Agent-based simulation validation: A case study in demographic simulation

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***Abstract*—Two of the crucial parts in the process of performing a simulation study are validation and verification. The reason is these techniques help on increasing the confidence in the model, since it is not possible to demonstrate its absolute validity in all contexts. This paper presents the results of a white-box validation performed in an agent-based simulator for population dynamics. The tool provides a way to simulate the demographic evolution of large populations in a parallel environment. The purpose is to obtain population projections that can be used afterwards for policy analysis. Although the tool has been studied in terms of performance and scalability, its validation hasn't been addressed. With a white-box validation we expect to increase the confidence of policy analysers and social scientists in our simulation model.**

***Keywords*-White-box Validation; Agent-based Simulation; Parallel Simulation; Demography**

I. Introduction

Agent-based modelling is a model that is formed by a set of autonomous agents that interact with their environment (including other agents) through a set of internal rules to achieve their objectives [1]. An agent-based model, just like other types of model, is used to represent a real world system and to help us understand the system and to make decisions. An agent-based model is commonly implemented as a piece of computer code and run using a simulator. Agent-based simulation is the computer implementation of an agent-based model. Agent-based simulation has been applied in the physical sciences as well as the social sciences [2]. Many agent-based simulation tools have been developed in the last years to explore the complexity of social systems. Social phenomena are unpredictable and changing (dynamic). For this reason, agent-based simulation allows us to carry out experiments and studies that would not be feasible otherwise [3].

Agent-based simulation is recognised as one of the techniques which could contribute more in understanding complex social systems [4]. One of the application areas is demography. Onggo [5][6] has developed a parallel simulation tool for demography. Demography is often used as one of the important considerations in policy analysis and planning. The parallel simulation tool (Yades) was built for discrete-event simulation modelling paradigm [5][6]. In this paper, we have refactored the tool to separate the modelling component from the simulation execution component. The objective is to allow users to model population dynamics using agent-based simulation modelling paradigm. The agent-based model will be run on top of the parallel discrete-event engine. This paper reports the work that we have carried out to evaluate the correctness of the refactored simulation tool.

Validation and verification (V & V) is a significant element of any simulation study. As pointed by Robinson [7], "without V & V there are no grounds on which to place confidence in a (simulation) study's results". In simulation, we often differentiate between verification and validation. Verification is a process to determine whether a conceptual model has been implemented correctly in its computerized form. To borrow the computer programming term, we debug the model. Validation is a process to determine whether the model is an accurate representation of the system being studied for a given set of modelling objectives. Robinson states that it is not possible to prove that a model is valid in all contexts, because a model is only a simplified version of a real system. Consequently, a model cannot describe all aspects of a real system. Hence, the main objective of validation is to prove that a model is *sufficiently* accurate for parts of reality that is being studied. Indeed, one of the key aspects of validation is to assess whether the outcomes of a model can explain the real phenomenon under study [8]. This can be fulfilled by performing as many validation methods as possible during a simulation study until we (and users) can gain enough confidence in the model and accept its results. Edmonds [9] describes validation as a continuous process. Validation should also take into account the domain of the system under study [10]. Therefore, a validated model may not be valid for a set of different experimental conditions outside

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its domain.

Robinson identifies four different forms of validation in simulation modelling: conceptual model validation, data validation, white-box validation and black-box validation [7]. Conceptual model validation deals with issues such as the level of detail of the model and determines if it is enough for the purpose it was developed. Data validation is needed to determine whether the data used in the simulation study is sufficiently accurate. The black-box validation concerns with the relationship between inputs to the model and its outputs, ignoring the elements inside a model. The objective is to determine if the output of the model reflects the real world observation for the same set of inputs. Finally, white-box validation tries to answer the question *does each element of the model and the structure of the model elements represent the real world with sufficient accuracy?*

This paper reports our work in the validation of the agent-based simulation tool which has not been reported in our previous work. The validation is based on the white-box validation methods described in Pidd [11]. The rest of the paper is organised as follows. Section II presents an overview of the demographic simulation model that is used in this paper. Section III describes the simulation tool and Section IV presents the verification and validation work. Finally, our concluding remarks and lines of further work are described in Section V.

II. Demographic agent-based model

In demography the most commonly used paradigms are microsimulation, system dynamics and discrete-event simulation. In microsimulation, we need to specify a random sampling process for each individual at every simulation time point. On the other hand, in system dynamics, we do not keep track changes in the state of each individual but focuses on the population of individuals and the rates of individuals moving from one state to another. Similar to microsimulation, in discrete-event simulation, we keep track the individuals starting from their arrival in the system (through births and migrations) until they leave the system (through deaths and migrations). However, discrete-event simulation does not inspect each individual at every simulation time point. It inspects an individual only when the state of the individual changes.

It is commonly accepted that agent-based simulation can help to better understand a complex system where there is a need to model behaviours of many interacting individuals [12]. Agent-based modelling paradigm allow us to explicitly include human behavioural aspects into a model. This is one of the main reasons that motivates us to support the use of agent-based modelling paradigm in our demographic simulation tool. At the very core of a demographic model, we need to model key demographic components that represent basic population dynamics, such as: fertility (births), marital status, migrations, and mortality. On top of this, we can add components depending on the intended application of the demographic model. To take one example, for the application in tax and benefit systems, we may need to add another component that represents the change in economic status. With the agent-based modelling paradigm, we can evaluate the effect of a certain behaviour at the individual level on the population. This will make our tool more useful to wider potential users.

In Yades modellers can specify a model for each demographic component which will form a bigger model that represents the interactions between all components in a population. The detailed explanation on each demographic component can be read from our previous reported works [5] and [6]. The summary is as follows. The fertility model concerns with the representation of the number of children that a female individual may have, the age of the female individual when her first child is born, and the time between two consecutive births for female individuals who will have more than one child. The mortality model is used to represent the lifetime of an individual. The migrations model represents the mobility of individuals in a population. The marital status model is used to model the change in the marital status of individuals. Similarly, the economic status model represents the change in the economic status of individuals in the population.

III. Yades: A parallel simulator for population dynamics

Our parallel demographic simulation tool is called Yades. We have refactored the tool to allow modellers to model the individuals in a society using the agent-based simulation modelling paradigm and to run the model on top of a DES engine. The idea of running an agent-based model on top of a discrete-event simulator has been proposed by some writers [1][2][13]. It is one of the approaches that has been proposed to tackle the scalability issue of large-scale agent-based simulation models. The main advantage of this approach is that modellers who prefer to use agent-based modelling paradigm, do not need to change their modelling paradigm, and at the same time, a scalable parallel discrete-event simulation engine can be used to improve the overall simulation performance.

The simulation engine in Yades is implemented using μsik parallel simulation library. μsik is a parallel discrete-event simulation library that supports multiple synchronisation algorithms such as: lookahead-based conservative protocol and rollback-based optimistic protocol [14]. This library adopts the process interaction world-view in which a simulation model is formed by a set of interacting (logical) processes. Logical processes (LPs) communicate through events. Multiple LPs can be mapped onto a physical

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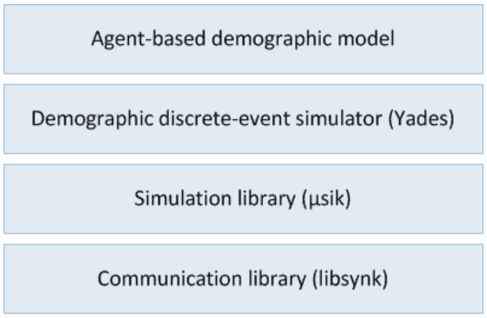

Figure 1. Software architecture

process (PP) that is run on top of a processing element (PE). A machine can have more than one PE (e.g., in multi-core architecture). The detailed description of the implementation can be read from [5] and [6].

Yades maps each agent in the model onto an LP. There are two types of agents in Yades. The first type of agent represents a family unit. In FRS data, a family unit is defined as a single independent individual or two independent individuals living together (as married or in cohabitation) and any dependent individuals (children). Hence, a family unit may represent an independent individual, a single parent, a childless couple, a nuclear family or an orphan. The main advantage of representing a family unit as an agent is that many public policies may apply to individuals as well as groups of related individuals, such as households and single parents. The behaviour of a family unit is defined by the five demographic components, i.e. fertility, mortality, change in economic status, change in marital status, and migration. Yades provides the placeholders for each demographic components where detailed behaviour can be specified by modellers. The second type of agent represents an administrative area where a number of families live. This agent will handle migrations and changes in simulation parameters and produce periodic reports. Yades allows users to model administrative area with different population characteristics. The main limitation of the current version is that it only allows one processing element to run one administrative area. The architecture of our tool is shown in Figure 1.

Yades allows users to provide data for the initial population. The data used in the model in this paper follows the structure of the UK Family Resources Survey (FRS) data. FRS is sponsored by the UK Department for Work and Pensions. It has been running since 1992 which provides useful cross-sectional and longitudinal data for the simulation. Hence, we can set the initial population parameters from a readily available data.

IV. Model verification and validation

A. Model verification

Although conceptually simple, verification can be challenging, especially when we are dealing with a relatively complex computer program. Law [15] and Banks et al. [16] lists a number of techniques that can be used in a verification process.The main technique that we use is the structured walkthrough of the program. This includes dividing the model into smaller components and test the correctness of each component. It is suggested that we start with the simplest possible behaviour so that the simulation output can easily be understood. Hence, errors can be easily spotted. This is the approach that we have used. We have tested the implementation of a simple model for each demographic component in our model. The explanation is given in the following subsections.

Another technique that we have used is the structured walkthrough of the program. The program developer (second author) presented the code line-by-line to the first author. It was done in a small meeting room with a projector showing the computer code. Before the structured walkthrough session started, the first author had been briefed with the conceptual model. We have found this technique very effective to uncover flaws in the computer implementation of the conceptual model. The most obvious explanation is because the non-developer(s) are independent and they may view the implementation from different perspectives. Hence, they can challenge the developer(s) on various implementation issues, such as the effectiveness of an implementation, the possible settings that can cause errors, and the correctness of the implementation. In the context of agent-based simulation, we have found this method especially effective, because of the many possible combination of interactions between agents in the model. When a conceptual model document was given to the non-developer(s) before a structured walkthrough session started, it gives a top level view of the model to the non-developer(s). Hence, the non-developer(s) focus more on the top-level view of the model and less distracted with the implementation detail. This has the potential to uncover the possible errors due to the combinations of interactions between agents that might have been missed by the model developer(s). We use Yades' facility to produce a trace to be examined to check any possible mistakes. This was done by the first author to minimize the developer's bias.

B. Model validation

From the 1990s, agent-based simulation has become increasingly popular [17]. However, according to the survey conducted by Heath et al. [17] on the articles related to agent-based models published between 1998 and 2008, 29% of the articles did not discuss the validation of their models.

They further divide the validation reported in the articles into two categories: conceptual (i.e. conceptual model validation) and operational (i.e. comparing the simulation result with the real observation). They found that 17% of the articles used the conceptual validation only, 19% used the operational validation only, and 35% used both. They also noted the dominance of qualitative validation methods in the validation of agent-based models. They provide a conjecture that this might be because many agent-based models are not conducive for quantitative validation methods. Klügl noted that agent-based models often exhibit behaviour that can be problematic for validation purposes, such as non-linearities and multi-level properties [18]. In addition, agent-based models often use significantly more assumptions which make the assessment of the validity of assumptions more difficult. Agent-based models also require the finer level of model detail in which data at that level of detail may be difficult to obtained.

Duong [19] also examines this issue and suggests that the greater uncertainty in social sciences compare to others, the lack of consensus on how to represent social environment, and the lack of experimental controls in data collection might contribute to the difficulties in the validation of agent-based models. Windrum et al. [20] examines a set of methodological problems in the empirial validation of agent-based models. The problems seem to have arisen due to, among other reasons, the lack of techniques to build and analyse these models and the lack of comparability between the ones which have already been developed. A number of validation techniques have been proposed for agent-based simulation modelling. Klügl [18] proposes a validation process for ABS models combining face validation and statistical methods. Moss et al. [21] use a declarative formalism to address the validation and verification of ABM with cognitive agents. However, there seems to be a general concern on the lack of validation framework or methodology in agent-based simulation.

In this paper we present a white-box validation of our simulation model based on the methods described in Pidd [11], especially on the static logic and the dynamic logic of the model. A white-box method focuses on the correctness of the internal workings of a model. This includes the correctness of the components and the interaction between components. A white-box method assumes that we know (and have access to) the components inside the model. Balci [22] defines white-box method as a technique that is intended to evaluate a model based on its execution behaviour. It can be applied to the programmed model (verification) or to the experimental model (validation) of the life-cycle process of a simulation study. We have applied this method to asess the correctness of the internal working of each component in the model introduced in Section III.

We divide the model into smaller components and test the correctness of each component. It is suggested that we start with the simplest possible behaviour so that the simulation output can easily be understood. Hence, errors can be easily spotted. This is the approach that we have used. We have tested the implementation of a simple model for each demographic component in our model.

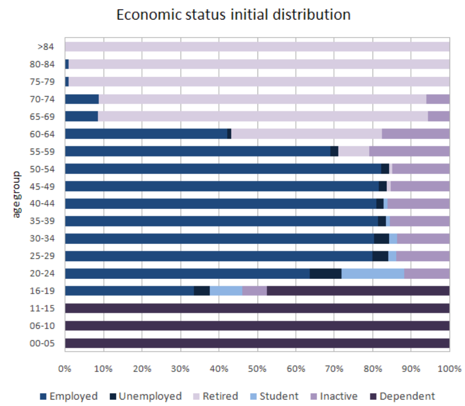

Figure 2. Initial distribution of economic status in the population

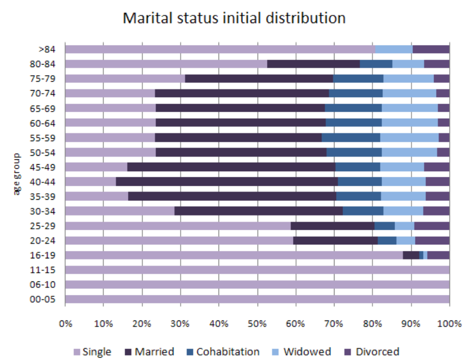

Figure 3. Initial distribution of marital status in the population

In the following subsections, we present the result of our evaluation on each model component using the white-box method. In the evaluation, we use a population of 110,000 family units. In each test, we run the simulation five times and report the average results . The explanation on the validation of each demographic components is as follows. Figure 2 shows the proportion of different economic statuses in the initial population by age group. Similarly, Figure 3 shows the proportion of different marital statuses in the initial population by age group.

1) Mortality: Yades allows modellers to sample the lifetime of individuals using two commonly used methods: life table and survival function. In order to evaluate this component, we disable all other demographic components. This helps us to detect any error and to isolate the root cause of the error easily. We vary the life tables. One of

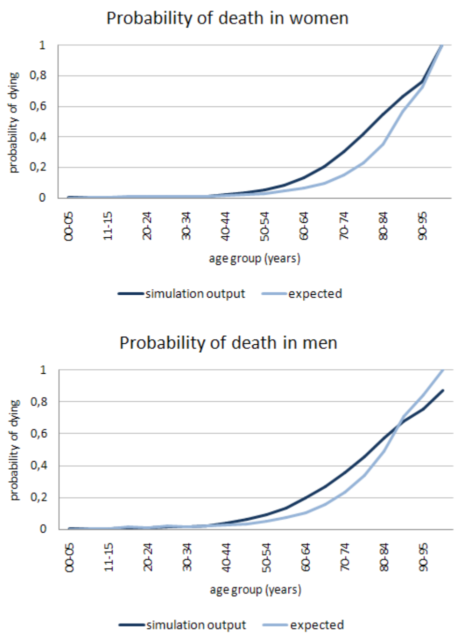

Figure 4. Simulation output and expected output for mortality model

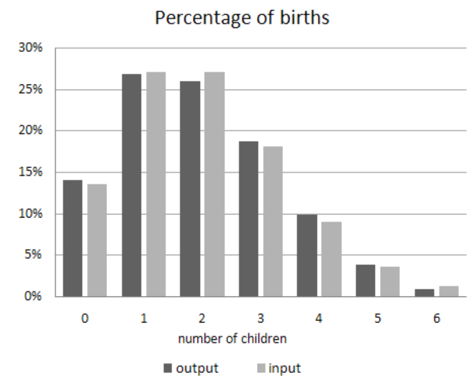

Figure 5. Simulation output and expected output for fertility model

the results is shown in Figure 4. In both cases, the Pearson product moment correlation coefficient of the original distribution and the outputs is very high, 0.9870 for women and 0.9783 for men. The same evaluation is repeated using various life tables. They also produce high correlation values. This has increased our confidence that the mortality component can produce the intended behaviour.

2) Fertility: Modellers can specify a number of fertility models in Yades using age-specific fertility model, parity-specific fertility model, birth spacing model and their combinations. To test the fertility model component, the rest of demographic components are disabled in order to isolate fertility results. To simplify the model, birth function is set to follow a Poisson distribution with parameter $\lambda = 2$ in women from 16 to 49 years old (assumed to be the reproductive age). Birth function is calculated for every woman regardless their marital status and birthspacing is uniformly distributed. After running the simulation the accumulated number of births by age group is obtained. In Figure 5 the percentages of births are represented according to the number of children's group. As we can see, the simulator is producing the expected number of births in the fertility interval. We repeat this experiment with different parameters and all of them produced the expected results.

3) Marital status: Yades recognizes the following marital statuses: single, married, cohabitation, separated, divorced and widowed. Individuals will move from one marital status to another during their lifetime. The transitions from one status to another can be specified based on a simple probability function, a regression function or a set of logical rules. Likewise, time spent in one status can be sampled using a distribution function, a regression function or a set of logical rules. In the formation of a family unit (e.g., marriage and cohabitations), we need to specify a function that matches a pair of individuals.

In the following evaluation we use a probability function for the state transition and apply a simple matching criteria where we choose the first person that we find in the list regardless of his/her characteristics. Transitions are uniformly distributed between 1 and 10 years. First, we want to test the correctness of family unit formations. Hence, we disable all other transitions. We also disable all other life events (as fertility and mortality). The top chart in Figure 6 shows the result. As expected, the number of marriages and cohabitations increases with time while the number of singles decreases progressively.

The second test has the same settings as before but we enable the mortality in the model. The result can be seen from the bottom chart in Figure 6. The figure shows that the number of widowed increases with time. This is the behaviour that we expect.

4) Economic status: As in the marital status, an individual may move from one economic status to another during his/her lifetime. Yades recognizes the following economic statuses: dependent, in employment, unemployed, in full-time higher education, pension and economically inactive. Modellers will need to model the transitions from one status to another and the time spent in any of the status. In the evaluations, the transitions are scheduled using a uniform distribution between 1 and 5 years. The top chart in Figure 7 shows the changes in economic status. As expected, without mortality, the number of pensioners increases steadily. At the same time, the number of dependent individuals, individuals in higher education, working individuals, and unemployed individuals decreases over time.

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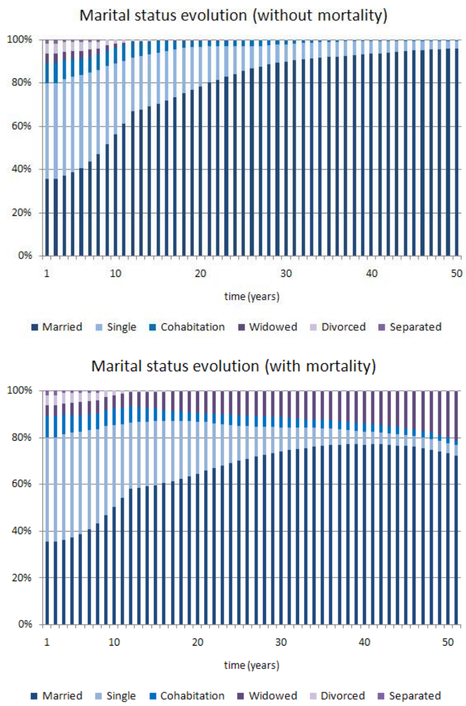

Figure 6. Validation results for marital status component model

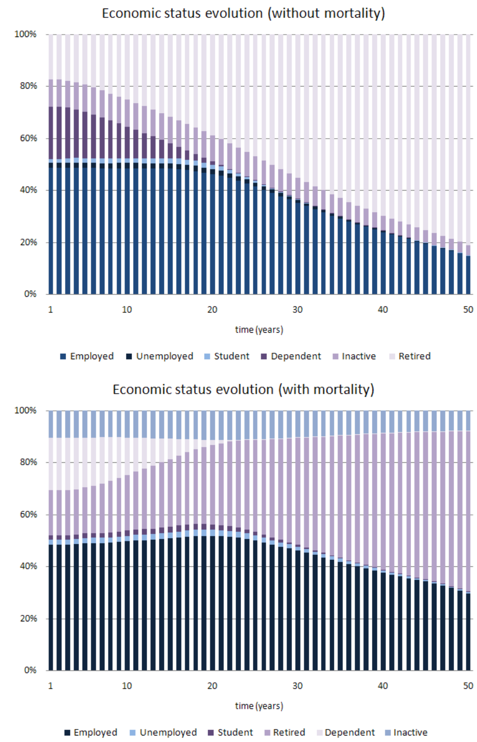

Figure 7. Validation results for economic status component model

In the second test, we use exactly the same setting but we enable the mortality. This should produce a similar behaviour as before but the proportion of retired individuals will be less because some of them will die. The result can be seen from the bottom chart in Figure 7.

5) Migrations: Yades provides a functionality for a modeller to define a model that determines whether a family unit is going to migrate. There are two types of migration: domestic migration and international migration (emigration and immigration). These models can be specified using a constant probability, regression or a set of logical rules. The destination region is determined using a probability matrix where each row represents the originating region and each column represents the destination. To validate this component we tried two different scenarios using 4 regions. In the first scenario, we set the probability to migrate in each regions to be the same. As expected, the number of population in each regions are relatively the same [6]. In the second scenario we set one of the regions (i.e., region 4) to be the most attractive, such that once people have move to that region they will never leave the region. In this example, we expect an increase in the population of region 4 while the rest of the regions experience a decrease in their population. The result is shown in Figure 8.

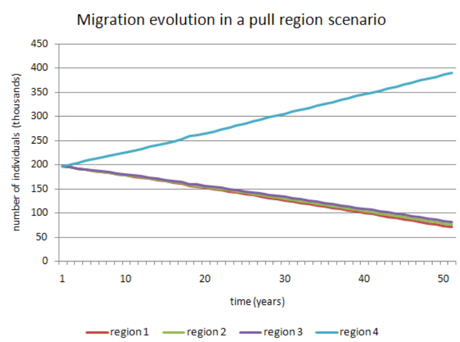

Figure 8. Evolution of population in a migration scenario

V. Conclusion and Future Work

The validation of a complex agent-based model is challenging. This is partly due to the quality of the available data that are needed to calibrate and to validate the model. The large number of model parameters makes it even more challenging. In this paper, we have presented the verification and validation of an agent-based demographic simulation model implemented using Yades using white-box method. This method allows us to assess the correctness of the model components and their interactions. The results obtained in this paper show that the five components of the simulator are behaving correctly in terms of what the modellers should expect from them for the given scenarios. To increase our confident in the model, we need to conduct more testing using different validation methods. At the moment, we are implementing a graphical user interface to help users specify the model more easily without having to write the codes. This would help potential users who do not have any programming experience to test their models and provide feedback on the tool.

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