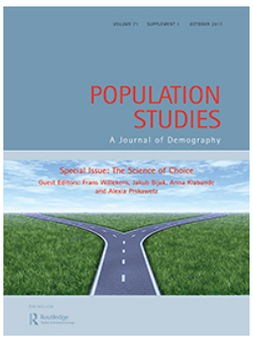

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The science of choice: an introduction

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Introduction

In October 2015, around 30 scholars convened at the Max Planck Institute for Demographic Research (MPIDR) in Rostock to discuss: (a) how individuals and families make decisions about marriage, childbirth, migration, retirement, and other transitions in the life course; and (b) how these decision processes can be operationalized in demographic models. The workshop was organized by the Scientific Panel on Microsimulation and Agent-Based Modelling convened by the International Union for the Scientific Study of Population (IUSSP) and by MPIDR. The report of this 'Science of choice' workshop and the papers presented are available from the workshop's website (see IUSSP 2015). The five papers included in this Supplement are revised versions of papers presented at the workshop in Rostock.

Populations change because people change. The explanation of population change requires a deeper understanding of why people change their behaviour and what causes these changes. These causal factors (e.g., motives) and causal mechanisms (e.g., decision-making processes) cannot be studied at the population level, because they operate at the individual (micro) level, with consequences felt at the population (macro) level (see, e.g., Billari 2015). This *generative explanation*, which states that patterns and dynamics at the macro level are generated by actions and interactions at the micro level, has become a dominant paradigm across the sciences. As noted by Courgeau et al. (2017), the 'downward' feedback effects, from the macro to the micro, imply that the macro-level patterns cannot simply be obtained by aggregation of micro-level behaviour. This necessitates the joint modelling of different levels affecting the phenomenon of interest. Early examples of the generative explanation include Schelling (1978) and Boudon (1979). In the social sciences, this approach is also known as *mechanism-based explanation* (see Hedström and Ylikoski 2010 for an overview and de Bruijn 1999 for an early application of mechanism-based explanation in demography, starting from Coleman 1990). Agent-based models (ABMs) and microsimulation can be used to gain insight into behavioural mechanisms and the transmission mechanisms that connect the micro and the macro.

In population studies, agent-based modelling was initiated in 2001, at a workshop at the MPIDR in Rostock (Billari and Prskawetz 2003), followed by workshops at the Vienna Institute for Demography in 2003 (Billari et al. 2006) and the University of Leuven in 2014 (Grow and Van Bavel 2017). The 'Science of choice' workshop in 2015 zoomed in on one of the core issues in agent-based modelling: namely, the theory and modelling of decision-making processes and the behaviours that follow.

A transition in the life course usually involves multiple choices at several levels (see also Hobcraft 2006). Some choices are related directly to the transition, while others are associated with intermediate factors and risk factors that condition, facilitate, or inhibit the transition. For instance, marriage is the outcome of a complex process involving partner search and matching, with choices along the way. It is common practice in demography to focus on events and to explain and predict events by relating their occurrence and timing to personal characteristics and contextual factors. The focus on events and the explanation by association have proven together to be a successful strategy for most of the time. But individuals and families with similar characteristics and in similar contexts do not always behave in the same ways. Understanding the differences requires a shift from events to processes and pathways, for example, from births to becoming a parent (Hobcraft 2007). Differences are often related to unobserved characteristics. Accounting for the distribution of unobserved factors in a population improves the explanation and prediction, even without knowing precisely what the unobserved factors are. Causal mechanisms consist of processes of decision-making as well as processes turning

decisions into action and behaviour. Explanation by association, on the other hand, disregards these causal mechanisms that produce observed outcomes.

The consequences of micro-level actions and behaviour for population change depend on diffusion processes. New behaviour adopted initially by some may later be adopted by many. Transmission and diffusion require communication, and the easier the communication is, the more rapid the diffusion. That explains the significance of proximity and information technology for diffusion processes. Hence, in general, a mechanism-based theory of population change rests on two pillars: a theory of action and a theory of social diffusion.

The focus of this Supplement is on decision processes and the actions that follow from decisions. In some of the papers, diffusion processes are also discussed, but not as extensively as, for instance, by Casterline (2001). To introduce the papers, we first picture what is known about the processes that result in demographically relevant choices, also referred to as life cycle choices. Next, we discuss the operationalization of that knowledge in ABMs: a class of simulation models in which population change is viewed as an outcome of actions and interactions at the micro level. In the third main section, we introduce the papers and highlight their contributions. In the final section, we reflect briefly on the likely impact of the study of decision processes and agent-based modelling on the discipline of demography.

Choice processes and demographic behaviour: what do we know?

The decision-making process

A decision-making process is the mechanism that links a decision to its determinants and intervening factors that facilitate or constrain the process and its outcome. Reaching a decision is often difficult and takes time. The complexity and duration of the decision process both vary with the nature of the choice to be made. Simple heuristics are usually sufficient for routine choices. Life choices, on the other hand, take time as they involve more deliberation and consultation, because the stakes and the uncertainty are high (Kahneman 2011). During that time, conditions may change, new information may become available, or events may occur that affect goals, preferences, and available resources, and thus the decision itself. Frequently, time is too short to collect all the necessary information to determine the set of options and to weigh them accurately. Deadlines may be self-imposed, imposed by other individuals, or by society, for example, age norms (Liefbroer and Billari 2010; Van Bavel and Nitsche 2013). A consequence is that individuals are forced to select an option based on incomplete information, knowing that a better option might have been selected, given more time. In a recent review of how married couples choose between divorce and reconciliation, Allen and Hawkins (2017) note that the decision to divorce is often constrained by time and influenced by other transitions in the life course, such as securing a stable job or children leaving home, which can be seen as competing risks to the divorce decision.

The notions of choice and decision are often used interchangeably, but it is better to distinguish between the concepts. A decision is a mental process, while choice is the outcome of that process. Decision theory is the study of how choices are made (positive or descriptive theory) or should be made (normative or prescriptive theory) to achieve a goal. A choice is usually, but not always, followed by an action. An action is the implementation of a choice. The use of the concepts ‘decision’, ‘choice’, and ‘action’ differ by discipline. Economists refer to decision theory and choice theory, and do not distinguish between decision/choice and action (e.g., Hess and Daly 2014). In social psychology, decision theory is known as theory of action (e.g., Heckhausen 1991; Fishbein and Ajzen 2010; Heckhausen and Heckhausen 2010). Heckhausen (1991) does distinguish between decision and action. In his theory, a decision implies a commitment to engage in an action, but even then, the action does not follow automatically. By making a decision, the individual crosses the Rubicon, that is, a point of no return or a tipping point. That distinction is useful, and it is central in Kley’s study of the migration decision (in this Supplement).

The Rubicon model, a multistage model of action, originated in developmental psychology (Heckhausen 1991). It starts from the view that individuals pursue developmental goals to produce the life course they want. Developmental goals are anticipated end states; they motivate an individual to act in a particular way. The process of action consists of several stages. It begins with the awakening of a wish to achieve a goal and ends after the goal has been accomplished. The initial Rubicon model (Heckhausen 1991) distinguishes four stages: the pre-decisional stage (phase); the post-decisional but pre-actional stage; the actional stage; and the post-actional stage. The stages are separated by clear

boundaries or transition points (hence the reference to Rubicon): the making of a decision; the initiation of actions; and the conclusion of actions.

More recently, Heinz Heckhausen and his daughter Jutta extended the Rubicon model to a theory of motivation that covers the entire life course, by introducing the time it takes to make a decision or to plan and prepare an action. That time is constrained by *developmental deadlines* in the life course. The deadlines are determined biologically (e.g., menopause), socially (e.g., age norms), or legally (e.g., duration of pregnancy at abortion). These deadlines introduce a sense of urgency and may result in suboptimal decisions (Heckhausen et al. 2010).

Properties of decision processes

Models are cognitive aids for comprehending complex processes. The decision processes covered in this Supplement have four basic properties. First, the outcome of a decision process is a choice between a *finite number of alternatives*, called prospects by Kahneman and Tversky (1979). This type of choice is usually referred to as a *discrete choice* because the variable that represents the alternatives (choice set) is a discrete variable. Second, each alternative carries considerable risk. The *uncertainties* complicate the decision. Utilities or benefits of each alternative cannot be anticipated with certainty, preferences are not stable, conditions may change, and unexpected events may occur. As a consequence, the outcome of the decision and the factors that influence the decision are usually modelled using random variables.

Third, decision-making takes *time*, which is needed to gather and process information and to deliberate about the relative merit of each alternative. This substantive interpretation of the duration of decision-making is supported in psychology, cognitive science, and neuroscience (Hawkins et al. 2013; Standage et al. 2015). The amount of time an individual takes depends on their cognitive interests and capabilities, and their experiences with similar decisions. The consequence is a great diversity of decision styles, decision rules (heuristics), and decision durations. The time needed to determine the merit of an alternative also varies with the alternative itself. If time only permits the collection of sufficient information (evidence) about a subgroup of alternatives, the individual is likely to favour these alternatives over other alternatives with incomplete information (Usher et al. 2013). Therefore, a choice is a trade-off between speed and accuracy.

These first three properties may be incorporated into the decision-making model by representing the discrete choice problem as a stochastic race, called a 'horse race' in random utility discrete choice models (Busemeyer and Rieskamp 2014). The horse race model and its extension, the speed–accuracy trade-off model (dating back at least to the pioneering work of Hale 1969), allow the diversity of decision rules and durations to be captured.

From a demographic standpoint, the stochastic race model is essentially a competing risks model (Marley and Colonius 1992; Colonius and Marley 2015). That important observation has not yet received much attention in the literature, although Marley and Colonius in psychology and Pudney (1989) in economics refer explicitly to the competing risks model.

The fourth, related, property of the decision process is *distinct stages*. Each stage integrates the achievements of earlier stages. The duration of each stage determines the total decision time. Klabunde et al. and Warnke et al. (both in this Supplement) implement the stochastic race model and distinguish several stages of the decision process.

Deliberation

Alternatives may vary in time and space. A first step in any deliberation is to find out what the options are, that is, to determine the choice set. Options that are theoretically possible may not be feasible in a particular cultural or political context. For instance, in some societies, partner search is highly regulated because partnerships and marriage affect the social status of the family and may involve a substantial intergenerational transfer of property. While not prohibiting them, society may discourage alternatives. For instance, in most parts of the world hypogamy (marrying down, i.e., marrying a person of a lower social status) is discouraged for women, although the social pressure is weakening. In this Supplement, Grow et al. investigate why this pressure is subsiding.

The options an individual can choose from change continuously as a result of sociocultural change, economic change, political change, technological change, or a combination of these. Changes in choice sets are major drivers of social and demographic change. For instance, the decision to postpone childbirth (e.g., because of career aspirations) has been made possible by advancements in reproductive technology and assisted reproduction. Similarly, globalization and the advancement of information and communication technology (such

as the Internet) have increased the options dramatically for people considering emigration in search of education, employment, or adventure, or for family reasons.

Deliberation is often a collaborative activity and results in shared decision-making. Shared decision-making has been studied extensively in the contexts of households (see, e.g., Becker 1991; Ermisch 2003), migration (see, e.g., Stark and Bloom 1985 and the 'new economics of migration' literature), and healthcare (see, e.g., Lippa et al. 2017). Partners in collaborative deliberation are not necessarily equal. Their bargaining power in the decision process and their impact on the choices made usually depend on available resources, including income, information, wealth, and cognitive capabilities. The influence may vary between the stages of the decision process. Partners may not enter stages of the decision process at the same points in time, causing frictions and complicating shared decision-making. Haley et al. (2002) provide an excellent discussion of the issues of joint decision-making involved in end-of-life decisions, involving various aspects of care arrangements, such as palliative, medical, or hospice care. Authors who study difficult and complex end-of-life decisions stress the need to distinguish personal perspectives on the transition, decision styles, and decision heuristics, and to educate those involved to make a truly shared decision (see, e.g., Barry and Edgman-Levitan 2012; Mathew et al. 2016).

Stages of decision-making

From the point of view of modelling, it is convenient to regard the decision process as a process with multiple stages. In what follows, we present a brief review of models of individual decision-making and action, in which processes are divided into stages. Janis and Mann (1977) were the first to distinguish stages in the decision process. They consider five stages: (1) appraising the challenge; (2) surveying alternatives; (3) weighing alternatives; (4) deliberating about commitments; and (5) adhering to the choice made, despite negative feedback. Haberkorn (1981) applied these stages to study the migration decision. The five stages are often considered in models of choice, for example, in discrete choice models (see, e.g., Hess and Daly 2014).

The prospect theory of decision-making under uncertainty distinguishes two stages in the choice process: an early phase of editing and a subsequent phase of evaluation (Kahneman and Tversky 1979, p. 274). During the editing phase, information is collected and a preliminary analysis of alternatives is performed, which determines how prospects are perceived. The authors claim that people perceive options as gains or losses. That framing of outcomes has a significant effect on the decision process and the choice made. During the evaluation phase, the value of each edited prospect is assessed using a valuation rule and a prospect is chosen accordingly. Tversky and Kahneman (1992, p. 299) refer to the two stages of the choice process as 'framing' and 'valuation'. The authors concentrate on cognitive biases during the editing (framing) and evaluation (valuation) stages that are not accounted for in the expected utility theory, the dominant theory of choice in economics (for a brief recent discussion of the expected utility theory, see, e.g., Moscati 2016).

Another theory of action that distinguishes stages in the process leading to action is the transtheoretical model (TTM) of action (Prochaska et al. 1992). This perspective, which was originally developed to understand and predict health behaviour, is called 'transtheoretical' because it integrates principles from different leading theories. In the TTM, intentions to act unfold over time and involve progress through six stages of change: (1) precontemplation (no action is intended); (2) contemplation (considering a change in the next period); (3) preparation for action; (4) action (making a change); (5) maintenance (sustaining the change over time); and (6) termination. A main reason for staying in the first stage is a lack of awareness of the consequences of the action. In the maintenance stage, an individual adjusts their life to accommodate the transition. Some people may regret a transition or cannot cope with the need to adjust. People who reach the termination stage have adjusted and internalized the transition. Tabor and Milfort (2011) applied the TTM in a study of British migrants to New Zealand. The decision process starts at a time when the individual has not given any serious consideration to moving abroad. The process ends with integration in the destination country. The authors found that the decision process starts well before the migrant leaves the country of origin and it continues indefinitely thereafter. A similar approach is followed by Grow et al. in this Supplement. Partner search does not end with marriage, but continues and may lead to divorce and repartnering.

McCall (1970) proposed a dynamic model of job search involving learning. During the early stages of job search, an individual learns their value on the job market and adjusts their wage aspirations in order to get a job. A job offer is only accepted if

the wage exceeds a minimum threshold (*reservation wage*). The rejection of job offers comes at a cost because of foregone earnings. The cost increases with the duration of the search. The reservation wage is a measure of how attractive an individual considers themself on the labour market. This attractiveness may initially be overestimated. Job search is a learning process and time matters. Oppenheimer (1988) discussed the similarity between job search and partner search. Todd et al. (2005) used this search model and found that individuals differ in the time they need to gather information to determine their own value on the marriage market. Cohabitation is a means by which partners may gather information.

The interest in how people make decisions led some scholars to introduce time into established theories of behaviour, extending the theories that initially focused on decision outcomes to theories that focus on multistage decision processes (*process theories*). That has been the case with the Theory of Planned Behaviour (TPB), which is widely used in the behavioural and social sciences, and has a long history in demography (Burch 1980). We briefly describe the theory first and consider the extensions next. The TPB (Ajzen 1991) originated in social psychology as an extension of Fishbein's theory of reasoned action (TRA) (Fishbein and Ajzen 2010). According to the TPB, intentions predict behaviour —to some extent. Individuals form intentions on the basis of personal beliefs about: (a) relative benefits of a given action (behavioural beliefs/attitudes); (b) social expectations (normative beliefs/social norms); and (c) their own ability to choose and act independently (agency), to mobilize resources, and to remove or conquer barriers (control beliefs/perceived behavioural control). The last element is inspired by Bandura's (1977) concept of *self-efficacy*, which is one's belief in the ability to accomplish a task.

Intentions predict behaviour, but the predictive power may be weak because the actual ability to accomplish a task may differ significantly from one's belief (actual behavioural control). For more detail on the TPB, the reader is referred to the paper by Klabunde et al. (in this Supplement). Recently, the theory inspired the conceptual framework of reproductive decision-making adopted in the Generations and Gender Survey (GGS) (Liefbroer 2011; Philipov et al. 2015). Klobas and Ajzen (2015) applied the theory to gain insight into the decision to have a child. The theory has also been applied to migration (for a review of studies, see Klabunde and Willekens 2016).

Courneya and Bobick (2000) extended the TPB to a decision process theory by integrating the TPB and the TTM. Armitage and Arden (2002) used the TPB for discriminating between the stages of the TTM. Klabunde et al. (this Supplement) also extend the TPB, by distinguishing four stages in the mental process preceding emigration (see also Willekens 2017).

Although conditions that trigger transitions between stages of a decision process have been studied extensively, the conditions that determine the onset of a decision process have been explored less. What causes people to consider or develop a positive attitude towards a life choice, such as marriage, divorce, or migration? It may be an event, the accumulation of experiences (e.g., dissatisfaction with current conditions), signals received from significant others (social network), or the context more generally. These factors influence all steps of the decision process, but they are particularly significant as initiators of the process.

Social context

Finally—and crucially in the context of agent-based modelling, as discussed in detail in the next section —the autonomy of an individual to make choices (agency) and the options available depend on the social context. Through social pressure and social sanctions, the social (plus cultural and political) context assures that individual behaviour stays within acceptable boundaries. For example, a person's religion may not allow divorce, same-sex marriage, or modern family planning, or their government may make abortion or euthanasia illegal. Such regulations seriously discourage people from even considering these life choices. Secularization was instrumental in the diffusion of modern family planning and fertility decline in eighteenth-century Europe (Lesthaeghe and Surkyn 1988). Past and current state policies are highly relevant contextual factors in individual choice (see, e.g., Presser et al. 2006 on birth control practices). Some authors have abandoned asking people about motivations for the choices they make and concentrate on the context instead.

In a study of the mechanisms of Mexico–US migration, Garip (2017) did not ask about migration motivations, to avoid recall bias and post factum interpretations, but obtained detailed accounts of each person's circumstances and events before leaving. One event was the US Immigration and Nationality Act of 1965, which blocked avenues for legal re-entry for the millions of Mexican temporary

workers in the US who would normally return home regularly for short stays. It resulted in a surge of illegal migration and an increase in permanent settlement in the US (Massey and Pren 2012). Immigration policies often have unintended consequences (Castles 2004; Czaika and de Haas 2013) because individual choice mechanisms and human agency are disregarded.

Decision processes in agent-based models

Classical demographic models, such as the life table or the cohort-component projection model, do not incorporate decision processes. The main parameter of a demographic model is the rate at which demographic events occur (i.e., births, union formations, separations, migrations, and deaths). That rate, which is usually referred to as the hazard rate or transition rate, relates observed or estimated number of demographic events during a given period to the duration of exposure during that period. The event count during a given period, however, depends not only on exposure time but also on the choices people make. For instance, the number of union formations during a given period is the number of couples that completed the partner search process, found a match, decided to form a union, and implemented that choice in the action of union formation. Similarly, the number of migrations during a period is the number of people who made the decision to migrate, completed the planning and preparation, and left their place of residence. Relating counts of events (process outcomes) during a given period to exposure during that same period disregards the duration of decision processes, which may start long before the period considered.

Since decision styles and decision processes differ greatly between individuals, couples, and families, models that incorporate decision processes are often simulation models, sometimes referred to as actor-based or agent-based models (ABMs). They differ from the more common population-based models in two respects. First, they model demographic events at the micro level and thus belong to the family of micro-demographic models (Keyfitz and Caswell 2005). Population characteristics are obtained by aggregating the experiences of members of that population. Second, they model events as outcomes of decision processes, which naturally take place under uncertainty and are influenced by other actors in the population. Interactions between actors underlie the diffusion processes of values, opinions, and behavioural patterns in a population. Decision and diffusion are micro-level processes that generate the patterns and dynamics observed at the population level.

Review studies have found that the majority of the decision models incorporated in ABMs are not based on an established decision theory but on a plethora of independent ad hoc assumptions about how choices are made (Huang et al. 2014; Klabunde and Willekens 2016; Schlüter et al. 2017). Among the theories used, the rational choice theory, which states that people maximize their utility, is most prevalent. The theory encompasses the Expected Utility Theory (Moscati 2016) and the Discrete Choice Model (Hess and Daly 2014), but also the Value Expectancy Theory (Fishbein and Ajzen 2010), key elements of which are incorporated into the TRA and TPB. The initial version of the rational choice theory was based on very restrictive assumptions. Extensions have made the theory more realistic by accounting for imperfect information, limited cognitive abilities (affecting the amount of information that can be collected during a given period), uncertainties, and effects of previous decisions (inter-temporal choice).

More recently, the divide between choice theories and models in economics, psychology, and cognitive science has started to be bridged. The outcome is a truly interdisciplinary 'science of choice'. These developments are beginning to be introduced in ABMs. The inadequacies of choice theories in ABMs constitute a serious weakness that needs to be overcome in order to make agent-based modelling an effective instrument for gaining insights into the causal mechanisms driving demographic change. That is what motivated the 'Science of choice' workshop in Rostock.

The papers

André Grow, Christine Schnor, and Jan Van Bavel address partner choice and focus on the impact of available alternatives on the outcome of the choice process. Individuals tend to associate with others who are similar; a phenomenon known as *homophily*. Social background and cultural identity are important attributes, but personality, interests, and world views are relevant too. Homophily is usually explained with reference to preferences. Recently, however, Kets and Sandroni (2016) explained homophily as a strategy for reducing uncertainty. Individuals face less uncertainty when they interact with others who are similar to them because it is easier to anticipate reactions and to coordinate decisions and activities. Homophily also explains assortative mating, which is often observed in partner search and marriage.

Homophily is only part of the story, however. For people with limited economic resources, partnership (and marriage in particular) is a strategy to achieve upward mobility. Grow et al. note that both homophily and upward mobility operate in the marriage market. The attractiveness of a partner depends on economic resources (earning potential) and similarity in cultural resources (educational attainment).

In the past, women attached relatively more importance to economic resources because their earning potential was less than that of men due to differences in educational attainment. They tended to marry better educated men (hypergamy) and to stay married. Over the past few decades, women's education has increased significantly and, since the 1990s, women have been surpassing men in terms of participation and success in higher education. A consequence of the reversal of the gender gap in education is that, today, many women are better educated than men, and the attractiveness of a possible partner is determined less by economic resources. Another consequence is that marriages are less stable because the attractiveness of the partner is compared continuously with the attractiveness of spousal alternatives. Grow et al. remind us that the partner search does not end with marriage. The risk of losing the spouse depends on two mechanisms operating simultaneously: the emergence of opportunities to start new relationships and the willingness to make concessions to maintain the current relationship. The authors present a search model that extends beyond marriage, which is unique in the demographic literature.

Stefanie Kley extends Heckhausen's Rubicon model, which distinguishes between decision and action, and applies that model of action to internal and international migration. When an individual believes they cannot realize their goals in the current place of residence, they may consider migrating to another place. When opportunities arise elsewhere, significant others support a migration, and financial and other resources are sufficient, the person may decide in favour of migration. That decision implies a commitment by the individual and most likely also by others. As a consequence, it is 'costly' to abandon the decision process after the decision is made. Having previous migration experience facilitates the decision process: people with migration experience are likely to need less time to accumulate information on alternative destinations and intervening factors, and thus may reach the decision sooner.

In her contribution, Kley focuses on factors and agents that facilitate or constrain the decision and the action. The decision process is often triggered by events in the life course or external events—political or other. Personal achievements, such as education or financial and other resources, facilitate migration. Other factors, such as the presence of school-age children and strong local ties, constrain it. Particularly important during the planning stage are facilitators at the destination, including social networks. Facilitators and constraints involve many uncertainties, resulting in a high proportion of people abandoning the decision process during the pre-decisional stage and even during the planning and preparation stages.

Anna Klabunde, Sabine Zinn, Frans Willekens, and Matthias Leuchter focus on international migration. They extend the TPB (Ajzen 1991; Fishbein and Ajzen 2010) to describe the *process* leading to emigration, which consists of four stages. A person in the first stage has never considered emigration. The person leaves the stage when they develop an interest in emigration or decide against emigration. In the second stage, the person develops behavioural beliefs, normative beliefs, and control beliefs, which ultimately result in an intention to emigrate or the decision to abandon the intention and stay. A person who has developed an intention to emigrate moves to the next stage and starts planning and preparing to leave the country. The preparation stage ends with the emigration. During the planning and preparation stages, the person needs to mobilize resources, to overcome barriers, and to take advantage of opportunities that may arise. Planning and preparation will be successful if the person is capable of dealing adequately with control factors. If the actual behavioural control is deficient, the person may decide or be forced to stay. Many people consider emigration but few leave their country, because the expected benefits do not exceed the expected costs, or the constraints that emerge during the decision process hinder them. The development and realization of intentions are embedded in the life course. Transitions in the life course may occur, for example, marriage, childbirth, or a change in activity status, and these may affect the emigration process at any stage. Individuals are also influenced by the opinions and support of members of their social network and by social norms. External events, such as increased border control and other policy changes in destination countries, may occur too. Transitions in the life course, social norms, social support, and external shocks are subject to uncertainties. These are incorporated by specifying a stochastic process model, more specifically a Markov process model.

A distinguishing feature of the model presented by Klabunde et al. is that most transitions in the life course are determined by transition rates, but migration is determined by behavioural processes and associated behavioural rules. Migration and other life events are competing risks; whether migration or another life event occurs is the outcome of a stochastic race. The transition rates, which are the parameters of the process model, are estimated from data, except for emigration. Emigrations are based on behavioural rules and rules governing the interactions between individuals. Individuals may leave the behavioural process at any stage. More people abandon the process in the early stages than in later stages, consistent with the theory. The model is calibrated using data from the Migrations between Africa and Europe (MAFE) survey.

The computational implementation of complex ABMs, such as the model described by Klabunde et al., can be troublesome. Specialized computer languages, if available, facilitate the implementation of ABMs. Tom Warnke, Oliver Reinhardt, Anna Klabunde, Frans Willekens, and Adelinde Uhrmacher present a new programming language that facilitates the implementation of agent-based stochastic models in demography. The language, called the *M*odelling *L*anguage for *L*inked *L*ives (ML3), allows for a compact description of life histories that involve complex decisions, interaction between individuals, and other behavioural processes. The language is domain-specific, which means that it is designed specifically for demography and uses the demographer's language. ML3 is inspired by the success stories of domain-specific languages in biology and other fields.

In ML3, a population is composed of individuals and institutions. An institution can be a cluster of individuals, such as a household, or a local or national authority or civil organization. Multiple levels of analysis are distinguished. Individuals and institutions, which in the ABM are both referred to as agents, have attributes that change during the life course following transition rates or behavioural rules. If decision-making and the planning and preparation of the action take longer than the waiting time to a rate-based competing transition, then the behavioural process is interrupted and the competing transition occurs. This is consistent with the theory of competing risks. Agents interact with other agents and develop links (ties) and social networks. Ties may be institutionalized, leading to new agents. ML3 is applied to the migration model presented by Klabunde et al. (this Supplement).

The integration of behavioural theories into demographic models through agent-based modelling is a nascent field. In the final paper, Jonathan Gray, Jason Hilton, and Jakub Bijak give directions. A critical issue is the choice between alternative theories from economics (including behavioural economics), sociology, psychology, cognitive science, and other fields. In order to enhance insights into demographic behaviour, the theory and any model that is based on the theory should meet several requirements.

First, the theory should situate individual behaviour in a context and the model should operationalize the context. There seems to be general consensus that the social context should be operationalized as a social network of individuals and institutions. The structure of the network matters, but also *what* flows over the network structure. Agents in a network exchange information and exercise influence. They may also exchange resources and provide support. An individual has some freedom to choose the social network but they are also moulded by the network. For instance, an individual's preferences are likely to be similar to the preferences of other members of the social network, because they are influenced by the same network. In ABMs, that is operationalized by deriving an individual's preference from information reported by other members of the network (e.g., desired income from reported income levels). The flow of information and other items in a network is not a passive process, but is actively influenced by members of the network. That may result in shared belief systems that may differ substantially from the belief systems in other social networks, leading to polarization. Such a mechanism can be accommodated relatively easily in ABMs.

A second requirement is that the theory and model should emphasize the *process* character of decision-making and actions, as illustrated in the papers by Kley, Klabunde et al., and Warnke et al. (all in this Supplement). By implication, time matters (see Abbott 2001). Time enters the ABM in at least two ways. First, time locates decisions and actions in a time-varying context. Age (individual time) situates decisions and actions in the life course, and calendar time locates decisions and actions in their historical contexts. Second, if an individual prefers to receive something now rather than later, a time preference exists and discounting is appropriate.

A third requirement is that the theories and models account for the various uncertainties. Gray, Hilton et al. (this Supplement) distinguish between epistemic uncertainty (lack of knowledge) and aleatory uncertainty (inherent randomness). Epistemic

uncertainty can be reduced by learning. Aleatory uncertainty cannot be reduced, but its effects can be mitigated by risk diversification and risk sharing. Finally, a fourth suggested requirement is that behavioural theories and models acknowledge heterogeneity: individuals differ in how they make decisions and how they plan and prepare actions. They differ in the way they frame situations and interpret messages, actions, and events.

The way forward

No single theory or model is likely to satisfy all requirements. Therefore, the way forward suggested by Gray, Hilton et al. (this Supplement) is to: (a) consider different theories and models (multimodel approach); (b) adopt a modular approach to modelling, which means developing building blocks (including computer code) that can be reused later and by other researchers; and (c) replace critical hypotheses and assumptions with empirical evidence on decision processes and behavioural mechanisms, including evidence produced by experiments. Ideally, model design guides data collection and better data lead to better models with fewer assumptions. This makes agent-based modelling an iterative process.

Decision and diffusion are micro-level processes that generate the patterns and dynamics observed at the population level. The extent to which behaviour at the micro level causes changes at the population level depends on the transmission of preferences, attitudes, and resources to other agents in the population, that is, on diffusion processes. Agent-based modelling is the proper strategy for combining decisions and diffusions. ABMs may combine conventional demographic rates with theory-based decision rules, behavioural (action) rules, and rules of social interaction and transmission, as illustrated in the models presented by Klabunde et al. (this Supplement) and Prskawetz (2017, p. 61). The adoption of ABMs that combine evidence-based rates of transition with theory- and evidence-based rules of transition would bridge the divide that exists between social demography and formal demography. In this way, agent-based modelling could unite social and formal demography, as originally proposed by Burch (2003).

Similar suggestions have been made in the decision literature. Ben-Akiva et al. (2012) advocated an extension of discrete choice theory to a theory on how people make decisions, including the introduction of insights from psychology and sociology into economic theories of choice. Individual beliefs play an important role in theories and models of decision-making and action. They are central in the Expected Utility Theory and the TPB. Beliefs form the cognitive structures or mental models that enable people to interpret events, actions, and situations, and that help to shape their values and preferences. The operationalization of beliefs, the combination of beliefs and empirical evidence, and the revision of beliefs in light of new information raise important issues in the modelling of decision-making and action. These issues can be addressed effectively by adopting a Bayesian perspective, which is not only based on the subjective interpretation of probability as a measure of belief, but also has explicit links to statistical decision theory (DeGroot 1969/2004; Robert 2007; Arló-Costa et al. 2017).

In the 1970s, Ajzen and Fishbein (1975) discussed Bayesian information processing and the use of Bayes's theorem to update beliefs in the light of new information. They never incorporated the Bayesian information processing model in the TRA or the TPB. They concluded, however, that Bayes's theorem could serve as a unified and integrated framework for the study of human behaviour. For many years, the paper received little attention, but that has now changed. The Bayesian perspective on how people reason, learn, and make choices is gaining importance in cognitive science, in particular since scholars identified the similarity between Piaget's theory of cognitive development (e.g., Piaget 1966) and Bayesian learning. Piaget distinguished between assimilation (where new information is incorporated into the existing mental model) and accommodation (where the existing mental model is revised in light of new information) (see, e.g., Miller 2016). That similarity stimulated the interest in Bayesian reasoning and learning (see, e.g., Perfors 2016; Tourmen 2016). Bayesian reasoning is the use of subjective probabilities to represent degrees of belief and the manipulation of these probabilities in accordance with rules of probability theory. The graphical representation of relationships between characteristics of interest is referred to as a Bayesian or belief network. In demographic agent-based modelling, a recent foray into this area compared the use of Bayesian decision theory with several alternative options (Gray, Bijak, et al. 2017).

Bayesian reasoning, Bayesian networks, and their extension, *decision networks*, offer a unified approach to the study of choices people make (Jern and Kemp 2015). These developments give rise to Bayesian cognitive science and Bayesian decision science (see, e.g., Colombo and Hartmann 2015 for a recent review). Even if human reasoning does not necessarily follow the Bayesian blueprint in many real-life settings (Gigerenzer and Goldstein 1996), the Bayesian

perspective can still provide a coherent language to address different aspects of the complex and uncertain demographic reality, and offer a way of integrating individual-level behavioural insights with a statistical analysis of population-level phenomena. Following Bijak and Bryant (2016), we therefore believe that demography can benefit greatly by adopting a Bayesian perspective on the processes and causal mechanisms underlying demographic change.

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