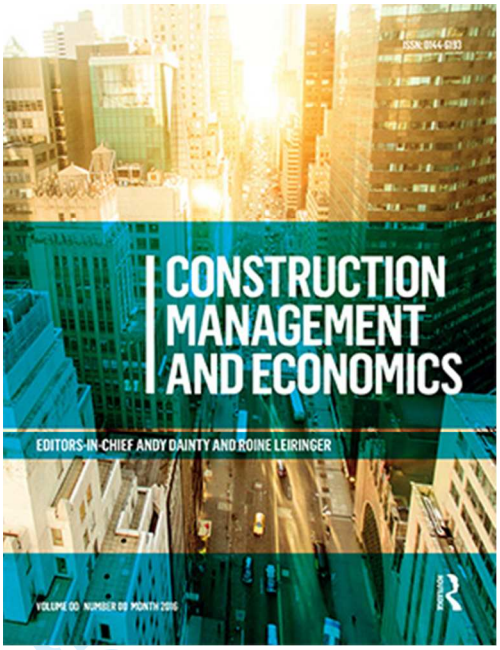

Agent-based modelling and construction – reconstructing antiquity's largest infrastructure project

Journal:	*Construction Management and Economics*
Manuscript ID	RCME-IP-16-0022.R1
Manuscript Type:	Invited Paper
Keywords:	Heritage, Project management
Keywords (user-entered):	Agent-based modelling, Byzantine Constantinople, Archaeological engineering

Agent-based modelling and construction – reconstructing antiquity's largest infrastructure project

Archaeological remains around the world are testament that large-scale construction projects have been successfully carried out for millennia. This success is particularly evident through the great infrastructural works of the Roman Empire. Yet, it was when the capital was moved from Rome to Constantinople that the largest of these projects was undertaken. This megaproject of the fourth- and fifth-century water supply was made of hundreds of kilometres aqueduct channels and bridges that brought fresh water to the city's complex system of reservoirs and cisterns. Unlike projects of the previous centuries, we are left with no written record of how this titanic project was undertaken and existing archaeological and historical commentaries on structures of this period do not provide details of organisation of construction. We explore the nature of building Constantinople's water supply through diverse sources of knowledge and the application of agent-based modelling— a method for simulating the actions, interactions and behaviours of autonomous agents and the resulting emergent properties of the system in which they are a part. This paper demonstrates the ability of ABM to develop and test richer hypothoses about historical construction organisatione and management than the sparse or missing physical and historical evidence on their own.

Keywords: heritage, project management, Byzantine Constantinople, Archaeological Engineering, agent-based modelling.

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 society has been an area of significant interest for centuries, if not millennia.

Project Management as a means of delivering solutions that meet these needs is often considered a modern concept, born from the systematic application of tools and techniques to complex engineering projects (Kwak, 2005). But if we turn to the classical sources for a perspective on construction projects and their organisation, we see the conceptual similarities to 'modern' project management. Vitruvius, a Roman architect and engineer from the first century B.C., wrote about the fundamental principles of architecture (*De architectura, 1.2.9)*, saying "Economy denotes the proper management of materials and of site, as well as a thrifty balancing of cost and common sense in the construction of works." A little over a century later, a politician named Frontinus was appointed *curator aquarum* (Commissioner of Water) for the city of Rome, during which time he wrote about the management of the city's water supply. This role included the responsibility for public work crews and he writes:

> *It was customary for members of each of these large crews to be withdrawn for use in private construction, through favoritism or negligence on the part of those in charge. I determined to recall them all to some orderly management, and I organized these public servants that I myself should prescribe a day in advance what each crew was to do and by having a record kept of their daily accomplishments (*Frontinus*, De Aquaeductu Urbis Romae*, 117.4).

While "we see much that resonates with contemporary 'good management practice'" (Morris 2013), it is important to keep in mind the differences between modern Project Management and the management of projects in history. Walker and Dart (2011) point to the way processes were enacted as being the most significantly difference from modern project management. They continue by explaining that Frontinus, as an "accidental project manager"

with sole responsibility for the success or failure of a project, wielded great authoritarian power over workers and contractors. This encouraged a project's success through fear of repercussions, a feature of Roman imperial culture rather than a systemic practice isolated to construction.

Constantinople's founding as the administrative capital of the empire in the early fourth century was rooted in a rapid infrastructural building programme, much of which is still visible in the great urban sprawl of modern Istanbul. However, unlike the extensive written evidence we have concerning earlier Roman construction from the likes of Vitruvius and Frontinus, there is very little to help answer how large-scale projects like the longest Roman water supply system were managed in Constantinople. This lack of written evidence has led many scholars to conclude that this aspect of Roman society was also part of the broad decline attributed to the Late Roman period, without the consideration of the physical evidence. Cases of failures and fissures in administration in the later empire are dwelled upon in Manas's (2010) book on projects in the Roman Empire. However, this is contrasted with the work of Chiu (2012), who produces a well-researched examination of important large-scale projects in the medieval period, particularly three case studies from the fifth and sixth centuries.

In order to gain a better understanding of the construction of the ancient mega-project of Constantinople's water supply, the expertise of archaeologists and engineers have been brought together in a unique initiative. The interface of archaeology and engineering is not common but not entirely new either. While they represent two very different cultures of research (Jerkø, 2009) the desire for most parts of modern society to understand and protect its cultural heritage perhaps requires a multi-cultural approach. In addition to providing insights into the factual aspects of these historical sites and indications of the needs of the

day, this interdisciplinary approach is used to addresses the *human side* of the construction of Constantinople's water supply including the organisation and governance of the project.

We have two primary aims to cover. First, we shall briefly outline the nature of the water supply of Constantinople, a fourth- and fifth-century AD infrastructure project. This will address the basic questions of *who, what, when, where and why* that are answerable by traditional historical, archaeological and architectural evidence. Our second aim is to explore the *how*— specifically, how was this megaproject realised? Not knowing exactly what type of construction management tools and practices early Byzantine builders had, we have generated hypotheses and examine how well they a) fit into facts about the site and historical information and b) yield results towards the completion of the water supply given the conditions of the time by using computer simulations. We will introduce and explore the use of Agent-Based Modelling 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— an important step in furthering the academic debate and theory-building about a topic and time period underrepresented in modern scholarship.

CONTEXTS

A brief history of Constantinople's water supply

Emperor Constantine's decision to move the administrative capital to an eastern fishing village called Byzantium in the early fourth century preserved a changing empire for over a millennium. Located on the Bosphorus Strait in the heart of what is now modern Istanbul, Byzantium was chosen as the 'New Rome' and was eventually renamed Constantinople after its founder (Treadgold 2001). With its new status came a massive population influx, creating a strain on the most valuable resource of a successful Roman city: water.

Unlike Rome, however, there was not a plentiful source of fresh water in the city or immediate environs. The mid-fourth-century court orator named Themistius described Constantinople as being at threat of becoming a city "girdled by gold but dying of thirst" (Mango 1995). Only 15 years after Constantine founded the city as 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.

The initial long-distance line was completed around 373 AD at an impressive length of 246 km in length stretching into the Thracian hinterland. This single-channel system was far longer than any other line from a Roman aqueduct, yet there was more to come. In the fifth century, an additional long-distance line was built even further west to spring sources near the modern town of Vize – a length of at least 181 km and likely much longer (see Ruggeri et al. 2016). This construction phase was marked by larger channels and monumental aqueduct bridges (Figure 1), some reaching almost 40 m in height and 140 m long. The overall development of the water supply system is shown in Figure 2.

Once the water reached Constantinople, it was collected and stored in the many cisterns and reservoirs throughout the city. While storing water in these structures was not a new phenomenon, the size and quantity of those found in Constantinople marked a great transition from typical Roman water management (Crow, Bardill and Bayliss 2008). At present count, 211 cisterns or reservoirs were built from the time the city was founded through Ottoman rule (Ward et al. 2016). These ranged in size from covered cisterns of only a few cubic meters to vast open-air reservoirs that could hold up to 240,000 m^3 of water. Covered cisterns were typically constructed with thick walls abutted against a hillside. Their ceiling was usually groin vaulted and supported by monolithic columns, providing a foundation for large structures to be built above (Ousterhout 2008). Open-air reservoirs were also built into embankments. Because the high walls would need to retain the embankment or the weight of

stored water, these structures featured buttressing of semi-circular niches projecting inward or outward respectively.

The structures of the water supply system are made up of three basic materials: stone, mortar, and bricks. Walls and vaulting of cisterns were commonly constructed of solid brick masonry whereas open-air reservoirs were built of *Opus vittatum*— a common building style in Constantinople made of brick courses alternating with mortared rubble courses faced with small dressed stone (Figure 3). Stone masonry was used exclusively on the fourth- and fifth-century aqueduct bridges and channels in Constantinople's hinterland. However, vast quantities of crushed bricks were still required to produce the waterproof mortar that was used in all structures of the water supply system.

In terms of procurement, much of the materials for constructing the water supply came from local sources (Snyder 2016). This was a common practice for non-decorative materials throughout the classical period. Just as today, land transportation was one of the costliest ways of travel, especially for freight. This was typically done with ox carts, particularly slow over uneven ground and requiring the added concerns associated with animal welfare. For a linear structure like the water supply, choosing raw material sources close to the worksite would be more economically viable than a single centralised quarry, for instance.

We know considerably less about the actual builders of the water supply. As mentioned above, the textual evidence for construction in late antiquity is sparse and archaeological remains reveal very little about the people who were involved in these projects. In fact, the only definitive information we have are masons' marks— ambiguous monograms possibly denoting individual masons, guilds or workshops— on the monumental fifth-century bridges (Figure 4) and stone water pipes within the city. An added difficulty is that this was a period of great cultural and administrative transition, reflecting a time between the formally educated Roman architect (engineer) and the experientially-trained Byzantine master builder.

As Constantinople grew with a massive population influx of peoples from diverse cultural backgrounds, it is likely that the labour force reflected this same diversity.

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 (Dilaver, 2015).

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 (AB) 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 purposes; though specific construction applications are more limited. Most 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. Sawhney et al. (2002) review the use of ABM in answering questions within complex construction systems. They conclude that by combining ABM with more traditional discrete event approaches, these systems can consider human factors that impact the construction site such as worksite safety, education, and the integration of a diverse workforce. These human factors have been investigated further using ABM in the work of Ahn and Lee (2014). They have provided additional credibility for modelling the influence of social interaction on worksites by comparing data collected through surveys of individual workers. Other 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.

CASE EXAMPLE – MODELLING THE CONSTRUCTION OF THE FILDAMI RESERVOIR

In this study, we focus on antiquity's largest infrastructure project and aim to reach a better

understanding of the management and organisation of this project. To this aim, we integrate different types data and information within an AB model, and use this model to re-construct an element of the water supply, Fildami Reservoir *in silico*. In this section, we will introduce the reservoir and the model.

The Reservoir

The Fildamı Sarnıcı (also known as the Cistern of Hebdomon) was one of the largest known open air reservoirs of Byzantine Constantinople (Figure 5), located outside of the Theodosian Land Walls of Constantinople in the modern neighbourhood of Bakirköy. There is also no clear date for its construction but it is suggested that it was built sometime in the later sixth century (Ergil 1974 and Crow 2012b) or during the seventh century (Bardill 2004).

The Fildamı reservoir serves as a vital case study for the understanding of infrastructural construction in the Byzantine Constantinople. Because of its location outside of the most densely populated areas of the modern city of Istanbul, it retains much of its original structural features. It has been extensively studied and surveyed and matches both the building styles and materials used on the three open-air reservoirs within the ancient city of Constantinople— Mocius, Aetius and Aspar. Furthermore, we know that it was located in an area that was close to stone quarries (Van Millingen 1899) and brick yards (Bardill 2004).

The dimensions of the reservoir vary very slightly between sources. 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 6). Ergil describes the reservoir 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.

The exact height of the reservoir 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 11 m. 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 reservoir floor was 1m below what was then the ground level (Ergil 1974). Comparison with other contemporary structures of similar height such as the Anastasian Wall (see Snyder 2013) suggests that the foundations go down to a depth of up to 3.25 m below current ground level.

Primarily, the walls of the reservoir are constructed in *Opus vittatum*. Focussing on the internal walls which reveal more of the facing - there are eight coursed stone and rubble layers, and nine brick. Despite no surviving evidence, it is assumed that a fine layer of waterproof plaster would have been applied to the walls of Fildamı and other open air reservoirs in a similar fashion to covered cisterns and channels.

A typical band of bricks consists of five courses of square bricks, approximately 33 cm long and 3-4 cm thick – with the mortar joints being horizontally and vertically the same thickness of the bricks themselves (Ergil 1974). The bricks contain no brickstamps, markers typically used to determine when and where they were made. It is entirely possible, based on the consistent size throughout the structure, that these bricks were not reused and may have been made specifically for the reservoir.

Modelling Approach and Implementation

The AB model in this study is used for three main purposes. Firstly, as briefly mentioned above, the model development exercise enables us to integrate different sources of historical and material evidence and benchmarks within a coherent framework of re-generating the construction process *in silico*—in a way comparable to experimental archaeology. Secondly, through simulation experiments, we explore the nature of core production and construction processes within their historical context and in a simple virtual environment that has similarities with the actual geography of the water supply. These explorations provide a better understanding of the material aspects and requirements of this large-scale construction project. Thirdly, based on this improved understanding of the material side, we generate new questions and experiment with different scenarios about the human side of the project, and identify where different management regimes would have a more visible impact. Overall, the AB model allows us to study the interdependencies between different production and construction processes, the effects of natural and built environment on these processes and the role of management strategies and practices on the project outcomes.

We used qualitative and quantitative archaeological and historical data both for conceptualising and calibrating the model. We focus on the model conceptualisation here as we explain calibration latter in detail later in the section. As it was common in Roman infrastructure projects, we thought of the construction project to consist of relatively small contract sections instead of, for example, one large and continuous project that is managed as a whole. Then, within these contract sections, we aimed to represent the core production processes as accurately as possible. This functioning core of the model was based on a work breakdown structure that analysed the processes involved in creating and transporting all of the materials from their source locations to site. Starting from the material evidence about

Fildami Reservoir, we studied construction materials that are used and investigated historical conditions related to the production of these materials. We studied the geographical conditions of the region, to have a general understanding of where material resources would be available and how scarce they might be in the natural environment. Finally, with respect to different management regimes, we focused on the narrative of Frontinus, who was appointed as the *curator aquarum* of the project. We used his vision of daily management of activities and his description of how it was before as two of our benchmark scenarios related to project management, as it is further explained below.

The model was implemented using the ABM modelling platform *NetLogo*, an open source, GPL programming environment developed by Uri Wilensky at Northwestern University in 1999 (NetLogo, 1999). At its core, it uses the concept of *turtles* and *patches*. A *turtle* is an autonomous agent that can move – for instance a stone mason or mortar mixer in our model; while a *patch* is one that is a stationary geographic location, such as a sand quarry, brickyard or construction site (Figure 7). ABM in general and Netlogo in particular allow for variable or static inputs to the model that reflect the states of agents and patches, as well as representing the context of the study (e.g. number of quarries, distance to travel, size and quantity of brick-kilns). This approach also enables execution of the modelling code by multiple heterogeneous agents using individual level or general (model level) variables, and thereby, allows for more direct representation of behaviour and interactions.

Conceptual Elements of the Model

Agents: There are three classes of agents in the model: people, sites and ox carts. People are further divided into workers and managers (including site managers and a project managers).

Although it is not explored in the preliminary experiments introduced in this paper, people are heterogeneous in various dimensions. They have different occupations and they vary in their skill levels for each production activity. They also have an age and home town. Sites organise production activities, hold capital (kilns), employ workers and procure input materials. Ox carts are used to carry material. They have a volume and weight capacity as well as an average speed.

Environment: The environment in our model conditions and settings that our agents find themselves in. These have three main components: natural, built and social environments. Regarding the natural environment, the model uses a hypothetical, flat landscape where there are multiple possible sites that clay, sand and limestone can be quarried. Among these three materials that can be acquired from the nature, clay is widely available, sand is relatively more specific to be available in certain areas and limescale is the most specific material available in multiple locations but not everywhere. We generate a hypothetical natural environment with these three resources and place our built environment within this geography.

More specifically, regarding the built environment, we assume the construction site is at the centre of the landscape and choose the locations for clay, sand and limestone among the proximate locations where these resources are available. We retrain the information that represents the environment to be able to re-generate it and run a broad range of experiments using the same virtual environment.

We conceptualised the social environment as a socially constructed technological setting which provides the agents set procedures for natural resources to materials of use-value. While these technological settings are socially constructed and part of the agency of humans as a whole in the very long run, we consider them part of the environment – the conditions and settings the agents find themselves in - for two reasons. Firstly, technological settings in

our case are also shaped by the physical conditions of the materials. Secondly, these production technologies stayed more or less the same for millennia and in this respect, from the perspective of our agents they were set and given realities rather than an area where they could use their agency.

There are eight different types of material that we represent in our model. These are: clay, sand, facing stone, rubble, lime, bricks, crushed bricks and mortar. The production of these eight materials involve diverse processes. While clay, sand and rubble are quarried and so acquired from nature by using labour, other materials such as crushed brick and mortar require material inputs. Lime and brick production also involves capital as material inputs are fired in kilns. Furthermore, while production of other materials are more or less continuous processes, kiln and lime production involves batches and processing (drying, firing and cooling) times.

The model represents these processes with two main functions. The first one represents quarrying; acquiring material from nature. In this context, we assume material is abundantly available at the quarry sites in comparison to the project needs. So production is a direct function of labour/skill hours.

$$\mathbf{FQ_i = f(L_i) = \alpha_i L_i} \quad \text{where } i=1,..4$$

L stands for labour days and $\boldsymbol{\alpha}$ represents productivity of a worker with average skill levels. If workers are more skilled than average, they can take less time to quarry, if they are less skilled they took longer. The second function represents transforming one type of material (inputs) into another form (outputs).

$$\mathbf{FPi = f(R_{ij}, L_i) = min\ [(R_{ij}/\beta_{ij}), L_i/\ \gamma_i]} \quad \text{where } i=5,..9 \text{ and } 0<j<5.$$

In this second function Rij are the quantity of material inputs j of production process i. The number of material inputs (and hence the upper bound of j) varies for different processes but is lower than 5. βij is the amount of material j required for production process i, and γ i is the same for Labour/skill hours.

Drying, kiln firing and cooling processes are mainly modelled as waiting processes, that are managed by variables and arrays in the model although two workers are constantly allocated when the kiln is being fired.

Actions and Interactions: The main dimension of agency we are focusing on this study relates to production and construction activities, and their management. One of the main sources of complexity related to the material side of the project is that the work in different sites of production and construction are interdependent on each other via input-output relationships. Among the eight materials that are used in the project facing stone, rubble, bricks and mortar are used directly in the construction. Clay and sand are used in the brick production, crushed brick and lime are used in mortar. At the same time, rubble, which is among the direct inputs of construction, is also used for producing lime. Similarly, brick is used for producing crushed brick that is needed for mortar.

In this regard, there are different hierarchies between materials. A practical implication of these hierarchies both in the real production processes and in our simulations is that different types of clients may have ordered material from a stone quarry or brick factory and these sites need a way of deciding which order to take first. These decisions are not trivial because extended delays in the delivery of orders to either type of client – the construction site or other production sites – can impede completion of the project. The decisions are not trivial also because the orders coming from the construction site have a different nature than those

coming from other production sites. More specifically, the orders coming from the construction site occur less often and they are much bigger in scale.

Regarding the agency of workers during the production processes, the model generates workers that are heterogeneous in their skill levels and therefore allows studying idiosyncrasies during day-to-day functioning of the project. Furthermore, by locating agents working on a particular process next to each other, we have constructed virtual conditions in which agents can learn from each other. While these properties of the model enable representation of various organisations of labour and work life, in the current study we focus on studying interactions between sites and leave worker-related processes for future research. Similarly, we employ a simple representation of project management in current experiments (Figure 8). This representation is based on allocation of workers to different production/construction processes. The project manager allocates a certain number of workers in a particular process and workers produce outputs according to production functions given above.

Calibration of the model

The AB model represents the construction project in contract sections. These sections are calibrated in the experiments as 4m-length sections of wall, built to full height and erected simultaneously with other sections. This representation is important for three reasons. First, it represents evidence of work gang practices found in the archaeological record. Unlike the larger contract sections discussed in the building of aqueducts (Hodge 1992), this is closer in similarity to the catacombs of Trajan's Market in Rome where archaeological evidence shows clear demarcations of vertical sections (Volpe & Rossi 2012). Second, this representation is consistent with 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. Third, and in relation to the simulated events, in a contract section project, unlike a course-by-course scenario, all the types of materials used in its construction will be considered throughout each run of the model. This simulates the constant need for all materials to arrive to the construction site in a timely manner considering both current and future need.

The levels of materials used in the construction are calibrated based on previous studies. The first set of inputs comes from reverse quantity surveying of Fildamı. Archaeological survey data was used to break down the total structure into volume and number (where applicable) of bricks, stones, and mortar. The volumetric estimate for mortar was separated further into the raw material constituents of crushed brick, sand and lime based on petrographic analysis of mortars from the water supply (Snyder 2016). This quantitative information is used as static inputs, which are dictated by the physical remains of the structure. In order to reflect the chosen scenario, these material quantities were also calculated for each band of brick and stone band within the designated 4 m stretch of wall.

The rate at which a given task can be carried out is also calibrated based on existing literature, in particular historical rates for manpower presented by DeLaine (1997) and based on Pegoretti (1869). The aim was to build a model that reflected a plausible real-life historical system representing construction processes and individual interactions, but we also used some simplifying assumptions in the current study. For instance, it is assumed that an average work day is twelve hours with a two-hour break and that construction would stop during months with unfavourable weather conditions (DeLaine 1997).

With respect to transportation of material, it is assumed that speed and weight limits would have applied to both short- and long-haul transportation. For example, a law from the fourth century limits ox-cart loads to a maximum of roughly 500 kg (*Codex Theodosianus* 8.5.30).

Scenarios and Experiments

The simulation experiments presented in this study cover four scenarios distinguishing between project management regimes and the way production sites decide on which order to deliver. While the development of different management regime scenarios was inspired by Frontinus's narrative as explained above, the scenarios related to the way sites pick which order to deliver came from initial experimentation. During the initial set of experiments, we observed a very high variation in project completion times. In some experiments, the project was never completed, even in long (10,000 ticks – days in this case) experiment runs. Further analysis of experiment flows showed that this variation was caused by the way production sites choose between orders in terms of delivering produced materials. As materials such as brick and rubble are both required by other production processes (crushed brick and lime respectively) in addition to the construction site, the way orders are picked for delivery affected the results. We, therefore, designed two different algorithms of randomly picking an order or a client. The four components of scenarios are summarised below.

i) Random Allocation of Workers: In this project management regime, trying to represent the chaotic setting Frontinus describes to exist before he started managing the project we envisaged workers that are randomly assigned to the the nine production and construction processes. That being said, there are many ways an algorithm that randomly assigns agents to sites can be designed. In the current model, we envisaged production sites that were previously functional but, in time, due to lack of management and contingencies, shifted into employing irregular numbers of workers. To implement this conceptualisation, we used the same number of rounds of allocations for each site, but we allowed previously assigned workers to be picked during the worker allocation process as well.

Workers remain in their sites once assigned and produce the same outputs with a constant production rate for each material throughout the experiments.

ii) Daily Planning of Worker Allocations: This scenario is based on Frontinus' management style of assigning tasks to workgroups in advance. In the current study we use a simple heuristic for representing Frontinus' worker allocations. Considering the lack of optimisation tools in his time but the Roman administrator's awareness of the general nature of the production process, we generated an *a priori* schedule that first allocates more workers in the quarry processes and gradually moves workers towards lime, brick, crushed brick, mortar and finally to construction processes. We used an input file that has such a shifting allocation to implement this regime.

iii) Random Order Pick: In this scenario, production sites decide on which orders they should deliver first by picking an order randomly from the set of open orders.

iv) Random Client Pick: In this scenario, production sites decide on the order they will deliver first by randomly picking a client from a non-repetitive list of clients with open orders.

Results

the outputs of the experiments are simulated data, which can be analysed both qualitatively and with statistical methods like in other modelling methods. Key outcomes from the model are presented here to show the potential of answering the research questions about the construction of Fildamı reservoir.

In the first scenario (random allocation of workers with selection between orders), we see a very high number of runs that did not complete the construction of the section of Fildamı

before the limit of 1000 days was reached. Of the nine runs of the experiment that did complete, the earliest completion was just shy of one year. The rest of the successful runs are scattered up to almost 800 days. In the second scenario (random allocation and picking clients), all runs of the model complete within the experiment time. There is a large variation in the time each run completes but almost all fall between 250 and 725 days with no runs completing before 175 days. Switching to the third scenario (daily plan for allocations and picking orders), just over half of the runs completed. While this scenario shows the greatest spread in the time to complete—between 50 and almost 950 days—the vast majority of those that complete do so rather quickly between 55 and 65 days. Finally, the fourth scenario (daily plan and picking clients) completed the section on every run. In this case, the time to completion varied very little between 52 and 64 days.

The difference in results with respect to picking orders versus clients occur because for project to be completed sufficient amounts of brick and rubble should be delivered to both other production processes that use these materials as inputs and to the construction site. The orders that other production processes issue are more frequent and smaller in quantity ordered compared to the orders of the construction site that are very few and very big. Thus, when brick and rubble sites cannot immediately satisfy all orders, if they choose randomly between open orders, they are more likely to choose an order from other production processes simply because they have more orders than the construction site. Moreover, as other production sites continue to send their orders and orders accumulate, the probability of the construction site's order being picked falls even further in simulated time. This leads to a bifurcation in project completion times; if the construction site's order is not picked in the early periods of the simulation experiment, they may not be picked at all. In this regard, without our intention, the way orders are randomly picked in the model created a Pólya urn process that leads to bifurcations.

In scenarios where the site picks randomly among clients, the production sites that have high number of small orders and construction site that has few big orders have equal likelihood of being picked. This practice creates enough variation in satisfying demand at different levels of material hierarchies leading to relatively quick completion times (Figure 9).

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

The case example above utilises agent-based modelling as a means to hypothesise the nature of constructing an ancient structure. Results can be generated by integrating different types of data to shed light on processes where little direct data exists. As mentioned above, this is crucial when studying construction in late antiquity, where evidence is sparse and seeing the complete picture is seemingly impossible. The model is manipulated to propose multiple 'what-if' scenarios on how the material production and delivery could be managed, with clear outputs available to make a judgement on the likelihood 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 and rigid mathematical representations of the input parameters.

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. Early runs of the model explored these inputs via Factorial Experimentation, with the conclusion that the brick kilns had greatest effect to the models

response—in this case the time it took to complete. These initial results confirmed that Fildamı could have been built under the most ideal, yet unrealistic conditions (unlimited labour and transport resources) in around 50 days with no need for large-scale stockpiling—with the exception of brick—or significant idle time for labourers.

When applying the experiments on labour distribution and order selection to the Fildamı model, it was clear that these management scenarios had a large impact not only on the time of completion but also on the successful completion of the project. When there was a daily plan even with a static, *a priori* plan, the chance of completing the project within days of the optimal time mentioned above greatly increased compared to a chaotic work environment shaped by individual contingencies and favouritism.

At the same time, among the scenarios we have tested, the biggest impact was the decision regarding which order was to be fulfilled. Our results showed that randomly picking clients was important in delivering completion, even when workers were distributed randomly to tasks. It should be noted that delivering orders on a first-come, first-served basis did not solve the problem either due to the size of orders coming from the construction site.

In our model, we kept the way sites pick from open orders the same throughout the experiments. In real life, when one method does not work well, agents can intervene to make changes. At the same time, the complexity we identified with the help of our model would still be an issue that requires attention, particularly in the context of simultaneous construction of many contract sections and limitations related to planning tools and communication. In this context, as our experiments indicate, procedural knowledge or established norms of trade with respect to which order should be delivered first can have unintended consequences on the overall project.

From an archaeological perspective, this model has been extremely fruitful as a confirmation exercise for the use of comparative data to study past construction projects. For instance, 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 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 for the model.

A somewhat unexpected result first appeared during reverse quantity surveying and was confirmed through Factorial Experimentation. Bricks would have had to have been produced specifically for the purpose of being crushed as an ingredient of mortar. It was initially thought that the unsuccessfully fired or broken bricks could have been used exclusively. However, the large quantity of mortar used with high proportions of crushed brick was far outweighed the quantity of structural brick. Furthermore, the critical nature of brick production and the resulting competition for supply would have required a separate industry—probably within the brick production industry—for this key material. This finding is of great interest to those studying late antique and Byzantine Constantinople as there is no archaeological or textual evidence about what must have been a massive brick industry.

Like most modelling platforms, ABM allows for 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 within a larger model. For instance, in the case study example above, the parameters from modelling the construction of a single structure of the water supply of Constantinople can then be inserted into 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. This is where the application of ABM to questions of a historical or archaeological nature have a strong advantage over other modelling techniques. Hypotheses about past social behaviour can be tested through changing rules of interaction based on partial or missing data.

ABM can also be coupled with Geographic Information Systems (GIS) to provide updatable and/or scenario based data input of a geographic nature. 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 at least 425 km in length (Ruggeri et al. 2016), this is an exciting possibility to explore innovative avenues of GIS and ABM applications within a vast and complicated terrain. Within the broader research project on the engineering of the water supply of Constantinople, the CLAWS (Constructing the Late Antique Water Supply) model is being designed on a much larger scale, encompassing a significant section of the channels and bridges that brought water to Constantinople (Figure 10). This model is bound by the output criteria of the Fildamı model while exploring the implications of managing a multi-site megaproject. Importantly, the CLAWS model takes advantage of geospatial elements of the Thracian environment. In the same way that modelling the Fildamı reservoir has started to inform us of the management of material procurement and supply, the larger CLAWS model should provide much needed historical information about the socio-political and economic framework involved in state-sponsored construction projects in the late antiquity.

The opportunities afforded as well as obstacles faced by the integration of ABM in modern construction is still to be seen. It is likely that some of the same limitations that have been encountered in this project will be faced in future applications. For instance, how do we identifying the necessary attributes required to depict the real world without the obfuscation

of unnecessary detail? How do we model the social characteristics of the agents that crucially influence interaction when the workforce has yet to be identified, let alone given their own voice?

In other cases, we foresee major advantages to applying ABM to modern projects. Where many of our inputs regarding material procurement, decision making, division of labour etc. are assumptions about historical constructs, the longstanding procedures of good management practice provide a clear framework for modelling. Furthermore, issues surrounding aspects of decision making hierarchy and cost are not necessarily muddled in ambiguity or hyperbole as is so often the case in the scant historical evidence.

CONCLUSIONS

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.

Via a case study of a historical construction example, ABM has been shown to be effective in dealing with the complex interactions of heterogeneous agents, allowing for the emergent properties of these systems in ways existing simulation methodologies might not manage. This can be assumed to be the case not only for the historical example presented here but also for modern construction applications. ABM has already shown its potential to grow from mostly sociology and economic applications to being a fruitful research approach for many

subject areas. The conclusions drawn have great potential to be used in a wide range of applications within production of the built environment.

The outcomes of the model of the Fildamı reservoir so far demonstrate that of all the agents and inputs to this system it was the way in which orders were received at production sites that had the largest impact on its construction. Even in the event that all tasks were planned a day in advance as Frontinus indicates, the management of input material orders would have to be taken into equal consideration— likely by someone more localised to the production area. All of this provides strong support for the hypothesis that a high level of management of tasks and resources from the top down was crucial in the timely success of construction projects. Within the larger context of the management of the larger megaproject of the water supply of Constantinople, the competition of resources between multiple worksites would require some heuristic strategy for the many levels of decision making.

Returning to the discussion in the introduction about modern project management versus the history of how projects were managed, we must remember that this is not an exercise about how history can inform modern project management or vice versa. While there are many similarities in the ways projects are managed, Walker and Dart (2011) and Morris (2013) provide clear explanations about the folly of applying Project Management principles to historical construction projects. What has been shown through a historical case example, however, is that ABM is an innovative method that allows an understanding of construction projects in the absence of detailed input data. Such scenarios are not uncommon from early stage construction planning activities seen in modern projects.

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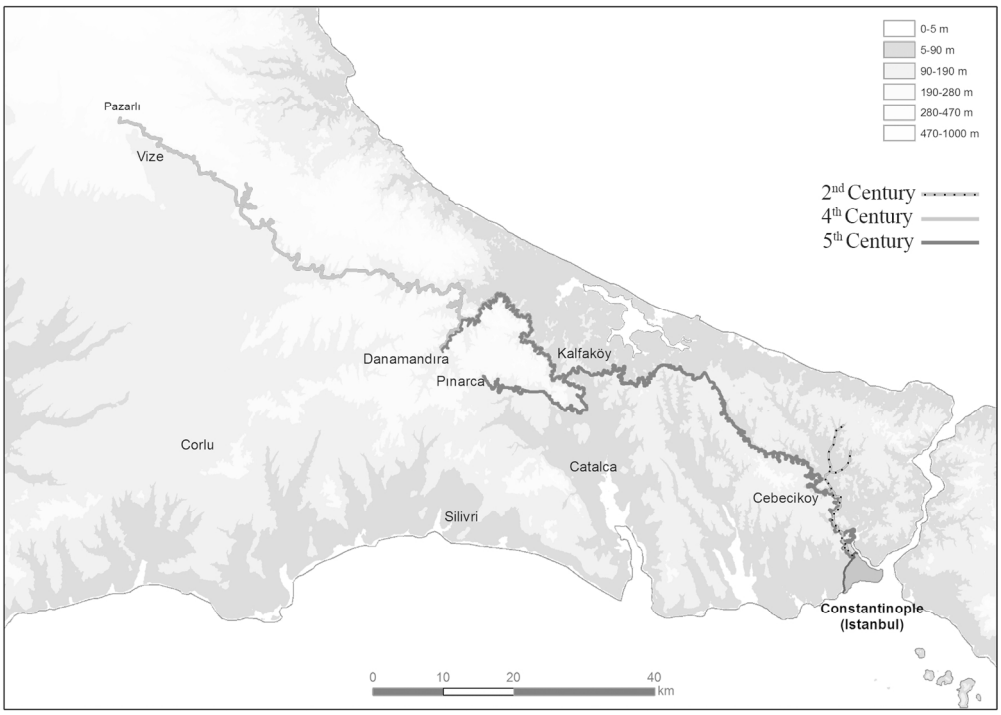
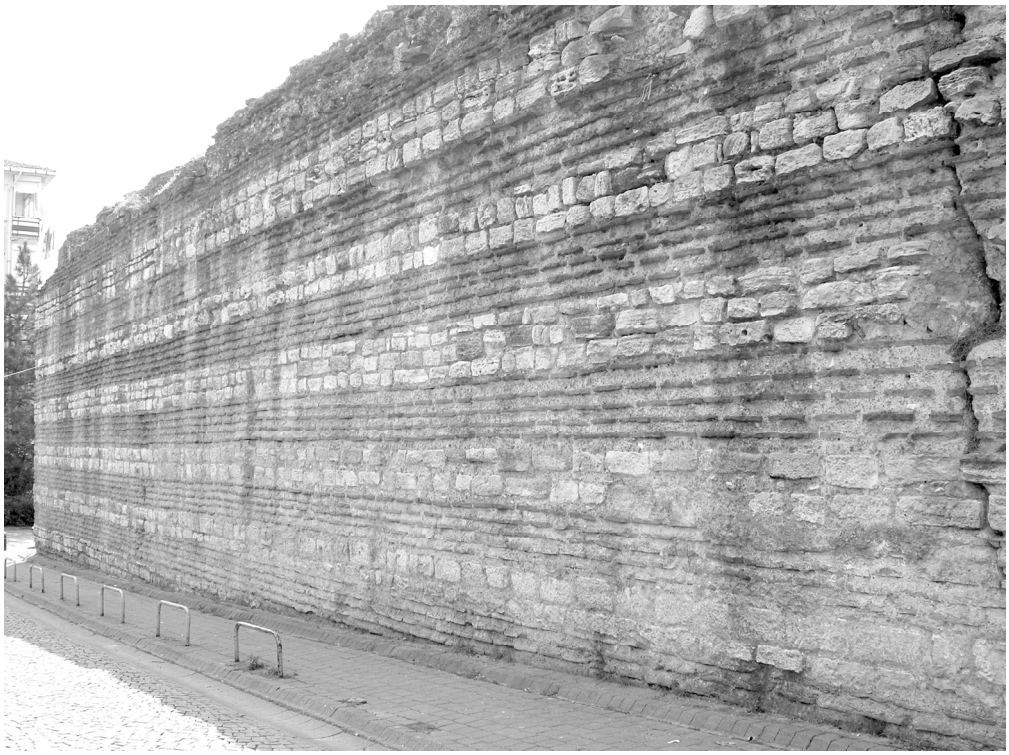
Kumarlıdere (L) and Kurşunlugerme (R) aqueduct bridges. (Smith 2015)

455x150mm (72 x 72 DPI)



Map of the Byzantine water supply of Constantinople and the spring sources feeding the system (after Ruggeri et al., 2016)

150x106mm (300 x 300 DPI)



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

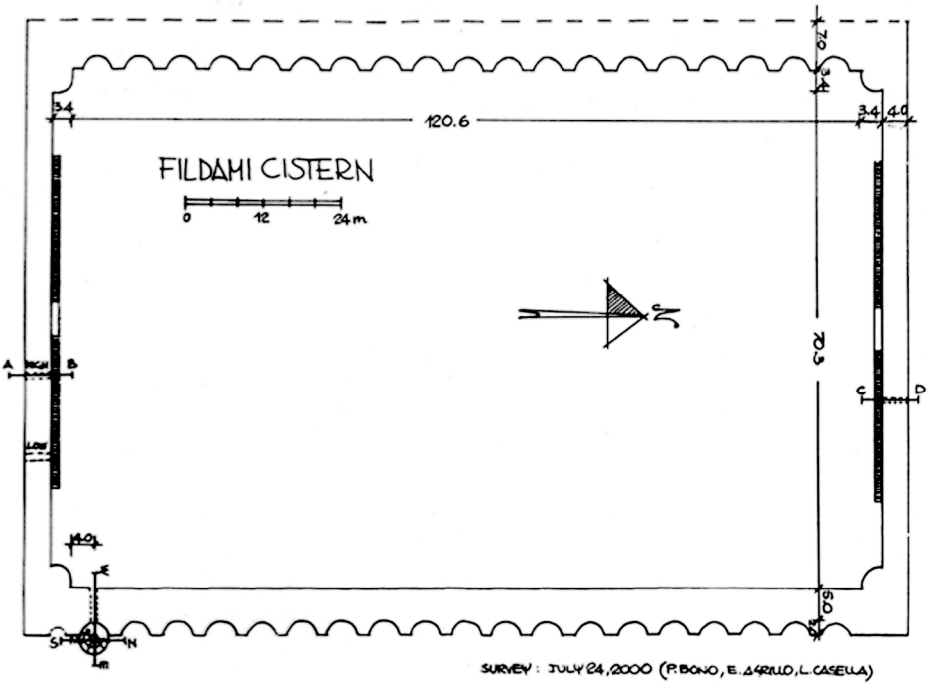
147x109mm (300 x 300 DPI)

A masons' mark from Kumarlıdere aqueduct bridge. (Snyder 2008)

142x106mm (300 x 300 DPI)

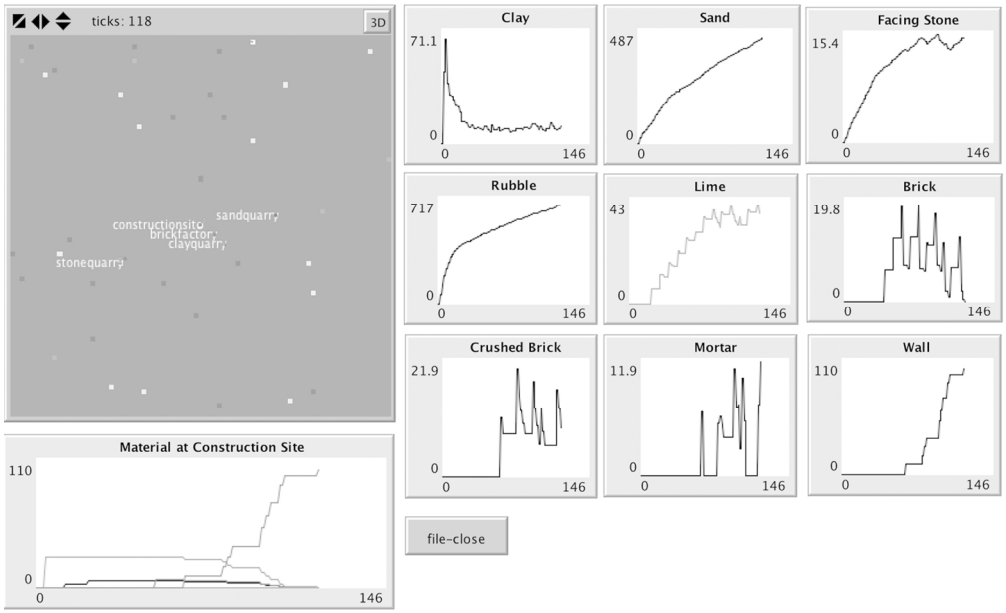
Fildamı Reservoir. (Smith 2015)

159x74mm (300 x 300 DPI)



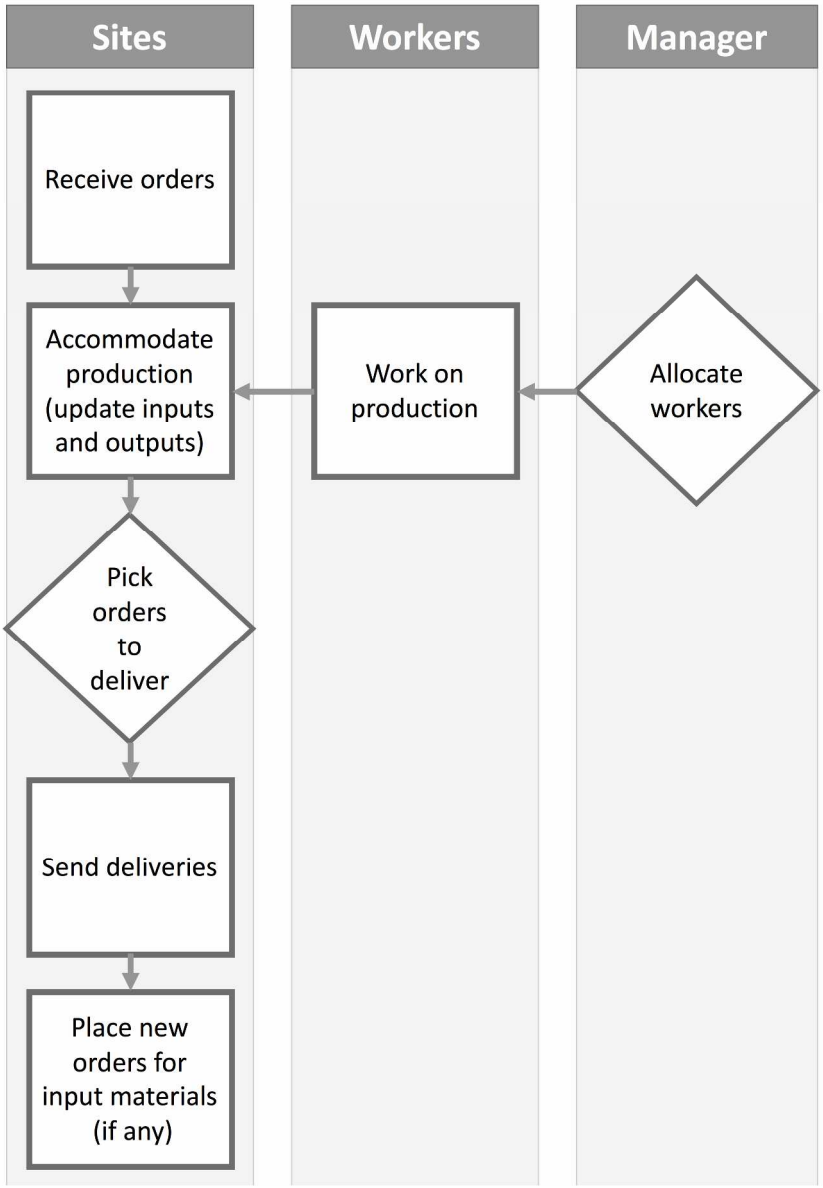
Plan of Fildamı Reservoir. (After Bono et al. 2000)

205x141mm (300 x 300 DPI)



Schematic of agent-based model of the building of Fildamı reservoir showing the production and delivery of materials to the construction site.

133x81mm (300 x 300 DPI)

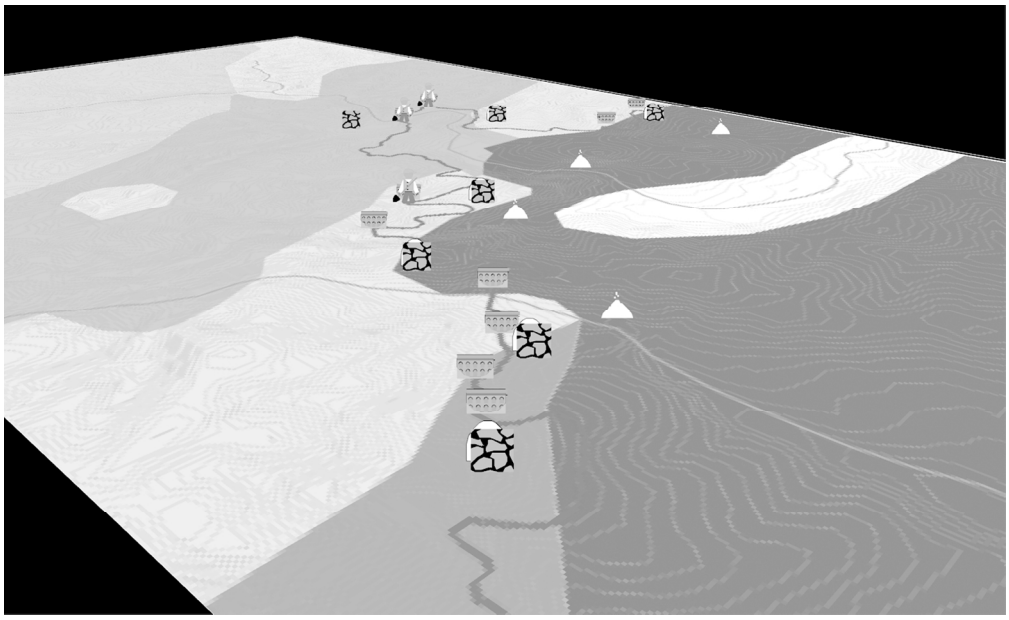


Flowchart showing the main algorithms used in the model for sites, workers and manager.

266x355mm (300 x 300 DPI)

Results of the simulation scenarios showing the time it took to complete the simulation. Each dot represents a run of the simulation where the wall of the reservoir was successfully completed.

353x231mm (300 x 300 DPI)



CLAWS model depicting the GIS environment of the fifth-century phase of construction.

120x73mm (300 x 300 DPI)