Agent-Based Model of Celtic Population Growth: NetLogo and Python

Kamila Olševičová, Richard Cimler, and Tomáš Machálek

University of Hradec Kralove, Faculty of Informatics and Management
Dept. of Information Technologies, Rokitanského 62,
Hradec Králové, 500 03, Czech Republic
{kamila.olsevicova,richard.cimler,tomas.machalek}@uhk.cz

Abstract. The agent-based model of Celtic population growth was developed using specific domain knowledge and general demographic assumptions about birth-rates and mortality. The model allows archaeologists to simulate the time series of available workforce and actual consumption of the population living in the given settlement agglomeration. Parameters of the NetLogo model were refined experimentally. The implementation in Python was created for validation and reporting. The simulated population is stable, with appropriate age distribution and growth rate. The model is used for further simulations of the settlement population dynamics and for testing hypotheses about the agricultural practices, trade and exchange etc. The final objective of our research project is to better understand the collapse of the Celtic society in Europe in the Late Iron Age.

Keywords: agent-based model, archaeology, NetLogo, population growth, Python, social simulation.

1 Introduction

Agent-based models and social simulations are being applied in archaeology for last two decades successfully, see e.g. Altaweel's realistic models of ancient Mesopotamian civilization [1] or investigation of cultural collapse of ancient Anasazi civilization [2, 6]. We intend to use the agent-based models for analyzing the conditions and circumstances of the development and collapse of the Celtic society in Europe in the Late Iron Age. Key aspects which formed the complexity of the society were settlement forms (oppida), demography, agricultural practices, producers/consumers ratio in society and the scale of work specialization, local and distant interactions (trade and exchange, monetary economy) and others [4].

The paper presents particular results related to the explanatory population growth modelling. The model was designed using domain knowledge (archaeological excavations of various oppida, regional landscape studies, demographical studies and assumptions, life-expectancy tables etc.) provided by experts. The population growth model is essential for further investigation of the carrying capacity of the settlement and available workforce.

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The organization of the rest of the paper is as follows. The formulation of the model and its description using the Overview-Design-Details (ODD) protocol [5] is provided in chapter 2, experiments are presented in chapter 3 and our further research directions are discussed in conclusion.

2 Formulation of the Model

Population growth is defined as the change in number of individuals over time. Natural growth is expressed as

$$\Delta P = Births - Deaths$$

It is assumed that all populations grow (or decline) exponentially (or logarithmically) unless affected by other forces. The simplest Malthusian growth model assumes the exponential growth is

$$P(t) = P_0 e^{rt}$$

where P_0 is the initial population, r is the growth rate and t is time. In case of the Celtic population living in the given settlement agglomeration, the initial number of inhabitants is said to be between 500 and 800 and the mild annual growth of population respect to high child mortality is estimated to 2%. The maximum number of inhabitants after 100-120 years is between 2000-5000. Emigration/immigration is not taken into account because massive emigration is one of possible causes of disappearance of settlement population therefore it will be investigated separately.

There are three types of peasant families: large size (approximately 20 members), medium size (approximately 10 members) and small size (4-6 members). A peasant family has got 2 adults, 1-3 children and 1 elder. Correspondingly the medium size family has got 4 adults and the large family has got 8 adults. In other words, the large family consists of approximately 7 infants (1 suckling, 3 toddlers, 3 up to 10 years), 3 older children (10-14 years), 2 young adults (15-19 years), 5 adults and 3 elderly. This information was applied in the definition of the initial age distribution of the population (see below). The same or similar age distribution of the final population is requested.

Social roles (basic family, nobility, servants, slaves etc.) as well as personal histories of individuals (marriages, children, siblings etc.) are ignored. The fertile age of women is 15-49 years and the fertility rate is 5.1. More than two children rarely survived infancy. This information was applied in the definition of the birth-rate procedure that operates with linear function (see below).

The probabilities to die are defined in abridged life-tables valid for the ancient Roman women population [7]. To obtain complete life-tables, the Elandt-Johnson estimation method [3] was applied. Experiments were performed using complete tables as well as abridged tables, and results are comparable (see below).

The model inputs are limited to:

- slider for setting the initial *number-of-years-to-be-simulated* (between 100-120),
- slider for setting the initial *number-of-inhabitants* (between 500 and 800),
- selection list of available *life-expectancy-tables*,
- selection list of available *initial-population-structure*,
- slider for setting the *birth-correction-parameter*.

There are two output variables:

- time series of *actual-consumption* of population (calories),
- time series of *actual-workforce* (number of men between 15-49 who are able to plough).

The daily calories requirements are defined (1360 for toddlers, 2000 for small children and elderly, 2500 for boys between 10 and 14 etc.) and it relates to the carrying capacity of the settlement.

According to the ODD protocol [5], the model is specified as follows:

- **Purpose:** The model is designed to explore questions about consumption and workforce of population of the Celtic settlement agglomeration.
- **Entities, state variables, scales:** Model has got one type of agents representing inhabitants. Each *inhabitant-agent* is characterized by *gender* (male, female), *age* (discrete value), *age-category* (sibling, toddler, child, older child, young adult, adult or elder). The simulations last 100-120 steps that correspond to years of the simulated time period. Auxiliary variables were added for monitoring characteristics of the whole population: *percent-of-sucklings*, *percent-of-todlers*, *percent-of-children*, *percent-of-older-children*, *percent-of-young-adults*, *percent-of-adults*, *percent-of-elders*. Summarizing variables *num-of-inhabitants*, *actual-workforce* and *actual-consumption* inform about the structure the population.
- **Process overview and scheduling:** Only one process is defined. On each time step, each *inhabitant-agent* executes *get-older* procedure. The procedure operates with selected life-table, either abridged or complete, with less or more optimistic life-expectancy (4 tables were available). The *inhabitant-agents* representing women between 15 and 49 years execute also the *birth-rate* procedure that operates with the *birth-correction-parameter*:

```
ask inhabitants with
[age>14 and age<50 and gender="female"]
    [ if random 100<((-9/17)*age+560/17)+birth-correction
      [  hatch 1 ]
    ]
```

Parameters of this linear function were refined experimentally with respect to domain knowledge. The function expresses the decreasing chance of pregnancy in relation to the age of woman *inhabitant-agent*.

- **Design concepts:** The basic principle addressed by the model is that the consumption and workforce of the whole population depend on properties of individuals and on specific rules defined by domain experts. Stochasticity (randomness) is used to represent the sources of variability such as particular age distribution in the initial population, life expectancy of individual *inhabitant-agents* etc. Other agent-based models' design concepts such as sensing, observation or emergence are not taken into account.
- **Initialization:** The initial population consist of seven age-groups (*sucklings, toddlers, children, older children, young adults, adults* and *elders*), the proportional distribution of each age-group was defined in NetLogo as follows. Parameters of the random function were identified experimentally:

```
let local-random random 35
if local-random<4 [report random 2]     ; sucklings
if local-random<6 [report 2+random 2]   ; todlers
if local-random<11 [report 4+random 6]  ; children
if local-random<15 [report 10+random 5] ; older-children
if local-random<18 [report 15+random 5] ; young-adults
if local-random<31 [report 20+random 30]; adults
if local-random<35 [report 49+random 20]; elder
```

- **Input data:** There are no input data during the run of simulation. All parameters are initiated at the beginning.
- **Submodels:** Different formulas can be defined inside *birth-rate* and *get-older* procedures. Together with parameters (*birth-correction*, *life-table*) it defines the submodels.

3 Experimental Results

See fig. 1 for graph and monitors from a single run of the simulation in NetLogo [8]. The exponential growth of population (all age groups respectively) is noticeable. Although the NetLogo interface is user friendly when defining the simulation inputs, for presentation of simulation outputs it is better to export data and process them in spreadsheet (we used MS Excel).

Our primary objective was to find a stable reliable model of the Celtic population growth, with matching initial and final age distributions. To achieve this, many different setups of the model were tested to refine the parameters in formulas. See fig. 2 and 3 for initial and final distributions for two sizes of the initial population (500 and 800 inhabitant-agents).

The effect of the *birth-correction-parameter* can be seen on fig 4 (the annual growth), fig. 5 (number of children per woman) and fig 6. (number of inhabitants). These characteristics differ in their sensitivity to changes of the parameter. The final population shown on fig. 6 is very sensitive to increasing value of the *birth-correction*. The results differ more than three times (1693 to 5476) in case of *birth-correction* values 6 and 14. The annual growth of the population and the number of children per woman are not so sensitive to the parameter.

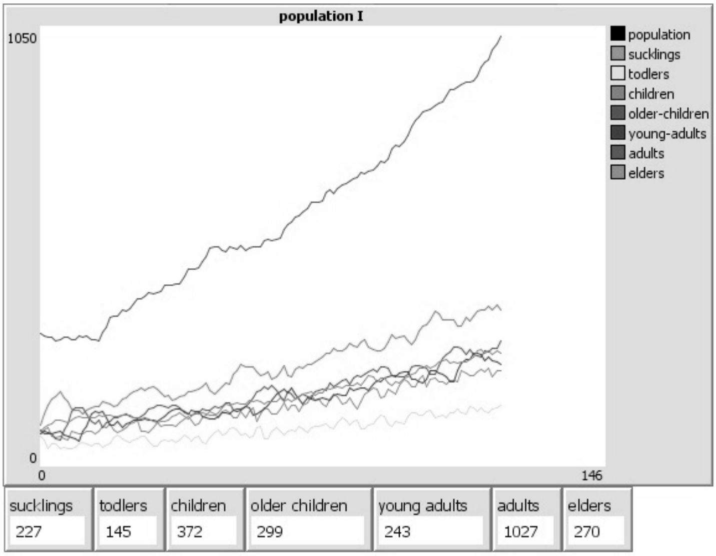

Fig. 1. Population growth during 120 years (NetLogo)

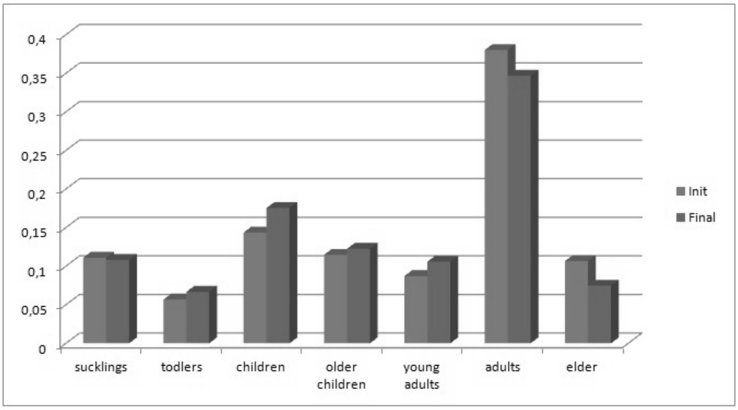

Fig. 2. Initial and final age distribution (initial *number-of-inhabitants* = 500) (NetLogo)

During the development of model, we have been also using Python language and environment along with packages SciPy (Scientific Python) and NumPy (Numeric Python) as a prototyping, validation and reporting tool. Due to Python's object oriented and modular nature, it was easy to decompose the model into smaller components which were developed and tested independently. Python has been also used to calculate extended versions of abridged life tables. Data were collected from 1000 repetitions of simulation.

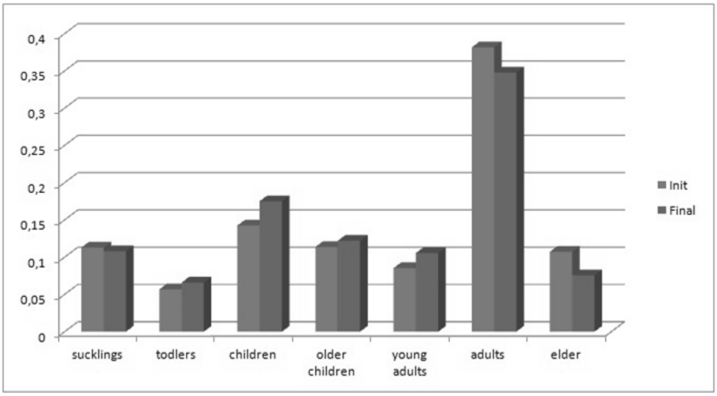

Fig. 3. Initial and final age distribution (initial *number-of-inhabitants* = 800) (NetLogo)

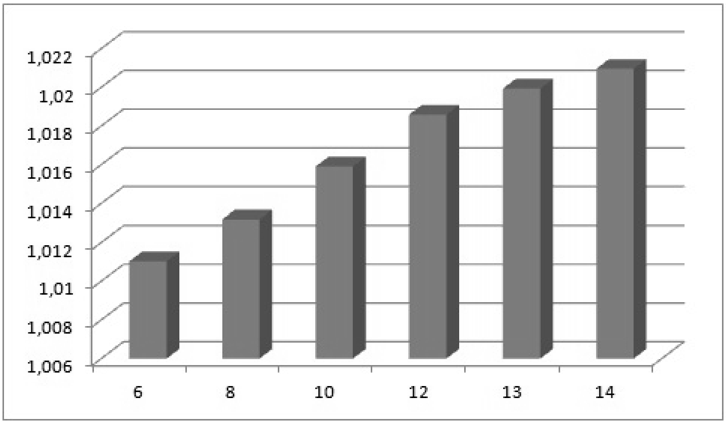

Fig. 4. Annual growth of the population related to *birth-correction* parameter (NetLogo)

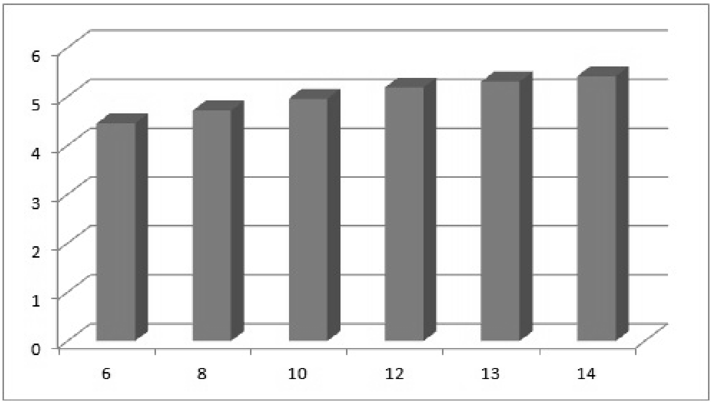

Fig. 5. Number of children per woman related to *birth-correction* parameter (NetLogo)

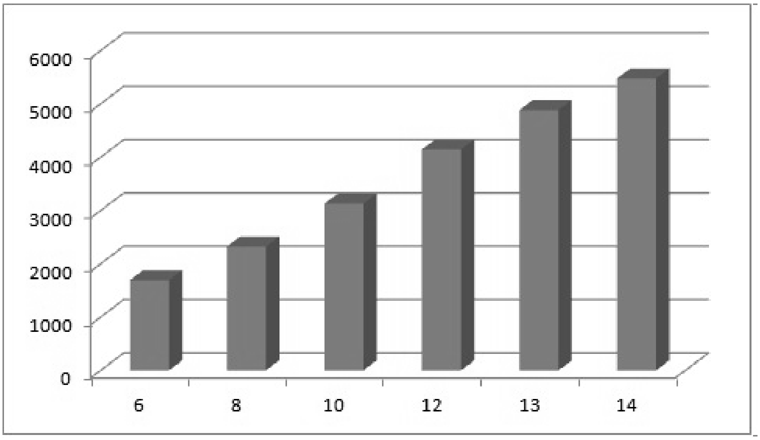

Fig. 6. Number of inhabitants related to *birth-correction* parameter (NetLogo)

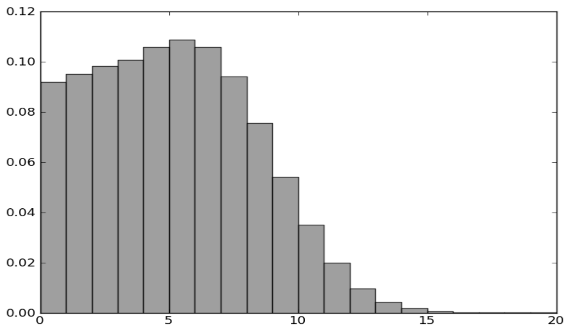

Fig. 7. Woman's probability of having specific number of children (Python)

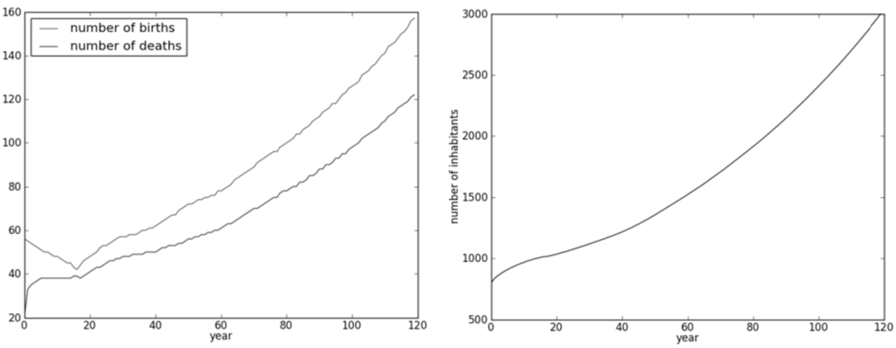

Fig. 8. Numbers of deaths and births per year and total number of inhabitants (Python)

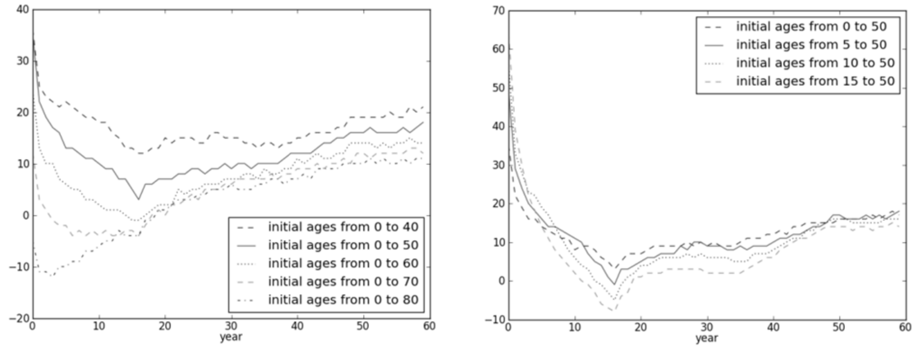

Fig. 9. Absolute annual population growths for miscellaneous initial configurations (Python)

See fig. 7 for Python model result for *birth-correction parameter* set to 6. Average number of children per fertile woman is 4.7 and median is 5, which is comparable with the NetLogo model.

See fig. 8 for Python model result for numbers of deaths and births per year (on the left) and total number of inhabitants (on the right), both for *birth-correction* = 6. The absolute annual growth of the population for miscellaneous configurations (all with uniform distribution of ages) is presented in fig. 9.

4 Conclusion

The agent-based models and simulations are expected to help to better understand the development and collapses of the ancient Celtic agglomerations in Bohemia. Our NetLogo model of the Celtic population growth is essential for further simulations of optional agricultural practices and economic mechanism. The model provides realistic time series of consumption, workforce and age distributions of population.

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