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Hunting for emergences in stone-age settlement patterns with agent-based models

1 Introduction

Complexity science focuses on explaining phenomena as systems composed of a multitude of components interacting with each other. This approach offers a good reflection of social systems which are composed of individuals. Social scientists have long been aware of how complex structures emerge from individual behaviors. During recent decades, researchers have also started to use complex systems to explore the past. These studies have mostly applied agent-based models in the field of archaeology and in fields specializing in modeling, for example those under the umbrella term cliodynamics. Until recently, the application of complexity science has largely been neglected by humanists and historians in particular.

This chapter discusses the opportunities offered by complexity science approaches, and particularly agent-based modeling (ABM), for humanities scholars studying the past. The discussion is based on explorative interdisciplinary research applied to the emergence of settlement patterns, as observed in archaeological material. Its main purpose is not to report the research results, which are published elsewhere, but to discuss the explorative process of the

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ABM-driven research project, along with additional values and unexpected insights gained during the study. Elements of the research process that could apply to other studies and fields are reflected upon using digital hermeneutics as put forward by historians as a reference model. Interdisciplinary contact points between the social and natural sciences and the humanities, that form the basis of the study, are discussed.

In the following sections, concepts of modeling, emergence, and complex systems are discussed from a humanist viewpoint, then an overview of a case study is presented and, based on the experience of the project, wider applications of ABM practices are discussed.

The research presented here is based on ideas and cooperation with people from an interdisciplinary context including fields like archaeology, history, quantitative geography, economy, computer science, and complex systems modeling.

2 Concepts and methods

2.1 Emerging complexity

Adoption of complex systems approaches becomes reasonable if the research object exhibits emergent behavior, which means that the system in general possesses properties that its individual elements do not have. Although research on complex systems has escalated quite recently, the general ideas behind complexity science are in fact very old.

Emergence was already being described in the ancient world by philosophers like Aristotle who, in the earliest known such record, wrote in his *Metaphysics*: “In the case of all things which have several parts and in which the totality is not, as it were, a mere heap, but the whole is something besides the parts, there is a cause; for even in bodies contact is the cause of unity in some cases, and in others viscosity or some other such quality.”

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5 The author wishes to thank Andreas Fickers for building the research environment behind this research, Geoffrey Caruso for his guidance on quantitative geography, Aivar Kriiska for archaeological data and insights, Juliane Tatarinov for initiating this volume, and Iza Romanowska for very helpful feedback on the research and text.

During the nineteenth century the axiom that the whole is greater than the sum of its parts (Renouvier), and Boutroux’s idea that higher levels of analysis are irreducible to the lower levels, became known among scholars studying society. Durkheim used these ideas to deduce the central concept of the newly born discipline of sociology: the *sui generis*, now referred to as emergence.

There are some well-known iconic examples of emergent systems observed by science. For example, through physics we know about rules governing subatomic particles, but those rules do not inform us about the chemical properties of the substance formed by those particles. Rules and theories in chemistry are formulated for another scale of analysis. The science of biology in turn considers life as an emergent property of chemical systems. Likewise human culture is not explained by the biological characteristics of humans but requires another level of observations. These gaps are unintuitive for the human mind and often form the boundaries of disciplines.\(^7\)

Social emergence can be illustrated by the power law governing the distribution of the connections that individuals have in a society, and which emerges as a result of a preferential attachment process. Individuals often prefer connections with others who already have more connections, for example because of better access to information or higher perceived trustfulness (doing business with rich people, being friends with people with more friends). This preference develops an exponential distribution of connections (friends, wealth) and the dynamic process described as “the rich get richer” emerges (the Matthew effect).\(^8\) From an individual’s point of view or level of analysis it might not be intuitive that the general trend of being friends with popular people leads to an increase in social inequality. This illustrates how phenomena usually observed at different levels of analysis are interrelated.

The remarkable thing about society is the ease with which simple individual rules and changes in individual connection lead to complexity – and, quoting Epstein and Axtell, “it is not the emergent macroscopic object per se that is surprising, but the generative sufficiency of the simple local rules.”\(^9\) This quote expresses that only very basic rules governing individual choices are required to form complex systems with new properties.


Analyzing emergent relations between different analytical levels became possible only after new fields of systems theory and cybernetics arose during the 1940s. New ideas morphed into the discipline of complexity science, which provided a toolkit for studying complex systems involving relations between their components and properties like adapt ion, nonlinearity, spontaneous order, feedback loops, and emergence. Agent-based modeling (ABM), an analytical approach to solving systemic issues, was developed and became practically applicable during the computational revolution of the 1980s.

2.2 Agent-based modeling – a tool for exploring complexity

ABM is a computational simulation method developed to explore complex systems by combining different levels of analysis. It lets us explore how the relatively simple behaviors of system components lead to the general emergence of complex phenomena. Building on the classical definition from Clarke, “a model is a mechanism which connects theory to data,” ABM is a mechanism that enables us to connect the theory of one level of analysis to data on another level.

The agent-based modeling process is accomplished in a number of key steps:

1) The characteristics of the environment and the rules governing individual agents (ontology) are defined.
2) These characteristics and rules are then formalized as algorithms and their configurations, so that the latter can be executed as a computer program.
3) The created models are calibrated to fit available observations.
4) The models are validated to behave as expected (face validation).
5) Any further analytical processes are performed, such as running simulations of scenarios which can be compared to empirical observations or theories, and model exploration to explain phenomena and build theories.

ABM as a simulation technique enables us to explore scenarios that cannot be observed in empirical reality and thus involves the experimental method in disciplines usually limited to descriptions and the comparative method.

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11 For an overview of the ABM workflow carried out for this research see Section 3, including Figure 1.
ABM can be used to build and test theories of individual behaviors by projecting them onto different social and spatial scales.\textsuperscript{13} These scales constitute different levels of observation and analysis. For example, written sources describe individuals’ perceptions, while archaeological observation could provide an aggregate understanding of dynamic phenomena in general.

The literature of ABM for historical scholarship has so far mainly been limited to discussion on the potential use of ABM.\textsuperscript{14} Nanetti and Cheong discussed how narrative-driven analysis of historical big data can lead to the development of explanatory agent-based models in the genre of counterfactual history, one possible application of ABM.\textsuperscript{15} Some studies utilizing ABM\textsuperscript{16} include research on infantry tactics,\textsuperscript{17} antiquities infrastructure projects\textsuperscript{18} and maritime trade.\textsuperscript{19}

The situation is different in the field of archaeology where ABM has seen considerable success in recent years. This may be due to the more quantitative nature of the discipline, having its sources reflecting the aggregated activities of people of the past and thus being easier to project onto different scales of time and space.\textsuperscript{20}


\textsuperscript{15} Andrea Nanetti and Siew Ann Cheong, “Computational History: From Big Data to Big Simulations,” in \textit{Big Data in Computational Social Science and Humanities}, ed. Shu-Heng Chen, Computational Social Sciences (Cham: Springer International Publishing, 2018), 337–63.


ABM has been used to explore hominid dispersal,\textsuperscript{21} hunter-gatherer foraging\textsuperscript{22} and settlement choice,\textsuperscript{23} the agriculture and economy of Neolithic village communities,\textsuperscript{24} the social and economic organization of ancient civilizations,\textsuperscript{25} and cultural transmission,\textsuperscript{26} among other topics.

The essence of ABM practice in archaeology lies in formulating the individual behaviors as choice rules, running the model, and comparing the simulation output to corresponding observations from empirical material. As archaeologists do not typically have access to knowledge about individual behaviors in the past, anthropological universals, contemporary analog, and other disciplines are used to define them.

3 Studying settlement choice using ABM

3.1 Case study: The Stone Age settlement of Estonia

The research question for this case study was initiated by the notion among a group of Estonian and Finnish archaeologists that it is relatively easy to find settlement sites from the late Mesolithic Narva stage (5200–3900 BC) and early


Neolithic Comb Ware period (3900–1800 BC) (which we will refer to together as NCW) on the landscape, but that sites from the Corded Ware stage (CWC; 2800–2000 BC) are only found by chance.\textsuperscript{27} We can rephrase this by saying that archaeologists’ implicit mind-models can predict the locations of the first group of sites but are unsuccessful for the second group.

The effectiveness of archaeological predictive models (here, we consider mind-models to belong to this group) has been thoroughly discussed and it has been hypothesized that, as social complexity grows, the direct relationship between settlement choice and environmental conditions decreases.\textsuperscript{28} The case study presented here explored this hypothesis as a cause of differences in the environmental predictability of settlement locations.

To do so, the research project integrated empirical data and theories of settlement pattern formation, including two levels of analysis. The empirical level was represented by the settlement locations of the given periods and the environmental conditions associated with those locations. Settlement systems can be approached as emergent phenomena formed by individuals making their decisions of where to live, which constitutes another theoretical level of analysis. Scholars have implicitly used this perspective but explicit approaches have been less explored so far. Separate levels of analysis and the complex nature of the formation process suggested ABM as an appropriate research tool to propose hypothesized models of individual behavior and test them against empirical observation.

Using ABM set several requirements that needed to be met to build, calibrate, validate, and interpret an ABM model. Although ABM can be developed based on verbal theories\textsuperscript{29} and validated qualitatively against descriptions, quantitative modeling steps were essential and considerably influenced the current research process. Those research steps created a research framework illustrated in Fig. 1 and discussed in the following sections.

\textsuperscript{27} Sikk et al., “Environment and Settlement,” 91.
\textsuperscript{29} Paul Smaldino, “How to Translate a Verbal Theory into a Formal Model,” preprint (MetaArXiv, 26 May 2020).
3.2 Data modeling

Data extraction and modeling involve defining entities of interest and their available and relevant characteristics. Being a prerequisite for following modeling practices it does, however, require a knowledge of both empirical data and the related theoretical frameworks. In the current study, preliminary development of both the empirical and the conceptual model was required before the final data structure was decided upon, requiring synchronous development.

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In addition to both empirical and theoretical explorations of available knowledge, data modeling also exposed three essential issues typical of quantitative studies of the past:

- contemporary conditions (environment) are different from those of the past
- the extent to which past environmental attractions can be observed in available variables is not known
- whether the mind-model of the archaeologists has already introduced a bias in the current knowledge.

To address these issues several new steps were introduced into the research process. The first of them required interdisciplinary cooperation with geologists who provided past landform and shoreline reconstruction models representing the periods of interest.

The second issue was solved by constructing a statistical model which proved the strong relation between environmental variables (e.g., distance to water, soil type, geomorphological derivatives) and settlement choice (see Section 3.3).

Data bias is a well-known issue to archaeologists and, as one critical comment by a reviewer stated, it is often considered to invalidate the results, without delving into complex theoretical frameworks. In the current case the survey strategies were studied and it was found that most recent surveys have ventured past predicted areas and undertaken additional trips in order to validate knowledge. This made the current knowledge significantly stronger, although awareness of possible bias is universally required during interpretation of archaeological results.

### 3.3 Statistical model of empirical data

A statistical model was created mainly as an evaluation of available environmental variables, to explore their relation to settlement choice. Statistical analysis was used to find and describe regularities in the empirical data. The dependence of settlement patterns on environmental conditions has been thoroughly researched in archaeology, with studies carried out since the 1970s. Later the exploration continued mostly with GIS-based predictive models for archaeological site prospection.

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The analysis of the current data showed the existing relation between environment and settlement choice and exposed useful variables describing it. Some of the results, like the sites’ proximity to water bodies in dry, sandy areas were already known to archaeologists. The results added new insights including the rugged nature of the preferred environment and the relative position of sites in local topography. The statistical analysis served as a tool for data reduction and helped to assess which variables were reflecting changes in settlement choice and were thus useful to include in further analysis.

This step revealed differences in settlement choice logic between the CWC and NCW settlements, with the first being less constrained by water bodies and in general situated in higher locations. The selection of variables (e.g., distance to water, soil type) and measures of their effect on settlement choice pushed the boundaries of interpretation and led to alternative hypotheses for explaining the data.

### 3.4 Spatial model

A spatial model was constructed in order to quantitatively assess the initial observation that the settlement choice of the CWC phenomenon was less predictable than that of the earlier periods. The analysis was done using methodologies from archaeological predictive modeling and eco-cultural niche modeling – the latter provided several additional measures and niche-related concepts from ecology.

Knowledge of the relation of environmental variables to settlement choice was extrapolated to the whole research area by creating a spatial inductive logistic regression model. The resulting probability rasters represented the environmental residential suitability maps associated with the two studied settlement systems. Created models could be compared for both the environmental influences and the spatial configurations of suitable areas. Comparison of the features confirmed the hypothesis that during the CWC stage the settlement choice was less restricted by environmental conditions.

Several spatial measures like spatial clustering and niche breadth were experimented with and provided measures to compare simulation results to empirical reality, thus helping to validate them. Through the modeling process the epistemological meaning changed from economically evaluating individual locations for potential archaeological remnants to reconstruction of the past

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vision of the landscape. The spatial interpretation of empirical data was a step closer to expressing individual perception of the landscape.

In addition to confirming the initial hypothesis of decreasing environmental influence this enabled formulation of new interpretations of the importance of spatial structure of past perception of the habitation areas. For this, the new concept of a residential suitability model (RSM) was developed, which was interpreted as the perceived potential of locations in an area for living and which is technically identical to niche models and archaeological predictive models. It could be asked: What are the differences between the suitable habitation areas, as perceived by people of the early Neolithic and the CWC cultures? It also helped to define hypotheses for explaining differing spatial structure RSMs of the settlement systems. Those hypotheses included the different mobility modes of the periods, growing social complexity, and technological innovation making wider areas usable by agriculture.

3.5 Agent-based framework

The central goal of ABM is to explain complex relations between processes that are out of the reach of verbal arguments by proposing a model which can be validated to empirical data. The model can then be explored further, thus building theory through interpreting it. For the current study the goal was to build a simulation model that produced synthetic data that could be compared to archaeological empirical data and through it to explain the observed variations in settlement systems. The foundation of such a model is the conceptualization of theoretical knowledge of individual behaviors.

The conceptual model was constructed to formally describe the settlement pattern formation process as cumulative settlement choices. The conceptualization drew from studies in ethnography and economic geography, incorporating abstract concepts most of which have previously been discussed in the context of archaeology. The conceptual model describing how people choose a place to live was based on theories from archaeology where most of the basic principles had been debated during the 1970s.\(^{35}\)

Constructing the abstract conceptual model was helped by the fact that general theories of settlement choice are similar in those fields and the main differences come from the empirical data used to back them. For example, archaeologists

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could categorize influences on choice as social (hypothetical) and environmental (partly observable) influences, but geographers would group influences by their spatial characteristics.

Individual agents’ selection of residence was formulated using principles of discrete choice, with every location having an abstract utility value for a settlement. From contemporary experience we know that there exist a multitude of factors influencing residential choice, for example access to a workplace and essential services, social context, the feeling of belonging to a group, and general environmental conditions. Such factors depend on observed society, but to abstract prehistoric settlement choice we categorized them into two major groups: influences arising from the social domain (other people) and those related to the physical environment.

The utility value of each location was then determined by a utility function composed of factors categorized as access to either ecosystem services or social services. Under ecosystem services we grouped factors like access to local shelter, drinking water, and a dry location, as well as access to fertile agricultural lands and hunting grounds. Social services include the benefits of keeping in contact with other people, including the availability of specialized goods, trade, and cultural and other benefits which can be associated with greater social complexity. It must be noted that neither group is completely nor directly observable in the archaeological record, but ecosystem services is certainly better represented through environmental variables.

A functional simulation model was constructed based on the conceptual model, and synthetic environments were generated, with ecosystem services and agent populations forming dynamic social attractions. Each agent in the system model represented a community that formed a residential settlement. Agents were made mobile and assigned a goal of searching for the best location in the randomly generated environments, using varying influences.

One of the powers of ABM is the ease of going directly from the conceptual model to the simulation model, thus enabling model exploration techniques to be used to gain theoretical insights. Exploration of the conceptual model showed that, for settlement choice, the factors which required access over longer distances, like trade, were of lesser importance in validating the significance of the relation between different environmental data for this decision. Although the result may be intuitive, ABM provided quantitative assessment of significant ranges of individual environmental influences. For example, local conditions influence specific location choice significantly more than access to resources in daily walking distance does.
3.6 ABM experiments

Three extended models were created to run simulation experiments testing the hypotheses. The first experiment was designed and run to explore the resource depletion that has long been considered to be the driving force of hunter-gatherer mobility. A central place foraging (CPF) ABM implementation was created and illustrated that, although the resource depletion based model is very useful for explaining mobility, it has only a modest impact on settlement location choice principles.\(^\text{36}\) The experiment indicated that the hypothesis of differing mobility was not the cause of differences between settlement systems of the periods concerned.

Another simulation experiment was conducted testing different variations of utility function, with agents prioritizing either environmental benefits or social connectivity. As expected in simulation runs with agents prioritizing social services more highly, the environmental value of location was sacrificed, resulting in greater population clustering (Fig. 2) – and, in the reverse case, population was generally more dispersed.\(^\text{37}\) The model confirmed the intuitive idea that, with greater social complexity, the selection of suitable sites was less environmentally determined – but it added a spatial factor: i.e. it should also result in higher population clustering.

Running a dedicated simulation experiment testing different spatial configurations of the environment led to another unexpected insight. The simulations revealed the idea that the spatial autocorrelation of attractions in the landscape influences the emergence of settlement systems and population clustering.

ABM enabled the conceptualization of the rather abstract but essential idea of a residential suitability model, as mentioned in Section 3.4. The most fruitful of the unexpected insights that came purely from ABM simulations was the understanding that the spatial configuration of attractions in the landscape influences the emergence of settlement systems and population.

It was personally interesting to observe how the ABM modeling process surprised and played with the researchers’ intuition.\(^\text{38}\) The simulation results were sometimes the opposite of their initial intuition but, after visual observation of the simulations, previously counterintuitive results started to seem intuitive. I


\(^{38}\) Andre Costopoulos and Mark W. Lake, *Simulating Change: Archaeology into the Twenty-First Century* (Salt Lake City: University of Utah Press, 2010).
Fig. 2: Varying spatial configuration of environmental suitability has an impact on clustering of the population as visualized by theoretical ABM simulation. Two simulation runs are visualized, with images showing settlement locations after 5, 10, and 50 steps. Upper row shows that more “smooth” environments lead to population clustering. 2020. © Kaarel Sikk.
experienced a similar situation while observing how smoother environments resulted in clustered populations and vice versa (Fig. 2), depending on the scale and importance of environmental variables. The intuition tricked researchers’ minds again when the resulting dynamics changed while introducing the mechanics of resource depletion.

4 Discussion on ABM and studies of the past

4.1 ABM as a “thinkering” tool

ABM is intended for exploring complex systems with emergent properties and other characteristic features. Some results of the current as well as other archaeological papers can also be described using simpler analytical models. As using the simplest possible method is a general scientific principle, a critique toward the use of ABM in archaeology is to ask: Is ABM really needed to confirm a theory?

Experience in archaeology, including the current project, indicates that ABM has proven its value as a tool to “thinker” with, even if emergent properties are not expected to be found. We argue that the process of developing ABM through formulating theories algorithmically is a very rewarding part of the research. Its unexpected additional knowledge gain often leads to new approaches, concepts, and research questions. This benefit of modeling is especially rewarding when dealing with the complexity of social systems, still relatively unexplored in humanities.

The explorative power of ABM is realized through the development process and the methodological toolkit associated with it. In addition to domain knowledge of the subject matter, this development requires researchers to be able to express their ideas algorithmically – a formal expression that forces them to explicitly state their knowledge and re-evaluate existing perspectives. It also opens up new angles to a research subject, with the challenge to select the most relevant one, thus requiring multiperspective exploration.

41 Costopoulos and Lake, “Simulating Change.”
Archaeologists have rather successfully developed a gut feeling for settlement locations from their experience of different landscapes. While searching for undiscovered settlement sites they use their mind-model empathetically: Where would I have camped or settled, in the past? The process is similar to agent-based modelers modeling the social system and describing the rules governing an individual (self) making a choice: “If I were to move it would (probably) be to a better place.” This very basic starting statement already raises several new questions that need to be solved and leads to a chain of “thinkering” exercises, experimenting with the synergy of empathetic and rule-based thinking.

If familiar with the algorithmic toolkit, ABM provides the researcher with a surprisingly intuitive process giving reflexive feedback and new perspectives on existing knowledge. These perspectives often lead to reconceptualizations of subject matter. In the current research a significant development was the reconceptualization of archaeological predictive models as residential suitability models.

4.2 ABM as an interdisciplinary trading ground

The research process showed that the skeptical view that modeling practices suppress multiperspective approaches was unfounded – and that in fact the opposite was true: describing influences on human choices required searching for new perspectives in order to describe the system as a whole in the most effective way.

Using ABM almost universally forces the researcher to enter an interdisciplinary trading ground and search for fields where specific problems have been solved in the most efficient way. A sentence in Section 4.1 reflected settlement choice as perceived by a person: questions on how to formally describe a choice can be studied in anthropology, psychology, or economics, as archaeologists often do. Although the developed settlement choice model was focused on spatial aspects it required mapping a wide range of literature from different sources and used input from various different domains, including geology and ecology.

Formal models are descriptions of a phenomenon with all irrelevant domain knowledge stripped out, which makes it possible for specialists from different fields to understand and evaluate the model and reproduce the research results. As a visual diagram can generally be read without knowing the scientific details of a topic, so an ABM can also be read and understood by anyone who has mastered the language of its development. This makes formal models efficient interdisciplinary communication tools.

In the case of ecology and archaeology, for example, there has been an exchange regarding predictive models of animal niches and archaeological
settlement sites. Despite these being different domains the literature is easily understandable by researchers – and joint methodological developments have even led to the new field of eco-cultural niche modeling. In the current research, geological paleoreconstruction models were directly usable as a direct input to archaeological models.

Following are some of the interdisciplinary points of contact that were communicated through modeling practices:
- archaeological and environmental data, through data modeling
- a paleoenvironment reconstruction model, with geologists using GISs and existing paleoenvironmental proxies
- spatial statistics, with inductive spatial models and geographical tools to compare them
- conceptual ABM integrating theoretical frameworks from economics, urban geography, and ethnography
- model exploration techniques for assessing and building theories and interpreting empirical data.

The techniques used in the current study also have surprising connections to very different fields. For example, inductive models used for predicting site locations are algorithmically identical to the ones used for text analysis, such as for topic modeling. They even share typical prediction algorithms (e.g., logistic regression and MaxEnt) and similarly produce a classification (e.g., habitation suitability versus topic) that can be used by scholars for searching (e.g., new sites versus new insights). These models add a new dimension of observation: in the case of topic modeling this might, for example, create a temporal dynamic description and in the case of archaeological sites the model can provide the spatial structure of a suitable area. Although having very different fields of research, scholars working with the same algorithm can create a surprisingly effective channel of communication.

ABM provides even more potential trading ground in the humanities. The individual-based approach enables more abstract models to be extended to represent particular cases in different fields. So a conceptual model of residential choice could be extended to represent hunter-gatherers on the landscape, or people living in early towns, but also global processes of immigration.

5 Conclusion: Remarks on the general usability of ABM for exploring the past

Systems modeling can be applied in cases where generalizations are relevant. When exploring an individual biography, or a narrative with no regularities, ABM practices might not contribute. But ABM can be applied when two levels of analysis – such as individuals and social groups – are included in the research. Navigating between these is quite intuitive in everyday life, for example when talking about individuals and their stories we tend to see them as unique, but when considering a person’s social role we classify and generalize.

Because of its more general level of usage, ABM’s potential use in humanities might have similarities with prosopography, the study of common features in historical social groups, as it is not in a constant search for the exceptional and unique.

In archaeology, ABM, among other modeling techniques, has seen considerable success. This may be explained by the discipline’s close relation to natural sciences and the pattern-like nature of archaeological data. It is also relevant that the data collection procedure used in excavation is a quantitative process. The archaeological record is organized by units of different scale like region, site, archaeological context, and artifact. The essential element of archaeology, the dating of items and contexts, traditionally uses the stratigraphical method borrowed from geology and has developed its own statistical methods, from seriation (introduced by Petrie) to radiocarbon dating interpreted through Bayesian statistics.

This indicates that a successful ABM project depends on proven formal frameworks and sufficient amounts of quantitative data, collected in a systematic fashion, so as to serve as a proxy for studied phenomena. Additionally, the observed sociocultural processes must be of sufficient scale to generate regularities that can be isolated from chaotic or unobservable randomness.

References


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