steps: $\in \{0, 1, \cdots, A_{max} + 25\}$ (for male agents fixed at 240, for female agents equal to $a_i + 25$)
y_i	Earnings prospects	$\in \{1,2,3,4,5\}$

Table 1 Overview of agents' state variables

Additionally, there are a number of auxiliary variables (`time_steps`, `simulation_year`, and `time_steps_this_year`) that help structuring the simulation flow (see details in Sect. '3.4 Submodels').

Physical space is not explicitly considered. However, the model considers social space, so that the likelihood that two specific agents will interact with each other is affected by the educational system (see details in Sect.s '2.1 Theoretical and empirical principles' and '3.4 Submodels').

1.3 Processes overview and scheduling

Figure 1 provides a flow diagram that details the process scheduling during the simulation. Each box represents a different submodel, which we describe in Sect. '3.4 Submodels'. White boxes pertain to submodels at the agent level; grey boxes pertain to submodels at the global level.

The length of a simulation run is measured in time steps and ten time steps represent one simulation year. The empirical input data that the model employs make it possible to study marriage and divorce decisions under plausible marriage market conditions between 1921–2012. However, each simulation continues until the year 2064, to ensure that differences in the divorce rates between marriages formed in the 1920s and the 2000s are not due to censoring among later marriages.

Parameter	Description	Values used
I	Total number of agents in the initial population	1,000
$A_{en,r}$, $A_{ex,r}$	Age at which agents enter and exit a given educational level r	See Table 3
A_{marr}	Age at which agents enter the marriage market	160
S_{max}	Maximal educational attainment of agents	4
Y_{max}	Maximal earnings prospects of agents	5
A_{max}	Maximal age of agents	1,100
w_s^m, w_s^f	Importance that male and female agents attach to similar education of partners	0.934, 0.385
w_y^m, w_y^f	Importance that male and female agents attach to high earnings prospects of partners	1.025, 1.201
w_a^m, w_a^f	Importance that male and female agents attach to the age of partners	6.887, 14.895
β^m, β^f	Commitment parameter for male and female agents	0.015, 0.015
σ^m, σ^f	Age pressure parameter for male and female agents	0.0015, 0.0030
δ	Structuring effect of the educational system	0.9

Table 2 Overview of run-time settable parameters

Educational level	r	$A_{en,r}$	$A_{ex,r}$
Not in the educational system yet	1	0	60
In primary education	2	60	100
In secondary education	3	100	190
In tertiary education	4	190	240

Table 3 Overview of ages at which agents transit between educational levels

Additionally, each simulation run is preceded by a burn-in phase that aims at generating plausible starting conditions for the simulation year 1921 (see Williams et al. 2016). The length of this phase is equal to 600 time steps (i.e., 60 simulation years) and agents interact during this phase in the same way as they do in the main phase of the simulation. After the burn-in phase has been completed, the value of `simulation_year` is set to 1921 and from then on increases by one after every ten time steps.

At the beginning of each simulation year, agents are added and removed from the model, based on the submodels ‘Fertility’ and ‘Mortality’. Additionally, agents transit to the next stage in their educational career, if appropriate, based on the submodel ‘Update educational enrolment status’. Subsequently, partner search begins and is modelled by the submodels ‘Update search probabilities’, ‘Meeting, dating, and divorce decisions’, and ‘Marriage decisions’, which are

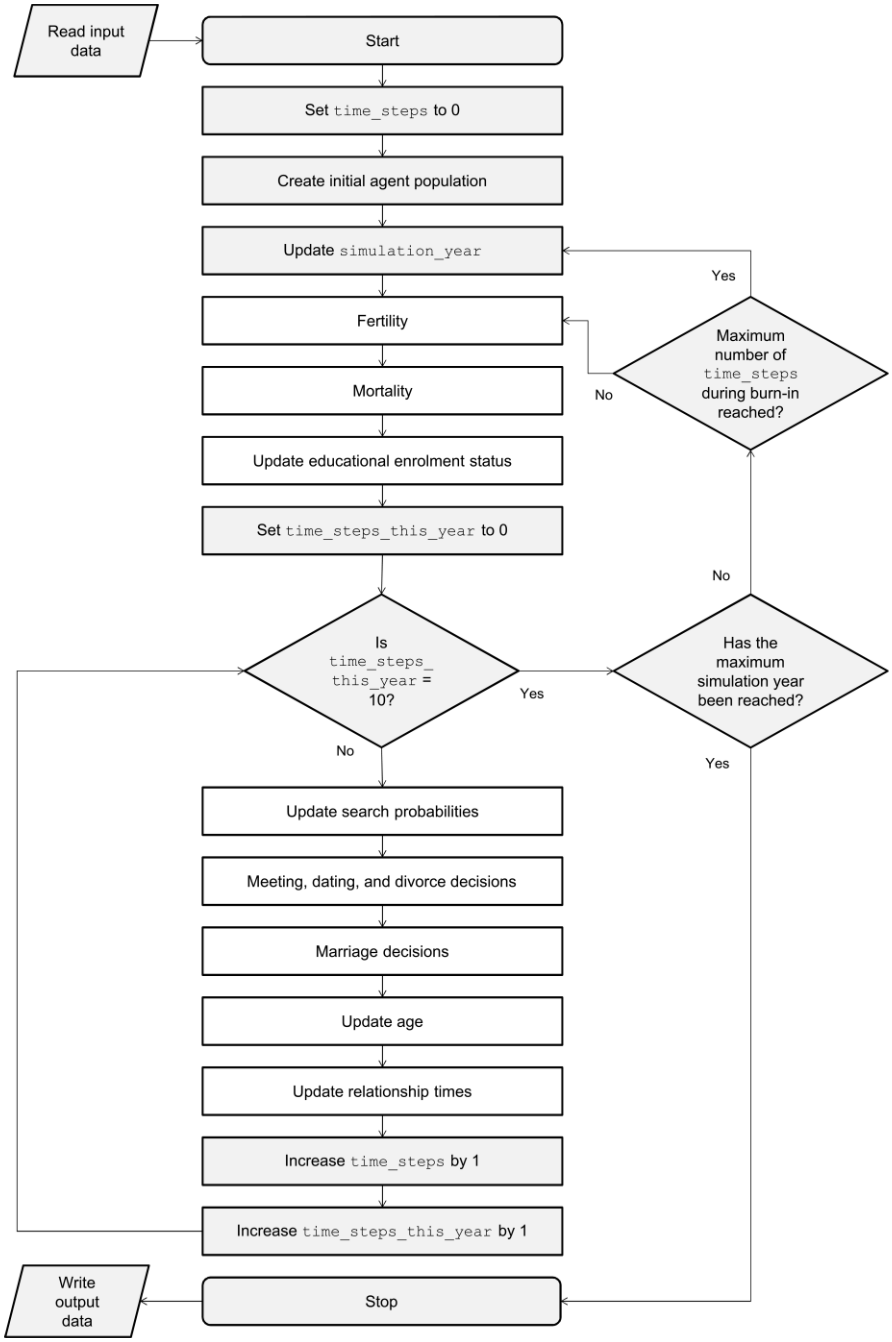

Figure 1 Overview of process scheduling

repeated ten times in every simulation year. At the end of each time step, the submodels 'Update age' and 'Update relationship times' ensure that agents' age and relationships times increase over the course of a simulation year.

Each simulation run ends with recording information about the marriages that have formed during the run.

2 Design concepts

2.1 Theoretical and empirical principles

2.1.1 The central theoretical mechanism

The theoretical mechanism that the model seeks to explore draws on the macrostructural-opportunity perspective on divorce (South et al. 2001). This perspective highlights the availability of spousal alternatives as an important factor in divorce decisions. Research from this perspective builds on two central assumptions. First, individuals tentatively remain on the marriage market even after marriage and potentially leave their partner when they encounter more attractive marital alternatives. Second, the likelihood of people encountering marital alternatives increases if there is an oversupply of opposite-sex members on the marriage market. Together these assumptions imply that the divorce rate increases if the sex ratio on the marriage market is imbalanced (South and Lloyd 1992, 1995; South 1995; South et al. 2001).

The model investigates the implications of the foregoing perspective under the condition that the sex ratio is specified by the level of educational attainment of potential mates. Research has consistently shown that educational attainment is an important dimension in mate selection (e.g., Kalmijn 1998; Lewis and Oppenheimer 2000), and the reversal of the gender gap in education implies a declining ratio of highly educated men to highly educated women. Combined with the assumptions of the macrostructural-opportunity perspective, this can be expected to have implications for divorce risks, by affecting the number of attractive alternatives that people can choose from for repartnering. The likelihood of a highly educated woman who is married to a less educated man encountering an alternative with more education than her partner has substantially decreased over recent decades. Conversely, the likelihood of a highly educated man who is married to a less educated woman encountering a more educated alternative has increased. As a consequence, the divorce risk of hypogamous marriages may have decreased, whereas the divorce risk of hypergamous marriages may have increased.

2.1.2 Core assumptions and principles

The notion of the marriage market holds that individuals “search for partners in a market in which people have preferences for mates but face constrained opportunities” (Schwartz 2013, p. 452). Constrained opportunities, in turn, can affect their aspirations during partner search (England and Farkas 1986; Oppenheimer 1988). The model therefore makes specific assumptions about the preference that govern mate selection and how the constraints of the marriage market affect these preferences.

The model focuses on education as a central factor in mate selection and takes into account that education is related to both economic and cultural resources. Cultural resources include “values and behaviours, such as child-rearing values, political attitudes, cultural literacy, taste in art and music, and styles of speech" (Kalmijn 1994, p. 426). Similarity in such values and behaviours can lead to mutual reinforcement of world views, can generate feelings of social confirmation, and facilitate the organization of joint activities within couples. As a consequence, people often prefer partners with similar cultural resources (DiMaggio and Mohr 1985). Economic resources, such as income and property, produce economic well-being and status. Such resources are typically shared within couples and people therefore tend to prefer partners with high economic resources, as this can improve their own economic well-being and status (Kalmijn 1994).

Education encompasses both economic and cultural aspects. It is commonly assumed to be "the most important determinant of occupational success in industrialized societies [… and] it reflects cultural resources influencing individuals' preference for specific partners" (Blossfeld 2009, p. 514). This link with economic and cultural resources is one reason why education is an important factor in mate selection and can explain why men and women tend to prefer spouses with a similar level of education and prefer more educated spouses over less educated spouses. A spouse with a similar level of education is attractive because of the likely similarity in cultural resources, but a more educated spouse may also be attractive because of the higher economic resources that often come with higher educational attainment. A less educated spouse, by contrast, is less attractive given the lack of similarity in cultural resources and the lack of economic resources.

In line with earlier research (Kalmijn 1994), the model approximates people's cultural resources by their educational level and their economic resources by their life-time earnings prospects. Thus, agents feel attracted to opposite-sex members who are similar to them in educational attainment, but they also feel attracted to those who have high earnings prospects. Education and earnings prospects are positively correlated, but this correlation differs between men and women. Furthermore, the model also considers age to be an important determinant of mate attractiveness, next to cultural and economic resources. It assumes that men feel most attracted to women who are in their mid-20s (other things being equal), whereas women feel most attracted to men who are slightly older than themselves (England and McClintock 2009; Skopek et al. 2011).

Agents enter the marriage market and start looking for a spouse when they have reached a marriageable age (at 16 years). The search takes the form of meetings with opposite-sex members who are drawn randomly from the marriage market. The model considers that the educational system tends to structure the daily actives and meeting opportunities of adolescents and young adults. In particular, while in education, people have an increased likelihood to interact with those who are currently attending at the same educational level (Mare 1991). Thus, agents progress through the educational system and, as long they are in education, they are more likely to meet somebody who is currently attending at the same educational level, rather than somebody who is attending at a different level or has left education already.

Whenever two agents meet, they both need to decide whether they want to start dating and to leave/divorce possible current partners for this; if two agents have started dating, they both may decide to marry. These decisions are modelled probabilistically, based on the assumptions of maximizing and risk averse behaviour (see details in Sect.s '2.2 Individual decision-making' and

‘3.4 Submodels’). That is, agents become more likely to accept each other for dating and marriage, the more attractive they perceive each other to be. Yet, at the same time agents become less selective as they grow older. This is based on the notion that even though men and women have specific preferences for the characteristics of their mates, they cannot know exactly if and when they will find the ideal partner. The less favourable the marriage market conditions are, the more difficult it becomes to find an attractive partner. The more time people have already invested in the search process, the riskier it becomes to pass up on potential spouses, given that the pool of available alternatives shrinks and the own market value often decreases with age. This is particularly the case among women, given that they are judged more by youthful appearance than men (England and McClintock 2009). In response to this increasing risk, individuals tend to lower their aspirations and become willing to accept partners who are ‘less than perfect’ as they grow older (Lichter 1990). In the model, this means that younger agents are more selective in choosing a mate than older agents. This decrease in selectiveness with age is stronger among women, given that also their attractiveness for men tends to decrease more with age.

Congruent with the macrostructural-opportunity perspective, the model assumes that agents remain on the marriage market, even after they have started dating or have married. They therefore continue to meet potential alternatives, but the likelihood that his happens decreases with the length of their current relation. This is consistent with the observation that the number of contacts that men and women have with opposite-sex members tends to decrease with relationship length (Rapp et al. 2015). Yet, if agents encounter an alternative that is more attractive than their current partner, there is a chance that they leave/divorce their current partner and repartner with the alternative.

2.2 Individual decision-making

The model considers individual decisions in three areas. First, it models individuals’ decisions to actively look for a (new) partner. Second, it models dating and divorce decisions. Third, it models marriage decisions.

2.2.1 Partner search

Agents who have reached a marriageable age (at 16 years) need to decide at the beginning of each time step whether they want to actively look for a (new) partner. Single and divorced agents always actively look for a partner, whereas agents who have a partner become less likely to do so the longer they are already in their current relation.

2.2.2 Dating and divorce decisions

Agents base mating decisions on multiple mate characteristics for which they have certain preferences. Their goal is to find a partner who is close to their ideals in terms of educational attainment, earnings prospects, and age, while at the same time minimizing the risk of remaining single. Agents who have no partner need to decide whether they want to start dating a given alternative they meet. For agents who have a partner, this is connected to the decision of leaving (if they are dating) or divorcing (if they are married) their current partner.

2.2.3 Marriage decisions

Agents who are currently dating need to decide at the end of every time step whether they want to propose marriage to their partner/whether they want to accept a standing proposal from their partner. They become more willing to do so the higher the mate value of their partner, the older they are, and the longer they are already together with their partner.

2.3 Learning

Agents do not learn.

2.4 Individual sensing

Agents are always informed about the states of all their own state variables. Agents who are looking for a partner are also informed about the educational enrolment status of the available alternatives. Agents who have to assess the attractiveness of a prospective partner are additionally informed about the educational attainment, earnings prospects, and age of the prospective partner. If they currently have a partner, they are also informed about the states of these three characteristics in their partner and they always know whether their partner has already proposed marriage.

2.5 Individual prediction

Agents do not predict.

2.6 Interaction

Agents randomly meet each other during their mate search. In each meeting, they assess each other's attractiveness and make dating and divorce decisions. Once agents have started dating, they can propose marriage to their partner/accept a marriage proposal from their partner. If both agree to marry, they actually get married.

2.7 Collectives

There are no collectives in the model.

2.8 Heterogeneity

Male and female agents differ in the age pressure they experience when looking for a partner, so that $\sigma^m \neq \sigma^f$. Furthermore, male and female agents differ in the importance that they attach to each of the three mate characteristics (educational attainment, earnings prospects, and age) that determine the attractiveness of potential partners. That is, $w_s^m \neq w_s^f$, $w_y^m \neq w_y^f$, and $w_a^m \neq w_a^f$. Furthermore, male and female agents differ in the ideal age they prefer in a potential partner, so that $u^m \neq u^f$. We discuss the exact parameterization in see Sect. '3.4 Submodels'. Additionally, male and female agents differ in their mortality rates, as defined by empirical input data (see details in Sect. '3.3 Input data'). Finally, only female agents can give birth to new agents, according to probabilities defined by empirical input data (see details in Sect. ‘3.3 Input data’), but this has no impact on their behaviour.

2.9 Stochasticity

Several submodels involve randomness. In each of these instances, a random number is drawn from an even distribution in the range 0–1. This number is then compared with an endogenously or exogenously determined probability. Such comparisons happen in the following processes:

1) The initialization of the first set of agents involves randomness in terms of assigning them their educational attainment, earnings prospects, and age. The exact probabilities are derived from empirical data, as described in Sect.s ‘3.2 Initialization’ and ‘3.3 Input data’.
2) Fertility involves randomness, so that at the beginning of each simulation year there is a chance that female agents give birth to a child. The exact probabilities are derived from empirical data, as described in Sect. ‘3.3 Input data’.
3) The initialization of new (born) agents involves randomness in terms of assigning them their gender, educational attainment, and earnings prospects. The exact probabilities are derived from empirical data, as described in Sect. ‘3.3 Input data’.
4) Mortality involves randomness, so that at the beginning of each simulation year there is a chance that agents die. The exact probabilities are derived from empirical data, as described in Sect. ‘3.3 Input data’.
5) Meeting, dating, marriage, and divorce decisions involve randomness in several aspects:
    a. Agents are randomly selected for looking for a potential partner, with a probability determined by Eq. (1), as described in Sect. ‘3.4.9 Update search probability’.
    b. If a given agent, i, is selected to actively search for a partner, j, j is selected randomly either from the set of agents who have the same educational enrolment status as i, or the set of agents who a different educational enrolment status than i. The probabilities with which either set is selected are determined according to Eq.s (2a) and (2b), as described in Sect. ‘3.4.10 Meeting, dating, and divorce decisions’. Once the relevant set has been determined, the probability that a specific member j of this set is selected is proportional to the number of agents in the set.
    c. Once the potential partner, j, has been selected, both i and j determine separately whether they want to start dating each other, based on probabilities determined by Eq.s (3) and (4), as described in Sect. ‘3.4.10 Meeting, dating, and divorce decisions’.
    d. For two agents, i and j, who are already dating, there is a chance that they propose marriage to their partner with a probability that is determined by Eq.s (3) and (5), as described in Sect.s ‘3.4.10 Meeting, dating, and divorce decisions’ and ‘3.4.11 Marriage decisions’.

2.10 Observation

At the end of each simulation run, the model collects information about the marriages that have formed during the run. This information includes the year in which the marriage was formed, the age and educational attainment of the spouses at the time of marriage, whether and when the marriage had dissolved, and the dissolution reason (if applicable).

3 Details

3.1 Implementation details

The model code can be obtained from https://www.openabm.org/model/5105. We have adjusted the NetLogo code provided by Grow and Bavel (2015) in two substantive aspects. First, we have introduced ‘marriage records’ as a new entity to facilitate the tracking of marriage histories (see details in the model code itself). Second, we have introduced more realistic procedures for modelling fertility and mortality, to take into account that men and women face different mortality risks as they grow older, which may affect remarriage opportunities. This has the consequence that the size of the agent population can now vary over time. Next to this, we have optimized the code to reduce computation time and we have adjusted the original input data, which is used for assigning agents their educational attainment and earnings prospects, to an annual format (instead of the original five-year interval format); see details in Sect. ‘3.3 Input data’.

3.2 Initialization

Upon initialization, the empirical input data is imported and the initial agent population is created. The size of this population is equal to I and it is created to resemble the population structure of the respective country in the year 1921. To achieve this, the sex ratio of the initial population is fixed at the empirical value observed in 1921 and agents are assigned their age, educational attainment, and earnings prospects probabilistically based on the empirical data for this year (see details in Sect. ‘3.3. Input data’). This implies that the structure of the first agent cohort in a given (simulated) country varies between runs, but always resembles the population structure that has been empirically observed in 1921 in the country under consideration.

Table 2 shows the parameter values that we employed in the main experiments reported in Grow, Schnor, and Van Bavel (2017). This parameterization is based on the calibration experiments reported in Grow and Van Bavel (2015), which aimed at generating patterns of educational assortative mating that are similar to those observed in the 12 countries under consideration (for a detailed description of the meaning of the different parameter values see Sect. ‘3.4 Submodels’). More specifically, in their calibration exercise, Grow and Van Bavel (2015) selected a subsample of five countries (Belgium, France, German, Spain, and Portugal) and conducted simulation experiments in which they systematically varied the models’ parameters to find a parameter combination that minimized the differences between model outcomes and the mating patterns that could be observed for these countries in the European Social Survey (rounds 5 and 6). The mating patterns of interest were the shares of educationally hypergamous, homogamous, and hypogamous marriages, as well as the average age differences within these marriages, among the members of the birth cohorts (1940–1950], (1950–1960], (1960–1970], and (1970–1980]. For more details of the calibration experiments see S1 Appendix in Grow and Van Bavel (2015).

We have adjusted the original parameterization in the following aspects. First, to take into account that divorce happens less often than marriage, we have increased the number of agents from 500 to 1,000, to ensure that we obtained enough observations for our analyses. Second, we have increased the value of A_{max} = 800 to A_{max} = 1,100, to make use of the full age range that is covered by the empirical mortality rates that we have used. Third, because of this change in A_{max}, we have also adjusted the values of w_a^m and w_a^f. These parameters govern in Eq. (3) (see Sect. '3.4 Submodels' for details) the effect that deviations from the ideal age that agents prefer in their partners (u_i) have on the perceived mate value, v_{ij} (representing the attractiveness that i perceives in j), contingent on the value of A_{max}. To account for the larger value of A_{max}, we have multiplied w_a^m and w_a^f by 1,100/800 = 1.375. In this way, we can consider values of a_i > 800, without altering the functional relation between $u_i - a_j$ and v_{ij} for values of $a_i \leq 800$, as defined by Grow and Van Bavel (2015).

To assess whether the adjusted model still generates patterns of assortative mating that are similar to those observed in empirical data, we have selected a random sample of 250 simulation runs per country from the main simulation experiment that we report in Grow, Schnor, and Van Bavel (2017), and compared the simulated marriage patterns with the empirically observed shares of hypergamous, homogamous, and hypogamous marriages among the members of the birth cohorts (1940–1950], (1950–1960], (1960–1970], and (1970–1980], as reported in Grow and Van Bavel (2015). Figure 2 shows the result of this comparison. It suggests that the modified model generates outcomes whose fit with the empirical data is very similar to that of the original model used in Grow and Van Bavel (2015).

3.3 Input data

The model employs empirical input data from several sources. First, the model draws on data from the International Institute for Applied Systems Analysis/Vienna Institute for Demography (IIASA/VID) (Lutz et al. 2007; KC et al. 2010) for probabilistically assigning agents their educational attainment at the moment they are born. The IIASA/VID data provide reconstructions (from 1970 until 2000) and projections (from 2005 until 2050) of the distribution of educational attainment in five-year intervals for five-year age groups for large number of countries. This data

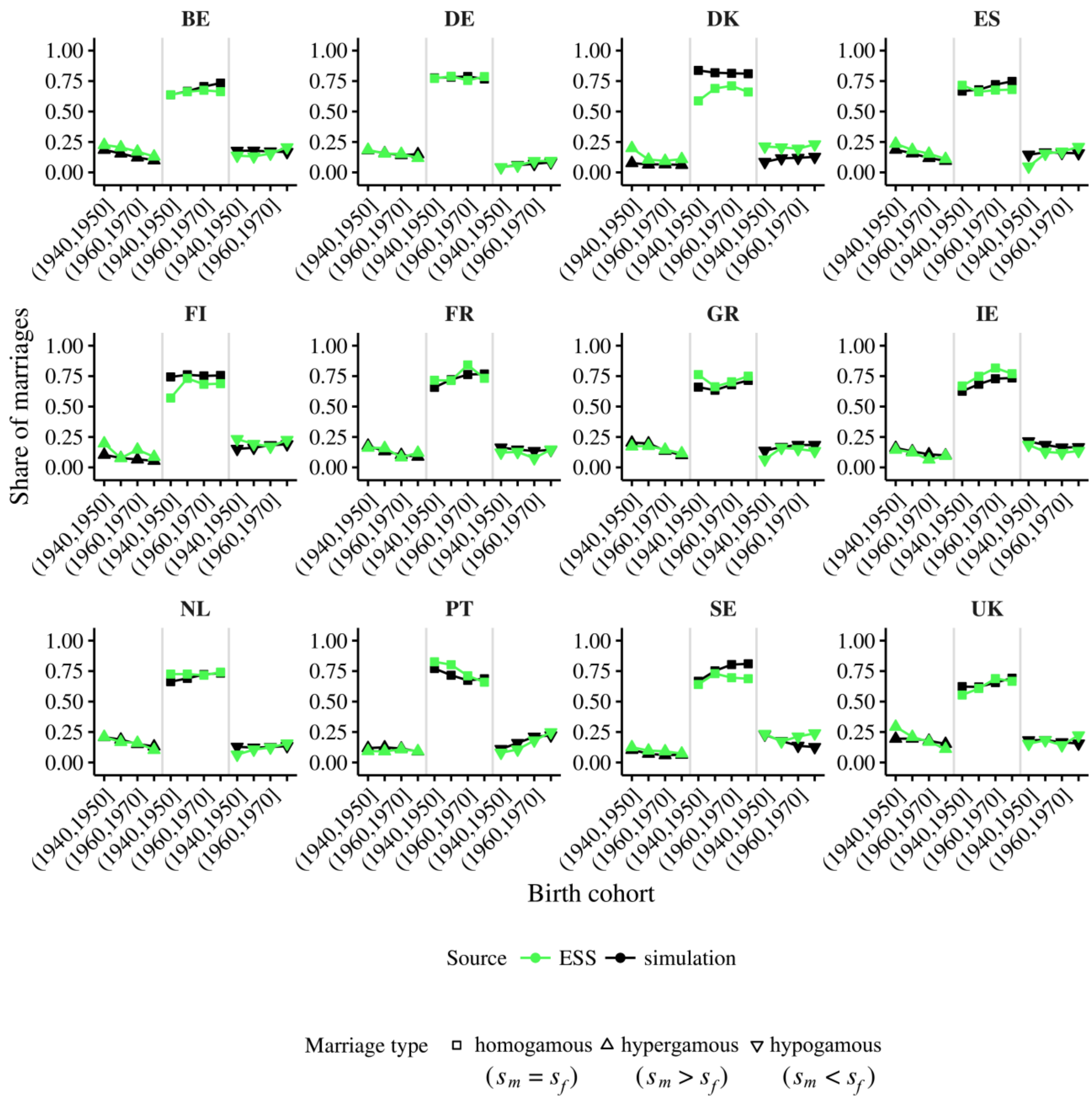

Figure 2 Comparison of model outcomes with empirical shares of marriages among the members of four birth cohorts per country, as observed in 2010 and 2012 in the European Social Survey (ESS, rounds 5 and 6)

Note: The simulation results are based on 250 independent simulation runs per country are based on the calibrated simulation model. The results based on the European Social Survey (ESS) come from Grow and Van Bavel (2015).

make it possible to approximate the share of men and women born in the period 1921–2012 who have attained one of four educational levels by the age of 30–34 (Grow and Van Bavel 2015). The model uses these shares as probabilities for assigning agents their educational attainment, contingent on their gender and year of birth. In the original model, this input data was provided in five-year intervals, given that also the IIASA/VID data is provided in five-year intervals. The current version of the model makes use of annual data, which we obtained by linearly interpolating the data for the missing years. More specifically, we assigned the original education data of each five-year interval to the year in the centre of the respective interval and linearly interpolated the data between these years. We employed this annualization to align the IIASA/VID input data with the annual data on fertility and mortality rates described later. For agents who are born in the burn-in phase, or who are born in simulation years after 2012, we used the input data for 1921 and 2012 respectively.

Second, the model draws on data from the European Community Household Panel (ECHP)[1] for assigning agents their earnings prospects, after they have been assigned their educational attainment. The ECHP provides information about the gender, age, educational attainment, and earnings of respondents in a number of European countries collected between 1994–2001. This makes it possible to generate realistic probabilities for agents to belong to one of five earnings prospects categories (ordered from low to high), given their gender, year of birth, and educational attainment (Grow and Van Bavel 2015). Similar to the IIASA/VID data, the original input data related to income is based on five-year intervals. We have converted this data to annual data with the same approach that we used to convert the data for educational attainment into annual data.

Third, in each simulation year there is a chance that female agents give birth to new agents, contingent on the country, simulation year, and the age of the agent. The underlying probabilities are derived from the annual age-specific fertility rates (ASFRs) provided in the Human Fertility Database (HMD).[2] Data was available for DE, DK, ES, FI, FR, IE, NL, PT, SE, and UK. In the cases of BE and GR, we had to rely on data provided by the Human Fertility Collection (HFC).[3] For this, we used ASFRs based on the age that individuals had reached during the year (ARDY). In the case of Belgium, this data was available for most years from Statistics Belgium (STAT); where possible, we substituted this data with information from the European Demographic Observatory (ODE). In the case of Greece, data was only available from the ODE. The model considers birth between ages 12–55 years, but some of the data sources only covered the ages 14–50 years. In these cases, we set the fertility rates for lower/higher ages to zero. Furthermore, the main simulation period covers the years 1921–2012 in all countries. Whenever the period that the empirical ASFRs covered was shorter than this period, we used the data from the closest available year for substituting

[1] Eurostat, the European Commission and the national statistical offices collecting the data have no responsibility for the results and conclusions which were drawn in this paper on the basis of the European Community Household Panel data.

[2] Human Fertility Database. Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria). Available at www.humanfertility.org (data downloaded on 24.04.2016).

[3] Human Fertility Collection. Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria). Available at www.fertilitydata.org (data downloaded on 24.04.2016).

Country	Years covered	Age range	Source
	ASFR		
BE	1940–1945	14–50	HFC (STAT)
	1952–1960	14–50	HFC (ODE)
	1961–2010	14–50	HFC (STAT)
DE	1956-2012	-12–55+	HFD
DK	1916–2014	-12–55+	HFD
ES	1922–2012	-12–55+	HFD
FI	1939–2012	-12–55+	HFD
FR	1946–2013	-12–55+	HFD
GR	1960-2009	14–50	HFC (ODE)
IE	1955–2009	-12–50+	HFD
NL	1950–2012	-12–55+	HFD
PT	1940–2012	-12–55+	HFD
SE	1891–2014	-12–55+	HFD
UK	1938–2013 (England and Wales)	-12–55+	HFD
	1945–2013 (Scotland)	-12–55+	HFD
	1974–2013 (Northern Ireland)	-12–55+	HFD
	Mortality/Population structure		
BE	1841–2012/1841–2013	0–110+	HMD
DE	1956–2013/1956–2014 (East Germany)	0–110+	HMD
	1956–2013/1956–2014 (West Germany)	0–110+	HMD
DK	1835–2014/1835–2015	0–110+	HMD
ES	1908–2014/1908–2015	0–110+	HMD
FI	1878–2012/1878–2013	0–110+	HMD
FR	1816–2013/1816–2014	0–110+	HMD
GR	1981–2013/1981–2014	0–110+	HMD
IE	1950–2014/1950–2015	0–110+	HMD
NL	1850–2012/1850–2013	0–110+	HMD
PT	1940–2012/1940–2013	0–110+	HMD
SE	1751–2014/1751–2015	0–110+	HMD
UK	1922–2013/1922–2014	0–110+	HMD

HFD = Human Fertility Database; HFC = Human Fertility Collection; HMD = Human Mortality Database; STAT = Statistics Belgium; ODE = European Demographic Observatory

Table 4 Overview of data sources for age-specific fertility and mortality rates

the missing years. In case there were gaps in the data, we linearly interpolated ASFRs based on the data in the years just before and after the gap. Table 4 provides an overview of the years covered by the different data sources.

Fourth, in each year there is a chance that agents die. The underlying probabilities are derived from the annual age-specific mortality rates provided in the Human Mortality Database (HMD),[4] that provides death probabilities for the ages 0–110+. Whenever the period that the empirical mortality rates covered was shorter than the simulation period, we used data from the year closed to the years for which data was missing.

Fifth, the sex ratio and the gender-specific age distribution of the first agent cohort is modelled after the population structure obtained from the HMD. Wherever possible, we used data from the year 1921. In case this data was not available, we used data from the year closest to 1921.

In the cases of DE and UK, the data for certain periods was only available for separate territories/political entities (e.g., in Germany, data was available separately for Western and Eastern Germany prior to 1990). For these periods, we combined the rates as the average across the different territories/political entities, weighted by population size.

3.4 Submodels

3.4.1 Read input data

Reads and imports the empirical data described in Sect. '3.3 Input Data'.

3.4.2 Set `time_steps` to 0

Creates a variable `time_steps` that stores information about the number of simulation steps that have been conducted in the current simulation run. This variable starts with the value zero.

3.4.3 Create initial agent population

In a first step, the initial set of agents is created. The size of this set is equal to I and the number of male and female agents is determined by the empirically observed country-specific sex ratio for the year 1921, as described in Sect. '3.3 Input Data'. In case the sex ratio implies non-integer numbers of male and female agents, these numbers are rounded to the closest integer.

In a second step, the newly created agents are randomly assigned their educational attainment given their gender, based on the data described in Sect. '3.3 Input Data' for the year 1921.

In a third step, agents are randomly assigned their earnings prospects, contingent on their gender and educational attainment, based on the data described in Sect. '3.3 Input Data' for the year 1921.

In a fourth step, agents are randomly assigned their age, contingent on their gender, based on the data described in Sect. '3.3 Input Data' for the year 1921.

Finally, agents are assigned their educational enrolment status, given their educational attainment, their age, and the threshold values defined in Table 3.

[4] Human Mortality Database. University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany). Available at www.mortality.org or www.humanmortality.de (data downloaded on 24.04.2016).

3.4.4 Update `simulation_year`

If the value of the variable `time_steps` is zero, a new variable `simulation_year` is created that contains information about the current simulation year. As long the value of `time_steps` is smaller than the number of time steps that are to be conducted in the burn-in phase, the value of `simulation_year` remains zero. After this, `simulation_year` is set to 1921 and is increased by one after every ten time steps. The length of the burn-in phase is 600 steps, so that there is enough time for the development of relationship patterns that are sufficiently plausible to serve as a starting condition for the main simulation period.

3.4.5 Fertility

At the beginning of each simulation year (also before every ten time steps during the burn-in phase) female agents who are between 12–55 years old are selected one at a time in random order (without replacement) for possibly giving birth to a new agent. The underlying probability is contingent on the simulation year and the age of the agent, as defined by the data described in Sect. '3.3 Input Data'.

Each time an agent gives birth, the newly created agent is randomly assigned its gender. The probability that the selected gender is 'male' ('female') is equal to .512 (1–.512), which is congruent with the empirical fact that in human populations usually 105 males are born per 100 females (Guilmoto 2012). Subsequently, the agent is assigned the age a_i= 0 and is randomly assigned its educational attainment and earnings prospects contingent on the data described in Sect. '3.3 Input Data'.

3.4.6 Mortality

In each simulation year (also before every ten time steps during the burn-in phase) there is a chance that agents die. For this, they are selected one at a time in random order (without replacement) and the probability of death is determined based on the period-, gender-, and age-specific probabilities defined in the data described in Sect. '3.3 Input Data'. Among those agents whose partner dies, the relationship status (l_i) and the relationship time (c_i) are adjusted to reflect their new situation.

3.4.7 Update educational enrolment status

Agents' educational enrolment status is updated contingent on their age and the transition thresholds defined in Table 3. The chosen values are based on typical transition ages across Europe. Every time agents reach the age at which they exit one stage ($A_{ex,r}$) and/or enter the next ($A_{en,r}$), the value of r_i is updated accordingly. Agents leave school once they have finished the level that corresponds with their state on s_i. The only exception from this are agents with s_i = 2 (primary education) who transition from primary to secondary education and leave school at a_i = 160. This takes into account the fact that a minimal number of years in the educational system is usually mandatory for those who participate in education (e.g., adolescents often have to attend secondary school for some years, even if they do not complete this level successfully). Agents with s_i = 3 (secondary education) stay in education until age 19 (a_i =190) and then leave the educational system, whereas agents with s_i = 4 (tertiary education) transition to college/university at this age and stay at this level until age 24 (a_i =240).

3.4.8 Set `time_steps_this_year` to 0

In case the value of `time_steps` is zero, a new variable `time_steps_this_year` is created that contains information about the number of time steps that have already been conducted in the current simulation year. The initial value of this variable is zero and it is increased by one at the end of every time step. The value is set to zero again after every ten time steps.

3.4.9 Update search probability

The model considers two stages of partner search: (a) 'not seeking a spouse'; and (b) 'seeking a spouse'. From the moment agents are born, they are in the stage of not seeking a spouse and they remain in this stage until they reach the age of 16 years. At this point, they enter the marriage market and start looking for a spouse (A_{marr}= 160). This transition is irreversible and agents remain in this stage for the rest of their lives, even after they have married (but their search effort can decrease, as described later), which is line with the assumptions of the macro-structural-opportunity perspective. Furthermore, partner search takes place irrespective of agents' educational enrolment status (that is, agents who are in education and those who have left education already engage in similar search processes).

Agents who are in the stage of seeking a spouse and currently have no partner invest full effort into finding a spouse, whereas agents who already have a partner reduce this effort contingent on the length of their relationship. This is consistent with the observation that the number of contacts that men and women have with opposite-sex members tends to decrease with relationship length (Rapp et al. 2015). The search effort is represented by the probability that agents will actively seek out an opposite-sex member in a given time step. It is determined as

$$Pr(i\ seek) = e^{-(c_i \beta)}. \qquad (1)$$

In Eq. (1), β is a 'commitment parameter' that governs the effect that the length of i's current relationship has on the probability that the agent will try to meet somebody. For single and divorced agents, c_i is always zero and the probability that they will seek out somebody is thus always one. As Table 2 shows, the value of β is positive and is the same for male and female agents, and Eq. (2) therefore implies that an agent's inclination to seek out alternatives to their current partner decreases exponentially with the length of their current relationship and approaches zero after about 25–30 simulation years. This is inspired by the observation that few divorces occur after more than 25–30 years of marriage (see Kulu 2014). Note that $Pr(i\ seek)$ can never become zero; yet, for technical reasons, values between zero and 10^{-324} are considered equal to zero.

3.4.10 Meeting, dating, and divorce decisions

In each time step, agents are selected one at a time in random order (without replacement) to determine whether they actively search for a partner, according to the probability determined by Eq. (1). If it has been determined that agent i actively searches for a partner, j, in the current time step, j is selected randomly from one of two sets of marriage market members: agents who have the same educational enrolment status as i (i.e., $r_i = r_j$), or agents who have a different educational enrolment status (i.e., $r_i \neq r_j$). The probability with which each set is chosen is determined by the 'structuring parameter' δ ($0 \leq \delta \leq 1$), so that

$$Pr(r_i = r_j) = \delta \tag{2a}$$

and

$$Pr(r_i \neq r_j) = 1 - \delta. \tag{2b}$$

The closer the value of δ is to one, the more likely agents are to meet somebody with the same educational enrolment status; conversely the closer the value of δ is to zero, the more likely agents are to meet somebody with a different enrolment status. In both cases, j is randomly selected from all agents in the respective set. As Table 2 shows, the chosen value for δ (0.9) implies that while in education, agents mostly encounter people who are currently attending at the same educational level. Conversely, agents who have left education already are most likely to meet agents who also have left education.

Once a potential partner, j, has been selected, both i and j assess the mate value they perceive in each other. From i's point of view, j's mate value value is denoted as v_{ij}, and from j's point of view, i's mate value is denoted as v_{ji}. It combines information about the attractiveness of j in terms of educational attainment (representing cultural resources), earnings prospects (representing economic resources), and age. Earlier research suggests that low attractiveness in one or more important partner characteristics cannot easily be substituted with high attractiveness in other characteristics (Li et al. 2002; Li and Kenrick 2006). In the literature on multi-criteria decision making, such interdependence between criteria is often expressed by multiplicative exponential weighting functions (introduced by Cobb and Douglas 1928), and the model uses such a function to determine v_{ij}. Its form is

$$v_{ij} = \left(\frac{S_{max} - |s_i - s_j|}{S_{max}}\right)^{w_s} \left(\frac{y_j}{Y_{max}}\right)^{w_y} \left(\frac{A_{max} - |u_i - a_j|}{A_{max}}\right)^{w_a}, \tag{3}$$

where S_{max}, Y_{max}, and A_{max} define the maximal education, earnings prospects, and age that agents can reach and the parameters w_s, w_y, and w_a govern how much agents 'penalize' deviations from their ideals in each dimension. The value of v_{ij} can vary continuously between 0 and 1. The value of v_{ij} comes closer to one, the more similar i and j are in their educational attainment, the higher the earnings prospects of j, and the closer j is to the age that i desires in a partner (u_i). Deviations from these ideals decrease the value of v_{ij}, and this decrease is stronger at higher values of w_s, w_y, and w_a.

Table 2 shows that some of the parameter values that we use in Eq. (3) differ between male (m) and female (f) agents. First, male and female agents differ in the ideal age they desire in partners (u_i). In line with empirical evidence, the preferred age of partners among male agents is 24 years, whereas female agents find partners who are about 2.5 years older than themselves most attractive. Second, male and female agents differ in the weight they attach to each of the three mate characteristics (w_s, w_y, and w_a). The parameterization implies that females penalize deviations from the ideal age more than males. This is in line with the observation that, as men grow older, they tend to marry women who are increasingly younger than themselves, but also increasingly further away from the ideal age of 24 years (implying a higher tolerance), whereas women tend to marry men who are two to three years older, regardless of their own age (implying a lower tolerance) (see England and McClintock 2009). The parameterization also implies that female agents attach relatively more importance to economic resources than to similarity in cultural resources (represented by earnings prospects and educational attainment, respectively). Male agents, by contrast, attach similar importance to both dimensions. This is in line with the notion that in the past, women often had less access to economic resources than men and therefore often attached more importance to the economic potential of their partners (Becker 1981). Evidently, this gap in financial resources has decreased with the increase in women's educational attainment relative to that of men and with the parallel increase in female labour force participation (see England 2010). Also, there is some evidence that differences in men's women's partner preferences have somewhat decreased in recent years (Zentner and Eagly 2015). Yet, a considerable gap often still exists in spouses' incomes to the disadvantage of women (Klesment and Van Bavel 2017) and empirical research suggests that women still tend to attach more importance to economic resources in their partners than men do (e.g., Li and Kenrick 2006; Hitsch et al. 2010).

After i and j have assessed each other's mate value, both need to decide whether they want to start dating the other. For illustration, we focus here on the decision process from i's point of view. If agent i has no partner (i.e., $l_i = 1$ or 4), they perceive any opposite-sex member as a potential spouse and therefore always consider dating j. By contrast, if i is currently dating or married (i.e., $l_i = 2$ or 3), they consider only those j whose mate value is higher than that of their current partner, k. If i encounters such an alternative, there is a chance that they choose to leave (if i is dating) or divorce (if i is married) their current partner. Formally, the probability that i is willing to date j (and to leave or divorce their current partner, k, if they have one), is determined by

$$Pr(i\ willing\ to\ date\ j) = \begin{cases} 1 - e^{-(a_i v_{ij} \sigma)} & \text{if } (l_i = 1 \text{ or } 4) \\ \left(1 - e^{-(a_i v_{ij} \sigma)}\right) e^{-(c_i \beta)} & \text{if } (l_i = 2 \text{ or } 3) \text{ and } v_{ij} > v_{ik}, \\ 0 & \text{if } (l_i = 2 \text{ or } 3) \text{ and } v_{ij} \leq v_{ik} \end{cases} \quad (4)^{5}$$

where σ governs the 'age pressure' that agents experience when looking for a partner as they become older. The first line of Eq. (4) implies that for agents who have no partner, their willingness to start dating j increases with j's mate value and with i's age (assuming that $\sigma > 0$). The second line implies that if agent i has a partner, k, and if the mate value of the alternative, j, is higher than that of k, i's willingness to date j (and to leave k for this) is attenuated by the length of their current relationship with k, as indicated by c_i (assuming that $\beta > 0$). Yet, as the third line indicates, if i has a partner, k, and if the mate value of j is lower than, or equal to, that of k, then i will not consider starting to date j. Finally, two agents only leave or divroce any current partner and start dating each other when both are willing to date. This implies two independent decision processes, in which Eq. (4) is applied separately to i and j.[6]

As Table 2 shows, in these decision processes female agents experience a stronger age pressure (σ) than male agents. This implements the notion that both men and women have access to a smaller pool of alternatives as they grow older, but women suffer an additional penalty owing to men preferring women who are in their mid-twenties, which increases women's pressure to find a partner while young (see England and McClintock 2009).

3.4.11 Marriage decisions

After all dating decisions have been made, agents who are dating are selected one at a time (without replacement) to decide whether to propose to their partner/whether they want to accept an existing proposal from their partner. The longer agents have already been dating their current partner, the more willing they become to marry and therefore to propose marriage to or accept a marriage proposal from their partner. When agent i (or k) proposes marriage to their current partner, k (or i), the proposal remains intact until k (or i) agrees to marry, or until one of them terminates the relationship or dies. They get married at the moment both agree to marry. The probability that agent i proposes to k, or is willing to accept a proposal from k, is calculated as

$$Pr(i\ proposes/accepts\ marriage\ with\ k) = \left(1 - e^{-(a_i v_{ik} \sigma)}\right)\left(1 - e^{-(c_i \beta)}\right). \quad (5)$$

The first term of Eq. (5) holds that agents are more likely to propose marriage to or accept a marriage proposal from their partner, the higher the mate value of their partner (v_{ik}) and the older they are

[5] Note that the distinction between the different equations in the first and second condition is not explicitly made in the model code. Instead, the equation shown in the second condition is applied to agents that meet either condition. The reason is that for agents who have no partner (i.e., to which the first condition would apply) c_i is always zero. This means that for them $e^{-(c_i \beta)}$ is equal to one. Hence, applying the equation in the second condition to them is equivalent to applying the equation in the first condition.

[6] Technically, to save computation time, the decision processes is modelled for i first, and is only modelled for j if i is willing do date j.

(a_i), assuming that there is some age pressure ($\sigma > 0$). This parallels the notion implemented in Eq. (4), that the more attractive an individual finds a given opposite sex member, the less hesitant they are to form a committed relationship, and the notion that the older they are, the less hesitant they will be to form such a relation in general. The second term holds that as the length of the relationship (c_i) increases, i becomes more likely to propose marriage to or accept a proposal from k (assuming that $\beta > 0$). This is achieved by subtracting $e^{-(c_i\beta)}$ (which is exponentially decreasing in c_i if $\beta > 0$) from one. Like Eq. (4), this implements the notion that relationship-specific capital tends to increase with relationship length, which renders outside alternatives less attractive and makes individuals less hesitant to form a permanent bond.

3.4.12 Update age

Agents' age a_i is increased by one at the end of every time step. Given that ten time steps represent one simulation year, this implies that agents age by one year every ten time steps.

3.4.13 Update relationship times

For those agents who are in a relation at the end to a given time step, the value of the relationship time, c_i, is increased by one.

3.4.14 Increase value of `time_steps`

Increases the value of the variable `time_steps` by one.

3.4.15 Increase value of `time_steps_this_year`

Increases the value of the variable `time_steps_this_year` by one.

3.4.16 Write output data

At the end of a simulation run, information about the characteristics of all marriages that have formed during the run is written to an external file for later analysis.

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