

LINKED LIVES: THE UTILITY OF AN AGENT-BASED APPROACH TO MODELLING PARTNERSHIP AND HOUSEHOLD FORMATION IN THE CONTEXT OF SOCIAL CARE

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ABSTRACT

The UK's population is ageing, which presents a challenge as older people are the primary users of health and social care services. We present an agent-based model of the basic demographic processes that impinge on the supply of, and demand for, social care: namely mortality, fertility, health-status transitions, internal migration, and the formation and dissolution of partnerships and households. Agent-based modelling is used in order to capture the idea of "linked lives" and thus to represent hypotheses that are impossible to express in alternative formalisms. Simulation runs suggest that the per-taxpayer cost of state-funded social care could double over the next forty years. A key benefit of the approach is that we can treat the average cost of state-funded care as an outcome variable, and examine the projected effect of different sets of assumptions about the relevant social processes.

1 RESEARCH CONTEXT

This paper is the first of three in a session on social-science simulation models from the Care Life Cycle project (CLC). The CLC project is funded by the UK's Engineering and Physical Sciences Research Council. It brings together demographers, gerontologists, operations researchers, and complexity scientists to look at the UK's health and social care landscape and how it is likely to be affected by the changing demographics of a 21st century population. This paper describes an agent-based model of the basic demographic processes that impinge on the supply of, and demand for, social care: namely mortality, fertility, health-status transitions, internal migration, and the formation and dissolution of partnerships and households. The second paper describes a more abstract but more comprehensive system-dynamics model of the factors at play in the social care system. The third paper is more tightly focused and uses a combination of discrete-event, system-dynamics, and agent-based simulation to look at the treatment of age-related macular degeneration, a health condition that illustrates the interaction between the systems of health and social care.

The CLC project was introduced at a previous Winter Simulation Conference by Brailsford et al. (2011). In brief, the project is motivated by the fact that the UK's population is ageing, which presents a challenge for government since older people are the primary users of health and social care services. As well as increasing the demand for care, an ageing population affects the supply of care professionals, as the

health and social care workforce itself ages. An ageing population also provides opportunities, however: most social care in the UK is informal and is delivered by family members (Vlachantoni et al. 2011). Thus a greater number of healthy retired people will provide a bigger pool of potential carers.

The project aims to use various modelling approaches to help social scientists better understand the processes behind social care — e.g., how decisions a young person makes about marriage and child-rearing can impact their options later in life when they need help with daily activities. We also want to help policymakers to understand the range of possible future scenarios (especially in terms of the balance between informal, privately funded, and state-funded social care) and to know which of the available policy “levers” are likely to be effective in steering the system towards preferred outcomes. In particular, our model allows us to calculate the expected tax burden (either in total or per taxpayer) of state-funded social care under different sets of assumptions.

To achieve our goals will require more than simply adding together models of the different sub-systems involved: individual households, the National Health Service, local councils, private care homes, the set of all UK taxpayers, etc. What is important is the way that these sub-systems interact and feed back on each other. In order to make progress on understanding the whole system, we believe that a complexity science approach must be taken. Complexity science (Mitchell 2009) is an emerging discipline that attempts to model, understand and manage systems that combine scale and connectivity of the kind exhibited by the UK’s health and social care systems. It has very broad application to biological, environmental, and physical systems, but here we are interested in applying it within a social science domain that poses unique challenges.

The questions we are asking are traditionally addressed in the domains of demography, gerontology, and social policy. Why do we propose an interdisciplinary strategy? Why not leave it to the statistical approach typical of quantitative social science? Modern demography certainly faces some critical challenges, with population growth and demographic change becoming ever more important areas of study as society struggles with global issues ranging from the economy to the environment.

We have recently identified three broad concerns that face demography in this research climate (Silverman, Bijak, and Noble 2011). Firstly, demography must examine effects across several levels of description, ranging from the individual to the whole society. In recent years attempts to address this problem of aggregation have been made using multi-level statistical analysis in the framework of the event history and micro-simulation approaches (Willekens 2005, Courgeau 2007, Zinn et al. 2009).

Of course, multi-level methods alone do not necessarily produce greater predictive accuracy, which is a central concern for demographers. As problems in population research become ever more complex, and thus data requirements continue to grow, we begin to see predictive uncertainty increase rather than decrease. In particular, for some demographic questions there may simply not be sufficient data available to inform statistical models. Thus, the second challenge facing demography is that we must also find ways to link traditional statistical data with less data-hungry methods that would allow for more cogent analysis of possible future demographic processes.

Finally, the third concern is that the increasing complexity of demographic models presents the challenge of balancing that complexity with the need for the eventual analysis and understanding of the models in question. This issue has grown in importance in recent years, as a desire for understanding of the micro-level processes that lead to macro-level population change has driven a new emphasis on multi-level multi-state models (e.g., Courgeau 2007). However, in the course of this process, potential data requirements can easily surpass data availability for models that include a high level of detail.

One aim of this paper is therefore to illustrate by example a modelling framework which would provide a possible way forward for demographers who wish to address these concerns. In particular, by developing an approach which merges demographic techniques with agent-based simulation, we suggest that demography will be better equipped to cope with the challenges presented by the complexity of the processes under study. We will therefore explore in this paper an agent-based model of the dynamics of a synthetic, closed

population, focused on the issue of social care supply and demand, which also incorporates elements of demographic modelling techniques.

Of course, we are not the first to propose a union between demography and agent-based modelling. From the demographic side, there have been some notable if isolated efforts (e.g., Billari and Prskawetz 2003, Todd, Billari, and Simão 2005, Billari et al. 2007) but the idea is commonly discussed (Gilbert and Troitzsch 2005, Moss and Edmonds 2005) in the burgeoning field of social simulation, which has its own publication venues such as the *World Congress on Social Simulation* and the *Journal of Artificial Societies and Social Simulation*. The argument is typically that traditional social science models cannot fully capture the complexities of micro-level agent behaviour and heterogeneity, nor can they address downward causation from macro-level entities or groups. Agent-based models can provide these possibilities, as well as a possible platform for understanding social interactions, social networks, and other processes lying at the root of demographic change.

2 AIMS OF THE MODEL

In the specific area of social care, we want to construct an agent-based model that allows us to represent the idea of “linked lives”, which is a key part of conceptualizing relationships over the life course (Dannefer 2003). This can best be illustrated by contrast with the norm in demographic micro-simulation (see e.g., Willekens 2005). In such models individual people or agents are represented, but they are usually somewhat solitary “statistical individuals” (cf. Courgeau 2012). At each time step during the model’s run, each agent may undergo transitions from one state to another, e.g., from smoking to non-smoking, or from healthy to sick. The transition probabilities are chiefly derived from demographic survey data. (Wanting to include overly complex conditional transition probabilities, such as the probability that a 35-year-old female smoker with two children living in a rural village will develop lung cancer this year, can lead to a combinatorial explosion in data requirements as discussed by Silverman, Bijak, and Noble 2011.) The model proceeds by updating the state of each individual at each time step, and the output is the aggregate of all these individual states at the end of the model’s run. These models have been very successful and have some utility in predicting demographic change. But note that the individual people are effectively independent Markov processes; there is no room for complex interactions between them. It is not possible to represent a hypothesis such as the idea that people whose friends are all getting married will feel more pressure to get married themselves.

We admit to a slight exaggeration: it is not that the individuals in these models are *totally* independent. In a closed-population micro-simulation model like the one described by Evandrou, Falkingham, Johnson, and Rake (2001), individuals transition from one state to another as above but the basics of partnership formation are present, in that an agent that moves into the “married” state must do so in connection with another specific agent.

What we are proposing to do is simply to extend this treatment of individuals in ways that allow relevant hypotheses to be framed and explored. Ultimately the simulation should capture the idea that people’s lives are connected in many different ways, e.g., through work, being neighbours, being friends or friends of friends, being a grandparent, being a half-sibling, being a distant relative, being an ex-partner or a divorced parent, etc. By linking the lives of the agents, we will be in a position to look at hypotheses in the social care landscape that are not representable in other modelling approaches. For example, if qualitative interview data were to indicate that people living in multi-generational households as children were either more or less likely, when adults, to invite their elderly parents to come and live with them, then our model would be able to capture this feedback cycle and assess its probable consequences.

To take an arbitrary example, another factor that could be captured in a linked-lives model would be the effects of differing geographical mobility between agents of different socio-economic categories. If middle-class agents are more mobile than working-class agents (e.g., when the children leave home they are likely to move further away for career or education reasons) how might that interact with care decisions later in life? A third example would be looking at the effects of a high divorce rate and the resulting

fragmentation of family structure (Sage, Evandrou, and Falkingham 2012). What if the propensity to care for someone when they are elderly is a function of whether they were a presence (i.e., lived in the same house as you) during your childhood? It seems plausible that a biological parent who left very early in a child's life is less likely to be offered care than a step-parent who was in the household for all 18 years of childhood. Building this assumption into the model, we could then vary the divorce rate and look at its effect on the projected figures for demand for state-funded social care.

These examples make clear that some of the predictive precision of statistical modelling in demography would have to be given up under this approach. In many cases we are talking about potential social effects that would be very difficult to get comprehensive data on. We can build in some "hard facts" about mortality or fertility for example (or, more accurately, we can make the inductive leap of assuming that the future will be smoothly related to the past) but data on the different forms of social connection that might drive one person to provide informal social care for another is always likely to be somewhat fuzzy. Our model would not be so much a forecasting tool as a scenario-generation sandbox, intended to give researchers and policymakers a way of asking productive "what if?" questions (Di Paolo, Noble, and Bullock 2000). However, given the inherent difficulties of precise point prediction for human social systems, we do not see this as giving up too much.

3 MODEL SPECIFICATION

In order to achieve our aims, certain entities and processes clearly need to be included in the model. Most obviously, we have to have agents representing human beings. Modelling the entire UK population of approximately 62 million people would be a prohibitive computational load, so in this first instance of the model we have opted for a scaling factor of 1:10,000 (i.e., one agent in the model stands in for 10,000 people in the real world, so around 6,200 agents would represent the current UK population).

Our agents need to undergo the basic demographic processes of birth, ageing, reproduction, and death. We have therefore set our time-step size at one year and included a simple Gompertz-Makeham mortality model, tuned to give appropriate mortality rates for a modern first-world country. Fertility is currently represented as a flat reproductive probability for all women aged 17–42 in any kind of partnership; a more sophisticated match to real-world fertility data is on our development list. Space constraints preclude a full description of these and other parameters in the model; the annotated Python code is freely available at <http://users.ecs.soton.ac.uk/jn2/software.php>.

Our agents live in houses that occupy particular points in space. These houses are grouped together in towns: clusters of up to 625 houses depending on local population density. The towns are themselves arranged on an 8×12 grid representing the UK. Figure 1 shows a screenshot of the live graphical output of the model; the map can be seen on the right. The brown-purple-yellow colour coding of the individual houses represents the socio-economic category (SEC) of each household, but the economic side of the model is not yet functional.

We need our agents to be able to enter and leave partnerships with each other. We have used the terms "marriage" and "divorce" but in fact we intend to cover all forms of relationship that are likely to lead to cohabitation or that might produce children. Each year agents not already in partnerships will decide to enter the marriage market at an age- and sex-specific rate. Our original intention was to model partnership formation as a mostly local process but the scaling rate of 1:10,000 made this impractical in low-population towns. The marriage market therefore operates on a national level; agents are randomly paired up with an opposite-sex agent if they mutually satisfy each other's criteria. Currently the only criteria are that the agents do not have the same mother and that the male should be no more than five years younger and no more than 20 years older than the female. Divorce is implemented as an annual age-specific probability that the male partner will leave a relationship. (We are aware that we are painting with a very broad brush here; again, these are model components that will eventually be replaced with more data-driven sets of conditions.)

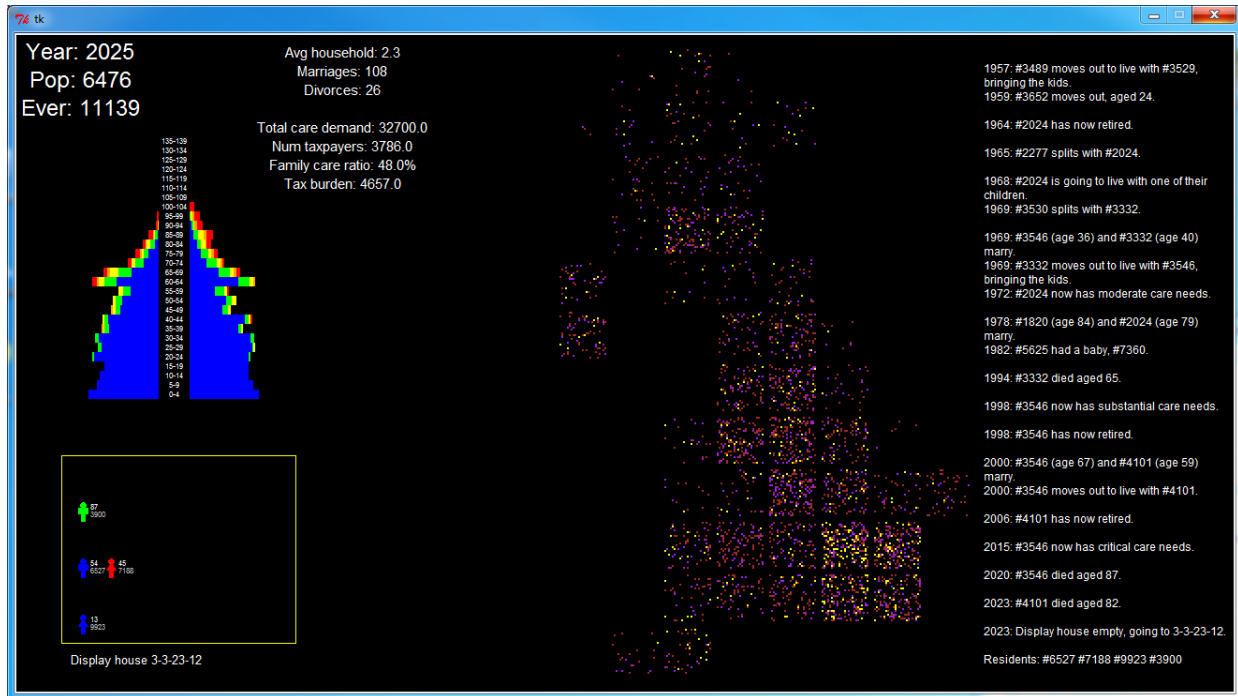


Figure 1: A screenshot of the simulation’s current graphical output. Clockwise from lower left: yellow box containing residents of an arbitrarily selected display house, showing its current residents and their colour-coded care status; a live population pyramid also with colour-coded care status (blue=none, green=low, yellow=moderate, orange=substantial, red=critical — see Table 1 for details); key information such as the year and the current population; secondary information such as the total care demand and the number of taxpayers; a grid-based map of the UK showing occupied households; and a list of recent events (e.g., births, deaths, marriages, divorces) in the lives of agents living in the display house.

All agents begin with a normal health status, represented by the colour blue in Figure 1. There is an annual age- and sex-specific probability that an agent’s health will degrade by one or more levels, putting them in a different care-need category; each category is characterized by the number of hours of care that person requires per week. The various categories are shown in Table 1; agents only move down this list of categories, never up. Care need level is currently not linked to mortality risk, although this could change in future development. Figure 1 includes a population pyramid that is colour-coded by health status; note the preponderance of care need amongst older people.

When agents are born they start out as dependent children. At 17 they become adults, and are assumed to enter the workforce (higher education is currently not modelled). Adults are divided into those who have moved out and are independent versus those who have not left home and still live with their parents. The model does not include a detailed economic system, but for the purposes of measuring the tax burden of state-funded social care, adults of both of the categories mentioned so far count as taxpayers. At age 65 all agents transition to the “retired” category and no longer pay tax.

The agents will, for several reasons, occasionally migrate to a new house on the map. First, the formation of a new partnership is independent of where the agents are living, but once a partnership is formed there is a 30% probability per year that the two agents will move in together. When they do so, there is a 30% probability that they will join whichever of their existing households is smaller; this can potentially lead to a new multi-family, multi-generational household if one agent brings existing children with them, for example. (Any adult agent that lives with their dependent children will always take them along when moving.) Married agents who move together but not into an existing household will set up

Table 1: The different care need categories, with colour coding and the number of hours of care required per week. Note that, like many parameters in the simulation, these hours-of-care figures are rough estimates that serve as placeholders until better data can be incorporated.

Care need category	Colour coding	Weekly hours of care required
None	Blue	0
Low	Green	8
Moderate	Yellow	16
Substantial	Orange	30
Critical	Red	80

a new house in or next to the town in which one of them had been living. When partnerships break up, the male partner will move to a new house elsewhere on the map; any children will stay with the female partner.

When children become adults, there is an annual, age-specific probability that they will move out and set up a new household, peaking at 22% for agents in their 20s. (This probability goes down over time, so a 40-year-old who has not yet moved out is unlikely to do so.) Single adults living alone have up to a 5% chance of moving per year, and family groups have up to a 3% chance per year of an arbitrary move. Finally, retired agents living alone (possibly due to death or divorce) have a base probability of 10% per year of making a move to live with any of their surviving children; this probability scales inversely with the distance between the towns of the parent and the child.

The graphical output of the simulation includes a detailed look at a randomly chosen focal household; this helps to illustrate some of the processes listed above. The focal household is shown in the lower left of Figure 1, and a more detailed example is shown on the left panel of Figure 2. The household display gives a good sense of how family structures develop over time. It also served to highlight some interesting edge cases, such as the possibility of orphans: children whose parents both die before they reach 17. If this occurs the children are assumed to be adopted by a randomly chosen couple.

By linking a care category to a specific number of weekly hours of care required we can measure the demand for social care. What about supply? The model does not currently include formal social care mechanisms, such as care homes or home-care services offered by local authorities. However, we can look at how household and family structure will influence the availability of informal care. We work on the assumption that each agent will provide informal care to anyone else in their household who needs it, subject to a maximum number of hours per week that the agent is able to provide. Furthermore, agents will provide needed informal care to either or both parents, if those parents live in another household, as long as the parent’s house is in the same town as the agent’s.

The maximum number of hours of informal care that an agent can deliver per week is dependent on their own status. Dependent children can provide up to 5 hours of care per week; for adults living at home the figure is 30 hours per week; working adults can provide up to 25 hours per week; and retired people can deliver up to 60 hours of informal care. Agents who themselves have low levels of care need can still provide care to others, but only for half of the usual number of hours. Agents with moderate, substantial, or critical care needs cannot provide care to others. Our model looks at the delivery of care in a very simple way: all care needs that *can* be satisfied by relevant agents (i.e., housemates, and children living in the same town) are assumed to be satisfied. Any remaining care needs are assumed to be satisfied by a formal care system that has not been explicitly modelled.

For example, a 90-year-old woman with critical care needs will require 80 hours per week of care. Let us assume that she lives with her retired 70-year-old daughter, and that there are no other surviving children. The healthy daughter can deliver up to 50 hours of care per week due to her retired status, and the remaining 30 required hours will be paid for by the state.

Each year, the total number of hours per week of care needed — i.e., the total care demand level — is recorded, as is the fraction of those hours that can be provided through informal social care. The remaining

hours of needed care are assumed to be paid for by the state at £20 per hour. This assumption allows us to put a figure on the total cost of state-provided care, but we have focused on the more useful figure of the average cost of state-provided care per taxpayer (i.e., the total cost divided by the number of taxpaying adults).

4 SIMULATION RESULTS AND DISCUSSION

The runs described here proceeded by taking an initial population setup for the year 2000, choosing a new random seed, and running 50 years of simulated time, out to 2050. To get our initial population, we first ran the simulation by seeding it with 375 starter couples aged between 20 and 40 and then simulating 140 years in order to reach an appropriate UK population of around 6000 agents, and to ensure plausible family and household structures were in place. The initial population used a higher fertility level until the equivalent of 1965, slowing to modern levels after that; this produced a population pyramid that better matched real data.

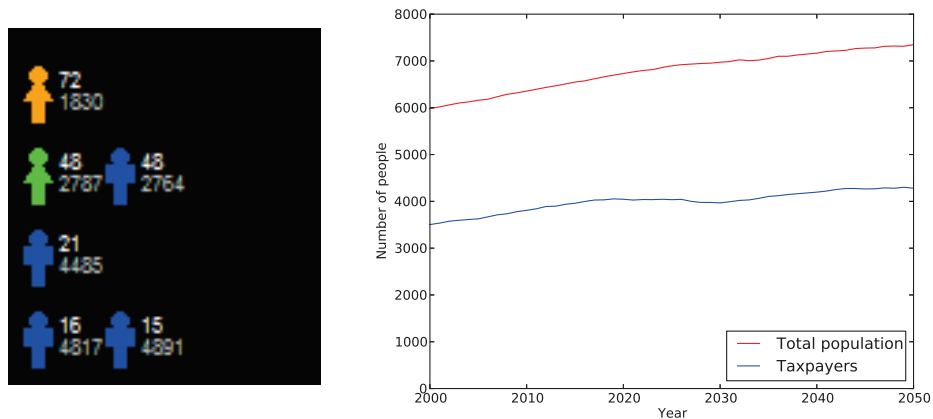


Figure 2: **Left:** detail of the focal household display. An agent’s sex and care status is indicated by shape and colour respectively; the numbers to the right of each agent show age and ID number. Agents are grouped into 20-year horizontal age bands in the display, highlighting the generational structure of the household. In this family the parents are both 48 years old, and the wife has low social care needs. The wife’s 72-year-old mother has substantial care needs and has recently moved into the household. The couple have three sons; the oldest is an adult at 21 but has not yet left home. The younger sons are 16 and 15. **Right:** Projections for total population and number of taxpayers, 2000–2050. Data is taken from an arbitrarily chosen sample run.

Our first concern was to look at population growth and other basics in order to see whether our model was at all plausible. Figure 2’s right panel shows the total population and the total number of taxpayers over a 50-year sample run. The population increases from 6000 to 7400, corresponding to a projected UK population of 74 million people in 2050. The average household size was around 2.4 near the start of the run and declined to 2.25 by 2050. These figures are broadly in line with official projections, which envisage a decline in the average household size from 2.33 in 2008 to 2.16 by 2033, which is the projection horizon (CLG 2010).

Next we looked at the projected social care situation. Figure 3’s left panel shows, in red, the change in the total demand for social care. This starts out at 20,000 hours per week in 2000 and doubles to 40,000 hours by 2050: this is a dramatic increase but is in line with expectations for an ageing population. Figure 3’s left panel also shows, in blue, the theoretical maximum supply of informal social care, if every agent were to deliver social care to its maximum potential (e.g., 25 hours per week for a working adult).

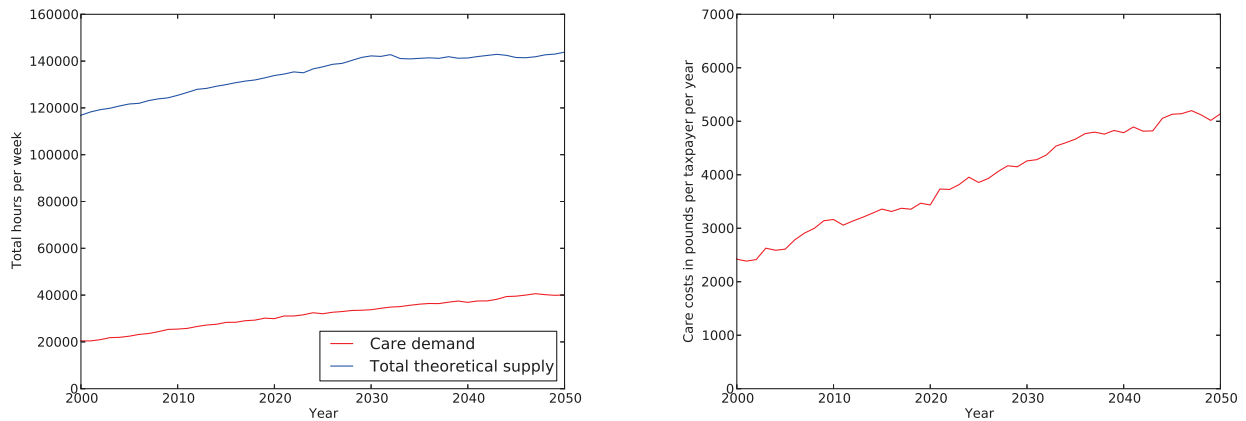


Figure 3: **Left:** projections for total care demand and total theoretical supply of informal care, both measured in hours per week. **Right:** projections for the tax burden of state-funded social care. The graph shows the cost in UK pounds per taxpayer of all social care needs that have not been met informally.

This value also increases over the course of the run, but the important thing to note here is that it is much higher than the projected care demand.

Using a modelling approach that did not fully consider “linked lives”, we might conclude at this point that there are no problems foreseen in the delivery of informal social care. Figure 3 (left panel) suggests that there will be plenty of available carers to meet the demand, surely? Of course, that is overly simplistic both in the model and in the real world. It all depends on who lives with whom, how far away children end up living from their aging parents, whether children chose never to leave home at all, whether divorce has split families up, etc. This is the strength of our approach: we cannot hope to make even a reasonable estimate of the amount of informal social care that will actually be delivered unless we model family and household structure and something of the interconnectedness of real people’s lives.

In the model and in the real world, not all care demand will be met through informal care. In the sample run shown above, it turns out that about 55% of the total care demand is delivered informally by family members and housemates; this figure declines to just under 50% by 2050. A canonical example in the model of someone whose care needs cannot be met informally would be an elderly person who has never had children, whose spouse has died, and who is living alone. In the real world this person might obtain informal support from friends or neighbours, of course, or might choose to move in with a surviving sibling. However, in our simple model these possibilities are not reflected: if there is nobody else living in the house, and if the person has no surviving children living in the same town, they receive no informal social care.

All care needs that are not met informally are assumed to be met by the state. Again, this is a simplification on multiple levels: our model does not yet include an economy, so we cannot capture the idea that some older people will be well-off and able to pay for private care services, whereas others will have no savings and be entirely dependent on state help. Additionally, of course, it is a sad possibility in the real world that some care needs are simply not met at all, leading to severe effects on the person’s quality of life.

But calculating things the way we do, how does it look for the taxpayer? Figure 3, right panel, shows the projected tax burden of state-funded social care in UK pounds per taxpayer per year. This is eye-opening: the cost per taxpayer increases from £2400 in the year 2000 to more than £5000 in 2050. If our assumptions are broadly correct, an ageing UK population will lead to an increased demand for social care, and at the same time changes in the demographic structure of UK society could lead to a proportionally reduced

supply of informal social care. It is highly likely that some of the burden of making up the difference will fall on state-funded services.

The results shown so far are not intended as precise projections, more as a sanity check that our model is producing reasonable results. The real benefit of the approach is that we can now treat the average cost of state-funded care per taxpayer as a key outcome variable, and ask how that value would change for differences in parameters and processes within the model.

We begin with an obvious example: what happens if we vary the annual probability that single retired people, living alone, will move in with one of their children? This was set at a base rate of 10% in the sample runs above. Figure 4, left panel, shows the results of trying values of this parameter ranging from 2% to 20%.

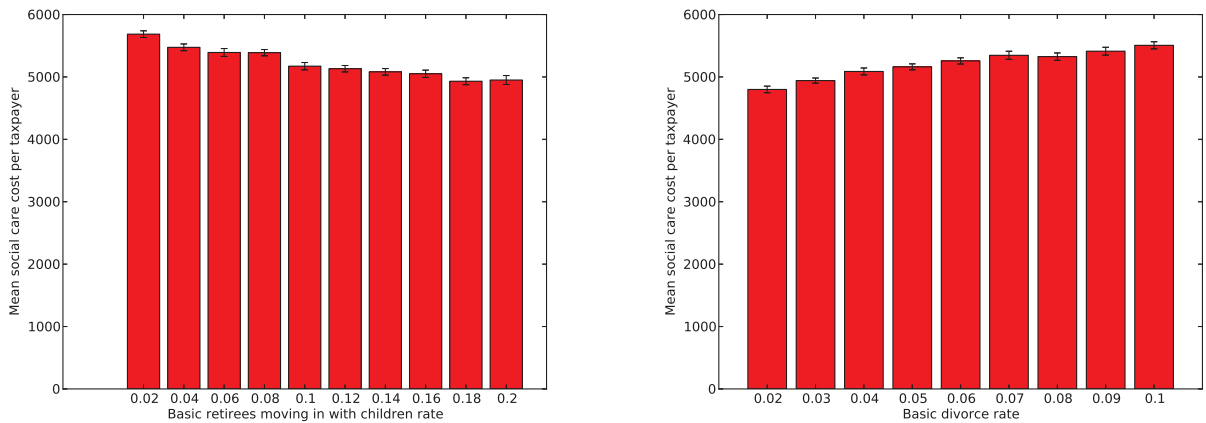


Figure 4: Parameter sweeps for **(Left)** the probability of single retired people moving in with one of their children, and **(Right)** the basic annual probability of divorce (actual divorce rates are further scaled by the age of the male partner). Bars depict the projected cost per taxpayer of state-funded social care across values of the parameter. Each result is a mean across 25 runs with different random seeds; standard errors across runs shown.

The results are not surprising: the cost to the taxpayer will be greater in a world where single retired people are less likely to move in with their children. This is of course because those retired people are less likely to receive informal social care if they continue to live alone. The differences across the various parameter values are, if anything, surprisingly modest.

What about a parameter that seems less obviously connected to social care? Can the model show that, due to the complex nature of the social system as a whole, there are factors that have unforeseen effects on the tax costs of state-funded care? There are many factors we could have chosen here, as discussed in Section 2. As a start, we decided to vary the divorce rate to see what sort of effect it might have on the social care environment. It is not immediately obvious which way this effect should go: a higher divorce rate may lead to more ageing single people who are not in a position to receive informal care, but the geographic moves prompted by a divorce could also have the opposite effect, e.g., if a newly divorced woman moves in with her adult children.

Figure 4, right panel, shows the results: an increase in the divorce rate has a disruptive effect, increasing the expected costs of state-funded care. (Note that the default divorce rate was 0.06.) It is interesting to note that a change in the divorce rate of a few percentage points up or down has a comparable effect on care costs as does a change in the rate of single retired people moving in with their adult children, despite the latter having a much more obvious connection to informal care delivery. It is exactly this kind of system exploration that we see as the strength of this modelling approach.

5 DIRECTIONS FOR DEVELOPMENT

Clearly, there are many things that could be added to the model, and many more interesting and potentially relevant outcomes that could be extracted even from the current version. In terms of further developments, one pathway would be to better align the parameters with the actual demographic data from population censuses, surveys, vital events registration, etc. Of course, the aim here is not to provide precise predictions, but as we argued before (Silverman, Bijak, and Noble 2011) we would ideally like to include as much data as practicable. Arguably, if the demographic fundamentals are as accurate as possible, it can only help the model's utility and credibility. To that end, we could benchmark the initial structure of the simulated population to the one observed in a selected past population census. Secondly, for mortality and fertility, we could utilise the past data on birth and death rates obtained from the vital events registration, extrapolated into the future using a standard demographic approach, such as a Lee-Carter model (Lee and Carter 1992).

Looking further down the development pathway, other possibilities include representing in the model the parallel issue of the social care of children, adding an economic component to the model and explicitly modelling socio-economic differences in access to care, and modelling the formal supply side of the health and social care system (i.e., hospitals, care homes, council-funded mobile care services, etc).

In conclusion: the value of our model is that it acts as a focus for further discussion with various stakeholders, such as civil servants, local government officials, care managers, etc. The stakeholders could be presented with a set of model outcomes, and asked for their views on different probable — or even just plausible — values for selected parameter settings, which will enable them to see the direct implications of changing these values for the outcomes of interest. As mentioned before, this is a key advantage of the proposed approach in general, which can serve as a coherent tool for policy-oriented scenario generation. The idea here is not to try to make precise point predictions about social systems that are inherently difficult to predict. Instead, we can use models such as the proposed one to examine how closely the various factors in the real system are likely to be linked or related, and also to get a sense of the kinds of dynamics the system is capable of, and thereby to build up an understanding of what kinds of steering or policy inputs are most likely to nudge it in desirable directions.

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REFERENCES

- Billari, F., B. Aparicio Diaz, T. Fent, and A. Prskawetz. 2007. "The wedding ring. An agent-based marriage model based on social interaction". *Demographic Research* 17 (3): 59–82.
- Billari, F., and A. Prskawetz. (Eds.) 2003. *Agent-Based Computational Demography: Using Simulation to Improve Our Understanding of Demographic Behaviour*. Heidelberg: Physica.
- Brailsford, S., E. Silverman, S. Rossiter, J. Bijak, R. Shaw, J. Viana, J. Noble, S. Efstathiou, and A. Vlachantoni. 2011. "Complex systems modeling for supply and demand in health and social care". In *Proceedings of the 2011 Winter Simulation Conference*. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- CLG 2010. "Household Projections, 2008 to 2033, England". Technical report, Department for Communities and Local Government, London.
- Courgeau, D. 2007. *Multilevel Synthesis: From the Group to the Individual*, Volume 18 of *Springer Series on Demographic Methods and Population Analysis*. Dordrecht: Springer.
- Courgeau, D. 2012. *Probability and Social Science: Methodological Relationships between the Two Approaches*, Volume 10 of *Methodos Series*. Dordrecht: Springer.

- Dannefer, D. 2003. "Cumulative advantage/disadvantage and the life course: cross-fertilizing age and social science theory". *Journal of Gerontology (Social Sciences)* 58 (16): S327–337.
- Di Paolo, E. A., J. Noble, and S. Bullock. 2000. "Simulation models as opaque thought experiments". In *Artificial Life VII: Proceedings of the Seventh International Conference on Artificial Life*, edited by M. A. Bedau, J. S. McCaskill, N. H. Packard, and S. Rasmussen, 497–506: MIT Press, Cambridge, MA.
- Evandrou, M., J. Falkingham, P. Johnson, and K. Rake. 2001. "SAGE: simulating social policy in an ageing society". ESRC SAGE Research Group Discussion Papers 1, London School of Economics.
- Gilbert, N., and K. Troitzsch. 2005. *Simulation for the Social Scientist*. Second ed. Maidenhead, Berkshire: Open University Press.
- Lee, R. D., and L. R. Carter. 1992. "Modeling and forecasting U.S. mortality". *Journal of the American Statistical Association* 87 (419): 659–671.
- Mitchell, M. 2009. *Complexity: A Guided Tour*. Oxford University Press.
- Moss, S., and B. Edmonds. 2005. "Towards good social science". *Journal of Artificial Societies and Social Simulation* 8 (4): 13.
- Sage, J., M. Evandrou, and J. Falkingham. 2012. "The effects of post-retirement marital disruption on intergenerational exchanges, and the obligations of mid-life adult children to care". Poster presented at the Population Association of America 2012 meeting.
- Silverman, E., J. Bijak, and J. Noble. 2011. "Feeding the beast: can computational demographic models free us from the tyranny of data?". In *Advances in Artificial Life, ECAL 2011: Proceedings of the Eleventh European Conference on the Synthesis and Simulation of Living Systems*, edited by T. Lenaerts, M. Giacobini, H. Bersini, P. Bourguine, M. Dorigo, and R. Doursat, 747–754. MIT Press.
- Todd, P. M., F. C. Billari, and J. Simão. 2005. "Aggregate age-at-marriage patterns from individual mate-search heuristics". *Demography* 42 (3): 559–574.
- Vlachantoni, A., R. Shaw, R. Willis, M. Evandrou, and J. F. R. Luff. 2011. "Measuring unmet need for social care amongst older people". *Population Trends* 145:60–76.
- Willekens, F. 2005. "Biographic forecasting: bridging the micro-macro gap in population forecasting". *New Zealand Population Review* 31 (1): 77–124.
- Zinn, S., J. Gampe, J. Himmelspace, and A. M. Uhrmacher. 2009. "MICCORE: a tool for microsimulation". In *Proceedings of the 2009 Winter Simulation Conference*. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

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