ERC Consolidator Grant 2016
Research proposal [Part B1]
(Edited version)

Bayesian Agent-based Population Studies: Transforming Simulation Models of Human Migration

BAPS

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Host institution for the project: **University of Southampton, UK**

Project duration: **48 months**

Proposal summary

The aim of BAPS is to develop a ground-breaking simulation model of international migration, based on a population of intelligent, cognitive agents, their social networks and institutions, all interacting with one another. The project will transform the study of migration – one of the most uncertain population processes and a top-priority EU policy area – by offering a step change in the way it can be understood, predicted and managed. In this way, BAPS will effectively integrate behavioural and social theory with modelling.

To develop micro-foundations for migration studies, model design will follow cutting-edge developments in demography, statistics, cognitive psychology and computer science. BAPS will also offer a pioneering environment for applying the findings in practice through a bespoke modelling language. Bayesian statistical principles will be used to design innovative computer experiments, and learn about modelling the simulated individuals and the way they make decisions.

In BAPS, we will collate available information for migration models; build and test the simulations by applying experimental design principles to enhance our knowledge of migration processes; collect information on the underpinning decision-making mechanisms through psychological experiments; and design software for implementing Bayesian agent-based models in practice. The project will use various information sources to build models bottom-up, filling an important epistemological gap in demography.

BAPS will be carried out by the Allianz European Demographer 2015, recognised as a leader in the field for methodological innovation, directing an interdisciplinary team with expertise in demography, agent-based models, statistical analysis of uncertainty, meta-cognition, and computer simulations. The project will open up exciting research possibilities beyond demography, and will generate both academic and practical impact, offering methodological advice for policy-relevant simulations.

Extended Synopsis of the scientific proposal

Background and objectives

The aim of BAPS is to develop a ground-breaking simulation model of international migration, based on a population of intelligent, cognitive agents, their social networks, and institutions, all interacting with one another. The project will transform the theoretical and methodological foundations of demographic migration studies, and help address key societal and population challenges: how migration – one of the most uncertain demographic processes (Bijak 2010) and a top-priority, high-impact EU policy area (EC 2015) – can be understood, predicted and managed. BAPS will build an ambitious agent-based model (ABM) of international migration following cutting-edge developments in demography, statistics, experimental design, computer science and cognitive psychology, and develop a pioneering modelling language to aid application.

Computer-based simulations, such as agent-based or microsimulation models, offer population scientists many new and exciting research possibilities. In particular, ABMs can represent the behaviour of simulated individuals – agents – in artificial computer simulations. In population studies, such models have been gaining prominence since the beginning of the 21st century (Axtell et al. 2002; Billari & Prskawetz 2003; van Bavel & Grow 2016). In a discipline notorious for its lack of strong theories explaining the phenomena of interest, the prospect of generating explanatory mechanisms through simulations and model-building is very appealing (Burch 2003). Besides, demography – a traditionally empirical area of social sciences with many policy implications (Morgan & Lynch 2001) – provides here excellent testing grounds.

However, demographic agent-based models are still in their infancy, and their theory-building potential has not yet been accomplished. The key theoretical gap in demography is the lack of solid micro-foundations of macro-level processes. The existing event-history and multi-level statistical studies do not offer *explanations* of the mechanisms driving demographic change (Courgeau et al. 2016). Microsimulation models are limited by the availability of survey data, and often follow simple assumptions on the mechanisms, for example Markovian 'lack of memory' (idem). On the other hand, agent-based models allow for explicit inclusion of feedback effects and modelling the impact of environment on individual behaviour, but the existing attempts are often based on unverifiable assumptions and axioms (Conte et al. 2012).

One pervasive feature of the social reality is uncertainty, which limits any modelling of micro-foundations of human behaviour (Frydman & Goldberg 2007). Assessing and managing this uncertainty to aid decision making is crucial in all areas of demography, but especially in migration (Bijak 2010). Given the complex and non-linear nature of ABMs, the uncertainty of their outcomes cannot be assessed directly. Instead, other methods need to be used: state-of-the-art solutions include Gaussian process *emulators* – Bayesian statistical models of the underlying computational models (Kennedy & O'Hagan 2001). In agent-based demography, their use has been prototyped by the PI and the research team (Bijak et al. 2013; Hilton & Bijak 2016).

To develop micro-foundations for studying migration, BAPS will apply Bayesian statistical principles to design the computer experiments, to model the simulated individuals (agents) and their decisions. The information gaps identified in this process will be filled by collection of bespoke experimental data on human decision making, on choice between different options, and on the role of uncertainty – especially the subjective probabilities and their possible biases – in this process. In this way, the project will address a key epistemological limitation of demographic simulations, by offering innovative bottom-up modelling based on a range of information sources, in line with the statistical and demographic empirical tradition.

This step change in demographic methodology will be achieved by building an innovative simulation model of international migration, integrating behavioural and social theory within an overarching framework offered by Bayesian experimental design (Chaloner & Verdinelli 1995). Following Ben-Akiva et al. (2012), the model will distinguish the *process* of migration decision making at the individual level, and the *context* at the group and societal levels. This approach will allow fulfilling important postulates of the *Manifesto of computational social science* (Conte et al. 2012): a joint modelling of different levels of analysis, and including experiments in computational models next to more traditional data sources, such as surveys.

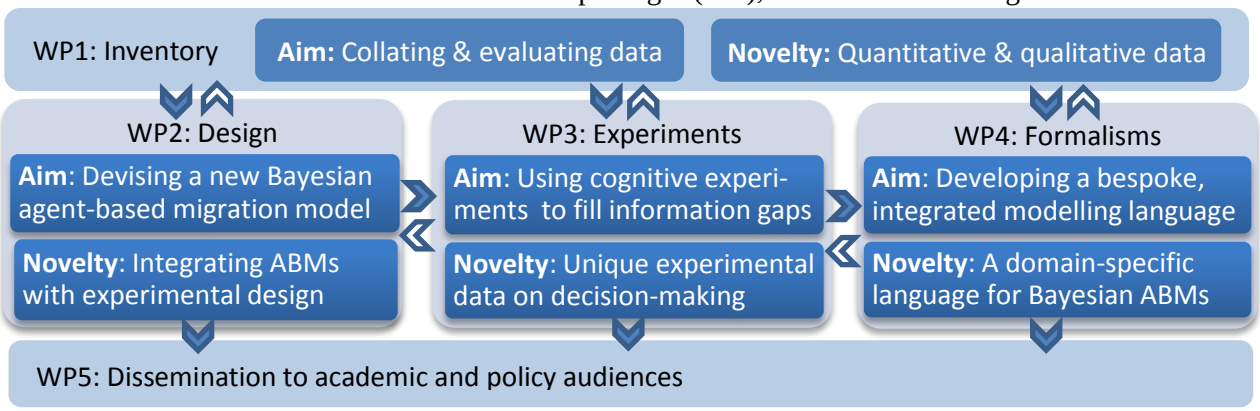
In particular, the project will: (1) collate an inventory of various types of information for constructing simulation models of migration; (2) build and test the simulations by applying the Bayesian experimental design principles, to enhance of our knowledge of demographic mechanisms; (3) collect new information on the underpinning mechanisms, including psychology of decision making, through psychological experiments akin to behavioural economics; and (4) design an innovative domain-specific modelling language for implementing Bayesian agent-based models in practice. The choice of a particular migration case study will be determined in the first phase of the project, following a survey of available information, to ensure that there is enough empirical material for modelling. The specific project tasks are discussed next.

Why is BAPS ground-breaking?

The key cutting-edge methodological features of BAPS are five-fold: (1) construction of a pioneering, bottom-up agent-based model of migration; (2) applying the principles of Bayesian experimental design in the modelling process; (3) integrating the analysis of uncertainty; (4) including additional information on migration-specific aspects of decision making from cognitive experiments; and (5) offering an innovative bespoke domain-specific modelling language that allows a compact description of the migration model and a comprehensive environment for experimenting with these models. By so doing, BAPS will provide a blueprint for including empirically-relevant micro-foundations in computational demographic models, and for acknowledging their epistemological limits: the project will identify the inherently uncertain aspects of modelling, describe their uncertainty, and offer policy recommendations under different predictability levels. As a result, the project will open up exciting research possibilities in demography and beyond, and will generate academic and practical impact, by offering methodological advice for policy-relevant simulations.

Work description

The work in BAPS will be divided into five work packages (WP), illustrated in the diagram below.



WP1. Inventory: *Data, methods and assessments (Months 1–15 and 43–48)*

- Aim: Collating all possible information on a chosen migration case study for use in the modelling, and assessing its quality and reliability in a formal way for describing the associated data uncertainty.
- Rationale: To be empirically relevant, agent-based demographic models need to be based on observations, rather than just from assumptions or axioms (Courgeau et al. 2016). Amongst crucial elements of such models are the *mechanisms* which generate the key functions of the observed processes (Franck 2002). For computational migration modelling, the existing approaches (Kniveton et al. 2011; Klabunde et al. 2015) offer a great starting point, but their main limitation is that they do not explicitly model some of the crucial mechanisms, such as the cognitive aspects of decision making. What is also lacking is a critical inventory of all available information, together with a comprehensive quality assessment.
- Approach: The inventory will include quantitative, as well as qualitative information (Polhill et al. 2010); the latter focusing on the mechanisms of the migration processes. The main novelty of WP1 consists in combining different types of available data, and in creating a comprehensive quality rating system for the reliability of data sources. By including qualitative information on decision making, including the role of time and decision horizon (Abbott 2001), WP1 will provide a comprehensive empirical base for migration models. Quality and uncertainty of the various data sources will be formally assessed through probability distributions, for direct use in the Bayesian modelling process in WP2. We will also identify and detail the requirements for the modelling language and the modelling and simulation environment in WP4.
- Outcomes: The key outcome will be an inventory of the identified data and other information, assembled in a database (open-access) with meta-information on the sources, and a system for assessing their quality and reliability, and translating these assessments into uncertainty measures (probability distributions) to be later used in the modelling process. These outcomes will serve as input to all remaining work packages, and will be updated in order to reflect findings from WP2 and WP3. The preliminary survey of the available information will also determine a choice of a migration case study for modelling – tentative candidates include flows from Poland to the UK, from Mexico to the US, or from North Africa to Europe.

WP2. Design: *Experimental design for agent-based models (Months 7–42)*

- Aim: Devising an agent-based model for the selected case study of migration, based on a comprehensive set of information, and following the principles of Bayesian experimental design.

- Rationale: To identify the role of different factors in the migration processes, the models need to be carefully designed, paying attention to the relative information gains from observing various features of migration. Computer simulations and methods of experimental design help with this task, by showing, which areas to focus on. The weakness of the current agent-based modelling approaches is that design is usually not done systematically, if at all; and that data are used in ad hoc way, rather than being embedded in the process of model building. As argued by Conte et al. (2012) and Courgeau et al. (2016), all data available for modelling should be used for construction of the models. Another limitation of the prevailing approaches is that uncertainty is typically reduced to the computer code, only one of the many sources of randomness in complex computational models (Kennedy & O'Hagan 2001).
- Approach: Based on the inventory in WP1, the case study model will include a range of push and pull factors of migration (Lee 1966), both at the process and context levels, which will enter into agents' decision making processes weighted by their subjective probabilities (DeJong & Fawcett 1991). The underlying mechanisms will be examined by recursive Bayesian networks, following Casini et al. (2011).

  Sensitivity analysis (Kennedy & O'Hagan 2001) and other methods of experimental design (e.g. Liepe et al. 2013) will enable identifying the important model parameters which cannot be identified from data. For those, additional information will be sought in WP3, focusing on the cognitive aspects of decisions. An important element of the modelling process will be the uncertainty analysis (Oakley & O'Hagan 2002), to establish how much is *known* and how much is *knowable* about the processes under study (Kirk et al. 2015). Bayesian methods are particularly well suited for the task, as they ensure coherent learning about the features of the model and provide a comprehensive description of uncertainty.

  WP2 will be based on the information collected in WP1, and its results will feed directly into WP3, by identifying information gaps that will need to be filled; and into WP4, by providing a model description. The novelty of WP2 will be threefold: (1) the bottom-up construction of the model; (2) directly applying the principles of experimental design; and (3) integrating the various sources of uncertainty in the model.
- Outcomes: The key outcomes of WP2 will be an agent-based model of migration, with documentation and guidance for further information collection, and related dissemination tasks: conference presentations, publications in demographic and social simulation journals, and other activities (see also WP5).

WP3. Experiments: *Cognitive agents and decision making (Months 13–48)*

- Aim: Using cognitive experiments under controlled conditions to learn about decision-making processes and the associated biases, in order to fill information gaps identified in the migration model.
- Rationale: The existing agent-based models typically use simplistic mechanisms of decision-making, whereby agents make binary choices based on the results of regression modelling (for examples, see van Bavel & Grow 2016), overlooking insights from cognitive science (Gigerenzer 2008) or more advanced aspects of choice modelling (Ben-Akiva et al. 2012). Hence, there is need for a firm empirical grounding of decision-making models by conducting bespoke experiments on the way decisions are made.

  Decisions under uncertainty have attracted much attention in different disciplines: from Bayesian decision analysis (DeGroot 2004) and its extensions to adversarial problems (Banks et al. 2015) in statistics, to more psychologically realistic prospect theory (Tversky & Kahneman 1992) and heuristics (Gigerenzer 2008) in cognitive science. Initial research by the PI and the research team showed that different decision-making approaches in agent-based models can yield conflicting results (Gray et al. 2016). Crucially, not only are agents' own uncertainty assessments – a cornerstone of Bayesian analysis – biased and mis-calibrated; so are the measures of calibration of such subjective probabilities (Higham et al. 2015).
- Approach: By conducting a series of controlled experiments on healthy adult volunteers, we will elicit information on the key features of the individual decision-making process. The novel elements featured in the experiments, specifically in the context of migration, will include: the mechanism – relative weights of different factors of migration (Lee 1966); the role of time and decision horizon (Abbott 2001); and the role of uncertainty. For calibrating the latter, the signal detection theory approach will be used, following Higham et al. (2015). The exact areas of experimentation in WP3 will be determined in WP2, based on the results of applying the experimental design and sensitivity analysis to the initial migration model.

  The results of cognitive experiments will allow for fine-tuning the model in WP2, and for including specific aspects in the modelling language developed in WP4. They will also allow for reducing uncertainty in the migration model where possible, and for describing the remainder in a coherent way.
- Outcomes: The key outcomes of WP3 will consist of the results of the experiments, and (indirectly) of the revised version of the migration model and its documentation, followed by conference presentations and publications in cognitive science and simulation periodicals, and other dissemination tasks (see WP5).

WP4. Formalisms: *Towards a domain-specific modelling language (Months 7–42)*

- Aim: Development of a bespoke, domain-specific language, integrating agent-based migration modelling, experimental design and model choice in a unified easy-to-use modelling and simulation environment.
- Rationale: Domain-specific languages are designed to address idiosyncratic issues that pertain to particular problem areas, in this case, the agent-based modelling of international migration flows. Languages for demographic agent-based models exist, including those co-designed by BAPS team members (Warnke et al. 2015) for models of migration (Klabunde et al. 2015), and other population phenomena (Noble et al. 2012) – the latter developed in Southampton with the involvement of the PI.

  However, there are no similar solutions for models built from the observations by following the principles of experimental design. Yet, for a piece of research to be truly successful, its results need to be transferable beyond the scope of a particular project. Hence, in WP4, BAPS will provide the academic and non-academic stakeholders and users an intuitive, high-level modelling language, in order to facilitate dissemination of the presented approach and its uptake in practice.
- Approach: BAPS will provide a step change in the existing approaches by unifying experimental design and Bayesian inference about model properties, following the recent advances in statistical computing (Hainy et al. 2014), and the work and expertise of the team members on developing domain-specific languages for model (Warnke et al. 2015) and experiment specification (Ewald & Uhrmacher 2014).

  WP4 will draw on the information collected throughout the project (WP1-WP3), and will provide feedback to the other work packages on how their results should be operationalised in order to be included in the language development process. The migration model from WP2 will be re-implemented in the domain-specific language in WP4, to have a clear, compact declarative description of the model, its experimental design process (WP2), and the associated models of human decision-making (WP3). The modelling and simulation environment will facilitate model analysis, discussion and further extensions. The language will allow the users to follow the modelling above for their own research challenges in an interactive way, identifying areas of potential information gains from additional domain knowledge.
- Outcomes: The key outcomes of WP4 will be the modelling language, an underlying efficient simulator, their documentation, as well as the reinterpretation of the migration model. Detailed validation studies will be enabled by the unified modelling and simulation environment. Conference presentations and publications in computer science outlets, as well as other dissemination activities will follow (see WP5).

WP5. Dissemination: *Academic and policy audiences (Throughout, esp. months 16–18 and 43–48)*

- Aim: Dissemination of the results, with focus on outreach, engagement with stakeholders – academics and policy makers in population-related areas (particularly migration) – and methods training.
- Rationale: Since the envisaged impacts of BAPS reach beyond academia, it will be necessary to pro-actively engage with selected stakeholder groups in order to promote the project and its results.
- Approach: Next to the dissemination of results through academic channels, publications of journal articles, an edited volume or special issue, conference presentations etc., this work package will engage with stakeholder groups directly through organising a workshop and a final dissemination event.
- Outcomes: A two-day workshop, under the auspices of the International Union for the Scientific Study of Populations (IUSSP) Scientific Panel on Micro-simulation and Agent-based Modelling in Demography and the ESRC Centre for Population Change, in London in late 2018, and an end-of-project dissemination event for academic and non-academic audience, policy and the civil society, in Brussels in mid-2021. In 2021, we will also organise a three-day, PhD-level training course on the BAPS methods and software.

Research team, timeframe and resources

BAPS will be carried out by the Allianz European Demographer 2015, recognised as a leader in the field for methodological innovation, who will direct an interdisciplinary team, providing additional domain-specific expertise in uncertainty analysis and experimental design, cognitive and computer sciences. The team will include four team members – Peter W Smith and Jonathan J Forster, University of Southampton (statistics and experimental design), Philip A Higham, Southampton (cognitive psychology), and Adelinde Uhrmacher, University of Rostock (computer science), reporting to the PI. They will bring in additional knowledge needed to achieve the project objectives and will strengthen BAPS with their expertise.

The ground work will be carried out by three full-time postdoctoral research fellows (RF), line-managed by the PI – a Bayesian statistician with experience in experimental design (RF1), an agent-based modeller with interest in cognitive science (RF2), both based in Southampton; and a computer scientist with experience in developing simulation methods (RF3), employed in Southampton, but sharing his or her time between Southampton and Rostock, where s/he will be managed remotely via regular (weekly) Skype/email contact.

BAPS is envisaged for four years, between 1 June 2017 and 31 May 2021. Overall, 13 person-years of effort are required. The involvement of the post-docs will amount to ten person-years in total: four years for RF1, and three years each for RF2 and RF3. The funds requested from the European Research Council, including staff and other direct costs (consumables, travel, events, publications etc.) and indirect costs (overheads), amount to € 1,455,590.

Project management, risk management and research ethics

The project hub will be the University of Southampton. BAPS will benefit from research synergies with the ESRC Centre for Population Change (www.cpc.ac.uk), the leading UK demography research centre, and will use the experience from the EPSRC Care Life Cycle project (www.southampton.ac.uk/clc). In terms of management, the PI will be responsible for all work packages, and a general oversight of the project. The PI has substantial experience in managing research staff and teams, including senior colleagues. Amongst the team members, Forster and Smith will contribute to WP1 and WP2, Higham to WP1 and WP3, and Uhrmacher to WP1 and WP4. Progress will be formally monitored, at least every three months, with four project meetings aimed at checking milestones and exchanging ideas.

BAPS will carry a high overall research risk: fundamentally, there is no guarantee that the micro-foundations will reduce the uncertainty of migration models, but given the very high social stakes, this is a crucial knowledge gap that needs filling. Specific research risks include the ability to identify additional sources of information for the modelling process (WP1, WP3), to construct adequate agent-based models and the tools of experimental design (WP2, WP3), and to create an appropriate simulation environment (WP4). These risks will be controlled by a gradual approach to relevant tasks, from simple solutions to more complex ones.

Managerial risks are mitigated by the experience of the PI in research, innovation and management and by appropriate risk management strategies, such as contingency plans for staffing. Since the ability to recruit and retain high-quality researchers is crucial for the success of the project, researchers will be appointed at post-doctoral, rather than doctoral level. For the same reason, the budget includes a margin for contingency.

As most of the work will be carried out *in silico*, the key ethical issues associated with BAPS are related to the experiments in WP3. To address them, University of Southampton Ethical and Research Governance procedures will be followed (www.southampton.ac.uk/about/conditions-policies/ethics-policy.page), and ethical clearance will be obtained prior to the commencement of the experimental work. The use of secondary or aggregate data, statistical and computer modelling are not associated with foreseeable ethical concerns. Data management will follow the Data Security Policy and Procedures (www.calendar.soton.ac.uk/sectionIV/research-data-management.html). Data, model code, and results will be shared via a website, developed and hosted in Southampton, which will contain both a public, as well as a restricted part.

Research impact

BAPS is expected to generate significant academic impact, by proposing pioneering, transformative methods for building agent-based models of population processes, with focus on migration. The academic stakeholders will include a growing community of computational population scientists, with key hubs at the University of Oxford, Catholic University of Leuven, Vienna Institute of Demography, Max Planck Institute for Demographic Research in Rostock, as well as teams working on other, related ERC projects, with whom closer collaboration will be sought.

The project will also have clear non-academic impact, regarding the way in which the policy makers will be able to use simulation models for testing different policy scenarios concerning population processes. **In particular, BAPS will allow evaluation of the efficacy of migration management and control policies through simulations**. Here, non-academic stakeholders will include policy makers, at the European, national and local levels, as well as planners, both from the private and public sectors. Project results will also be of interest for policy think-tanks, government and parliamentary researchers, special advisors, etc. To that end, BAPS will ensure dissemination of results both through academic channels (workshop, publications, conferences, seminars), as well as non-academic ones, such as the bespoke dissemination event organised within the project. As for other outreach activities, engagement with opinion-forming media is foreseen.

The project will serve as a springboard for additional research, furthering the proposed work in other areas of population sciences and elsewhere. Here, synergies will be sought with PI's involvement, as a founding member, in the IUSSP Scientific Panel on Micro-simulation and Agent-based Modelling in Demography (2015–18). In the career context, BAPS will consolidate the various threads of PI's existing research agenda, and will become a catalyst for building a platform for interdisciplinary, complex, quantitative studies of the micro-foundations of population change: something that currently is critically missing.

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