

System-Based Modelling: A New Paradigm for Demography? ¹

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1. Introduction

Over its 350-year history, demography has progressed through successive paradigmatic changes, from period analysis (Graunt 1662) through to multilevel analysis more recently (Courgeau 2012). Currently, the recent prominence of agent-based models (ABMs) has indicated an increased focus on individual behaviours and interactions in the study of populations, and also a desire to bolster the theoretical foundations of demography (Burch 2003a,b; Silverman, Bijak and Noble 2011). Here we posit that ABMs can be classed as one manifestation of a broader paradigm, *system-based modelling*, which is focused primarily on understanding interactions. In our view, this paradigm can form the foundation of the next step in the cumulative progression of demographic knowledge.

This paper proceeds first by detailing the successive paradigmatic changes evident in the history of demography in Section 2, and describing the methodologies dedicated to the examination of interactions in Section 3. In Section 4 we outline the case for system-based modelling as a new paradigm for demography, and finally in Section 5 we propose a research programme to address the challenges ahead.

2. Cumulativity in Demography

Since the origin of demography in the 17th century, the field has progressed through a series of paradigmatic changes as the scientific study of population has grown in scope. Here we characterise these paradigms in a somewhat different sense from Kuhn (1962), and instead follow Granger (1994), who proposes that paradigms allow us to move from experienced phenomena toward a 'scientific object' of enquiry. In the context of demography, successive paradigms have specified different relationships between the observed phenomena and the scientific object in question (Courgeau and Franck, 2007).

This becomes evident when we delineate the four major paradigms in demography since its inception. From early work in *period analysis* we see a focus on macro-level phenomena, measured according to historical time; later progression into *cohort analysis* marks a shift toward the study of macro-level phenomena along the lifetimes of individual cohorts. The advent of the *event-history analysis* brought with it a new focus on individuals, with micro-level effects measured according to individual time. *Multilevel analysis*, which appeared around the same time, brings together observations of individual, population-level and interim-level phenomena, measured according to multiple perspectives (Courgeau 2012).

However, in demography these developments have not led to a patchwork landscape of competing approaches, but instead to a *cumulativity* of knowledge. Successive paradigms have addressed the shortcomings of previous ones, providing means to surpass some of their limitations, but in doing so have not eliminated the progress made in those prior paradigms. As Courgeau (2012, p.239) has put it:

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Cumulativeness of knowledge seems self-evident throughout the history of population sciences...: the shift from regularity of rates to their variation; the shift from independent phenomena and homogeneous populations to interdependent phenomena and heterogeneous populations; the shift from dependence on society to dependence on the individual, ending in a fully multilevel approach. Each new stage incorporates some elements of the previous one and rejects others. The discipline has thus effectively advanced thanks to the introduction of successive paradigms.

Each of these paradigms frames the relationship between observations and scientific object differently, and in so doing allows for new methodologies that can alleviate difficulties associated with other methods. Yet each also occupies a different context, and therefore previous paradigms remain relevant despite the proliferation of new ones. This is quite readily seen in the demographic literature of course – cohort analysis is still perfectly sufficient to answer a broad array of demographic questions, right alongside event-history analysis and multilevel analysis.

3. Systems, Interactions and Complexity

In recent decades, the evolution of demography has coincided with shifting perspectives on the epistemological challenges facing the studies of human populations. In particular, demographers and other population scientists are now paying ever more attention to the issues of different levels of analysis, and to the uncertainty and complexity surrounding population phenomena. This new understanding of the limits to demographic knowledge (Silverman et al. 2011) has led to the investigation of new modelling methods. Some have advocated the instantiation of demography as a ‘model-based science’ (Burch, 2003b), mirroring similar movements within the study of biological systems and evolution (Levins, 1966; Godfrey-Smith, 2006). However, as argued by Xie (2000), building models of the social realm carries its own unique challenges, due to the complex nature of social interaction and the underlying processes.

Agent-based models have been of particular interest in this context, partially due to their capacity for explanatory power (see Burch 2003a,b; Silverman et al., 2011). ABMs aspire to represent the import and impact of individual actions on the macro-level patterns observed in a complex system, and vice versa. Given this focus, agent-based approaches belong to a broader class; models specifically analysing systems of interacting elements. In the demographic context, there are many systems worthy of enquiry, comprised of interacting individuals, groups, or institutions. In this way, population sciences, including demography, can become more model-based by making those *interactions* between different population systems an explicit scientific object of interest. In so doing, our models become capable of representing complex, interacting behaviours at the micro-level, and investigating the ensuing emergent behaviours at the macro-level. Such models have clear potential for contributing to theory-building within demography, and perhaps even social science more broadly.

Of course, model-based approaches come with their own shortcomings – in particular, models attempting to represent the complexities of individual-level behaviour and their impact on population change are naturally dependent on sensible theories regarding this behaviour. However, such theories are not only many and varied, but can be notoriously difficult to formalise (Klüver, Stoica and Schmidt 2003), and validate, especially in the social science realms (see e.g. Moss and Edmonds 2005, for examples from sociology and economics). Without such theories, it may be difficult – or even impossible – to build an adequate model of the population under study. A possible way forward from this conundrum could be to move beyond *causal* theories, and look into *functional* approaches, which focus on ‘reverse engineering’ different *functions* of the social systems in question based on their inputs and outputs (Franck 2002).

4. System-Based Modelling

These investigations of the limits of demographic knowledge and of agent-based modelling, and the consequent search for alternative model-based approaches, are indicative of a broader need for a fifth demographic paradigm. Some of the clear strengths of demography lie in its applied character, empirical relevance, and its capacity for responding to the needs of the broader society. In order to surmount the limits to agent-based approaches, owing to their dependence on causal theories, new computational modelling methods should be fully integrated into the empirical, scientific and inductive character of demographic enquiries. The result of such an effort would be the development of a fifth paradigm and a shift toward another scientific object.

The fifth paradigm we propose for the future of demography is thus a *system-based* one, firmly rooted in a wider functional-mechanistic research programme. Agent-based models can conceivably belong to this paradigm – as long as they are scientifically rigorous – but even then they clearly do not exhaust it. Within this paradigm, we posit that demography should investigate the *interactions* between various population *systems*, as well as the functional *mechanisms* behind them. The interactions and mechanisms are best described by formal models based on data and theory-based rules, derived from observations of system properties by following the Baconian inductive method. This paradigm cumulatively extends the previous four in a natural way, whilst broadening the scope of scientific exploration in demography. In particular, we hope that this approach would enable demographers to enhance the theoretical base of our discipline, whereby theories represent formal conceptual systems rather than necessarily empirical ones (Franck, 2002; Burch, 2003b). A summary of the successive five paradigms of demography is provided in Table 1.

No.	Paradigm	Period	Key focus
1	Period (cross-sectional)	1662–	Population-level (macro) phenomena, observed and measured according to the historical time
2	Cohort (longitudinal)	1950s–	Population-level phenomena, observed and measured along the lifetime of individual cohorts
3	Event history	1980s–	Individual-level (micro) phenomena, observed and measured according to the individual time
4	Multilevel	1980s–	Individual, population, and interim-level phenomena, observed and measured from multiple perspectives
5	System-based	2000s–	Interactions between population systems of individuals, groups and institutions

Table 1: The five paradigms of demography – a summary

5. Looking Forward

This proposed fifth paradigm of *System-Based Modelling* carries with it substantial promise: it extends the previous four extant paradigms while incorporating insights gained from model-based science. However, in order to develop this paradigm fully, novel demands are placed upon demographers and other population scientists – after all, these new elements in this paradigm call for a different conceptualisation of the relationships between various population systems, and at the same time require proficiency with a new set of tools.

With this in mind, we propose that this fifth paradigm should proceed via the inductive investigations of links between observed demographic properties and the modelled population systems – which would allow us to investigate the interactions of interest. We must first begin (1) with the observation of those properties (data) of the given population; then we may (2) infer the formal (conceptual) structure of the population systems implied by these properties. This formal structure will then (3) guide our study of the social mechanisms and interactions which we believe generate the observed properties. A model-based investigation of these formal structures can then allow for the (4) verification of these formal structures, given the observed data (Franck 2002). Statistical modelling and uncertainty quantification could be used to infer

the formal structures from data in the first two steps of this procedure, rather than to verify hypotheses *ex post*.

The system-based approach provides us with the means to move beyond the benefits already provided by multilevel modelling. Not only do we gain similar insights into the interactions between various population systems as part of the methodology, but we also gain the capacity to explore the parameter space of the simulations by generating hypothetical “what-if” scenarios. Simulation parameters govern the way in which the complex, interacting social processes in the model work, and therefore exploring the parameter space enables us to investigate numerous such scenarios, which could represent policy changes, individual behavioural changes, societal-level changes, and similar (Silverman et al., 2013). Given the construction of these simulations, running them under these varied scenarios can illustrate the unforeseen, non-linear impact of changes to these complex processes.

In practice, system-based population modelling can rely to some extent on the existing agent-based approaches, insofar as they are subjected to the inductive principles of the scientific method. However, a key open question remains: what principles should be followed to illuminate the inductive construction of such models? We suggest that this question is fundamental to the future direction of demography, and we have no doubt that vigorous and open debate on this question will be a vital part of efforts to take demography in a new direction.

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