AGENT-BASED MODELLING AND THE BYZANTINE: UNDERSTANDING THE CONSTRUCTION OF ANTIQUITY'S LARGEST INFRASTRUCTURE PROJECT

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Agent-Based Modelling (ABM) is an established method for simulating the actions, interactions and behaviours of autonomous agents. These agents can be individuals or collective organisations and the tool is able to assess the effects of these agents on the system as a whole. Based on theories of emergence and computational sociology, the ideas behind ABM were first developed many years ago but computational power of recent decades has allowed their utility to provide success in areas such as pollution, transmission of disease, culture, effective teams and cognition. Research is not yet widespread in the construction field, but successes have been seen in areas such as supply chain and network management. The aims of this paper are twofold. We ultimately intend to demonstrate the applicability of ABM in construction management and archaeological engineering; but initially we will outline its potential use via an overview of the Byzantine Water Supply system for the ancient city of Constantinople. Unlike similar counterparts in Classical Antiquity, the Eastern Roman Empire's 4th- and 5th-century water supply megaprojects, whose channels and bridges spanned hundreds of kilometres to bring fresh water to the burgeoning capital of Constantinople and its complex system of reservoirs and cisterns, is relatively under-explored. The paper demonstrates that ABM is able to provide greater and richer understanding of the use of resources in these ancient constructions.

Keywords: agent-based modelling, archaeological engineering, byzantine, heritage engineering, project management.

INTRODUCTION

The work of the modern construction manager, or construction management academic, concerns the ability and resourcefulness of society to provide for its needs via the built environment. We are concerned and interested in aspects such as value for money, project quality, care for the worker, sustainability etc. and investigate how these can be theoretically understood and continually improved. We forget, however, that these needs are not new and that the ability of the built environment to meet the demands of a civil society has been an area of significant interest for centuries, if not millennia.

We have two primary aims to cover in this paper: we shall briefly outline the nature of the infrastructure project built in the 4th and 5th centuries AD and the overall archaeological engineering research project that is currently investigating it; and we

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Snyder, J R, Stephenson, L C, Mackie, J E and Smith, S D (2016) Agent-Based Modelling And The Byzantine: Understanding the Construction of Antiquity's Largest Infrastructure Project. *In*: P W Chan and C J Neilson (Eds.) *Proceedings of the 32nd Annual ARCOM Conference,* 5-7 September 2016, Manchester, UK, Association of Researchers in Construction Management, Vol 2, 963-972.

will introduce and explore the use of Agent-Based Modelling (ABM) as a means to model a system for which there is a great deal of uncertainty and only partial understanding of the drivers that dictate its inputs.

CONTEXTS

The construction of Constantinople's water supply

It is the beginning of the decline of the Roman Empire in the third century A.D. and the emperor Diocletian has decided to split the empire into East and West. The small fishing village of Byzantium located on the Bosporus Strait was destined to become the successor of Rome. It was under the rule of Constantine that the city became the new capital of this reunified empire, which was to be renamed after its founder: Constantinople (Treadgold 2001). With this new status came a massive influx of population, and Constantine and his successors were determined that the city would have the prestige and luxury of a legendary metropolis which included that characteristic luxury of the Roman people: water.

Unlike Rome, however, there was not a plentiful source of natural water in the city. While, as Crow (2012) explains, there was already a short distance aqueduct from the Forest of Belgrade, believed to have been built during the reign of Hadrian, modern analysis (Crow et al., 2008) shows that the maximum hydraulic head of this source could not have provided running water for areas of the city higher than 35m above sea level. Thus, as the city expanded well beyond what the 'Hadrianic' line could provide, only 15 years after Constantine deemed the city as 'New Rome' and the new heart of the empire, his son, Constantius II commissioned a new water supply – showing their commitment to the development of Constantinople as a real long-term investment. Pointed out by the orator at the time, Themistius, a city can be impressive with public buildings and ornate decorations, but if it does not have water it will never thrive. He described Constantinople as being at threat of being a city "girdled by gold but dying of thirst" (Crow 2012).

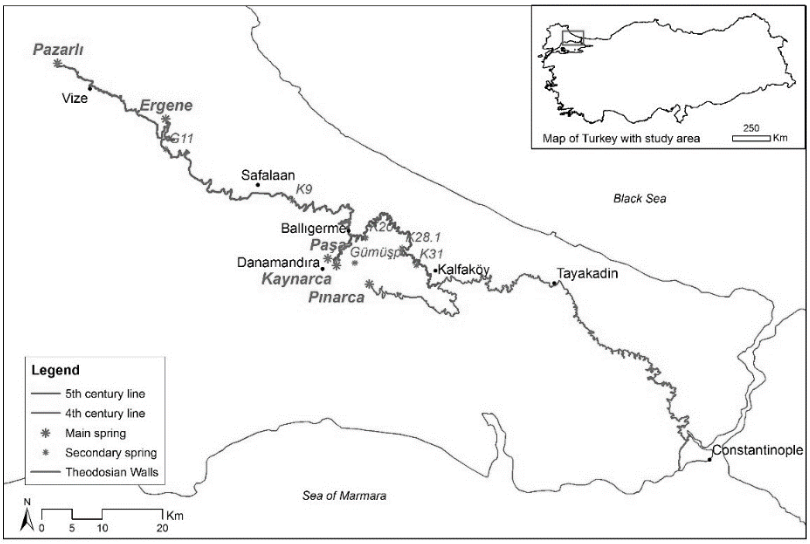

Figure 1: Map of the Byzantine water supply system, showing the 4th and 5th century lines (in blue and red respectively) and the spring sources feeding the system (Crapper et al, 2016)

The initial long distance line, approximately 246km in length (Ruggeri et al. 2016), was completed in approximately 373 AD, and is largely accredited to emperor Valens. Yet there was more to come – in the fifth century a further 181km line from Vize was added, with more monumental structures. The overall development of the water supply system is shown in Figure 1.

The system was not just vast but innovative, requiring sophisticated surveying to navigate the undulating landscape over several hundred kilometers and maintain sufficient fall. While the aqueducts themselves are quite modest, mostly channels ranging from 0.65m to 2.20m in width, many bridges were were required to cross the many valleys of the terrain. Two such examples are shown in Figure 2.

Figure 2 Kumarlidere (L) and Kurşunlugerme (R) aqueduct bridges (Photos: Smith 2015)

Agent Based Modelling

Agent-based modelling (ABM) is a constructive research approach that enables the modeller to create a detailed hypothetical reality by generating virtual representatives (‘agents’) of the concepts that are relevant to the study, to assign qualitative or mathematical properties to these representative entities and to define logical rules that govern, constrain or produce their behaviour and interactions.

At its heart, ABM embraces the concept of emergence whereby the actions and behaviours of individual entities lead to patterns and regularities at a macro level that are not shown by the individuals. In the social sciences much research is given over to understanding not only how individuals behave but also how the interaction of these individual entities lead to macro-scale outcomes. ABM has thus become a popular tool in the social sciences, including economics, sociology and the interdisciplinary field of sustainability studies.

Like other types of modelling, ABM brings about simplifications of the perceived reality (Gilbert and Troitzsch 2005). Yet, it offers a different way of simplification by enabling the study of non-linear systems dynamically and as a whole, rather than in parts. It facilitates systematic reasoning and analysis in complicated or complex settings by generating virtual elements that are intended to imitate real-life processes. Agent-based models generate many independent and interacting virtual agents that are also the primary units of analysis. These agents are ‘self-contained programs which can control their own actions based on their perceptions of their operating environment’ (Huhns and Singh, 1997) and they can be built to represent independent and adaptive individuals or elements in a system.

While the social sciences have seen much of the early development of ABM, it is also increasingly being used for analysing social behaviour and organisation in an archaeological context. Important studies include Kohler et al.’s influential work on Anasazi populations (1996) and Graham’s spatial and social network analysis based on Antonine itineraries (2006). ABM is also increasingly seen in more natural science and engineering applications, though specific construction applications are more limited. Notable examples consider the construction supply chain, such as the early work by Tah (2005) who used ABM to simulate alternative approaches to supply chain management. More recently, Son et al (2015) have reviewed the use of ABM in construction research and note, in particular, its ability to deal with emergent behaviour in complex systems and the advantage that ABM might have over more reductionist approaches.

In the wider research studies, for which this paper forms a part, ABM will be mobilised to allow an understanding on three fronts: firstly, we aim to integrate information from different domains (archaeological, textual, historical and ethnographic) into a coherent narrative that can be visualised in simulation models. Secondly, simulation experiments will generate hypotheses about the day-to-day construction activities, different levels of agency and major organisational decisions taken in these levels. Finally, we intend to improve our understanding of the life of the individual as well as the socio-political and economic framework involved in large-scale construction projects in late antiquity through the reassessment of labour and material organisation set within a geographical and temporal framework.

This paper is an early exploration of ABM and will focus not on the construction of the aqueducts and bridges of the system, but instead on a resevoir built in what is now the south west of current Istanbul, the Fildamı cistern.

CASE EXAMPLE: MODELLING THE CONSTRUCTION OF THE FILDAMI CISTERN

The Resevoir

The Fildamı Sarnıcı (Turkish) or κινστέρνη τοῦ Ἕβδομου (Greek – Cistern of Hebdomon) was one of the largest known *open air* cisterns (or resevoirs) of Byzantine Constantinople (Figure 3).

The dimensions of the cistern vary very slightly between literature. We have used Ergil's (1974) interior measurements – 127 m by 76 m – and the survey completed by Bono et al in 2000 for the thickness of the walls (Figure 4). Ergil describes the cistern as being North-South orientated, and talks of how the land on which it sits slopes downwards to the east. This land orientation is also interesting because it is the motivation behind the monumental niches that are constructed into the outer face of the east wall – in order to strengthen the ability of the wall to resist the force applied by the water – and the inner face of the west wall – similarly to resist the force of the soil.

Figure 3 The Fildamı Cistern from South-West corner in 2014 (Photo: Crapper, 2014

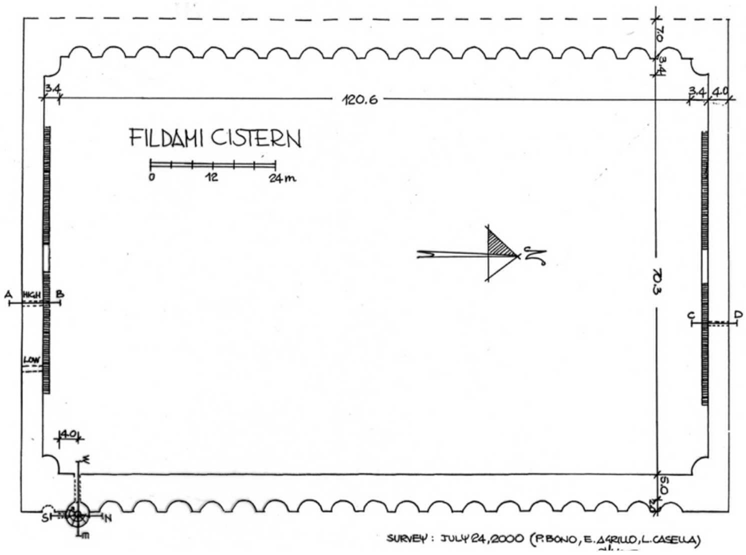

Figure 4 Plan of Fildamı Cistern (Bono et al., 2000)

The exact height of the cistern is slightly varied across several of the sources, since the remains of the structure no longer reaches the full height when first constructed. The survey carried out by Paolo Bono in 2000 suggests that at its highest point, the internal wall would have measured 11m. This suggestion is supported by Ergil, who stated that the interior walls were visible to a height of 10m, but that soundings taken at the time suggested that the cistern floor was 1m below what was then the ground level (Ergil 1974). Comparison with other contemporary structures such as the Anastasian Wall (see Snyder 2013) suggests that the foundations go down to a depth of 3.25m below current ground level.

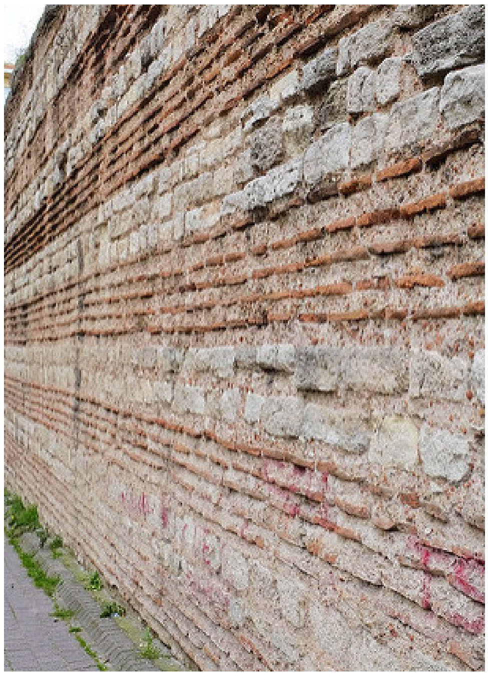

Figure 5 'Opus vittatum' construction – alternating courses of stone and brick. (Photo: Smith 2014)

Primarily, the walls of the cistern are constructed in *Opus vittatum,* a typical Roman form of construction in this example consisting of alternating layers of bricks and of cut stone facings with a rubble core. Focussing on the internal walls which expose more of the facing - there are eight stone and rubble layers, and nine brick. A typical layer of bricks consists of five courses of square bricks, approximately 33 cm long and 3-4 cm thick – with the layers of mortar between the brick horizontally and vertically being the same thickness of the bricks themselves (Ergil 1974). The bricks were all made specifically for the purpose, and contain no brickstamps to betray when they were made.

Modelling scenarios

As a historical artefact, modelling the structures of Constantinople's water supply presents interesting challenges: that they were built cannot be disputed, their presence and mass are clear tributes to the engineering and construction skills of the time. Yet how they were built is more difficult to know. This of course is a primary aim of the overall research; but most modelling exercises will be undertaken with some degree of how a specific system works and this is, unfortunately, absent for the water supply of

Constantinople. A number of scenarios of possible representations of the construction plan and sequence, based on analogous archaeological and historical data, were considered in order to allow modelling to commence. These ranged from a strategy of stockpiling, whereby all materials arrived to the site before construction commenced, to the completion of a single course of stone or brick masonry over 40m of length before continuing to the next course. Each scenario represented a plausible stratigy for construction based on our limited knowledge of historical building practices of the Late-Antique and Byzantine east. The scenario modelled for this paper was chosen to be that construction occurred in 4m-length sections of wall, built to full height.

The advantage of this scenario is fourfold: First, it represents evidence of work gang practices found in the archaeological record such as in the 'contract sections' seen at the Eifel Aqueduct in Cologne (Hodge 1992). Second, unlike the course-by-course scenario, all the types of materials used in its construction can be considered (if not the whole quantities) in each run of the model. Third, this allows for the rapid upward construction evidenced by thick mortar joints and creep from increased load on masonry whose mortar has not fully cured. This is typical of Late Antique and Byzantine structures, most commonly discussed in regards to Constantinople's Hagia Sophia (Mark and Çakmak 1992, 1994), which was finished in just under five years. Fourth, from a purely pragmatic standpoint, this scenario significantly reduces computational runtime compared to the others, making it possible to test a wider range of inputs.

The development of the working model

Using the scenario outlined above, the model was constructed using the ABM modelling platform *NetLogo*, an open source, GPL programming environment developed by Uri Wilensky at Northwestern University in 1999 (NetLogo, 1999) which uses at its core the concept of *Turtles* and *Patches*. A *Turtle* is an autonomous agent that can move – for instance a Stone Mason (worker) or Limestone (material); while a *Patch* is one that is a stationary geographic location, such as a quarry or brickyard. Alongside the agents are the inputs to the model, such as number of quarries, distance to travel, size and quantity of brick-kilns etc. The levels of these inputs have to be hypothesised – unlike the modelling of modern construction where time and motion studies might be undertaken, no such data exists. Therefore historical and archeaology texts are used, principally that of DeLaine's *The Baths of Caracalla* (1997) to provide estimates for manpower and ox-cart productivity.

The agents are set up using the input parameters and are then subject to procedures that dictate their function and govern how they interact with other agents. Utilising these core principles, a model logic is constructed to recreate the production and transportation of the materials to the Fildamı worksite.

It is important to note that in this early form of the model the actual construction of the wall itself is not modelled, only the delivery of the materials. It is reasonably assumed that a separate model could be created to represent the actual construction but this is not yet done. Instead we need to ensure that the materials are delivered in a timeous manner to allow the construction to proceed.

Figure 6 shows an annotated, typical arrangement of the turtles and patches for the developed model.

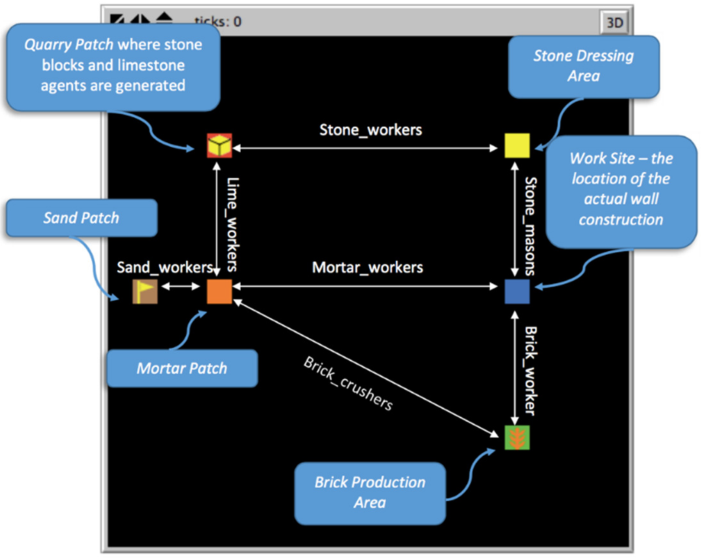

Figure 6 Schematic of Agent Based Model of Fildamı Cistern Wall Materials Production and Delivery

RESULTS

The outputs from the model of the system can be manipulated, tested and experiemented with in a manner consistent with normal modelling methodologies. Key outcomes from this model include:

- The most obvious outcome and easiest to appreciate is the overall time to complete this modelled system, that is the production and delivery of the materials necessary to construct the 4m width, full height (approx 13.5m) of the Fildamı wall is approximately 36,500 minutes – just over 50 days. But clearly this is dependent on the nature and level of the inputs to the model.
- These inputs will affect the outcomes or 'response' of the model and a working, valid model can be subject to a sensitivity analysis to determine which are the most prominent. This was done via Factorial Experimentation with the conclusion that the brick kilns had greatest effect among all inputs, that is the response to the model, in this case time to complete, was most sensitive to the number of brick kilns used.
- With no historical or archaeological data pertaining to the construction of Fildamı other than the structure itself— i.e. size and type of workforce, completion time, material acquisition, planning— this model has allowed us to input analogous information from other historical construction projects. Intitial results have so far confirmed that under similar conditions, Fildamı could have been built of local raw materials in a timely manner with no need for large-scale stalkpiling (with the exception of brick) or significant idle time for labourers.
- Previous research in the archaeological community has been limited in its ability to fully justify certain parallels that have been drawn between both historical and modern phenomenon. This model has provided a means of testing scenarios built upon common late-antique building processes attested to in the wider archaeological and historical records as well as test plausability of conclusions drawn in other studies in the field of engineering archaeology.

DISCUSSION: APPLICATION OF ABM TO ARCHAEOLOGICAL ENGINEERING AND MODERN CONSTRUCTION MANAGEMENT

The case example above is an early overly simple implementation of Agent Based Modelling to attempt to hypothesise the construction of an ancient structure. Nevertheless, the usefulness of ABM has been demonstrated. Results can be generated even when there is very little direct data to represent the input to the system and, as mentioned above, this is crucial when studying construction in late antiquity, where evidence is sparce and seeing the whole picture is seemingly impossible. The model is manipulated to propose multiple 'what-if' scenarios on how the materials production and delivery could be undertaken, with straightforward inspection used to make a judgement on the likelhood and efficiency of the resulting output. As Siebers et al (2010) acknowledge, this contrasts with alternative modelling platforms such as Discrete-Event Simulation, which, while having been thoroughly tested with simple modern cyclic processes (see for example the early work of Smith, 1998) require robust mathematical representations of the input parameters.

From an archaeological perspective, this model has been extremely fruitful as a confirmation exercise for the use of comparitive data to study past construction projects. Using pre-industrial labour rates (manpower) has been commonplace in the field of archaeological engineering since DeLaine's (1997) seminal work on the Baths of Caracalla in Rome. These figures play a central role in our model, acting as the parameters for the rate at which a process can be completed. The common assumption has been that the labour rates would be similar for any craftsman before mechanisation, as long as the tools and general social conditions were the same. While the results of this model do not secure these rates as fact for late antiquity, they have proven to be reliable constraints in all scenarios.

The real beauty of ABM is its scalability and adaptability and this is realised on a number of levels. First is that a model, once constructed, can in itself be then used as an agent in a larger model. For instance, in the case study example above the model for the construction of a single section of wall can then be inserted as an agent in to another model of the construction of the whole cistern; this in turn could be an agent in a model of the whole infrastructure system. The second feature of ABM to be noted is that the rules and procedures that are written in to the code to dictate how the agents behave and interact can be easily updated, again in a way that the 'hard-wired' logic of say Discrete-Event simulation cannot. In our early application, these rules are very simple such as 'move one ox-cart load of limestone from the Quarry Patch to the Mortar Patch'. This does not have a stochastic aspect nor does it include human social behaviour. However, it could be investigated how social interactions influence the system output where each agent is given a decision-theoretic model of the world, varying beliefs about its environment and individual motivations on how to respond to the actions of others. This is a future aim of our research, where we can build upon extensive work already well established in the psychology field (see for instance Marsella et al 2004).

Finally, ABM can be coupled with Geographic Information Systems (GIS) to provide updatable and/or scenario based data input on the geographic nature of a system. Archaeologists have been using GIS within ABM for some time but mainly as a means of investigating settlement and movement patterns. In the case of constructing the water supply of Constantinople, where the system to be modelled is approximately

470km in length (Ruggeri et al. 2016), this is an exciting possibility to explore innovative avenues of GIS and ABM applications. Early work coupling QGIS with NetLogo is already underway on the water supply with an adapted model presented in this paper as a part.

CONCLUSIONS

- Via a short modelling example ABM has been shown to be effective in dealing with the complex interactions of seemingly autonomous agents, allowing for the emergent properties of these systems in a way that existing simulation methodologies might not manage.
- This can be assumed to be the case not only for the historical example shown in this paper but also for modern construction applications: ABM has potential to grow from its mostly sociology and economic applications to being a fruitful research approach for many construction applications.
- The outcomes of the model of the Fildamı resevoir demonstrate that of all the agents and inputs to this system it is the ‘Brick Kiln’ that is the most significant. The importance of this finding to the archaeology community is very significant. While there is good understanding of the process of historic brick production, the involvement of bricks in the actual construction process as a whole is rarely properly explored in modern research, let alone viewed as a critical player in scheduling. The results here suggest that brick production and brick use are potentially more significant in the overall management and undertaking of Byzantine construction than previously thought.

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from The Leverhulme Trust, grant number RPG-2013-410, which has enabled the research behind this paper to be undertaken.

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