Utilizing Agent-Based Modeling to Gain New Insights into the Ancient Minoan Civilization

(Extended Abstract)

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ABSTRACT

In this paper we develop an agent-based model to study land use, settlement, and social organization patterns at a particular region of the island of Crete during the Bronze Age. Considering farming as the main activity for sustaining the early Minoan civilization, we evaluate the impact of different social organization models and agricultural strategies on population viability and spatial distribution of settlement locations over a 2000 year period. Interestingly, one of the social models examined promotes the *targeted redistribution of wealth*, and is inspired by a recent framework for *self-organizing agent organizations*. Model parameters are based on archaeological studies, but are not biased towards any specific assumption. Results over a number of different simulation scenarios demonstrate an impressive sustainability for settlements adopting a socio-economic organization model based on self-organization; while the emerging "stratified" populations are larger than their egalitarian counterparts. This provides support for theories proposing the existence of different social strata in early Bronze Age Crete, considering them a pre-requisite for the emergence of the complex social structure evident in later periods. Moreover, observed population dispersion agrees with existing archaeological evidence.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence; I.6.3 [**Simulation and Modeling**]: Applications

General Terms

Algorithms

Keywords

Agent-based modeling, self-organization, archaeology

1. INTRODUCTION

Agent-based modeling (ABM)[1] is increasingly used in Archaeology during the past decade, as a tool for assessing the plausibility of alternative hypotheses regarding ancient civilizations, their organization, and social and environmental processes at work in past ages [5, 4]. Its emerging popularity is due to its ability to represent individuals and societies, and to encompass uncertainty inherent in archaeological theories or findings. Indeed, the unpredictability of interaction patterns within a simulated agent society, along with the strong possibility of emergent behaviour, can help archaeology researchers gain new insights into existing theories; or even come up with completely novel explanations and paradigms regarding the ancient societies being studied.

2. AGENT-BASED MODEL AND RESULTS

In this work we have developed a functional ABM system prototype for simulating an artificial ancient society of agents residing at the *Malia* area of the island of Crete during the Bronze Age. In contrast to most existing ABM approaches in archaeology, agents in our model are completely autonomous, and can build and maintain complex social structures. Furthermore, though our work here is inspired by existing case studies, our model itself is quite generic, and does not aim to prove or disprove a specific theory.

Agents and resources are located within a two dimensional space, specified in terms of coordinates and cells. The spatial resolution is 20×25 km area with a 100×100 m cell size for the grid space. The time slot investigated is $\approx$ 2,000 years (3,200 to 1,200 BCE), with annual time steps. Agents correspond to households, each containing up to a maximum number of *individuals*, which are considered to be the main social unit of production for the period [7]. Each household agent resides in a *cell* within the environmental grid, with the cell potentially shared by a number of agents. Adjacent cells occupied by agents make up a *settlement*. Resources exist in cells at fixed locations, and they may vary with respect to the amount of energy they embody, and their availability through time. The productivity of an individual cell (in *kg*) is a function of the cell's geo-morphological characteristics (in particular, land slope) given its location on the map, and the *soil fertility*, which depends on the amount of labour applied on the cell by the agents. Population size affects the land productivity in two ways: positively, since the continuous occupation or cultivation of an area by a large populace leads to experience and subsequent higher crop yield; and negatively, since the soil quality of lands cultivated continuously by a large population degrades due to erosion processes. Population levels at a given area are affected by migration, as well as natural population change by birth and death of the agents.

The model operates as follows: at every time step, agents (i.e., households) first harvest resources located in nearby cells (corresponding to the fields they are cultivating). Then, they check

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[1]We will be using the acronym ABM to refer to both "agent-based modeling" and "agent-based model".

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whether their harvest (added to any stored resource quantities) satisfies their minimum perceived needs. If not, they might ask others for help (depending on the social organization model in effect), or they might even eventually consider migrating to another location. A shortage of resources leads to a reduced reproduction ability. Thus, it gives rise to a *task* for an agent which needs to *accumulate produce equal to the perceived deficit*. This is done by consuming resources in its storage or by allocating the task to another agent.

Agents also employ actions by which they interact with each other. These correspond to distinct *social organization paradigms*, describing the way by which the distribution of harvested resources takes place among the population: *independent*, where agents act independently and there is no sharing of harvest or stored resources among the agents; *sharing*, an egalitarian society paradigm, by which agents may equally share harvested energy amounts within a settlement; and *self-organized*, where agents re-arrange their (hierarchical) structure autonomously, without any external control, to adapt to changes in requirements and environmental conditions.

Now, *stratified* societies normally have larger populations than their egalitarian predecessors, as they deploy more powerful productive forces. The emergence of the palaces in the Cretan Early Bronze Age marks a transition from an egalitarian to a more complex, state-like society with a clear hierarchical structure crowned by a central, administrative authority [1]. Social structure is, naturally, subject to continuous reorganisation. To study these phenomena, we developed and tested a *self-organization algorithm* that builds on the work of [6] on self-organizing agent organizations used for problem-solving and task execution. Our algorithm has two main steps: a *decision making mechanism*, and a *decentralized structural adaptation method*.

Interactions between agents are regulated by the settlement's social structure, as agents interact with one another for the proper allocation of resource needs. Relations among agents are classified into three types (i) *acquaintance* (aware of the presence, but having no interaction), (ii) *peer* and (iii) *authority* (a *superior – subordinate* relation). Thereafter, agents reorganize and *adapt* their relations based on the *relative difference of resources transferred*, maintaining a stratified social structure. This dynamic adaptation process effectively promotes a targeted redistribution of wealth, leading to increased overall sustainability. Every task execution action of an agent has an associated load (resource energy offered). Loads on the various agents are assumed to be known to everyone in the community. Agents use the information about all their current year allocations to evaluate their relations with their subordinates, superiors, peers and acquaintances. An *authority* relation means that there is a relative difference in the amount of load per assigned tasks between them; a superior (wealthier) agent has more tasks assigned, while the subordinate agent (in need) has less. A *peer* relation instead implies a relatively equal amount of load per agent. The evaluation is based on the overall load between a pair of agents in case the relation had been different.

Moreover, the ABM allows us to explore the sustainability of *intensive farming* ("garden" cultivation with hand tillage, manuring, weeding, and watering) leading to greater production per hectare and *extensive cultivation* (large-scale tillage by ox-drawn ards) agricultural technologies in use at the time [2, 3], and to examine their impact on population dispersion. In addition, the ABM attempts to assess the influence of the different social organization paradigms on land use patterns and population growth.

Our ABM model was developed using the *NetLogo*[2] modeling environment. Various scenarios were taken into account for the experimental setup, with different parameterization for: the three different behavioral modes (i.e., the social organization paradigms used); the two different agricultural regimes; and the proximity of a new location to an aquifer (i.e., spring, river or coast). Since there is no available past vegetation data, at the beginning of each scenario resources where spread randomly over the land, but with resource amounts at a particular cell depending on its slope. Each scenario was simulated for thirty runs, generating a total of 360 runs. We clarify at this point that the only forces affecting the population dynamics in our simulations was the agricultural and the social organization paradigms used.

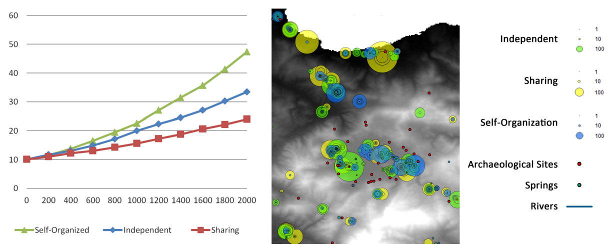

Figure 1: *(Left):* Population size for Intensive Agriculture over 2000 years with aquifer proximity considered. *(Right):* Settlement location buffers when *Extensive* Agriculture is used with no aquifer proximity considered.

Population growth results with respect to the *intensive* agricultural strategy are shown in Fig. 1*(Left)*. Results for the *extensive* agriculture regime are similar: self-organized societies thrive under both regimes. Indeed, our simulations indicate that a *self-organized* behaviour is better at sustaining the Minoan civilization through time; while the *independent* behaviour appears to be better than the egalitarian *sharing* approach as well. We also report some results on the density and spatial distribution of settlements over the area of interest at n Fig. 1*(Right)*. The figure depicts final settlement locations after 2000 years when the *extensive* agricultural strategy is used, averaged over all 30 runs for a particular scenario—buffered with a radius proportional to the years settled (last 500 years). Regardless of aquifer proximity or agricultural strategy employed, settlements are concentrated near actual (depicted) archaeological sites in the coastal regions or at the Lassithi plateau.

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[2] See *http://ccl.northwestern.edu/netlogo*.