Modelling Prehistoric Mining

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Abstract: Mining structures are among the most complex economic systems in prehistory. Until recently, research into prehistoric production processes has strongly focused on technological reconstruction. The complexity of production processes, their interconnectedness with the surrounding socioeconomic network and issues of quantification have, quite regrettably, been addressed to a much lesser extent. Simulation can contribute important insights into the latter problem areas, however, the lack of consistent methodological discussion on data collection, model building and comparability of results still represents a significant gap in research, which we address in our work.

Keywords: Archaeology, Prehistoric Mining, Agent-Based Simulation, System Dynamics, Process Simulation.

1. INTRODUCTION

Mining areas are not only characterized as centres of production, but also as centres of consumption - yielding high demands with respect to workforce, means of production (mining tools, raw materials) and means of consumption (e.g. food, clothing). The necessity of expert knowledge, intra- and superregional communication, traffic and trade networks further adds to the complexity. All these interdependent conditions demand an analytic approach combining different levels of observation, both spatially and in context of the model used.

We argue that a consistent and methodical analysis of prehistoric mining structures can best be done by the combination of several different simulation techniques in connection with a multidisciplinary database drawing on experimental archaeology, ethnography and historical records. This combinational method, which we will demonstrate by using data gained through the modelling of the Bronze Age salt mining complex of Hallstatt/Austria (1458-1245 BC), lies at the core of our efforts.

In more detail, our contribution is broken down into the following parts:

First, we give a background over *previous uses of simulation* in the field of archaeological research, listing formalization efforts targeted at ensuring comparability of the models used (see “Related work”, Section 2).

We further deal in some length with *experimental archaeology* and *ethnographic analogy*, which are methods of data collection specifically suited for dealing with data gaps, which are omnipresent in the archaeological record (see “Data Collection”, Section 3).

We then proceed to the archaeological basis concerning prehistoric mining in Hallstatt, looking specifically at input data and research questions that are to be answered by applying simulation (see “Archaeological background”, Section 4).

We then report on the types of simulation models that have been used so far (see “Simulating prehistoric mining”, Section 5).

2. RELATED WORK

The idea of using computer simulations in archaeological research has been around for nearly half a century. The 1970s saw considerable enthusiasm which was then thwarted by the limitations of contemporaneous computer technology and the lack of a sufficiently sophisticated theoretical framework. The developments in computer technology and scientific theory (complex systems theory) in the 1990s have given the application of computer-based modelling to archaeological research a considerable new boost (Kohler and van der Leeuw 2007, pp.1-12; Costopoulos, Lake and Gupta 2010). Especially Agent-based Modelling (ABM) has been popular with the scientific community since the late 1990s. It has been applied to a multitude of research topics, from the development of social complexity, decision-making, culture change, and spatial processes (Doran et al. 1994; Dean at al. 2000; Bentley and Maschner 2003; Beekman and Baden 2005; Premo 2006; Clark and Hagmeister 2006) to the exploration of civil violence in the Roman World (Graham 2009) and the work flow analysis in prehistoric mines (Kowarik et al.

2010). What makes ABM especially attractive to archaeology is its potential to model social phenomena on a very advanced level. The bottom-up approach inherent to ABM enables researchers to address individual actions and emergence, thus truly dealing with the complex behaviour of social systems (Premo et al. 2005).

Other simulation approaches, such as System Dynamics (SD), are not as widely used in recent archaeological research: Although having been successfully employed in a wide area of fields (e.g. economics, effects of climate change, complexity research), archaeology has not taken much note of it. This might seem surprising, as economy, collaborative structured action and complexity all represent important issues in archaeological research. The explanation might be found in the fact that SD deals in a more static and deterministic way with systems and system behaviour. Such an approach to social systems is viewed by many archaeologists today with a certain amount of suspicion. Much of the shortcomings of archaeological modelling projects in the 1970s are attributed to its static and schematic view of social systems rooted in classical systems theory (Costopoulos, Lake and Gupta 2010). Although we do share the criticism pertaining to the classical systems theory approaches, we also take into account that SD modelling provides us with an additional perspective on systems and system behaviour. If applied carefully, in the theoretical framework of complex systems theory, it adds analytical levels and categories not provided through ABM.

Apart from employing different types of simulations, we also argue that models and results need to be described in a formalized manner, in order to be scrutinized and understood by the scientific community. We employ the so-called ODD protocol, developed by Grimm et al (2006), for the description of agent based models (especially in the field of ecology). According to its authors, “the basic idea of the protocol is always to structure the information about an IBM (sic!) in the same sequence” (Grimm et al. 2006, p.117). The protocol describes the model structure in the three blocks: Overview, Design concepts and Details (ODD). The intention is to make the presented models quickly understandable and reproducible for independent testing. In its main outlines we consider this protocol also well suited for the description of our System Dynamics simulation.

3. DATA COLLECTION

It has already been stressed that computer based modelling offers considerable benefits for archaeological research, as it enables archaeologists to deal with social complexity, and (in the case of ABM), even allows us “to grow artificial societies” and use them as “cultural laboratories” (Premo et al. 2005).

However, the very nature of archaeological sources presents us with a specific problem – considerable data gaps: Archaeology deals with the material remains of past cultures. These materials have not been preserved in a representative manner. Organic materials, such as wood, bast, fur, textiles etc. made up far more than 90% of prehistoric material culture. The chances that these materials are preserved for several thousand years are slim in contrast to objects made of stone, metal or ceramic. Accordingly the percentage of organic objects in the archaeological record is small, the bulk of it being made up by stone, metal and ceramic objects. Even at sites such as the Hallstatt salt mines or the Swiss and German lake side dwellings, which yield far better preservation conditions, we have to deal with the problem that what is excavated is not a representative sample of prehistoric material culture, but an assemblage that has undergone numerous selection and filtering processes. More aggravating archaeology mainly (although not exclusively) deals with the remains of non-literate societies. This means that no texts inform us about beliefs and ideas of prehistoric cultures.

The mentioned problems become especially pressing when working with computer based models, as data gaps cannot be simply ignored, but need to be filled. We argue that experimental archaeology and ethnographic analogy present two approaches well adapted to answer this problem:

Experimental archaeology is a method that attempts to build and test models by way of experiments (Richter 1994: 12). But it represents “a particular type of experimentation” (Outram 2008, p. 2). The special approach of experimental archaeology consists in testing hypotheses not under laboratory conditions but, in environmental contexts that aim to reflect “historical” conditions. “Such experiments investigate activities that might have happened in the past using the methods and materials that would actually have been available” (Outram 2008, p. 2). This approach has mainly been applied to investigate prehistoric technology (e.g. copper smelting, bronze casting, textile production, construction works) and site formation processes (e.g. monitoring the remains of a burnt house over 10-20 years).

For our simulation work, data obtained through experimental archaeology acts as input data (e.g. time taken to perform mining, salt output produced).

Ethnographic analogies are used to compare two phenomena, a *source* of which detailed information is known and a *subject* in which important information is lacking (Bernbeck 1997, pp. 85-86). The approach is founded on the assumption that “after having assessed similarities and differences further similarities can be inferred” (Bernbeck 1997, p. 86, translation K. Kowarik). Usually archaeology takes its “source” from ethnographic and historical studies. The method has been applied to diverse areas of archaeological research, ranging from technology to economy to belief systems.

Our work mainly uses Experimental Archaeology, but shows considerable potential for the integration of ethnographic and historic data sets. The combination of both presented methods for data collection is especially beneficial in bridging data gaps, however, it also raises significant problems with regards to comparability of results. Therefore, we have invested additional effort in detailing our data collection strategies.

4. ARCHAEOLOGICAL BACKGROUND

The prehistoric salt mines of Hallstatt are located in southern part of Upper Austria in the alpine Dachstein region. The mining areas as well as the famous Early Iron age cemetery lie 400 m above the historical mining town of Hallstatt, in the *Salzberg Valley*. The topographic and geographic situation can be described as difficult to access and remote. The contemporaneous settlement areas were located about 30 km north and south to Hallstatt. In addition the climatic and geographic situation of the region are badly suited for agricultural activities.

The oldest salt mining activities are dated to the Middle Bronze Age. Dendrochronology fixes the Bronze Age mining phase to 1458-1245 BC (Grabner et al. 2006). The actual state of research indicates that three huge shafts systems (depths up to 170 m) operated in parallel (Barth, Neubauer 1991).

The enormous amount of archaeological finds and the perfect conditions of preservation in the mines due to the conserving faculties of salt allow for a reconstruction of the working process in the mining halls (Barth 1993/94, p. 28). All organic material left in the prehistoric mines has been conserved undamaged due to the preserving faculties of salt (mine timber, wooden tools, strings of grass and bast, hide, fur, textiles, human excrements etc.). This mine waste – also called heathen rock – was left in the mines and has been compressed to solid rock through mountain pressure.

The excavated archaeological material from the mines represents almost exclusively tools (e.g. pick handles, collecting tools, carrying buckets) and work assets (e.g. lightning chips, mine timber).

Three major areas of Bronze Age mining activity are known, vertical shaft systems can be reconstructed (see Fig. 1).

Salt was mined with bronze picks (see Fig. 2), producing small pieces of salt (chips), which were then collected with a scraper and trough (see Fig. 3) and filled into carrying buckets (see Fig. 4). These were then carried to the shaft and hoisted to the surface using a wool sack or cloth attached to a linden bast rope. It is assumed that salt was mined on several levels in one mining hall (see Fig. 5).

The data on mining technology and working processes is dense and of high quality. However important information is lacking as no settlement and no cemetery pertaining to the Bronze Age mining phase is known.

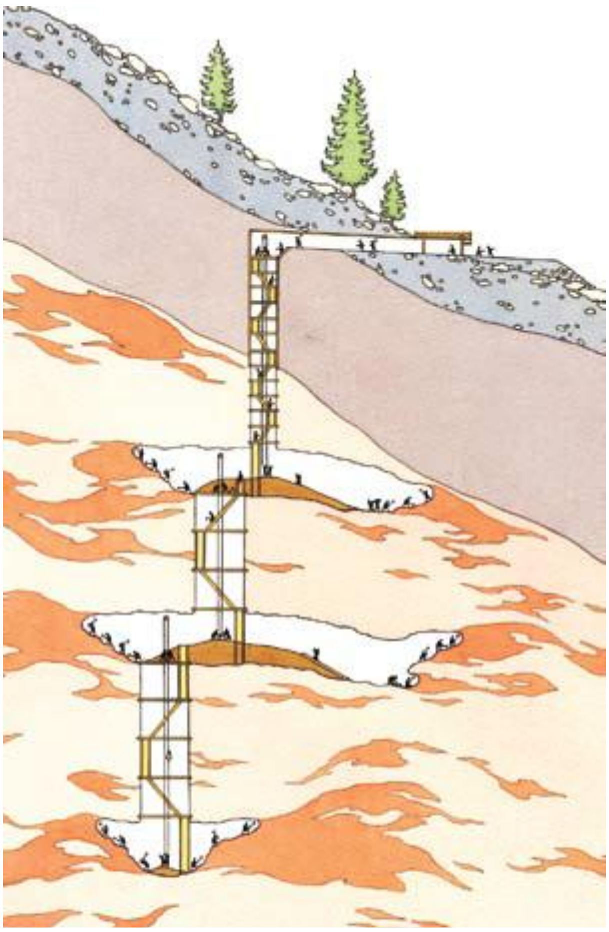

Fig. 1. Schematic view of the Bronze Age shaft system reconstructed on the basis of the excavations in the Christian v. Tuschwerk with implied salt distribution. (© D. Gröbner, H. Reschreiter/NHM Wien).

Fig. 2. Reconstructed Bronze Age pick. (© A. Rausch, NHM Wien).

Fig. 3. Salt collecting tools. (© A. Rausch, NHM Wien).

Fig. 4. Carrying sack: The special construction of this sack allows emptying it without having to put it down. (© A. Rausch, NHM Wien).

Fig. 5. Bronze Age mining hall as reconstructed for the Christian v. Tuschwerk. (© D. Gröbner, H. Reschreiter, NHM Wien).

4.2 Verbal model

The verbal model conceptualizing the salt mining structure is highly detailed and complex:

- salt mining was organized in an efficient and near industrial manner (Barth 1998)
- large production volume
- high demands concerning workforce and working materials (quantity and quality) (Kowarik 2009)
- workforce with specialized knowledge with respect to mining technology, but also infrastructural processes, forest utilization, wood technology
- the working process in the mining halls was specifically designed to avoid stops in the production process (Barth 1992)
- highly segmented working process (Barth 1992)
- non-seasonal: considering the size and complexity of the mining structure as well as the technical requirements of mining salt in such depths (Stöllner 2003, p. 420) it is assumed that mining wasn't seasonal but took place during the entire year or at least presupposed the permanent presence of a small working unit.

A large body of evidence underpins this theoretical framework:

- the size of the mining areas
- the enormous amount of prehistoric artefacts found in the mines
- the high degree of standardization observable on certain groups of tools (e. g. pick shafts, Fig. 2) (Barth 1967, 1973)
- highly functional groups of tools and other work assets (e. G. carrying sack, stair case, Figs. 4, 6) (Barth 1992; Reschreiter, Barth 2005)
- highly specialized groups of tools (i. e. salt collecting tools, carrying sack, see Figs. 3-4) (Barth 1992; Reschreiter, Barth 2005)

Fig. 6. Oldest wooden staircase, dated to 1343 BC. The construction allows for adapting the inclination of the staircase to every angle needed. Broken steps can be replaced easily. (© A. Rausch, NHM Wien).

Furthermore: Several important hypotheses on Bronze Age mining are derived from the results of the anthropological investigations of the Early Iron Age cemetery (9^{th}-4^{th} cent. BC) in the *Salzberg Valley*. These represent analogic inferences.

The anthropological analysis of the musculoskeletal markers of the excavated skeletons indicates a high workload and specialization on a rather limited range of movements that were iterated over a time span of many years (Pany 2005). The reconstructed movement patterns fit in well with activities related to mining such as breaking salt with a pick and carrying heavy loads. Gender related work division was clearly practiced (Pany 2005). Working patterns observed in all studied samples[1] rather exclude work tasks related to agricultural activities (Pany 2005).

The anthropological analysis has shown that the age and gender structure of the cemetery correlate with age and gender distributions of a "normal village" (Pany 2005).

This has leads us to infer several hypotheses for the organization of the Bronze Age working process:

- Bronze Age miners were working "fulltime" in the mine.
- All members of the mining community were involved in the mining process.
- Consequently other groups had to provide them with means of subsistence (food, clothing).
- The mining community was living in the *Salzberg Valley* next to the mines.

4.3 Research questions

Until recently, research into prehistoric production has strongly focused on the technological reconstruction of the production process. The complexity of production structures and especially their interaction with the natural and socioeconomic surroundings has been addressed to a much lesser extent. One essential aspect in assessing the dependency of production structures on their surroundings as well as their impact on them is quantification (Kowarik et al. 2010), e.g.:

What were the demands concerning workforce, means of production and subsistence?

How many people had to be supplied with means of production and subsistence?

Were the local resources sufficient?

Addressing these questions is essential to the understanding of the prehistoric salt mines. But we are lacking essential information:

The actual amount of mined salt is unknown.

The size of the mining community is unknown, as no cemetery or settlement relating to the Bronze Age salt mines has been discovered up until now.

5. SIMULATING PREHISTORIC MINING

In the course of our research, simulation tools allowing for extensive exploratory work with the existent archaeological model have been created. They offer us important insights into the problem areas mentioned under section 4.3. We argue that the analysis of prehistoric social systems requires the *combination of several simulation techniques*, in order to broaden the scope of the analysis. For example, we have used Agent-Based Simulation to build a model of the working processes in one mining hall (breaking salt, collecting salt, transporting salt to the shaft), in order to gain insights into spatial organization, allocation of tasks and workload balance and to relate the time span of mining to the size of the workforce and the amount of mined salt. A System Dynamics Simulation was applied to correlate the size of the workforce (population dynamics) with food consumption and demand for mining tools. Through Process Simulation, we were able to display and analyze the workflow of an entire shaft system encompassing several mining halls.

5.1 Agent-Based Simulation

An agent-based simulation (see Fig. 7) based on Netlogo (Tisue and Wilensky 2004) was used to simulate the working process in one Bronze Age mining hall. Targeted questions were: (1.) Salt output (amount of

[1] 215 skeletons were available for the anthropological analysis, due to the state of conservation 99 adult skeletons were available for musculoskeletal analysis (Pany 2005). This represents a small proportion of the entire cemetery, with a minimum of approx. 1500 graves. Musculoskeletal analysis of 40 subadult skeletons gives clear indications that children carried out hard physical labour (Pany-Kucera et al. 2010).

mined salt), as given by the underlying distribution of salt in the mining hall, the size of the mining community and the shape of the mining hall being worked on (2.) Coordination of different work tasks between the involved roles (workers breaking salt, transporters carrying salt).

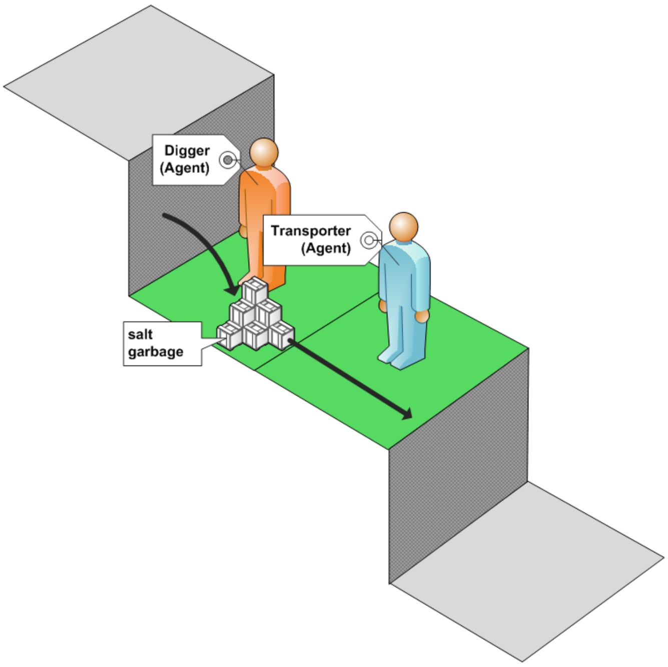

Fig. 7. Concept of the ABM of Hallstatt: Salt is produced on multiple levels, in a stair-like setup. Simulated agents perform actions according to their role (digger, transporter).

The reason for employing an ABM rather than performing hand-calculation (i.e. "time needed per m³ of mined material") was that the salt distribution is varying over the simulated area. The distribution is known (salt bands progressing vertically through the mountain) and can easily be imported into the simulation's discretized cell space. Furthermore, the division of work load between different process roles presented a challenging topic that is easily expressed within the simulation. As a further benefit, the formalization needed for the simulation narrowed down the rather large body of evidence to the subset relevant for answering on the previously presented problems (see "Research questions", Section 4.3).

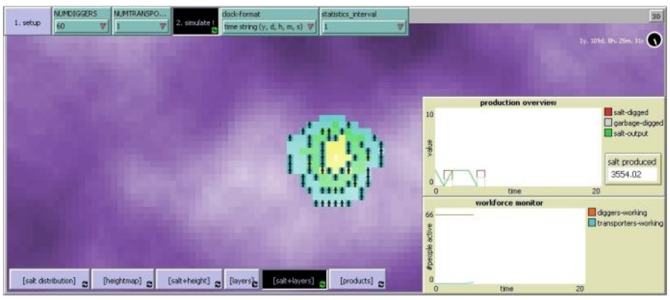

Fig. 8. Hallstatt salt mining simulation.

The main results of the ABM model (see Fig. 8) are:

The most important resulted from model building: The role of the transporters in the working process is nearly negligible, since the time necessary to mine a sufficient amount of salt for transportation largely exceeds the time necessary to transport the salt to the shaft (see Fig. 9). Thus our model of the working process (transporting is taking place *in parallel to* breaking the salt) must be reconsidered. The initial model of the workforce structure as being specialized down to the level of the individual work tasks (distinct groups of miners and transporters) must therefore also undergo scrutiny – it would be possible that there is no separate group of transporters altogether.

In quantification terms: we could show that the number of people actively working in the mining hall might have been smaller than initially assumed. Furthermore, the time it takes to fully exploit the given area severely underruns the timespan the mining hall was in use (213 years). For example a workforce of 26 (25 agents breaking salt, 1 transporter) took 23 years of uninterrupted work in a hall of 40x100x10 m to exhaust the salt deposit. Applying the work performance model (see "Comment on data collection and model building", section 5.5.1) this would mean 120 years in real time. One possible explanation is that the mine, after being fully exploited, served as hub space and/or storage for other mining halls, and therefore was being maintained.

5.2 Formalization of Agent-Based Mining Model

Overview

Purpose: The model simulates the Bronze Age working process in one mining hall: breaking salt, collecting salt, transporting salt to the shaft (the transport through the shaft to the surface is not part of the model). The model has two purposes 1) test the following hypotheses: a) large work force needed to exploit a mining hall of the dimensions 40 m x100 m, height 6 m to 19 m. b) time needed to exploit the given mining hall is close to 213 years. c) working process: working tasks are carried out in parallel (breaking salt, transporting salt).

2) Quantify: a) size of the workforce and b) the time needed to exploit one mining hall c) the most efficient miner/transporter ratio.

3) Gain insight into spatial organization: a) identify "bottle neck" scenarios.

State Variables and Scale (Low-Level):

Miner (Agent):

state machine (precompiled, *find mining spot*, *mine*)

assigned mining spot (single spot per agent) **-** chooses cell with highest salt concentration available and closest proximity to initial mining area

Transporter (Agent):

state machine (precompiled, *wait for material, transport*)

amount of salt transported (in m^3 < capacity of carrying bucket)

transports salt from the mining spot to the shaft

Cell: $1m^2$ area, 2m high

purity: (initial) percentage of salt at this spot, varies per spot (up to 70%, as given by salt distribution map, created statistically using cloud rendering algorithms)

highest elevation mined: the topmost layer of salt that has been mined

amount of mined salt being available at this spot (in m^3)

amount of rock lying at this spot, i.e. impure material not being usable as salt (in m^3)

agent having reserved this spot (max. one agent per spot)

State Variables and Scale (High-Level):

amount of agents standing by/being idle

mined volume of salt (m^3)

mined volume of unusable rock (m^3)

time (in s, a scheduler is employed on top of ABM, time horizon is 213 years, 1458-1245 BC)

Process Overview and Scheduling:

Miner (repeatedly):

if idle, find a new mining spot (select by percentage of salt followed by proximity from entry area)

until spot is fully mined: produce salt volume that fills one bucket (as a whole, using scheduler), then fire signal that salt is ready

Transporter (repeatedly):

wait for signal salt ready

obtain salt (schedule travel to spot, bucket filling end, travel to shaft, filling of vertical transport end)

Design Concepts:

Sensing: Sensing of percentage of salt present in a block of salt, as given through experience of miners (being realistic).

Stochasticity: Dependency on salt distribution map, which is generated by using cloud algorithm with mean/max distribution of salt.

Initialization:

Salt distribution is loaded, initial entry area is created (corresponds to shaft). Miners and transporters are put into the world

Simulation period: middle to late Bronze Age, 1458-1245 BC, 213 years

Environment: underground salt deposit of a surface of 40m x 100m, made up of cells with 1 m2 and 2 m of height

Time per work step: Digging performance using a bronze age tool (0.0000034 m^3/s), walking speed while carrying a sack of 20l on even ground (1.03 m/s,), filling speed (0.001323 m^3/s)

Height of layer being mined by one agent (2 m)

Amount of layers being mined (3-9)

Capacity of carrying bucket (0.02 m^3 of salt)

Decompression: As material is broken out of the mountain, it decompresses and increases in volume (in our case: 170%).

Submodels

No sub-models

5.2.1 Comment on data collection and model building

Work performance

Quantification was provided through Experimental Archaeology. The three work steps: a) breaking salt, b) collecting salt and c) transporting were reconstituted. Targeted data: digging performance m^3/s, filling speed m^3/s, walking speed with carrying bucket of 20 l on even ground m/s.

The work steps were carried out in the Hallstatt salt mines with reconstitutions of the original tools. The tools were reconstructed on a 1:1 scale with the authentic materials and had been tested during excavation over several years: a) bronze pick with wooden shaft b) scraper and filling trough and c) carrying bucket. (The experiments were carried out in the salt mine (breaking was carried out on the typical mixture of rock salt and gypsum in the Hallstatt salt mine) by experimentators experienced in handling these tools. Time and volume was measured, the experimentation recorded in writing and picture. Future work: large scale reruns of the experiments, ethnographic data collection on work performance.

Measured Data Item	Value	Unit
Digging with a Bronze Age Tool	4,2 l / 20 min	
Filling a Carrying Sack of capacity=20 l in height=1,7m	60 s 57 s 56 s	
Walking with a filled Carrying Sack of 20 l on a Plane	9,5 s / 10 m 9,9 s / 10 m 9,6 s / 10 m	
Fill into Lift	10,5 s / 15 l 13,3 s / 15 l 10,3 s / 15 l	

Fig. 9. Quantification of working process.

Time

The time model underlying this simulation is not based on real time, i.e. the agents are working 24 hours every day. This is, they do not stop for recreation, sleep etc. Thus in order to relate the model output to actual historical conditions for the discussion of results the time spans given by the model need to "calibrated" with a real time model (see "Comment on data collection and model building", Section 5.5.1).

Gender

The modelling of the working process is not gender specific. As the archaeological record for the Bronze Age salt mines does not provide us with enough information on female/male work division. Future work: ethnographic and historic data collection on gender related work division in mining areas, analogical use of work division patterns recorded in the Iron Age cemetery (Pany 2005).

5.3 Discussion of Agent-Based Mining Model and its Results

Coming to the results (see Fig. 10), we can see an almost linear case of exploitation time (y axis) versus workers employed (x axis) for 3 layers (blue line). However, the exploitation time deviates from linear when using 9 layers (red line) and more miners, because of space issues (agents hindering themselves in mining because they are standing in each other's way). The nonlinearity is even more effective when using a salt distribution which has abrupt changes – in this case, the geometry dictates the possibility to build stair-like levels, and hinders overall mining speed.

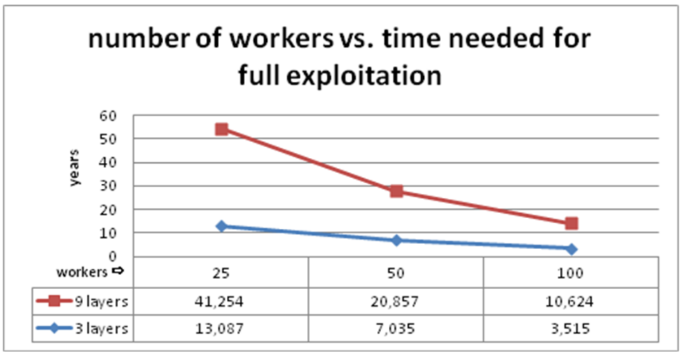

Fig. 10. Results showing performance for 9 layers (red) as well as three layers, for 5, 10, 25, 50 and 100 workers (only three classes shown). 50 Simulation runs were conducted per parameter variation.

5.4 System Dynamics Model

A System Dynamics simulation (see Fig. 11) was applied to perform a demographics simulation concerning the sustainability of the Bronze Age population in Hallstatt, with added computation over consumption of food and mining tools. The purpose of this model was to assess the extent of the "provisioning efforts" necessary for the Hallstatt mining community to sustain a stable production performance over at least 213 years. This question cannot be merely restricted to the consumption of food and tools by the miners: the question of resupplying the workforce must also be considered.

Basic assumptions of the model:

Workers were only or mainly recruited from the ranks of the mining community itself.

We assume as well that the miners were working full time in the mine (see "Archaeological background", Section 4).

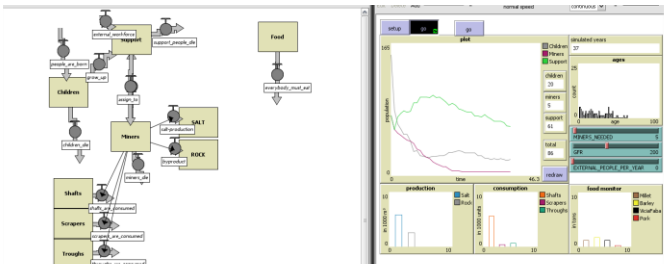

Fig. 11. Hallstatt system dynamics simulation.

Technically, the simulation performed is a hybrid – it is based on a SD that is linked in the background to an agent simulation, performing computation in the following manner: The system dynamics module in our simulation platform (NetLogo) performs computation at discrete time steps ("ticks" * *dt*), with each full tick representing a year's time span. There are three main stocks in the SD, "children", "support" and "miners", between which an exchange in profession (and in the background: demographic growth) happens, in the following manner:

We simulate the development of the population, beginning with adding births to the stock of children (flow *birth*⇒children) and at the same time creating agents of age 0 in the linked ABM. The birth rate is controlled by the general fertility rate.

The progression from the children stock to the stock containing people doing support work (i.e. juveniles, old people, people for whom there is currently no employment in the mines) is controlled by age (flow children⇒support). Furthermore, mortality is modelled by the flow children⇒*dead*, as specified by a mortality table among every age class (which is based on excavation data of the Early Bronze Age cemetery of Franzhausen: Berner 1992). In this case, the linked agent-based simulation removes the specified number of agents from the corresponding age class.

If needed, people in the support stock will be assigned to the miners stock, or released from the latter into support (flow support⇒miners). As always, mortality is also modeled by the flow support⇒*dead*, miners⇒*dead*.

Depending on age and occupation, the population requires food and mining tools. Therefore, we have computed the food and tool consumption of each stock (food required per age class, in kcal). As derived result, we can obtain the demand (in tons) of basic agricultural goods. Furthermore, through the number of people working in the mine, we can derive the number of mining tools, which can then be compared with the supply.

5.5 Formalization of System Dynamics Model

Overview

Purpose: Simulates demographics for sake of answering on sustainability of Hallstatt's population. The core is the computation of population, for which (in each year) also production and consumption are determined.

State Variables and Scale (Low-Level):

Agent (used to model aging, using linked ABM):

Age

Containing stock (used to connect SD with ABM)

Age class (used for mortality)

State Variables and Scale (High-Level):

Time (one simulation tick corresponds to one year, SD is computing in terms of fractions i.e. *dt*, ABM on full ticks)

Time horizon: middle to late Bronze Age, 1458-1245 BC, 213 years

Persons per stock (children, miners, support)

Production (m^3 salt, m^3 rock) and consumption (miners: shafts, scrapers, troughs, mining community: needed kcal)

Process Overview and Scheduling:

Initialization (once):

Clears the ABM, eliminating all agents, insert the preset initial population into SD and ABM.

Simulate a year (repeatedly):

Simulate progression of population over the existing stocks (*birth* ⇒ children ⇒ support ⇒ miners ⇒ support, or ⇒ death from each stock).

Simulate the production and consumption with reference to occupation (i.e. only miners need tools) and age class (i.e. mining community: kcal per age)

Details:

Initialization

Production: in m^3 per miner per year (8.1434 m^3 salt, 3.49003 m^3 rock).

Consumption: in items per miner per year (7.7944 shafts, 0.4653 scrapers, 0.81434 troughs), food in kcal per person per year, according to age based on Klever-Schubert, Endres 2009, pp. 10, 14-15 (in format [from to kcal]): [0-1]: 700 kcal, [1-3]: 1050 kcal, [4-6]: 1450 kcal, [7-9]: 1800 kcal, [10-12]: 2150 kcal, [13-14]: 2450 kcal, [15-18]: 3936 kcal, [19-24]: 3852 kcal, [25-50]: 3696 kcal, [51-64]: 3420 kcal, [65-100]: 3096 kcal. The calorie consumption is converted in a diet model: millet (3120 kcal/kg, 27%), barley (3387 kcal/kg, 41%), vicia faba (3384 kcal/kg, 27%), pork (3760 kcal/kg, 5%). The ratio is based on Bertieri 2009 and the calorie content Ebersbach 2002: CD-Rom, Tab. 1, except vicia faba, calorie content according to A. Heiss (personal communication).

General Fertility Rate: The number of live births during the year per 1,000 female population between 15-49 years (WHO).

Mortality Rate according to age classes, in percent. Data was taken from the Bronze cemetery of Franzhausen (Lower Austria) (Berner 1992, 42 Tab. 8: with corrected ratios for infant mortality) but corrected to set the mortality to 100% from age 75 onwards. The mortality table is given here (in the format [from age - to age]: mortality): [0-4]: 58%, [5-9]: 17%, [10-14]: 11%, [15-19]: 12%, [20-24]: 19%, [25-29]: 19%, [30-34]: 21%, [35-39]: 28%, [40-44]: 33%, [45-49]: 29%, [50-54]: 33%, [55-59]: 50%, [60-64]: 38%, [65-69]: 60%, [70-74]: 50%, over 75: 100%

Age classes per occupation: [0-5]: child class: do not work, [6-74%]: support class: work, [14-50]: miner class: can work in the mine.

Initial population: 300 people, divided in: 50% children, 25% support, 25% miners.

Age distribution for immigrants: assumed to be between 10 and 16 (uniform distribution).

Amount of miners needed: the number of people employed in mine.

Immigration per year: assumed external workforce entering the support class.

Submodels

No submodels.

5.5.1 Comment on data collection and model building

Population dynamics

Our SD represents a very simple model that does not take e.g. sicknesses and violent conflicts directly into account. The female/male ratio of the initial population is set to 1:1 as simplifying assumption. Future work: using mortality rates from other prehistoric populations (different environmental and chronological settings), mortality rates of historic cemeteries.

Age classes per occupation

Start of working life set to 6 years: based on analysis of the musculoskeletal marker of children in the Early Iron Age Hallstatt cemetery (Pany 2010).

14-50 years: work in the mine, this age class was chosen based on biological assumptions (physical ability to sustain long-term heavy work load). Future work: ethnographic and historic data collection on age related occupation classes in mining areas, anthropological investigation in age related occupation patterns of the Early Iron Age cemetery (Hallstatt) (cf. Pany 2010).

Mortality is set to 100% from age 75 onwards based on Pany 2005.

Gender and occupation

Gender related division of work tasks is not integrated in our SD as archaeological data for the Bronze Age mining phase is lacking. Future work: ethnographic and historic data collection on gender related work division in mining areas, analogical use of work division patterns recorded in the Iron Age cemetery (Pany 2005).

Time

In contrast to the ABM our SD is based on real time. We use a model that assumes that one hour of physical work given by the ABM had to be translated in two hours of real time. This is based on the work experience of modern day miners in the Hallstatt salt mines. Furthermore we assume daily 10 hour shifts and 3 free days per month. The last two points represent simple assumptions. Future work: ethnographic and historic data collection on work performance and leisure time in mining areas.

Production

Time measurements for breaking, collecting and transporting salt are taken from data set generated for the ABM.

Food consumption

Calorie requirements are related to age class based on modern data (Klever-Schubert, Endres 2010). Food in kcal per person per year, according to age, gender is not specified. Values were calculated as arithmetic means of male/female requirements based on Klever-Schubert, Endres 2010, pp. 15: [0-1]: 700 kcal, [1-3]: 1050 kcal, [4-6]: 1450 kcal, [7-9]: 1800 kcal, [10-12]: 2150 kcal. Furthermore, the consumption in age class 0-1 is assumed as 700 kcal, because the increased consumption for nursing mothers is omitted. And for the following age classes values were calculated as arithmetic means of male/female requirements and multiplied with a factor of 2.4 for heavy physical work based on Klever-Schubert, Endres 2010, pp. 10, 14: [13-14]: 2450 kcal, [15-18]: 3936 kcal, [19-24]: 3852 kcal, [25-50]: 3696 kcal, [51-64]: 3420 kcal, [65-100]: 3096 kcal. The values used per age class are (in format [from to kcal]): [0-1]: 700 kcal, [1-3]: 1050 kcal, [4-6]: 1450 kcal, [7-9]: 1800 kcal, [10-12]: 2150 kcal, [13-14]: 2450 kcal, [15-18]: 3936 kcal, [19-24]: 3852 kcal, [25-50]: 3696 kcal, [51-64]: 3420 kcal, [65-100]: 3096 kcal. We converted these requirements into a diet composed of millet (27%), barley (41%), vicia faba (27%), pork (5%). The ratio is taken from Bertieri 2009. The calorie values are based on millet (3120 kcal), barley (Hordeum vulgare) (3387 kcal), vicia faba (3384 kcal), pork (3760 kcal). The calorie content is based on Ebersbach 2002, CD-Rom, Tab. 1, vicia faba: calorie content according to A. Heiss (personal communication).

Based on the large amount of organic findings (i.e. excrements) in the Hallstatt mines it can be assumed that these food stuffs represented the largest part of the mining community's daily diet (Barth 1999). This overly simple diet model could be extended to a more elaborate form of diet computation. Future work: ethnographic and historic data collection on calorie requirements and diet composition in large scale production structures (e.g. mining, construction work).

Tool consumption

The calculation of tool consumption per m^3 is based on the excavation data of the prehistoric mining area in the modern day Christian v. Tuschwerk. (With one exception: carrying buckets are only known from the prehistoric areas in the modern day mining districts Grünerwerk and Appoldwerk not from the Christian v. Tuschwerk). 50 m^2 have been excavated, approximately

300 shafts (2008: 155 complete shaft heads and 285 halves of shaft heads), 17 scrapers and 30 troughs have been found. The archaeological record indicates that the most likely dimension for the height of the mining hall is 10 m, giving us a volume of 500 m^3. Site formation process in this area is well known and allows for the assumption that all mining tools were left in the mine and didn't undergo reuse or destruction, thus we can assume that we are in possession of the full material inventory. (Site formation processes in the Early Iron Age mining districts show fundamentally different dynamics with large scale reuse and destruction (burning) of objects!)

Consequently we calculate a consumption of 0.6 shafts, 0.03 scrapers and 0.06 troughs per m^3 of mined rock, i.e. in the course of mining 1 m^3 of rock 0.6 shafts, 0.03 scrapers and 0.06 troughs were broken ("consumed") and left as waste in the mine.

5.6 Discussion of the System Dynamics Model and Results

Coming to the results (see Figs. 12-13), we have tried to answer the question of how high the General Fertility Rate (GFR) would need to be to sustain a population fit to provide a fixed set of miners. Simulation runs were conducted for GFR range from 200 to 425, 50 experiments per parameter variation. Our results show that the population can sustain itself beginning at GFR 375, meaning that (roughly) every women (15-49 years) needs to have a child every 2.5 years. The initial population of 300, however, is reached only if increasing the GFR to 405. This is relatively arbitrary, because the simulation stops after the preset time span of 213 years, but the population would still grow (exponentially). Clearly, a GFR of 405 would represent an extreme case that may be hard to justify (e.g. because of the capacity of the surrounding environment for maintaining a big population). Clearly, more research would be needed in this context.

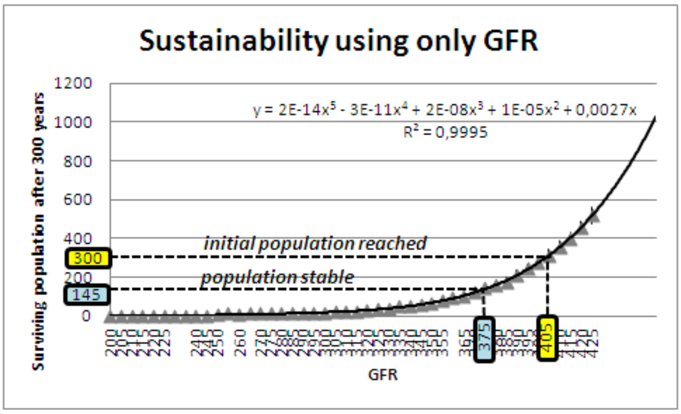

Fig. 12. Results showing that sustainability of population would begin at General Fertility Rate of 375.

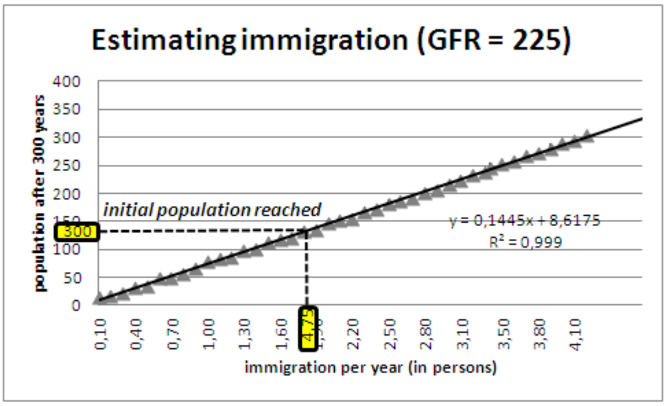

Fig. 13. Results showing linear effect of immigration on population (General Fertility Rate assumed as 225).

Another result of the simulation is a probable likeliness of immigration: Using a GFR of 225 (fixed), probable immigrants per year were simulated (range 0,1 to 4,1 immigrants per year, 50 repetitions per parameter variation). Even for the smallest value (0.1 immigrants per year meaning 1 immigrant in 10 years), the population could sustain itself on a low level. The reason for this lies in the age structure of immigrants, who come as juveniles (aged 10-16) and have already passed the initially high mortality. They contribute both in terms of reproduction as well as workforce for the mine. After 213 years, the initial population is reached when 4,75 persons per year immigrate. However (and for the reasons discussed also in the GFR experiment), the population would constantly grow afterwards, which seems rather unrealistic. We have found that a value of 2 immigrants per year keep the population stable at around 150 persons, which (as the ABM suggests) could be fairly enough for up keeping mining operation for the whole time span under consideration.

5.7 Process Simulation and Visualization

Simulating mining as a business assumes that operation proceeds in a highly optimized manner. Because some of the tools that have been found exhibit a unusually flexibility and ergonomic design (e.g. salt buckets carried similar to a rucksack, which can be emptied single-handedly without taking them off), we have reason to believe that methods employed foremost in business simulation should also be transferred into research of prehistoric mining. Our preliminary efforts have so far focused on defining process chains for a whole mine – i.e. transfer of material into the different mining halls and delivery of products to the surface. The so-produced simulation (see Fig. 14) is rather a visualization of the whole process than a simulation answering on specific archaeological questions: It lacks typical aspects such as queuing for shared servers (which, in turn, have a finite amount of resources), process constructs such as forking and joining, a elaborate event handling mechanism, interruptions and exceptions, etc. The named constructs are easily implemented, however, the archaeological formalization still lags behind what is technically possible, and uncertainties when looking at the whole mine as system are still large. Therefore, a consolidation and scrutiny of existing knowledge has to be performed in order to conduct serious (future) work. Our preliminary process simulation in the sense of a visualization is, nevertheless, beneficial for discourse and understanding.

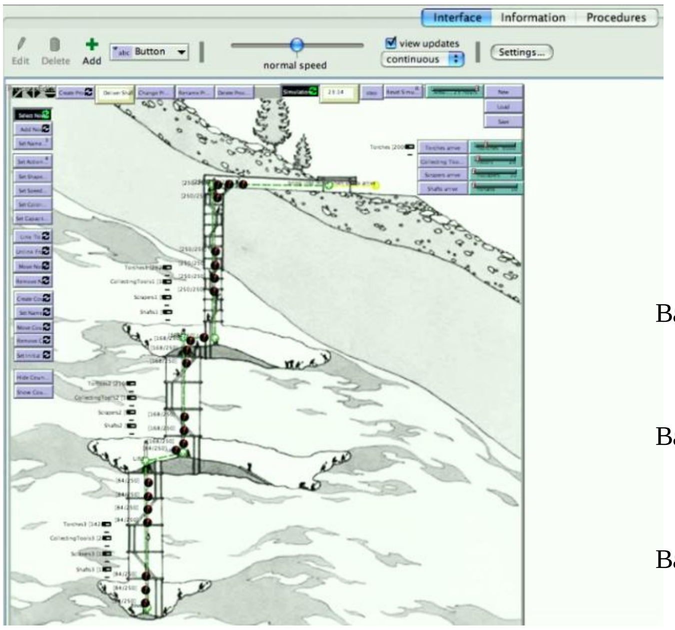

Fig. 14. Process simulation

6. Conclusion

Simulation can contribute important insights into archaeological research questions. For the prehistoric Hallstatt salt mines the contributions are located in two areas: 1) model building and 2) quantification.

1) A fundamental assumptions of the verbal model has to be reconsidered: the concept of working groups specialized on one step of the working process (breaking salt, transporting salt). This is not only of consequence for the actual verbal model but also for the method of model building. The most important arguments for the assumption of specialized working groups stem from the analogic use of data from the Early Iron Age cemetery. As has been detailed above other important hypotheses for the Bronze Age simulation rely on the same method. Thus future work will include a careful assessment of the Early Iron Age cemetery's validity as analogic source and consequently a revaluation of the actual verbal model.

It is important to stress two points here: 1) we do not question the existence of labour division, i.e. specialization, in prehistoric mining fundamentally. It is the scale of functional differentiation that we wish to reconsider! 2) We do not question the validity of the ethnographic analogy as a method for archaeological model building.

Combining different methods of data collection, especially experimental archaeology and ethnographic analogies, bears great potential as it allows to diversify data sources. Gaining data through different methods also allows for independent testing.

But in this context we wish to highlight an important task for future work: discussion on ways of formalizing and presenting underlying archaeological assumptions, methods of data collection and the process of model building. We suggest that the development of a protocol and a standardized visual representation is an important requirement in the effort to ensure comparability and reproducibility of results. This is especially valid for models relying on a multidisciplinary data basis.

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