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Evolutionary Agent-Based Modeling of Past Societies' Organization Structure

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Abstract. In this work, we extend a generic *agent-based model* for simulating ancient societies, by blending, for the first time, *evolutionary game theory* with multiagent systems' *self-organization*. Our approach models the evolution of social behaviours in a population of strategically interacting agents corresponding to households in the *early Minoan* era. To this end, agents participate in repeated games by means of which they exchange utility (corresponding to resources) with others. The results of the games contribute to both the continuous re-organization of the social structure, and the progressive adoption of the most successful agent strategies. Agent population is not fixed, but fluctuates over time. The particularity of the domain necessitates that agents in our games receive *non-static* payoffs, in contrast to most games studied in the literature; and that the evolutionary dynamics are formulated via assessing the perceived *fitness* of the agents, defined in terms of how successful they are in accumulating utility. Our results show that societies of *strategic* agents that self-organize via adopting the aforementioned evolutionary approach, demonstrate a sustainability that largely matches that of self-organizing societies of more cooperative agents; and that strategic *cooperation* is in fact, in many instances, an emergent behaviour in this domain.

1 Introduction

Over the past two decades, archaeology has utilized agent-based models (ABM) for simulating ancient societies [2]. This is due to the ABMs' ability to represent individuals or societies, and encompass uncertainty inherent in archaeological theories. At the same time, incorporating ideas from multiagent systems (MAS) research in ABMs can enhance agent sophistication, and contribute on the application of strategic principles for selecting among agent behaviours [4].

To this end, a recently developed ABM with autonomous, utility-based agents explores alternative hypotheses regarding the social organization of ancient societies, by employing MAS ideas and algorithms [1]. The model incorporates different social organization paradigms and subsistence technologies (e.g., types of farming). Moreover, it employs a self-organization approach that allows the exploration of the historical social dynamics–i.e., the evolution of social relationships in a given society, while being grounded on archaeological evidence. However, the various social organization paradigms explored in that work assume a cooperative attitude on behalf of the agents. Specifically, agents were assumed to be willing to provide resources out of their stock in order to help agents in need, and such transfers drive the evolution of the social structure. In reality though, people are often driven by more individualistic instincts and exhibit more egotistic societal behaviour. Therefore, if one is to model societal transformation accurately, agent behaviour has to be analysed from a strategic perspective as well. Assuming that agent interactions are based on rational decision-making, and also influenced by their very effect on the society as a whole, then the evolution of the social dynamics can be studied via a game-theoretic approach. The "mathematics" of evolution are the subject of *evolutionary game theory (EGT)* [3], which takes an interest in the *replicator dynamics* by which strategies evolve.

In this work, we adopt such an approach for the first time, and provide an alternative "social self-organization" approach to that of [1]: here, social self-organization is driven by the interactions of *strategic* agents operating within a given social organization group, and the effects these interactions have on agent utility. As such, our ABM employs a self-organization social paradigm where the evolution of the social organization structure is driven by the interaction of agent strategies in an evolutionary game-theoretic sense [3]. This allows us to study the evolution and adaptation of strategic behaviours of agents operating in the artificial ancient community, and the effect these have on the society as a whole. We are not aware of any archaeological ABM that explicitly adopts an evolutionary game-theoretic approach. By contrast, our work here shows how EGT can be utilized within an archaeological ABM.

2 A utility-based ABM

We build on top of the ABM developed in [1] for simulating an artificial ancient society of agents evolving in a 2D grid environmental topology. The agents correspond to *households*, which are considered to be the main social unit of production in Minoan societies for the period of interest (3,100-1,100 BCE) [5], each containing up to a maximum number of *individuals* (household inhabitants). Households are *utility-based autonomous* agents who can settle, or occasionally re-settle in order to improve their utility, and cultivate in a specific environmental location.

The total number of agents in the system changes over time, as the annual levels of births and deaths is based on the amount of energy consumed by the household agent during the year. This in turn depends on the energy harvested, that is, the agent's *utility*. These rates, produce a *population growth rate* of 0.1%, when households consume adequate resources. This corresponds to estimated world-wide population growth rates during the Bronze Age.

The ABM incorporates a *self-organization* social paradigm, where agents within a settlement continuously re-assess their relations with others, and this affects the way resources are ultimately distributed among the community members, leading to "social mobility" in their relations. Self-organization gives rise, naturally, to implicit agent hi-

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erarchies. Agents are assumed to be helping out agents in need (if they possess enough resources in their own storage), resulting to a continuous *targeted redistribution of resources*, so that utility flows from the more wealthy agents to those more in need within the organization, maintaining a dynamically stratified social structure. Simulation results indicate that a *heterarchical* social structure, having emerged by the continuous re-adaptation of social relations among Minoan *households*, might well have existed in the area of study.

3 An evolutionary game-theoretic extension

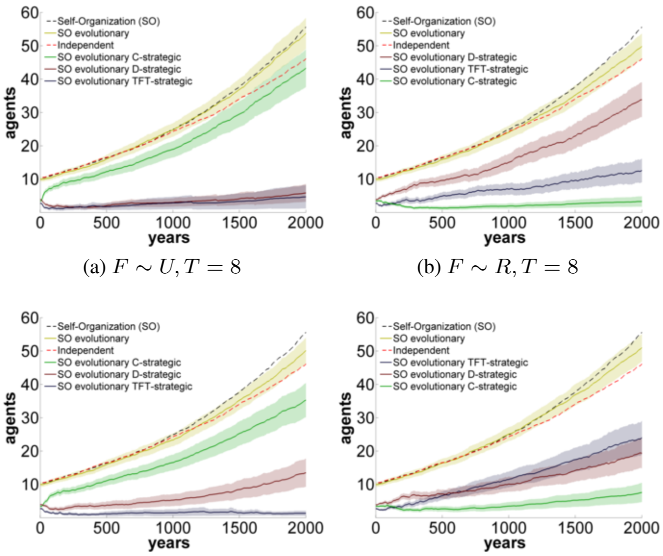
We simulate *repeated "stage games"* played by pairs of household agents, with agents belonging to the same settlement. Agents are considered as "players" in "stage games" that take place every time-step corresponding to one year. At any given time-step, a single player may be interacting at a one-on-one basis with all other agents within the settlement simultaneously. We assume a finite, but not fixed, population size (since new households are created or old ones cease to exist). Intuitively, the games model resource exchanges (utility transfers) among the households. In contrast to most matrix games studied in the literature, our agents receive *non-static payoffs* (depending on their current utility, largely acquired via working the lands). This in effect leads to an alternative model to the classic fitness-based evolution strategy selection: a strategy's reproductive success depends on *dynamic* payoffs, and thus agents using the same strategy do not necessarily receive the same payoff when interacting with other agents. We assume three different player strategic behaviours: a *cooperative* one, C, willing to share resources with another player; a *defective* one, D, refusing to share resources; and one which starts with cooperation and then behaves as the other player did in the previous game round, namely *Tit-for-Tat*, TFT. Considering these different strategic agent types as playing games against each other, we explore the evolutionary dynamics which arise. If we assume static payoffs in our "stage games", defection is the dominant strategy for any agent, and mutual defection is the only strong Nash equilibrium.

In our work, a series of (yearly) time steps during which each agent employs a specific strategy when playing in the stage games, is followed by a strategy review stage during which agents assess and possibly modify their strategies; while the results of each stage game played contribute to the continuous alteration of the social structure, which evolves as in [1], given the evolution of the differences in relative wealth among the agents. Strategy review and adoption is performed in various ways. Specifically, fitness can be evaluated with respect to solely the reward achieved in the games, or the overall utility of the strategic agent (derived from game-playing and land cultivation); while the relative success of the agent's current strategy can be assessed at either the settlement or the societal level, with respect to the average fitness of all strategies at that level, or the average fitness of the strategy itself (calculated across agents adopting this particular strategy); and the adoption of an alternative strategy can be deterministic or stochastic.

4 Simulations and results

Several scenarios were taken into account for the experimental setup, with different parameterisation. We evaluate the impact of the evolutionary self-organization social paradigm to population viability. ABM's initial settings are the same as in [1] for evaluation purposes. We adopt a uniform distribution of initial strategies, depending on agents numbers within a settlement for every simulation run. Agents review their strategy every 8 or 16 years ($T = 8$ or $T = 16$). Simulation results are *averages over 30 simulation runs* across a period of $2,000$ years. We compare the performance (in terms of population growth achieved) of strategic agents that play games and use self-organization, which we term "SO evolutionary" agents, against those that *(i)* are benevolent and self-organize, as in [1], termed "SO" agents; or *(ii)* adopt the "independent" social behaviour, trying to maximize their utility without interacting with others [1].

Overall, scenarios that sustain a higher average population of "SO evolutionary" agents, are those where agent fitness is evaluated *wrt. utility*, while agents adopt new strategies in a *stochastic* manner. Moreover, better performance is observed when agent fitness is compared to that of the *settlement* group, rather than the entire society; and especially when the performance of only the agents in the settlement that adopt the *same* strategic behaviour is taken into account, as illustrated in Fig. 1. Notably, we observe high percentages of emergent cooperative behaviour, despite this behaviour being in contrast to that prescribed by the stage game Nash equilibrium.



(a) $F \sim U, T = 8$ (b) $F \sim R, T = 8$

(c) $F \sim U, T = 16$ (d) $F \sim R, T = 16$

Figure 1: Agent population for scenarios with *stochastic* strategy review and F calculated across agents in the *settlement* that share the *same strategy*. $F \sim U$ / $F \sim R$: agent fitness function is calculated *wrt.* utility or reward accumulated in games, respectively.

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