Chapter 7
Mining with Agents: Modelling Prehistoric Mining and Prehistoric Economy

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7.1 Introduction

Mining areas are characterized as centres of *production* and *consumption*. Aspects such as expert knowledge, intra- and superregional communication, the operation and maintenance of traffic and trade networks further add to its complexity and require consideration. All these interdependent conditions demand an analytic approach combining different levels of observation, both spatially and in context of the model used.

With its spatial modelling approach, Agent-Based Simulation (ABS) can aid a clear formalization with respect to one of these levels (within a mining gallery, considering the whole mine as a system, considering mining facility with its supporting settlements, considering a whole region, see Fig. 7.1). The spatial data basis that is used in this respect largely depends upon context (refer to Fig. 7.2):

- Continuous representations involve vector data coming from GIS or CAD, while discretized representations import per-cell raster data from GIS or bitmap images. To be precise, space in an ABS is a locality-based data source for a set of defined properties (or layers, in GIS jargon). An evaluation at spot (x,y) yields the values of properties $p_1 \dots p_n$, where n is the number of layers present.

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G. Wurzer et al. (eds.), *Agent-based Modeling and Simulation in Archaeology*,
Advances in Geographic Information Science, DOI 10.1007/978-3-319-00008-4_7

Fig. 7.1 A multi-level simulation approach involves several stages of increasing complexity. ABS can be used to formalize models such that each level acts as a black box for the next-higher stages, thereby making results reusable and composable

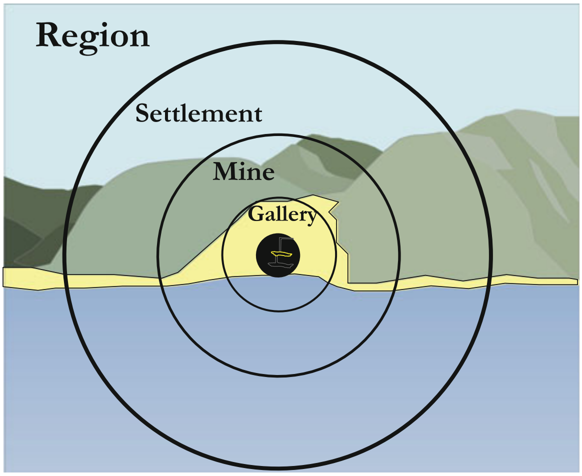
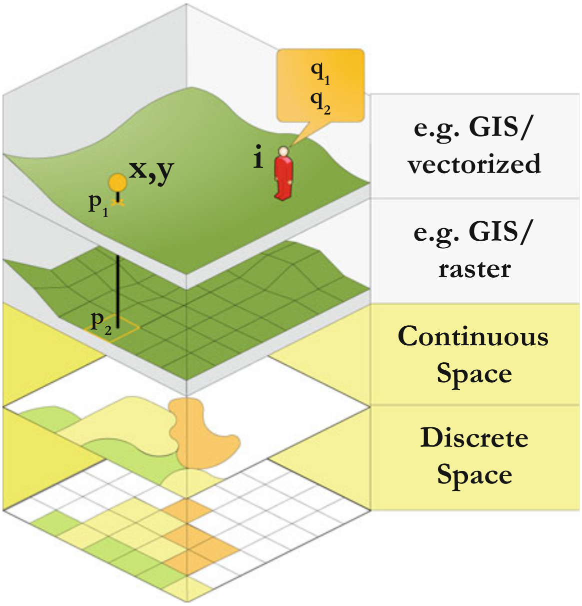


Fig. 7.2 ABS excels at spatial simulation, where space can be either continuous or discrete (i.e. consisting of cells). Space acts as a data source, providing properties $p_1 \dots p_n$ at a certain location (x,y). Agents are movable entities within this environment that can query and alter these spatial properties. They also have an identity i and carry properties $q_1 \dots q_m$ with them. Thus, different agents can be queried from the outside for their locality (and properties residing there) as well as their own properties, which makes complex interactions between agents and space possible



- Quite similarly, agents are movable entities residing at a certain location x,y. They hold their own properties $q_1 \dots q_m$, which are typically defined per agent type (e.g. persons). Agents furthermore have an identity i that can be used to query a specific agent.

Even though literature sometimes speaks of "agents possessing a brain of their own", we see this as a completely separate matter: For us, agents are essentially moveable containers for data, governed by the actual simulation code that also influences all other parts of the environment such as the underlying space. The statement of the simulation model is therefore the choice "what to do" with all of these data-holding entities, which is exactly what we focus on with this contribution, giving prehistoric mining as an example case.

7.2 The Prehistoric Salt Mine of Hallstatt/Upper Austria

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 and 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 work process in the mining galleries (as mentioned in Barth 1993/1994, 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. Salt was mined with bronze picks, producing small pieces of salt, which were then collected with a scraper and trough (see Fig. 7.5) and filled into carrying buckets. 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 gallery. 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. However, we do have hypotheses based on Bronze Age mining that are derived from anthropological investigations of the Early Iron Age cemetery (9th–4th cent. BC) in the Salzberg Valley. In more detail, 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. Working patterns observed in all studied samples exclude work tasks related to agricultural activities. The anthropological analysis has shown that the age and gender structure of the cemetery correlate with age and gender distributions of a “normal village”. Summing up, our inferred hypotheses conclude that (1) Bronze Age miners were working “full-time” in the mine (2) all members of the mining community were involved in the mining process and, in consequence, (3) other groups had to provide them with means of subsistence (food, clothing), (4) the mining community lived in the Salzberg valley.

7.3 Agent-Based Simulation of Mining

7.3.1 Previous 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 (e.g. Kohler and van der Leeuw 2007, pp. 1–12; Costopoulos and Lake 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 et al. 1999; Beekman and Baden 2005; Premo et al. 2005; Clark and Hagemeister 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). The simulation which we are going to present in the forthcoming sections have also previously been reported in Kowarik et al. (2012), in which additional details beyond the scope of this chapter are given. Furthermore, our simulation models are available online http://www.iemar.tuwien.ac.at/processviz/hallstatt as well as upon request to the authors.

7.3.2 Simulating Work Processes

Work processes are given as sequences of actions which are executed repeatedly in order to reach a set goal (in our case: the production of salt). Our agents have no freedom of choice over these strictly defined actions, but execute them as-is. Methodologically, this approach is significantly different from other models that focus on *behaviour*, using a set of rules from which an agent chooses freely. The main difference is that we look at whole work processes as stated by archaeological model building, not emergent behaviour that occurs when agents interact (according to some hypothesis). Arguably, this way of modelling is rather "Tayloristic"; the reason for employing an ABS rather than performing hand-calculation (i.e. "time needed per m^3 of mined material") is that there are dynamic factors which make the result not easily computable lest simulation is used: for example, salt distribution is varying over the simulated area. This can easily be expressed as spatial property 'salt density', which can either be imported or generated, since the typical concentration and form of salt bands are typically known for a specific mountain. Another factor that is dynamic and easily expressed in ABS is the division of work load between different process roles: This may be fixed, or it may vary according to some preset condition (such as a staff schedule, for example).

Our model uses discretized space, in which each cell corresponds to a spot of 1 m × 1 m within a mining gallery. By using an additional property, we introduce an additional height of that patch, in multiples of 2 m. Such a *constraint* also applies to the maximum dimension of the mining gallery, which is set to 100 m × 40 m, 18 m height. Each patch also carries a property that states its salt density, as percentage of salt versus other material present (and which is just 'garbage' in the context of the process). Typically, this density is around 80 %, in a cloud-like shape that can be generated by using a e.g. fractal noise filter peaking at that value. We load this salt distribution as a raster map, i.e. we use a two-dimensional distribution even though our environment is three-dimensional. This approach is nevertheless sound, as salt progresses in vertical bands through the mountain; given this circumstance, we may assume salt distribution to be constant among all layers for the small area in which our model simulates. In other mining simulations which do not satisfy this assumption, the distribution would need to be loaded per layer (i.e. as a set of bitmaps).

As to the simulated personnel, we distinguish between two different agent types (*process roles*): The miner (who breaks the salt) and the transporter (who is responsible for moving the product to a vertical shaft). Current archeological finds suggest a mining process progressing in levels: Each was 2 m high and could be reached from the level below. Furthermore, a spot on the same level could be reached directly, without having to climb up or down. Formalized, this means: a mining spot (see Fig. 7.3) must be at least two cells wide: one for the actual miner agent, one for transporter and reachability. This constraint can be given up if it is assumed that digging and transport take place in sequence.

The maximum number of levels in which the mining is conducted is given as a parameter (the absolute maximum, which comes from the stated maximum dimensions, are nine steps). Initially, we carve out an area of 3 m × 3 m, which represents the space taken by a vertical access shaft. Furthermore, the first row of patches on each layer are carved out, giving the miners a place to stand on. This initialisation gives a minor deviation from a simulation that would calculate everything from the begin on (i.e. establishing a vertical shaft and the first row

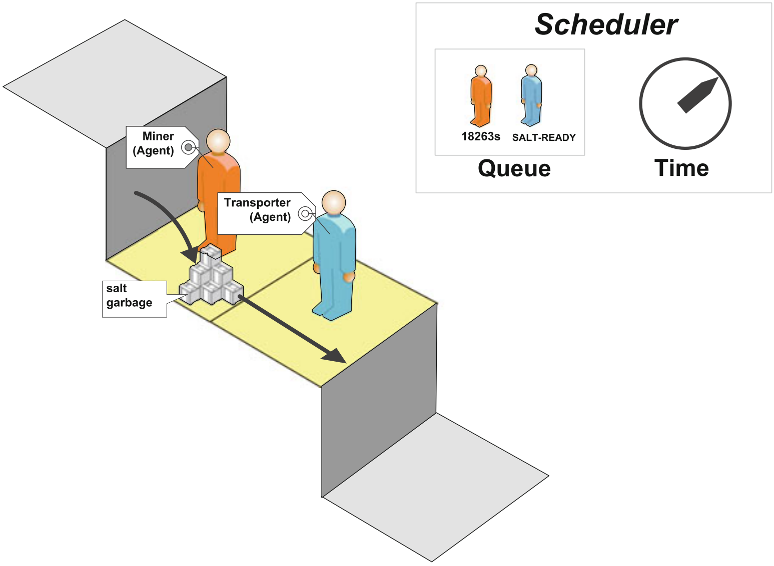


Fig. 7.3 Model of the simulated digging process: miners dig the salt, which is then transported by an own person group to the vertical shaft. Because of the large timespan that has to be simulated (250 years), we have implemented a scheduler that can passivate agents and activate them again when a certain point in time is reached or a specific wake-up signal is broadcast

of patches in each level). The reason for doing so lies in the lack of evidence that would underpin this "mine establishment" part. A detailed discussion of the resulting tradeoff in accuracy is given in the discussion (see Sect. 7.6).

With the levels in place, the agents are now put to work: Miners first query the bottommost layer for all possible mining spots. Mining spots are unoccupied cells which lie beneath a cell on a higher level (i.e. one that has the rock which is to be digged) that contains salt and is also unoccupied. If it has found any such spots, the agent selects the one with the maximum salt concentration, assumes a standing position beneath it and begins digging. If there are no such spots at the current layer, the search advances to the next layer. If all layers are exhausted, the simulation ends.

After having selected a new mining spot, the agents start the actual digging work. Classically, the time base for ABS are ticks of a virtual clock, where each tick stands for equidistant unit of time (e.g. second, hour, year). A unit of work—in our case: the actual digging, takes days (see Sect. 7.5.3). Other processes, such as transport, take only tens of seconds. We have implemented a scheduler *on top of* the ABS, that is made to progress time while the agent is working, which helps us deal with both time resolutions:

- Upon reaching a time-dependent task, the agent is made passive and written into the so-called *future event list* of the scheduler. This list contains all agents that are waiting for a specific instance in time, sorted according to the nearest future activation time.

- Instead of advancing by a second in each turn of the simulation, the scheduler is given control of time. It removes the first agent from its future event list, reads its activation time and advances the clock to that timestamp. Then, it reactivates the agent. It repeats this process while there are agents waiting for the current timestamp.

The scheduler therefore advances time in non-equidistant intervals. For miners, we can specify if the digging should be performed "one whole cell at a time", which means that the scheduler will passivate the agent for the whole amount of time it takes to dig $2\,\mathrm{m}^3$ of mountain rock. We can also specify that the time that the miner uses is proportional to the capacity of a carrying bucket, which will be used to transport the salt up to the surface. Regardless of what of the two modes is used, the reactivated agent will mine the amount given by the time passed, taking the salt density (given in percent of salt per cell) into account. It also raises a signal that salt is now available for transport, which will be explained in due course.

Both materials—salt and "garbage" (impure mined rock) increase their volume upon being mined. The increase in volume is fairly significant (in our case $+70\,\%$) for the transport process: There is a special type of agent which is called "transporter", which has the sole duty of collecting the mined salt once the miner agents signal that it is time to do so. For this to be possible, we have extended the scheduler with an additional list, the *future signals list*, that can be used to passivate agents and reactivate them when a certain signal is issued. In more detail:

- Transporters are created, immediately passivated and written to the future signals list in order to wait for *SALT_READY*.
- Miners raise *SALT_READY* after having produced salt. As a matter of fact, the scheduler reactivates all transporters waiting for that signal. The activated agents then go to find salt, one bucket at a time. This means: finding a spot with salt, filling a bucket, transporting this to the vertical shaft. Additional processes, such as the actual transport to the surface and further, are not modelled: We restrict the simulation to the actual process within one mining gallery, in order to make it composable with a simulation of the whole mining facility.

7.4 Implementation

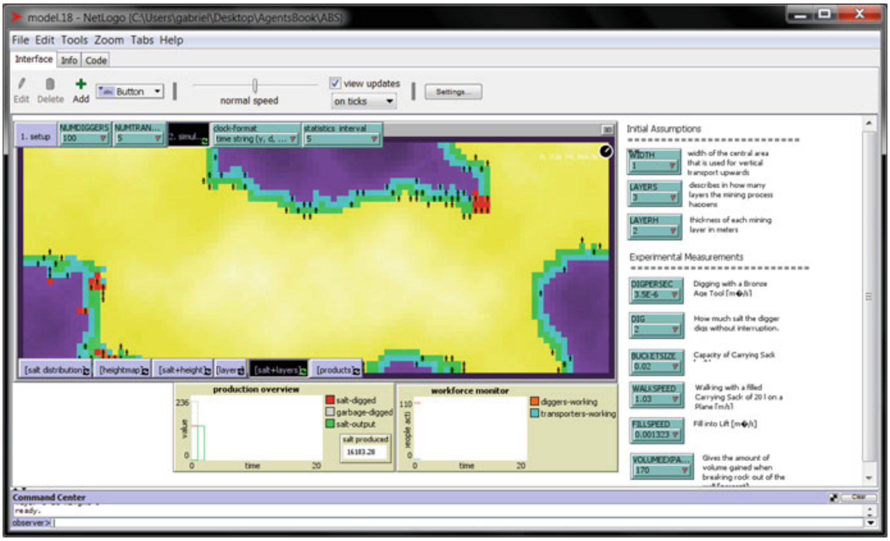
We have implemented the stated model using NetLogo (Wilensky 1999), an open-source simulation that runs on the Java Virtual Machine and is therefore available over a wide range of platforms.

Netlogo itself is a dynamic scripting language, meaning that every command can be issued at run-time (without compilation). Since NetLogo does not support Coroutines (i.e. passivation and reactivation of a piece of code), we had to emulate them using functions: All code that is to be run without interruption is put into a function (or 'Procedure', in NetLogo lingo). At the end of the execution of the function comes the code to passivate the agent. This sets the agent property *active* to false and sets its *resume function*. The agent is then written into either queue (future event or signal list, as described earlier), which is then sorted. The implementation of the future event list uses a priority queue to do that, as the timestamps give the priority.

In every step of the simulation (Fig. 7.4), the scheduler is called and advances its clock to the time of the first item in the future even list. It then takes this agent out of the list, sets its property *active* to true and executes the *resume function*. While there are agents waiting for the same timestamp, this is repeated. The result of this is a set of active agents, which then execute their resume function. Note that, for newly created agents, this is always set to be the first action of the process (e.g. find salt in the case of miners).

Active agents then execute their resume function, which will (1) raise signals such as *SALT_READY*, which are written into a buffer, and (2) also call upon the scheduler to passivate the agent again when a certain time is reached. After that, all agents waiting for a signal are reactivated: For every item in the signal buffer, corresponding agents in the signals list are made active and immediately execute their resume function.

With the help of these constructs, we were able to let an agent simulation compute 200 years of mining in just 5 min (depending on the number of levels). NetLogo's parameter sweeping implementation (*BehaviourSpace*) furthermore allowed us to vary the input parameters and run experiments in unattended mode (e.g. over night).



NUMDIGGERS 100

NUMTRAN... 5

clock-format time string (y, d, ...

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☑ view updates

salt produced 16183.28

Initial Assumptions

WIDTH 1 width of the central area that is used for vertical transport upwards

LAYERS 3 describes in how many layers the mining process happens

LAYERH 2 thickness of each mining layer in meters

Experimental Measurements

DIGPERSEC 3.5E-6 Digging with a Bronze Age Tool [m�/s]

DIG 2 How much salt the digger digs without interruption.

BUCKETSIZE 0.02 Capacity of Carrying Sack

WALKSPEED 1.03 Walking with a filled Carrying Sack of 20 l on a Plane [m/s]

FILLSPEED 0.001323 Fill into Lift [m�/s]

VOLUMEEXPA... 170 Gives the amount of volume gained when breaking rock out of the

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ready.
observer>
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Fig. 7.4 Actual implementation of the digging process, in NetLogo. The salt distribution is given by the white areas of the world, which the miners follow. At the edges, colour-coded steps are depicted (here for three layers). Both salt production and workforce activities are given as plots. Initial assumptions (constants) are shown on the *right side*

7.5 Experimentation

7.5.1 Parametrization

The simulation was used to obtain the time it would take the agents to fully exploit a mining gallery, given a fixed salt map as basis.

In a pre-step, timing experiments for the described work processes were made inside the mine, using reconstructed bronze-age tools as means. The average of the timings obtained are shown in Fig. 7.5. Furthermore, our simulation used the following parameters as input:

- *Number of layers* (1–9)
- *Number of miners* (25, 50, 100), *number of transporters* (5, 10, 25, 50)
- *Minimal standing space*—number of cells to stand on for each level (1 cell: mining, then transport, 2 cells: mining and transport in parallel)
- *Volume of salt to dig without interruption* (0.02 m^3: one carrying bucket, 2 m^3: one complete cell). This corresponds to the passivation time of the agent, and depends on the salt concentration of the current mining spot.

As maximum simulation time, 250 years were set. This figure is larger than the actual usage time, as dendrochronology gives us 213 years between the youngest and the oldest wood found inside the prehistoric mine. The higher number is considered a safe margin, though.

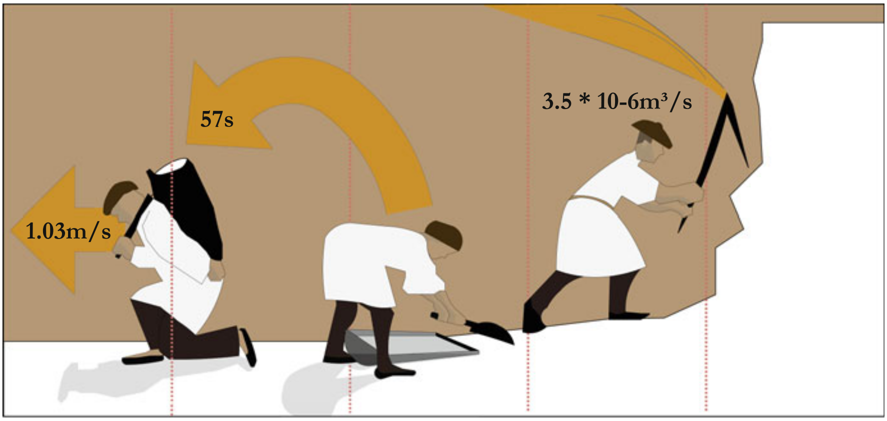

Fig. 7.5 Timings have been derived from experiments which were conducted in the mine, using reconstructed bronze-age tools

7.5.2 Pre-experiments for Narrowing the Parameter Space

The parameter space stated above had to be narrowed down before conducting the parameter sweep experiments:

- Number of layers: Using spreadsheet-calculation, we first obtained the projected total time (number of cells × time per cell), which is dependent on the number of layers that are due to be mined and the minimal standing space. No option could be eliminated, to the contrary: With 25 miners, we calculated 5 years (1 layer) to 39 years (9 layers)—a very small number indeed. It must be noted, however, that these calculations do not take the topological rules stated earlier into account, and are thus the absolute lowest bound.
- Number of miners and transporters: Both of these agents require space. Thus, it is quite possible in initial situations of the simulation that there are too many of them to fit into the mining gallery. The simulation was extended to make non-fitting agents inactive until a space becomes available. Concerning the number of agents, our initial tests confirmed that the time until full exploitation was rather low even when taking topology into account, for example (3 layers, 25 miners digging 2 m^3 at a time, 5 transporters) 13.88 years of work time. As no constraints concerning the digging workforce were in place, we sticked to the default range (25, 50, 100). It must be noted that a mine that stands still is never 'idle'—even it is fully exploited, since it can still serve as a transit space for horizontal and vertical traffic that has to be maintained through refurbishment of the timber supporting structures.
- The number of transporters was rather insignificant(!) for the total exploitation time. Upon looking closer, the volume of salt that was constantly produced is too small for having a real need to employ distinct transporters. Pictorially speaking, it would have been enough if every miner took the produced salt with him, upon ending his shift. The number of transporters was therefore kept at the minimum (5).
- With the discovery that the transporters were insignificant, it was clear that the minimal standing space could be limited to 1 instead of 2 cells, since parallel transport and mining are rather unrealistic without a surplus of salt at the standing spot of the miner that needs to be brought away.
- The unit of work for the miner did not affect the outcome of the simulation (2.5 % delta for 3 layers, 25 workers, 5 miners). It had, however, a large impact on performance: For 0.02 m^3 digging at a time, one simulation experiment would compute in the order of hours, whereas the digging of 2 m^3 would need only minutes (both depending on the number of levels). Therefore, we used 2 m^3 of digging throughout the simulation. The lack of significance in having a small unit of work is clear when we look at the time it takes to mine a bucket full of salt versus the transport: Assuming 80 % salt density, the miner would interrupt after 1.5 h. The called transporter would need a few minutes to scrape the salt together, load it into a bucket and bring it to the shaft—before becoming idle again. On the contrary, having 2 m^3 of salt mined in one piece requires 1.7 h

of work for five transporters (assuming a transport takes 3 min in average), which is still insignificant. As a note of caution, we once again state that all of these considerations of transport do not take the vertical lifting from the shaft to the surface into account, which is currently being researched using physical simulation.

7.5.3 Experiments

In the actual experiments we simulated the reduced parameter space that we got as result of the pre-experiments. We used 10 repetitions per for layers 1–7, and one run per parameter variation of layers 8 and 9. As justification, it is noted that there was no variation in the produced values of layers 1–7 (<0.01 years), and the required time for a run in levels 8 and 9 was very large (>1 h).

7.5.3.1 Quantitative Results

We could show that the number of people actively working in the mining gallery might have been smaller than initially assumed, given the necessary time for totally exhausting a mining gallery. Depending on the number of levels (see Fig. 7.6), 25 workers need between 4.74 and 41.39 years. Adding more workers does not decrease the work time in a directly proportional manner: For example, doubling the 25 workers found does not decrease the needed time to 50 %, but only to 54 %.

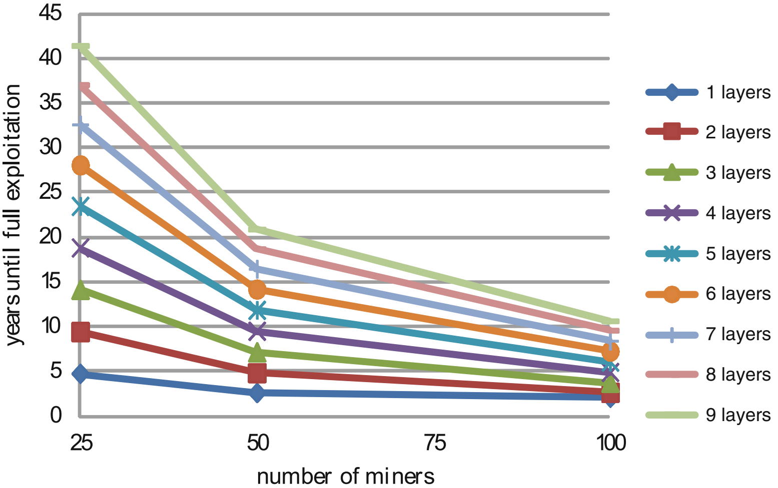

Fig. 7.6 Results of our mining model. Time until full exploitation (y axis) vs. number of workers (x axis) vs. number of mining galleries ("layers", see graph lines)

Much of this effect is caused by the limited space in the initial stages of the simulation, where not every agent can be fitted inside the given space and must therefore stay idle (waiting in the vertical access shaft), along with the obvious different mining pattern occurring if more agents are at work.

7.5.3.2 Qualitative Results

The shape of the mining galleries produced can be seen as *emergent outcome*: In contrast to the initial idea that mining would produce large mining galleries with carved-out levels along the boundaries, we observed a multitude of connected halls with smaller connecting hallways. The agents tend to dig on one level in a sweep-like motion, before breaking creating a hallway and passing through into the next mining gallery. We interpret this to be the caused by the shape of the salt concentration map, in which the salt distribution is "cloud-like" (as in reality) and the behavioral rule to focus on the piece of rock with the highest amount of salt. Recently another possibility has entered the archaeological discussion: It is now assumed that the galleries were mined according to a preconceived plan: Based on different findings from the excavations in the salt mine, it seems to emerge that the prehistoric miners did not simply start mining wherever they found the highest content in rock salt. It rather seems that already before the mining started a "construction plan" for the mine existed or to put it differently the shape of the mining halls was fixed even before they came into existence.

As a further qualitative outcome, we found that the idea of having an extra walkway of at least one patch in each level makes sense only if the mining work must proceed highly parallel between miners and transporters, which is doubtful at least when looking at the production rate for salt. As transporters are rather insignificant given our result, this constraint does really not seem to apply, if not other considerations than parallelism come into play.

7.6 Discussion

Our simulation computes pure working times, in years. We have no social model or other forms of time constraints that govern our miners behind our model. Even if we did try to apply such a mechanism, e.g. 8 h for work, 8 h free time and 8 h sleeping, the time until full exploitation would be far smaller than the actual period of use for the mine (213 years). Some questions are therefore: Was the mining hall exhausted and then only used for accessing deeper-lying mining galleries? Or, was salt production on such a small scale that it would fill the whole time-span?

When considering our simulation results in further consequence, we also find that they sometimes contradict longstanding archaeological assumptions. For example, bronze picks, salt buckets and scraping tools were thought to be designed to optimize the working process, as they both consist of standardized parts and were intended for performing the same work steps over and over in rapid succession. However, the simulation suggests that such a kind of efficiency was not needed, due to the slow rate of salt production.

What have we left out? A specific trail that we did not follow is the change in the spatial environment, which is assumed to be static in our model. Leftover debris and burnt-down torches effectively alter the shape of a mining hall to such an extent that movable (wooden) staircases had to be put on the rubble to establish walkways. Clearly, simulating and verifying the distribution of the rubble nowadays found in the prehistoric mine would be an interesting work for the future. It does, however, not change the overall exploitation time, which we have simulated here.

Another shortcoming, which we have accepted because of the lack of data and consequently also of experimentation results, is the way in which the vertical shafts were built. It is clear from the excavated parts of the mine that a certain amount of timber constructions were installed in the vertical shaft. However, a large part of reconstructing these shafts needs to be based on the lifting mechanisms, which we are still trying to understand. Clearly, linden bast ropes were used to lift weights; the actual lifting construction has been not excavated to its full extent, and therefore, the surrounding staircases and/or ladders need to be clarified. Some preliminary results point at the weight of the lift itself, which might have been very large considering the frictional forces and the weight of the rope itself. Several alternatives—a closed-loop rope versus an open one—are still being researched, which is why we do not seek to jump to conclusions at this early stage. The vertical circulation represents one of the most challenging issues that we are faced with, which is going to occupy us for the next few years further on the research trail. Current efforts in that context are: The physical simulation of the lifting mechanism, the staircase construction (based on the wood distribution coming from the actual, collapsed staircase) and the research into the collapse itself.

7.7 Extensions: Towards Prehistoric Economy

As augmentation of the basic mining model, we have developed a mixed system dynamics/ABS model for simulating demographic development in the Hallstatt region (see Fig. 7.7). The basic question was: If the results from the presented mining simulation cannot be used to narrow down on the number of people working simultaneously, demographic development can perhaps give a measure on how many people might have been available.

System Dynamics (SD) is a method for simulating complex systems with nonlinear behaviour, roughly consisting of two conceptual parts:

- *Stocks* holding a numeric quantity (of people, in our case)
- *Flows* connecting to and leading away from stocks, used for controlling how much of the quantity enters and leaves a stock in each time unit (which is continuous, in contrast to ABS).

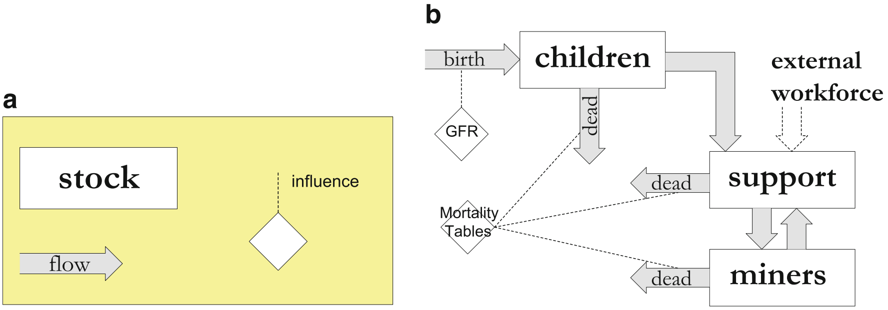

Fig. 7.7 (**a**) System Dynamics concepts: stocks containing quantities, flows modeling the change in quantities, variables giving influences on flows and stocks. (**b**) SD model used for the demographic simulation

The model is entered as graph: Stocks are being shown as nodes and flows as edges (see Fig. 7.7a). In our SD extension, the stocks stand for different stages population, i.e. non-working children, support workers, miners, and time of the simulation naturally corresponds to growing up. Since SD has no notion of identity for the contents of a stock, and thereby no way of telling "how many persons of what age" are contained, we have used a coupled ABS to actually represent the individuals of a population. This way, we can apply age-based mortality rates according excavation data of the Early Bronze Age cemetery of Franzhausen (Berner 1992). For births, we used a fairly high General Fertility Rate (GFR, defined by WHO as "number of live births during a year per 1000 female population aged 15–49 years (reproductive age group)") starting with 200 as base number. Such a high number is found nowadays in developing countries (see e.g. United Nations 2009), which is an analogy we wish to draw.

In each step of the simulation, the SD computes population continuously in terms of *changerate* * dt, where each unit of time stands for a year and the changerate corresponds to the time-dependent flow. In contrast to that, the coupled ABS does only know of integer quantities. Therefore, changes have to be rounded down (e.g. 20.2 births yield 20 agents in the ABS, the remaining 0.2 are accounted for in the next cycle of the SD).

The actual population simulation is summarized as follows (refer to Fig. 7.7b):

- We start by adding births to the stock of children (flow birth – children), where birth depends on the GFR. Simultaneously, agents of age 0 are created in the linked ABS.
- 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 given by the flow children – dead is calculated, as given by mortality for every 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.

We aimed to answer the question of how high the General Fertility Rate needed to be in order to sustain a population fit to provide a fixed set of miners (e.g. 5, 10, 15, 20) over a longer time period (here: 300 years). The first simulation runs confronted us with the problem that we had to choose a rather big initial population and considerable fertility rates to sustain a stable population over 300 years. Therefore we focus here on the necessary parameters for sustaining a stable population.

Simulation runs were conducted for a GFR range from 200 to 425, 50 experiments per parameter variation. We worked with an initial population of 300 people. Beginning at a GFR of 375 (every woman between 15 and 49 needs to have a live birth every 2.5 years), stable conditions over a time span of 300 years are obtained (see also Fig. 7.8). The simulation was then expanded to integrate migration to Hallstatt.

Migration is characterized by the addition of people into the support class (age between 10 and 16). These people have already passed the initial hurdles (most noteworthy: 58 % mortality in between 0 and 4 years) and are on the edge of their reproductive age. Figure 7.9 shows the simulation results of such a population dynamics (GFR 225 is assumed):

- An estimated migration of 4.75 persons per year sustains the initial population.
- However, even a lower migration of 1 person per year establishes a stable population of 75 persons, which would probably be in the range that allows to run a mining facility.

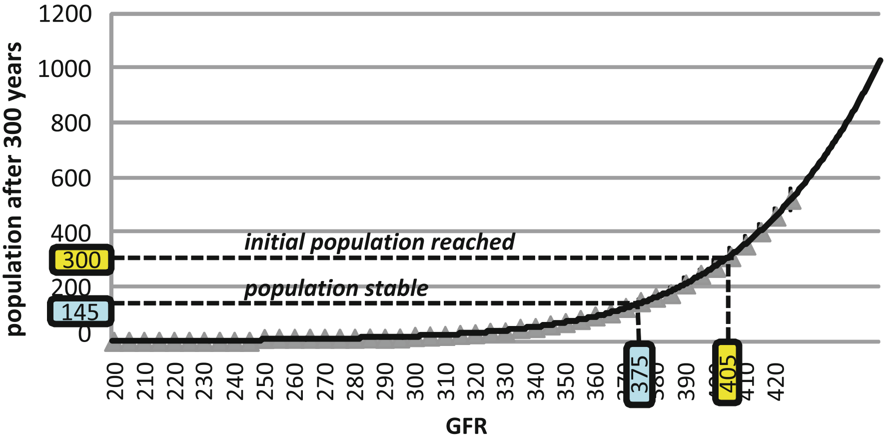

Fig. 7.8 Sustainability of the population in Hallstatt when only GFR is taken into account. A GFR of 375 would lead to the stabilization of the population on a very limited level, a further increase would produce the initial population of 300

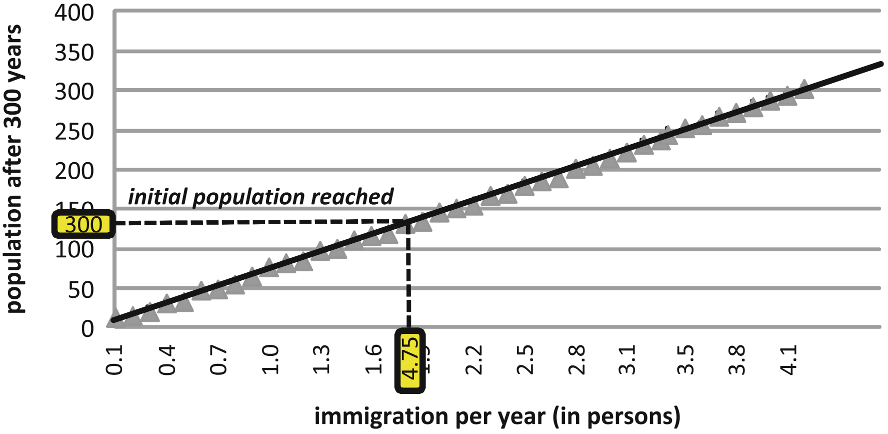

Fig. 7.9 After introducing immigration and leaving the GFR at 225, the initial population is reached quite easily. This is due to the fact that immigrants have already lived through their childhood, which has a high associated mortality

Several aspects need to be taken into account before discussing this output any further:

- Mortality rates were taken from an early Bronze Age cemetery in the lowlands of Eastern Austria (Franzhausen/Lower Austria, according to Berner 1992).
- The demographic model is based on a rather simple structure not taking into account illness, warfare, natural catastrophes. The model needs to be reevaluated as it represents a first trial version.

Keeping these points in mind two possible scenarios emerge under the given model constraints (also see Sect. 7.2):

- a local population without migration, but, in our view, high General Fertility Rates
- a local population with a certain amount of migration to Hallstatt and somewhat lower fertility rates

Looking at the archaeological and anthropological record arguments can be made for both scenarios.

Concluding, the demographic simulation provides important “food for thought” introducing demography as a possible important limiting factor in the operation of the salt mines.

A further perspective would then be to model the whole support community versus the actual workforce occupied in digging. As in modern-day business engineering, we have used a business process simulation (see Fig. 7.10) to model multiple levels of mining activities, the tools needed and salt produced. The model is still in its early stages, solely concentrating on the mine as a system which integrates the presented simulations, in order to answer on demand and supply levels. Still, it is

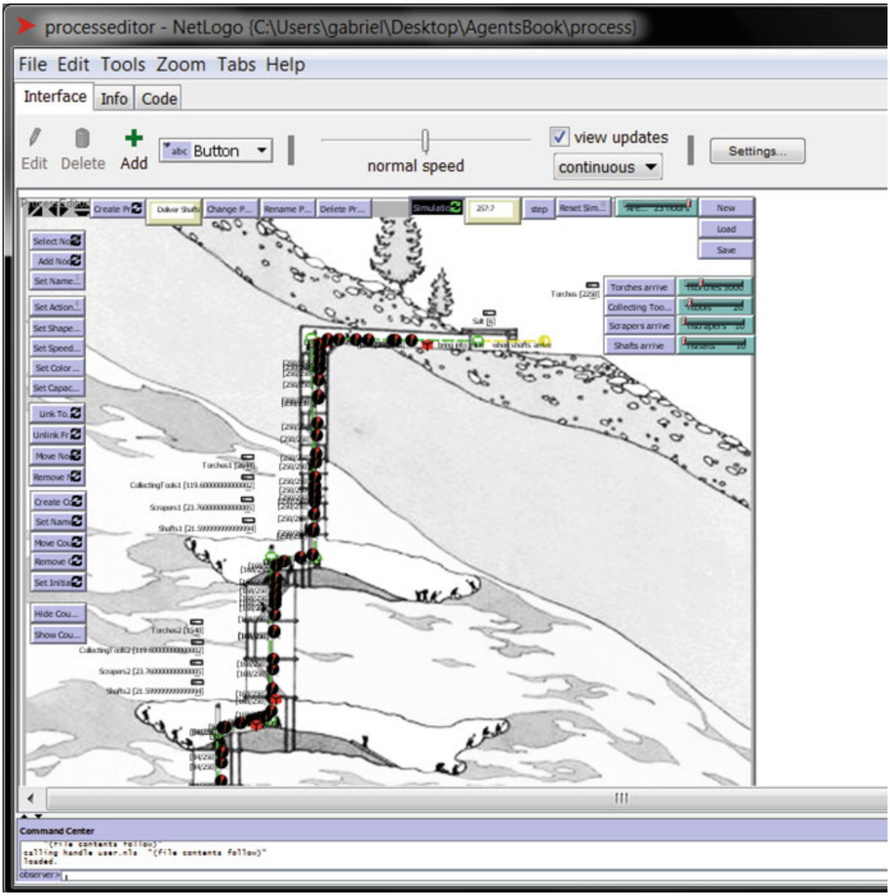

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Fig. 7.10 A business process simulation can simulate the prehistoric mine from a systems view, i.e. amount of materials needed for producing the needed quantities of salt, just like in a current enterprise that has to optimize its daily work procedures. It is arguable, though, if the prehistoric mine was set up in exactly this spirit

to early to give decisive results on this simulation, whose role is to visualize the different parts coming together, and ask about probable exploitation strategies (one mining gallery at a time, or multiple mining galleries in parallel).

7.8 Conclusions and Future Work

We have presented a mining model that acts on the basis of the reconstructed work process for digging salt in the bronze-age mines of Hallstatt/Upper Austria. Our results obtained so far seem promising: We could show that (1) the work force needed for exploiting such a mine would have been smaller than previously assumed and (2) that it might have been a severely limiting factor in the mining system.

As future work, we need to look at the vertical transportation of the salt to the surface, which is currently being investigated using physical models of the lifting process and the vertical shaft construction itself. Furthermore, we have a huge need for investigation of the surrounding settlement: Sustainability of the population (based on landscape properties), also including migration, trade of goods, social models of a mining community and the like will keep us occupied for the coming years, to say the least. All in all, the contribution of simulation in this respect lie not solely in the actual results: The formalization of verbal models alone augment the daily archeological practice in ways that were previously unthought of, and will continue to inform other scientific disciplines also involved in the research in ways that are yet neither imaginable nor foreseeable.

Authorship Information

All authors have contributed equally to this chapter. As head of the excavations in the prehistoric mines of Hallstatt, Hans Reschreiter has provided the necessary background that the whole team then formalized into a simulation model. Kerstin Kowarik has played a key role in this formalization, by filling in the gaps during the constant back and forth between current state of research and the possibilities of the simulation, which Gabriel Wurzer implemented in Netlogo.

Acknowledgements The excavations in Hallstatt have reached a scale at which research cannot be made in isolation; we are grateful for a large body of institutions and people supporting the work that is being conducted, among which we want to explicitly name the Natural History Museum Vienna (especially the Prehistoric Department), the Salinen Austria AG, the Vienna University of Technology (Department of Architectural Sciences, Department of Analysis and Scientific Computing), the University of Natural Resources and Life Sciences Vienna (Department of Material Sciences and Process Engineering) and the Vienna University (Institute of Prehistoric and Historical Archaeology). From the on-site staff, we would especially like to thank Ralf Totschnig for conducting the experiments and Andreas W. Rausch for his documentation. Furthermore, we are grateful for the earlier work conducted by Fritz-Eckart Barth, which has paved the way for all of the current research activities that we undertake.

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