# Modelling Population Dynamics for Archaeological Simulations

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**Abstract.** We intend to apply the agent-based modelling and social simulation to study the complexity of the Celtic society in Central Europe in the late Iron Age. Key aspects which form the complexity of the society are settlement forms, demography, the scale of work specialization etc. Our objective is to determine under what conditions the collapse of the Celtic society might have taken place. The paper presents particular results, especially the explanatory population dynamics model which was implemented in NetLogo. The model is based on specific domain knowledge and general demographic suppositions about birth rates, mortality and immigration. The model allows archeologists to simulate the time series of available workforce and actual consumption of the population living in the settlement agglomeration Staré Hradisko. The population dynamics model is essential for further husbandry management model. The hypotheses related to extensive and/or intensive agricultural practices should be verified.

**Keywords:** agent-based model, archaeology, NetLogo, population dynamics, social simulation

**JEL Classification:** J10
**AMS Classification:** 68U20

## 1 Introduction

The *agent-based modelling* and *social simulation* is being applied in many domains including the archaeology for last ten years successfully. The agent-based modelling is characterized by the use of microspecifications (agents, rules, environments) that are sufficient to generate the macrostructures of interests. The creation of social simulation consists of (1) *conceptual modelling* of processes and objects of real world according to research questions and hypotheses, (2) *implementation* of models, (3) running experiments with *data analysis*, (4) *verification* and optional revisions of the model, (5) *sharing results* and (6) *reproducing the simulation*.

Benefits of this *generative social science* approach have been highlighted in [4]. Typically there are two types of research results: (1) interdisciplinary domain models and (2) simulation platforms, methodologies and guidelines. For example Altaweel's realistic models of ancient Mesopotamian civilization are presented simultaneously with the ENKIMDU chassis [1]. The simulation of behavioral patterns of early hominids [5] is described together with the demonstration of applying the Overview-Design-Details protocol [6]. The well-known investigation of cultural collapse of ancient Anasazzi civilization [2] is discussed along with the replication the model in NetLogo [7].

We intend to apply agent-based models and social simulations to analyze the conditions and circumstances of the development and collapse of Celtic society in Central Europe in the late Iron Age. Key aspects which form the complexity of the society are: 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 [3].

The paper presents particular results related to the explanatory population dynamics modelling. The model is based on domain knowledge provided by experts (archaeological excavations of various oppida, regional landscape studies at Staré Hradisko, demographical studies and assumptions, life-expectancy tables [9] etc.). The population dynamics model is essential for further investigation of the *carrying capacity* of settlement agglomerations.

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The organization of the rest of the paper is as follows. The overview of our population dynamics model is provided in chapter 2, the NetLogo implementation and interfaces are presented in chapter 3, further research directions are discussed in conclusion.

# 2 Overview of the Model

A population dynamics model answers the question how a population is going to change given (1) its current status, i.e. the total number of individuals and the composition of the population in terms of old/young individuals) and (2) the environmental conditions that the population is exposed to. The population change is characterized by births, deaths, immigration and emigration. It is assumed that all populations grow (or decline) exponentially (or logarithmically) unless affected by other forces [8].

Following basic assumptions and requirements related to our model were provided by archaeologists:

- The period of 100-120 year has to be simulated.
- The initial number of inhabitants in the settlement is between 500 and 800. The maximum number at the end of simulation is between 2000-5000.
- There are three types of peasant families: large size (aprox. 20 members), medium size (aprox. 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 todlers, 3 up to 10 years), 3 older children (10 - 14 years), 2 young adults (15 - 19 years), 5 adults and 3 elderly.
- Social roles (basic family, nobility, servants, slaves etc.) are ignored.
- 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.
- The probabilities to die are defined in five-year life tables [9], complete one-year life tables could be estimated using demographic methods.
- Mild annual growth of population in settled conditions and with respect to high child mortality is estimated to 0.2%.
- Very probable immigration should be considered; typically one small or medium size household is established every five years.
- Emigration should not be taken into account at the moment. Massive emigration is one of possible causes of disappearance of settlement population and it will be investigated separately.
- The workforce is expressed as the number of men between 15-49 years 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.).

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),
- Slider for setting the initial *number-of-large-families* (between 20 and 40),
- Selection list of available *life-expectancy-table*,
- Slider to setting *the birth-probability*,
- Slider for setting the *immigration-probability*.

There are two output variables:

- time series of *actual-consumption* of population (calories),
- time series of *actual-workforce* (number of men between 15-49).

# 3 Implementation and interfaces

The model is implemented in NetLogo, a multi-agent programmable modeling environment [10]. Two types of agents are defined:

- *household-agent* – has got its *type* (large, medium, small),
- *inhabitant-agent* – has got its *age* and *gender*, is linked to the *household-agent.*

Auxiliary variables were added for monitoring characteristics of each *household-agent* and of the whole population: *num-of-sucklings, num-of-todlers, num-of-children, num-of-older-children, num-of-young-adults, num-of-adults, num-of-elder*, and summarizing *num-of-inhabitants*, *actual-workforce* and *actual-consumption* inform us about the structure the population.

The initialization of the model involves creation of appropriate *household-agents*. The number of small and medium households is derived from the initial *number-of-inhabitants* and the initial *number-of-large-families*. For each *household-agent* the set of *inhabitant-agents* is created. Random numbers from the normal distribution with appropriate mean and standard deviation are generated to obtain particular numbers of sucklings, toddlers, children etc. for each household.

The current population structure of households is visualized (Fig. 1). Each circle diagram represents one household, i.e. the total number of family members (in the center of the diagram) and the ages of individuals ascending clockwise. The diagrams are updated periodically as well as the graph of the population growth (Fig. 2).

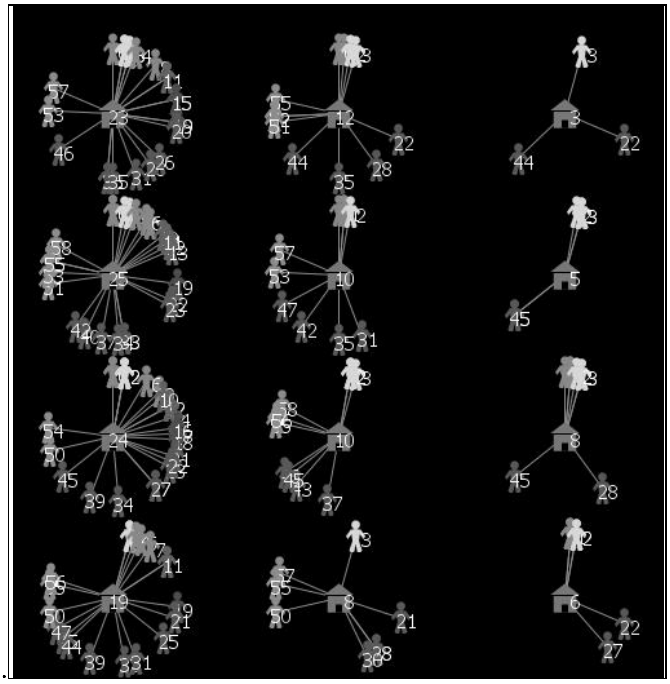

**Figure 1:** Visualization of households and inhabitants (part of the screenshot)

The model is comprised of nested cycles characterized by updating the state of *household-agents* and *inhabitants-agents*. For each year of the simulation, three procedures repeat:

- *birth rate procedure* – the probability formula for adding a newborn *inhabitant-agent* is based on current number of fertile women in the household and the *birth-probability* parameter,
- *mortality rate procedure* – the probability formula for removing *inhabitant-agent* from the model is based on *life-expectancy tables*,
- *immigration rate procedure* – the probability formula for adding a new small or medium size family is based on the *immigration-probability* parameter.

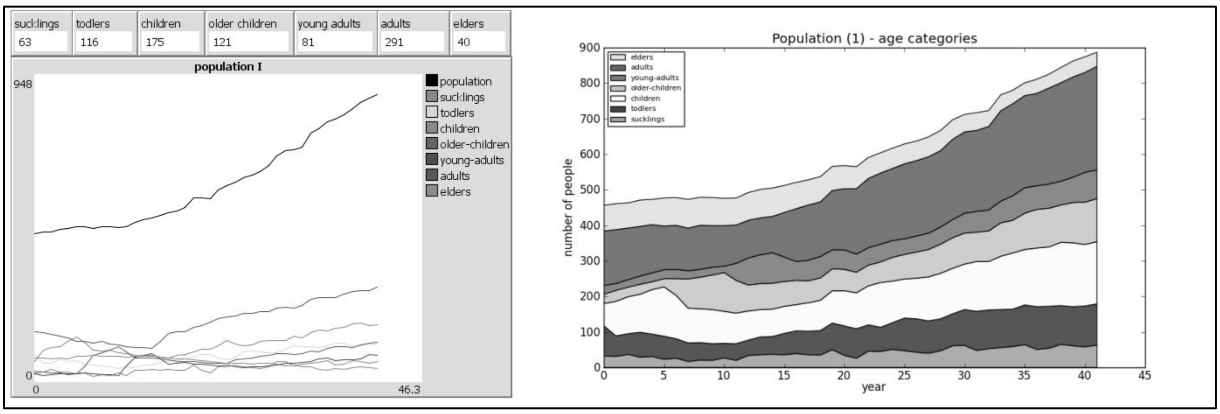


**Figure 2:** Population structure

# 4 Conclusion

Our agent-based population dynamics model of the Celtic oppidum enables experimenting with birth rates, mortality and immigration rates. The formulas can be further refined according to expertise (e.g. different calorie requirements tables or interpolations of life-expectancy tables can be inserted, parameters of normal distributions in setup procedure can be particularized etc.). If necessary the life-cycle of the *household-agent* could be enhanced by defining social roles and personal histories of *inhabitant-agents* and other features that would make the model more realistic (but also highly complex).

The outputs of the population simulations are intended to become inputs of the agricultural model. The time series of *available-workforce* and *actual-consumption* can help us to estimate the *carrying capacity* of oppida, (the environment's maximal load), one of explanatory variables important for understanding the circumstances of the collapse of Celtic society. It is known that Celts received 80 percent calories from cereals. It means that the effective husbandry practices on more or less fertile arable land in walking distance around the settlement were crucial. The archeologists assume some combination of extensive and intensive husbandry and the agricultural model should help them to verify particular hypotheses about the Staré Hradisko settlement area.

The agent-based models applied in social sciences are sometimes criticized for oversimplifications and the lack of flexibility. We hope that with two relatively independent models it is possible to avoid this risk. The population dynamics model operates with *individual-agents* and *household-agents* while the agricultural model should conceptualize the land use, i.e. its basic element is a *land-patch-agent*.

Further research will be focused on:

- refinement of the population dynamics model,
- development of the agricultural model,
- development of scripts for better presentation and visualization of data exported from NetLogo.

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## References

[1] Altaweel, M. Investigating agricultural sustainability and strategies in northern Mesopotamia: results produced using socio-ecological modeling approach. *Journal of Archaeological Science*, **35** (2008), 821-835.

[2] Axtell, R.L. et. al.: Population Growth and Collapse in a Multi-Agent Model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences*, **99** (2002), 7275-7279.

[3] Danielisová, A.: *The oppidum of České Lhotice and its hinterland*. Ph.D. dissertation, unpublished, 2008.

[4] Epstein, J.M., Axtell, R.: *Growing Artificial Societies: Social Science from the Bottom Up*. MIT Press, 1996.

[5] Griffith, C.S., Long, B.L., Sept, J.M.: HOMINIDS: An agent-based spatial simulation model to evaluate behavioral patterns of early Pleistocene hominids. *Ecological Modelling*, **221** (2010), 738-760.

[6] Grimm, V. et. al.: The ODD protocol: A review and first update. *Ecological Modelling*, **221** (2010), 2760-2768.

[7] Janssen, M.: Understanding Artificial Anasazi. *Journal of Artificial Societies and Social Simulation*, **12** (2009), (4) 13.

[8] de Roos, A.M.: *Modeling Population Dynamics*. Course material, http://staff.science.uva.nl/~aroos/downloads/pdf_readers/syllabus.pdf. Universiteit van Amsterdam, 2011.

[9] Saller, R.: *Patriarchy, Property and Death in the Roman Family*. Cambridge, 1994.

[10] Wilensky, U.: *NetLogo*. http://ccl.northwestern.edu/netlogo/ Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL, 1999.