Modelling the Bronze Age Salt Mines of Hallstatt

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Introduction

Any social or economic system is complex and must be considered a complex system¹. When studying complex systems such as mining structures the use of special adapted computer based modelling techniques might prove beneficial.

Mining structures of the size and kind of the Hallstatt salt mines show complexity on several levels. On the one hand the internal structures and processes of the mining complex itself must be considered.

On the other hand its impact on the local, regional and superregional structures must be taken into account. Any mining structure given a certain size will be part of a complex economic network providing a good that will be subject to short- and long-distance trade, and also generating high demands concerning workforce, means of production and means of subsistence (Kowarik & Reschreiter, 2010).

The necessity of quantification

When addressing topics such as provisioning or the impact of mining structures quantification becomes a major issue:
- 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?

¹ Complex systems are part of complexity theory. Which must be considered as an approach to systems whose behaviour „cannot be explained by reduction to their component parts“ (Bentley / Maschner 2003: 1). Through interaction of the system parts new unpredictable behaviour might arise (emergence). System behaviour cannot be explained through simple linear cause and effect relations. These systems are open systems and do not necessarily tend towards equilibrium (Bentley / Maschner 2003).
For this purpose two different computer based modelling techniques\(^1\) adapted to the analysis of complex systems were chosen:

- Agent-based modeling (ABM)
- System Dynamics

The data base for the simulations is provided through:

- Experimental Archaeology
- Historical and ethnographic analogies

Such a multidisciplinary approach has been shown to be very promising (Pollmann et al., 2007; Ebersbach, 2002).

The Bronze Age salt mines of Hallstatt

Bronze Age salt mining is dated by dendrochronology between 1458-1245 BC. The actual state of research indicates that three huge shafts systems (depths up to 170 m) operated in parallel.

It is estimated that salt mining was organized in an efficient and near industrial manner with strongly optimized working and producing processes, assuming furthermore:

- intensive salt production with a high output rate
- high demands concerning: workforce, means of subsistence, means of production
- division of labour
- mining community: By this expression we characterize the group of people engaged in the mining process. Based on the anthropological analysis of the Early Iron Age cemetery (Pany, 2005) we assume that this group had a demographic and social structure comparable to a normal village population with men, women, children and old people. Everyone being to a greater or lesser extent engaged in the mining or provisioning process. This model represents a simple analogy. Up to now no indications of the demographic and social structure and gender relations of the Bronze Age mines are known. We are fully aware that a multitude of other models might be applied to the Bronze Age situation, either stemming from ethnographic or historical sources (which would again only represent analogies).

\(^1\) Software: Netlogo: http://ccl.sesp.northwestern.edu/netlogo/
Notwithstanding the excellent state of knowledge some important data is missing:

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

Agent-based model

Agent-based modelling (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 behavioural rules, depending on the research objective in question. On this basis they are able to make „independent“ decisions (Altaweel, 2006: 30). Contrasting other modelling techniques, such as System Dynamics, ABM allows for individual decision-making.

The Bronze Age salt mines

For a detailed description and discussion see: Kowarik et al. 2009.

The simulated process encompasses:

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

No recreative phases were included in the model.

Two types of agents exist: miners breaking the salt and transporters transporting it to the shaft.

The following parameters can be changed before every simulation run:

- the number of miners
- the number of transporters
- height of the mining hall

The simulation 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.
Results

By using an agent-based model we gained insight into:

- Spatial organization: It became clear that lack of space slowed down the working process considerably. Such a situation might arise in the initial mining phase.
- The organization of the working process: The importance of the transporters in the working process is nearly negligible. This represents an important deviation from our verbal model. Up to now it was considered that collecting and transporting had to be carried out while the salt was broken.
- We related the time span of mining to the size of the workforce and the amount of mined salt. Only one example is given: 26 workers took 23 years of uninterrupted work in a hall of 40x100x10 m to exhaust the salt deposit.

From Worker to System

The agent-based simulation did focus on work flow, performance and organization. But to evaluate the demands (workforce, food, tools) of the mining complex a different modelling approach had to be chosen – a System Dynamics simulation.

Based on the above outlined theoretical framework we built the following model:

- As initial assumption we stated that the mining community was able to sustain a stable production performance over a given period (dendrochronological dating of the Tuschwerk). This implies that the mining community was able to meet the demands concerning workforce, means of production and subsistence during this period.
- We assume as well that the miners were working full time in the mine. This assumption is based on the Early Iron Age situation where the anthropological analysis of the musculoskeletal markers of the excavated skeletons indicates a high workload and working patterns fitting for mining activity (Pany, 2005). A variety of other models is thinkable as historical research shows.
- Workers were only or mainly recruited from the ranks of the mining community itself. Thus workforce demand must have been mainly met by demography.

The entire model is focused on keeping the group of miners stable and the entire mining community in condition to work with high performance over a given time of observation.
System dynamics

System dynamics is a computer simulation technique for dealing with complex systems. As a method to understand the dynamic behaviour of complex systems it is part of systems theory. System Dynamics describes a system and its behaviour with the use of feedback loops, stocks (entity that depletes or accumulates over time) and flows (rate of change in a stock) (Bossel, 2004: 13-34; 111-112).

The Bronze Age salt mines

The following aspects were put into relation (Fig. 1):
- size of the mining workforce
- population dynamics
- consumption of working materials and calories

For a detailed presentation and discussion of the database see Kowarik et al. (2010).

Population dynamics: mortality relative to age\(^1\), the number of live births per year\(^2\) (General Fertility Rate, GFR\(^3\)), male/female percentage of the population (50:50)\(^4\).

Work performance: To translate the pure working time given by the ABM into real time we used a work performance model that assumed that one hour of physical work given by the ABM had to be translated in two hours of real time (Unterberger, 1978).

We assume daily 10 hour shifts and 3 free days per month. The last two points represent simple assumptions.

Technological Data: Based on the archaeological record we calculated the number of broken tools for one 1m\(^3\) of salt. The time span needed to break 1m\(^3\) of salt was gained through Experimental archaeology and the application of our work performance model.

Subsistence: On the basis of medical (Kalorien & Nährwerte, 2009: 12-15) and ethnographic data (Ebersbach, 2002: 115-119) we fixed a calorie requirement relative to age.

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\(^1\) Mortality rates of the Bronze Age cemetery of Franzhausen (Berner, 1997, 36-42 esp. Tab. 8) with corrected ratios for infant mortality (Berner, 1997, 42 Tab. 8).
\(^2\) This data proved difficult to obtain. Initially we used information given by the United Nations. But working with the simulation showed that the GFR should rather be used as a dynamic parameter to explore population dynamics.
\(^3\) The number of live births during the year per 1,000 female population (between 15-49 years) (WHO Definition).
\(^4\) Simplifying assumption.
Critique: The data base must be criticized and improved on several levels, the most crucial points being: i) that gender is not taken into account (mortality, work allocation, calorie consumption) ii) the modelling of population dynamics might be too simplified (Kowarik et al., 2010).

Implementation

The simulation starts with an initial population that is subdivided into:

- non-workers: children between the age 0 and 5 years
- workers: 5 years to death:
  - people between the age of 14-50 who can work in the mine if needed
  - the rest of the working population assigned to other tasks

For the sake of simplification we ignored gender related task allocation. Meaning men and women do the same work in the model.

Everyone in the mining community consumes calories. For a better „visualization“ we translated those into the main ingredients of the „Hallstatt Ritschert“ (Barth, 1992): millet, barley, Vicia faba and pork. The ratios given by F.-E. Barth were changed according to Bertieri, 2009: 27% millet, 41% barley, 27% Vicia faba and 5% pork.

The miners produce salt and consume tools (here: shafts, scrapers, throughs).

The simulation provides the following information at every simulation step (Fig. 2):

- broken salt, other broken material, number of miners, number of children, number of support workers, number of consumed or broken tools, the number of eaten calories.

In the simulation run, the model is computed until either everyone is dead or when a population equilibrium is reached until the simulation is stopped.

In the actual simulation there is only one “limit to growth” – population dynamics. The consumption of food and tools do not come in as limiting factors yet.

The model is highly dynamic as all discussed parameters can be changed for each new simulation run. For the time being we focused on three parameters: i) the number of miners, ii) the number of life births per year, iii) and the number of people migrating to Hallstatt. The last point represents a result of our first simulation runs.
Results

Just one example will be discussed: In the ABM 26 workers took 23 years of uninterrupted work to exhaust the salt deposit. This results in 120 years real time (work performance model, free days).

With an initial population of 300 people we would need a rather high number of live births per year (about 10 per woman in 34 years) to keep the number of 26 workers stable over a time span of more than 100 years. But if we assume one person migrating to Hallstatt (age 10-16) per year we get very stable conditions.

In consequence:

- we either must take migration into account
- or reduce the size of our mining group considerably to approach a somewhat realistic number of live births (e.g. 10 workers, GFR 250, 160 years stable conditions).
- or reconsider the population dynamics.
- or conclude that our model of a stable work group is not a good working hypothesis.

Looking at consumption: After 120 years with an initial population of 300, a GFR of 220 (6 children per woman in 34 years), one person migrating to Hallstatt per year and 26 workers in the mine production and consumption in Hallstatt will have been (Fig. 2):

- Production: 27,000 tons of salt (225 per year)
- Consumption: 26,000 shafts (217 per year), 2000 scrapers (17 per year), 3000 throughs (25 per year)
- Consumption: 3000 tons of millet (25 tons per year), 5000 tons of barley (42 tons per year), 1000 tons of pork (8 tons per year)

This is of course only one example.

The next tasks include working with both simulation models, analysing and critically discussing the data produced. A reappraisal of our basic data and fundamental assumptions is necessary as well (especially population dynamics and gender).

A major aim will the be to introduce consumption as a limiting factor.
Fig. 1: Visualization of the System Dynamics model for the Bronze Age salt mines of Hallstatt.

Fig. 2: Screenshot of the System Dynamics simulation for the Bronze Age salt mines of Hallstatt.
Discussion and Conclusion

What are the benefits and the disadvantages of this method?

Beginning with the disadvantages it has to be said that a computer model is only as good as its theoretical foundation and its data base.

The data produced must always be seen and discussed in the context of its theoretical framework and basic data. Another problem stems from the fact that the more refined a model gets the more assumptions must be made. And it must be taken into account that although simulations do represent valuable tools of analysis they might not be suited to all research questions. Their application should be carefully considered.

On the other hand simulation models allow for rapid hypothesis and data testing. Data sets and even fundamental assumptions, for example mortality or work organization, can be easily changed and explored.

Thus simulation models could be understood as „cultural laboratories“ (Premo et al., 2005) and are in this function of essential value for cultural and social sciences.

Through the combination of ABM and System Dynamics complex economic and social developments can be assessed, workflows and production processes mapped and calculated. Quantification is easily achievable.

The data gained through the iterative simulation runs might lay the foundations for a better understanding of the nature of the system under study.
References


