Computers, Environment and Urban Systems 85 (2021) 101568

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Modelling forced migration: A framework for conflict-induced forced migration modelling according to an agent-based approach

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ARTICLE INFO

Keywords:
Forced migration
Agent-based simulation modelling
Migration simulation
Humanitarian modelling

ABSTRACT

The challenge posed by the management of sudden migration of large groups of people lies in the ability to portray and predict the scale and dynamics of such movement accurately. This is further complicated by the fact that associated data pertaining to such migration are largely incomplete or untrustworthy. In view of the shortcomings in respect of modelling instances of conflict and the lack of data related to the associated movement patterns of forcibly displaced individuals, a generic framework is proposed for aiding in the design of agent-based models for simulating conflict instances along with the localised decision-making processes underlying the movement of refugees, undocumented migrants and internally displaced persons fleeing conflict-affected areas. A concept demonstrator is developed based on the framework in an attempt to demonstrate the usefulness and practicability of the framework in the context of conflict-induced forced migration in Syria. The value of such a model lies in the fact that it produces as output the corresponding emergent large-scale migration patterns which may assist in understanding the movement patterns of forcibly displaced people and predicting anticipated destinations of these individuals, and serve as a decision support tool for humanitarian relief.

1. Introduction

In 2019, one in every 97 people worldwide was forcibly displaced from his or her place of residence, whether as an asylum-seeker, a refugee or a person displaced within the borders of their own country. The United Nations High Commissioner for Refugees (2020) further estimated the total number of forcibly displaced people in 2019 to be 79.5 million, 45.7 million of whom were people displaced within their countries of origin, and 33.8 million as refugees and asylum-seekers fleeing across international borders.

The Global Opportunity Network (2017) identified several topics pertinent to global unstable regions as some of the most important opportunities to pursue with respect to social impact. The gross impact of persecution and violent conflicts is evident worldwide as millions of people are continually forced to flee their homes and seek refuge elsewhere. By 2030, it is anticipated that 46% of individuals will reside in unstable and conflict-affected areas. A methodological approach is required to manage and mitigate humanitarian crises due to the scale, complexity, continuance and reoccurring nature of this phenomenon in recent times (Global Opportunity Network, 2017).

The potential impact of humanitarian intervention efforts in these crises bring about many challenges that require innovative problem-solving approaches. Researchers such as Alhanaee and Csala (2016) and Greenwood (2005) have attempted to identify the motives of migrants in order to better understand the spatial phenomenon of migration in economic and social contexts. It is imperative for humanitarian support organisations and policy makers to understand the motive behind a person's migration movements in an attempt to plan for necessary resources and logistics aimed at facilitating their arrival (Harrison, 2016).

The lack of adequate and complete data presents a serious problem to humanitarian aid, especially with respect to forced displacement. Efforts towards improving the reliability, quality and scope of data concerning forcibly displaced people are required to address the gaps in these data currently available for assisting in long-term development planning during crises (Sarzin, 2017).

Simulation and the *agent-based modelling* (ABM) paradigm, in particular, can be utilised to develop models that may potentially explore the behaviour of forcibly displaced people in an attempt to better understand migration patterns. Developing such models, however, is a fairly complex process, especially as it comprises an extensive number of aspects to be considered. The framework proposed in this

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https://doi.org/10.1016/j.compenvurbsys.2020.101568
Received 2 April 2020; Received in revised form 30 October 2020; Accepted 9 November 2020

paper is intended to assist in the development and application of agent-based simulation models for modelling and predicting conflict-induced migration.

Other than this introductory section, the remainder of this paper is structured as follows. In Section 2, a background and literature review of computer simulation modelling and the use thereof in existing models pertaining to forced migration are given. The proposed framework is introduced in Section 3, while a model concept demonstrator aimed at validating the framework is discussed in Section 4. In conclusion, a discussion on the proposed framework and the model concept demonstrator is given in Section 5.

2. Background and literature review

Edwards (2008) discussed the potential of employing computational models in order to predict the spatial patterns of forcibly displaced individuals, emphasising the assistance that such models may be able to provide humanitarian aid organisations and policy makers. Groen et al. (2016) affirmed the importance of utilising such models in order to capture the movements of refugees on a global scale. The notion of numerical modelling is a tool utilised to study the behaviour of large complex systems and, in particular, their dynamic behaviour, when the complexity does not allow for analytical evaluation (Simon, 1990). One of the most powerful tools available for comprehending the behaviour of complex systems and processes is simulation modelling (Shannon, 1998).

Simulation modelling is the computer-based imitation of a real-world system (Stewart, 2004). Furthermore, agent-based simulation is the modelling of a collection of autonomous decision-making entities, where the behaviour of each agent depends on a basic set of rules that guide decision making (Bonabeau, 2002). ABM allows for the consequences of individual decisions to be modelled locally, taking into account the complexities of social systems such as behaviours, motivations and relationships between individual agents, and provides an aggregated global emergent behaviour as output (Anderson, Chaturvedi, & Cibulskis, 2007). The ability of agent-based models to simulate the interactions among individuals makes it well-suited for the purpose of modelling sociological and psychological behaviour, and human interaction with one another, as well as with the environment (Johnson, Lampe, & Seichter, 2009).

ABM is capable of facilitating a synthetic environment which allows for an understanding of the collective behaviour of forcibly displaced persons through computational experimentation (Anderson et al., 2007). With knowledge pertaining to the migration behaviour of people, an agent-based model may potentially be developed and implemented by researchers to predict the number of people displaced, identifying likely destinations for refugees, as well as the population size of refugees per destination region. Furthermore, such a model may aid in identifying appropriate locations for aid distribution points, as well as predicting the anticipated demand for aid (Edwards, 2008).

Existing simulation models of this nature in the literature include, among others, a model developed by Lemos, Coelho, and Lopes (2013) for simulating social conflict and civil violence aimed at capturing the characteristics associated with its spread, a model developed by Crooks and Wise (2013) for aiding humanitarian relief after the occurrence of natural disasters, a model simulating the autonomous decision making of environmentally induced migrants developed by Smith, Wood, and Kniveton (2010), and a model explicitly incorporating the social network among people migrating between Ecuador and the United States, developed by Rehm (2012).

Anderson et al. (2007) utilised ABM in simulating the effect of changes to humanitarian assistance policies with respect to the health and safety of refugee communities. The concept of simulating the implementation of policies allows for the evaluation of the potential impact of decisions and the testing of various planning strategies. In a similar fashion, Simon, Schwartz, Hudson, and Johnson (2018) developed a data-driven agent-based model for evaluating the impact of immigration policies on the decision making of those forcibly displaced. The model was calibrated using survey and experimental data pertaining to the Jamaican population. Simon (2019) further employed ABM, along with social network theory, to demonstrate path dependencies that emerge in migration systems and certain deviations in these paths that may occur in response to immigration policies.

Collins and Frydenlund (2016) proposed an agent-based model for simulating strategic group formation of refugees when fleeing. This model is aimed at investigating the evacuation time of refugees, assuming that they tend to form groups when travelling over long distances. Another agent-based model, developed by Orfano (2015), simulates empirical economic factors leading to migration and the long-term effects of forced migration.

Johnson et al. (2009) calibrated an agent-based model for use in the context of peace keeping within a refugee camp scenario. Owing to quantitative data not being available, the calibration was performed by relying on experimental designs and plausible situations considered with the help of subject matter experts. The spread of disease in refugee camps, another pertinent issue faced by humanitarian agencies at refugee camps, was modelled by Hailegiorgis and Crooks (2012), taking the social behaviour of people and their movements into account. Another simulation model focussing on the displacement of Syrians within the city of Aleppo was developed by Sokolowski, Banks, and Hayes (2014) as a method of investigating the decision making of citizens during forced migration.

Klabunde and Willekens (2016) reviewed the use of agent-based models in modelling the decision making of an agent during migration, concluding that ABM is still in its infancy when considering migration. Although a number of migration models exist, they differ in scale, complexity and documentation owing to the influence of different disciplines and limited knowledge. The decision-making processes of agents are often modelled in a rudimentary manner and the criteria determining decisions should not only include behavioural rules (as in ABM), but also rates and probabilities (as in microsimulation). A further notable challenge in this field is the validation of agent-based models, owing to a general lack of empirical data, and effectively modelling the manner in which migration decisions are influenced by a human's life course.

Awareness of crises and, in particular, conflict-induced forced displacement, has increased notably within the international community over the last few years. The challenge, however, is to portray the true scale and dynamics of the issue accurately, as not all available data are credible or complete. Currently, there are significant gaps in the data required to facilitate long-term development planning in crisis situations. The aggregate number of 68.5 million currently forcibly displaced people is only an estimate and data concerning those displaced within specific countries of origin are even less reliable (Martin & Singh, 2018; Sarzin, 2017).

More often than not, research does not focus on those internally displaced or on undocumented migrants, which augments the gap in available data (Aksel, 2017; Davenport, Moore, & Poe, 2003). The unknown number of forcibly displaced people represents an obstacle to humanitarian support organisations, especially in times where the situation is critical in nature (Hailegiorgis & Crooks, 2012; United Nations Office for the Coordination of Humanitarian Affairs, 2019).

The greatest overall challenge faced by researchers and humanitarian support organisations when addressing forced displacement is the problem of predicting the destinations of displaced individuals. Attempts have been made to address this problem, although the main obstacle when predicting such random movement remains the facts that migration is a highly structured process dependent on patterns, historical context and the manner in which an individual's decision-making process develops (Dragostinova, 2016; Edwards, 2008). The ability to predict the movement of forcibly displaced people with some measure of accuracy is critical to aid organisations in facilitating the planning of logistics and procurement of resources aimed at supporting those fleeing violence and persecution (Collins & Frydenlund, 2016). Groen et al. (2016) endorsed the use of simulation modelling to account for the shortfalls of incomplete empirical information in the monitoring infrastructure and predictions of refugee movements.

3. Methodology

In view of the aforementioned shortcomings in respect of modelling instances of conflict and the lack of data related to the associated movement patterns of forcibly displaced individuals, a generic framework is proposed in this paper for aiding in the design of an agent-based model for simulating conflict instances along with the localised decision-making processes underlying the movement of refugees, undocumented migrants and *internally displaced persons* (IDPs) fleeing conflict-affected areas. The value of such a model lies in the fact that it produces as output the corresponding emergent large-scale migration patterns which may assist in understanding the movement patterns of forcibly displaced people and predicting anticipated destinations of these individuals, as well as that it may serve as a decision support tool for humanitarian relief.

The design and development of these models is, however, challenging as a vast number of factors of a complex system have to be considered at an acceptable level of accuracy. Moreover, existing models in this realm are often developed with little or no knowledge accumulation (Klabunde & Willekens, 2016). The proposed generic framework provides a structured guide to modellers as to a model design and development process based on accumulated knowledge which will facilitate in the various dimensions in which critical modelling choices have to be made.

The *Conflict-induced Forced Migration Modelling using an Agent-based approach* (CoFMMA) framework proposed in this paper comprises five phases, namely formulation, conceptualisation, model development, model execution, and documentation. The framework, the primary components within its phases, and the flow of activities between these phases, are illustrated in Fig. 1. The remainder of this section is dedicated to a detailed discussion on each of the framework phases.

3.1. Phase 1: formulation

The application of an agent-based simulation model in the social, political and economic sciences is highly complex and it is therefore important that such a model be scoped sufficiently narrowly and developed at an appropriate level of detail (Bonabeau, 2002). Within the first phase of the CoFMMA framework, *formulation*, the modeller should identify and select a particular conflict situation to which to apply the framework. The modeller should gain a background understanding of the particular conflict situation, including the historical progression of the conflict, as well as the state of the conflict situation during a selected time period. The geographic and time scales of the model also have to be determined as these will influence the level of detail incorporated into the model and, in effect, determine the computational capability required for its implementation.

The modeller should keep in mind any limitations with respect to computational power which may lead to either a reduction in geographical scale, or the aggregation of agents. The modeller further has to consider which types of forced migration movement to include in the study. Clarity with respect to the model's purpose and scope will aid in progressing to the next phases of the framework.

3.2. Phase 2: conceptualisation

There exist many challenges and important considerations when developing a model of social behaviour within the realm of conflict-induced forced migration. These include the gathering of qualitative and quantitative data, the quantification of qualitative data and the understanding of motives and constraints which affect the movement of a population. The second phase of the CoFMMA framework is *model conceptualisation* which consists primarily of an iterative flow between conceptual modelling and data collection.

The modeller is required to model the real-world scenario conceptually by stating assumptions and limitations of the agent-based model to be developed pertaining to the modelling of conflict, the modelling of the particular population, and the modelling of movement decisions made by the people. These assumptions and limitations to be considered during the modelling process should be based on qualitative data and insight, as well as available quantitative data. Within the conceptualisation phase, the modeller should consider various data inputs, agent definitions and attributes, as well as conflict, population and movement considerations, while further detailing the geographic and time scales of the simulation model.

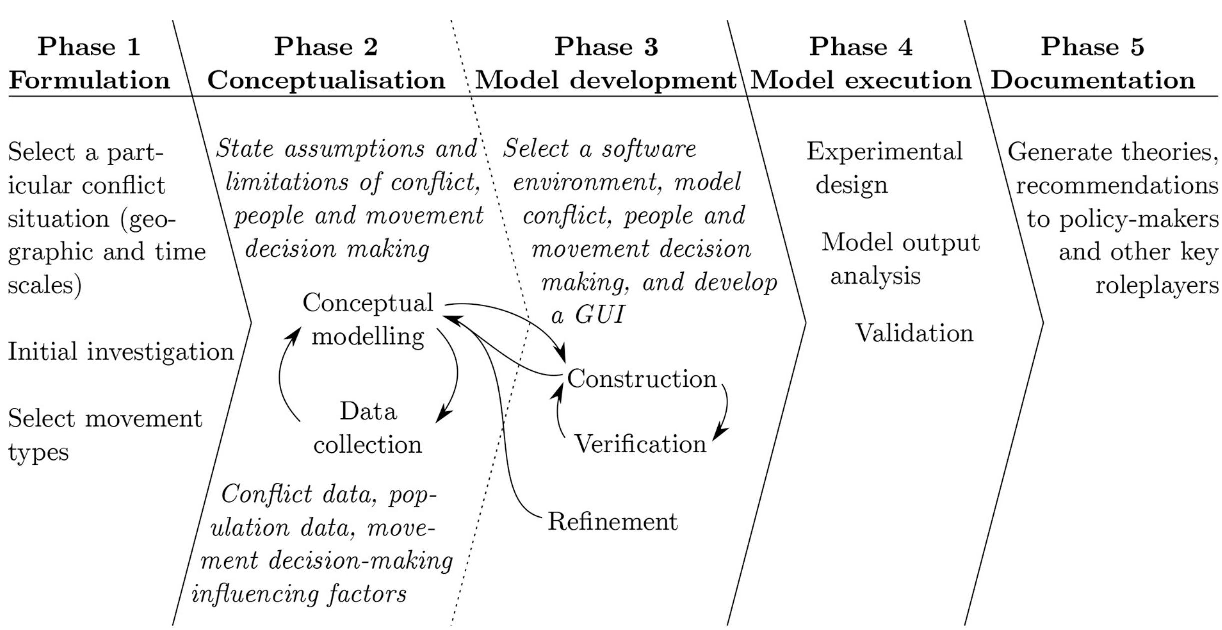

Fig. 1. Schematic representation of the various phases of the generic CoFMMA framework.

3.3. Phase 3: model development

Phase 3 of the CoFMMA framework concerns the *development* of the agent-based model. The modeller is required to select an appropriate software environment in which to develop the model, before modelling the four primary elements — the conflict, the people, the movement decision making of the people, and the graphical user interface (GUI) which will assist users in utilising the model. The model development phase should follow an iterative process whereby the modeller constructs a portion of the model and verifies that portion before moving on to the construction of the next portion.

It is recommended that an agent-based model should be developed in a continuous fashion by starting to construct a simple model which captures certain essentials and, only after verification, adding complexity in a systematic manner. Each iteration should add depth and realism to the model, thereby further refining it. If, at some point during this iterative process, the modeller finds a portion developed inadequate or unsuitable, he or she should revert back to Phase 2. Adjustments may be made to the conceptual model if the model development phase requires it. Such changes to the conceptual model should be addressed adequately during the model development phase. The model development may require more than one iteration between Phases 2 and 3, allowing for a reasoned, adequate model to be developed.

3.4. Phase 4: model execution

A significant component in the simulation model development process is determining the extent to which a simulation model accurately represents the real-world system under consideration. This is to be achieved in Phase 4, *model execution*, by the implementation of an appropriate experimental design, model output analysis and validation of the simulation model developed. Experimental design is a methodology for designing experiments with the aim of investigating certain scenarios or the optimisation of a system (Kleijnen, 1998). In a similar vein, model output analysis is aimed at gauging performance of a simulation model by determining the simulation model's true parameters and characteristics during model execution (Stewart, 2004). The objective during validation is to determine whether or not the simulation model is a true representation of the actual system to the extent necessary in order to meet the model objectives (Sturrock, 2013).

3.5. Phase 5: documentation

The final phase of the CoFMMA framework entails the *documentation* of the simulation model developed by the modeller as he or she progressed through the aforementioned phases. The modeller should be able to present the model and its results clearly, succinctly and in a compelling manner (Shannon, 1998). This phase should include the various theories generated, recommendations to policy-makers and other key roleplayers based on results obtained during model execution (Phase 4).

Carefully planned and well-written documentation will contribute towards the establishment of a more user-friendly and credible tool in the eyes of the user, as well as a reference for any future amendments or expansions of the existing model. The modeller should consider using appropriate vocabulary with as little technical jargon as possible in order for the user to understand the model and the issues that are considered as important to the end-user should also be taken into account.

The modeller should further document the model as a decision-support tool to the user. The documentation should facilitate the selection and variation of parameters in a simulation model so as to allow for scenario analysis and experimental design by the user (Van Vuuren, Potgieter, & Van Vuuren, 2017). The model developed will most likely possess the capability of being implemented as an investigative tool in an attempt to analyse various scenarios which may occur in the field of forced migration. The analysis of these different scenarios may facilitate a better understanding of the behaviour and decision making exhibited by people when confronted with conflict. The inclusion of this feature will further increase the usability and flexibility of the model.

4. Model concept demonstrator

In order to demonstrate and validate the proposed CoFMMA framework, a concept demonstrator is developed in this section according to the framework to model conflict-induced forced migration in Syria according to an agent-based approach. The design and development of this model concept demonstrator is discussed according to the phases of the CoFMMA framework.

4.1. Phase 1: formulation

Since 2011, an estimated five million people have fled Syria to seek refuge in Lebanon, Turkey and beyond. In conjunction, even more Syrians have been displaced internally within the borders of the country. By the end of 2015, an estimated total of 11.7 million Syrians (more than half the Syrian population) had been displaced forcibly as a result of the civil war (Jonson, Mouamar, Huber, Reid, & Koenig, 2017; United Nations High Commissioner for Refugees, 2016). The instability in certain areas of Syria has forced families and individuals to abandon their homes to find safety elsewhere.

Syrian refugees have typically chosen one of four feasible options to find safety. These are internal displacement, encampment (*i.e.* settlement in refugee camps), self-settlement (settlement in urban areas) or the challenging journey of attempting to settle in European countries (Betts, 2016). In conjunction with the first phase of the CoFMMA framework, an understanding of the Syrian conflict situation is formulated upon an initial investigation. This phase further includes the consideration of time and geographic scales, as well as the movement types to be modelled.

4.1.1. Geographic and time scales

The aim of the model concept demonstrator is to represent the movement of forcibly displaced Syrians during the Syrian war. On a geographic scale, the model includes the Syrian Republic and its neighbouring countries in order to model the entire Syrian population (approximately 23.7 million people). This calls for a medium level of model abstraction, as a model with millions of agents would be computationally too complex. A medium level of model abstraction requires the aggregation of agents. The exact scale (*i.e.* the number of people represented by one agent) and manner (*i.e.* the way in which aggregate groups are formed) of aggregation is determined during Phase 2 of the model concept demonstrator development. In order to model the Syrian war, a time scale of years is considered, as the war has been ongoing since 2011.

4.1.2. Movement types

Since the model abstraction is restricted to a medium level, the exact paths along which the people move do not necessarily have to be modelled. The focus is rather on which movement type an agent selects as well as the anticipated destination of this move.

Agents flee conflict according to three movement types in the model concept demonstrator: (1) IDPs, (2) asylum-seekers/refugees (who are henceforth referred to as refugees) and (3) undocumented migrants. IDPs are Syrians who are forcibly displaced, but choose to stay within the borders of Syria, whilst refugees are those who choose to cross the Syrian border legally, either by applying for asylum in the destination country, or being registered as refugees living in refugee camps. The category of undocumented migrants represents those people who choose to cross the Syrian border without following the required legal and documented procedures.

4.2. Phase 2: conceptualisation

The primary assumptions made and limitations considered in the model are related to the geography, time, data and agent attributes within the simulation model, as well as the conflict, population and movement decisions made by the population. The conceptualisation phase is applied to the model concept demonstrator in this section.

4.2.1. Geographic considerations

Only neighbouring countries of Syria are considered as plausible destinations for immigration by forcibly displaced people as, according to data from the United Nations High Commissioner for Refugees (2020), more than 83% of Syrians who had fled their country have moved to a neighbouring country. These countries include Turkey, Iraq, Jordan, Lebanon and Greece. Other countries are not considered in the model concept demonstrator owing to modelling complexities. Israel, although a neighbouring country of Syria, is not considered as a destination country for Syrian refugees owing to the ongoing war between Israel and Syria, rendering the border between these two countries sealed (Fargues & Fandrich, 2012; Lewis, 2018).

The model concept demonstrator captures the movement of agents within Syria, as well as the movement of agents from Syria to neighbouring countries. Once an agent has moved to a neighbouring country, the model is no longer required to keep track of that agent's subsequent decision-making processes and movement, since consideration is limited to the first country of entrance with respect to cross-border movement. Movement of displaced Syrians from one neighbouring country to another is therefore not considered in the model concept demonstrator.

4.2.2. Time considerations

The Arab Spring[1] was initiated in Syria at the end of January 2011 (Mercy Corps, 2017; United Nations High Commissioner for Refugees, 2015, 2016). The simulation model execution therefore commences at the start of 2011, just before the occurrence of Arab Spring, and runs until the end of 2016. The simulation commences before the occurrence of the Syrian war and continues over a period of five years.

4.2.3. The agents

Among other characteristics, an agent's gender, age, education and economic status are considered. Agents in the model constitute an aggregate of 10,000 individuals with similar characteristics. Therefore, aggregation of attributes such as health status and social networks is not possible at a useful degree of accuracy. Furthermore, the health of a person should be considered in conjunction with other attributes (such as economic status and age). For example, an older individual with poor health and of low economic status might not be able to move at all, or only move within Syria, whereas a young working individual with a chronic health illness might choose to seek asylum in another country where proper medical facilities are available. Owing to the complexity of considering health as an attribute and the complexities surrounding the inclusion of social networks, these aspects are regarded as outside of the model scope. Lemos (2017), a subject matter expert, affirms this decision, advocating that agent attributes be restricted to only essential inclusions.

4.2.4. Movement considerations

To replicate the movement of forcibly displaced Syrians, who usually flee by foot, a fixed average movement speed of 4 *km/h* is employed (Saarinen & Ojala, 2017). Agents do not always leave immediately and the waiting period correlates to the maturity of the conflict (Mercy Corps, 2017). During the beginning of Arab Spring, people were still reluctant to relocate, but as the conflict began to extend over years, increasing in maturity, people were more inclined to relocate when confronted with conflict at a more mature state.

The geographic area of neighbouring countries utilised in the model is not considered in detail. That is, the model only considers the area as a representation of the entire country. If an agent decides to move to a neighbouring country, the model tracks to which country it decides to move (in order to keep track of the associated fluctuating populations), but not the exact location within that country where the agent might choose to settle.

4.2.5. Data inputs

The quantitative data employed in the model are available to the public and was gathered from various sources, such as the [dataset] GDELT Project (2016), the [dataset] United Nations Department of Economics and Social Affairs (2017), the [dataset] World Bank (2017) and the [dataset] Central Intelligence Agency (2015). Exact data do not always exist or are not always available — in such cases, sensible estimates, based on various sources and given arguments are provided.

4.2.6. Conflict considerations

Material conflict (according to the [dataset] GDELT Project, 2016 classification of conflict events) is modelled in Syria over the aforementioned timeline, taking into account the intensity of these conflict occurrences. Other attributes of these conflict events, such as the type of actors involved (*e.g.* police forces, government troops or rebels) or the reason for occurrence are not considered as the modelled outcome is not effected by these factors. Only conflict events initiated within Syria are captured by the model.

4.2.7. Population considerations

Various factors may lead to a fluctuation in a population. Internal displacement, new asylum applications and impetuous arrivals of migrants across the border are considered. Furthermore, the model accounts for births and deaths, as well as IDPs fleeing across the border, but it does not accommodate other decreasing factors of refugees and undocumented migrants such as repatriation and asylum rejections, owing to the associated modelling complexities.

4.2.8. Factors influencing movement decision making

In an attempt to understand the process of modelling the decision making of forcibly displaced people, advice and insights were sought from various subject matter experts, including Aksel (2017), Frydenlund (2017), Groen (2017), Lemos (2017), Shomary (2017), Smith (2017), and Stewart (2017). Their fields of expertise range from simulation and conflict modelling, to global studies, decision-making theories and subfields of the social sciences.

The two primary movement decision making aspects considered in the model concept demonstrator are the adoption of an agent to a movement type, as well as the selection of an alternative destination.

Making a choice between the different movement types is mainly influenced by a person's characteristics and attributes (Arous, 2013). Initially, a fast-and-frugal tree (refer to Katsikopoulos, Durbach, and Stewart (2017) and De Kock (2019)) was considered for use in modelling this decision-making process, but predetermining the order in which to present the alternatives based on the person's attributes was found to be infeasible, since none of the attributes dominate the rest in determining the movement type of a person. As a result, the additive model (refer to Dillon (1998) and De Kock (2019)) was considered and deemed fit for the purpose of determining a person's movement type, as it takes into account all attributes according to scores assigned by the modeller. This allows for a total score to be calculated for each alternative movement type. This total score may be considered to correlate with the probability of that alternative being selected. Klabunde and Willekens (2016) agreed that the most apparent manner in which to evaluate such choices is to enumerate the alternatives and select the option that achieves the highest valuation.

[1] A series of anti-government protests which sparked the initial uprising and armed rebellions, subsequently spreading across the Middle East.

The decision of where to move to depends on the movement type of a person. Factors such as safety, distance and population density should be taken into consideration. Shomary (2017) agreed that people fleeing will take the population density of possible destinations into account when deciding where to move. In the case of IDPs, an exact location within the country needs to be identified as a new destination for the person, whereas refugees and undocumented migrants simply have to choose which destination country to move to (not necessarily a specific location within that country) for modelling purposes.

The decision-making method deemed appropriate for modelling the selection of a new destination for an IDP is the conjunctive model (refer to Dillon (1998) and De Kock (2019)). A set of potential solutions has to be identified based on certain criteria, such as safety and population density. The subject matter experts consulted, along with various sources from literature, agreed with these selected criteria (Davenport et al., 2003; Frydenlund, 2017; Lemos, 2017; Moore & Shellman, 2007; Shomary, 2017; Smith, 2017). The weighted sum multi-criteria decision-making method (refer to Guitouni and Martel (1998) and De Kock (2019)) may be employed to identify the group of potential solutions by allocating weights to the aforementioned criteria. The purpose of the evaluation function is to minimise the distance between the person's current location and his or her new destination. The set of potential solutions is then explored to find an alternative which minimises this distance. This allows for the selection of an adequate, although not necessarily ideal, alternative. This feasibly replicates the decision making of a person who, due to bounded rationality, also tends not necessarily to pursue optimality but to satisfice instead (Dillon, 1998).

Refugees and undocumented migrants are required to choose a destination country. In order to model this decision-making process, the weighted sum multi-criteria decision-making method is again employed. Each alternative (destination country) is scored, based on weighted factors such as the distance from the person's current location to the closest point along the border of that country, the ease with which a person will be able to enter that country (measured by an *openness index*) and the number of people from the country of origin already in that country at a given time instant (referred to as its *popularity*). The total score calculated per country is then expected to correlate with the probability of a person selecting that country as destination. Lemos (2017) agreed with this modelling approach and also with the use of openness indices.

4.3. Phase 3: model development

A map of Syria and its surrounding countries and ocean is employed within the simulation model concept demonstrator, based on a scale of 1 *km*: 1 *pixel*, established over the 1 000 × 600 *pixel* model space. The comprehensiveness of the model scale, in that the entire country is modelled, allows for realistic conflict initiation and spread to be replicated. When confronted with conflict, agents have to decide whether to move or not, as well as where to move. The manner in which this decision-making process is captured in the model concept demonstrator is based on the aforementioned decision-making factors so as to incorporate the qualitative data which form part of this decision-making process. Finally, a GUI is developed to assist users in the model application.

4.3.1. The AnyLogic simulation software suite

The design and development of the agent-based model concept demonstrator is conducted in the AnyLogic 8 Personal Learning Edition 8.4.0 software suite. This multi-method simulation modelling tool enables a modeller to gain deeper insights into complex systems and processes across various industries (AnyLogic Company, 2016). AnyLogic includes a sophisticated suite of model development tools which, along with the Java modelling language, allows modellers to create complex graphical simulation models (Van Vuuren et al., 2017).

4.3.2. Modelling of conflict

The modelling of conflict is discussed in a paper by De Kock (2019) and comprises the initialisation of a conflict-related incident, the spread of this conflict, as well as its eventual depletion. Historical data pertaining to conflict incidents that have occurred in Syria during 2011–2016 are mined using the event data analysis service of the [dataset] GDELT Project (2016) Project.

Arrays are computationally overlayed across the physical model space, thereby mapping out a 200 × 120 two-dimensional cellular space for facilitating the modelling of conflict. Each of the cells within this space represents a physical area of $5 \times 5\ km^2$ in the simulation model (De Kock, 2019).

Data from the [dataset] GDELT Project (2016) project are used as input to model the conflict instances. For each occurrence, the processed data file includes the date, Global Positioning System coordinates and total number of information sources citing this event. The total number of information sources citing an event is normalised so as to determine a significance or intensity rating for each conflict event (De Kock, 2019). The spread and depletion of conflict is modelled organically in a reaction-diffusion-like manner employing the rules of a typical cellular automata.

4.3.3. Modelling of people

For the modelling of people, each agent in the simulation model concept demonstrator is characterised by six parameters — gender, age, whether or not it has received tertiary education, economic status, whether or not it has family living outside of Syria, and anticipated age at death. These attributes and their associated values are initialised according to the probability distributions in Table 1.

An agent's anticipated age at death is determined by generating a random number from a truncated normal distribution with mean the average anticipated age at death over the six years and with default standard deviation of 12. The parameter value is clipped to have a lower bound of 0 and an upper bound of 100.

Certain variables, such as the birth rate and initial population, are utilised to control the initialisation and growth of the population. According to the data from the [dataset] United Nations Office for the Coordination of Humanitarian Affairs (2010), the estimated population size of Syria in 2011 was 23,720,000, while the average annual number of births between 2010 and 2015 was 24.4 per 1000 persons in the population. The annual number of deaths during the same period was 5.4 per 1000 persons ([dataset] United Nations Department of Economics and Social Affairs, 2017).

To manage the geographic spread of agents, presentation elements within the AnyLogic environment are employed to underlay a background representing the shape of each governorate within Syria. These shape files, shown in Fig. 2, allow for interaction between the environment and the agents. At the start of a simulation run, the percentage of agents populated per governorate correlates with the percentage of the total Syrian population per governorate as recorded in 2010 ([dataset] United Nations Office for the Coordination of Humanitarian Affairs,

Table 1
Probability distributions according to which agent attributes are initialised.

Parameter	Determine value
Gender (male)	$P(true) = 0.500$
Age	$P(0 < age < 15) = 0.364$ $P(15 \leq age < 65) = 0.602$ $P(age \geq 65) = 0.034$
Tertiary education	$If(age > 18) \rightarrow P(true) = 0.330$
Economic status	$P(LowEconomicStatus) = 0.119$ $P(MediumEconomicStatus) = 0.600$ $P(HighEconomicStatus) = 0.281$
International family	$P(true) = uniform(0.05, 0.2)$
Anticipated age at death	$If(male) \rightarrow AgeAtDeath = normal(12, 64.7)$ $If(female) \rightarrow AgeAtDeath = normal(12, 76.6)$

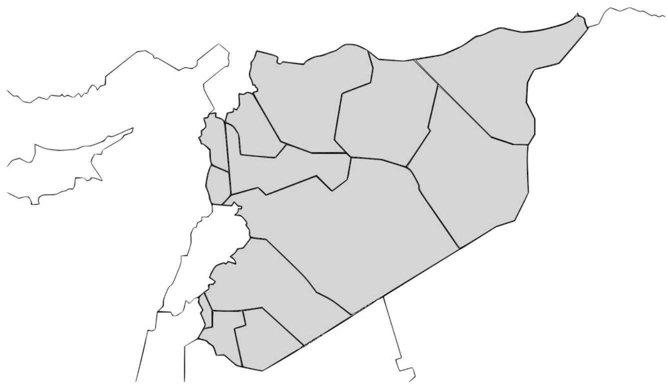

Fig. 2. Shape files representing the Syrian governorates used to underlay the primary screen of the GUI.

2010).

Another annual event included in the modelling of the agent population is the ageing of agents. This is explicitly incorporated in the model since age is one of the parameters influencing a person's movement choices and, as this simulation takes place over a number of years, it is necessary to account for ageing.

The behaviour exhibited by an agent in an agent-based model is governed by the statechart of that agent (Borshchev & Filippov, 2004). This statechart portrays the actions taken by the agent, contains the different states in which an agent can reside and is shown in Fig. 3. The changing of states is either condition-triggered or timeout-triggered.

At the point where an agent enters the system, attributes are assigned to the agent and the agent is located within Syria according to the geographic distribution of people in Syria. The agent immediately enters the Residing state and remains there unless the conflict within the agent's immediate vicinity exceeds the agent's tolerance threshold. In this case, the agent's movement type will be determined as the agent enters the WaitingPeriod state; after a certain number of days the agent will move to the SearchMove state. Within this state, the function associated with the movement type to which the agent belongs to will be activated, prompting the agent to search for a safe location to move to. As soon as the agent arrives at the identified destination, it will, if it is an IDP, enter the CheckSurroundings state where it will scout its immediate environment for any further conflict. If no threats exist, the agent will return to the Residing state. Otherwise, the agent will return to the SearchMove state and continue the search for an alternative safe destination. If, however, the agent is either a refugee or an undocumented migrant, it will bypass the CheckSurroundings state when arriving at its destination and directly revert to the Residing state.

If an agent spends more than a specified time within the SearchMove state without successfully finding a safe destination, it is assumed that the agent is stuck within the conflict. The agent is then directed to the Stuck state where there is a probability that it will die, or decide to move through the conflict towards a safer location. In the latter case, the agent will move to the MoveThroughConflict state where, based on the agent's movement type, a destination will be chosen. Once the agent finds and moves to the new destination, it transitions to the CheckSurroundings state and, if its current location is indeed a safe zone, it progresses further to the Residing state. At any moment during a simulation run, an agent may die, either because it reached its anticipated age at death, or due to being stuck amid conflict. If this occurs, the agent simply exits the system. The probability of an agent dying due to being stuck is by default set to 50% as an exact probability cannot be determined and the stochastic nature of the decision-making process should allow for sufficient randomness.

Another important agent attribute is the agent's tolerance threshold towards violence. This attribute is defined as a value between 0 and 1, which is empirically calculated based on a combination of factors or other attributes, such as age, gender or location.

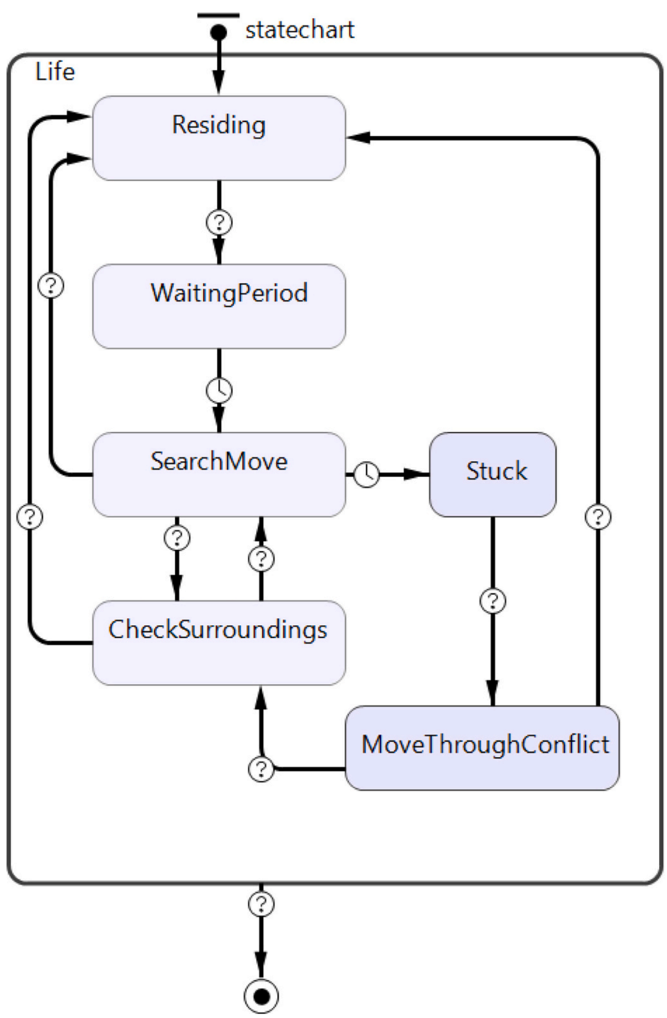

Fig. 3. The statechart of an agent.

4.3.4. *Modelling the decision making of an agent*

In the model concept demonstrator, movement type 1 pertains to those individuals who decide to leave their places of residence, but remain within Syria (referred to as IDPs). Movement type 2 refers to people who cross the Syrian border in order to seek refuge in refugee camps and/or apply for asylum in some country of destination (referred to as refugees). Movement type 3 is relevant to those individuals who cross the Syrian border and relocate to other countries without following documented procedures (referred to as undocumented migrants).

Depending on the movement type of an agent, it will select a proposed destination. Agents possess segmented knowledge about the current state of the modelling environment (conflict and population spread) depending on their locations and may use this information to predict what their future might entail. This assists agents in accounting for their future well-being when making decisions (Klabunde & Wilkens, 2016).

Within the simulation model concept demonstrator, an agent's movement type is determined as it enters the WaitingPeriod state. As discussed in §4.2.8, an additive model is employed to determine the movement type of each agent. Various agent attributes may influence this decision.

A probability matrix is populated per attribute to indicate, for each class of that attribute, the probability that an agent will adopt movement type 1, 2 or 3. Let $\mathscr{C} = \{c_1, \ldots, c_i, \ldots, c_u\}$ denote the set of criteria corresponding to each attribute. Let $\mathscr{A} = \{a_1, a_2, a_3\}$ denote the set of alternatives where a_j represents movement type j. A probability p_{ij} is assigned to the i^{th} criterion for the j^{th} movement type. Let

$$\boldsymbol{E}_T = \begin{array}{c} \\ c_1 \\ \vdots \\ c_i \\ \vdots \\ c_u \end{array} \begin{array}{c} \begin{array}{ccc} a_1 & a_2 & a_3 \end{array} \\ \begin{pmatrix} p_{11} & p_{12} & p_{13} \\ \vdots & \vdots & \vdots \\ p_{i1} & p_{i2} & p_{i3} \\ \vdots & \vdots & \vdots \\ p_{u1} & p_{u2} & p_{u3} \end{pmatrix} \end{array}, \tag{1}$$

where $T \in \{1, \ldots, n\}$ is an attribute label. These probabilities are populated by numerical values derived or inferred from qualitative data pertaining to the attributes of forced migrants corresponding to each movement type. For each movement type, a_j, the probability that an agent will move according to that movement type is given by

$$p(a_j(i)) = \frac{1}{n}\sum_{T=1}^{n} p_{ij}(T) \tag{2}$$

For each attribute probability matrix, $\boldsymbol{E}_T$, the criterion i corresponds to the specific criterion of the attribute associated with the specific agent. According to the probability associated with each movement type $p(a_j(i))$, the agent is allocated a movement type.

The actions of an agent towards selecting an alternative destination correlate directly with the movement type attributed to it. Distance and population density (or popularity) are important criteria in this respect, as individuals tend to move to the nearest location when fleeing conflict, typically choosing a destination where others have gone before (Davenport et al., 2003; Moore & Shellman, 2007). When an agent has been assigned movement type 1, the main considerations are the safety of the proposed destination, the distance between the current location and the proposed destination, and the population density of the proposed destination. For movement types 2 and 3, the agent considers the openness index of each neighbouring country (*i.e.* the ease with which a person can relocate to that country), the distance from its current location to the neighbouring country borders, and the number of Syrians who have already relocated to the countries under consideration.

In modelling the decision towards selecting an alternative destination for IDPs (movement type 1), arrays are superimposed over the physical modelling space, each with a granularity of 100×60 cells, in order to facilitate the modelling of conflict, the population density, and the attractiveness of destinations within Syria, based on these two weighted criteria. Each of these cells represent a 10 *km* x 10 *km* area.

The conflict array represents the conflict intensity within each of these cells which is updated on a monthly basis. Simultaneously, the number of agents in each of the simulated cells covering Syria is counted and normalised to values between 0 and 100 to determine the population density array. Finally, the attractiveness of each of the cells are determined. Cell [i,j] is allocated a weighted sum of the conflict and population density. The greater the conflict intensity, the less attractive the cell, whereas greater population density increases attractiveness. People are drawn to places with a higher population density and therefore the inverse of the conflict intensity value is used when calculating the attractiveness value of a cell. The attractiveness value per cell is therefore calculated as

$$w_1(100 - GS[i][j]) + w_2(\text{PopDensityNorm}[i][j]), \tag{3}$$

where w_1 and w_2 denote the weights allocated to the conflict and population density, respectively. Both of these weights are user inputs with default values of 0.6 and 0.4, respectively. Furthermore, these attractiveness values are normalised and stored within the attractiveness array as values between 0 and 100.

An agent of movement type 1 will search through the list of alternatives in the attractiveness array, attempting to minimise the distance between its current location and the various destination alternatives before finally selecting a location as its destination.

When an agent adopting movement types 2 or 3 selects a country as proposed destination, the distance, popularity and openness index are taken into account. Let $\mathcal{N} = \{n_1, \ldots, n_i, \ldots, n_I\}$ denote the set of alternatives or neighbouring countries and let Dist_i denote the normalised inverse value of the distance between an agent and the border of country i, whilst Popularity_i represents the popularity of country i and OpennessIndex_i denotes the openness index of country i. Then the overall score of country i is calculated as

$$S_{n_i} = w_1(\text{Dist}_i) + w_2(\text{Popularity}_i) + w_3(\text{OpennessIndex}_i), \tag{4}$$

where w_1, w_2, and w_3 are the weight factors associated with the criteria. The probability of an agent selecting a specific country as proposed destination directly correlates with the overall score of that country. According to this probability distribution, an agent selects a country of destination.

4.3.5. *The graphical user interface*

The GUI employed in the model concept demonstrator consists of a configuration screen and a primary screen which facilitate interactions with the user. The configuration screen appears upon initiation of the simulation model concept demonstrator and it is designed to prompt the user for certain user inputs required before the model is executed. These input values include the choice of manual or data-based initialisation of instances of conflict, the criteria weights pertaining to the various movement types, as well as the initial openness indices of the neighbouring countries. If the user chooses not to enter any inputs, the model concept demonstrator can still be executed by employing default values which are determined during the model execution phase.

The primary screen of the simulation model concept demonstrator, shown in Fig. 4, is visible to the user during the execution of the model concept demonstrator. The user-specified values on the primary screen may be altered during a simulation run, while the user-input settings on the configuration screen may only be set before execution of a simulation run.

4.3.6. *Verification*

Along with the model development, this phase includes the continual verification of the model developed. The fundamental building blocks of the simulation model concept demonstrator are verified individually before considering the model concept demonstrator as a whole, when all of these building blocks are implemented together. These elements include the modelling of conflict, the population, the movement decision-making process and the GUI. A number of cases were tested within each of the modelling divisions for verification purposes. For the modelling of conflict, cases based on the manual initiation of conflict and global positioning system accuracy were considered, along with cases based on the effect of varying the probability of the spread, depletion and intensity of conflict. The manner in which the population is modelled was verified by means of test cases referring to the allocation of agent attributes, the transitioning of an agent between states within its statechart, the ageing of an agent over a period of time, the calculation of an agent's tolerance threshold, the fluctuation of the agent population, as well as the initial geographic distribution of agents. In verifying the modelling of decision making, cases considered included the process by which an agent adopts a specific movement type based on its attributes, the attractive zones of IDPs and the associated weighted criteria, as well as the effect of varying the openness scores of neighbouring countries.

4.4. *Phase 4: model execution*

Validation and output analysis are performed within the fourth phase on the model concept demonstrator development. The manner in which conflict is modelled in the model concept demonstrator was calibrated and validated by means of graphical data comparison. The conflict simulated indicated a reasonable replication of the actual spread

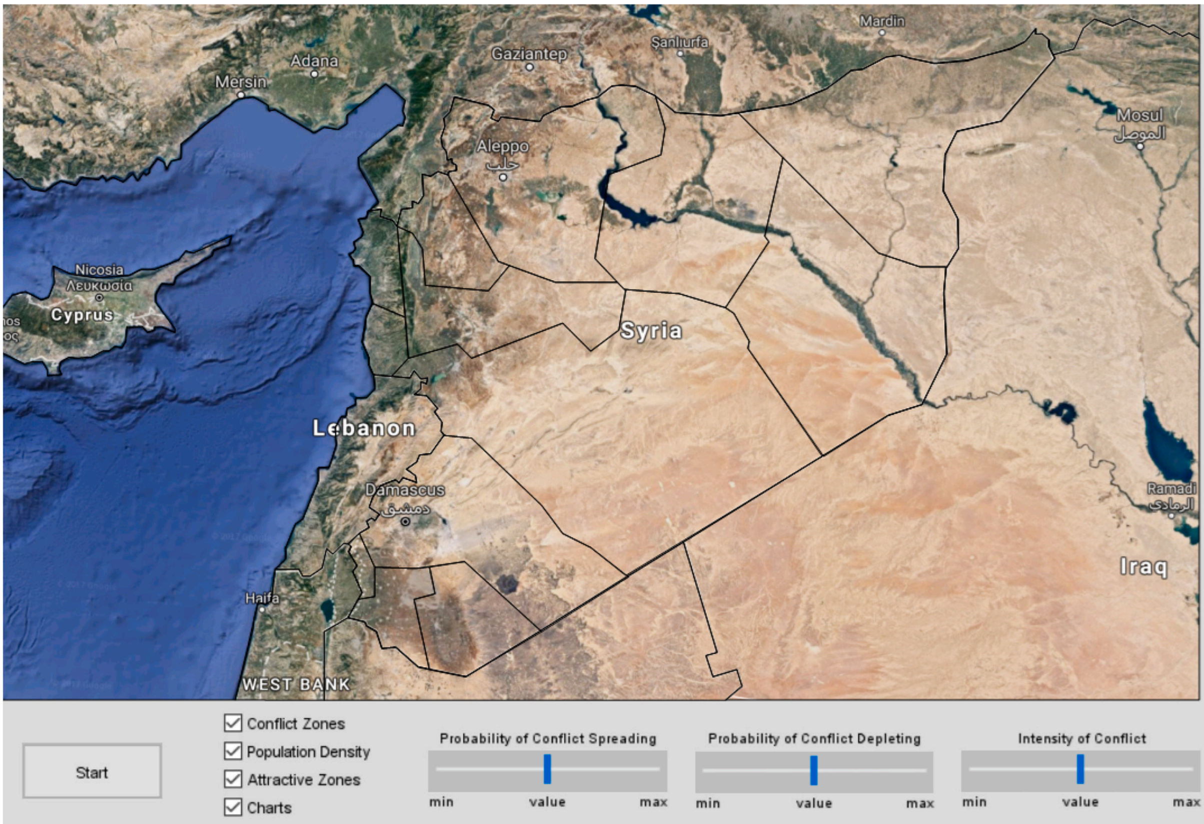

Fig. 4. A screenshot of the simulation model concept demonstrator's primary screen.

of conflict, and visually correlated with the recorded data.

This is followed by a validation of the agent aggregation by means of a statistical analysis during which the model concept demonstrator was executed at various levels of granularity. In comparing the model output where one agent represents 10,000 people to that where one agent represents 2000 people, the level of granularity may indeed have an impact on the estimated number of Syrians in some neighbouring countries, although it was evident that there was no statistical significance between the different levels of granularity when considering the number of individuals per movement type.

Furthermore, a face validation is performed, based on corroboration by subject matter experts in respect of various important components of the model concept demonstrator. Existing data were considered by means of a parameter establishment analysis during which suitable model parameters were sought to recreate the documented scenarios. The simulated output for such a scenario with respect to the total number of Syrians remaining in Syria and the total number of Syrians per neighbouring country are shown graphically in Figs. 5 and 6, respectively. Furthermore, the ratios of the different movement types, namely IDPs, refugees and undocumented migrants, for the specific scenario are illustrated in Fig. 7.

In view of the model concept demonstrator's capability to recreate specific scenarios pertaining to conflict outbreak and the associated flight of forcibly displaced people, parameter variation was employed to investigate the efficacy of the model concept demonstrator as a decision support and analysis tool.

4.5. Phase 5: documentation

The development of the model concept demonstrator according to the CoFMMA framework is thoroughly documented as part of the fifth phase (De Kock, 2019). The agent-based model concept demonstrator

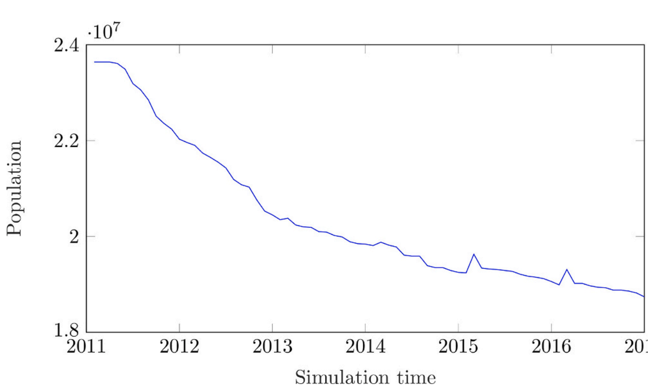

Fig. 5. The total number of Syrians remaining in Syria as simulated.

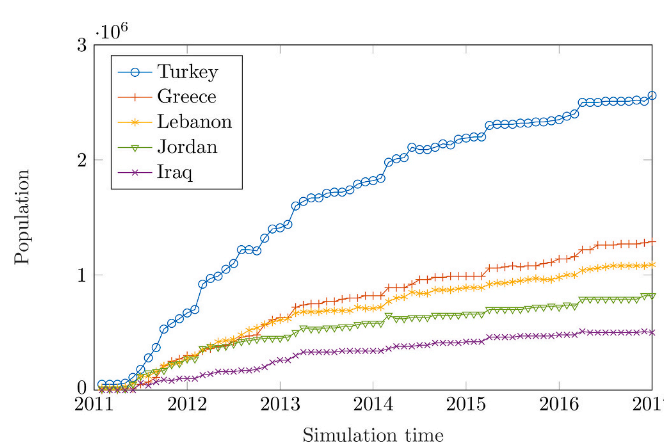

Fig. 6. The total number of Syrians per neighbouring country as simulated.

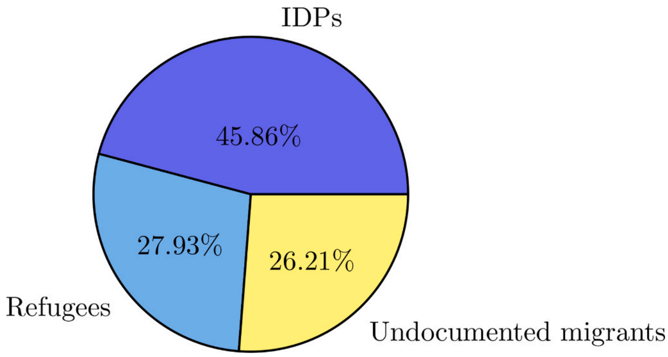

Fig. 7. The distribution of the movement types as simulated.

developed is equipped with a GUI, detailed in Section 4.3.5, for the purpose of utilising the model concept demonstrator as a decision support and analysis tool. Refer to De Kock (2019) for the default values of certain user input variables as determined during calibration an validation (Phase 4).

The decision-support tool facilitates the generation of model output which provides graphical data pertaining to the number of refugees and undocumented migrants who flee to identified regions neighbouring a selected region. This has the potential to assist governments and humanitarian support organisations in preparing for the influx of people requiring aid.

5. Conclusion

The CoFMMA framework proposed in this paper comprises five phases which encapsulate the components required when developing agent-based models of forcibly displaced migrants. The framework applies to models that pertain not only to information typically recorded in available data sources, but also recognises various movement types. Both Aksel (2017) and Groen (2017) emphasised that, aside from refugees and asylum-seekers, models of IDP and undocumented migrant movement are important, because there are at present no adequate data sources of this movement. In view of this, the proposed framework has the potential to contribute to research in this respect by providing the possibility of modelling conflict-induced forced migration and generating inference data for further investigation.

The CoFMMA framework is focused on conflict-affected areas in which forced migration is observed and assumes the use of agent-based simulation as the underlying dynamic modelling approach. In utilising the framework, an agent-based model may be developed with the capability of capturing emergent large-scale movement patterns of forcibly displaced people by modelling their individual or group movement decision making on a local level in order to gain an understanding of the phenomenon of migration pattern emergence on a more global level, to predict anticipated destinations of these individuals, and to assist in humanitarian support decisions.

The model concept demonstrator developed incorporates notable aspects in the decision-making process of forcibly displaced people. It allows for the calculation of a person's ability to withstand conflict, based on personal characteristics, as well as a quantification of the decision making of a person in selecting a movement type. The decision-making process modelled also accounts for the selection of a destination based on the movement type adopted by a person, his or her characteristics, and other external factors. The GUI accommodates user inputs with respect to the weights of the various decision-making criteria which influence the destination selection process.

Acknowledgments

Harry Crossley (South Africa) and Stellenbosch University (South Africa).

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