Review

A Literature Review on the Usage of Agent-Based Modelling to Study Policies for Managing International Migration

Gabriele De Luca [1,*], Thomas J. Lampoltshammer [1], Shahanaz Parven [2] and Johannes Scholz [3]

1   Department for E-Governance and Administration, University for Continuing Education Krems,
     3500 Krems an der Donau, Austria
2   Department for Political Processes and Analysis, RUDN University, 117198 Moscow, Russia
3   Research Group Geoinformation, Institute of Geodesy, Graz University of Technology, A-8010 Graz, Austria
*   Correspondence: gabriele.deluca@donau-uni.ac.at

Abstract: This literature review is dedicated to the subject of agent-based modelling for the system of international migration, and of the modelling of policies that are known to aid in its management. The reason for the selection of agent-based modelling as a framework for studying international migration is that the system of international migration presents the characteristics of a complex system: notably, its property of emergence, which therefore imposes the usage of a methodology for its modelling that is capable of reflecting its emergent traits. The policies that we study are those that intervene in the country of origin of emigrants and that are aimed at decreasing the aggregate volume of emigrants from that country. The reason for this choice is that policies in the countries of origin have become particularly attractive today, especially in European countries, under the assumption that it should be possible to prevent the migrants from reaching the point of destination of their journey if some kind of action is undertaken before the migrants arrive. We start by discussing the theoretical constraints that suggest how this approach may only partially be valid. Then, to assist the development of future agent-based models that study migration, we identify via topic mining the ten topics that are most commonly discussed in the literature on the application to the international migration of agent-based models; this lets us highlight the characteristics of an agent-based model that should be included when the research task relates to the usage of ABM to study international migration and its associated policies. Finally, we indicate why the existing literature on the modelling of international migration is missing a key aspect that is required to correctly model policies: the integration between agent-based approaches and systems dynamics.

Keywords: agent-based modelling; international migration; migration policies; system dynamics

1. Introduction

This paper analyses the usage of agent-based modelling in migration studies and, in particular, its application for studying migration policies in the country of origin of migrants. The objective of this study is the identification of the "known-knowns" in the literature on migration, concerning the types of policies that can be applied to manage emigration, as they can be studied through agent-based models. We also want to find the limitations and knowledge gaps that are present in the literature, in order to improve the capacity of models to represent the real-world phenomenon, which would, in turn, assist in the management thereof.

It is arguable that politics, and in particular European politics, has a strong desire to manage immigration to Europe in such a manner as to reduce it (Carling 2011). Legislative mechanisms for immigration control are in place (Brochmann and Hammar 2020), and their stated objective consists of the creation of instruments by means of which immigration can be limited. Whether the underlying phenomenon can be controlled through instruments, and in particular legal instruments, remains however the subject of controversy. A common

illusion in the sector of political science, and in particular in the branch of the discipline that studies norms and regulations and their impact on society, is the idea that, through laws, it is possible to control social systems. This may be incorrect (Hejl 1990), and, if it is incorrect, then all legal constructions that depend upon it are also incorrect. Let us replace for a second the object, which is supposed to be regulated by law, and shift it from a social to a physical object, to clarify why this is the case. Immigration is often described as a *flow* of persons across a political border (Nica 2015), with the alternative term of *streams* also found in the literature (Capps et al. 2012). Let us suppose that the phenomenon that a particular law is supposed to regulate is not a flow of immigrants, but rather the flow of water proceeding down a river (see Figure 1).
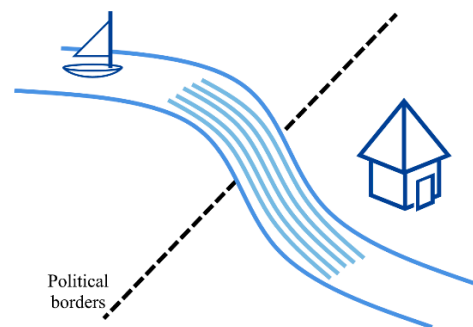

Figure 1. Particles of water, a river, flowing through a political border.

Let us now consider the situation in which we, as the political decision-makers of the country into which the river flows, decide to control the flow of water in the sense of its reduction. The only instrument that we have available for our purpose is the law because this is the toolset that our office provides. We could, in this case, attempt to adopt a law that makes it illegal for the particles of water to cross through the arbitrary border that we claim to correspond to our territorial area of competence, and we would be surprised when we find out that the water does not comply to our instructions. Instead, we could also attempt to control the flow by adopting a law that favours the development of, say, a dam, which would let us reshape the river and modify its course (see Figure 2).
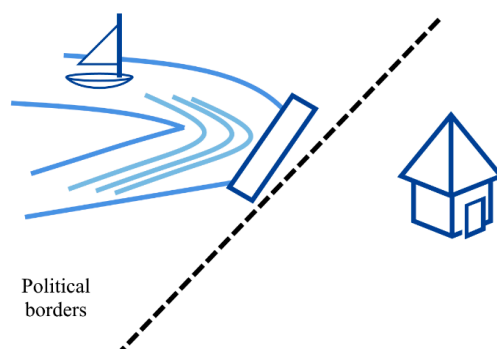

Figure 2. How to modify a flow of water.

The reason why the first approach, based on law, does not work is that the river does not function in such a manner that human laws can influence it. A person or politician who believed otherwise would be deluded and is bound to be eventually disappointed upon finding out that their policies are not followed by the moving particles. The reason why the second approach, the one based on engineering, may work is that the latter is based upon the scientific understanding of what a flow of water is, and the technical way to intervene in it; moreover, and more importantly, it is based upon the rules that its behaviour follows, independently from the human intervention. A river such as the one we described, regardless of whether any specific human observer would see it, would behave according to the same immutable rules.

Now, as we shift from the consideration that water flows through political borders, to the consideration that humans also 'flow', we might be tempted to claim that humans are special systems and that they do not behave like the water particles in a river. Namely, we might be tempted to say that the law of the State can regulate them and can influence their behaviour; this may or may not be true: of course, we may find out that, in some particular cases, the words of a legislator as they are embedded in a policy are being followed by the humans that flow, but there is no reason to think that this *has* to be the case. An engineering- or physics-based approach to the study of migration, aimed at learning its rules and at developing technology around it, might function where the policy-based approach might fail.

Notice that this is generally not how we look at international migration: instead, we consider the interaction between migration drivers and policy in some pair of countries, as a non-linear process that is mediated by the migration flows that take place between those two countries (Czaika et al. 2021). We do not assume that migration happens autonomously, and void of any attempt on the part of some humans to regulate it, mainly because we observe that governments, indeed, meddle with it significantly. The effects of governments' intervention on migration, then, differ significantly from the intended ones, and may even end up causing the opposite of the intended effects, such as by increasing irregular migration while intending to decrease it (Czaika and Hobolth 2016).

Notice also that building dams for managing migration flows is, in practice, very common: for example, we can observe that there is an actual fence (a dam *sui generis*) that separates India from Bangladesh (McDuie-Ra 2014), which leads to a variety of human right violations. Another fence also exists between Israel and Palestine, and one could argue that the political identity of the Palestinians is indeed a derivation of the physical artefact (the fence) located along the border (Mana et al. 2015); this suggests that, hidden in the idea that migration can be managed, lies the consideration that migration must follow some kind of physical constraints of the environment, and that by intervening on those physical constraints it is possible to shape migration accordingly.

This is not an argument in favour of the securitisation of political borders, as one may incorrectly think by extending the analogy between rivers and dams, on one hand, and migration streams and walls on the other. Instead, this is an argument in favour of the application of a reductionist approach, first, and a systems approach, second, to model migration and understand the way in which it functions. Not the normative approach (Ghosh 2000), then, but an approach that might be based upon systems thinking.

This is also an argument in favour of discarding the idea that policies can necessarily regulate the behaviour of a social system, and in favour of considering them instead as something that operates in the system. Their outcome, within this context, needs to be assessed functionally, regardless of the intended or stated objectives that a policy holds. We will learn that, if we distance ourselves from the idea that migration policies can *in principle* manage migration, we may find out that policymakers, instead, are conducting for us, the scientists, a very important task: they are testing the validity of hypotheses concerning the rules that describe the behaviour of migration systems.

This paper is structured as follows. First, we study the alternative approaches that can be applied in social sciences for modelling migration systems. We will argue, in particular, that the approaches that originate from the sector of complexity theory and artificial intelligence are particularly prone to be further developed by the literature on the subject. Then, we discuss in more detail the theoretical problems that are related to the idea that the public management of political systems is possible. Finally, which comprises the core of this review, we identify the main themes that are discussed today in the literature on migration studies at its intersection with agent-based modelling and argue that the interaction between systems approaches and agent-based approaches to study international migration remains limited.

2. Theoretical Foundations

2.1. Reductionism and Emergence in Migration Systems

The study of migration through a reductionist approach has a long history (Ravenstein 1889), and indeed it produced an important research trail which was, however, eventually marginalised due to its highly descriptive, not explicatory, power (Davis 1988). More generally, though, the reductionist approach to the study of migration came out of fashion with the increased role that complexity theory has played in the discipline of migration studies. While generally less descriptive as an approach than reductionism, the application of complexity theory to international migration (Tranos et al. 2015) allows scholars to study the emergent properties of that system, which by definition would be missing in any reductionist approach. The application of complexity theory to international migration has been done, from the perspective of modelling, according to two branches: agent-based modelling and systems dynamics (Parunak et al. 1998).

Systems dynamics is based upon the modelling of a system under ordinary differential equations, or difference equations for time-discrete systems, which describe the topology of a system and, notably, its configuration space. In the sector of migration, systems dynamics are suitable, for example, for the study of the Ravenstenian laws and their applications to some particular societies (Benassi et al. 2019). An interesting and unexplored application of systems dynamics to migration consists in the application of the so-called principle of least action in classical mechanics, which has been hypothesised to explain Ravenstein's laws as the paths of least action in the configuration space of a system of migration (Zelinsky 1971). In general, the approach to systems dynamics is based upon the idea that migration as a whole is a phenomenon that depends only on the demographic, social, and economic parameters of any given system that is being studied. The implication for this is that it does not account for the individual agency of the migrants themselves, which are presumed to behave according to characteristics of the system and not of themselves.

Agent-based modelling, instead, is based upon the idea of representing an individual (or groups of individuals) with software agents acting in a defined environment. Each agent can act autonomously and interacts with other agents and the environment alike; it draws heavily upon the research in artificial intelligence and its translation into social sciences conducted by Axelrod (2006). Agent-based modelling is founded upon the idea that individuals think, or at least that they make decisions, and studies the resulting aggregate behaviour of the population as an emergent property of the individual agents' decisions. Further, agent-based models do not require the hypothesis that the system eventually reaches equilibrium, however this is defined; instead, they can help answer questions related to how the system reacts to changing situations (Macal and North 2005).

The policies for managing migration are necessarily based upon an idea or a set of assumptions regarding how migration works; in other words, on a certain theoretical understanding of it (Castles 2010). Because the systems dynamics approach accounts for primarily macro descriptions of the systems of migration, it opens the door for managing it by employing macro policies such as development (Skeldon 2010), or criminalisation (Dowling and Inda 2013); this, however, closes the door to the methods for behavioural modifications that arise out of the studies in cognitive sciences and psychology, and notably the usage of media (Musarò 2019) or the cognitive behavioural approaches (Armitage and Conner 2000). The latter have a limited application in the sector of migration as of today and are used primarily for the treatment of mental health conditions by immigrants (Ooi 2013). In general, the systems approach misses out on all the dimensions of migration that are internal to the migrant, and therefore the policies that are developed on top of it also fail to address them.

On the other hand, one can assume that the migrants are thinking agents, whose behaviour is a reflection of some kind of cognitive processes that take place in their brains. Contemporary sociological models are, in fact, oriented in this direction (Burns et al. 2018); this is the underlying epistemological assumption of the application of agent-based modelling to migration, as discussed above; if one does that, then it opens the possibility to

manage the observable behavioural phenomenon, the emigration of an individual, utilizing the techniques that can affect that individual's cognition. We can see how this opens the possibility to formulate a more refined, intellectual rather than physical, method for managing migration, that aims at influencing the decision to emigrate rather than the emigration itself.

2.2. Why Using Agent-Based Modelling to Study International Migration

The methodology of agent-based modelling originates from the studies conducted in the sector of artificial intelligence (Russel and Norvig 2020), and from its implementation in the sector of social and political science (Riolo et al. 2001). The methodology presumes the existence of an intelligent agent, in this case, a human being, who operates in an external environment from which it is epistemologically but not functionally separated, and in which it takes decisions that affect the agent's state and behaviour. The behaviour of the agent can normally be grouped into one of two possible classes: proactive behaviour, also known as goal-directed behaviour; and reactive behaviour, also called perceptive behaviour. The lack of full information comprising the status of the system in which the agents are embedded takes the name of bounded rationality, which is the standard hypothesis for agent-based models and accounts for the necessity of humans to conduct decisions despite limited thinking capacities, and of an approximate knowledge of reality (Yan et al. 2018).

In the context of migration, the environment is loosely defined as the social (Van Hear 2010) and ecological system (Hermans-Neumann et al. 2017) in which the human is embedded. Within that environment, the human agent makes decisions in general; for the purpose of studying migration, though, the decision to migrate is the one that is relevant (Haug 2008); this decision is made according to a variety of observations that the human performs, and which constitute the external input to the decision-making process for that human (Panda and Mishra 2018); it also takes place according to specific decision-making mechanisms that occur inside the psyche of the individual, and which affect the outcome of the decision itself (Heekeren et al. 2004). The output of the decision-making process is the decision itself, which is an observable behaviour that is represented by the physical displacement of the individual from their community of origin. The migration researchers do not, however, directly observe the single decisions to emigrate, or not emigrate, by each individual in a given society that is being studied; instead, they observe the aggregate stream of emigration for that society in a given time frame and use it to conduct predictions (Fertig and Schmidt 2001); this aggregate stream depends on the individual decisions to emigrate, and is therefore linearly dependent on it; any given number of individual decision-making processes can, however, constitute the aggregate, observable number that constitutes the actual emigration stream. In fact, in a population with n individual and k observed emigrants, the possible combinations of decisions to emigrate that result in the observed value of k is the binomial coefficient $\binom{n}{k} = \frac{n!}{k!(n-k)!}$, which means that a significant number of possible distributions of individual decisions may correspond to any given observed aggregate number of emigrants. The human agents who emigrate are not, however, undifferentiated individuals; instead, each of them acts according to their own rules, which may or may not be shared in common with other agents. The usage of the aggregate value of immigrants to describe the characteristics of the system of international migration, without accounting for the individuality of the migrant, greatly oversimplifies the description of a phenomenon. The modifiable areal unit problem also tells us that, whenever we aggregate data that is spatially distributed along modifiable borders, such as political borders, it can be aprioristically predicted that the aggregated data will not be representative of the underlying, or ground distributions (Wong 2004).

Instead, we can use agent-based models to map the possible configurations of the internal components of the system of international migration which, when we measure the aggregate level of migrants that move, results in the observed distribution of persons. The more the aggregate number of migrants is the consequence of emergent dynamics, the

more this type of approach matters: if the system of international migration could be purely described through systems dynamics or ordinary differential equations, then the agent-based models would not be needed. In conducting this literature review, we argue that this is not the case. Because migration systems are characterised by emergence, and because the individual migrant has at least some level of agency, it is then required to merge the modelling approaches based upon systems dynamics and ordinary differential equations with those based upon the idea of an agent; this is particularly important, especially, if we aim to regulate or manage the system of international migration.

2.3. The Public Management of Social Systems

The public management of social systems can be conducted under the assumption that, if a particular phenomenon was sufficiently well understood, it would then be possible to control it and cause it to appear, disappear, or change, according to one's own volition (normally the politicians, legislators, or policymakers); this type of approach is based upon the idea that a public administration can, by means of the policies that it adopts, affect the social system in a deterministic manner; this idea is false, and indeed it can be argued that all policies that are aimed at some particular scope will end up causing such involuntary consequences that the decision to adopt those policies, in the first place, will become questionable.

Instead, what can be done is to study whether the social phenomenon of interest, in this case, international migration, is conducive to the emergence of characteristics of the system of interest, in this case, the system of international migration, or not. If it is not, it is then important to determine whether a certain phenomenon is contributing to a decrease in complexity of the system to which it belongs; that is, if it increases the system's entropy. If it does, it then becomes reasonable to attempt to control that single variable that corresponds to an entropy-increasing phenomenon, in order to decrease that variable by increasing the system's entropy. Let us look at an example, that lets us clarify this concept further.

One of the theoretical and policy approaches to the study of migration is called securitisation (Lazaridis and Wadia 2015). Securitisation considers migration as a phenomenon that should be treated within the security policies of a state because it is believed to impact the national, social, and economic security of the country that receives incoming migrants; in other words, it frames migration as part of the risk (or risky) strategy of a state (Boswell 2007). The idea is that, by using measures such as the adoption of criminal laws against migrants (Gerard and Pickering 2013), one can effectively control the volume of incoming immigrants and the impact that they have on a metric of our choice for measuring security or stability. Further, under securitisation, it becomes appropriate to deploy military assets at the land (Galemba 2018) or maritime (Léonard and Kaunert 2020) border of a country, to prevent immigrants from physically crossing it. In doing so, the expectation is that the security of the host country is higher than the one that would have existed, or that would have been measured if the immigrants were let through the border. In other words, the securitisation approach toward migration is based upon the assumption that a certain set of consequences derive from the arrival of migrants into a host country, and that these consequences are primarily or generally negative (Jaskulowski 2019); however, whether or not this is true is a matter of science, not of politics, and if the underlying assumption were false then this would also prove the theoretical impossibility to achieve the desired result through the selected policy. Now, let us assume for a moment that there may be a mistake in the application of, say, the securitisation approach to policymaking. That is to say, let us assume that no matter how high a wall we build, human migrants will always find a way to get through or around it. Regardless of whether or not the policy that we adopt attains its expected goals, are there any predictable consequences that operate in the universe, regardless of the effects that the policy has on the system that it attempts to manage? For example, a policy of securitisation may cause an actual wall to appear somewhere, where previously there were none; it may also cause the expenditure of energy, necessary to mix the cement that is required to build a wall.

Now, the answer to this last question does not depend upon the stated political objective that the policy is attempting to achieve; it is, therefore, important to notice that whatever the objectives that are stated in association with a given policy, this has no impact at all upon the real-world effects that that policy produces; this consideration may lead us to formulate an interesting thought: maybe, when policies do function correctly, it is because they are representing in human language the real-world phenomenon that would take place regardless of them; this is an important alternative explanation as to what policies do in relation to social systems: when they work, they may not be causing the phenomenon that they describe; but rather, they might be correctly describing a phenomenon that takes place regardless and despite them. The failure of the policies for the management of migration is established in the literature (De Haas 2007); although it has also been argued that the failure of migration policies concerns their lack of effectiveness concerning their declared intentions, and it is unknown whether the concrete implementation of policies is what determines their efficacy (Czaika and De Haas 2013). We will get back to the distinction between declared intentions and actual implementation of a policy in a moment. Let us now, instead, consider the case in which the legislator attempts to regulate the behaviour of a falling apple (see Figure 3).
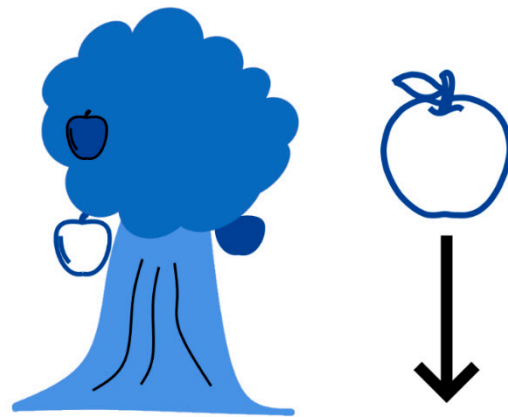

Figure 3. A falling apple.

Let us now assume that the legislator is unfamiliar with the rules that describe the behaviour of a falling apple; this may happen, for example, because Newtonian gravity has not yet been formulated into words (or maths). The legislator produces laws since that is part of their job description; and some of these laws may dictate the behaviour that a falling apple is expected to keep in compliance with the legal system. The legislator has two mutually exclusive options, in our scenario: it could mandate that all apples that leave the tree should move downward, or it could also mandate that all apples leaving the tree should move upward instead. We can call these two possible policies the "law of downward motion" and the "law of upward motion", respectively. Notice how the options available to the legislator are independent of the physical behaviour of the apple and are normally the result of political processes that are inaccessible and unknown to the plants themselves. Upon adopting one of the two laws, the legislator then proceeds to check whether the law is being respected, by observing whether the apples that fall from the try comply or not with the legal prescriptions related to their expected movement. Of course, the legislator who adopts a law of downward motion will observe that the falling apple, indeed, respects the law, while the legislator who adopts a law of upward motion will be perplexed and disappointed. Table 1 sums up the two possible cases that may emerge, as the legislator attempts to regulate the behaviour of the moving fruit.

Table 1. The relationship between policies, expectations, and their observed results.

Policy adopted	Law of downward motion	Law of upward motion
Observed behaviour	The apple falls downward	The apple falls downward
Efficacy of the policy	Efficient	Inefficient

Notice how the observed behaviour of the system which is being managed does not change in the two cases; this does not surprise us, because we do not have any theoretical expectations concerning the capacity of the legislator to affect the behaviour of the system by means of policy. The legislator, however, may believe that by using policy it is indeed possible to affect the trajectory of the apple: this is the case, for example, if legislators have been appointed because the population demanded them to regulate the falling apple (Dennison and Geddes 2019), regardless of whether or not the system can be regulated *in principle*. Now we get to the interesting part: we know that, in adopting either policy, the legislator has no capacity whatsoever to affect the behaviour of the system; however, as the legislator tries various policies and observes whether the intended effects are being achieved, the legislator is effectively testing hypotheses concerning the behaviour of the system which he is incorrectly trying to regulate. If the legislator adopts the law of downward motion, he observes that this law is efficient because the law embeds a description in the natural language of the physical rules according to which the system functions, independently and regardless of the legislator and their policies. If the legislator chooses instead the law of upward motion, he notices that their legal provisions are systematically violated; they would claim that the behaviour of the downward-accelerating apple is criminal, but what they would be concretely doing is assessing the empirical falsity of the physical law which has been embedded in the language of the policy.

If we renounce the idea that policy has the capacity to affect migration, we gain instead the possibility to treat the policies that are classified as "effective" by policymakers as containing some measure of validity in describing the autonomous, independent behaviour of the system of migration. Further, and more interestingly, we also gain the possibility to treat policies that are ineffective as falsified hypotheses concerning the possible laws that describe the autonomous, independent behaviour of the same system.

This is a possibility that we do not explore sufficiently when we study the computational modelling of social systems. Policies, and in particular those that can be classified as either effective or ineffective, comprise a precious corpus of knowledge concerning the shape and type of the functions that describe or do not describe if ineffective, any particular human system. For example, if we accept that policies aimed at establishing social connections between a community of origin and a host community are capable of generating migration (Parven 2019a), then this means that whatever laws describe migration need to operate on a social network (Pitoski et al. 2021a, 2021b). If we accept that economic reasons explain part, but not all of the emigrations to certain countries (Parven 2019b), then this means that there is a function that is at least bivariate, and which maps the wage differential plus some other variable to the set of destination countries by the migrants. If we accept that the promotion of diversity is a method for managing immigration (Doytcheva 2021), then this means that a policy can be considered effective if it increases the information entropy that is measured on the distribution of the population after its adoption; this argument becomes particularly important because there are datasets that classify migration policies and includes some measures of their effectiveness, such as the IMPIC for immigration (Helbling et al. 2017), and the MIPEX for integration (Solano and Huddleston 2020). We do not do this in this article, but we want to point out the possibility to exploit failed policies for the management of migration in place of the empirical testing of hypotheses concerning the rules that the system of international migration follows.

3. Methods

3.1. Formalisation of the Research Questions and Hypotheses

For this literature review, we formulated three research questions that integrate one another, and that shed light on the relationship between systems dynamics, agent-based modelling, and policy formulation in the specific context of migration.

The first research question concerns the application of agent-based modelling in particular. We can assume that the decision-making process of the individual can be modelled as a finite-state machine (Saini et al. 2011), that takes as an input the social and ecological factors perceived by the human, and then processes them to reach the behavioural output for that human (see Figure 4).

Figure 4. The first research question.

The question then becomes, what finite-state machine predicts the aggregate level of emigration that is measured in one society?

As discussed above in the introduction, the implication for public policy formulation is that it might be possible to affect the aggregate level of emigration, by intervening in the social and ecological factors that are identified as having the highest weight in the formulation of the output of the finite state machine.

The second component of the research question corresponds to the interaction between the agent-based approaches to study migration, which is embedded in the finite-state machine discussed above, and systems dynamics. The foundational approach to the study of international migration, since time immemorial (Greenwood 2019), comprises the application of laws that describe the system of international migration; these laws are very prone to be modelled under a systems dynamics approach, but for some reason, the discipline of migration studies has not investigated this possibility thoroughly. One of these reasons may be the identification of empirical constraints that falsify the laws of Ravenstein (Malmberg 1997) since these comprise the theoretical foundations of the discipline of migration studies and also possess a quasi-mathematical format.

The third component of the research question comprises the joint application of agent-based and system dynamics modelling to the formulation of policies toward migration. If it turns out that agent-based modelling is an appropriate methodology to study migration, and if it turns out that system dynamics is appropriate, too; further, if we decide that integration between agent-based modelling and system dynamics is possible, we then deduce that we can use their hybridization to formulate policies that affect migration dynamics.

3.2. Inclusion and Exclusion Criteria

The data source for this article consists of the articles that answer to the query "agent-based AND modelling AND migration" in the scientific database Scopus by the publisher Elsevier; this query resulted in 369 documents. To avoid the trap of overreliance on one single data source, we also queried the scientific database Directory of Open Access Journals, by sending GET requests to its API. For the latter, the search query we used is "agent-based migration", which resulted in a total of 319 articles. The code that we used to query the DOAJ and prepare a dataset out of the returned objects can be found in our online repository.[1] Both searches were conducted on 28 June 2022, and the dataset corresponds to all of the entries recorded up to that point in time. The searches were conducted over the field "Abstract, title, and keywords" (for Scopus) and over "all fields" (for DOAJ).

Alternative scientific databases, and in particular Web of Science, were not selected because the authors do not hold a paid subscription with Clarivate Analytics, while both Scopus and DOAJ can be queried free of charge.

We then computed an overlapping index for multi-database searches, calculated as the Szymkiewicz–Simpson coefficient (Vijaymeena and Kavitha 2016), which corresponds to:

$$\text{overlap}(\text{Scopus, DOAJ}) = \frac{(\text{Scopus} \cap \text{DOAJ})}{\min(|\text{Scopus}|, |\text{DOAJ}|)}$$

It is important here to note that we are not conducting a systematic literature review, but rather topic modelling; for this reason, it is appropriate to use overlapping metrics that are commonly used in the literature on topic mining and consider less appropriate those that derive from the literature on systematic reviews, such as those contained in (Bramer et al. 2017).

In the expression above, the names of the two databases, in this case, refer to the set of elements retrieved from them and, for the min function in the denominator, to the size of the retrieved sets. The resulting overlapping coefficient is 0.0470 out of a maximum of 1 and a minimum of 0, which indicates that each database greatly adds to the other one in terms of coverage. The two datasets were then merged, and the duplicate elements were removed. The merged dataset, at this stage, comprised 671 elements.

The inspection of the merged datasets showed that a significant portion of the retrieved documents related not to human migration, but rather to the migration of animals, biological organisms, and diseases, or to theoretical networks and computer science. There is no value for this literature review that derives from the inclusion of articles from branches of science other than social science; thus, all articles were subsequently labelled, manually, according to whether they belonged to social sciences or not. The labelling was conducted by us on based of the content of the title and the abstract of each article: we judge that no expert knowledge is required to conduct this task, besides an undergraduate degree in social sciences. The 671 references were therefore subdivided according to the following classes, as presented in Table 2.

Table 2. Social sciences versus non-social sciences in our dataset.

Class	Number of Papers
Social Sciences	205
Not Social Sciences	466
Total	**671**

In case of doubt concerning its class affiliation, a paper was associated with the category of social sciences. The question we had in mind when assigning labels, and whose answer constitutes the class affiliation of each article, was "Does this particular article mention humans, individuals, human populations, or economic systems?". Edge cases, in which the article mentioned "humans" but in which humans were mentioned exclusively as biological organisms, were labelled as "Non-Social Sciences"; some papers on the migration of human cells fell for example under this case. Epidemiological models, however, which included the diffusion of diseases in a human population, were included in the category "Social Sciences" at this step.

It should be noted that some papers proposed agent-based models that fell into the category of theoretical computer science because of their high level of abstraction, and would thus apply in principle to agents other than humans; these were considered "non-social sciences". Some others, instead, presented an analogous level of abstraction but were described by the authors as relevant for social simulations, and were therefore inserted into the category of social sciences. The 205 references in the cluster of social sciences were then further subdivided into two binary subcategories, according to whether they related to international migration. A paper was considered to correspond to international

migration if, in either the title or the abstract, there was an explicit mention of at least two states, or a continent, or one state versus the rest of the world, such that the affiliation with the sub-class of "international migration" could be decided undoubtedly. If it was not possible to decide whether an article related to international migration or not, by reason for example the lack of identification of the type of migration that was discussed therein (e.g., rural-urban as opposed to international), then the article was classified as "non-international migration". If a paper referred to migration between very large regions, such as between continents or across an ocean, it was assumed that the migration described therein referred to "international migration" as opposed to "non-international migration", even where explicit mentions of nation-states were not found; this type of classification allowed us to develop the following distribution of papers (Table 3).

Table 3. Distribution of articles according to their supra and subclasses.

Supra-Class	Number of Papers
Non-Social Sciences	466
Social Sciences	205
Sub-Class	
Non-International Migration	142
International Migration	63

The text of all articles 63 included in the category "international migration" was then downloaded and inserted into the dataset that entered the analytical pipeline. At this stage, all texts were inspected manually, and some had to be excluded or adapted, as indicated in Table 4 below.

Table 4. Exclusion and adaptation post-download.

Article	Excluded or Adapted?	Reason
(Oleynik et al. 2021)	Excluded	Language: Russian, not English
(Jahani et al. 2021)	Adapted	Inaccessible due to paywall. Abstract used in lieu of the full text
(Makarov et al. 2018a)	Excluded	Language: Russian, not English
(Liu et al. 2017)	Adapted	Inaccessible due to paywall. Abstract used in lieu of the full text
(Skinner et al. 2018)	Adapted	Inaccessible due to paywall. Abstract used in lieu of the full text
(Makarov et al. 2017a)	Excluded	Language: Russian, not English
(Makarov et al. 2017b)	Excluded	Language: Russian, not English
(Ruiz et al. 2014)	Adapted	Inaccessible due to paywall. Abstract used in lieu of the full text
(Barbosa Filho et al. 2013)	Adapted	Inaccessible due to paywall. Abstract used in lieu of the full text
(Soto 2007)	Excluded	Language: Spanish, not English
(Makarov et al. 2016)	Excluded	Language: Russian, not English

Notice that the comparatively large number of publications that were excluded because of the language is due to the fact that the initial screening had been conducted on the basis of the abstract alone, and that the scientific databases that we used had indexed the English version of the abstract which was eventually retrieved by us. Texts that were "adapted", as indicated in Table 4 above, have had their abstract used in lieu of the full text; these texts thus contributed to topic identification; but since the full text itself was not accessible, we

have not included them in the subsequent (human) analysis. Reasonable efforts at finding online some accessible versions of the five "adapted" papers were attempted but failed. With only one exception, all of the adapted papers belong to a topic that will be considered "residual" in the later sections of this analysis, so their impact on the topic formulation or the conclusions of this review can be considered limited.

The figure below represents the flowchart of the procedure that we followed, in order to generate from the original search queries a final dataset that we then subjected to text processing (Figure 5).
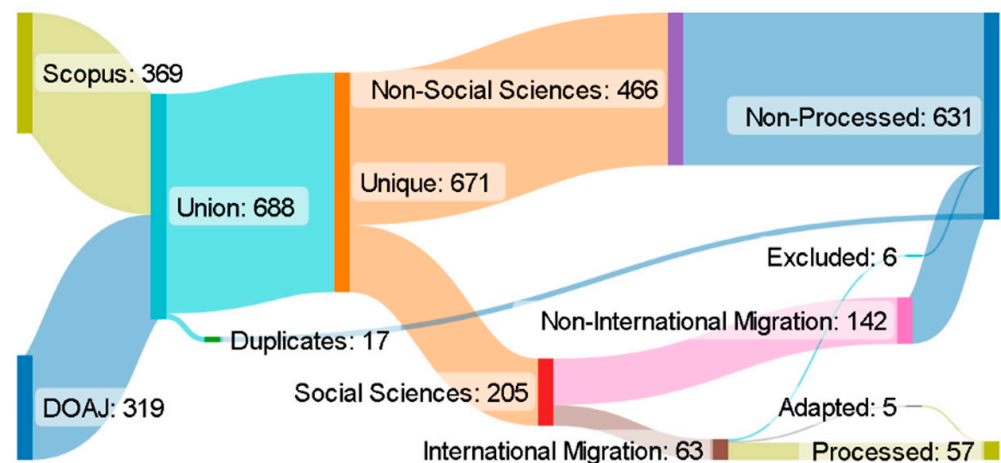

Figure 5. Flow chart of the classification procedure that we followed.

3.3. Topic Mining

The quantitative methodology that we used for the analysis of the texts in the sample takes the name of topic extraction or topic mining (Liu et al. 2003). The task that we attend is solved by constructing an ontology that is representative of the topic contained in a text corpus, and the features contained therein; this methodology is consistent with the one employed in the literature by others (Abirami et al. 2018), and is based upon the application of a matrix decomposition technique. In our case, we have first preprocessed the text corpus by stemming, lemmatising, and removing the stop words, and then we have converted each document into a vector by aggregating according to the bag-of-words approach. For the purpose of extracting lemmas, we have assigned the first token encountered by our parser as the lemma for all words whose stemma corresponded to that of this first token. The matrix decomposition technique that we used, instead, is the Latent Dirichlet Allocation (LDA), which is a standard methodology for topic mining (Campbell et al. 2015). LDA has found previous usage in text analysis for social and political sciences (Sakamoto and Takikawa 2017), and is appropriate for research tasks such as ours. The features identified by LDA as comprising an individual topic were used to populate an undirected graph. The vertices of the graph comprised a sequence of numbers that identified the topics into which the documents were decomposed, and a set of vertices corresponding to the word features extracted by LDA. We then connected via edges all features with their corresponding topics. In doing so, the connection between topics emerged and became visible in the form of a path that connected vertices representing topics. Topics that, instead, were disconnected, were characterised by the absence of a path that connected them. In other words, a connected graph would indicate topics with at least some degree of overlapping, while a disconnected graph would indicate topics with no overlapping. Finally, the topics were labelled by the researchers, according to human knowledge, in order to provide a descriptive name to which they could be referred subsequently.

4. Results

The choice as to what number of topics to extract via LDA is largely arbitrary, though it is customary to select 10 (Abirami et al. 2018). For this reason, we extracted the ten most

important topics present in the corpus, and we represent below the graph that corresponds to them (Figure 6).

Figure 6. The topic decomposition of the set of articles that we analysed.

The graph is fully connected, and this indicates that all topics relate to some of the others. The most central keywords in the graph are *agents*, *data*, *migration*, *simulation*, *modelling*, and *population*, and this is consistent with the expectations that we have, since these are the keywords that we have selected for querying the databases.

The table below reports the list of keywords associated with each topic and retrieved from the list of most significant keywords associated with each topic in the LDA model (Table 5). The label for each topic was assigned manually by us. The keywords correspond to the best predictors for each topic, sorted from the one with the most influence. We decided to cut the list of predictors to the tenth greatest, as this allows the list of keywords to remain intelligible to the human researcher.

Notice that the keywords that we used to select the articles in the first place, such as "modelling" or "migration", figure in most topics and are therefore deemed to not be informative (indeed, it would be surprising if these keywords were not present in the topic decomposition).

This set of topics, extracted according to the methodology we have described, represents the set of topics that are discussed today in the scientific literature on the usage of agent-based models for migration studies. The table below shows the topic most closely associated with each of the articles that have been reviewed in this study (Table 6).

Table 5. Topics extracted from the corpus of articles.

Topic	Label	Keywords
0	From individual behaviour to group dynamics	new, migration, cities, groups, agents, modelling, residents, social, planned, urban
1	Data-driven policies for migration	migration, agents, unauthorized, migrants, scientist, modelling, policies, channels, location, restricted
2	Migration and the environment	agents, modelling, population, dispersion, resources, data, pastoralist, variable, hominin, environments
3	Geographical economy and migration	arctic, migratory, process, problem, robustness, modelling, types, economic, dynamics, zone
4	Health, genetics, and households	modelling, population, data, households, simulation, useful, times, individual, areas, asian
5	Conflicts and refugees	modelling, refugees, agents, simulation, conflict, parameter, movements, country, data, displacement
6	Income and refugees	modelling, migration, simulation, population, useful, agents, times, country, refugees, income
7	Ethnic violence	modelling, agents, violence, useful, simulation, ethnic, process, number, message, computer
8	Economic migration from Hispanic countries	migrants, migration, country, return, distribution, home, useful, modelling, border, number
9	Computational and simulation aspects	modelling, agents, migration, useful, social, data, migrants, abm, simulation, study

Table 6. Strongest associations between topic and articles in the LDA model.

Topic	Articles
0	(M'hamdi et al. 2019; Alghais et al. 2018; Collins and Frydenlund 2016; Alghais and Pullar 2018)
1	(Simon et al. 2018; Vaccario et al. 2021)
2	(Bijak et al. 2020; Nelson et al. 2020; Norman et al. 2018; Frydenlund et al. 2017; Hölzchen et al. 2016; Wren et al. 2014)
3	(Shultz and Costopoulos 2019)
4	(Jahani et al. 2021; Vallée et al. 2016; Vogel et al. 2015; Gaube and Remesch 2013; Truscott and Ferguson 2012; Kishore et al. 2021)
5	(Suleimenova et al. 2021; Searle and van Vuuren 2021; Hébert et al. 2018; Groen 2016)
6	(Gürsoy and Badur 2021; Termos et al. 2021; Meyer and Vasey 2020; Bystrov et al. 2019; Reinhardt et al. 2018; Picascia et al. 2018; Klabunde et al. 2017; Picascia and Yorke-Smith 2016; Lin et al. 2016; Warner and Afifi 2014; Heiland 2003; Padmanabha et al. 2015)
7	(Makarov et al. 2018b; Groen 2018; Bakhtizin et al. 2017; Klügl and Bazzan 2012; Weidmann and Salehyan 2013)
8	(Klabunde 2014; Hüttinger 2020)
9	(McAlpine et al. 2021; Dyble 2021; Huang and Unwin 2020; Al-Khulaidy and Swartz 2020; Harris et al. 2018; Liu et al. 2017; Skinner et al. 2018; Blandin et al. 2017; Ruiz et al. 2014; Sokolowski and Banks 2014; Nemiche et al. 2013; Barbosa Filho et al. 2013; Kniveton et al. 2011; Smith et al. 2011; Sokolowski and Banks 2010)

The articles in italic, above, correspond to those that were "adapted" and thus excluded at this step from further analysis.

The figure below (Figure 7) indicates the distribution of articles per topic.
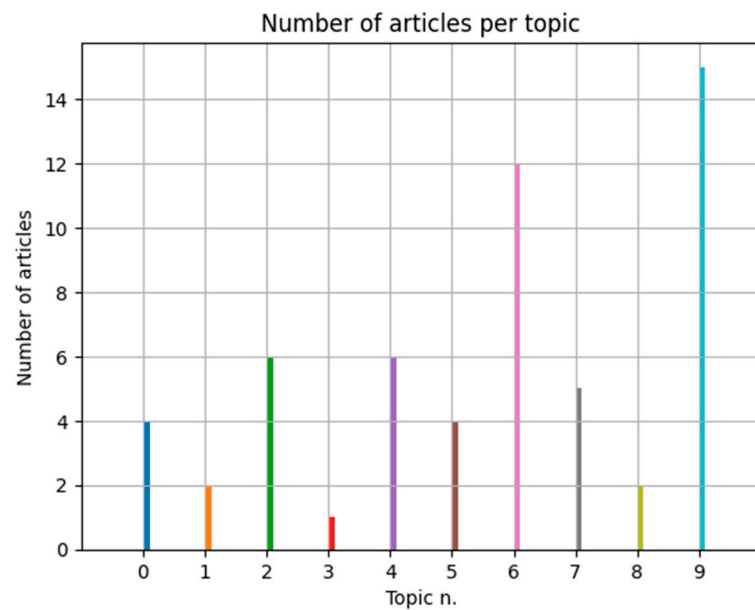
Number of articles per topic

Figure 7. Distribution of articles per topic extracted via LDA.

It can be noted that the relative majority of the articles fall into the last topic; indeed, it appears that the distribution follows an exponential law (Figure 8), with almost half of the articles concentrated on the two most populous topics.
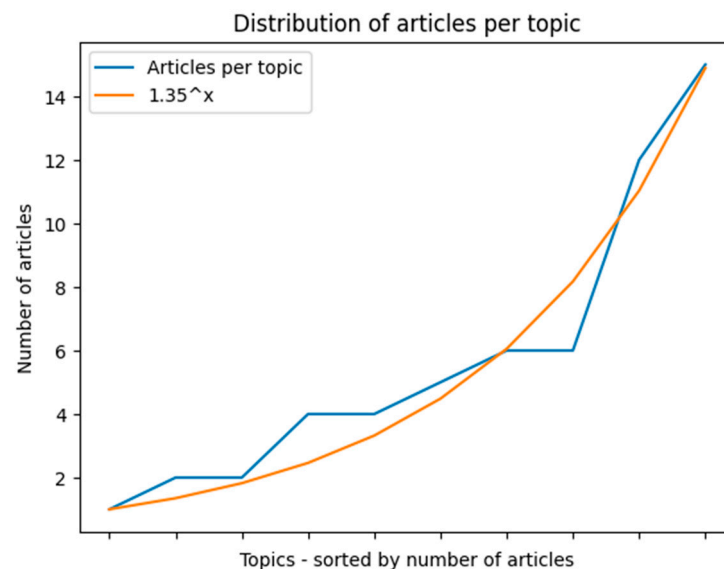
Distribution of articles per topic

Figure 8. Distribution of articles per topic extracted via LDA.

5. Discussion

We can now analyse the topics and the contribution that each specific article brings to the scientific knowledge associated with it.

The first topic relates to the problem of identifying the correspondence between individual rules of behaviour for single agents, on one hand, and the characteristics of the society to which those agents are below, on the other; this topic comprises four articles.

The article by M'hamdi et al. (2019) studies the problem of dual or parallel evolution in artificial societies, with the intent of modelling the separate evolutionary dynamic and the eventual convergence of Eastern and Western countries. The underlying, basic argument of this article is that, even though some features of separated societies, such as the tendency towards individualism or collectivism, may evolve independently, these features may be modified via a process of migration. When this happens, two autonomous lines of

evolution may eventually converge into a similar social system. The agent, in their model, migrates according to a decision function that considers both the availability of resources (and thus, economy) and the level of repression that they suffer (and thus, politics); their study concludes that, if a society is experiencing a crisis, the emigration of some of its components may help it survive and continue evolving, whereas in absence of emigration that society is more likely to perish.

The topic also includes two sufficiently similar articles written by Alghais and Pullar (2018) and Alghais et al. (2018). The articles both came out in the same period and relate to the same subject, the process of urban development in Kuwait and the usage of agent-based models to simulate it. The background of the research consists of the observation that urban areas in Kuwait are experiencing significant pressure, as international migration of labourers from overseas leads to a decreased availability of houses for the resident population; this, in turn, also affects the already congested infrastructure for transport. The authors opted to use ABM for the purpose of predicting future scenarios of the evolution of Kuwait's urban areas, and for that purpose, they developed a representation of the country where the district is the elementary unit of analysis. The district is then characterized by a population, corresponding to the time series of the demographic data that had been observed in the previous decades. The population evolves according to a projection in the future of the trend observable in the demographic time series: as the population increases, this then applies pressure on the limited housing in the country. The government can then react to housing shortages in consortium with real estate developers, and subsequently shape the expansion of the urban areas by moving part of the population, primarily the immigrants, towards those newly-developed areas.

In the second article by Alghais et al. (2018), the authors claim to be describing internal migration between residential areas in Kuwait; however, since the population that they consider is differentiated between Kuwaiti and non-Kuwaiti, with the latter comprising foreign nationals that immigrate into the country, it is, therefore, reasonable to consider this article as related to international migration. In particular, the authors ask themselves the question of what role urban planning by the government has in generating segregation between Kuwaitis and foreign nationals. The idea of studying ethnic segregation via agent-based models as an emergent phenomenon is not new, and it is indeed one of the cornerstones of the field (Schelling 1971); in the particular implementation by Alghais et al. (2018), however, this carries the added value that it becomes possible to estimate the impact of some government policies on housing. The specific policy that they consider is the creation of dedicated "global cities" where foreigners have the right to reside in the same areas as the local population.

The last article on this topic is Collins and Frydenlund (2016), which focuses on the problem of group formation in a population of refugees that leave a country due to violence. The basic argument that they make is that, if it makes sense to consider the kinematic of a fleeing crowd as qualitatively different from the kinematic of a river, it is therefore not sufficient to model the crowd's motion via partial differential equations as one would model the flowing water. In this regard, the authors conceptualise a crowd as a group that comprises subgroups (the various subsets of persons in the powerset of individuals), with the subgroups then influencing the crowd in the same manner in which the crowd influences each subgroup. As the agents move, they join or drop off groups of moving individuals according to certain rules: in doing this, the individuals and the group both change velocity, and the distance between individual persons is modified. The contribution of this paper to the literature on ABM and international migration consists of a theoretical framework that allows the integration of differential equations that model the behaviour of an independent particle (the individual), with the rules that model the behaviour of groups thereof.

The second topic comprises two articles, more closely related to the modelling of migration policies via agent-based models. The first article, by Simon et al. (2018), addresses the question of changes in the behaviour of a migrant as a response to changes in the immi-

gration policies that affect them personally. Specifically, the authors study the transition of a migrant from a legal pathway to the country of destination, to the preference for irregular migration in response to a tightening of the immigration policies. The model that they propose has few assumptions on the capacity of a migrant to understand the state of the political environment around them, which avoids the pitfall of having "omniscient agents" that hold global (not local) information available in the simulation. The use case that they consider for model calibration consists of the various classes of voluntary migration from Jamaica, primarily comprising students and labourers. Their main finding consists in the consideration that migration behaviour, and in particular the choice by an individual to not migrate as opposed to migrating, is largely insensitive to policies: only in cases where enforcement is very strong, does the decision to migrate change into non-migration. In all other cases, where enforcement of restrictions is lax, the migratory behaviour itself is unaffected, but the migrants end up classified by the legal system of the hosting country as "irregular" rather than "regular".

The second article on this topic focuses on the effect that a special type of migration policy, the policy for academic hiring of scientists, has on the mobility of the latter (Vaccario et al. 2021); this study includes a significantly large number of observations, extracted from the affiliation of scientists over several decades of their career. In use as a fitness function for an individual scientist the number of publications, and in measuring the academic importance of a city as a function of the publications produced by its universities, the authors conclude that certain preferential trajectories exist in the career path of a moving scientist; these, in turn, are affected not only by academic and scientific factors, but also by some measure of the selectiveness of the city where the scientist may relocate. The latter is calculated as a function of the individual scientist's publication record, and the publication record of the universities located in the city of potential migration; this, interestingly, suggests that measures that promote the publication activity of universities could impact the number of highly skilled immigrants that enter a country, and the authors find empirically that there are possible tradeoffs between the distance of relocation of a moving agent and this measure of selectiveness.

These articles have in common two aspects: one, that they both focus on the relationship between policies and migratory behaviour; and the second, that they are both data-driven in the sense that their parametric configuration was calibrated against a real-world use case.

The third topic includes six articles that mainly relate to each other by their shared theme: the relationship between the moving human and the environment around them. In these articles, the environment can assume the identity of an ecological environment, in its more natural sense of the term, but also of a social environment, where other people constitute the environment for some given individual.

The first article by Bijak et al. (2020) is a review of the methodologies for developing agent-based models. More specifically, the authors address the various steps involved in the development of an agent-based model that simulates migration: from the selection of data and the identification of decision functions to the selection of programming languages and the development and evaluation of the models, the authors formulate an iterative process for development that respects the computational limits available to the modellers while at the same time progressively increasing in realism. Particularly important is the consideration that the transition from discrete-time evolution to continuous time provides a better way to model stochastic events, and thus results in better correspondence between statistical models of population behaviour and agent-based models that describe that population's movement.

The second article, by Nelson et al. (2020), discusses the nomadic behaviour of shepherds in Somalia, and the way in which the civil war and the ecological environment interact with them. The authors integrate geospatial data into an agent-based model, and simulate the process by which a nomadic pastor may decide to move between areas to feed their livestock. If unable to do so, and in particular in case of death of the livestock due

to undernutrition, the nomadic pastor may transition to the status of internally displaced person, which is eventually picked up in the corresponding statistics. The authors' model finds a strong relationship between the access to vegetation by pastors and their permanence in that role; however, it remains unclear about the nature of the existing relationship between conflicts and the generation of internally displaced persons: this article reinforces the idea of an existing connection between economic hardships (and not necessarily the conflict alone) and the generation of internally displaced persons, which has also been noted in other countries (Yigzaw and Abitew 2019).

The third article by Norman et al. (2018) describes the process of colonisation of Australia by the earlier modern humans, which was undertaken some 65,000 years ago. The purpose of the article is to help identify possible trajectories along which migration might have been undertaken, along a network of landmarks that were characterised by a reciprocal line of sight. The underlying idea is that, for migration to take place in absence of navigation tools, each additional step in the trajectory must have happened between landmarks that were visually connected: this, in turn, imposes constraints on the possible trajectories that a moving human might have followed while transitioning through the Pleistocene continent of Sahul. The approach followed in this model may matter to study modern international migration, insofar as its assumption for migration trajectories to satisfy local visual connectivity remains valid for a population of refugees moving largely on foot and over small water bodies, such as the Rohingya "boat people" (Roy Chowdhury and Abid 2022).

The fourth article, by Frydenlund et al. (2017), discusses the problem of the formation of political identity among refugees that reside in camps for prolonged periods. The idea behind the paper is that, as a refugee remains in a camp for longer periods, they may be less linked to the national identity that they held in the country of origin and may either acquire a local identity based on the territory where the camp is situated, or a global identity based upon the interaction with international governmental organisations or aid workers. The model proposed in the paper is theoretical in nature and does not represent any particular refugee camp; in it, the refugees are modelled as agents that interact with NGO and IGO workers, as well as with the local population. As the interaction continues and as they move inside a camp, the political identity of refugee changes in one direction or another, towards a global or local identity. The "environment" that is considered in this model comprises mostly of other people, and thus assumes the characteristics of a "social" rather than "ecological" environment.

The fifth article (Hölzchen et al. 2016) evaluates a long-held hypothesis in a certain model for anthropological migration: the idea that some ancestors of the *Homo sapiens* had emigrated from Africa prior to them, as opposed to the *Sapiens* being the first hominin that left the continent. The model attempts to explain migration as an adaptive response to environmental challenges such as the lack of resources, and also considers the impact that the perceptual range of an agent has on the decisions by that agent to emigrate or not. In this sense, it calls back to the same idea that was mentioned earlier: that the visual connection between the current position of an agent and the future destination is a constraint for any valid migration trajectory, in absence of navigation tools (Norman et al. 2018). The usefulness of this article for studying modern migration consists of the consideration that the cognitive functions of the migrating agent may be a relevant factor in determining that agent's decisions to migrate: whereas the authors use the extreme cases of different brain sizes between *H. erectus* and *H. sapiens*, which are not valid for research that relates to modern international migration, it is however commonly accepted that the level of education matters in determining migration decisions (Knapp et al. 2013), so this could be included in a modern version of an ABM for international migration.

The last article for this topic, too, relates to the role that cognition, and in particular, the capacity to predict the future, has on the migratory behaviour of hominins (Wren et al. 2014). The authors consider two factors: the spatial heterogeneity of the environment, as measured according to the non-homogeneity of the distribution of resources; and the

capacity to foresight, which is a preference for trajectories that maximise the long-term benefit for the agent. Interestingly, the authors find that agents with a very high capacity for foresight end up stuck in local maxima, whenever the complexity of the environment is such that transitioning from a local to a global maximum would require an exploratory behaviour that can generate short-term losses in favour of an uncertain long-term gain; this consideration, which the authors make in relation to the food resources that were required to nourish the hominins, should, however, remain valid if we consider instead the economic resources that are needed for a modern human to survive in society.

The fourth topic comprises only one article, by Shultz and Costopoulos (2019), that forms a topic of its own. The article discusses the problem of wealth inequality that is generated in the pastoral communities of the Mongolian Empire, as a function of environmental and economic conditions. By inspecting the keywords associated with this topic and extracted by the LDA model, it may seem that this article fits into the previous topic; however, one of the important features associated with it is the term "robustness", and it is our opinion that this feature (associated with the fourth but not with the previous topics) results in the separation of this article from the previous. In particular, the robustness aspect of this model is implemented by conducting the same simulations several times (100 times), and computing statistical averages rather than point predictions; this, considering the stochastic nature of most agent-based models, helps ensure that the initial random configuration of the system has a smaller impact on the output of the models themselves.

The fifth topic comprises six articles, five of which we analyse here (see Section 3.2, above, for details); this topic relates primarily to health and genetic factors that affect migration, and to the differences between families and households in migration models.

The article by Vallée et al. (2016) is a genomic study that reconstructs the mobility behaviour of Neolithic populations in South East Asia on the basis of the genetic profile of the modern resident population. More specifically, the authors simulate the process by which individuals from continental Asia move towards the islands in South East Asia, and as a consequence of this, they interact with the local Papuan population which results in the genetic admixture of the two groups. The model by them developed runs in time steps of one year, which is appropriate given the large breadth of the study (4500 years) and given that genetic events (births, marriages) are not likely to happen with frequencies higher than a year. The considerations made by this model, that it is possible to use ABM to simulate migratory behaviour over long time intervals on the basis of genomic data, remains valid; however, its impact to study modern international migration over much shorter time frames remain limited, even though it may still be possible to use genetic admixture in order to retroactively predict migration when the latter includes multiple generations of migrating individuals.

The second article, by Vogel et al. (2015), models the process of diffusion of infectious diseases in West Africa, as a consequence of the regional mobility of individuals and as measured by mobile phone position. The authors suggest that simulations that predict future mobility patterns could be used to determine migration policies with the objective of preserving public health, and that in this sense the development of simulations should be considered an integral part of the process of policy-making. In light of the fact that, a few years after the authors' published work, the COVID-19 pandemic caused strong restrictions to mobility as a consequence of the predicted impact that the latter would have on public health and as measured via predictive simulations, this argument may be considered to be particularly relevant today (Tully et al. 2021).

The third article by Gaube and Remesch (2013) describes the development of an ABM to simulate the consequences of urban planning policies in Vienna on the decisions by families concerning the location of their residences. The article is based upon the consideration that immigration is the single factor that most strongly affects the demographic development of the city. In the model, the authors focus on the sustainability aspects of the decisions to establish residence, and find that the spatial distribution of single households is the largest determinant of the spatial distribution of energy consumption, which is the

subject of their study. The inclusion of the article on this topic is primarily due to the keyword "household", and we should interpret its inclusion in the corpus of texts on agent-based models as an indicator that the unit of aggregation for individuals in an ABM should include households; this would imply the linking of individuals not only in terms of genetic or familial relationships, as considered in the other papers within this topic, but also in terms of the location where they establish residence, so that persons who share housing with non-relatives become connected with them by reason of the joint domicile.

The article by Truscott and Ferguson (2012) relates once more to the problem of epidemiological modelling, this time in the context of the SIR model *vis-à-vis* the gravity model. The agent, in this model, does not comprise an individual but rather a node in the network (generally, a city), and the individuals flow between nodes as per the assumption of the gravity model. The usefulness of this article for the more general study of international migration via ABM is that, in absence of data on the position of the individual, one can use the gravity model in order to calculate a probability distribution of the likelihood of transitioning from one city to another, and thus use that distribution to generate synthetic trajectories of individual mobility.

The last article, by Kishore et al. (2021), relates to the impact on human mobility that was caused by the lockdowns adopted in response to the COVID-19 pandemic. The authors of this study show that, shortly after the lockdown had been approved but before it entered into force, a significant increase in mobility was observed. Contrary to expectation, the adoption of lockdown measures aimed at decreasing mobility in the long term and thus preventing diffusion of pathogens, may rather cause an increase in diffusion in the short term and a spread to areas that would otherwise not be reached in absence of lockdown measures. The relevance of this study for the broader discipline of migration studies consists in the consideration that individuals react not only to mobility policies that are enforced, but also to mobility policies that have been approved but not yet applied. The implication is that, if the decision-making process of individuals is included in an ABM, this should include some form of foresight as was also supported by the anthropological studies contained in topic three (Norman et al. 2018).

The sixth topic contains four articles, connected by the shared thematic of conflicts and war, and the impact that these have on the movement of refugees.

The first article, by Suleimenova et al. (2021), discusses a methodology for developing ABMs incrementally and via the iterated usage of sensitivity analysis (Sobol 2001). The use-case for the model by them developed comprises refugees, hence the paper's inclusion in this topic. The authors validate the choice of parameters for their model on the figures by UNHCR on the arrival of refugees to refugee camps in Mali, Burundi, South Sudan, and the Central African Republic. Upon an initial choice of parameters that describe the motion of a moving refugee, they apply sensitivity analysis to determine which ones are more pivotal to predicting the model's validation dataset; they then update the most influential parameters according to some rules, and then repeat the process of sensitivity analysis and validation of the model. The argument that they propose is that, by iterating this procedure a sufficient number of times, the model would converge to a parametric configuration that would correspond to some measure of optimality; however, this hypothesised convergence remains unproven and may correspond to a local rather than the global optimum.

The second article presents a general framework for modelling refugees and forced migration (Searle and van Vuuren 2021). The case study that the authors use comprises the movement of internally displaced persons and international refugees in Syria, but the framework that they develop is applicable in other contexts. In the model that they built, an agent is an individual that possesses a state matrix and a corresponding state transition matrix. The transition from one state to the next is stochastic, and accounts for different types of behaviour including different types of migratory decisions. In the particular model that they build, they incorporate three types of migration decisions: to move inside the country, and thus become an internally displaced person; to cross the international border, and apply to become an asylum-seeker; and finally, to cross the international border but

not to apply for asylum, thus remaining irregular. The advantage of the approach by them presented is that, if the decision-making process of an individual is modelled via a stochastic state-transition matrix, this matrix can be interpreted as a probability distribution and learned via e.g., regression or statistical analysis. Other forms of representation for the migratory behaviour of an individual, such as the development of synthetic data that corresponds to gravity models (Truscott and Ferguson 2012), would not allow deducing the rules for individual behaviour whereas the work by these authors is more prone to it.

The next article relates to the same case study as the previous one: the modelling of migration trajectories undertaken by refugees in Syria (Hébert et al. 2018); this paper, though, develops a model to study the concrete datasets that the authors have available, rather than considering Syria as a use-case for a theoretical model. In the ABM developed by the authors, the individual is considered to be affected by the frequency of death in the region where they are located, and also by demographic characteristics such as their age and gender. Further, the more the conflict is prolonged, the more likely the individual is to undertake movement. Upon arrival at the destination (generally, a refugee camp), the migrant can decide to stay or relocate according to the sanitation and infrastructural conditions that they find there. After simulating the process of migration, the model is then validated by the authors on the basis of a refugee census by the UNHCR for camps located in Iraq, Jordan, Lebanon, and Turkey. The interesting characteristic of the model, which the authors do not highlight particularly in the conclusions of their paper, is that the choice by a human to migrate is significantly affected by the danger of the area where the human lives, as measured according to the death toll in that same area: if the persons that die are included in a simulation prior to their death, and if survival is considered as a measure of fitness, this then opens up the possibility to apply reinforcement learning and to model the decision functions of a moving human with that particular approach, which the authors have not considered.

The final article for this topic is a short paper that describes a simulation model of the movement of refugees escaping from the civil war in Mali (Groen 2016). The author of this study validates the result against UNHCR data, and finds that the figures for refugees crossing into Niger are overestimated by their model; they suggest that the movement on foot is poorly captured by the simulation that they developed. In fact, their model uses a network of streets between cities as the topological structure over which migration occurs, and this may not be accurate for countries with poor road networks or transportation infrastructure.

The seventh topic comprises the second largest in the corpus, with 12 items in total.

The first article is a study on the effect that economic and social differences between two countries can have in generating a brain drain from the poorest to the wealthiest (Gürsoy and Badur 2021); in it, the authors implement an ABM that simulates the discrete-time evolution of a social system characterised by brain drain, in which each step corresponds to one year. The objective is to produce a model that could replicate the statistical distribution of highly skilled migrants, which are normally sampled at intervals of one year. The authors find that emigration is promoted by the average degree of connections between nodes in a social network, but also that it is largely insensitive to the structure of that same network, and in particular as to whether a random graph or a preferential attachment network are used.

The next set of articles originates from the research of a group of scholars that collaborated over the course of a few years to study the relationship between housing and population dynamics in Lebanon. In the first article (Picascia and Yorke-Smith 2016), the authors develop a NetLogo model of Beirut that abstracts over the most salient features of the city's neighbourhoods, such as housing prices, income, and conditions. The simulation runs at intervals of one month and accounts for scenarios in which a large influx of refugees enters the country and competes with the local population for access to housing. The authors' model shows that the arrival of a large number of refugees over a short time can cause a shock, which results in turn in the subsequent emigration from the city of both

refugees and locals alike. The second article (Picascia et al. 2018) presents a variation of the same model, in which this time the city is represented in a manner that corresponds more closely to GIS data. In the previous iteration of the model, the city was represented as a rectangular array of cells; in this second iteration, the authors have implemented a representation of the city and its neighbourhood that resembles the geographical map; this second article is otherwise similar to the previous, and comprises a shorter description made of just two pages. The third article of this set (Termos et al. 2021) contains a significant improvement over the previous ones. In this latter version, the authors have included a method that uses structural equations for simulating demand and supply for houses, and also includes validation and sensitivity analysis for the model's outputs. The conclusions remain similar to those of the previous two models, though: refugees that arrive in Beirut are likely to cause a worsening of the housing conditions, which in turn makes it more likely for both the residents and the local population to emigrate abroad.

The next article contains a study on the ethnic segmentation of the population in a city that experiences the immigration of unskilled labourers (Meyer and Vasey 2020). The model represents the process of hiring by firms in Los Angeles, and the diffusion of information related to vacancies along the links of a social network that contains the employees of those firms. The findings of this study indicate that firms that are ethnically homogeneous may emerge naturally, and thus ethnic segmentation of the population may emerge as a consequence of the fact that the hiring process takes place along the network of social contacts, and that these are generally denser among people of the same ethnicity.

The article by Bystrov et al. (2019) contains instead a simulation of the migration processes towards the Artic regions of Eurasia, with the inclusion of Iceland, Sweden, Finland, Norway, Denmark, and Russia, as the countries that the model simulates. The dataset used by this study is public and is based on the demographic data of Eurostat. The model is then used to forecast bilateral migration flows between these countries; however, in absence of a validation step and because the model itself is not published, it appears that this study may suffer from difficulties in replication.

The next article contains a presentation of a tool developed to facilitate the merging of two previously independent tools for social simulation: the Simulation Experiment Specification on a Scala Layer (SESS), and the Modeling Language for Linked Lives (ML3) (Reinhardt et al. 2018). The tool is then used in a couple of abstract contexts in order to show its potential; one of these, which is relevant for this paper, is the simulation of return migration by labourers. The tool should in principle allow the extension to concrete cases, such as for the purpose of simulating mobility between two countries.

The article by Klabunde et al. (2017) presents a model for migration between Senegal and France (Klabunde is also mentioned in the ninth topic for another article that they published); this particular case is an instantiation of a demographic multistate model to which the authors added an extra component to represent the intention to migrate. The multistate model, in turn, is characterised by a probability transition between any two states that depends on the age of the individual and the time spent in a given state. To this model, the authors have added a decision function that concretely comprises an extra term in the state transition function. The challenges that the researchers identify consist of the problem of determining which aspects of the state transition function are "automatic", and that occur regardless of the cognitive processes of the individual, and which ones comprise wilful decisions by the migrant, that should then be modelled via decision functions. The answer is not present in the article, but the question is presented as an important research direction.

The next article is a global model for human migration (Lin et al. 2016), where a set of 194 countries possesses a population that they redistribute along themselves. The model includes a representation of pair-wise linguistic similarity between countries, under the idea that countries that share similar languages are *ceteris paribus* more likely to experience bilateral migration; it also includes a measure of political friendship between countries, under the assumption that friendly countries are more likely to observe higher flows of people moving between them.

The next study relates to climate adaptation by humans, and to migration as an adaptive strategy against the variability of rainfall (Warner and Afifi 2014). The researchers, in this article, present an agent-based model in which the rainfall enters the ecosystem in which humans live; and as a consequence of changes in precipitation, the capacity of the resident population to extract food decreases. The claim by the article is that the changes in precipitation (either sign, as opposed to merely the decrease) cause a decrease in food by reason of the uncertainty concerning the cultivation: as rainfall variability increases, first, the farmers decide to plant fewer crops, and then the markets receive less produce to display on the shelves; this mechanism, eventually, leads to the emigration of the population that does not find sufficient food to satisfy its necessities. The model's assumptions were based upon survey data administered in various agricultural regions in South America, Africa, and South East Asia, and therefore the paper's conclusions have broad geographical scope and applicability.

The next article contains a model that simulates the migration patterns from East to West Germany as a consequence of the reunification of the country at the end of the Cold War (Frank Heiland 2003). The model uses state-level data (*Land*) and considers as an agent the individual citizen who attempts to maximise their own utility function. The model finds that distance negatively affects migration, and that unemployed persons are more likely to emigrate than employed persons, which is consistent with the general knowledge in migration studies.

The final article for this topic contains an ABM on the diffusion of Dengue fever in Colombia (Padmanabha et al. 2015). The reason for the inclusion of this article in this corpus is that it considers immigration and long-distance mobility as two of the factors that affect the diffusion of the disease, and hence it was captured by the keyword queries. The article finds that the visiting by individuals with social contacts that live a long distance from them may constitute a method for transmission of the disease between otherwise isolated areas.

The eighth topic includes five articles on the subject of computation in agent-based systems. The problem of optimisation, scalability, and parallelisation of ABMs is considered in these articles; these are open problems for agent-based models that aim at representing the dynamics of large groups of people, and are relevant for international migration whenever the behaviour of a large social system (e.g., a country or a continent) is considered.

The first article, by Makarov et al. (2018b), discusses a methodology for developing large-scale agent-based simulations that include agents in the order of one billion, which is intended to replicate one-to-one the evolution of social systems in Eurasia. The model was used to simulate economic migration from China to Russia and allowed to represent the flow of information between agents. In its application to the regional migration between the Chinese province of Heilongjiang and the Far East Federal District in Russia, the authors claim that the model can accurately represent the changes in the flow of labour migrants across the border, in response to changes in the bilateral currency exchanges and in the availability of job offers.

The next paper by Bakhtizin et al. (2017) is related to the one we just discussed, and indeed it slightly predates it chronologically. While the intended use case is migration studies, this particular paper does not, however, focus on it and describes instead the technical implementation of the simulation system; this paper, together with the previous, should be considered together if one attempts to develop a scalable system for ABMs that simulate large numbers of individuals. Notice, however, that the framework developed by the authors does not allow the inclusion of some objects that are common in ABMs, such as the geographical environment, or distinct classes of agents.

The article by Groen (2018) treats a similar topic as the previous two, that of parallel computing in its application to an agent-based model. The simulation framework presented in this paper was developed by the author in Python, and shows benefits in terms of speedup by a factor of 3 when the simulation is parallelised as opposed to running on a single thread. The author tests their framework on a variety of scales, ranging from a smaller

model of 10,000 individuals up to a million. The author comments on this improvement by attributing it to the poor performance of Python in computing-heavy contexts, and assumes that the same simulation framework, if rewritten in C, would perform better regardless of parallelisation.

The next article, by Klügl and Bazzan (2012), is introductory in nature, and comprises a review of the basic concepts and tools commonly used in ABM. In particular, the authors describe the primary features of Swarm, Repast, SeSAm, MASON, and NetLogo, and provide a list of their comparative advantages and disadvantages. Other tools that are common for modelling phenomena like migration that are eminently geospatial in nature, such as GAMA (Drogoul et al. 2013), are not however mentioned as they are more recent.

The final article for this topic, by Weidmann and Salehyan (2013), contains a computational model that links ethnic violence to migration during the war against insurgency. The inclusion by LDA of this article in this topic may derive from the frequent usage of the words "computational model", in many places where other texts would have referred to "agent-based models" instead. In this model, the authors represent the decision to migrate as a response to attacks of a certain class of agents, the "insurgents", against a population that is ethnically differentiated between Sunni and Shia. The proximity to the location of a terrorist attack is the factor that affects the decision to migrate, with a decreasing effect as the distance increases. The model also considers the role that policing and counterinsurgency operations have as policies for managing migration: if terrorist attacks are a factor that causes people to flee, then the arrest of terrorists can be considered as a policy of its own for reducing the number of people displaced by the violence.

The ninth topic is the second smallest, accounting for only two articles; these articles relate both to the economic emigration from Hispanic countries, and therefore we labelled this topic accordingly.

The first article, by Klabunde (2014), comprises a study on the agent-based modelling of economic migration from Mexico. The model developed by the author considers typical push/pull factors for economic migration, such as income differentials and age of the migrants, but also less frequent factors, such as some idiosyncratic preference for the home country as opposed to the host country; this latter is to be intended as an emotional preference or a bias, in the author's conceptualisation of the model, but it is concretely built by using as a proxy the level of homeownership in the country of origin, which may simply reflect the level of wealth of a migrant household. The model is calibrated via Monte Carlo simulations, and holds only four hyperparameters while being able to accurately represent the circular migration of Mexican workers across the border.

The second paper on this topic also concerns migration from an Hispanic country: in this case, the economic migration of Colombian women to Catalonia (Hüttinger 2020); this article makes a frequent reference to Colombian immigrants to Catalonia as "agents of development" and "agents of social change", while at the same time referring to the "transnational networks" that the same agents create in the country of origin and the country of destination. While this article contains all the keywords that are common in agent-based models, it does not however have an explicit reference to them, so it should be considered syntactically but not semantically related to the topic.

The tenth and final topic is the largest: it can also be interpreted as a residual topic, in the sense that it contains a variety of articles that do not necessarily fit into any other category; these are the articles that are most closely related to each other via the specific subject that we used to retrieve them: that of agent-based models and migration.

The first article is a literature review on the subject of slavery and human trafficking, and the problem of its modelling via ABM approaches (McAlpine et al. 2021). The review is aimed at assessing the suitability of ABM for the purpose of promoting Sustainable Development Goal 8.7 on the eradication of slavery and forced labour. The research finds that the role that social networks have in affecting slavery (by either causing it or preventing it) is not well studied, and claims that there is potential for opening a research avenue in that direction.

The study by Dyble (2021) considers instead the problem of altruism and its emergence in war. The model developed by the author shows that the number of altruists in a population was correlated with the size of the group, as well as with the propensity for migration.

The research by Huang and Unwin (2020) focuses on the comparison between ABM and Markov chains to simulate the Burundi refugee crisis. Markov chains with no hidden nodes are stochastic finite state machines, and can thus account for probabilistic rather than deterministic state transition functions for the behaviour of an agent.

Al-Khulaidy and Swartz (2020) developed an agent-based model to simulate the patterns of migration from Mexico to the United States, and evaluate the effects that changes in the migration policy can have on the migratory behaviour of the individuals.

Harris et al. (2018) developed a simulation system based on swarm architectures for monitoring borders and detecting border crossings by migrants. The system is aimed at maximising the probability of detection of migrants by integrating sensors located on the various surface and air assets, and was validated on data on the Search and Rescue missions by the Italian Coast Guard.

The next paper describes a computational framework for developing simulations at a global scale, written in Python and optimised for parallelisation (Blandin et al. 2017). The system works in Jupyter and thus allows for graphic elements to be displayed; further, it is released in open source format and can thus be forked and modified by any interested developer. The framework is tested on a population with 7 billion individuals, and shows a scaling in computational time that increases linearly with population size.

The article by Sokolowski and Banks (2010) studies the relationship between the degree of interconnection between countries, by them called "global connectivity", and a special kind of migration: the migration of cultures. The authors define culture as an object comprising a set of features, with each feature comprising a set of possible traits. The combination of traits present in a culture (or more accurately, their numerical encoding) forms a string that defines that culture and any agents that share it. The interesting aspect of this research, for the studies on international migration, consists in the suggestion that categorical features of an agent could be encoded in some sort of genomic string, and that the latter can then evolve as a response to the events that affect that agent.

The same authors, Sokolowski and Banks (2014), also published a second paper that is also contained in this topic, and which relates to the computational modelling of population displacement in Syria; in it, the agent is represented by the government troops that patrol Aleppo, who is in charge of preserving security in the city. The agent is characterised by a variable called "disposition", which in turn depends upon the agent's emotions, rationality, and the influence that the disposition of other agents has on the agent themselves. In reaction to the increased presence of the rebels, the government troops represented in the simulation develop stress and may end up shooting towards areas in closer proximity to civilians, thus increasing their risk of death. Areas that suffer attacks are considered dangerous, and thus generate refugees that attempt to escape them.

The paper by Nemiche et al. (2013) presents a framework for developing computational models of artificial societies capable of evolving. Their model includes rules for the reproduction and the death of each agent, and accounts for technological progress that allows a certain society to increase in size. The model also includes a function that allows agents to roam the environment, though the behaviour associated with the agent's mobility is determined exclusively by the availability of resources; this consideration makes the framework suitable for modelling economic migration, but would demand additional work to be extended to other types of migration.

The next two papers both relate to the computational modelling of migration from Burkina Faso. The authors overlap and the period of publication was the same; for this reason, it makes sense to consider them as one single product even though their text differs in wording. The first is a book chapter (Smith et al. 2011), while the second is a journal article (Kniveton et al. 2011); we discuss the latter here but either could have been included

since the content is sufficiently similar. The last article on this topic, therefore, and the last article of our review, is a model that describes climate change and its relationship with migration; this model uses the case study of Burkina Faso, and addresses the applicability of the theory on bounded rationality and the theory on planned behaviour for the purpose of modelling the cognitive processes of an individual in relation to their decision to migrate.

To sum up this section, if our objective is to develop agent-based models that replicate the behaviour of a system of international migration, this literature review helps us identify the characteristics that a model should have, in order for it to be consistent with the literature itself. Each of the ten thematic contained in the respective topics is current and is a valid research direction to address the problem of the relationship between ABMs and international migration; the selection of a specific topic then depends upon the research task being conducted, and cannot be established a priori.

6. Conclusions

We now have a set of characteristics that corresponds to the application of agent-based approaches for the modelling of migration. The findings that we have indicated in this section thus need to inform the construction of future agent-based models for international migration. The most notable conclusion, however, is that non-linear approaches or systems dynamics are seldom integrated with them, which suggests the importance of opening a research direction that covers the subject.

In this article, we have presented a review of the literature on agent-based models and their application to the simulation of systems of international migration. We first identified a set of articles on the topic using keyword queries on popular scientific databases. Then, we extracted the list of topics contained therein, by means of matrix decomposition. We proceeded to label the topics according to the human understanding of the researchers, and then queried the corpus of articles in order to identify the ones that pertained to each topic; this, finally, let us identify the characteristics that agent-based modelling for international migration should have, for it to be grounded upon the domain knowledge which is embedded in the discipline of migration studies.

In relation to the first research question, we find that a finite machine that represents an individual in a system of migration should be able to perceive violence as it takes place in the environment of their usual residence. A special case of the perceived violence needs to be political terrorism, since this its migrational responses are behaviourally distinct from the general responses against violence. The agent should also possess a decision-making process that includes the positions of their family members towards migration and, more generally, the network of immediate social contacts around them.

In regard to the second research question, we find that the interaction between the individuals and the environment should be modelled by means of a system that merges agent-based approaches for the modelling of the individual and system-based approaches to model the environment and its evolution. The components of the environment that should be considered include the political boundaries of states, the distribution of cultures and the relationships thereof, the presence of refugee camps and of systems for the management of refugees, and a description of climate and its evolution over time; these structures are positioned on orthogonal layers and complement rather than replace each other in the computational representation of migration systems.

In regard to the third research question, we find that the joint usage of agent-based modelling and systems dynamics for the purpose of formulating policies towards migration is limited, which calls for further research to be conducted in that direction.

In conclusion, we noted that the discipline does not treat or cover possible forms of interaction between agent-based systems and approaches based on systems or non-linear dynamics; this, in turn, calls for the possibility to explore those forms of interaction between alternative computational approaches to migration studies, that might be aimed at developing hybrid or mixed forms of models for the simulation of systems of international migration. Our research also points to the potential that may derive from analysing the

existing policies that attempt to manage migration, not in terms of their effectiveness or ineffectiveness; but rather, to consider policies as hypotheses concerning the functioning of the system of migration, and their acknowledged ineffectiveness as the empirical falsification of those hypotheses; this could be conducted based on existing datasets that classify migration policies, such as IMPIC, and will therefore be possible in the immediate future.

Note

[1] The code can be found at the following URL for validation purposes and for replicability of the results: https://github.com/G-DL/literature-review (accessed on 27 April 2022). The user needs to insert the copy-past from the text of each article that is included in the analytical pipeline into one of the .txt files contained in the "./data/" folder of the repository. The order or the name of each .txt file does not matter, but they must preserve the numerical order and hold the leading zeros. We cannot include the texts of the articles themselves for copyright reasons, but the dataset can be recreated in a short time by the interested reader, or obtained from the corresponding author.

References

Abirami, Ariyur Mahadevan, Abdulkhader Askarunisa, R.A. Shiva Shankari, and Raman Revathy. 2018. Ontology based feature extraction from text documents. In *Applications of Security, Mobile, Analytic, and Cloud (SMAC) Technologies for Effective Information Processing and Management*. Hershey: IGI Global, pp. 174–95.

Alghais, Nayef, and David Pullar. 2018. Modelling future impacts of urban development in Kuwait with the use of ABM and GIS. *Transactions in GIS* 22: 20–42. [CrossRef]

Alghais, Nayef, David Pullar, and Elin Charles-Edwards. 2018. Accounting for peoples' preferences in establishing new cities: A spatial model of population migration in Kuwait. *PLoS ONE* 13: e0209065. [CrossRef] [PubMed]

Al-Khulaidy, Amira, and Melanie Swartz. 2020. Along the border: An agent-based model of migration along the United States-Mexico border. Paper presented at 2020 Spring Simulation Conference (SpringSim), Fairfax, VA, USA, May 18–21.

Armitage, Christopher J., and Mark Conner. 2000. Social cognition models and health behaviour: A structured review. *Psychology and Health* 15: 173–89. [CrossRef]

Axelrod, Robert. 2006. Agent-based modeling as a bridge between disciplines. In *Handbook of Computational Economics*. Amsterdam: Elsevier, vol. 2, pp. 1565–84.

Bakhtizin, Albert R., Valery Makarov, Elena Sushko, and Gennady Sushko. 2017. The development of the agent-based demography and migration model of Eurasia and its supercomputer implementation. *Advances in Systems Science and Applications* 17: 34–45.

Barbosa Filho, Hugo S., Fernando B. Lima Neto, and Wilson Fusco. 2013. Migration, communication and social networks—An agent-based social simulation. In *Complex Networks*. Berlin: Springer, pp. 67–74.

Benassi, Federico, Corrado Bonifazi, Frank Heins, Francesca Licari, and Enrico Tucci. 2019. Population change and international and internal migration in Italy, 2002–2017: Ravenstein revisited. *Comparative Population Studies* 44: 497–532. [CrossRef]

Bijak, Jakub, Philip A. Higham, Jason Hilton, Martin Hinsch, Sarah Nurse, Toby Prike, and Adelinde M. Uhrmacher. 2020. Modelling migration: Decisions, processes and outcomes. Paper presented at 2020 Winter Simulation Conference (WSC), Orlando, FL, USA, December 14–18.

Blandin, Nicole, Carl Colglazier, John O'Hare, and Paul Brenner. 2017. Parallel python for agent-based modeling at a global scale. Paper presented at 2017 International Conference of the Computational Social Science Society of the Americas, Santa Fe, NM, USA, October 19–22.

Boswell, Christina. 2007. *The Securitisation of Migration: A Risky Strategy for European States*. Copenhagen: Danish Institute for International Studies.

Bramer, Wichor M., Melissa L. Rethlefsen, Jos Kleijnen, and Oscar H. Franco. 2017. Optimal database combinations for literature searches in systematic reviews: A prospective exploratory study. *Systematic Reviews* 6: 1–12. [CrossRef] [PubMed]

Brochmann, Grete, and Tomas Hammar. 2020. *Mechanisms of Immigration Control: A Comparative Analysis of European Regulation Policies*. New York: Routledge.

Burns, Tom R., Ewa Roszkowska, Nora Machado Des Johansson, and Ugo Corte. 2018. Paradigm shift in game theory: Sociological re-conceptualization of human agency, social structure, and agents' cognitive-normative frameworks and action determination modalities. *Social Sciences* 7: 40. [CrossRef]

Bystrov, Vitaliy, Svetlana Malygina, Maxim Shishaev, and Dmitry Maevsky. 2019. Combination of analytical and agent-based modeling in studying migration processes in the Arctic regions of Eurasia. Paper presented at IOP Conference Series: Earth and Environmental Science, Moscow, Russia, May 27–June 6.

Campbell, Joshua Charles, Abram Hindle, and Eleni Stroulia. 2015. Latent Dirichlet allocation: Extracting topics from software engineering data. In *The Art and Science of Analyzing Software Data*. Edited by Christian Bird, Tim Menzies and Thomas Zimmermannpp. Burlington: Morgan Kaufmann, pp. 139–59.

Capps, Randy, Kristen McCabe, and Michael Fix. 2012. *Diverse Streams: African Migration to the United States*. Washington, DC: Migration Policy Institute, vol. 2.

Carling, Jørgen. 2011. The European paradox of unwanted immigration. In *A Threat against Europe*. Brussels: Brussels University Press, pp. 33–46.

Castles, Stephen. 2010. Understanding global migration: A social transformation perspective. *Journal of Ethnic and Migration Studies* 36: 1565–86. [CrossRef]

Collins, Andrew J., and Erika Frydenlund. 2016. Agent-based modeling and strategic group formation: A refugee case study. Paper presented at 2016 Winter Simulation Conference (WSC), Washington, DC, USA, December 11–14.

Czaika, Mathias, and Hein De Haas. 2013. The effectiveness of immigration policies. *Population and Development Review* 39: 487–508. [CrossRef]

Czaika, Mathias, and Mogens Hobolth. 2016. Do restrictive asylum and visa policies increase irregular migration into Europe? *European Union Politics* 17: 345–65. [CrossRef]

Czaika, Mathias, Marta Bivand Erdal, and Cathrine Talleraas. 2021. Theorising the interaction between migration-relevant policies and migration driver environments. *Changes* 1: 7.

Davis, Kingsley. 1988. Social science approaches to international migration. *Population and Development Review* 14: 245–61. [CrossRef]

De Haas, Hein. 2007. Turning the tide? Why development will not stop migration. *Development and Change* 38: 819–41. [CrossRef]

Dennison, James, and Andrew Geddes. 2019. A rising tide? The salience of immigration and the rise of anti-immigration political parties in Western Europe. *The Political Quarterly* 90: 107–16. [CrossRef]

Dowling, Julie A., and Jonathan Xavier Inda. 2013. *Governing Immigration through Crime: A Reader*. Stanford: Stanford University Press.

Doytcheva, Milena. 2021. Diversity as immigration governmentality: Insights from France. *Social Sciences* 10: 237. [CrossRef]

Drogoul, Alexis, Edouard Amouroux, Philippe Caillou, Benoit Gaudou, Arnaud Grignard, Nicolas Marilleau, and Jean-Daniel Zucker. 2013. Gama: Multi-level and complex environment for agent-based models and simulations. Paper presented at AAMAS'13—12th International Conference on Autonomous Agents and Multi-Agent Systems, St. Paul, MN, USA, May 6–10.

Dyble, Mark. 2021. The evolution of altruism through war is highly sensitive to population structure and to civilian and fighter mortality. *Proceedings of the National Academy of Sciences* 118: e2011142118. [CrossRef]

Fertig, Michael, and Christoph M. Schmidt. 2001. Aggregate-level migration studies as a tool for forecasting future migration streams. In *International Migration: Trends, Policy and Economic Impact*. London and New York: Institute for the Study of Labor, pp. 110–36.

Frydenlund, Erika, Jose J. Padilla, and David C. Earnest. 2017. A theoretical model of identity shift in protracted refugee situations. Paper presented at Agent-Directed Simulation Symposium, Virginia Beach, VA, USA, April 23–26.

Galemba, Rebecca B. 2018. 'He used to be a Pollero' the securitisation of migration and the smuggler/migrant nexus at the Mexico-Guatemala border. *Journal of Ethnic and Migration Studies* 44: 870–86. [CrossRef]

Gaube, Veronika, and Alexander Remesch. 2013. Impact of urban planning on household's residential decisions: An agent-based simulation model for Vienna. *Environmental Modelling & Software* 45: 92–103.

Gerard, Alison, and Sharon Pickering. 2013. Crimmigration: Criminal justice, refugee protection and the securitisation of migration. In *The Routledge Handbook of International Crime and Justice Studies*. Edited by H. Bersot and B. Arrigo. London: Routledge.

Ghosh, Bimal. 2000. *Managing Migration: Time for a New International Regime?* Oxford: Oxford University Press.

Greenwood, Michael J. 2019. The migration legacy of EG Ravenstein. *Migration Studies* 7: 269–78. [CrossRef]

Groen, Derek. 2016. Simulating refugee movements: Where would you go? *Procedia Computer Science* 80: 2251–55. [CrossRef]

Groen, Derek. 2018. Development of a multiscale simulation approach for forced migration. Paper presented at International Conference on Computational Science, Las Vegas, NV, USA, December 12–14.

Gürsoy, Furkan, and Bertan Badur. 2021. An Agent-Based Modeling Approach to Brain Drain. *IEEE Transactions on Computational Social Systems* 9: 356–65. [CrossRef]

Harris, Caleb M., Max-Daniel R. Sokollek, Luis S. Nunez, John T. Valco, Michael Balchanos, and Dimitri N. Mavris. 2018. Simulation-based UAS Swarm Selection for Monitoring and Detection of Migrant Border Crossings. Paper presented at 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA, USA, June 25–29.

Haug, Sonja. 2008. Migration networks and migration decision-making. *Journal of Ethnic and Migration Studies* 34: 585–605. [CrossRef]

Hébert, Guillaume Arnoux, Liliana Perez, and Saeed Harati. 2018. An agent-based model to identify migration pathways of refugees: The case of Syria. In *Agent-Based Models and Complexity Science in the Age of Geospatial Big Data*. Berlin: Springer, pp. 45–58.

Heekeren, Hauke R., Sean Marrett, Peter A. Bandettini, and Leslie G. Ungerleider. 2004. A general mechanism for perceptual decision-making in the human brain. *Nature* 431: 859–62. [CrossRef]

Heiland, Frank. 2003. The collapse of the Berlin Wall: Simulating state-level East to West German migration patterns. In *Agent-Based Computational Demography*. Berlin: Springer, pp. 73–96.

Hejl, Peter M. 1990. Self-Regulation in Social Systems. In *Selforganization: Portrait of a Scientific Revolution*. Edited by W. Krohn, Gunter Küppers and H. Nowotny. Berlin: Springer, pp. 114–27.

Helbling, Marc, Liv Bjerre, Friederike Römer, and Malisa Zobel. 2017. Measuring immigration policies: The IMPIC database. *European Political Science* 16: 79–98. [CrossRef]

Hermans-Neumann, Kathleen, Joerg Priess, and Martin Herold. 2017. Human migration, climate variability, and land degradation: Hotspots of socio-ecological pressure in Ethiopia. *Regional Environmental Change* 17: 1479–92. [CrossRef]

Hölzchen, Ericson, Christine Hertler, Ingo Timm, and Fabian Lorig. 2016. Evaluation of out of Africa hypotheses by means of agent-based modeling. *Quaternary International* 413: 78–90. [CrossRef]

Huang, Vincent, and James Unwin. 2020. Markov chain models of refugee migration data. *IMA Journal of Applied Mathematics* 85: 892–912. [CrossRef]

Hüttinger, Arantxa Rosa. 2020. The Migration-Development-Nexus from a gender-sensitive perspective: The Case of Colombian Women in Catalonia. *Análisis Jurídico-Político* 2: 101–25. [CrossRef]

Jahani, Alireza, Hamid Arabnejad, Diana Suleimanova, Milana Vuckovic, Imran Mahmood, and Derek Groen. 2021. Towards a Coupled Migration and Weather Simulation: South Sudan Conflict. Paper presented at International Conference on Computational Science, Kraków, Poland, June 16–18.

Jaskulowski, Krzysztof. 2019. The securitisation of migration: Its limits and consequences. *International Political Science Review* 40: 710–20. [CrossRef]

Kishore, Nishant, Rebecca Kahn, Pamela P. Martinez, Pablo M. De Salazar, Ayesha S. Mahmud, and Caroline O. Buckee. 2021. Lockdowns result in changes in human mobility which may impact the epidemiologic dynamics of SARS-CoV-2. *Scientific Reports* 11: 1–12.

Klabunde, Anna. 2014. *Computational Economic Modeling of Migration*; Ruhr Economic Papers. RWI—Leibniz-Institut für Wirtschaftsforschung, Ruhr-University Bochum, TU Dortmund University, University of Duisburg-Essen. Available online: https://EconPapers.repec.org/RePEc:zbw:rwirep:471 (accessed on 27 April 2022).

Klabunde, Anna, Sabine Zinn, Frans Willekens, and Matthias Leuchter. 2017. Multistate modelling extended by behavioural rules: An application to migration. *Population Studies* 71: 51–67. [CrossRef] [PubMed]

Klügl, Franziska, and Ana L. Bazzan. 2012. Agent-based modeling and simulation. *AI Magazine* 33: 29. [CrossRef]

Knapp, Thomas A., Nancy E. White, and Amy M. Wolaver. 2013. The returns to migration: The influence of education and migration type. *Growth and Change* 44: 589–607. [CrossRef]

Kniveton, Dominic, Christopher Smith, and Sharon Wood. 2011. Agent-based model simulations of future changes in migration flows for Burkina Faso. *Global Environmental Change* 21: S34–S40. [CrossRef]

Lazaridis, Gabriella, and Khursheed Wadia. 2015. *The Securitisation of Migration in the EU: Debates Since 9/11*. Berlin: Springer.

Léonard, Sarah, and Christian Kaunert. 2020. The securitisation of migration in the European Union: Frontex and its evolving security practices. *Journal of Ethnic and Migration Studies* 48: 1–13. [CrossRef]

Lin, Larry, Kathleen M. Carley, and Shih-Fen Cheng. 2016. An agent-based approach to human migration movement. Paper presented at 2016 Winter Simulation Conference (WSC), Washington, DC, USA, December 11–14.

Liu, Bing, Chee Wee Chin, and Hwee Tou Ng. 2003. Mining topic-specific concepts and definitions on the web. Paper presented at 12th International Conference on World Wide Web, Budapest, Hungary, May 20–24; pp. 251–60.

Liu, Pengfei, Xiaxu He, Weifeng Zhang, and Enkai Chen. 2017. Exploring Migration Issue Based on Multi-agent Modeling. Paper presented at International Symposium on Intelligence Computation and Applications, Guangzhou, China, November 18–19.

M'hamdi, Ahmed, Fatima-Ezahra Sfa, Mohamed Nemiche, Saida Hachimi El Idrissi, and Rafael Pla-López. 2019. Modelling "Occident/Orient" duality and migration process with mobile agents. *Systems Research and Behavioral Science* 36: 750–64. [CrossRef]

Macal, Charles M., and Michael J. North. 2005. Tutorial on agent-based modeling and simulation. Paper presented at Winter Simulation Conference, Orlando, FL, USA, December 4–7.

Makarov, Valerii, Albert Bakhtizin, and Elena Sushko. 2016. Agent-based models as a means of testing of management solutions. *Upravlencheskoe Konsul'tirovanie = Administrative Consulting* 12: 16–25.

Makarov, Valerii, Albert Bakhtizin, Elena Sushko, and Alina Ageeva. 2017a. Agent-Based Approach for Modelling the Labour Migration from China to Russia. *Ekonomika Regiona = Economy of Regions* 2: 331–41. [CrossRef]

Makarov, Valerii, Albert Bakhtizin, Elena Sushko, and Alina Ageeva. 2017b. Simulation of the socio-economic system of the Eurasian continent using the agent-based models. *Applied Econometrics* 48: 122–39.

Makarov, Valerii, Albert Bakhtizin, Elena Sushko, and Alina Ageeva. 2018a. An agent-based model of Eurasia and simulation of consequences of large infrastructure projects. *Ekonomika Regiona = Economy of Regions* 4: 1102. [CrossRef]

Makarov, Valerii, Albert Bakhtizin, Elena Sushko, and Gennady Sushko. 2018b. Supercomputer simulation of social processes: New technologies. *Herald of the Russian Academy of Sciences* 88: 200–9. [CrossRef]

Malmberg, Gunnar. 1997. Time and space in international migration. In *International Migration, Immobility and Development: Multidisciplinary Perspectives*, 1st ed. Edited by Tomas Hammar, Grete Brochmann, Kristof Tamas and Thomas Faist. Abingdon: Routledge, pp. 21–48.

Mana, Adi, Shifra Sagy, Anan Srour, and Serene Mjally-Knani. 2015. On both sides of the fence: Perceptions of collective narratives and identity strategies among Palestinians in Israel and in the West Bank. *Mind & Society* 14: 57–83.

McAlpine, Alys, Ligia Kiss, Cathy Zimmerman, and Zaid Chalabi. 2021. Agent-based modeling for migration and modern slavery research: A systematic review. *Journal of Computational Social Science* 4: 243–332. [CrossRef]

McDuie-Ra, Duncan. 2014. The India–Bangladesh border fence: Narratives and political possibilities. *Journal of Borderlands Studies* 29: 81–94. [CrossRef]

Meyer, Ruth, and Huw Vasey. 2020. Immigration, social networks, and the emergence of ethnic segmentation in a low-skill labor market. *Social Science Computer Review* 38: 387–404. [CrossRef]

Musarò, Pierluigi. 2019. Aware Migrants: The role of information campaigns in the management of migration. *European Journal of Communication* 34: 629–40. [CrossRef]

Nelson, Erica L., Saira A. Khan, Swapna Thorve, and Paul Gregg Greenough. 2020. Modeling pastoralist movement in response to environmental variables and conflict in Somaliland: Combining agent-based modeling and geospatial data. *PLoS ONE* 15: e0244185. [CrossRef]

Nemiche, Mohamed, Ahmed M'Hamdi, Mohamed Chakraoui, Vicent Cavero, and Rafael Pla Lopez. 2013. A theoretical agent-based model to simulate an artificial social evolution. *Systems Research and Behavioral Science* 30: 693–702. [CrossRef]

Nica, Elvira. 2015. Labor market determinants of migration flows in Europe. *Sustainability* 7: 634–47. [CrossRef]

Norman, Kasih, Josha Inglis, Chris Clarkson, Tyler Faith, James Shulmeister, and Daniel Harris. 2018. An early colonisation pathway into northwest Australia 70-60,000 years ago. *Quaternary Science Reviews* 180: 229–39. [CrossRef]

Oleynik, Elena B., Natalya V. Ivashina, and Yu D. Shmidt. 2021. Migration processes modelling: Methods and tools (overview). *Computer Research and Modeling* 13: 1205–32. [CrossRef]

Ooi, Chew Sia. 2013. *The Efficacy and Social Validity of a Group Cognitive Behavioural Therapy for Young Migrants from War-Affected Countries*. Singapore: Curtin University.

Padmanabha, Harish, Fabio Correa, Camilo Rubio, Andres Baeza, Salua Osorio, Jairo Mendez, and Maria A. Diuk-Wasser. 2015. Human social behavior and demography drive patterns of fine-scale Dengue transmission in endemic areas of Colombia. *PLoS ONE* 10: e0144451. [CrossRef] [PubMed]

Panda, Shilpi Smita, and Nihar Ranjan Mishra. 2018. Factors affecting temporary labour migration for seasonal work: A review. *Management Research Review* 41: 1176–200. [CrossRef]

Parunak, H. Van Dyke, Robert Savit, and Rick L. Riolo. 1998. Agent-based modeling vs. equation-based modeling: A case study and users' guide. Paper presented at International Workshop on Multi-Agent Systems and Agent-Based Simulation, Paris, France, July 4–6.

Parven, Shahanaz. 2019a. Political management of emigration from Bangladesh in the framework of a social network theory. *Upravlenie* 8: 123–32. [CrossRef]

Parven, Shahanaz. 2019b. A social change theory for interpretation of the migration flows of the Bangladeshi labor emigration. *Upravlenie* 7: 113–19.

Picascia, Stefano, Ali Termos, and Neil Yorke-Smith. 2018. Initial Results from an Agent-Based Simulation of Housing in Urban Beirut. Paper presented at 17th International Conference on Autonomous Agents and MultiAgent Systems, Stockholm, Sweden, July 10–15.

Picascia, Stefano, and Neil Yorke-Smith. 2016. Towards an agent-based simulation of housing in urban Beirut. Paper presented at International Workshop on Agent Based Modelling of Urban Systems, Singapore, May 10.

Pitoski, Dino, Thomas J. Lampoltshammer, and Peter Parycek. 2021a. Network analysis of internal migration in Austria. *Digital Government: Research and Practice* 2: 1–24. [CrossRef]

Pitoski, Dino, Thomas J. Lampoltshammer, and Peter Parycek. 2021b. Network analysis of internal migration in Croatia. *Computational Social Networks* 8: 1–17. [CrossRef]

Ravenstein, Ernest George. 1889. The laws of migration. *Journal of the Royal Statistical Society* 52: 241–305. [CrossRef]

Reinhardt, Oliver, Jason Hilton, Tom Warnke, Jakub Bijak, and Adelinde M. Uhrmacher. 2018. Streamlining simulation experiments with agent-based models in demography. *Journal of Artificial Societies and Social Simulation* 21: 9. [CrossRef]

Riolo, Rick L., Michael D. Cohen, and Robert Axelrod. 2001. Evolution of cooperation without reciprocity. *Nature* 414: 441–43. [CrossRef]

Roy Chowdhury, Arnab, and Ahmed Abid. 2022. Treading the border of (il) legality: Statelessness, "amphibian life", and the Rohingya "boat people" of Asia. *Inter-Asia Cultural Studies* 23: 68–85. [CrossRef]

Ruiz, Nancy, Adriana Giret, Oscar Alvarado, Victor Perez, Rosa M. Rodríguez, and Vicente Julián. 2014. Agent-Based Simulation for Border Crossing Modeling. *Cybernetics and Systems* 45: 650–70. [CrossRef]

Russel, Stuart J., and Peter Norvig. 2020. *Artificial Intelligence: A Modern Approach*, 4th ed. London: Pearson, p. 1136.

Saini, Simardeep, Paul Wai Hing Chung, and Christian W. Dawson. 2011. Mimicking human strategies in fighting games using a data driven finite state machine. Paper presented at the 2011 6th IEEE Joint International Information Technology and Artificial Intelligence Conference, Chongqing, China, August 20–22.

Sakamoto, Takuto, and Hiroki Takikawa. 2017. Cross-national measurement of polarization in political discourse: Analyzing floor debate in the US the Japanese legislatures. Paper presented at 2017 IEEE International Conference on Big Data, Boston, MA, USA, December 11–14.

Schelling, Thomas C. 1971. Dynamic models of segregation. *Journal of Mathematical Sociology* 1: 143–86. [CrossRef]

Searle, Christa, and Jan H. van Vuuren. 2021. Modelling forced migration: A framework for conflict-induced forced migration modelling according to an agent-based approach. *Computers, Environment and Urban Systems* 85: 101568. [CrossRef]

Shultz, Daniel R., and Andre Costopoulos. 2019. Modeling environmental variability and network formation among pastoral nomadic households: Implications for the rise of the Mongol Empire. *PLoS ONE* 14: e0223677. [CrossRef]

Simon, Miranda, Cassilde Schwartz, David Hudson, and Shane D. Johnson. 2018. A data-driven computational model on the effects of immigration policies. *Proceedings of the National Academy of Sciences* 115: E7914–23. [CrossRef]

Skeldon, Ronald. 2010. Managing migration for development: Is circular migration the answer. *Whitehead Journal of Diplomacy and International Relations* 11: 21.

Skinner, Shawn Wesley, Sarah Urdahl, Thomas Harrington, Michael G. Balchanos, Elena Garcia, and Dimitri N. Mavris. 2018. UAV Swarms for Migration Flow Monitoring and Search and Rescue Mission Support. Paper presented at 2018 AIAA Information Systems-AIAA Infotech @ Aerospace, Kissimmee, FL, USA, January 8–12.

Smith, Christopher, Dominic R. Kniveton, Sharon Wood, and Richard Black. 2011. Climate change and migration: A modelling approach. In *African Climate and Climate Change*. Berlin: Springer, pp. 179–201.

Sobol, Ilya M. 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Mathematics and Computers in Simulation* 55: 271–80. [CrossRef]

Sokolowski, John A., and Catherine M. Banks. 2010. Investigating social dynamics and global connectivity: An agent-based modeling approach. Paper presented at 2010 Winter Simulation Conference, Baltimore, MD, USA, December 5–8.

Sokolowski, John A., and Catherine M. Banks. 2014. A methodology for environment and agent development to model population displacement. Paper presented at 2014 Symposium on Agent Directed Simulation, Tampa, FL, USA, April 13–16.

Solano, Giacomo, and Thomas Huddleston. 2020. *Migrant Integration Policy Index*. Barcelona/Brussels: CIDOB and MPG, p. 262.

Soto, Ricardo Contreras. 2007. La antinomia antípoda como forma de relato en los trabajadores migrantes mexicanos en Estados Unidos. *Historia Actual Online* 13: 199–211.

Suleimenova, Diana, Hamid Arabnejad, Wouter Edeling, and Derek Groen. 2021. Sensitivity-driven simulation development: A case study in forced migration. *Philosophical Transactions of the Royal Society A* 379: 20200077. [CrossRef]

Termos, Ali, Stefano Picascia, and Neil Yorke-Smith. 2021. Agent-based simulation of west asian urban dynamics: Impact of refugees. *Journal of Artificial Societies and Social Simulation* 24: 2. [CrossRef]

Tranos, Emmanouil, Masood Gheasi, and Peter Nijkamp. 2015. International migration: A global complex network. *Environment and Planning B: Planning and Design* 42: 4–22. [CrossRef]

Truscott, James, and Neil M. Ferguson. 2012. Evaluating the adequacy of gravity models as a description of human mobility for epidemic modelling. *PLoS Computational Biology* 8: e1002699. [CrossRef] [PubMed]

Tully, Mark A., Laura McMaw, Deepti Adlakha, Neale Blair, Jonny McAneney, Helen McAneney, and Lee Smith. 2021. The effect of different COVID-19 public health restrictions on mobility: A systematic review. *PLoS ONE* 16: e0260919. [CrossRef]

Vaccario, Giacomo, Luca Verginer, and Frank Schweitzer. 2021. Reproducing scientists' mobility: A data-driven model. *Scientific Reports* 11: 1–11. [CrossRef]

Vallée, François, Aurélien Luciani, and Murray P. Cox. 2016. Reconstructing demography and social behavior during the Neolithic expansion from genomic diversity across Island Southeast Asia. *Genetics* 204: 1495–506. [CrossRef] [PubMed]

Van Hear, Nicholas. 2010. Theories of migration and social change. *Journal of Ethnic and Migration Studies* 36: 1531–36. [CrossRef]

Vijaymeena, M. K., and Kavita Kadam Kavitha. 2016. A survey on similarity measures in text mining. *Machine Learning and Applications: An International Journal* 3: 19–28.

Vogel, Nicholas, Christopher Theisen, Jonathan P. Leidig, Jerry Scripps, Douglas H. Graham, and Greg Wolffe. 2015. Mining mobile datasets to enable the fine-grained stochastic simulation of Ebola diffusion. *Procedia Computer Science* 51: 765–74. [CrossRef]

Warner, Koko, and Tamer Afifi. 2014. Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity. *Climate and Development* 6: 1–17. [CrossRef]

Weidmann, Nils B., and Idean Salehyan. 2013. Violence and ethnic segregation: A computational model applied to Baghdad. *International Studies Quarterly* 57: 52–64. [CrossRef]

Wong, David W. 2004. The modifiable areal unit problem (MAUP). In *WorldMinds: Geographical Perspectives on 100 Problems*. Berlin: Springer, pp. 571–75.

Wren, Colin D., Julian Z. Xue, Andre Costopoulos, and Ariane Burke. 2014. The role of spatial foresight in models of hominin dispersal. *Journal of Human Evolution* 69: 70–78. [CrossRef] [PubMed]

Yan, Jie, Renjing Liu, and Guangjun Zhang. 2018. Task structure, individual bounded rationality and crowdsourcing performance: An agent-based simulation approach. *Journal of Artificial Societies and Social Simulation* 21: 12. [CrossRef]

Yigzaw, Gedifew Sewenet, and Endalsasa Belay Abitew. 2019. Causes and impacts of internal displacement in Ethiopia. *African Journal of Social Work* 9: 32–41.

Zelinsky, Wilbur. 1971. The hypothesis of the mobility transition. *Geographical Review* 61: 219–49. [CrossRef]