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

<u>*Model description V1 – June 2016*</u>

This document describes the model presented in [*reference to be added after review*], following the ODD+D standard (Groeneveld et al. forthcoming; 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.[1] Wherever possible, our ODD+D description builds on the description in [*reference to be added after review*].

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, that has been observed in empirical research.

Over the last decades, Europe, North America, and many other parts of the world have experienced dramatic changes in the educational attainment of women relatively to that of men. Until the 1970s, university education was mostly a male domain, but female participation steadily increased. Since about the 1990s, women excel 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 couples, wife and husband have a similar level 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; De Hauw et al. 2015; Grow and Van Bavel 2015).

Earlier studies have shown that marriages in which the wife is more educated than the husband were less stable, giving rise to the concern that the increasing prevalence of hypogamous unions might lead to higher divorce rates (see Schwartz and Han 2014 for a review). However, Schwartz and Han (2014) showed that in the United States in recent cohorts hypogamous unions no longer exhibit a higher divorce risk than other union types. The authors suggested that this convergence might be the result of changing norms and family values. Hypogamous marriages used to be uncommon and violated the norm that a husband should have a higher socioeconomic status than

[1] For example, the NetLogo code includes ‘relationship links’ and ‘marriages’ as additional entities next to the ‘individuals’ that we described here. These additional entities have no substantive meaning and were only introduced to facilitate the tracking of relations and marriages between individuals in NetLogo.

his wife, in line with the male breadwinner family model. In recent years, as women's educational attainment increased and their market participation continued to expand, family values have become more egalitarian. This may have rendered hypogamous marriages less non-normative and might have reduced the threat that a more educated spouse poses to a man's gender 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 assumes 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), Netherlands (NL), Portugal (PT), Spain (ES), Sweden (SE), and United Kingdom (UK). We have adjusted their model in a number of technical aspects to make the detailed study of divorce decisions possible (see details in 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 it 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), school 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 it is already in a relationship with its current partner c_i (measured in time steps), and the ideal age it prefers in a partner u_i (expressed in time steps). Finally, agents evaluate other agents j in terms of their overall attractiveness as a spouse. We refer to the outcome of this evaluation as the 'mate value' v_{ij} that i perceives in j. 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/exist 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

Variable	Description	Possible states
g_i	Gender	1 = male 2 = female
a_i	Age	Time steps: $\in \{0, 1, \cdots, \infty\}$
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 relation	Time steps: $\in \{0, 1, \cdots, \infty\}$
u_i	Ideal age that agent i prefers in a partner	Time steps: $\in \{0, 1, \cdots, \infty\}$ (for men fixed at 240, for women equal to $a_i + 25$)
y_i	Earnings prospects	$\in \{1,2,3,4,5\}$
v_{ij}	Mate value that agent i perceives in agent j	$0 \leq v_{ij} \leq 1$

Table 1 Overview of agents' state variables

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 education 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 are described in Sect. '3.4 Submodels'.

Additionally, there is 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').

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 effects of the educational system	0.9

Table 2 Overview of run-time settable parameters

Educational level	$\boldsymbol{r}$	$A_{en,r}$	$A_{ex,r}$
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

Physical space is not explicitly considered. However, the model considers social space, so that the likelihood that two specific agents will interact 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 processes that occur at the agent level; grey boxes pertain to processes that occur at the global level.

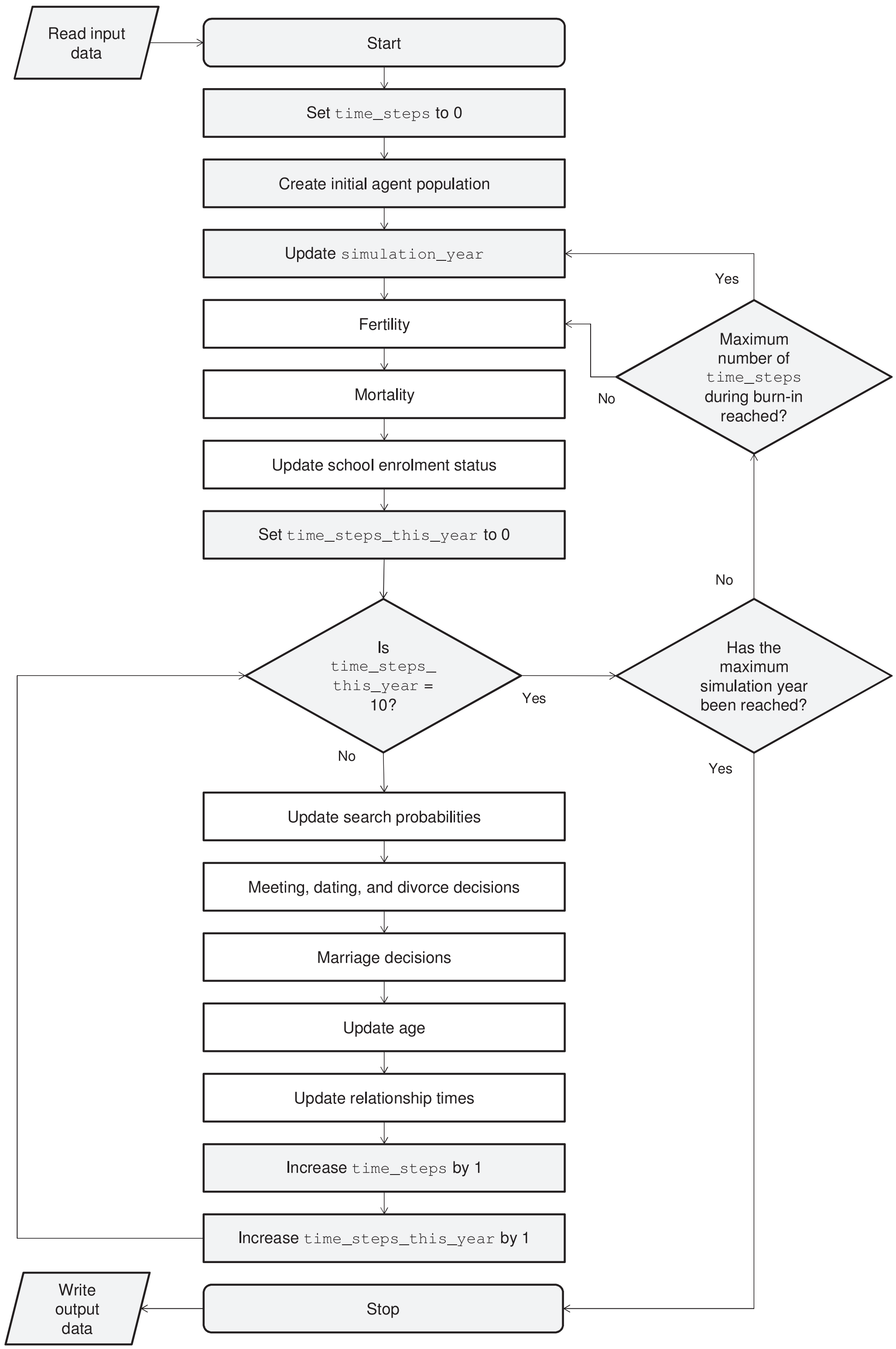

Figure 1 Overview of process scheduling

The length of a simulation run is measured in time steps and 10 time steps represent 1 simulation year. The empirical input data that the model employs makes 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. Additionally, each simulation run is preceded by a burn-in phase that aims at generating realistic starting conditions for the simulation year 1921 (cf. cf. Williams et al. forthcoming). The length of this phase is equal to 600 simulation 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 1 after every 10 simulation steps.

At the beginning of each simulation year, agents are added and removed from the model, based on the processes ‘Fertility’ and ‘Mortality’. Additionally, agents transit to the next stage in their educational career, if appropriate, based on the process ‘Update school enrolment status’. Subsequently, partner search begins and is modelled by the processes ‘Update search probabilites’, ‘Meeting, dating, and divorce decisions’, and ‘Marriage decisions’, which are repeated 10 times in every simulation year. At the end of each time step, the processes ‘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 that people will encounter 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

(Kalmijn 1998; Lewis and Oppenheimer 2000; Hitsch et al. 2010; Skopek, Schulz, and Blossfeld 2011), 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. The likelihood that a highly educated woman married to a less educated man encounters an alternative with more education than her partner has substantially decreased over the last decades. Conversely, the likelihood that a highly educated man married to a less educated woman will encounter a more educated alternative has increased. As a consequence, the divorce risk of hypogamous marriages might have decreased, whereas the divorce risk of hypergamous marriages might have increased.

The use of an agent-based model to study the foregoing mechanism is beneficial because of the potential complexity that derives from the fact that people's divorce decisions are highly interdependent (Chiappori and Weiss 2006). For example, individuals who are single or divorced are more easily available for repartnering than individuals who are married (cf. Stauder 2006). Thus, if the marriage market contains many married individuals, people will be less likely to meet alternatives who are easily available for repartnering than when fewer people are married. The simulation model makes it possible to deal with such complexities.

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 about 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 (Kalmijn 1994; Lewis 2016). Cultural resources encompass "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). Within couples, similarity in such values and behaviours can lead to mutual reinforcement of world views, create feelings of social confirmation, and facilitate the organization of joint activities. People therefore tend to prefer spouses with similar cultural traits (DiMaggio and Mohr 1985). Economic resources, such as income and property, produce economic well-being and status (Kalmijn 1994). Within couples, such resources are typically shared and people therefore tend to prefer partners with high economic resources as this can improve their own economic well-being and status. This relation with different types of resources is one reason why education is an important factor in mate selection and can explain why men and women tend to prefer similar and more educated spouses over less educated spouses. A similar educated spouse is attractive because of the similarity in cultural resources that comes with similarity in education, but a more educated spouse might 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. The model disentangles the economic and the cultural dimension of education and assumes that agents have a desire for high economic resources but also desire similarity in the cultural dimension of education.

In line with earlier research, the model approximates people's cultural resources by their educational level and it approximates their economic resources by their life-time earnings prospects (Kalmijn 1994). Thus, the model assumes that agents feel attracted to opposite-sex members who are similar to them in educational attainment, but they feel also attracted to those who have high earnings prospects. Education and earnings prospects, in turn, are positively correlated, but this correlation differs between men and women. Furthermore, the model also considers age as a fundamental 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 (everything else being the same), whereas women feel most attracted to men who are slightly older than themselves (Eagly et al. 2009; England and McClintock 2009; Skopek, Schmitz, and Blossfeld 2011).

Agents enter the marriage market and start looking for a spouse that matches their preferences as closely as possible once they have reached a marriageable age. The search takes place in the form of meetings with opposite-sex members who are randomly drawn from the marriage market. The model considers that educational tracking tends to increase the likelihood that people with similar educational backgrounds will encounter each other as long as they are in the educational system (Mare 1991; Kalmijn and Flap 2001; Blossfeld 2009). That is, agents progress through the educational system and as long they are in school/at university, they are more likely to meet somebody who is currently attending the same educational level than to meet somebody who is attending a different level or has left school 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 might decide to marry. These decisions are modelled probabilistically, based on the assumption of maximizing and risk aversive behaviour (see details in Sect. 2.2 'Individual decision-making'). That is, agents become more likely to accept each other for dating and marriage the more attractive they perceive each other. 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 decreases with age. This is particularly the case among women, given that they are judged more by youthful appearance than men. 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 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 implements the notion that couples tend to build up relationship-specific capital and commitment that is lost when the relation is terminated; this renders outside alternatives less attractive (Stauder 2006). Yet, if agents encounter an alternative that is more attractive than their current partner in terms of its mate value, 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 need to decide at the beginning of each simulation 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. Earlier research suggests that low attractiveness in important partner characteristics can usually not 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 different evaluation criteria is often expressed by multiplicative exponential weighting functions (Zanakis et al. 1998). The model assumes that education, earnings prospects, and age are central partner characteristics that cannot be substituted and therefore employs multiplicative exponential weighting functions (see details in Sect. 3 'Submodels').

Whenever two agents meet, they need to decide whether they want to start dating. Agents who have no partner perceive any opposite-sex member j as a potential spouse and therefore always consider whether they want to start dating j. Agents who are currently dating or married, by contrast, only consider those opposite-sex members as a potential spouse whose mate value is higher than the mate value of their current partner (i.e. when $v_{ij}^{alternative} > v_{ij}^{partner}$). If they encounter such an alternative, there is a chance that they leave or divorce their current partner (depending on whether they are dating or married) and start dating the alternative.

2.2.3 Marriage decisions

Agents who are currently dating, need to decide at the end of every simulation step whether they want to propose marriage to 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. From the moment agent i (or j) proposes marriage to its partner j (i), the proposal remains intact until j (i) agrees to marry, or until one of them terminates the relationship or dies. They get married at the moment both propose to marry.

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 additionally informed about the school enrolment status of the available alternatives. Agents who have to assess the mate value 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 about whether the 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 mate value and make dating and divorce decisions. Once agents have started dating, they can propose marriage to their partner; at the moment both agents propose, they 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 they attach to each of the three mate characteristics (educational attainment, earnings prospects, and age) that determine the mate value 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, accordingly 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 processes 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, 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 from the set of agents that that have the same as the focal agent or the set of agents with a different school enrolment status than the focal agent. 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. '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, the length of the marriage, whether the marriage had dissolved, and the dissolution reason (if applicable).

3 Details

3.1 Implementation details

The model code can be obtained from [*add link to openabm.org when established*]. We have adjusted the NetLogo code by Grow and Bavel (2015) in two substantive ways. First, we have introduced 'marriages' 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 might affect remarriage opportunities. This has the consequence that the size of the agent population can now vary over time. Next to this, we optimized the code to reduce computation time and we adjusted the original input data used for assigning agents their educational attainment and earnings prospects to an annual format (instead of the original 5-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 empirical data for this year (see details in Sect. '3.3. Input data'). This implies that the structure of the first agent population in a given country varies between runs, but always resembles the structure observed in 1921 in the country under consideration.

Tables 2 and 3 show the parameter values that we employed in the main experiments reported in [*reference to be added after review*]. This parameterization is based on the calibration experiments reported in Grow and Van Bavel (2015), that aimed at generating realistic patterns of educational assortative mating in the 12 countries under consideration (for a detailed description of the meaning of the different parameter values see Sect. '3.4 Submodels'). We adjusted the original parameterization in the following aspects. First, we have increased the size of the initial agent population from 500 to 1,000, to increase the reliability of our results, given that divorce happens less often than marriage. Second, we have increased the value of A_{max} = 800 to A_{max} = 1,100, to make full use of the age range covered by the empirical mortality rates that we use. 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 partners (u_i) have on v_{ij}, 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 1,110/800 = 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).

3.3 Input data

The model employs empirical input data from several sources. First, the model draws on data from the 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 5-year intervals for 5-year age groups for large number of countries. This data make it possible to approximate the share of men and women born in the period 1921–2012[2] who have attained one of four educational levels by the age of 30–34 (see details in Grow and Van Bavel 2015, in particular S1 Appendix). 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 5-year intervals, given that also the IIASA/VID data is provided in 5-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 5-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 below. 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)[3] 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 for 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

[2] Compared to Grow and Van Bavel (2015), we shortened the focal simulation period from 2016 to 2012 to align the period covered by the different data sources.

[3] Eurostat, 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.

Country	Years covered	Age range	Source
		ASFR	
BE	1940–1945	12–55	HFC (STAT)
	1952–1960	14–50	HFC (ODE)
	1961–2010	12–55	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	12–55	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

prospects categories (ordered from low to high), given their gender, year of birth, and educational attainment (for details see Grow and Van Bavel 2015, in particular S1 Appendix). Similar to the

IIASA/VID data, the original input data related to income is based on 5-year intervals. We 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 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).[4] Data was available for DE, DK, ES, FI, FR, IE, NL, PT, SE, and UK. In the case of DE and UK, the data for certain periods was only available for separate territories/political entities (e.g., in Germany, prior to 1990 data was available separately for Western and Eastern Germany). For these periods, we combined the ASFRS as the average across the different territories/political entities, weighted by population size. In the cases of BE and GR, we had to rely on data provided by the Human Fertility Collection (HFC).[5] For this, we used ASFRs based on the age individuals had reached during the year (ARDY). In the case of Belgium, this data was available for most years from Statistics Belgium (STAT);[6] where possible, we substituted this data with information from the European Demographic Observatory (ODE).[7] 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 0. 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 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 over 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),[8] 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 population is modelled after 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.

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[4] 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).

[5] 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).

[6] Statistics Belgium (2012). Age-specific fertility rates (ACY 15-49), 1939, 1961-2009 [electronic resource]. Brussels: Statistics Belgium. Data downloaded on 04.05.2012.

[7] European Demographic Observatory (ODE). Data collection submitted to the HFC by Jean-Paul Sardon, 2011.

[8] 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 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 0.

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 school enrolment status, given their educational attainment, their age, and the threshold values defined in Table 3.

3.4.4 Update `simulation_year`

In case the value of the variable `time_steps` is 0, 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 to be conducted in the burn-in phase, the value of `simulation_year` remains 0. After this, `simulation_year` is set to 1921 and is increased by 1 after every 10 simulation steps. The length of the burn-in phase is 600 steps and was selected so that there was enough time for the first agent cohort to develop relationship patterns that are sufficiently realistic to serve as a starting condition for the main simulation period.

3.4.5 Fertiltiy

At the beginning of each simulation year (also before every 10 simulation 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 an empirical fact that in human populations 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 10 simulation 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 and the relationship time are adjusted to reflect their new situation.

3.4.7 Update school enrolment status

Agents are selected one at a time in random order to update their school enrolment status, 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 implements the notion that for those who participate in education, a minimal number of years in the educational system is usually mandatory.

3.4.8 Update `time_steps_this_year`

In case the value of `time_steps` is 0, 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 0 and it increase by 1 at the end of every simulation step. The value is set to 0 again after every 10 simulation steps.

3.4.9 Update search probability

Agents enter the marriage market at the age of 16 years (A_{marr} = 160) and from this moment on potentially search for a partner. This probability that this is the case is determined at the beginning of each time step for all agents by

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

In Eq. (1), β governs the effect that the length of i's current relationship has on the probability that it will try to meet somebody. We therefore refer to β also as the 'commitment parameter'. For single and divorced agents, c_i is always 0 and the probability that they will seek out somebody is thus always 1. As Table 2 shows, the value of β is positive and the same for male and female agents. The value implies that agents' inclination to actively seek out alternatives to their current partner decreases concavely with the length of their current relationship and approaches 0 after about 25–30 years (i.e. after 250–300 time steps). This is inspired by the observation that divorces hardly occur after 25–30 years of marriage (cf. Kulu 2014).

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, an opposite-sex member j is selected randomly from one of two sets of agents on the marriage market: agents who have the same school enrolment status as i (i.e.$r_i = r_j$), or agents who have a different school enrolment status than i (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 1 (0), the more likely agents are to meet somebody with the same (different) school 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 implies that while in school, agents mostly encounter people who are currently attending the same educational level. Conversely, agents who have left school already are most likely to meet agents who also have left school.

Once a potential partner j has been selected, both i and j assess the mate value they perceive in each other. The overall attractiveness that a given agent i perceives in another agent j is expressed in the mate value v_{ij}. This value 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 important partner characteristics can usually not 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 different evaluation criteria is often expressed by multiplicative exponential weighting functions (Zanakis et al. 1998). The model assumes that education, earnings prospects, and age are central partner characteristics that cannot be substituted. It therefore employs a multiplicative exponential weighting function to determine v_{ij}. The function has the form of

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

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 0–1. 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), the closer v_{ij} comes to 1. 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. Note that each of the three factors in Eq. (3) is bound to the range 0–1. In combination with the multiplicative structure of Eq. (3), this implies that low attractiveness in one characteristic cannot be substituted by high attractiveness in other characteristics.

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 female agents penalize deviations from the ideal age more than male agents. This in line with the observation men tend to marry women who are increasingly younger than themselves, but also increasingly further away from the ideal age of 24 years, as they grow older (implying a larger tolerance), whereas women tend to marry men who are 2–3 years older, regardless of their own age (implying a lower tolerance) (cf. England and McClintock, 2009). The parameterisation also implies that female agents attach relatively more importance to economic resources than to similarity in cultural resources (represented by earning prospects and educational attainment respectively). Male agents, by contrast, attach similar importance to both dimensions. This is in line with the notion that women often have less access to economic resources than men and therefore attach more importance to economic resources than to other characteristics of prospective partners (cf. Becker 1991; Kalmijn 1994; Li et al. 2002).

Once agents i and j have assessed each other's mate value, they need to decide independently whether they want to start dating the respective other. Agents who have no partner perceive any opposite-sex member j as a potential spouse and therefore always consider whether they want to start dating j. Agents who are currently dating or married, by contrast, only consider those opposite-sex members as a potential spouse whose mate value is higher than the mate value of their current partner (i.e. when $v_{ij}^{alternative} > v_{ij}^{partner}$). If they encounter such an alternative, there is a chance that they leave or divorce their current partner (depending on whether they are dating or married) and start dating the alternative.

The exact probability that i is willing to date alternative j (and to leave/divorce its current partner for this, if there is one) ($Pr(i\ date\ j)$) is determined by

$$Pr(i\ date\ j) = \left(1 - e^{-(a_i v_{ij} \sigma)}\right) e^{-(c_i \beta)}, \tag{4}$$

where σ governs the pressure to find a partner that agents experience as they become older; we therefore refer to σ also as the 'age pressure parameter'. The first factor of Eq. (4) implies that i's willingness to start dating j increases with j's mate value and with i's age (assuming that $\sigma > 0$). Yet, the second factor of Eq. (4) implies that this willingness is attenuated when agents are currently in a relationship (assuming that $\beta > 0$). Note again that for single and divorced agents, c_i is always equal to 0. For such agents, the second factor of Eq. (4) is therefore always equal to 1. Thus, all that matters for their willingness to start dating is the mate value of the potential partner and their own age in combination with σ. By contrast, for agents who are currently dating or married, the value of $Pr(i\ date\ j)$ is attenuated by the time they are already in the relationship (c_i), in combination with the commitment parameter (β). Two agents only start dating (and leave/divorce possible current partners) when both are willing to date. This implies two independent decision processes, in which Eq. (4) is applied separately to i and j.

As Table 2 shows, the model assumes that in the above decision process female agents experience a stronger age pressure (σ) than male agents. This is in line with the notion that both men and women suffer from a smaller pool of alternatives as they grow older, but women suffer additionally from the fact that men prefer women who are in their mid-20s.

3.4.11 Marriage decisions

The longer agents are already dating their current partner, the more willing they become to marry and therefore to propose marriage to/accept a marriage proposal from their partner. From the moment agent i (or j) proposes marriage to its partner j (i), the proposal remains intact until j (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 j, or is willing to accept a proposal from j, ($Pr(i\ marry\ j)$) is calculated as

$$Pr(i\ marry\ j) = \left(1 - e^{-(a_i v_{ij} \sigma)}\right)\left(1 - e^{-(c_i \beta)}\right). \tag{5}$$

Eq. (5) holds that agents are the more likely to propose marriage to/accept a marriage proposal from their partner, the higher the mate value of their partner (v_{ij}), the longer they are already in the relationship (c_i), the higher the commitment parameter (β), the older they are (a_i), and the higher the age pressure parameter (σ).

3.4.12 Update age

Agents' age a_i is increased by 1 at the end of every time step. Given that 10 time steps represent one simulation year, this implies that agents age by 1 year every 10 time steps.

3.4.13 Update relationship time

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 1.

3.4.14 Increase value of `time_steps`

Increases the value of the variable `time_steps` by 1.

3.4.15 Increase value of `time_steps_this_year`

Increases the value of the variable `time_steps_this_year` by 1.

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