Mining with Agents

Agent-based Modeling for the Bronze Age Salt Mine of Hallstatt (Upper Austria)

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Abstract: The existing archeological model of the Bronze Age salt mines in Hallstatt (Upper Austria) leaves some important questions open: What was the size of the mining area, how long did mining activities proceed, what was the amount of mined salt, how big was the size of the mining community. This is regrettable, since answers to these questions would provide important insights into the economic and social history of prehistoric Europe.

By using agent-based modeling (ABM), we have translated the body of theories conceptualizing the mining complex into a simulation. As a matter of fact, we could check the consistency of the existing archeological knowledge and obtain answers to the aforementioned questions using computation. We are convinced that our solution can be taken as powerful tool for the analysis of complex production as well as for explorative computation of working processes.

Keywords: Salt Mining, Bronze Age, Hallstatt, Economic Archeology, Agent-Based Simulation

Introduction

The actual body of theories conceptualizing the mining complex of Hallstatt is highly detailed and complex (see section *Agent-based modeling in archaeological science*). Up to now a tool permitting to explore the numerous possibilities of this concept was missing.

To test the existing verbal model and explore its alternative possibilities an agent-based model of the working processes in the mining halls has been built. Our tool allows for testing our theoretical framework under changing conditions (i.e. size of workforce, height of the mining halls).

It is in the nature of highly detailed and complex models that implicit, unquestioned assumptions develop and are built into the explanatory framework without systematic analysis. Building up a digital model will eventually highlight these assumptions and force one to question these rigorously. Our contributions to the field of computer-based archeology are thus:

- To build a multi-agent simulation based on the existing knowledge of the Bronze Age salt mines of Hallstatt, thereby creating a logical and computable program. In the course of the working process several problems had to be overcome:
    - Selection of data: The available information had to be reduced to data directly relevant for the analysis (see section: *Selection and collection of data*).
    - Collection of data: Missing relevant data had to be collected (see section: *Selection and collection of data*).

- To explore the verbal model exhaustively and in an explorative way, using in silico experiments. This lead to the questioning of certain implicit and untested assumptions (i. e.): We were able to show that exhausting the salt deposit of one mining hall took only a small percentage of the time and workforce that was initially supposed to be necessary (see section *Execution and Results* and *Discussion and Conclusion*).

- Our results represent one step towards building a systems emulation of the entire Bronze Age salt mining structure in Hallstatt. We see this as basis on which future work can build up (see section *Discussion and Conclusion*).

- Our simulation allows for experimenting with concepts of prehistoric production and working processes (chaîne operatoire) well beyond the borders of Hallstatt (see section *Discussion and Conclusion*).

Agent-based modeling in archaeological science

Agent-based simulation is one common method in the array of computer based modeling techniques that have been used by anthropological and archaeological science for more than a decade (ALTAWEEL 2006: 30-31).

ABM uses software objects, so called agents, that are able to perceive, on a limited scale, a virtual environment and interact with it (PREMO et al. 2005: 11). These agents can be given simple behavioral rules, depending on the research objective in question, that they will follow (GRAHAM / STEINER 2006: 50). On this basis they are able to make „independent" decisions (ALTATWEEL 2006: 30). It is possible to define a different set of behavioral rules for any single agent. Two main model types exist: Either a single agent is placed in a defined virtual environment and interacts with this environment (BRANTINHAM 2003; PREMO 2005, 2006). Or a number of agents (up to thousands or hundred thousands) respectively groups of agents interact with their environment and each other by this forming „ artificial societies"(KOHLER et al. 2000; PREMO 2005, 2006).

ABM allows for conceptualizing and analyzing interactions between human individuals and its environment as well as inter-human relations on an individual level.

> *Agent-based models of this type allow for insights into individual behaviors that create group level phenomena eventually observable by us in the archaeological record as artifact, household and settlement patterns* (GABLER 2006: 47).

ABM was introduced to archaeological and anthropological science in the early 1990s (ALTAWEEL 2006: 30). The method has since then been mainly applied to the behavioral analysis of complex systems focusing on how behavioral change in subsystems (households, individuals) might influence higher order systems (ALTAWEEL 2006: 31 with further literature). ABM has also been used for socio-economic research questions (ALTAWEEL 2006: 30). Lately ABM has been applied to a growing multitude of research topics, spanning from early hominid food sharing (Premo 2005, 2006) to analyzing Hohokam water management (MURPHY 2006)[1]. In addition there has been much discussion on how ABMs should be used for archaeological and anthropological research and the heuristic implications of the application of ABMs to archaeology and anthropology (CLARK /

HAGMEISTER 2006: 16-59; PREMO 2007). On the one hand the potential of ABM for hypothesis testing has been pointed out (i. e. GABLER 2006: 43; 47, PREMO et al. 2005).

> *Once encoded a computer model can do what our limited imaginations do not permit: follow the implications of our ideas to find where they lead and, often, where they are inconsistent* (PREMO 2005 et al.: 11).

On the other hand it has been proposed to use ABM as „cultural laboratory" exploring a multitude of alternative historical scenarios instead of aiming at building the one model matching best the archaeological record and being as realistic as possible (PREMO 2005 et al., 2007).

The present contribution is mainly concerned with hypothesis testing and exploring the possibilities of the actual existing verbal model.

The Bronze Age salt mining – theoretical framework

The actual state of knowledge concerning the Bronze Age salt mines in Hallstatt and the resulting theoretical framework will be shortly summarized in the following section:

Salt mining in Hallstatt is proved for the 15th century BC. The actual state of research indicates that three huge shafts (depths up to 170 m) operated in parallel (fig. 1) (BARTH 1986; BARTH / NEUBAUER 1991; RESCHREITER / KOWARIK 2008a).
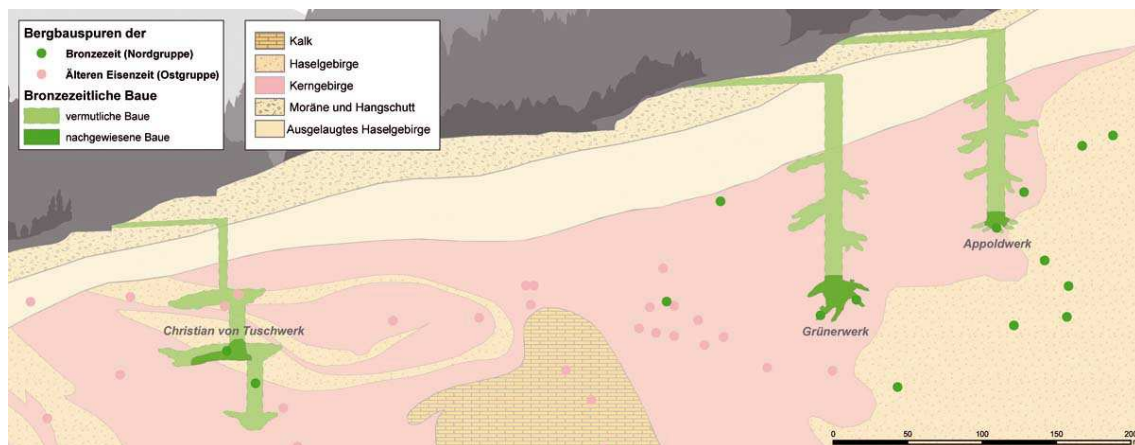

Fig. 1 - Schematic representation of the three known Bronze Age shaft systems (Appoldwerk, Grünerwerk und Christian v. Tuschwerk) (© K. Löcker/H. Reschreiter, NHM Wien).

The agent-based simulation is mainly based on the data stemming from the mining hall in the modern day Christian v. Tuschwerk where the actual archaeological excavations conducted by the Prehistoric Department of the NHM, Vienna, are carried out. Dendrochronological dating of all analyzable wood samples from this mining hall fixes the period of use to 1458-1245 BC (GRABNER et al. 2006; GRABNER et al. 2007). Shortly after 1245 the entire mining area was filled up with material from the surface (GRABNER et al. 2006). The hall in question was used over a time span of 213 years. This does not necessarily imply that the time span of the mining activities in this hall corresponds to 213 years. Archaeological evidence shows that above and underneath the discussed halls other mining halls connected by a shaft existed (fig. 2) (RESCHREITER / KOWARIK 2008a).
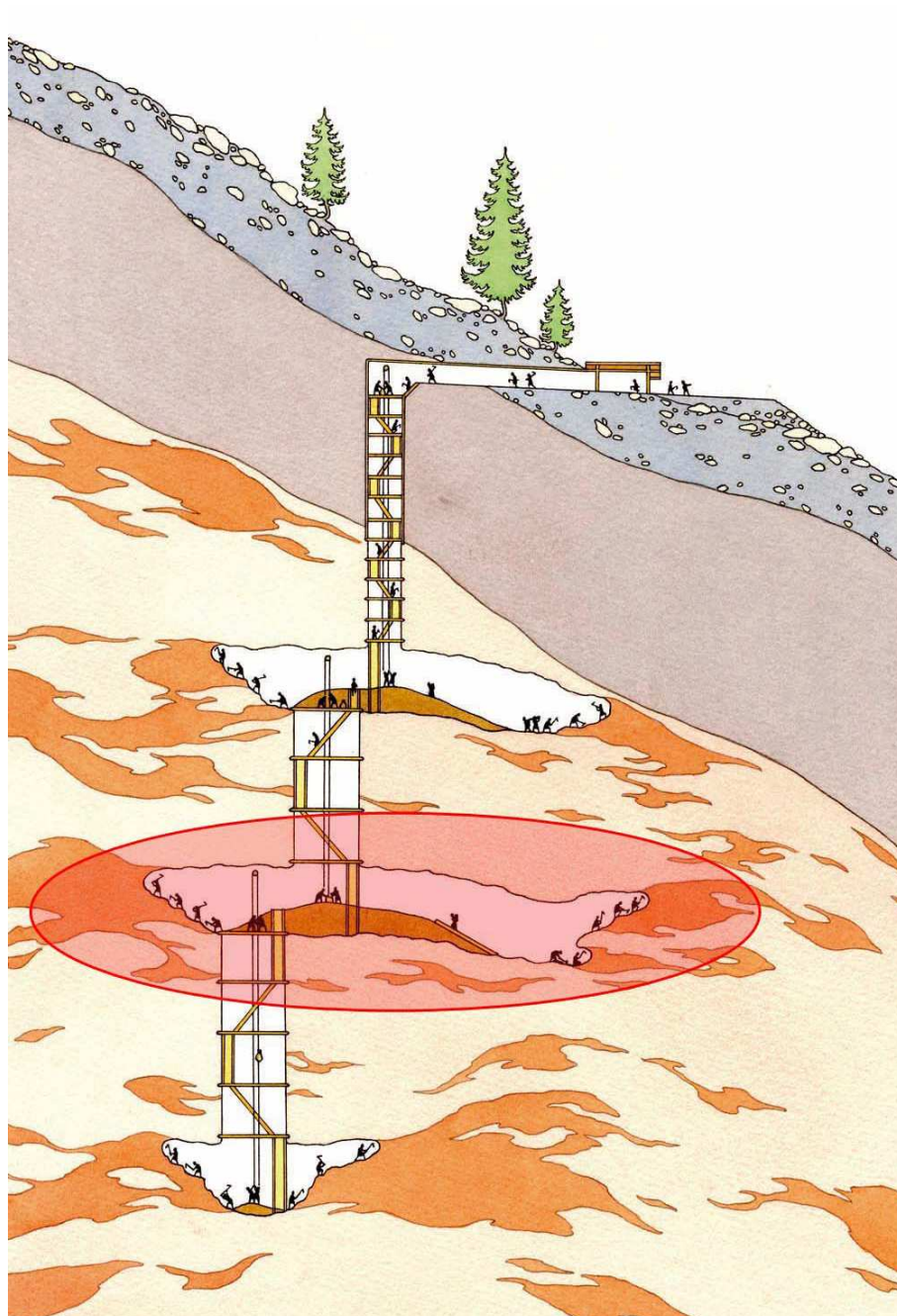
Fig. 2 - The Bronze Age shaft system in the modern day Christian v. Tuschwerk. The discussed mining hall is marked by circle (© D. Groebner/H. Reschreiter, NHM Wien).

The enormous amount of archaeological finds and the perfect state of preservation due to the conserving faculties of salt allow for a reconstruction of the working process in the mining halls spanning the breaking of the salt to transporting the salt through the shaft up to the surface[2] (BARTH 1993/94: 28; BARTH / LOBISSER 2002: 18; RESCHREITER / KOWARIK 2008a: 57).

It is estimated that the salt mining was organized in an efficient and near industrial manner with strongly optimized working and producing processes (fig. 3) (BARTH 1993/94, 1998; BARTH / LOBISSER 2002: 14; RESCHREITER / KOWARIK 2008a).

Fig. 3 - Visual representation of the actual archaeological model of the Bronze Age salt mining in Hallstatt (© D. Groebner/H. Reschreiter, NHM Wien).

A large body of evidence underpins this theory: 1, the enormous amount of prehistoric artifacts 2, the high degree of standardization observable on certain groups of tools (i. e. shafts, fig. 4) (BARTH 1967; BARTH 1973; RESCHREITER / KOWARIK 2008a)

Fig. 4 - Wooden shafts for the bronze picks from the Christian v. Tuschwerk (© A. Rausch, NHM Wien).

3, highly functional groups of tools and other work assets (i. e. carrying sack, stair case, fig. 5-6) (BARTH 1992; BARTH / RESCHREITER 2005; RESCHREITER / KOWARIK 2008a).

Fig. 5 - Carrying sack: The special construction of this sack allows emptying it without having to put it down (© A. Rausch, NHM Wien).

Fig. 6 - Wooden staircase, timber dated to 1344/1343 BC. The special construction of this staircase allows to adapt it to any inclination and broken steps can easily be replaced (© A. Rausch, NHM Wien).

4, highly specialized groups of tools and other work assets (i. e. *Schwinge, Kratze* (salt collecting tools), carrying sack, fig. 7) (BARTH 1992; BARTH / RESCHREITER 2005; RESCHREITER / BARTH 2005; RESCHREITER / KOWARIK 2008a).

Fig. 7 - Salt collecting tools. With these tools the salt was collected and filled into the carrying sack (© A. Rausch, NHM Wien).

Main Hypotheses:

- a working process specifically designed to avoid stops in the production process.
- division of labor (highly segmented working and production process)
  - It is assumed that for every work step a specialized group of workers was used (i. e. miners, transporters).
  - Based upon the special construction of the carrying sacks and the considerable width of the staircase it is assumed that many transporters were necessary to upkeep a continual working process.
- high demands concerning workforce and working materials (accordingly high infrastructural and logistical demands)

Notwithstanding the excellent state of knowledge some data vital to the social and economic analysis of the mining structure is missing:

1, The actual amount of mined salt is unknown. Furthermore the size of the entire prehistoric mining area is unknown as we only know of those sites that were discovered through medieval or modern mining activities. It is probable that the prehistoric mining area was much bigger than we now today (RESCHREITER / KOWARIK 2008b).

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

The Agent-based simulation

Modeling the work process

The realization of this task required a precise formulation of archeological assumptions (i.e. high degree of organization, efficiency, working process, segmentation of working process) and plausibility criteria (i.e. minimum and maximum of the mining area) as well as selecting and collecting the relevant data. The simulated working process encompasses the following activities (fig. 8-9):
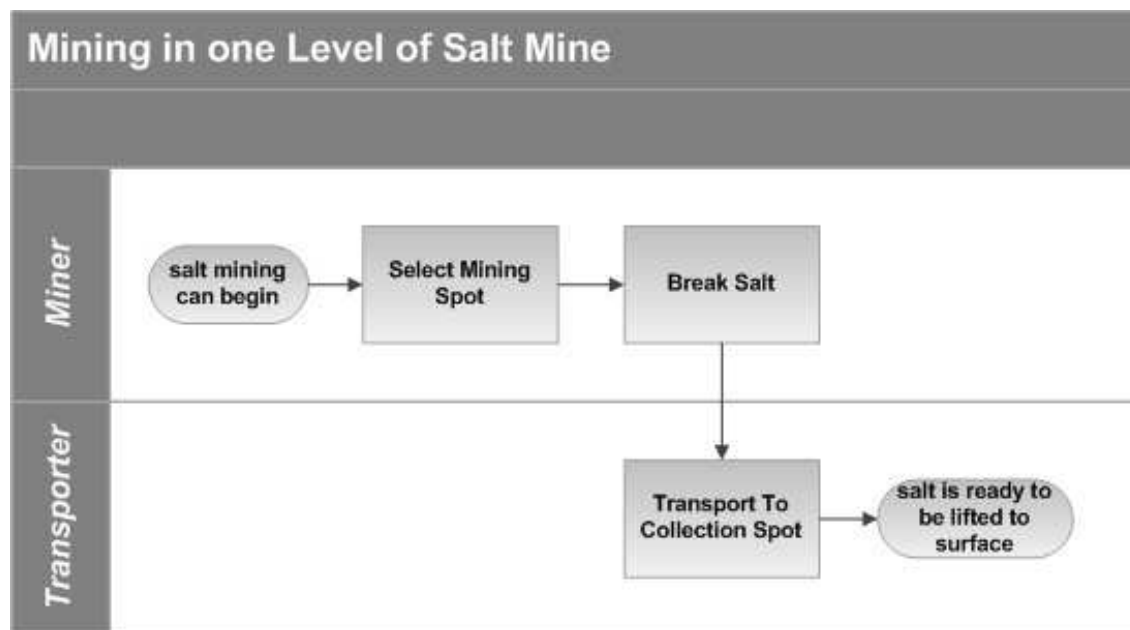

Fig. 8 - Schematic representation of the simulated working process (© G. Wurzer, K. Kowarik).
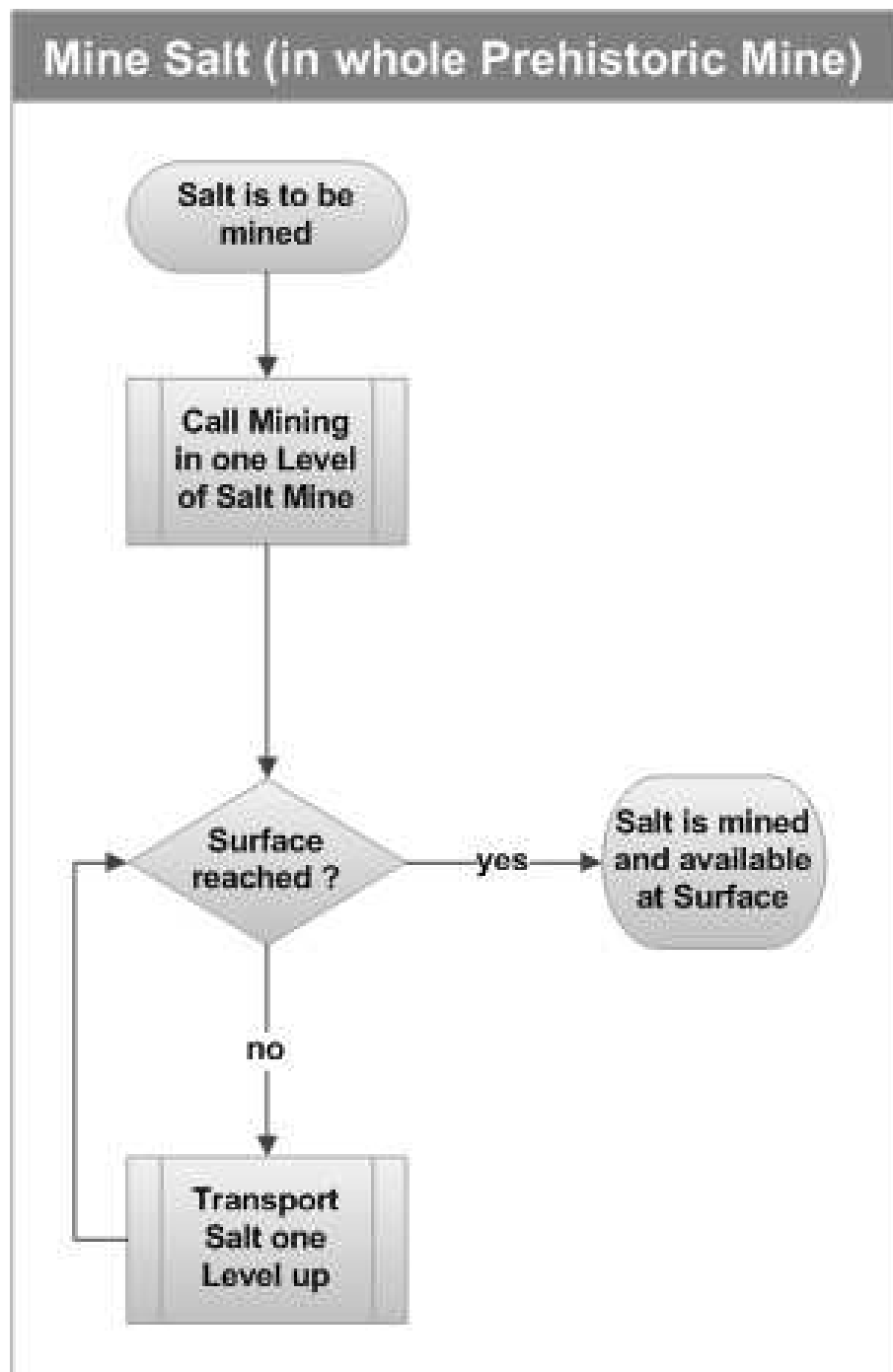
Fig. 9 - Schematic representation of the simulated working process (© G. Wurzer, K. Kowarik).

- Salt is broken with bronze picks (fig. 10).

- The broken material undergoes decompression (this is taken into account in the simulation).

- collecting broken salt

- The carrying sack is filled with salt and the salt is transported to the shaft (fig. 11-12).

- The amount of salt reaching the shaft represents the output of the mining hall.

Fig. 10 - Breaking salt with a bronze pick as it was used in the Bronze Age salt mines (©A. Rausch, NHM Wien).

Fig. 11 - Transporting salt with the carrying sack (© A. Rausch, NHM Wien).

Fig. 12 - Emptying the carrying sack (© A. Rausch, NHM Wien).

The simulated working process is limited to one mining hall (fig. 2) and encompasses:

- the choice of the site where salt is broken
- breaking the salt
- collecting and transporting the salt

Transporting the salt through the shaft into the next mining hall and eventually to the surface is not part of the simulation.

Two types of agents exist:

- miners: breaking the salt
- transporters: collecting and transporting the salt

Selection and collection of data

The data used for the simulation stems from data collection through experimental archaeology and archaeological assumptions based on the actual state of research:

Data collected through experimental archaeology: The steps of the working process were reconstructed with replicas of the prehistoric working tools; time was measured (fig. 13); the volume of the carrying sack was measured (20 l)[3]. There is one especially interesting factor that influences the amount of produced salt: When breaking the salt out of the mountain, the material is decompressed, thereby yielding 1,7 m³ broken material for 1 m³ solid rock.

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. 13 - Table with the data collected by way of experimental archaeology (© NHM Wien).

Archaeological assumptions: maximum time of usage of the mining hall (213 years), size of the initial mining space (18 m^3). The maximum height of the mining hall (19 m) must be assumed based on the following arguments: the next archaeological find spots are located 30 m above the discussed hall, considering that for security reasons (stability) a layer of 6-7 m must be left between the two halls one obtains a maximum height of 19 m for the discussed hall. Based on archaeological evidence the size of the mining hall is limited to 40 m x 100 m x 6-19 m. Based on geological data of the mountain it is supposed that the mined rock is made up of 70% pure rock salt and 30% other material (clay, gypsum). In addition it is assumed that salt mining took place on several levels (fig. 3 and 14). Based on the archaeological state of research it is assumed that the working process was highly efficient, aiming at maximum output in minimal time. Based on the same data it is assumed that the working process was segmented (division of labor). For the sake of simplification no recreative phases were included (i.e. time for meals, sleep, „weekend").
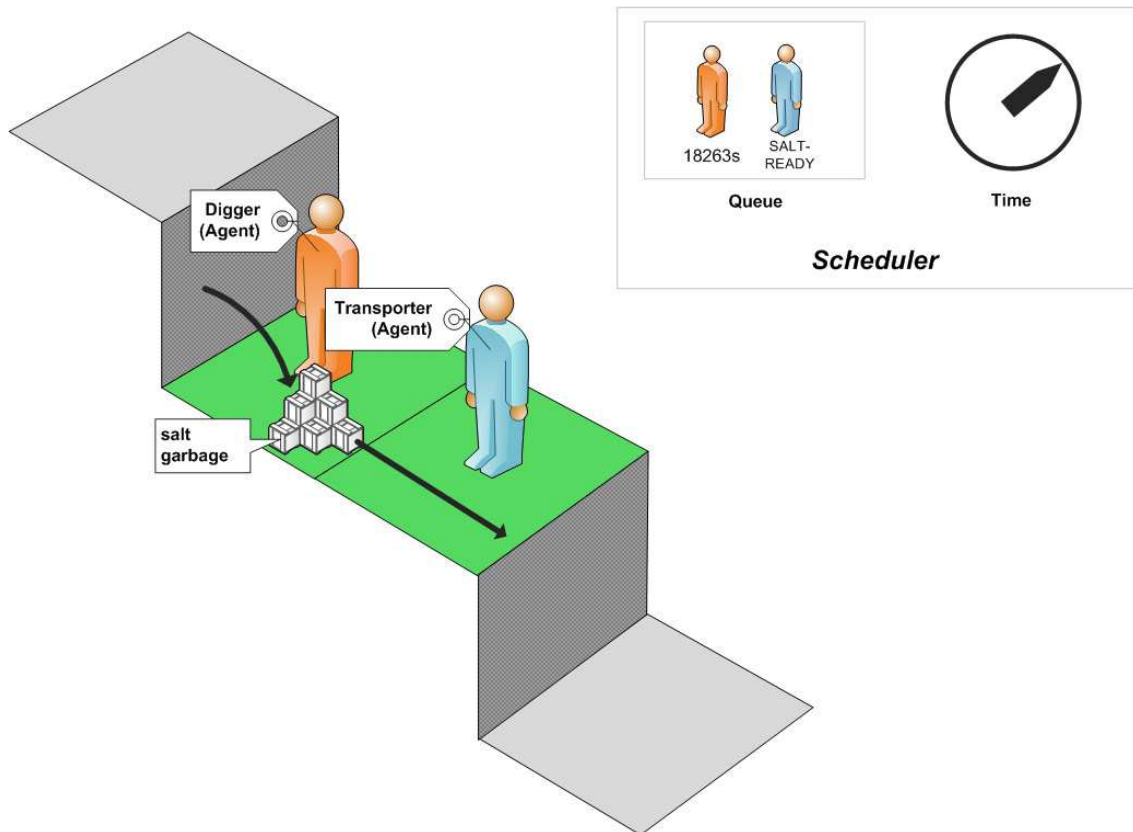
Fig. 14 - The world in the simulation is cell-based, each cell having a base area of 1 m² and a height of 2 m. The cells model units of rock which must be mined one after the other (© G. Wurzer, K. Kowarik, H. Reschreiter).

Implementation

ABM was chosen as simulation method for two reasons: 1, interaction with a virtual environment 2, because interaction between the different types of workers (miners, transporters) had to be modeled. The world in the simulation is cell-based, each cell having a base area of 1 m² and a height of 2 m. The cells model chunks of rock which must be mined one after the other (fig. 14).

To speed up the simulation process, the agent-based simulation was combined with a discrete simulation: Mining one cell takes 6.6 days. This mining process is not simulated in real-time, but rather in one step, using a scheduling list. Each agent who wants to perform an action is written into a list (e.g. Agent 1, Dig Salt, Start Time=100s). This list is ordered such that the agent who will act earliest is at the beginning (fig. 14). The simulation algorithm then removes the first agent from the list, advances its internal clock to the start time of the agent and hands control over to the agent. After performing the intended action, the agent may write itself again to the waiting list (e.g. "Agent 1, wait for end of Dig Salt, Start Time = t+6,6T"). Apart from agents who wait for a certain point in time, there is also the possibility to wait for a named event (e.g. "Wait for Digging Spot is Free"). These events are triggered by other agents, thereby making synchronization among them possible.

As implementation environment, the multi-agent simulation software Netlogo (TISSUE / WILENSKY 2004) was used. Our program provides the following information at every simulation step: broken salt, other broken material, salt ready for transport to the surface (output), number of agents working,

number of inactive agents (fig. 15). This data is also transferred to a table in Spreadsheet-format (comma separated values).

The agents themselves are programmed in a custom-tailored agent editor, in which it is possible to edit the agent's brain with its states and links, roughly resembling the intended work process the agent has to follow. This brain model is compiled into a state machine which is executed at runtime.
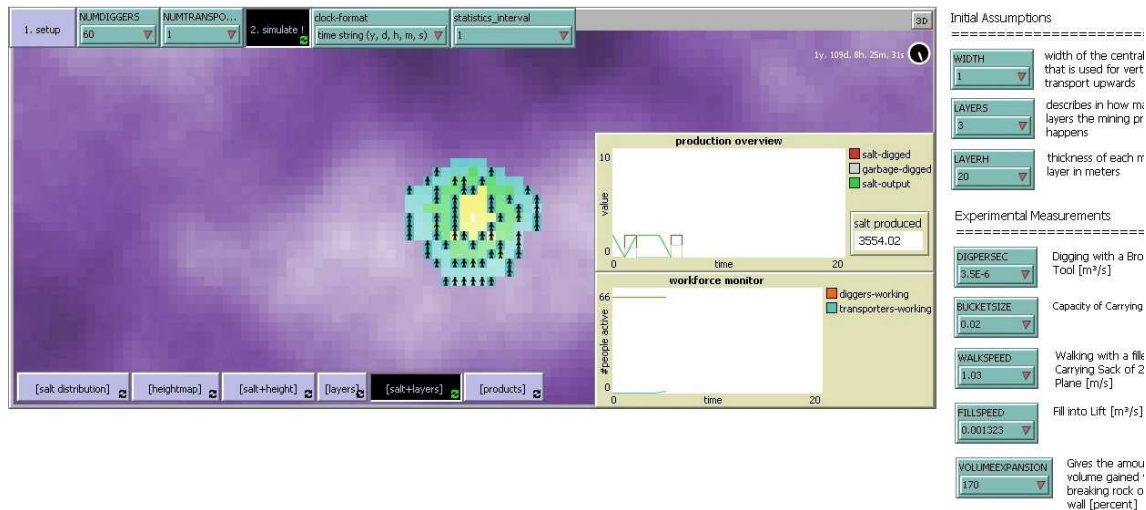

Fig. 15: Screen shot of the simulation. The following information is provided at every simulation step: broken salt, other broken material, salt ready for transport to the surface (output), number of agents working, number of inactive agents (© G. Wurzer, K. Kowarik, H. Reschreiter).

Execution and Results

In the simulation run, the model is computed until the whole salt mine is exhausted (i.e., there are no more agents waiting to be called up by the scheduler). The simulation run is influenced by the following parameters:

- number of workers (miners and transporters are handled separately)
- height of the mining hall and consequently number of mining levels

The simulation proceeded in multiple simulation runs, in order to rule out stochastic errors. The results show that exhausting the salt deposit took significantly less workforce and time than had been initially supposed. We will discuss only one example as this contribution aims at presenting a method and not discussing the archaeology of prehistoric mining[4]: It took 25 workers mining for 14 years of uninterrupted work in a hall of 6 m height to exhaust the salt deposit completely. This comes nowhere near the maximum time span of 213 years. Although it has to be considered that no recreative phases have been included. We must as well consider that those 14 years will very probably represent 14 years of the most productive and vital period of a human life.

If we assume that the simulated 25 workers were working „fulltime", meaning that they did not have the time to cater for their substantial needs (i. e. food, housing, maintenance of the mine) we must conclude that other people took up those charges, and by this adding to the size of the mining community. Should we wish to assume that new workers were only or mainly recruited from the ranks

of the mining community itself, then the size of this community must be augment further. In addition, it must be taken into account that most probably more than one mining hall and more than one shaft system was in operation, which also increases the total workforce (fig. 1).

Our result also point out that the importance of the transporters in the working process is nearly negligible. This represents another important deviation from our verbal model as up to now it was considered that collecting and transporting had to be carried out while the salt was broken. Maybe it should be considered that collecting and transporting took place after a certain amount of salt had been mined (Maybe salt breaking was stopped altogether while collecting and transporting took place). Furthermore, it also became clear that the lack of space slowed down the working process considerably. Such a situation might arise in the initial mining phase.

Concluding, we are convinced that our gained results as well as our method can act as basis for more advanced modeling techniques on a higher scale (e. g. simulation and modeling of the entire Bronze Age salt mining activities in Hallstatt, including the local surroundings).

Discussion and Conclusion

With our agent-based simulation we aimed at providing a tool that allows for exploratory work with the existent archaeological model of the Bronze Age salt mines in Hallstatt. Furthermore, our approach shows that simulation modeling can be applied in order to identify central parameters of a process (in our case: the mining process) within a theoretical framework. Our results are promising, as we could correlate the output rate of the salt mine with the time span of active mining and the size of the work force. Furthermore, we were able to identify several side-benefits in using simulation modeling in the archeological context:

- The spatial structure of working processes can be analyzed systematically.
- The division of tasks within a working process can be dissected, allowing to find a balance between the workload among different working groups (How many transporters, how many miners?). This can lead to a assessment for the degree of labor division within the initial assumptions of the theoretical framework.
- It is possible to find critical working phases and tasks, which is of vital importance to production.

We consider our agent-based model as first step towards building a systems model of the entire salt-mining structure including its catchment area and infrastructure network. With our work, we have demonstrated the potential of agent-based simulations for conceptualizing and analyzing complex working and producing processes. Furthermore, using slight adaptation, we could apply our simulation also to other prehistoric mining structures well beyond the borders of Hallstatt.

We consider the major benefits of this method to be located not purely in the computational results, but in its suitedness for analyzing complex working and producing processes. This is especially true in relation to the following research topics:

- spatial structure of working and producing processes
- organization of working and producing processes:

- o structuring of processes and assignment of tasks
- o division of labor
- o granularity (i.e. level of detail when looking at the work processes in question)

Concluding, we find that ABMs are especially well adapted to assess complex economic and social developments while at the same time being able to map and calculate workflows and production processes (chaîne operatoire).

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[1] For a exhaustive survey of ABM-projects see the CAA Session 2006 on „Social Modeling and Simulation Symposium" in: Clark / Hagmeister 2006: 16-59 and the website of the Agent-Based Modeling Group at the University of Arizona webpage (www.u.arizona.edu/<jtmurphy/ABM/ABM.htm).

[2] 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 gras and bast, hide, fur, textiles, human excrements etc.). This mine waste – also called heathen rock – was left in mines and has been compressed to solid rock through mountain pressure.

[3] The data was collected by R. Totschnig, B. Gabriel, T. Koch-Waldner, M. Obenaus by A. Rausch.

[4] An exhaustive analysis of the simulation results is part of a PhD-Thesis at the Institute of Pre- and Protohistory, University of Vienna (K. Kowarik).