MEDIEVAL WARFARE ON THE GRID

by

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ABSTRACT

Although historical studies are frequently perceived as clear narratives defined by a series of fixed events; in reality, even where critical historical events may be identified, historic documentation frequently lacks corroborative detail to support verifiable interpretation. Consequently, interpretation rarely rises above the level of unproven assertion and is rarely tested against a range of evidence. Agent-based simulation can provide an opportunity to break these cycles of academic claim and counter-claim.

This thesis discusses the development of an agent-based simulation designed to investigate medieval military logistics so that new evidence may be generated to supplement existing historical analysis. It uses as a case-study the Byzantine army's march to the battle of Manzikert (AD 1071), a key event in medieval history. It describes the design and implementation of a series of agent-based models and presents the results of these models. The analysis of these results shows that agent-based modelling is a powerful tool in investigating the practical limitations faced by medieval armies on campaign.

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1 Introduction

1.1 Introduction

Warfare has always been an integral part of human society and whether the military succeeds or fails often has a massive impact on societies in general. For this reason a key part of state bureaucracy is the organisation of the military for offensive and defensive action, ensuring sufficient people are in the right place at the right time and in the right condition to threaten or achieve military supremacy. However despite its importance, far more effort has been expended on examining the battles and personalities of military history than has in examining the systems required to get military forces across often hostile environments in sufficient shape to win those battles, mainly because far more of the primary sources focus on these topics (Luttwak 1993, 5–6). Modern developments in information technology have placed new tools in the hands of archaeologists that allow us to understand the issues involved with military logistical organisation.

The movement of an army depends on the interrelationship between its constituent elements, with individuals often numbering in the tens or hundreds of thousands. Previous work on military logistics has tended to treat an army as a single entity, moving and consuming resources as a unit. New techniques such as Agent-Based Modelling (ABM) allow us to add more complexity to investigation into the movement and provisioning of armies. This thesis focusses on the use of ABM to more fully understand the complexity involved with moving large numbers of people across pre-industrial landscapes. It takes as its case study the march of the Byzantine army of Romanos IV Diogenes across Anatolia to the Battle of Manzikert in AD 1071. This presents an attractive subject for study due to the significant gaps in the historical record and the importance of the battle to the medieval world and beyond. With this in mind, the Medieval Warfare on the Grid project (MWGrid) was conceived by Professor Vince Gaffney and

Dr Georgios Theodoropoulos of the University of Birmingham and Dr. John Haldon of Princeton University as a way to provide new types of evidence to add to the historical debate on the significant gaps in knowledge regarding this important milestone in European and Asian history. It was funded by a joint AHRC-EPSRC-JISC e-Science grant and commenced in 2007. This Ph.D. was produced as a part of the MWGrid project. The project also included the development of a distributed computing infrastructure however, due to the departure of the original Computer Science Research Fellow, this was not completed in time to be used during this Ph.D. with implications that are described in more detail on page 107.

This thesis is a result of my work on the project and aims to examine the way individual behaviours affect the performance of the Byzantine army as a whole, focussing on its march across Anatolia to Manzikert in AD 1071. It will apply ABM to the field of medieval military logistics, a technique never previously used, in order to increase the detail of traditional top-down, systemic approaches and examine the emergent behaviours of an army on the march. It will focus on the two main concerns of military logistics: movement and supply, and highlight the advances in knowledge possible using detailed computer simulation. It will also add a quantitative element to the evidence surrounding the Manzikert campaign, giving new impetus to the stagnant historical debate regarding the size and conditions of the marching Byzantine army.

The MWGrid project was conceived as a distributed ABM, running in a grid computing environment. It was designed with this in mind and anticipated an ABM that could model the march of the army across Anatolia in one run of the simulation. Due to problems with the development of the distributed infrastructure, the decision was made to focus on individual day's marches as a way of reducing the computing resources required. These day's marches form a discrete unit that can be used to examine the effects of army size and composition on overall movement rates and food requirements. Although grid computing is not specifically used in the scenarios presented as part of this Ph.D. the distributed infrastructure is still being developed and the ABM has been designed with this in mind.

In this chapter I will outline the events of the Manzikert campaign and illustrate their significance to the Medieval world. I shall then highlight the problems with the historical record and our attempts to understand it. I will demonstrate that computer modelling has the ability to test old hypotheses and provide new evidence against which to test our knowledge of the Manzikert campaign. In chapter 2 I will describe the design of the macro-scale ABM that will allow us to fill in the gaps identified in chapter 1. This will include the characteristics and behaviours of the army derived from contemporary accounts, military treatises and more modern reports. In chapter 3 I will describe the implementation of the ABM including documenting the development process and specifying the outputs created. In chapter 4 I will look at the results from a series of scenarios run using the model, each simulating a day's march under various conditions, and describe the implications of these results. In chapter 5 I will assess the impact of the research, discuss how the results can be applied to other contexts and describe how the model can be used for other purposes. Text in *Courier Italic* font refers to Java code used in the ABM itself, all maps have north at the top.

1.2 The Manzikert Campaign

In 1068 the Byzantine Empire was in a more precarious position militarily than it had been for almost a century. Basil II left an expanded empire with a strong successful army and a healthy treasury when he died in 1025. Basil died childless and left his brother Constantine VIII as head of the Empire and since then Byzantine military strength had suffered from civil wars, rebellions and a preponderance of bureaucratic Emperors (Haldon 2008, 165). Basil II's successes meant that the Bulgars no longer provided a threat across the Danube and in the east the aggression from Muslim lands was limited. Due to a series of military revolts in the 11th century, driven by the anti-military policies of the Emperors, the thematic levies had been unused and in some cases disbanded in favour of regionally recruited tagmata, whereas the field armies had been partially replaced by foreign mercenaries (Haldon 2008, 165).

Figure 1: Byzantine Anatolia showing the Turkish raids

By 1068 the reduction in defences of the East had led to a series of raid by Turkish nomads (Attaleiates 1853, 148) (Figure 1). The nomads were encouraged by the Seljuk Turk rulers to prey on Byzantine Anatolia instead of Seljuk controlled areas further east (Haldon 2008, 168). Seljuk successes against Armenia, including the sack of Ani in 1064, had met with no strong resistance from the distracted or inept Byzantine rulers, so when the Empress Eudokia's husband Constantine X Doukas died in 1067 it became clear to even the pro-bureaucrat Empress that a military leader would benefit the empire. It was in this spirit that the general Romanos Diogenes, brought to Constantinople in order to be punished for leading a revolt, was instead chosen by the Empress to be her husband and the next Emperor (Ostrogorsky 1969, 344).

Romanos IV Diogenes as he then became, established as his first priority the need to stop the Turkic nomads from raiding Anatolia. Hampered by the lack of experience of the thematic troops and the hostile, bureaucratic Doukas family in Constantinople he hastily assembled an army to try and engage the nomads in battle. The nomads themselves consisted of a series of mobile bands, elusive and difficult to commit to an engagement. Romanos reasoned that if he were to engage them in pitched battle, superior Byzantine organisation, numbers and heavy troops would triumph over mobility. During 1068, Romanos chased the nomads across Anatolia without ever being able to decisively engage them. A similar campaign took place in 1069 (Vratimos-Chatzopoulos 2005). In 1070, Romanos left the general Manuel Komnenos to fight the Turks while the Emperor stayed in Constantinople attempting to secure his position on the throne. Manuel Komnenos had no more success than Romanos had done although none of these campaigns could be said to be a complete failure either (Attaleiates 1853, 139). At least there was now a more hostile environment in Anatolia for the nomadic raiders.

In 1071 the Emperor set out with an army that the Armenian monk Matthew of Edessa called "more numerous than the sands of the sea" (Dostourian 1972, 231). Although Byzantine sources give no numbers and those quoted by Arabic sources are likely to be inflated to emphasise the scale of the Byzantine defeat, it seems likely that this army was much bigger than those used in the previous three years. As the Arabic historian al-Husayni recorded in the early 13th century, "Byzantium threw its own lifeblood at the Sultan and the Earth brought forth its burdens of men and equipment" (Hillenbrand 2007, 53). The Emperor's aim was to engage the Seljuk Turk Sultan, Alp Arslan, in battle and destroy Turk military strength on the eastern borders. Alp Arslan had in 1070 taken the border fortress of Manzikert and also besieged Edessa in 1071 although he was subsequently more involved with action against the Fatimids than he was with battling the Byzantine Empire.

In March or April 1071, Romanos sent an embassy to Alp Arslan demanding that he abandon his siege of Edessa and withdraw from the eastern border of the Empire, although by this point Romanos had already left Constantinople with his army so the extent to which the Emperor expected the Turkish Sultan to comply is debated (Haldon 2008, 169). Alp Arslan reacted by hastily assembling a force to resist the Byzantine army, although critically Romanos thought he had headed back to Persia to do this. In actual fact Alp Arslan had gathered a reasonably sized army on the eastern borders of the Empire long before Romanos had expected him to be able to do so. By the time Romanos reached Manzikert and recaptured the fortress without a fight (the defenders were released without harm), Alp Arslan was in the area with a sizeable force (Friendly 1981, 173).

Romanos headed out of the fortress on August 26th and arrayed his forces for battle. Advancing towards the Seljuk Sultan's camp the army were peppered with arrows from the mobile bands of nomads, using their mobility to avoid close combat. By the time the day was coming to a close the Byzantine army had still not been able to force the Turks into close combat and were prepared to retreat back to the fortress and try again the following day. It was at this point that a fatal strategic flaw of the Emperor's was made manifest. Romanos had brought a member of the Doukas clan, Andronikos Doukas, along with him despite knowing that his loyalty was questionable to say the least (Haldon 2008, 170). This was probably done so that he would act as a hostage to guard against any traitorous moves back at the capital while the Emperor was away. Andronikos had however been given command of the rearguard. When Romanos reversed his banner to signal the retreat, the rearguard should have covered the army as it left the field. As it was, Andronikos spread the rumour that the Emperor had been killed then ordered his units to retreat back to the fortress. Bereft of cover the other parts of the army were left to fend for themselves against the opportunistically attacking Turks.

The centre of the army was savaged and the Emperor captured. Possibly preferring an Emperor that could be beaten as opposed to an unknown successor, Alp Arslan treated Romanos relatively well. He extracted agreements from the Emperor, kept the Emperor's lavish baggage train that had been captured in the aftermath of the battle and released him after a week. By this time, however, word had got back to Constantinople that Romanos had been slain and the Doukas' had taken control of the Empire (Ostrogorsky 1969, 345). Romanos attempted to regain his throne by force but his revolt was defeated and he was captured. He was blinded by the new Emperor Michael VII Doukas with the intention of being confined to the monastery at Proti but died from the effects of the blinding soon afterwards.

1.2.1 The Importance of Manzikert

Manzikert is a pivotal moment in Medieval history and affected areas far dispersed from Eastern Anatolia. Runciman called it "the most decisive disaster in Byzantine history" (Runciman 1951, 61). The Byzantine Empire were afflicted by a period of civil wars from the defeat at Manzikert until Alexios I Komnenos took the throne in 1081 (Cheynet 1980). It was this unrest more than the military defeat at Manzikert that weakened the Empire (Haldon 2008, 165) but the usurping of Romanos by the Doukas family was the beginning of this unrest. The Byzantines never again controlled all of Anatolia and the Turkic peoples were never fully driven out, culminating in the fall of Constantinople in 1453 and the triumph of the Ottomans. The defeat at Manzikert also stoked European fears of the Muslim world and was in small part a catalyst of the First Crusade (Hillenbrand 2007, 1). The Ottomans in their turn gave way to the modern Republic of Turkey and Manzikert was the first major military victory of Turkic peoples within the borders of the modern state. As such it is well know in modern Turkish society and within the modern town of Malazgirt there is a statue to the Seljuk Sultan Alp Arslan. Manzikert occupies the same status as a pivotal event for the modern state of Turkey as the Battle of Hastings does for England (Hillenbrand 2007, 205). As the Byzantine Empire was a direct continuation of the Eastern part of the Roman Empire the Battle of Manzikert resonates through the ancient, medieval and modern worlds.

1.2.2 The Campaign

Of the actual campaign we know relatively little. Contemporary Byzantine sources include Michael Psellus, an anti-military bureaucrat who disliked Romanos and stayed behind in Constantinople (Psellus 1966), and Michael Attaleiates, a military nobleman who accompanied the Emperor on the campaign (Attaleiates 1853). A few decades after the battle, Nicephorus Bryennios, the grandson of a general of the same name who was on the Manzikert campaign, wrote an account (Bryennios). From contemporary sources we know that the Emperor left Constantinople for Manzikert in either late February or early March, crossed the River Halys near a place called Krya Pege where he expelled some German mercenaries from the army (Friendly 1981, 168), travelled via Sebastea and Theodosiopolis and split his army into two not far from Lake Van in order for half his forces to take the fortress at Khliat (Cheynet 1980, 424). There is no mention of any specific logistical problems en route so we can provisionally assume no exceptional disasters regarding provisioning or movement occurred. Attaleiates (1853, 146) does mention that at some point the Emperor split his own entourage away from the rest of the army and travelled independently but we do not know how long this arrangement continued for.

1.2.3 What is Missing?

The historical records have very different priorities than providing a practical account of the Byzantine army's logistical requirements. Michael Psellus is a committed supporter of the bureaucratic faction at court and his account is mainly concerned with emphasising Romanos' failings as a leader. In any case he stayed behind in Constantinople while the army went on campaign. Michael Attaleiates was on the campaign and was a supporter of Romanos but focussed more on the events surrounding the battle than on the march. As eyewitness accounts provide inadequate information specific to the Manzikert campaign, we must look to other works in an attempt to provide specific details as to how the army might have organised itself. Military treatises and accounts of campaigns are sparse from the middle of the 11th century as this was a comparatively peaceful period of Byzantine history. In comparison, the 10th century saw the publication of the three military treatises associated with Constantine Porphyrogennetos (Haldon 1990) along with The Tactika of Leo the VI (Dennis 2010) , originally written in the late 9th or early 10th century but subsequently expanded in around AD 1000 by Nicephorus Ouranos. The three military treatises translated by Dennis (Dennis 1985) may also belong to the 10th century but only the Strategikon of Kekaumenos remains as a major military work from the pre-Manzikert 11th Century. That is not to say that these works are of no use at all. Even the Strategikon of Maurice (Dennis 2001), written in the late sixth century carries useful organisational detail that may well have remained current until the 11th century. The probably 10th century treatise translated by Dennis as *Campaign Organisation and Tactics* for instance (Dennis 1985) provides details on how the Byzantine army should set out its camp. It also provides some practical details useful in moving the army such as the need to send surveyors a day in advance to set out the following camp site.

However certain key facts are missing from the historical record. The size of the Byzantine army on the Manzikert campaign is a matter of conjecture, discussed by Haldon (2008, 172) and Norwich (1991, 346) among others, modern estimates of 40-60,000 being considered reasonable but without sufficient evidence (Haldon 2006, 13). No numbers are given by Byzantine sources at all, although not because they were reticent to exaggerate numbers. Leo the Deacon claimed

400,000 for the army of Nicephorus II Phokas (Talbot and Sullivan 2005, 41:104). Some Arabic sources give numbers of soldiers for the Byzantine army at Manzikert but these seem more motivated by the desire to exaggerate the scale of the defeat than to provide accurate information. The numbers quoted in Arabic sources, often written hundreds of years after the battle, range from 50,000 through 100,000 and 300,000 to 600,000 soldiers (Table 1). Numbers in excess of 100,000 are considered highly unlikely by modern historians but the fact that the practical implications of moving large numbers of troops around Anatolia cannot be demonstrated is significant. Historians have, as yet, no framework within which to evaluate these numbers except other contradictory sources. Existing theories based on historical research suffer from a lack of testability (Haldon 2006, 4).

Historian	Approximate date of death	Size of Byzantine army	Page number in Hillenbrand, 2007
Aqsara'i	1333	50,000	96
Rashid al-Din	1318	100,000	260
Ibn al-Athir	1233	200,000	64
Ibn al-Azraq al-Fariqi	1177	300,000	34
Ibn al-Jawzi	1200	300,000	38
Nishapuri	1187	300,000	36
Sibt ibn al-Jawzi	1256	about 300,000	69
al-Husayni	1225	over 300,000	53
al-Bundari	1226	300,000	59
Rawandi	early 13th c.	600,000	259
al-Turtushi	1126	600,000	27
Ibn al-Qalanisi	1160	600,000	30

Table 1: Size of the Byzantine army from Arabic sources

Other gaps are apparent from the historical record. Although certain points along the route are known, the exact route is not detailed. No mention is made of the effect that the passage of the army had on the communities that it passed through. Direct archaeological evidence of the march of the army is non-existent due to the ephemeral nature of an army on the march.

This lack of metrics also applies to quantification within the military treatises, indeed there is a lack of quantifiable evidence throughout the historical debate (Haldon 2006, 2). No systematic survey is recorded where armies of various sizes marching various distances over various terrains are detailed along with departure times, arrival times and lengths of column. This information is important in enabling us to recreate the Byzantine methods of moving their armies. The military treatises themselves survive as a selection of hints and tips rather than an extensive how to guide to moving and supplying an army.

1.3 The Need to Model

The primary aim of this research is to study the movement of the Byzantine army on campaign and its implications on the settlements on which they relied. As the Byzantine army no longer exists it cannot be studied directly, and even if it did it would be a costly and complex endeavour to observe it in all circumstances. For this reason we have created a series of models. A model is an abstraction of the system to be studied containing only the aspects relevant to our research. The values we put in are hypothetical values rooted in real world metrics in order to ensure validity. The models can be used to express hypotheses and run simulations over time in order to compare the results. Because reality is too complex and the available data too sparse, it is unfeasible to build a single model and run it once, several models must be created and run multiple times with differing parameters in order to provide comparative data. The hypotheses must be tested against each other and against historical data in order to draw conclusions. The difference between the models' outputs and both the historical record and the outputs of other models will provide new evidence within which to frame the historical debate over the events of the Manzikert campaign. If the results of the models agree with the historical data, it doesn't necessarily follow that the model is an exact representation of our research target, different processes may end up with the same state. Similarly, if the results of the simulation do not fit observed data it does not mean that the model is of no use, the differences may be caused by known phenomena that are not included in the model. In the end the models will not produce an answer, what did happen, but we will be able to say what could have happened had circumstances been a particular way.

1.3.1 Why Can This Not Be Filled With Conventional Research?

Although much work has been done on Byzantine military organisation and logistics (McGeer 1995), the information given in military treatises and historical accounts can only take us so far. There is rarely enough information given for us to recreate the mechanisms of transport that were used, even if they were homogeneous across all circumstances. Despite the recommendations detailed in military treatises, there may have been situations in which the established order was altered to fit the circumstances. The issue of competence is also relevant, even if the treatises describe best practice it doesn't necessarily follow that this was adhered to.

The historical sources have been exhausted in the search for this information, all that is left from a historical point of view are arguments of claim and counter-claim. No new evidence is likely unless a previously undocumented account is discovered. It is possible to construct a model of the army, containing within it the characteristics we need to create new evidence within which we can frame the historical debate. Human and animal dietary requirements are well studied by medical professionals, veterinary biologists and sports scientists (Carpenter 2010). There is no reason to think that the space a human being or animal takes up in a marching column and speed at which it travels have changed significantly within the last 1000 years. It is possible to use these values to construct hypothetical models of an army on the march in order to test certain practical circumstances. This approach has been used by, among others, Jonathan Roth in his work on the Roman army (Roth 1999), Donald Engels on the Macedonian army of Alexander the Great (Engels 1978) and John Pryor on the Crusaders (Pryor 2006).

1.3.2 Adding Complexity to Engels and Pryor

Just such a system was used by Donald Engels in his book about the logistics of the army of Alexander the Great. Working from the historical record and filling in the gaps with more modern terrain and physiological data, Engels constructed a compelling model of the Macedonian army that was able to demonstrate that certain types of logistical arrangements were necessary in order to keep Alexander's force supplied. Working on the basis that each human required 3 lbs of grain and 2 quarts of water he was able to calculate a total weight of food supplies for the army. Adding to this the weight of food and water for the animals he could calculate the number of pack animals required for various sizes of armies marching for various numbers of days between resupply. He was able to take into account areas where water would be abundant and therefore unnecessary to be carried in bulk and areas such as the Gedrosian Desert where water would not have occurred at all. This practical approach allowed him to calculate the diminishing amount of space on each pack animal for the food of others as the amount of its own food that it needed to carry increased. With this he could demonstrate quite clearly the ever increasing number of pack animals required as the length between resupply locations increased. In one example an army that required 1,121 pack animals to carry one day's worth of supplies would require 2,340 for two days, rising to 40,350 for 15 days and 107,600 for 20 days (Engels 1978, 19).

By consulting the historical accounts he was able to produce a hypothetical size of the army at each point of its route and calculate how many pack animals it would need to get from supply point to supply point. In the process he demonstrated that without sophisticated logistical arrangements the Macedonian army could never have successfully travelled the distances that it did. By eliminating unlikely or impossible hypotheses he was able to demonstrate not only that Alexander's logistical arrangements frequently involved arranging in advance with the states on his route to provide resources but that logistical considerations at many times dictated how and where he would move.

Pryor uses this approach slightly differently, to examine the journey of Bohemond and his troops on their march to Thessaloniki in 1096 (Pryor 2006). Pryor uses an in depth examination of the historical records and contemporary evidence for supply requirements to attempt to frame Bohemond's journey in a practical context. He uses a hypothetical size and organisational framework of the marching column to estimate the column length and calls on Engels' work and others to examine the food requirements of both human and animal participants. Although basic and highly conjectural, as admitted in the concluding remarks, Pryor's work adds new evidence to a historical problem. More disturbingly it is the first application of Engels-inspired systemic logistical modelling to the First Crusade, and this almost 30 years since 'Alexander the Great and the logistics of the Macedonian army' was published.

1.3.3 Individuals

Another aspect often ignored by military historians is the effect of the individual. Historic analysis is often centred on the actions of eminent individuals yet armies in general are overwhelmingly constructed of the masses of people lower down the societal hierarchy than generals and Emperors. This is to a certain extent a factor of the biases inherent in the historical record, the focus of medieval writing is almost invariably the upper echelons. Any approach that can shed some light on the actions of the *hoi polloi* must be a good thing, expanding the scope of historical research in ways impossible to do when research is restricted to documentary evidence.

1.4 There is a Technology That Can Do This, ABM

The approaches detailed above are relatively simple to calculate, consisting of a series of values multiplied by the number of individuals. They take top down, systemic approaches to determining the behaviour of the army as a whole. However the army is not one organism for the purposes of movement but its overall progress is affected by the interactions between the individuals that comprise it. If one part of the army moves slowly, succeeding units must either bypass the hold-up or be reduced to the same speed. Various tactics can be used to mitigate against this kind of situation, from moving in a broad column where possible to splitting the army over several parallel columns or even marching parts along the same route but on following days. Different types of organisation can be used within the column and different combinations of cavalry and infantry are likely to change the overall dynamic. Larger armies should, all other things being equal, move slower than smaller forces. This all indicates that the system at work when an army moves is more complex than can be adequately modelled by the approaches of Pryor and Engels.

A complex system is one in which the overall behaviour of the system depends on interactions between the individual elements, or agents, which constitute the system and the environment within which they work (e.g. Resnick 1997; Holland 1998; Corning 2002). The behaviours that result from these interactions are called emergence and although they often arise from simple rules at the level of the individual agent, the interactions between the agents themselves and between the agents and their environment generates complexity that is often impossible to model using 'top down' approaches. The study of complexity in nature has been a growing area of scientific research from the second half of the 20th century but even before that, the work of such diverse researchers as Adam Smith, Friedrich Engels and Charles Darwin all touch on some of the central ideas of emergence such as the self-organisation of systems with no overall controller (Johnson 2002, 18). The term "emergence" as it relates to a specific process has been around since the 19th century although it was in the 1920s that it became widely discussed across a range of sciences (Goldstein 1999, 53).

Complex systems with emergent behaviours cannot be easily predicted just by knowing the parameters that control the behaviour of one of the individuals involved. If you know the speed of a car on an empty motorway you can calculate how long it will take to reach its destination. If however 100 other cars are using the same part of the motorway then knowing the speed of one car will not be enough information to help determine its arrival time at its destination. This is because of its interactions with other road users. It will be able to speed up when the road is clear but will have to slow down when other vehicles impede its progress. You would have to model the whole system in order to accurately calculate its arrival time. The whole system however has no overall controller determining how each car behaves. Each vehicle contains within it its own rules determining its behaviour and it is the interactions of these individuals that gives us the state of the motorway as a whole. So it is with moving large bodies of people. ABM is a computer modelling technique that replicates complex emergent systems such as these (Gilbert and Troitzsch 2005, 172).

It contains two main elements: the agents and their environment. The agents are autonomous software units that contain within themselves the rules for their behaviour and the characteristics that describe relevant attributes. The environment is the area within which these agents act and can be as sparse or as rich as required. The overall behaviour of the system comes from the interactions between the agents and between the agents and the environment. This system of autonomous agents operating within an environment is ideal for examining military logistics as the movement of the army itself is a complex system. John Holland lists some of the common elements of emergence (Holland 1998, 115), all of which apply to an ABM of the Byzantine army.

- **The model should model the world.** Our ABM models the march of the Byzantine army to Manzikert in AD1071, a real world event (see page 3).
- **The model should consist of multiple interacting copies of a limited number of components.** The MWGrid ABM consists of tens of thousands of agents of just five types; Soldier, Cavalry Soldier, Officer, Cavalry Officer and Column Leader (page 118).
- **The configuration of the model's components changes as time elapses.** Movement of agents is essential in a model of an army on the march (page 126).
- **Interactions are constrained by a succinct list of rules.** Each agent has a limited number of behaviours available to it (page 66).

1.4.1 The History of ABM

The concept of ABM has been around since the middle of the 20th century but it wasn't until the 1990s that computing power had advanced to the point where it became feasible. Prior to that, Conway's Game of Life (Conway 1970) and the cellular automata of von Neumann and Ulam (Von Neumann 1951) had laid the theoretical underpinnings while remaining low technology, Ulam's cellular automata being worked out on sheets of paper. Craig Reynolds' computer models of flocking behaviours were among the first that would be recognisable as modern agent-based models and were an early example of how a group of individuals with simple internal rules could replicate real world phenomena (Reynolds 1987). Agent-based modelling became much more technically feasible once Object-Oriented Programming (OOP) languages such as C++ and Java could be combined with sufficient computing power to take advantage of them. Object-oriented programming emphasises interactions between encapsulated data fields and methods in a way that makes ABM easier to implement. Since then the technique has been applied in a wide variety of disciplines, from architectural planning and emergency management (Thompson and Marchant 1995) and the development of computer games (Nareyek 2001; Schulz and Reggia 2002; Van Lent et al. 1999) to more abstract applications in social science (Epstein and Axtell 1996).

1.4.2 ABM in Archaeology

Although ABM, the modelling of the actions and interactions of autonomous agents within an environment, can be traced back through Conway's Game Of Life to the beginnings of cellular automata in the 1940s, its use in archaeology has a much shorter history. As early as the 1960s and 70s, interest was growing in the ability of computing to explore general systems theory (Doran 1970) however computational power had not advanced to the levels required to model complex systems dynamics. From the mid 90s onwards archaeologists started to appreciate the use of agent-based modelling for exploring the interactions involved in socionatural systems.

ABM's constituent elements of an environment containing autonomous agents acting within it have naturally attracted archaeologists interested in the development of societies. Taking archaeological evidence and using ABM to construct “what if?” scenarios in an attempt to fill in the inevitable gaps in our knowledge has enabled archaeologists to examine such problems as the rise of settlement complexity in the Bronze Age Fertile Crescent (Wilkinson et al. 2007), the emergence of states in Central Asia (Cioffi-Revilla et al. 2007) and the link between ecology and observed settlement patterns in the American south west (Kohler 2010). State-level ABMs dealing with societal complexity require data from many different fields as the problem is affected by many variables. This typically results in large, multidisciplinary projects comprised of a wide range of specialists.

The Village Ecodynamics Project (VEP), run by Timothy Kohler and Donna Glowacki, involves archaeologists, geologists, geographers, computer scientists and economists and seeks to explain key aspects of the societies inhabiting the area around south west Colorado between AD 600 – 1300 (Varien et al. 2007; Kohler et al. 2008). It couples detailed modelling of terrain and weather with human societies, plant and animal resources and water availability. By treating these elements as one socionatural system, a system where neither social factors or natural processes takes precedence, they have provided a complex model with which to test established theories and propose new ones. Building on established work such as Van West's published estimates of landscape carrying capacity when used for maize agriculture, the VEP were able to add detail to this work by incorporating it into an environment that simulated temperature and rainfall. This, along with the modelling of other plants used as food by humans and animals, enabled an environmentally deterministic model to be created which was able to be used as a null hypothesis to be compared with the data gathered by field survey. This model was also built on by adding sociological models such as Turchin and Korotayev's theories on warfare frequency in order to see how the data from the model matched up to Turchin's predicted outcomes.

Archaeological ABMs do not just consist of large interdisciplinary projects amassing large quantitites of data in order to solve a specific problem. More abstract models exist that focus on either one small aspect of a historical situation or a general process appropriate to various places and times. These projects require smaller teams, often being the product of just one or two researchers, Smith and Jung-Kyoo Choi's work on inequality (E. A. Smith and Choi 2007) and

Shawn Graham's NetLogo models of Roman civic violence (Graham 2009) being recent examples. These are unable to draw upon the breadth of knowledge that a large multidisciplinary project can muster but are typically smaller and more accessible, enabling independent researchers to download and alter them at will on easily available platforms such as a standard home PC.

Archaeology as a discipline is making increasing use of ABMs in order to fill gaps where archaeological and historical methods of enquiry cannot provide a full picture due to the very nature of the evidence they draw upon. The new types of evidence being created by ABMs are enabling archaeologists to ask questions previously considered unanswerable, whether they concern specific instances or more general themes. Due to modelling's modular nature, facilitated by its basis in object-oriented programming, individual elements can be reshaped and reused by further projects. The ability to take individual elements from previous projects and retest and tune them in a different setting means that future models will be easier to create and more thoroughly validated. Each project leaves a legacy, not only in conclusions on a specific topic, but also in a further set of tools to be utilised by future modellers.

1.4.3 Is the Byzantine Army a Complex System?

If agent-based models are ideal for studying complex systems that result from emergent behaviour, can we say that the Byzantine army on the march is such a system? Yes! Complexity theory shows that where emergent behaviours occur, our knowledge of an individuals state and behaviours will not allow us to predict the behaviour of the system as a whole (Gilbert and Troitzsch 2005, 10). This is a situation that applies to an army on the march, as the interactions between the agents and the constraints of the environment prevent accurate predictions of overall speed of the army based on the speed of its constituent elements. There is a concertina effect of stops and starts that prevents soldiers simply moving from one location to another at whatever speed they like. This is described beautifully by George Armand Furse in his book, *The Art of Marching*.

> *"This lengthening is brought about by the oscillations which the column undergoes, owing to the want of uniformity in the individual movements, which have their origin within the column itself like the wave of the oscillatory motion in a hanging rope. Every single oscillation produces a contracted wave, in which all the individuals are compelled to stop, to this follows a rarefied wave, in which the individuals accelerate their pace. But the checks being instantaneous, as it is natural and laid down, the individual quickening being gradual, the rarefied wave is always greater than the contracted, from which ensues gradually an abnormal lengthening out of the formation." (Furse 1901, 206)*

1.4.4 The Limitations of ABM

However ABM is only a modelling technique, it may be the most applicable to certain real world phenomena but it works within the limits of all models. In creating a model of an army on the march it is not saying that the model is what actually happened on the Manzikert campaign. A model is a hypothesis, waiting to be tested, ready to be refuted or upheld until a better model comes along that more plausibly describes reality. "All models are false, but some are useful" (Box 1979). In modelling the march of the Byzantine army it is accepted that it is not possible to model all aspects of the individuals or even all relevant aspects. It is possible to model enough of the important aspects to have a model whose results can be compared to the historical record to useful effect. The model will not show what did happen, it will show what would have happened should certain conditions be met. This can then serve as a benchmark against which existing theories about the Manzikert campaign can be compared. ABMs, particularly within archaeology where the actual processes involved can no longer be observed, can suffer from the problems associated with equifinality. Equifinality describes the condition whereby a particular end state may have come about by several different processes (Premo 2010). Just because there is a model that produces a similar end state to that seen in the archaeological and historical record it does not necessarily follow that the model accurately reflects the system at work. It may be that an entirely different system is responsible.

Archaeology presents many specific problems to ABM. Unlike medicine or physics, archaeological modelling generally starts with only a very small percentage of the originally available data. Similarly the end state of the process to be modelled will be poorly evidenced and may be almost completely opaque.

1.4.5 The Potential of ABM

Making models is a key part of scientific research, mental models representing hypotheses to be tested are formed when trying to fit data into a coherent system. There are many advantages to formalising these models in a computer system:

- Computer models allow quantification
- Computer models are replicable
- Computer models can be easier to show to others
- Computer models can be expanded and altered by others
- The process of modelling is useful to hypothesis formation

Computer models allow real world quantities and metrics to be reliably used. The classical Greek word 'logistike' when used in a military context specifically refers to any strategic or tactical operations based on quantitative calculation (Roth 1999, 1). Mathematical equations can be easily represented and resolved allowing data to be calculated reliably and quickly. The ability of modern computers to handle massive amounts of data means that computer models can reach sizes impossible with mental models. Computer models can be replicated, either by the original creator or other interested parties. They can be run with exactly the same parameters to verify that the model produces consistent output or with different parameters to compare the results. These parameters must be explicit, computer models deal with absolutes. It should be possible to examine all the data involved with a model and the processes that are enacted upon it. The processing and output of computer models can be used to explain hypotheses to others, whether it is another specialist seeking to examine the methodology behind the model or a generally interested observer. Even just the process of modelling often forces a researcher to think of circumstances and aspects of a problem that are often ignored, even if a computer model itself is never created (Aldenderfer 1981).

Among the many different types of computer model, agent-based models have specific advantages that make them useful to military logistics researchers:

- They are modular
- Their structure mirrors that of an army
- They can make use of similar work in other disciplines

The modular nature of agent-based models allows elements of the model to be changed easily. Agent types, behaviours and environment variables can be easily changed in order to compare with results from other models. It is this characteristic that makes them so suitable to object-oriented languages. Their modular nature allows elements from other disciplines to be fitted into the system as a whole. Specialists from other subjects can work on individual modules that can be plugged into the system when finished, only the inputs and outputs need to be specified beforehand. The hierarchical and modular nature of object-oriented programming mirrors that of the army itself, with divisions consisting of several brigades which are made up of several smaller units right down to the individual level. The hierarchy of classes in the software is similar to the hierarchy within the army itself.

1.5 Summary

The Battle of Manzikert stands as a pivotal point in the history of both Europe and Asia. It marks the beginning of the end of the Eastern Roman Empire and the beginning of the beginning of modern Turkey. Despite its importance, significant gaps occur in our knowledge of the events of the Manzikert campaign. Filling these gaps will also lead to a greater appreciation of the challenges involved in moving large numbers of people across a pre-industrial landscape. Lessons learned from this research can be used to benefit research in other locations and eras. Agent-based modelling is an appropriate tool to begin filling these gaps as it is able to provide new types of evidence against which we can test established hypotheses. Even the act of designing and constructing a simulation of the army's march can enhance our understanding of what happened on the Manzikert campaign. The next chapter deals with designing a simulation that can help us answer questions about the movement of the army and its effect on the landscape through which it travelled.

2 The ABM Design

2.1 Introduction

A model is an abstraction of reality, created in order to fulfil a specific purpose. In order to use agent-based modelling to fill in some of the gaps in the historical evidence, the model has to be designed to contain only the mechanisms and behaviours that will affect our results. Unnecessary detail will increase the complexity of the software without providing any benefit to the data produced. The design of the model is therefore of paramount importance as not only can a thorough design reduce the time and effort taken during implementation but the modelling process itself can provide valuable insights into the system to be modelled.

An agent-based model consists of two main elements; the agents themselves with their behaviours and characteristics, and the environment which acts as a modifier and constraint to the agents' behaviour. The model also needs to output its data in a useful format that allows analysis of the data and presentation of that data to the wider world. The design process needs to be substantially complete before implementation can begin in order to minimise time spent implementing features that are unnecessary. In this chapter I will describe the design of an agent-based model that will examine the march of the Byzantine army to the battle of Manzikert. I will detail the historical and modern data sources for the environment and the agents and detail which elements are applicable to answer the important questions of the Manzikert campaign and which can be omitted. I will also state the lessons learned from the design of this model, not only regarding the design of archaeological ABMs but also specifically about the Manzikert campaign. The act of designing a model should be itself instructive and any lessons learned will be described here. I will also describe issues regarding the dissemination of the results, including the problems associated with visualising ABM output and tailoring the output to fit the audience.

2.2 Modelling Considerations

Some aspects of the Manzikert campaign have been recorded in contemporary accounts, some aspects can be plausibly assumed to have been the same as they are in modern times and some can be recreated from archaeological, historical and environmental research. A useful ABM design must start with the known information about the campaign and fill in any necessary gaps with hypothetical values and systems in order to produce a model that will help answer the questions we have about the march of the army. The primary questions are:

- How did the army organisation affect the overall speed?
- How do size and composition of the army affect the overall speed?
- What effect did the supply of the army have on the settlements through which it passed?

By starting with the more secure aspects of the model and testing the more speculative elements it may be possible to eliminate the less plausible hypotheses enabling us to enlarge the model to encompass other hypothetical aspects. Our known data is therefore added to the hypothetical elements in order to create each model. The outputs of the model can be used to formulate new hypotheses that can then be fed back in to the process in order to create new models and so on (Figure 2). As can be seen, multiple models will be required. This is essential not only for the purposes of software development in order to add features one at a time but also in order to tailor individual models to answer specific questions. A one-model-fits-all approach is more likely to result in a model not ideally suited to answer any one of our research questions (Murgatroyd 2008).

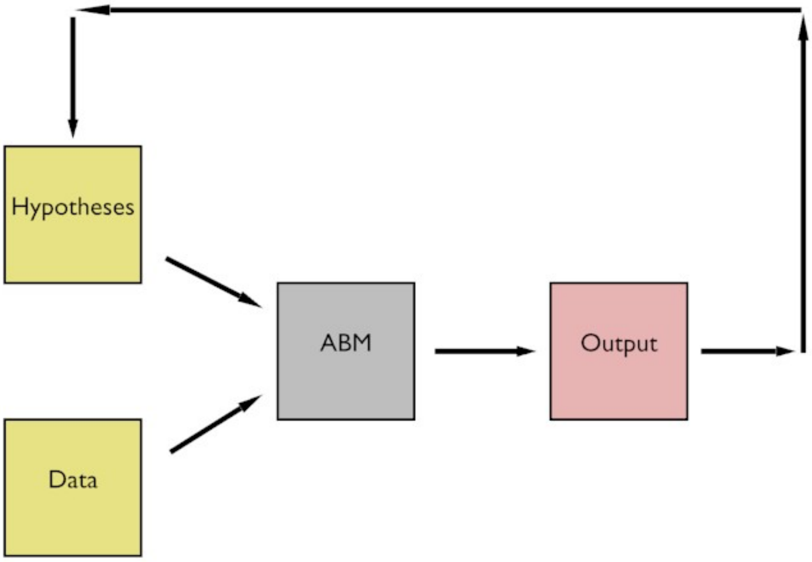


Figure 2: The modelling process

2.2.1 What We Want to Find Out

We cannot use the ABM as a complete model of the Manzikert campaign, the processes are too complex and the data too incomplete for us to be able to replicate reality. There are no aspects of either the army or the environment for which we have sufficient data. Even if the data existed, the software required to run the model needs to be simple enough to develop within the timescale of the project and the hardware required needs to be available for it to run within a reasonable time.

We can, however, create plausible hypotheses regarding the processes at work in order to investigate the relationship between the size and composition of the army and how that affects the overall movement speed of the army. Based on the elements of the model that we can plausibly model, we can take the size and speed of individual agents and add hypothetical army compositions and ways of organising movement in order to investigate how the behaviour of individuals affects the overall performance of the system. By measuring how much energy is used for movement we can create plausible quantities of provisions that would be required to feed the army at each point in the march. From this we can make an assessment of how this would affect the communities that the army passed through.

The model forms a null hypothesis against which to test the historical record. It is to a certain extent deterministic, dealing mainly with movement rates, energy expended and supplies consumed. This can, however, be used to produce parameters within which historical hypotheses can be re-evaluated. This approach, along with the largely simple goal of the army, to get to Manzikert in a good enough physical condition to win a battle, means that some of the pitfalls of sociological ABMs (Lansing 2002; Richardson 2003) can be avoided or at least mitigated.

2.2.2 Appropriate Abstraction

One of the key elements in a successful model design is in using appropriate levels of abstraction (Kramer 2007). A model should only contain the elements that affect the desired result of the model. Unnecessary detail will increase the processing time of the model without affecting the result or even worse adding inaccuracy. Based on our stated aims, any elements that do not affect the speed and organisation of movement and use of resources can be safely omitted. The size of each agent is important as one of the key factors affecting the speed of the army is crowding. The number of agents that can pass through any given space depends on the size of the agents and the speed at which they can travel. These factors then are essential in any model in which movement is a key concern. Obviously agents can move at a variety of different speeds but the speed at which they *can* move is less important than the speed at which they *do* move. Armies on the march tend to move at a comfortable speed unless there is any kind of time pressure on them. In the Manzikert campaign there is no evidence that undue haste was seen as necessary. In actual fact the level of urgency seems to have been somewhat less than required as the Emperor thought the Seljuk army was further away than it actually was. In this case the maximum speed of both cavalry and infantry is irrelevant, it is their likely actual speed that is important. In this case having agents that can move at any speed from stationary to their maximum is unnecessary, we just need agents that can move at any of the likely speeds.

2.2.3 Stochastic Elements

Certain aspects of the model contain stochastic elements, that is they rely on random or pseudo-random behaviours within the model. The particular branches of the route planning algorithm are not always searched in the same order so the route planned may not be exactly the same on each occasion. During crowding, if an agent moves to a nearby cell then this cell is chosen via a pseudo-random number generator. This means that minor changes in the results of the model are possible in each run. Sufficient similar scenarios have been run to allow us to be able to determine that the effects of this randomness are insignificant.

2.2.4 Issues With the Environment

Although landscape studies are a major part of the archaeological discipline (e.g. Aston 1997; Barker 1995; Gillings, Mattingly, and Dalen 1999, among others), coverage is almost always of variable quality and resolution. Inevitably modern datasets will have to be used in some form, even if it is as a base from which more plausible values can be derived. Some elements of the environment have stayed substantially the same, the weather is very similar in modern times as it was in the 11^{th} century AD (England et al. 2008) and the physical shape of the terrain is substantially the same. Nevertheless certain factors that affect movement and supply may well have changed to some degree. Land use is probably very different in some areas although there are technological limitations on how much change could have occurred, mountain tops being unlikely to have been converted to agriculture for example. The size and flow of water courses may have been altered by natural changes or as a result of Turkey's extensive hydroelectric dam construction programme (Hay 1994). The resolution at which the environment is modelled depends on the aspect of the environment under consideration. If the small scale movement of individual agents is to be modelled then the environment needs a very fine resolution to be able to simulate crowding. Not all aspects of the environment need this kind of resolution though, and even if they were modelled to this scale the resulting files would be massive. They would also convey a false impression of the certainty we can place on such environmental factors. This will be dealt with below.

2.2.5 Issues With the Agents

Although the size and speed of agents in the Byzantine army is comparable to modern humans and therefore modern data can be used, the organisational aspects of the army and the behaviours of individuals are less certain. Comparative data from both medieval and more modern sources can give us plausible hypotheses to test. The Byzantine military treatises give some details as to how the army was organised. More modern accounts such as *The Art of Marching*, an early 20th century book written by a veteran of the British army, also deals with a lot of situations that would have been familiar to the 11th century Byzantine army (see below). The resolution at which the army is to be modelled needs to take into account the effects of crowding within movement. As it is precisely the effects that individual movements have on the overall speed of the army that we wish to simulate then the model has been designed to use 1 agent to represent 1 member of the Byzantine army. As horses have limited independent movement and would either be ridden or lead they are included in the same agent representation as their riders. Agents are dealt with in more detail below.

2.2.6 What We Want From the Output

The project not only produced this Ph.D. thesis but also must communicate its results to the wider community. This includes military historians, agent-based modellers, archaeologists and the general public. The model consists of many runs of a simulation that deals with four dimensional data, spatial data run through time. This presents a different set of problems depending on the media involved. Presenting the results of the model on the Internet allows us to use animation to illustrate modelled behaviours. Due to the large number of scenarios being run it becomes impractical to present each scenario in real time. Some form of statistical aggregation is needed, not only to make sense of multiple scenarios but also to compare scenarios with others. This is especially important as some of the project's outputs will be in purely written form in the case of journal articles.

We will deal with each of the ABMs elements separately below, first detailing the design of the agents and their behaviours, then the design of the environment .

2.3 The Agents

2.3.1 The Sources

The first stage in designing the agents of the MWGrid ABM is to examine the historical and archaeological sources for the Byzantine army of AD1071. Historical sources from the Manzikert campaign are obviously more likely to be an accurate representation of the army. Any sources relating to the Byzantine army of the mid-11th century are likely to be more representative of the army on the Manzikert campaign than any from after Manzikert as the army was changed by first the period of civil wars after 1071 and then by the availability of Turkic troops after the loss of much of Anatolia to the Seljuks (Treadgold 1998, 7). Earlier Byzantine military treatises are useful as there is evidence they were relied upon for advice long after they were written, the Taktika of Nikephorus Ouranos containing large chunks of not only 10th century Byzantine works but also chapters derived from Onasander's Strategikos, a military text from the 1st century

AD (McGeer 1991). The need for armies to move large numbers of men and horses from one place to another is not just restricted to the ancient and Medieval worlds, even well into the 20th century there was a need for armies to use horsepower in the traditional sense, rather than the mechanical. While the provisioning of armies changed with the advent of better food storage technology and their movement was transformed by more extensive road networks and the invention of the steam locomotive, some of the procedures needed to transport and feed soldiers in the 19th and 20th centuries are potentially valid sources of information for the 11th century.

Byzantine armies from the 11th century onwards could be an eclectic bunch and Romanos IV Diogenes' army on the Manzikert campaign was no exception. The army consisted of full-time soldiers, mercenaries, the Emperor and court officials as well as the thematic tagmata, some of whom would have been experienced and well drilled and some who would have been essentially farmers and labourers. The physical characteristics of these people are important to the modelling process. The size and speed of each agent will affect movement and crowding. The non-human elements of the army are equally important. Some of the Turkic mercenaries may have had 7 or 8 horses each which would have exacerbated any movement problems and altered the amount of food required. Ultimately we cannot know the physiology of everyone on the Manzikert campaign so we must create a hypothetical model which will not negatively affect the accuracy of the model. Archaeological work on past human food requirements for groups of people has tended to use the same top down approach to modelling as that used by Engels and Pryor, multiplying an average by the appropriate number of individuals, e.g. (Gaffney and Tingle 1989; Goodchild 2006).

The composition of the army is something on which we have more information. There are certain categories of participant that all members of the army can be fitted into. There may have existed within these categories no end of fine variation with individuals having subtly different behaviours and amounts of equipment but our agents have been placed in our simulation to do a limited number of things. Agents move and consume resources, any behaviour not linked to these is to a certain extent unimportant and will be abstracted out of the model. Any types of agent whose differences only exist in the behaviours abstracted out should be placed in the same category, regardless of how different their daily lives would have been in reality. Therefore, knowing whether an individual travels on horseback or on foot is important for the movement of the army. Knowing whether they are a scribe or a priest or a general is not.

The sources allow certain assumptions to be made for the purposes of modelling, around which our movement model can be constructed. These are:

- The army would have picked up troops along the way
- Supplies would also have been picked up along the way
- There would have been a route planned in advance
- The army would have a regular routine for marching
- The army would have had a consistent and organised method for setting up camp
- The army would have a set order of march
- The emperor makes all the strategic decisions
- The length of a daily march must be flexible and practical

2.3.1.1 The Army Would Have Picked Up Troops Along the Way

Some elements of the army, particularly the provincial levies, would have been scattered across various parts of Anatolia in February 1071. Requiring these troops to march all the way to Constantinople only to have to march all the way back through their own territories on their way to Manzikert seems highly impractical. The Anatolian *thematic* troops in particular, being levies that spent most of the year as farmers, would have been locally mustered at towns near where they lived and would have waited for the army at the nearest large settlement on the route (Haldon 1990, 83). These settlements would have had the resources and infrastructure to feed and shelter hundreds or thousands of troops as they will also have been stockpiling supplies from the surrounding area for the main body of the army (Haldon 1999, 182).

2.3.1.2 Supplies Would Also Have Been Picked Up Along the Way

There are plenty of contemporary historical accounts of the army requiring settlements to provide supplies of both food and equipment in return for the commutation of taxes (Haldon 1999, 140). Engels' work on the army of Alexander the Great illustrates that there are many problems involved with carrying supplies for too many days, with 25 days being given as an absolute maximum (Engels 1978). Given the total length of the journey, around 6 months for those that started at Constantinople with the Emperor, the army would have needed resupplying many times along the route.

2.3.1.3 There Would Have Been a Route Planned in Advance

Picking up supplies and personnel on the way necessitates a knowledge of the route in advance, at least in general terms. If Constantine Porphyrogennetos' treatises on military organisation are indicative of campaign planning, a great deal of effort went into ensuring the route of march was suitable for the army and its objectives (Haldon 1990, particularly text B).

The entirety of the route would be through lands at least nominally under Imperial control and as such would have been well known to the Empire's administrative machinery. Officials would have been dispatched to warn settlements along the proposed route that an army would be passing through and that supplies would be needed. This enabled the *themes*, the administrative districts of the Empire, to muster their men and resources in settlements convenient for the army. Michael Attaleiates' eyewitness account places the army in Ankyra, at Krya Pege (thought to be on the River Halys between Ankyra and Charsianon) and at Theodosiopolis, giving us some set points for the route. One of the advantages of agent-based modelling however is the ability to create 'what if?' scenarios in order to examine the circumstances behind the decisions made. Based on the information alternative models can be run in which the overall route is not pre-determined but is based on certain criteria. We can then investigate the implications in choosing each route which in turn will enable us to form hypotheses regarding the decision making process of the army on campaign.

2.3.1.4 The Army Would Have a Regular Routine For Marching

The treatise on Campaign Organisation and Tactics (Dennis 1985, 277) gives a series of steps for organising movement for the day. It specifies that the Imperial tent is the first to be set up at a new camp and the first to come down when leaving the camp. Each morning a set routine is followed:

- The trumpets sound to get everybody up
- Officers in command go to the Emperor to get their orders
- The trumpets sound again and some units are sent out of the camp to cover the movement of the rest of the army as it exits the camp

- Everyone ensures that equipment and baggage is loaded onto pack animals
- The trumpets sound for a third time and the Emperor rides out of the camp with everyone else following in turn.

Although this treatise is not exactly contemporaneous with the Manzikert campaign, this series of actions forms a plausible starting point for our own modelling. It does not require a computationally intensive model to tell us that the movement of tens of thousands of troops cannot be organised as an uncoordinated free for all, even if circumstances may cause it to end up that way.

2.3.1.5 The Army Would Have a Set Order of March

Historical sources contain a sample order of march (e.g. Haldon 1990, although this varied depending on circumstance) which can be used as a template for the way the army moves in the ABM (Figure 3). A set order of march enables each unit to know its place in the army and creates a framework for movement. New units can quickly determine their place within this framework. In some medieval armies the order of movement is varied to ensure different units get first access to clean water and have less problems with the dust kicked up by preceding units (Rogers 2007, 76). It is not certain to what size of army this applies; certainly a smaller army with fewer units would find this easier to organise. For the purposes of this simulation the army on the Manzikert campaign is assumed to be too large for this to be feasible.

Having a set order of march also helps with setting up and breaking camp. Units arriving first can head to the far side of the camp area and be out of the way when later units arrive. Similarly when setting off the first units will already be at the side of the camp nearest the direction of travel and will not have to manoeuvre round units who will be setting off later.

The order of movement in friendly territory as described by John Haldon (Haldon 1999, 162) is:

- Advance scouts
- Vanguard
- Infantry centre
- Cavalry centre + Emperor
- Cavalry right wing
- Infantry right wing
- Baggage and siege train
- Cavalry centre second line
- Infantry left wing
- Cavalry left wing
- Infantry rearguard
- Rearguard

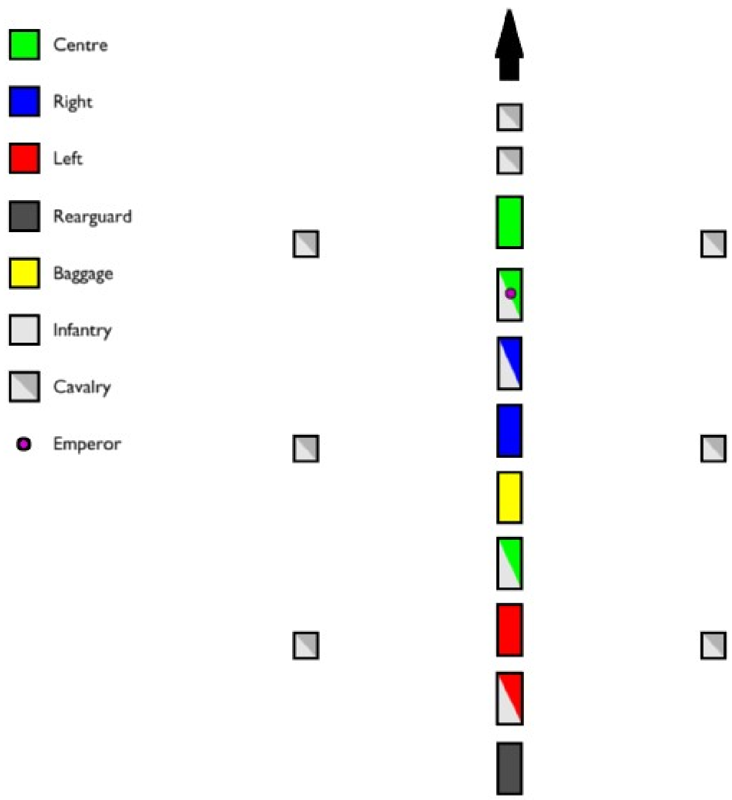


Figure 3: March formation in friendly territory (after Haldon, 1999)

There were units of outriders on either side of the column. The linear nature of this marching formation as opposed to the semi-deployed formation that was used in enemy territory ensured that roads could be more closely followed, resulting in less damage to properties on the path of march. Within the model, each unit needs to be assigned to one of these categories when joining the main body of the army. The Emperor and his household troops can be considered the cavalry centre. Other troops can be added on an arbitrary basis to ensure all other categories are of roughly equal quantity, with the advance scouts and vanguard as cavalry and the rearguard as infantry.

2.3.1.6 The Army Would Have Had a Consistent and Organised Method for Setting up Camp

It is obvious from the treatise on campaign organisation that there were well established rules for setting up camp.

The best generals and those who have acquired a good deal of experience over a long period can study the size of the body of troops drawn up within the fortifications and determine well in advance the precise circumference of the site in which the whole army, horse and foot, is going to encamp. (Dennis 1985, 247)

Although there is no consistent and reliable camp plan illustrated in the treatise for campaign organisation, George Dennis (1985, 335) managed to piece together the details from the text to create a hypothetical plan. This plan has been used as the basis for camping locations for each of the units (Figure 4).

The camp will be positioned so that the units at the head of the column are camped nearest to the side of the camp facing 'forwards' (usually east). This will ensure they do not have to manoeuvre round everyone else's tents on the way into or out of camp. Taking the order of march from Haldon, it is clear that it is possible to fill in the camp plan from Dennis in an orderly way, ensuring the furthest reaches of the camp are set up first. Although no location is specified for the baggage train in the treatise, a space has been allocated for it on the plan as it will form a discrete unit on the march and therefore will simplify organisation if it is separate. Dennis points out that there are no specific instructions on how the corner areas are used other than for light infantry if they are too numerous to fit into their allocated areas (Dennis 1985, 329). This then can be used as valuable overspill space in case the camp becomes too tightly packed or extra space for baggage is required.

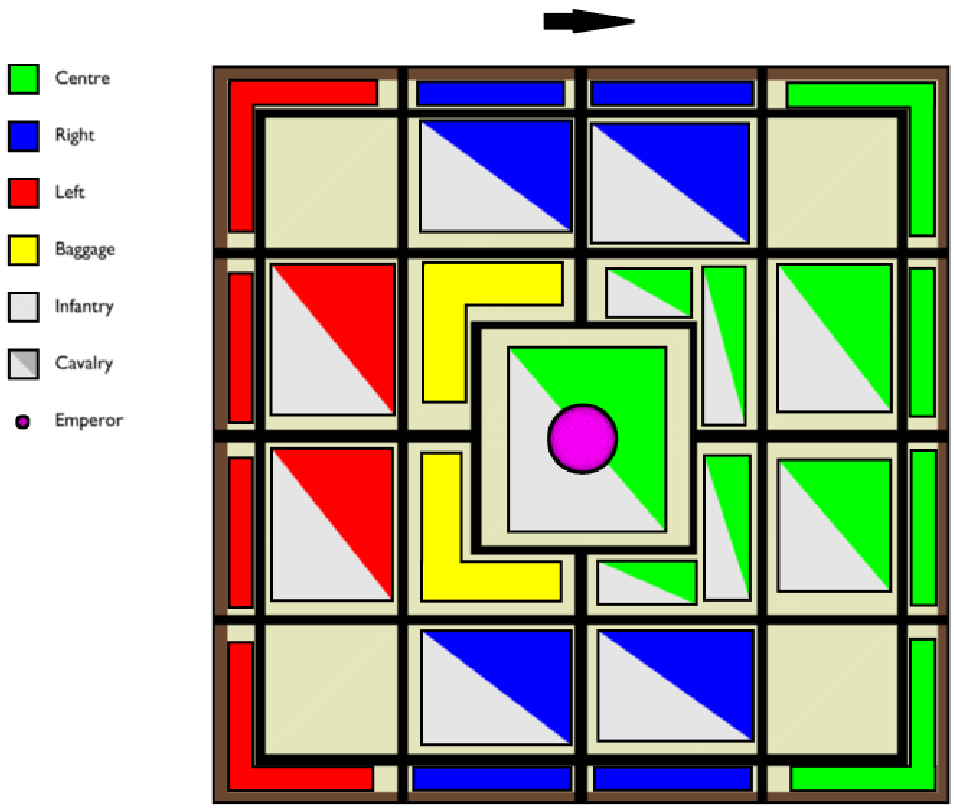


Figure 4: The camp, populated by the units from Figure 2

2.3.1.7 The Emperor Makes all the Strategic Decisions

Strategic decisions regarding the route the army will take or whether the army will split into separate columns will all be made by the Emperor within the ABM. In reality the strategic situation will have been discussed within the upper ranks of the army. The extent to which this happened on the Manzikert campaign is unknown and this level of detail is unnecessary from the point of view of the model. Some historical sources mention that the Emperor detached his baggage train from the main body of the army at some point on the route and went a separate way. If this event is modelled a substitute 'Emperor', who is the highest ranking officer remaining with the main body of the army, will adopt all the emperor's decision making functionality.

2.3.1.8 The Length of a Daily March Must be Flexible and Practical

Past work has assumed either a certain distance for the army to move in a day (Engels 1978) or has tried to calculate this based on the size of the army (Pryor 2006). Calculating a daily movement distance runs contrary to our goals in building an ABM; the distance an army can move is determined by its size and organisation and not vice versa. The model should also be able to help examine the relationship between army size, organisation, composition and speed of movement, along with other factors such as weather and terrain to be dealt with in future publications. Therefore the model requires a dynamic system where the length of a day's march is dependent on how far an army of a given size can comfortably move. If an army struggles to reach the day's camp in time to get set up in the daylight, then the length of march must be shortened. If the army finds itself arriving in plenty of time its length of march can be increased.

Our system cannot assume that the army simply moves until the end of the day and then stops. Historical sources state that it was standard Byzantine practice to send a group of surveyors a day's march ahead to set out the next camp site (Dennis 1985, 249). This camp was set out to the same layout each time so each unit would know upon arrival where they were supposed to pitch their tent. Our model replicates this system yet still allows some flexibility in the case of movement problems; it is dynamic but always a day behind. By the time the army has all reached the day's camp the surveyors have already planned out the following day's camp. If the length of a daily march is too long and the troops are arriving late in the camp the surveyors will have to make allowances for this when setting up subsequent camps.

The sources give us a framework around which to base our movement rules. They indicate locations along the route that can allow us to construct hypothetical routes of march. The usefulness of agent-based modelling, however, lies in the creation of 'what if?' scenarios that let us examine the implications of changing parts of the system. In the initial ABM each agent will follow its rules based on the information it has. This creates an ideal example of behaviour that can be used as a null hypothesis to compare with information derived from other sources such as archaeological or historical research. If under optimum conditions an army of a certain size takes longer than six months to reach Manzikert, then it is highly unlikely that in real life it would fare any better. But the model's performance can also be deliberately degraded to introduce negative aspects, such as incompetence, into the system. We can investigate what happens when the camp is not set up in advance and the location has to be chosen on an ad hoc basis by the units at the front of the column. This enables the ABM to model what happens when water needs are ignored or streams dry up. Historical sources give little information about the organisational problems that *did* happen but the model can provide new evidence for what *could have* happened.

Creating a historically plausible framework is only the start of the process of modelling. It must also be translated into a working computer model. The mechanisms by which the agents plan and execute their movement are vitally important to the model as a whole. The whole point of the campaign was to get the army across Anatolia to Manzikert; if the movement aspect of the ABM does not work accurately, efficiently and reliably this will not happen, regardless of the historically derived parameters.

2.3.1.9 How Did it Move?

When looking at how the organisation and composition of the army affects its overall speed, the important factors that will affect the result include the space taken up by each individual, the speed of each element of the army, the organisation of the movement and the terrain and transport infrastructure over which the army will move. The space taken up by the human and animal participants can be assumed to be fundamentally the same as their modern equivalents. Any small size differences between ancient and modern populations should make no difference with respect to the crowding of an army on the march. This also applies to the speed of the individuals, especially as the individuals within the army will never be moving at maximum speed.

Although sources exist that can give us an idea as to the organisation of the army on the march, the specific rules regarding how the army sets off and deals with hold ups are uncertain. Different hypothetical models will have to be created in order to determine which are more plausible. The composition of the army is also unknown although it can plausibly by narrowed down to within a set of parameters. These can be modelled to determine their effects on the movement speed of the army as a whole.

The way the human body expends energy has not changed in the 1000 years since the Manzikert campaign so if we can model the movement of the army we can evaluate the amount of food would be required to transport the army across Anatolia and reach Manzikert. The way that an army supplies itself is a key aspect of military logistics and the ability of modern computer hardware to process the mathematical equations used to model energy expenditure offers the ability to increase the complexity of work such as that by Engels (1978)and Roth (1999).

2.4 The Art of Marching

As can be seen, although past work can provide a plausible framework within which the design process can take place, significant gaps exist especially with regard to quantitative measurement. A record of similar military expeditions with the sizes, speeds and composition of the forces involved would provide a valuable tool, not only to fill in the gaps of the army's organisational mechanisms but also to provide useful data for calibration of the model. Thankfully such a book exists, although it is practically unknown within military history or the study of logistics.

The Art of Marching was written by Colonel George Armand Furse CB (1834 - 1906), "late of the Black Watch", and is a military treatise published in 1901 by an ex-officer of the British

Army. It uses the author's own experience and historical sources, mainly from the 17th, 18th and 19th centuries, to examine the practical issues involved with moving large bodies of soldiers. The majority of examples come from the Boer War, Stonewall Jackson's movements in the American Civil War and both French and English sources from the Napoleonic Wars, although other military writers such as Clausewitz and von Schellendorf are also quoted.

The book covers some of the same kind of situations commonly found in Byzantine military treatises, but in much greater detail and with the metrics almost entirely absent from Byzantine sources. Like the Byzantine treatises, the book is concerned with giving solid practical advice to officers and as such goes into great detail regarding how many soldiers and support staff armies contained, how far they moved and what kind of problems they encountered. It is written in an accessible style yet its sources are referenced, albeit less rigorously than a modern academic paper. Furse quotes extensively from Napoleon and Wellington's personal correspondence as well as 19th century military writers but also adds personal anecdotes when appropriate.

Due to its longer and more comprehensive nature, *The Art of Marching* can be used to fill some of the gaps where 10th and 11th century Byzantine sources neglect to provide detailed information. Certain aspects of the military situations detailed by Furse are common with the Manzikert campaign. Humans and animals move at around the same rates and are subject to similar welfare issues. The armies examined by Furse tend to be in the 10,000 - 100,000 range, ideal for the MWGrid model and although rail travel is mentioned, the book deals primarily with armies moving away from railway infrastructure.

There are also certain significant differences between the movements detailed by Furse and the Manzikert campaign. Furse is largely dealing with periods where tinned food is available, even though provisioning is very rarely mentioned. This will naturally have an impact on any information involving supplies and foraging. The campaigns also tend to involve baggage transport using wagons rather than the pack animals primarily used in the Manzikert campaign. This no doubt affects the speed and maximum length of columns. The state of the road systems in the examples quoted by Furse as compared to the one existing in Byzantine Anatolia are also unknown, undoubtedly affecting the usefulness of the text, albeit in ways that can not easily be quantified. Nevertheless, the book is a major source of information regarding military movements of the scale employed in the Manzikert campaign.

The book examines a series of issues directly relevant to the MWGrid model. The information contained in *The Art of Marching* can be used both to create plausible behaviours for the model and as a comparison for the model's results. Specific issues of direct relevance are:

- The size of an army column
- The speed at which armies move in different circumstances
- How the army organises its movement
- Caring for soldiers and animals

These will be dealt with separately below along with some general notes and an overview of any conclusions drawn. This will hopefully explain how the information contained in *The Art of Marching* can be used in the MWGrid model.

2.4.1 The Size of the Column

> *"The smaller the mass of the troops in one column, the greater the ease and precision with which the march can be performed." - Clausewitz (Furse 1901, 306).*

Furse recognises the importance in the size of the army on the march, both as an aid to organising the breaking of camp and to help in deciding whether to split the army into separate columns that travel on different routes. To help with this he gives information about how much space individual elements of the army will take up on the march as well as expanding that to give measurements for whole armies of different sizes.

2.4.1.1 Individual Units

Some information is given for non-human individuals, however infantry are assumed to be marching in their units so the space taken up by a single human is not detailed. Four cavalry troopers abreast are reported to occupy a front of 4 yards, and allowance being made for officers and serrefiles, the width of front extends to 5 yards with 2 rows occupying a depth of 8 yards (Furse 1901, 193). A bullock occupies 4 yards of road, a camel 5 yards and a carriage drawn by 2 horses, mules or bullocks 10 yards x 4 yards 15" x 6 yards 20" (Furse 1901, 381).

2.4.1.2 The Whole Army

Furse supplies us with the following rule of thumb, 2000 troops with baggage train will occupy a column 1 mile long. Divorced from their baggage train, 3000 troops will occupy 1 mile, 5000 if really tightly packed. This would cause problems though and no sensible commander would attempt >3500 troops per mile (Furse 1901, 303).

2.4.1.3 The Lengthening of the Column

However the length of the column is not just the sum of the space required for each human or animal participant. The column will lengthen as the day's march progresses due to the variation in speed of the units it contains as well as problems occurring *en route*. "The lengthening of the column should be taken into account, both in the calculations for the march and for a deployment. The opinion on the average lengthening varies. Hamley calculates it at one-third; Home sets it down at one-sixth of the normal length of the column; Berthaut says it amounts sometimes to two thirds; General Lewal also sets it down at two-thirds. We may take it that 25 per cent, or one fourth, will not be found an excessive allowance to be made for this deviation from the regulations" (Furse 1901, 206). This is a factor not included in Pryor's examination of Bohemund's march to Thessalonike and would affect his conclusions. Pryor estimated that his smallest hypothetical force of 4.5 companies would have been able to travel a maximum of 22km per day (2006, 9). Factoring in a column lengthening of around 25% would put the total distance to that estimated for 5.5 companies, 17km.

2.4.2 The Speed of the Army

Whether the rate is measured by an average per day and thereby reduced by rest days or only counting days when the army actually moved, Furse's examples of comparable forces show armies moving 15 miles on a good day, 10 in more troublesome conditions and even less when disorganisation, terrain, supply or weather is against them. Furse's suggestion of 13 miles for large bodies of troops doesn't include the distance getting out of and into camp. When a rest every 4^{th} or 5^{th} day is included, this becomes 10 to 11 miles per day over an extended period, averaging 7.5 hours from camp to camp on marching days. This time is measured from the setting out of the first troops to the arrival of the last (Furse 1901, 217).

Rustow, in his "L'Art de la Guerre" disagrees, stating that anywhere between 15 to 20 km (9 - 12.5 miles) can be considered a good day (Furse 1901, p.217). von Schellendorf goes along with Rustow, saying anything over 14 miles in a day is severe. Colley goes with 12 to 15 miles per actual marching day giving an average movement of 10 miles per day when rest days are included (Furse 1901, 218). Although rest days become less necessary when daily distances are short, anything between 15 to 20 miles is not sustainable and 20+ miles should only be attempted in an emergency. Schellendorf goes further in suggesting anything over 10 5/8 miles can be called a forced march (Furse 1901, 221). Under favourable circumstances, a large mixed body of troops is calculated to cover a kilometre, 1100 yards, in twelve minutes (Furse 1901, 191). The French under Napoleon required their infantry to march 2.5 miles in the hour, including a ten minute break (Furse 1901, 192).

2.4.2.1 Cavalry and Baggage

Furse states that cavalry horses ordinarily walk 4 miles per hour, trot 8 miles, and gallop 12. And, whereas the rest of the army seldom does more than 13 miles, the cavalry can march 25 to 30 miles a day. They are not recommended to stay at the rear for long because it wearies them to march at the same speed as infantry (Furse 1901, 192). A smart trot of 6-7 mph is recommended as it is more fatiguing for both riders and horses at a walk (Furse 1901, 193). On a good road a wagon is supposed to travel about 2.5 miles in the hour, and in a hilly country 1 3/4 miles. However when heavily laden and among others it will only do 2 mph under very favourable conditions, usually much worse. Hired transport is even slower (Furse 1901, 198).

The regulations for encampments in India fix the average for baggage animals as follows :

Pack animal	Load (maunds)	Load (kg)	Speed (mph)
Elephants	15	559.86	3.5
Camels	5	186.62	2
Bullocks	2	74.65	2
Cart drawn by bullocks	-	-	1.25

Table 2: Pack animals with their loads and speeds from the British Army's regulations (after Furse 1901, p198)

2.4.2.2 Forced Marches

Forced marches are only recommended with experienced troops of good morale (Furse 1901, 226). In cases of extreme need, cavalry can move 50 miles and infantry 31.25 miles in 24 hours (Furse 1901, 222) but this will take a full 24 hours and plenty of rest should be provided afterwards. General Lewal sums up his remarks on forced marches in the following words. "Recent examples tend to prove that the men who have best succeeded in war have rarely demanded from their soldiers abnormal marches. Their prevision, the nicety of their combinations, their foreknowledge, one might almost say, of the events, have enabled them to attain their object, without imposing on the men efforts ruinous to their health." The Roman adage *festina lente* (hasten slowly), finds favour with most military writers, who, on good grounds, are averse to long marches (Furse 1901, 236).

2.4.2.3 Barriers to Progress

Crowding and column length are considered to be the greatest hindrances to movement, both mutually contradictory unfortunately. If a division can march 2.25 - 2.5 mph, a corps in one column can only do 2mph (Furse 1901, 200). When poor roads, hilly terrain or heavy traffic are encountered then this reduces the expected speed down to about 1.5 mph. When marching across country or when multiple adverse factors exists then around 1mph can be expected from a corps (Furse 1901, 202). Defiles and bridges are obviously major barriers to the progress of an army. In one instance 50,000 troops are recorded as crossing a bridge in 10 hours (Furse 1901, 213). Terrain can also greatly affect movement speed, Furse recommends slowing the pace when marching uphill. Quickening the pace when marching downhill however is to be avoided due to the necessity for everyone else to hurry to catch up (1901, 201). As the Duke of Wellington puts it, "it is better that the head should halt than that the rear should be hurried" (Furse 1901, 202).

2.4.3 How the Army Organises its Movement

> *"Stonewall Jackson always marched early; so much so that the men of his brigade used to say that he always marched at dawn, except when he started the night before." (Furse 1901, 331)*

Furse stresses the need to plan marching sensibly throughout the day. When and how far to march during the day is seen as being of great importance to both the speed of the army and the comfort of soldiers and animals (Furse 1901, 22). Marshal Bugeaud recommended the following routine: half an hour before daybreak the cooks and men to draw billets should set out. At daybreak the horses receive a partial grooming and are fed. Two hours later the troops have their breakfast, followed half an hour later by the boot and saddle. Furse however, notes that it should take about an hour for troops to get ready to actually set off (1901, 332).The army should arrive at the following day's camp with enough time to see to its chores before settling down for food and rest (Furse 1901, 24), therefore the reveille should sound half an hour before daybreak and the march finished before nightfall. The camp should preferably be occupied at least 2 hours before nightfall (Furse 1901, 328).

2.4.3.1 Breaking Camp

The army should start as early as comfortably possible to maximise the hours of daylight and the coolest hours of the day however starting too early upsets the troops and leads to packing up in the dark (Furse 1901, 327). Troops should not form up until it is actually time to set out though. In large forces there can be quite a long time between the first troops setting off and those at the end of the column. If this time is spent at the ready, both men and horses become unnecessarily fatigued (Furse 1901, 333). This was an error Murat made during the 1812 campaign to Russia, exacerbated by moving all his cavalry in one column (Furse 1901, 332). This also applies to pack animals (Furse 1901, 378).

2.4.3.2 Marching Formations

Troops should march on as broad a front as possible, preferably with a gap in the middle of the column to let air in. There should be space on the road left for local commercial traffic though, this free space also helps communication (Furse 1901, 205). The march order should be rotated so the same units do not get to camp first (Furse 1901, 358). In an undisciplined army, the big strong ones block up the road at the front whereas the weaker ones struggle to keep up, then drop out (Furse 1901, 207).

Units should have the standard distance between them, plus a quarter of the distance they take up when stationary. The column can be split into secondary columns with larger gaps between them so that movement problems in one column do not transmit to the others. If movement problems do occur, the distance should be made up slowly, not at the double (Furse 1901, 208). If two army corps need to share the same route then the second should travel one day behind the first (Furse 1901, 324). The rearguard is more useful for picking up stragglers than protecting the column (Furse 1901, 336).

2.4.3.3 Splitting the Column

> *"Conversing one day with his lieutenants, Napoleon defined the art of war as l'art de se diviser pour vivre, et de se concentrer pour combattre" (Furse 1901, 304)*

As a general principle, the more the army is broken into separate, parallel columns, the less frequent the halts will be and the quicker it will form up into battle order. If this is done, the infantry should get the shortest route, the cavalry the longest and the artillery the most level and hard (Furse 1901, 303). One of the key factors in splitting the columns is deployment time when facing the enemy, no more than 30,000 – 40,000 can travel on the same road and still be deployed in battle (Furse 1901, 304).

Care should be taken to avoid the separate columns meeting or crossing paths on the march as this would negate any benefits in splitting the column in the first place. Splitting also increases movement complexity meaning it is more likely for a unit to end up following the wrong column (Furse 1901, 306) and it can be difficult maintaining communication in mountainous areas (Furse 1901, 320).

2.4.3.4 Resting on the March

Between 5 - 10 minutes rest per hour is recommended whilst on the march, not only to give soldiers time to sit down or answer the call of nature but also to help the column stay together, units straying behind using this time to catch up a little. These should be had at regular intervals; every hour for infantry, less frequently for cavalry and baggage (Furse 1901, 202). Proper rest is not only conducive to good health but also good speed, with an example of 130 miles being covered in 70 hours considered to be inefficient due to the half hour breaks every 20 miles ensuring that soldiers slept rather than ate (Furse 1901, 194). Longer breaks of an hour or more are only recommended when the march is abnormally long, when the troops are too tired from continuous marching, or when the heat of the day is too much as the quality of rest is less than that to be had at the end of the day's march. This longer rest should be taken off the road. It is considered perfectly acceptable, if away from the enemy, to allow the rear portion of the column to rest to escape the day's heat (Furse 1901, 203).

2.4.3.5 Navigation Aids

In order to prevent troops becoming lost, signboards can be put up at road junctions. In towns (Furse 1901, 212) or at night (Furse 1901, 358), soldiers can be left at junctions to point people the right way. A party of engineers is advised to accompany the advance guard in order to cope with transport infrastructure problems that could delay the main column (Furse 1901, 344). These are also in charge of the signboards (Furse 1901, 357). Signboards can also be used to direct troops to their camping location when arriving at camp (Furse 1901, 556) and towards water for drinking and bathing (Furse 1901, 562).

2.4.3.6 If You Fail to Plan...

Should the march not be properly organised, Furse is in no doubt as to the severity of the consequences on the movement of the army. Regarding Irwin McDowell's untrained Union soldiers during the American Civil War, he states "After a while, however, the excitement began to die away, and the recruits not broken in to marching, succumbed to the unusual exertion. The heat was oppressive, and the roads lay deep in dust ; the rifles, knapsacks, and blankets became a burden hard to bear. The columns opened out, all regular formation was soon lost, regiments mingling with regiments. The men fell out in numbers to appease their thirst at each roadside brook, and knots of stragglers surrounded every blackberry bush. The rear was a confused mass of laggards, and, heedless of their officers, of orders and remonstrations, scores of men quitted the ranks and sought repose in the surrounding woods. In the evening McDowell's army had not advanced further than six miles from their bivouacs, and many of the stragglers did not rejoin their corps till late the following day" (Furse 1901, 114)

In summary: "To start in good time in the morning, to encamp about midday, to occupy the rest of the day in providing for the ordinary wants of the army, and to use the night for repose would be a convenient method for carrying on war." (Furse 1901, 326)

2.4.4 Caring for the Soldiers and Animals

> *"We were many days without water, or victuals of any kind, and even without the means of procuring any. In five or six days - I speak without exaggeration - we lost six or seven hundred men by thirst alone. We are exceedingly reduced in numbers. We have had several soldiers who blew out their brains in the presence of the Commander-in-chief, calling out to him, 'Voila ton ouvrage.' " (Furse 1901, 177)*

The welfare of the soldiers is considered a primary concern throughout the book. Again and again Furse stresses the effect that marching conditions have on fighting ability (1901, 564). Wellington was convinced that all soldiers, whether young or old, could march long distances and answer all calls that could be made on them in reason, as long as their officers were properly attentive, saw to the men's food, prevented them from straggling from their corps on the march, and could influence them to withstand the temptation of wine (Furse 1901, 18).

Prime among all aspects of caring for the soldiers are the need for comfortable sleep and good footwear. Brandt von Lindow writes, "Foot ailments therefore lessen not only the number of serviceable recruits, but also of the soldiers required for daily duty; they render defective the marching power of the soldier, they diminish the pleasure of a soldier's calling, they tend to make him pusillanimous, fainthearted, and churlish, and they fill the hospitals." (Furse 1901, 125). Furse devotes several sub-sections of the book to the importance of boots, also noting that practice in marching improves the foot health of the soldiery, ensuring well shod soldiers endure diminishing numbers of foot ailments (e.g. most of chapter V).

Sleep is also important, with 7 - 8 hours per night recommended, as is enough time at the start of the day to eat a proper breakfast (Furse 1901, 327). Camp should only be broken when a particular unit is due to set off to maximise the rest time of the soldiers (Furse 1901, 333). De Brack observes, "The mechanism of war hinges on two things, fighting and sleeping; to use up and to repair one's forces. The science lies in maintaining the indispensable equilibrium of this balance" (Furse 1901, 552).

2.4.4.1 Food & Water

Food is barely dealt with in Furse's book, no doubt due to it having been dealt with in his 1899 work, '*Provisioning Armies in the Field*', sadly now unavailable. Furse does mention that in the 1877-78 campaign, Russian soldiers had a pound of hard bread and half a pound of stringy beef a day (Furse 1901, 566).

The availability of water is considered of prime importance when selecting a camp site but little is mentioned of ensuring water on the march. Furse highly recommends the Indian water bearer who can keep shuttling between water sources and the marching soldiers, filling their cups when required (Furse 1901, 143). Men need about 5 gallons of water a day, horses 8 - 12 gallons and oxen 6 - 7. Water sources near camp can be partitioned so that water for drinking is obtained from upstream, animals can be watered in the middle and all washing and bathing is carried out downstream. Each horse can drink 1.5 gallons in 2 minutes, or 3 minutes if access is disorganised (Furse 1901, 563).

2.4.4.2 Other Hazards

The weather is described as being an important factor in the comfort of the troops. Rain is fatiguing due to the extra effort required to march in wet clothing (Furse 1901, 180). Hot weather is described as affecting infantry the worst, presumably as they expend more effort on the march, and is also to be avoided (Furse 1901, 181) or else sunstroke may result (Furse 1901, 212). Another fatiguing factor is the regularity of the pace of march, if the lead troops march at an irregular pace it means more effort is expended by troops further back (Furse 1901, 201).

It's not just the length of the day's march that wearies, the cumulative effect of marching without rest days also reduces performance (Furse 1901, 216). Forced marches can also increase cases of pneumonia, pleurisy, bronchitis and rheumatism, long rides are also injurious to the spine and bowels (Furse 1901, 225).

2.4.4.3 Animal Care

Horses needs are primarily identified as rest, water and food. Ensuring the cavalry is spread out is a recommended tactic to ensure food supply problems do not affect the horses' health (Furse 1901, 142). They also benefit from being out of the saddle at every opportunity, with their riders having periods where they walk beside, rather than ride (Furse 1901, 195). Unlike people, they cannot be coaxed into expending more effort than they want to, and when overworked will not eat. They develop health problems by being hard worked and overfed (Furse 1901, 226).

The health of pack animals is also an important factor in the speed of the army with spare animals kept in the convoy to relieve any that are suffering (Furse 1901, 382). It is recommended that the baggage is kept moving in order that the pack animals get to camp in time for any problems to be sorted in the light of day (Furse 1901, 383). When General French in 1900 marched his force 150 miles in less than 6 days it cost him 1474 of his 5000 horses (Furse 1901, 225).

2.4.5 General Advice

> *"Marching is indeed an art in itself, and a complicated one too, as so many circumstances, amongst others the season of the year, the nature of the climate, the state of the roads, the actual physical and moral condition of the troops, the attitude of the population, and the urgency of the situation, have all to be taken into account. The more numerous an army is, the more difficult it becomes to move it, the more imperative becomes the necessity for methodical arrangements in everything which concerns its transition, down to the most minute details." (Furse 1901, 4)*

This neatly summarises the factors involved in moving the army. Of these, the attitude of the population is known, the march to Manzikert takes place almost entirely in friendly territory with only the last few miles being through hostile, or more likely depopulated, areas. Therefore the army can, up to Theodosiopolis, count on the support of the settlements along the route. The season of the year is also known to a certain extent, the Emperor sets out from Constantinople in late February or early March and arrives in Theodosiopolis in late June, arriving at Manzikert near the middle of August.

Factors that are unknown but can be simulated with some degree of confidence include the climate (roughly similar to modern Anatolia, see below), the urgency of the situation (non-critical beyond the supply situation) and the physical situation of the troops (probably relatively fit, if undrilled, see below). The morale of the troops represents a difficult simulation task, maybe being inferred from the physical condition. The state of the roads is also largely unknown due to the sparse nature of previous work carried out on the Byzantine road system (French's work notwithstanding) "however, as a general rule, the more enclosed and parcelled a country is, the more numerous are the roads" (Furse 1901, 160). The relationship between army size and speed will of course be investigated as part of this project.

To these factors are also added standard of equipment such as boots and provisioning levels (Furse 1901, 159). While provisioning levels can be modelled by using human and animal health data, the benefits of a good pair of boots and penalties for their absence, while important, seem unquantifiable at this point.

2.4.6 Conclusions

As seen above, a march length of 25 miles for even a force of 40,000 soldiers and attendants can be considered wildly overoptimistic. The reasons, according to Furse, are adequately demonstrated above. The length of the column and necessity of coping with delays and rest periods coupled with there being no strategic reason for forced marching means that we would expect the Byzantine army to march anywhere between 8 - 15 miles per day on days where they actually move. This number would probably be closer to 6 at stages where new troops join the column and are unused to the organisational procedures. This not only allows them to get used to marching but also to wear in boots and make repairs and changes to equipment. Furse also confirms the need to tailor the day's march to the camping location (Furse 1901, 216), not being afraid to recommend a march of just a few miles if no suitable camping spot exists at a more reasonable distance.

A concern regarding the accuracy of any health mechanisms in the model relates to the many factors that Furse regards as fatiguing. Furse often doesn't distinguish between mental and physical fatigue however both are clearly relevant. Factors such as irregular marching speed, poor sleep and wet clothes clearly will have an effect beyond the physical, yet this will manifest itself physically in slower marching speed. Having these factors unmodelled does not affect the credibility of the model, it is used as a null hypothesis against which historical hypotheses can be compared. They do need to be kept in mind at the analysis stage though as effects that would have had a say in the efficiency of the army.

Some examples of behaviours from other sources are advised against by Furse. Furse warns against taking dogs as the nocturnal barking is distracting, yet Western Medieval sources recommend them for their companionship and help with sentry duties (Furse 1901, 564). The recommendation to rotate the order of march (Furse 1901, 358), one that also occurs in Western Medieval contexts may explicitly work against the idea that a set order of march starting with the nearest units to the camp exit eases the marching process (Furse 1901, 560). We will be able to measure any strictly physical effects of non-rotation. If a unit's position in the order of march is negatively affecting its health compared to other units, this may reveal itself in the results of the ABM.

In common with Byzantine military treatises, Furse advises as little impedimenta to be taken as possible in order to simplify logistic arrangements (Furse 1901, 363). That this advice went ignored during the Manzikert campaign is specifically mentioned (Friendly 1981, 165) and cannot have helped either the movement of the army or the morale of its participants. A further complicating feature, unquantifiable in the case of Manzikert, is the accompanying crowd of hawkers that follow an army on campaign (Furse 1901, 364). These create delay both in their unnecessarily increasing the size of the column and by the fact that civilian transport lacks the military discipline that normally aids the army's movement. Still, reducing baggage to levels below that required by the army is a false economy (Furse 1901, 366).

> *“The assertion that an army marches on its belly applies in a pre-eminent manner to our own ; but to attach excessive importance to the supply, so that the men shall never want a ration, runs away with an enormous amount of transport” (Furse 1901, 370).*

So from the contemporary accounts there are some details that can help calibrate the model, if an army is simulated that cannot reach Theodosiopolis by late June even in favourable circumstances there must be a practical disadvantage when compared to the real army on the Manzikert campaign. Military treatises can give organisational details that will have been known to Romanos IV Diogenes due to their persistence through time. Hypothetical systems from *The Art of Marching* can help fill in the blanks. This may include anachronistic details but is borne out of the practical study of the movement of horses and men and some of the more obvious conclusions should be able to be applied to the Manzikert campaign quite plausibly.

2.4.7 Which Elements are Necessary for Which Aspects of the Project?

The agents in the MWGrid ABM represent all the human and animal constituents of the Byzantine army. Although not all tasks will be directly replicated, the army has to contain an agent for each member of the army as size is a critical factor affecting movement and provisioning. Therefore most agents won't actually do much except eat and move. The agents of the army can be divided into a series of types based on behaviour and characteristics. As mentioned above, agents that exhibit the same behaviours and share the same characteristics within the model should belong to the same type regardless of how different they are in real life. Diversification based on behaviours and characteristics that are not modelled within the ABM increases complexity for no gain.

2.4.8 The Army's Behaviour

It is the job of the system under consideration, the army as a whole, to move itself from it's starting point, in this case Nicomedia, to its destination, Manzikert. It must do this while keeping the agents that constitute it in reasonable condition. The army must select a campsite for every night and fortify it by digging a ditch around it. As this is an ABM and not a systemic, top-down model the behaviour must come from the actions and decisions of the agents themselves and not be determined by an overall controller in the software. For this reason the design of the agents is of paramount importance, they must be able to produce the macro scale behaviours from their micro scale interactions with each other and the environment. The agents' organisation, behaviours and attributes are detailed below.

2.4.9 Agent Organisation and Types

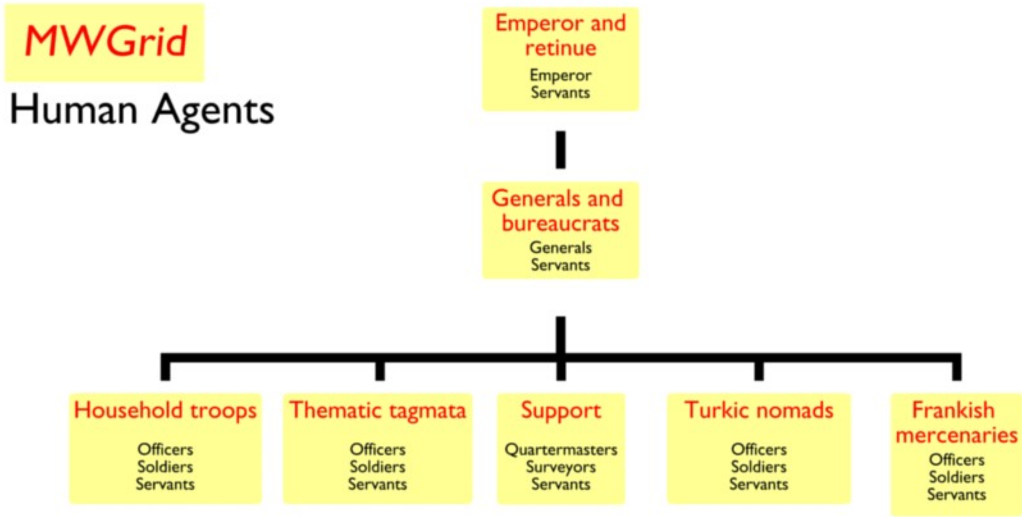


Figure 5: Agent Organisation

As can be seen (Figure 5) there are groups of agents who inhabit separate groups within the model. Each group has their own goals although the agents within each group may have radically different tasks to complete.

2.4.9.1 The Emperor and His Retinue

This group exists to service the Emperor's needs. In general there will have been many flunkies and hangers on in this group whose precise function it is unnecessary to replicate in the model. Suffice to know there is the Emperor, his hangers-on, enough servants not to have to do anything themselves and the Emperor's bodyguards, soldiers tasked with guarding the Emperor's person.

2.4.9.2 Generals and Bureaucrats

This represents a lower stratum of official with their attendant administrative machinery. There would have been a great many mercenary liaison officers, people in charge of people in charge of people and groups of people who correspond to what would be known in industry as 'middle managers'. Their exact function is unnecessary to replicate although they will occupy a place in the army hierarchy in order to lengthen the chain of command between the combat units and the decision makers.

2.4.9.3 Household Troops

These are the supposedly elite units based at Constantinople. Units such as the Hetaireiai, Scholai and Stratelatai (Haldon 2006, 13) would have followed the Emperor from the capital and had higher status than the other army units. This would manifest itself in the model by having access to more food and being required to do less work. They would be exclusively made up of cavalry.

2.4.9.4 Thematic Tagmata

These are the remains of the thematic levies of earlier Byzantine armies. Depending on where they were from they would have had widely varying amounts of experience. Some would have been largely untrained and poorly equipped. They would be mainly infantry and have been the troops expected to fortify the camp each night.

2.4.9.5 Turkic Nomads

These are mercenary troops from a variety of nomadic peoples, including the Pechenegs and Oghuz mentioned in contemporary accounts (Haldon 2006, 13). Being mercenaries they would probably take no part in digging the camp's fortifications. Their primary difference is in the number and type of horses. Nomads will all be cavalry with numerous spare horses per soldier. The steppe horses tend to be smaller than the Byzantine horses.

2.4.9.6 Frankish Mercenaries

These are also mercenary troops and again the main difference is the number and type of their mounts. Frankish cavalry were known for the large size of their warhorses, although baggage animals will be of normal size.

2.4.9.7 Support

This group contains the support staff whose function is being replicated in the model. Surveyors represent the minsouratores who travel a day ahead and plan out the next camp, quartermasters organise and operate the highest level of the army's baggage train. Quartermasters and surveyors will need servants to handle equipment and pass messages.

2.4.10 Agent Types

Agents can be divided into three types:

- Human agents
- Animal agents
- Settlement agents

Settlement agents are a separate type, utilised mainly for technical reasons. They will be detailed elsewhere.

2.4.10.1 *Human Agents*

Name	Tasks
Emperor	Macro route planning
General	Transfer info up and orders down the chain of command
Quartermaster	Handle army baggage train
Surveyor	Set out following day's camp
Byzantine cavalry	Foraging
Byzantine infantry	Dig camp fortifications
Turkic cavalry	Move and eat
Frankish cavalry	Move and eat
Servant	Fetch objects and organise local baggage

Table 3: Types of human agents

2.4.10.2 *Animal Agents*

Type	Tasks
Baggage mule	Carrying equipment
Baggage camel	Carrying equipment
Baggage donkey	Carrying equipment
Horse	Carrying equipment or people
Turkic horse	Carrying equipment or people
Byzantine warhorse	Carrying people
Frankish warhorse	Carrying people

Table 4: Types of animal agents

Each agent has a structure as shown in Figure 6. Each element is more fully described in Chapter 3.

2.4.11 Agent Architecture

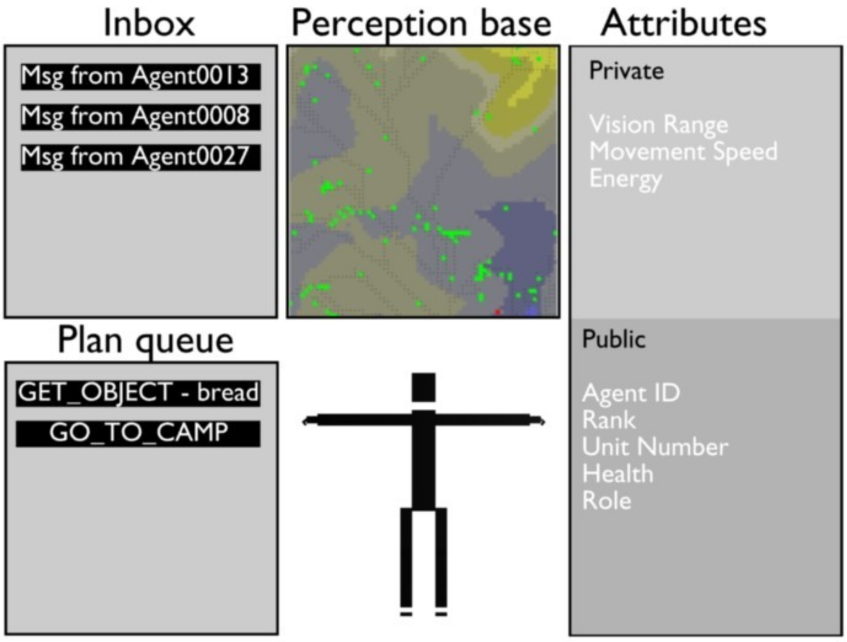


Figure 6: Agent architecture

2.4.11.1 Inbox

Each agent has an Inbox which operates like an email inbox. Any messages from other agents are placed here where they wait until the agent can process them. They are then removed.

2.4.11.2 Plan Queue

The plan queue is the list of tasks that the agent has to fulfil. They are placed in the order in which they will be processed. Processing tasks may result in more plans being added to the queue.

2.4.11.3 Perception Base

The perception base or context contains the information that the agent knows about the world including information about the environment and other agents.

2.4.11.4 Attributes

The attributes of an agent specify those aspects of the agent that can change from agent to agent. They can modify behaviours.

2.4.11.5 Behaviours

An agent's behaviours are hard-coded into the model and govern the way the agent processes messages and plans from its queue.

An agent will either receive a message or sense a situation in its perception base that requires a response. It will then process the resulting plan from its plan queue that will trigger its internal behaviours. The actions of these behaviours may be modified by the agent's attributes.

2.5 Human Agents: Attributes

The model is primarily concerned with the movement and provisioning of the Byzantine army and the agent's attributes should be restricted to those we need to accomplish our objectives. Some attributes are set during the model's initialisation and do not change while some vary during the operation of the model. The use of each agent's attributes and the circumstances under which they change are described in more detail in Chapter 3.

Attribute	Variable Type	Notes
ObjectID	Integer	A unique agent identifying number
Unit#	Integer	A number identifying the unit to which the agent belongs
Weight	Integer	The agent's weight in kilogrammes
AdHocUnit#	Integer	Used to enable agents from different units to be formed into temporary units to perform certain tasks (foraging, ditch digging etc.)
VisionRange	Integer	The distance in metres that the agent can see unless interrupted by objects or terrain
MovementSpeed	Double	The maximum speed that the agent can move in each time step of the simulation
CarryingCapacity	Integer	The maximum load that the agent can carry for extended periods in kilogrammes
Superior	Integer	The ObjectID of the agent's superior in the army's chain of command

Table 5: Human attributes

2.6 Human Agents: Behaviours

2.6.1.1 Health

An agent's primary responsibility is to its own survival. It will obey its own plan queue until its health reaches a certain point, at which point the agent 'fails'. This will result in it dropping out of the army's organisational structure. A similar process occurs when the agent's energy expenditure exceeds its consumption. If this happens regularly over an extended period or catastrophically in a short time then the agent will inform his superior but will continue normal operation until his health is affected (Figure 7).

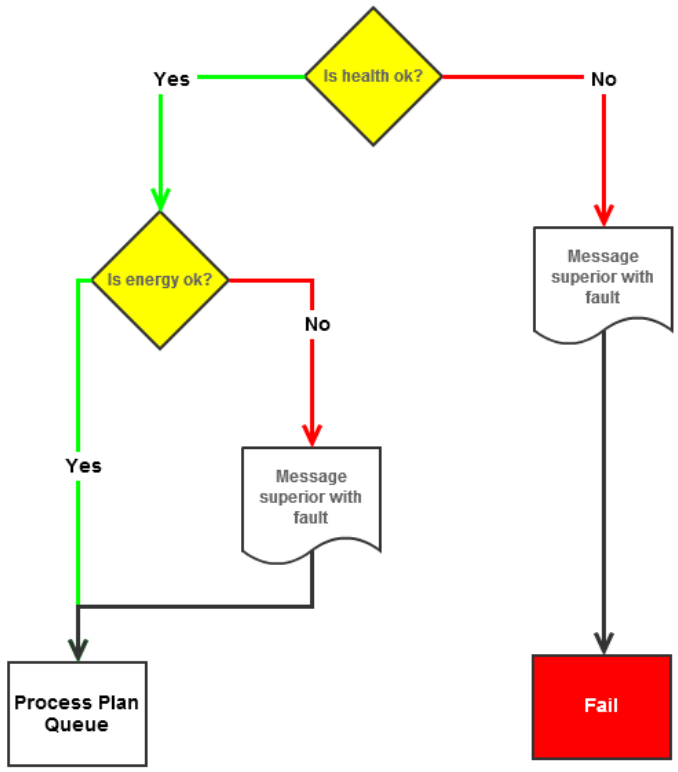


Figure 7: Agent health decision making

Generals have different health decision making as befits their higher status within the army. This also applies to mercenaries, surveyors and quartermasters (Figure 8). As can be seen, higher status members of the army will first turn to the army's baggage train and then other units' supplies rather than starve. This ensures they will never be without food, the army will fail before a general starves to death. Also note their response to fatigue, instead of merely reporting themselves in need of a rest like common soldiers they will overestimate the need for their unit to rest when messaging the Emperor. This will ensure they have a higher chance of getting a rest day for the army. Naturally the general will rely on servants to do all the actual work in this process.

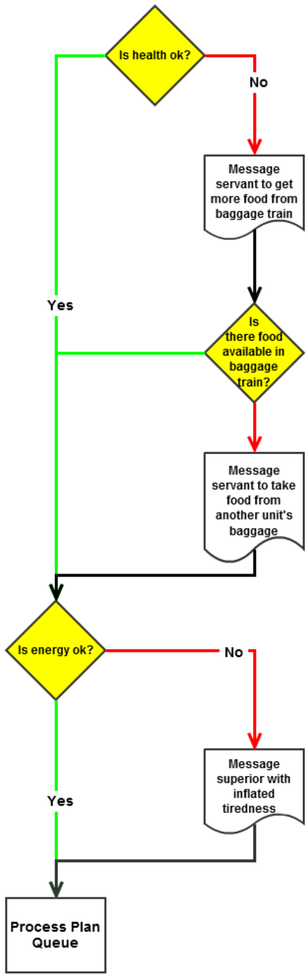


Figure 8: General's health decision making process

2.6.1.2 Emperor

The Emperor is responsible for planning the overall route to Manzikert. He will decide which settlements to pass through and on which days to move (Figure 9). The army will need at least one day of rest per week regardless of condition otherwise the horses will develop health problems. It is possible that the condition of the army will demand more rest than that at times, especially after a period with insufficient rest or food.

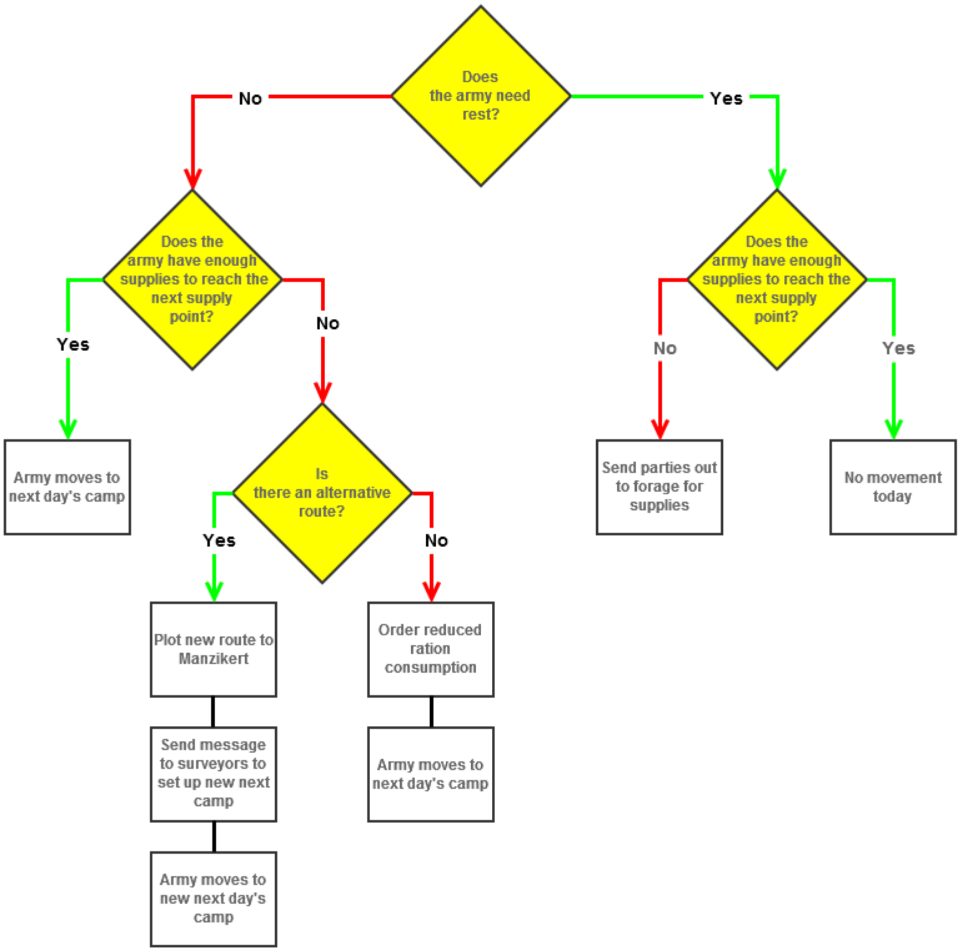


Figure 9: Emperor's decision making process for each day's march

The Emperor will already have the location of the next camp as the surveyors will have sent a messenger back the previous day. The Emperor will have a daily status update from each General regarding the units under their command. The generals will supply the emperor with a percentage of units that have insufficient food and need rest. The emperor can then make his decisions on this basis. The Emperor goes through this decision making process each morning. Each evening he does nothing but consume food.

2.6.1.3 General

Generals have a different decision making process regarding their own well-being as described above. They include members of the bureaucracy and their function in the ABM is primarily to act as intermediaries between the combat units and the Emperor. In the Byzantine army their tasks would have included liaising with mercenaries, making decisions regarding the discipline of the army and dealing with organisational matters too trivial for the Emperor to be bothered with. In the ABM however all decisions affecting the whole army are taken by the Emperor agent. This represents a reality of consensus, meetings and slightly devolved power that is hard to model and does not significantly affect the movement or supply factors of the army's march. Some of the officer class will also have their commissions based on personal wealth or power and so this strata of the army will have been padded with largely unnecessary roles anyway.

Each morning the generals immediately under the Emperor in the hierarchy will deliver messages containing the army's status allowing the Emperor to decide whether the army moves, rests or forages (see above). Beyond this and the passing of messages up and down the army's structure they have no decision making processes. There will be Generals with unit numbers that do not have a place in the army's hierarchy to represent members of the bureaucracy. This ensures they use the General's health decision making process but play no other role in the army.

2.6.1.4 Quartermaster

The quartermaster's primary responsibility is to determine the ration rate of the army. The ration rate is a percentage value that affects how much food an agent eats each day. 100% represents the full value of calories needed to sustain a human during moderate activity. This can be lowered as a response to dwindling stocks of supplies. There is a separate value for food and water.

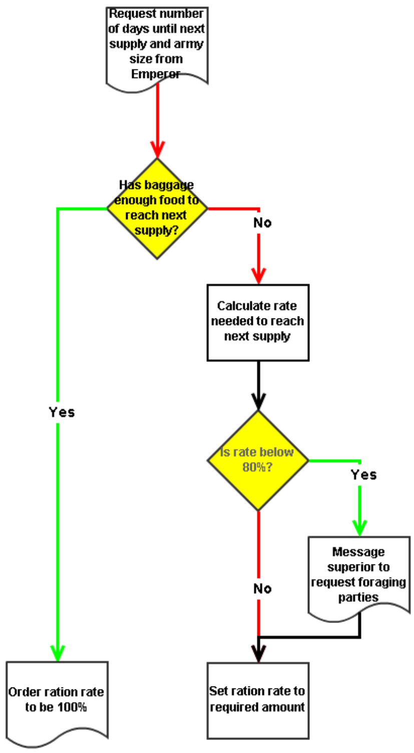


Figure 10: Quartermaster's decision making process

The quartermaster leads the army's baggage train and travels with it. Individuals from the army can come and request food or water from the army's baggage train as their own units run out. This will generally happen in camp. As the baggage train camps in the same part of the camp each night then all agents will know where it is. Each morning the Quartermaster will go through the process in Figure 10 and then message his servants to pass this message on to the generals who will pass it down the chain of command. Thus the generals will know the ration rate as well as having the info regarding troop energy and health from their subordinates.

2.6.1.5 Surveyor

The Surveyor is responsible for setting out the following day's camp. Like the Quartermaster, the Surveyor is an agent representing the whole of the decision making apparatus of the surveying team. In reality there would be a number of agents with specialised tasks related to the planning and setting out of the camp. Within the ABM this is abstracted down to a surveying agent who makes the decisions (Figure 11) and a series of servants who respond to his commands. This simplifies the ABM architecture while still giving a reasonable number of agents for movement and supply purposes.

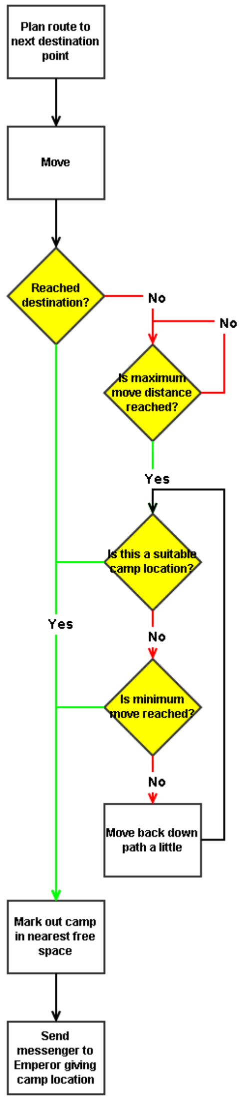


Figure 11: Surveyor's decision making process

The surveyor receives from the Emperor the location of the next waypoint, usually a settlement. The surveyor will plan a route to this location using the A* route planner. It will then travel along this route with its team of servants. When it reaches the maximum distance that the army can travel in a day it will assess whether this location is suitable for a camp. This will be based on the availability of water and enough flattish ground to place the camp. If this place is unsuitable the surveying team will travel back down the path looking for suitable locations. As soon as it find one it will send a servant back to inform the Emperor where the camp is located and then order the other servants to set out the camp. If it reaches the minimum march distance without finding a suitable location it will return to the maximum move distance and declare that the 'best worst' camping location and set up there.

The surveyor agent will have 2 variables no one else has, MaximumArmyMoveDistance and PreviousArmyMoveDistance. The maximum distance is the furthest distance the army can move during one day. If the army regularly manages to march this distance with plenty of time to set up camp this will be increased. If it finds itself arriving at camp too late then it can be decreased. The minimum march distance is 60% of this figure. The previous move distance is recorded because the army will not always move its maximum distance due to the availability of decent camp sites. Recording how far the army actually moved will avoid the increasing of the maximum due to early arrival if the army only moved part of the maximum.

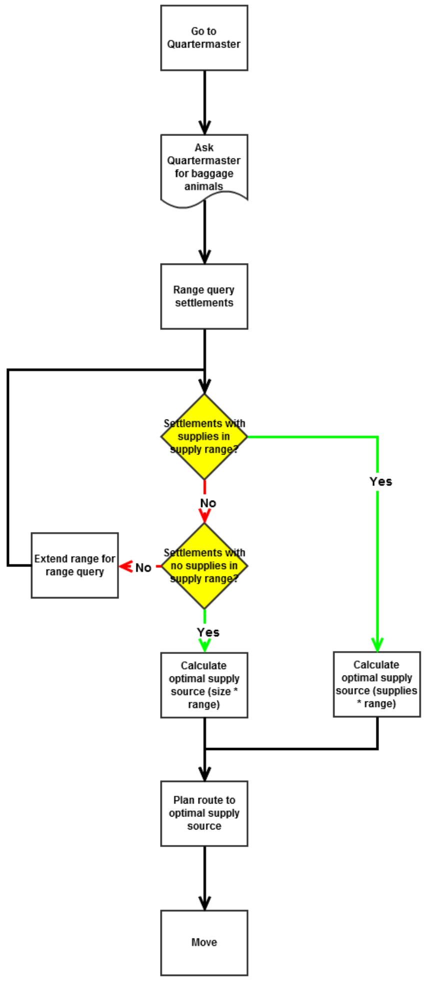


Figure 12: Foraging leader's decision making process

2.6.1.6 Byzantine Cavalry

The Byzantine cavalry units will be primarily responsible for foraging if and when this is required. Their increased speed and Greek language proficiency makes them more suited to this role than infantry or mercenaries. An entire unit will be assigned to foraging, with the size to be determined by the Emperor based on how much food or water is required. The leader of that unit is designated the leader of the foraging party and his decision making process is detailed in Figure 12.

2.6.1.7 Byzantine Infantry

The army's Byzantine infantry will be responsible for digging the ditch around the camp every evening. Each unit of the infantry will be responsible for digging a particular stretch of ditch. When a definite camp location is communicated back from the surveying team.

2.6.1.8 Turkic Cavalry

Turkic mercenaries will have two unique attributes: NumberOfHorses and CurrentHorse. Due to the Turkic tendency to have many horses and to rotate which horse they ride in order to spread the load each Turkic mercenary will keep track of which horse they were riding each day and each morning.

2.6.1.9 Frankish Cavalry

Frankish mercenaries will tend to have a warhorse and another horse or two for riding. The warhorse will be bigger and not carry equipment. The other horse(s) will be of regular size and will be rotated between being ridden and carrying equipment if possible.

2.6.1.10 Servant

The servant is ubiquitous in the ABM, primarily because many tasks are aggregated into just a few agents. Everyone with no definite function will either be a General or Servant depending on their status. Servants will have a superior and will follow their superior until given an order by them. They will also follow the soldier's health decision making cycle as detailed above.

2.7 Movement

Central to the MWGrid ABM is the movement model. The movement of the army as a whole depends on the movement of each individual so if this movement is unrealistic, the output of the ABM will suffer. Agent-based modelling is a computer-based simulation technique that has already been used to simulate the movement of large groups of individuals, from Craig Reynolds' work on flocking behaviours (Reynolds 1987) through to work in safety science and sociology

(Lansing 2002; Thompson and Marchant 1995). There are also a number of archaeological ABM projects from the small and abstract (E. A. Smith and Choi 2007) to the large and multidisciplinary (Kohler et al. 2008). Its architecture of autonomous software entities behave according to their own internal rules and inhabit a landscape that can act as a source of resources and a constraining factor to movement and is ideal for examining military organisation and supply.

Creating an ABM involving tens of thousands of agents moving across a distance of over 700 miles presents many challenges, both technical and historical. Due to the incomplete nature of the historical record there is no single source for agent organisation, behaviours or attributes. The environment around which each will move is also based on incomplete and inadequate data. All historical ABMs share similar problems but by modelling various hypothetical scenarios and noting where and how they differ we can rule out the more impractical scenarios and establish a set of parameters within which we can re-evaluate the historical record.

Modern agent-based models are widely used in the simulation of crowd movement (Thalmann and Musse 2007) and this is an important part of this research into Byzantine army logistics. How the many members of the army are organised while on the march affects the speed of the army as a whole, which in turn affects consumption of resources and the subsequent impact on the communities providing those resources. Efficient movement was acknowledged by Byzantine military writers as being essential to the success of a military expedition (Dennis 2001, 20; Dennis 1985). Unfortunately there are few sources regarding the organisation involved and the procedures followed, contemporary histories being more concerned with the battles and personalities of the time. It is this subject's very mundaneness that results in a lack of adequate descriptions of the daily routine of an army on the march and no detailed analysis of how this affected the territories passed through.

There are two types of movement required by the MWGrid ABM: macro-scale and micro-scale. The macro-scale movement deals with the movement of the army as a whole. Although one of the goals of the ABM is to examine how the movements of individuals translate into the overall movement of the army, the movement of the army does not occur like a swarm of ants relentlessly covering Anatolia until they reach their destination. As described above, some element of control over the daily movement of the army is required. The intention must be to have the whole of the army arrive at the following day's camp in plenty of time to set up their tents and feed themselves. The army must also move in such a way as to be able to pick up sufficient supplies in order to feed itself. For this reason an overall route plan will have been made in advance so that the communities through which the army passes will have had the opportunity to stockpile the required resources (Haldon 1999, 182). This overall route may have been so specifically detailed as to include individual roads to be taken and settlements to be visited down to very small villages or it may have operated on the regional level, specifying no more than the regional centres at which supplies should be collected. For this reason, the ability for the macro route to be determined during the run of the simulation is important. It can be used to create a complete route from scratch using various hypothetical models or it can be used to alter or provide fine detail to a route already specified in advance. All route planning is based on the A* route planning algorithm, the technical details of which will be covered in Chapter 3.

2.7.1 Macro-Scale Movement

Macro-scale route planning operates over the course of more than a day and determines the overall route of the army. It specifies a series of waypoints through which the army will attempt to travel. This can either be set in advance or be determined by environmental factors such as access to food and water or in order to take advantage of major roads. It simulates the route planning usually done in advance by the Emperor and whoever constructs the overall plan for the campaign. The A* planning algorithm allows us to assign costs to various types of moves so that if, for example, we assign lower costs to moves which pass through large settlements the macro route will tend to go through large settlements. In this way many different considerations can be modelled in order to examine their effect on route planning.

2.7.2 Micro-Scale Movement

Micro-scale movement is something that happens at the level of the individual and is done by all agents looking to move from one location to another. At this level the majority of agents will just be following the macro route chosen in advance by the Emperor but still need to move from location to location avoiding other agents. As crowding is an important mechanism in the overall movement of the army, this must be simulated in some way. As there cannot be an infinite number of agents inhabiting the same space, the model compares the size of each environment cell with the sizes of all the agents within it to see if there is space for an agent to move into the cell. If there is not, the agent's route planner will attempt to get to its destination while avoiding cells with insufficient space.

2.7.3 Intermediate-Scale Movement

Due to the massive difference in scale between the macro route plans and the micro route plans, there is a need for an intermediate layer at which the officers of squads move from terrain data point to terrain data point (see Figure 13). This is done to improve accuracy and performance and is detailed in Chapter 3.

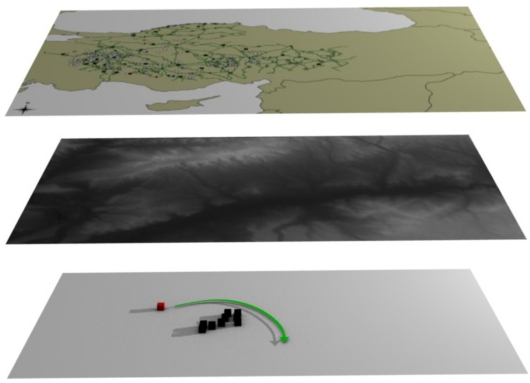


Figure 13: The three levels of route planning

2.8 Calorie Expenditure

Being able to determine the calorie expenditure of each agent has obvious modelling benefits. Previous work such as Pryor and Engels have assumed a static figure for food requirements per person per day. The resolution of the MWGrid ABM allows a more accurate calculation of the energy expended for each agent. Not all activity by every agent will be modelled but the coarse estimates produced by the MWGrid ABM can still be much more finely nuanced that the top down approaches tried previously. As the ABM is able to record the location and activity of every agent throughout the run of the simulation, conventional equations from exercise and sports science can be used to calculate how many calories an agent uses in any given situation. The following scheme is taken from the American College of Sports Medicine's Guidelines for Exercise Testing and Prescription (Balado 1995, 276).

In order to calculate the calories expended while walking, we first need to calculate the volume of Oxygen consumed (VO_2). This can then be used to calculate the calories burnt compared to the amount of carbohydrates and fat consumed.

$$VO_2 = R + H + V$$

R = 3.5ml per kg per minute

H = 0.1 x walking speed (in m/min)

V = 1.8 x speed (in m/min) x grade (as a decimal)

There are acknowledged flaws in this equation but these relate to people under the age of 18 and for walking on the level. By assuming all the members of the army are aged 18 and over the first of these situations is avoided. As each agent will not be walking on the level for very long due to the undulating nature of the Anatolian terrain any inaccuracy derived from this should be minimal.

For example, an agent walks for an hour at 3mph up a slope of grade 0.05, or 1 metre up for every 20 metres across. This would give us:

3.5 + 8.047 + 7.2423 = 18.7893 ml per kg per minute

This first value is in ml of O_2 per kg of body weight (plus any weight carried) per minute. This provides a good value against which to calibrate our data as values of over 50 can only be accomplished by a fit individual and values of 80+ are probably unreasonable for anyone likely to be in the Byzantine army. If this result is multiplied by a plausible weight for an individual plus clothing, 70kg, we get:

18.7893 x 70 = 1315.251 ml per min or 1.315251 litres per minute

Any carried weight would be added onto the weight of the individual, allowing a calculation of how energy expenditure is affected by increased load. Using Table 13 of Carpenter's Tables, Factors and Formulas for Computing Respiratory Exchange and Biological Transformations of Energy (2010) we can find a figure which, when multiplied with our result for litres of O_2 per minute, will give us the value of kilocalories burnt per minute. The multiplier depends on the amount of carbohydrate or fat consumed as they are transformed into energy differently. For this example we will assume 100% carbohydrate consumption, this gives us a figure of:

1.315251 x 5.047 = 6.638071797 kcals per min

In our example of an agent walking for an hour they would burn about 398.28 kilocalories per minute.

Several points can be noted from these calculations. There are standard ways of calculating calorie expenditure that can easily be calculated by the MWGrid ABM. These can give a coarse indication of the amount of energy expended by each agent which will in turn relate to the amount of food required. This could be affected by how much equipment or supplies each agent was being asked to carry. There is also a feedback between the types of food eaten and the amount of calories required. Although the differences aren't extreme, around a 7% difference between 100% carbohydrates and 100% fat, they make become significant when multiplied by the number of agents and over the length of the campaign.

Not all of our agents are infantry so the ability to determine the energy expenditure of riding a horse would be essential in order to calculate energy expenditure for the whole army. A small study was carried out by Devienne and Guezennec (2000) in which oxygen consumption was measured for 5 different riders and 4 different horses during dressage. Oxygen consumption varied depending on the person and on the type of movement, as seen in Table 6.

Rider	Walk - VO_2 (litres per minute)	Trot - VO_2 (litres per minute)
1	1	1.85
2	0.56	1.4
3	0.72	1.55
4	0.6	1.17
5	0.64	1.43
Mean	**0.7**	**1.48**

Table 6: Oxygen consumption of horse riders (after Devienne and Guezennec 2000)

These values are in litres per minute and already have the weight of the rider taken into account. The only further calculation that would need to be performed is multiplication by the modifier from Carpenter. The above only allows a coarse measurement of calories expended however if we assume all other activities remain the same we can estimate the difference between different types of activity and how this relates to supply consumption. This in turn allows us to coarsely estimate the effects on the settlements on whom the supply burden fell.

2.9 The Environment

2.9.1 What Was the Environment Like?

The environment of the MWGrid ABM is the environment of Byzantine Anatolia. Not all of Anatolia needs to be modelled as there are only a certain number of viable routes between Nicomedia and Manzikert. The environment needs to be large enough to encompass all the viable routes but with as little extra detail as possible in order to minimise data storage. Each aspect of the environment is treated separately due to the differing resolutions and data formats of the source data. Each aspect of the environment is detailed below.

The environment consists of two elements.

- Environment slices
- Weather data

An agent-based model (ABM) consist of two main elements; autonomous agents and the environment they move around in and interact with. In the MWGrid ABM the environment represents Byzantine Anatolia in AD 1071. The ABM environment is split up into slices with each aspect of the environment occupying a separate slice. This assists the organisation and storage of the environment.

The environment slices are brought together in ArcGIS and GRASS (using QuantumGIS as a front end) and output as ESRI ASCII text files. This is necessary because the data sources are of insufficient resolution and in inappropriate formats to be simply imported into the ABM as is. Continuous data such as terrain can be read directly into the ABM as ESRI ASCII files in either $5m^2$, $50m^2$ or $500m^2$ resolutions. Sparse data sets must be written to ESRI ASCII files first but can then be converted into a simple list of locations that occupies much less disk space.

The area covered by the environment lies between 38° - 42°N and 28° - 44°E (Figure 14). The resolution of the data varies depending on the slice. The ABM uses a resolution of 0.0000449944° N-S and 0.0000570004° E-W giving a cell size of roughly 5m x 5m. This was chosen as it represents the smallest reasonable gap size that troops will have to travel through. If this resolution were used for the environment slices each would need a standard ESRI ASCII raster file of 24,954,230,000 cells (280,700 x 88,900). This would create an unusably large single ESRI ASCII file, requiring around 140Gb of disk space for a single slice. It is also much finer than the resolution of the base data, the finest resolution data we have is the ASTER terrain data at roughly 50mx50m.

Initially, the ASTER data was intended to be interpolated to the 5mx5m resolution however standard methods of interpolation cannot introduce the kind of fine grained detail needed to represent the narrow defiles and awkward terrain originally intended to be modelled. Fortunately the movement of the army in highly restricted circumstances will be modelled in circumstances such as the exit from the daily camp and the crossing of the Halys. For these circumstances a 5mx5m terrain resolution is unnecessary. This also means the ASCII files containing the environmental data are more practically sized.

When the ASCII data is loaded into the ABM it will be fitted into the model's 5mx5m grid. In the case of raster data such as the ASTER and Globcover terrain data, each cell of data from the

ASCII file will be expanded over 10 or 100 ABM cells depending on the resolution. In the case of settlement vector point data, the settlement will be placed in the centre of the block of 100 cells. Road vector data will be converted into an ASCII raster grid and imported in the same way as settlement point data. The ABM will then create road links between the points at the appropriate width.

Size label	N-S resolution (degrees)	E-W resolution (degrees)	Rows	Columns	Approx cell size	Approx file size
LOW – low	0.00449944	0.00570004	889	2807	500m^2	14Mb
MED - medium	0.000449994	0.000570004	8889	28070	50m^2	1Gb
FUL – full ABM	0.0000449944	0.0000570004	88900	280700	5m^2	50Gb

Table 7: The different sizes of environmental slice

No environmental slices use full ABM resolution as this is unnecessary and creates files of unwieldy size, it is purely used inside the ABM. Medium resolution is used for data that is supplied in a similar resolution such as the ASTER terrain data or for features of small size such as roads. Low resolution is used for features of large size such as settlements of for data where higher resolution is not needed such as the Globcover land use data.

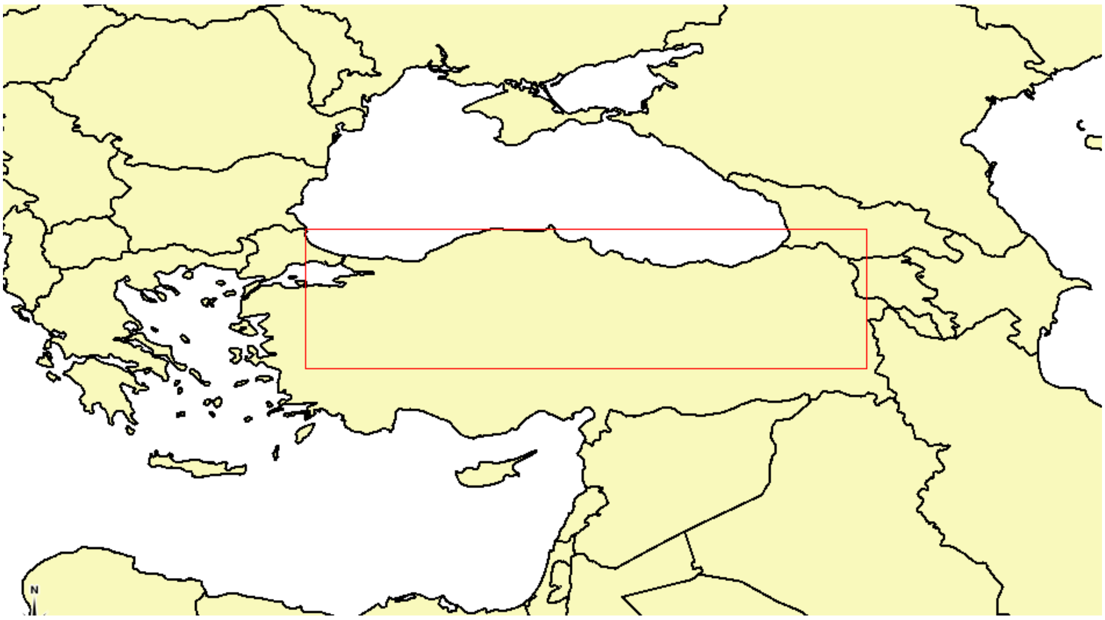


Figure 14: Anatolia with the MWGrid environment boundary in red

2.9.2 Environmental Slices

*2.9.2.1 **Height** – A Digital Elevation Model of Anatolia.*

2.9.2.1.1 Resolution

Medium

2.9.2.1.2 Source

The height data is derived from ASTER GDEM data. The ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) is a joint operation between NASA and Japan's Ministry of Economy, Trade and Industry (METI) and was released for public use on 29th June 2009 (Tachikawa et al. 2011). It was created by compiling 1.3 million visible and near-infrared (VNIR) images taken by the ASTER satellite using single-pass stereoscopic correlation techniques, with terrain elevation measurements taken globally at 30 meter intervals. Using modern height data is justified as the terrain of Anatolia, while part of a geologically active region, is not significantly different to that of the 11th century.

As the file containing this data is approximately 1.4Gb it has been zipped and is separated into partitions that are only loaded when required.

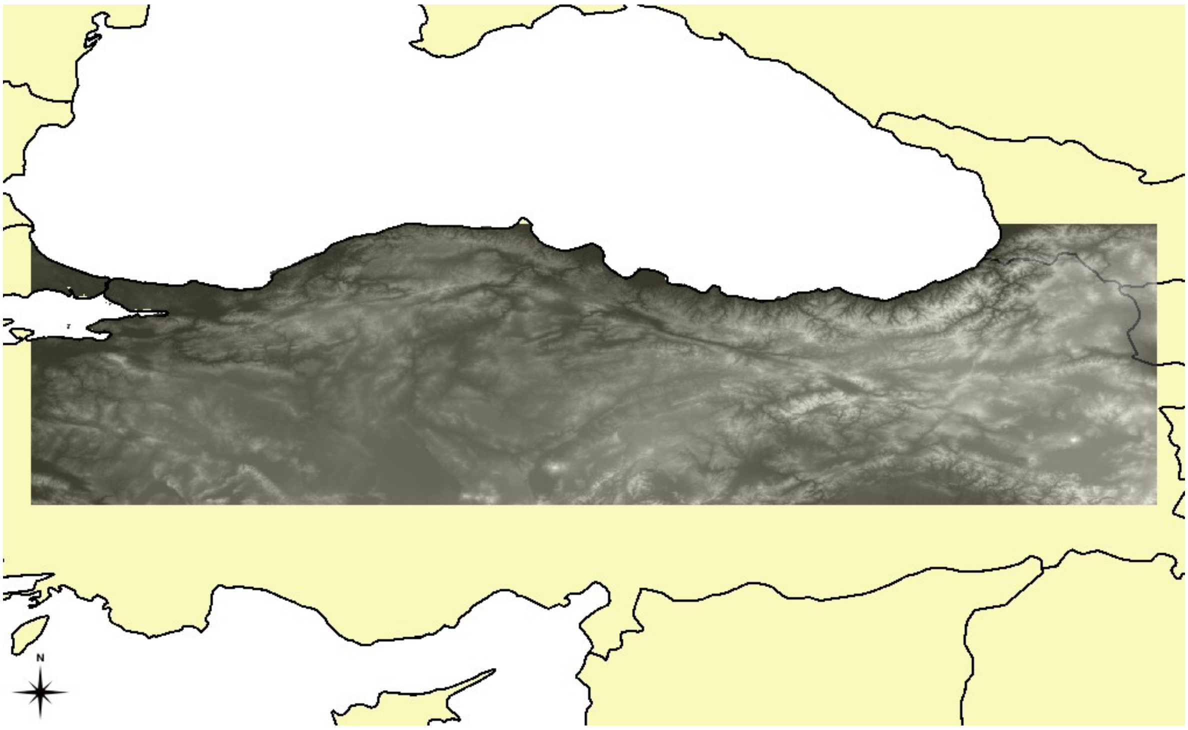


Figure 15: ASTER GDEM data for Anatolia

2.9.2.1.3 Format

Integer. Height above sea level in metres

2.9.2.1.4 Effect

Height affects route planning and is used with weather to calculate how many calories are burned during movement. It is also used with Transport and Terrain to affect movement speeds.

2.9.2.2 ***Settlement*** *– Indicates Location and Type of Settlement.*

2.9.2.2.1 Resolution

Low

2.9.2.2.2 *Source*

The settlement data is digitised from the *Tabula Imperii Byzantini* (TIB) maps (e.g. Koder and Hild 1976; Belke and Mersich 1990; Hild and Hellenkemper 1990), inserted from ancient sources and extrapolated from known data. The Tabula Imperii Byzantini maps are part of an attempt by the Austrian Academy of Sciences to map the geography of the Byzantine Empire. The results have been published since 1976 in geographically separate sections and rely on historical records, archaeological evidence, toponyms and the physical state of the landscape (St Popović 2009).

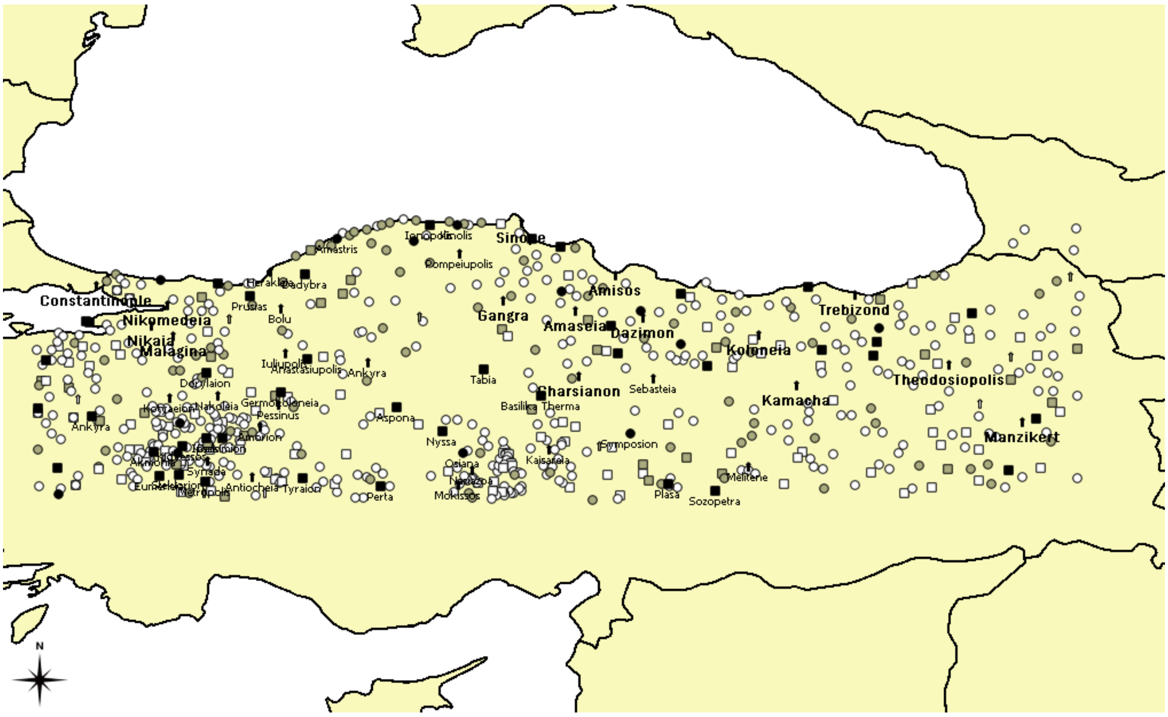


Figure 16: Settlements from all sources

2.9.2.2.3 *Format*

Location, name and type of settlement. The settlement types are taken from the TIB maps as described in Table 8.

GIS layer	Subcategories	Description
Walled settlements	Seat of archbishop Seat of bishop None	Cities with defensive walls, subdivided according to ecclesiastical status
Citadel settlements	Seat of archbishop Seat of bishop None	Cities with no extensive defensive walls but with an acropolis or citadel, subdivided according to ecclesiastical status
Unfortified settlements	Seat of archbishop Seat of bishop None	Cities with no significant defensive feature, subdivided according to ecclesiastical status

Table 8: Settlement types

Only the walled cities are named, other sites are recorded by position and subcategory only. Due to the difficulties of incorporating the TIB maps into the co-ordinate system of GIS, the areas of overlap do not precisely correspond. This resulted in minimal distortion of the settlement data. Locations of the settlements that appeared on two maps were captured somewhere between the locations indicated on each digitised map.

As the TIB data does not cover the whole of the area simulated in the ABM, some method of extrapolating the data from the TIB across the whole area was needed. As modern settlement location data was available, this was used to generate the extra settlements required. To this end, the area was split into 3 different areas; the area covered by the TIB maps, the area of Anatolia west of this and the area to the east (Figure 17).

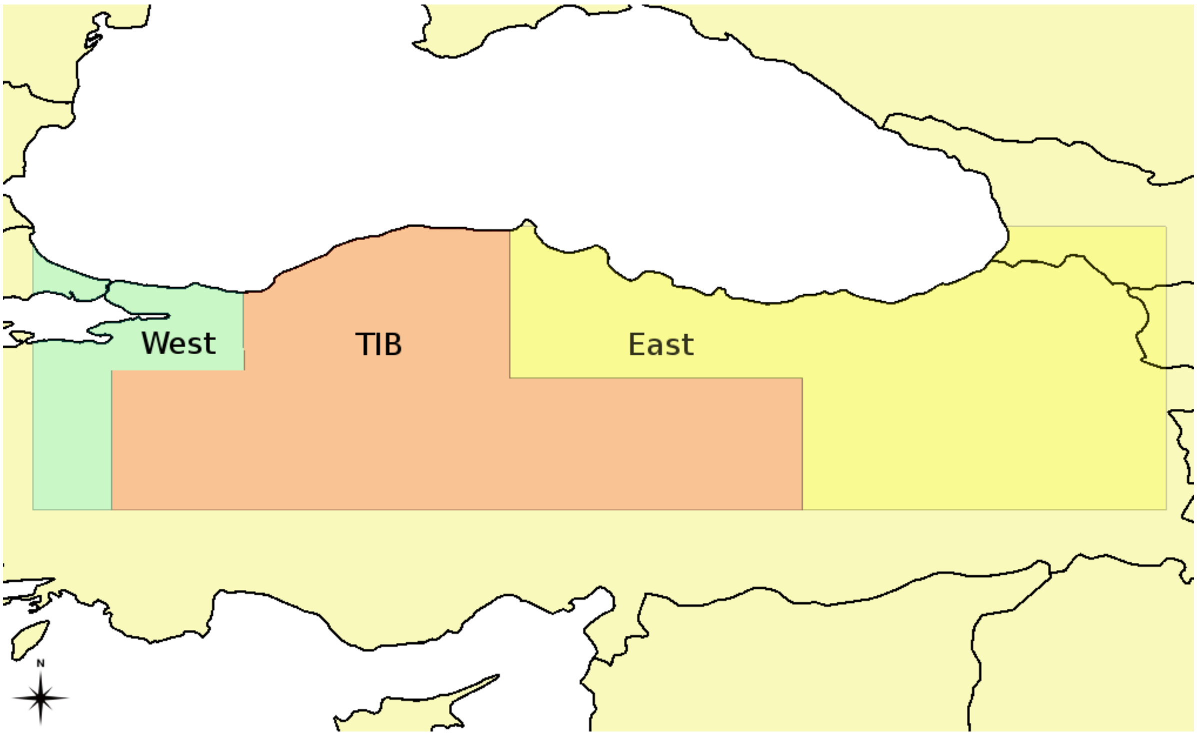


Figure 17: The area covered by the TIB maps with the West and East areas of extrapolated data

By analysing the data from the area covered by the TIB we can examine the proportions of each type of settlement and use these same proportions to add detail to the settlements of the extrapolated areas. We can also compare modern settlement densities in each of the three areas to give a more plausible density in the simulated environment. Modern Anatolia is more densely settled towards the west than the east, a pattern likely to be reflected in the Byzantine era, especially considering the Seljuk raids of the 1050s onwards (Attaleiates 1853, 148). For this reason the fact that the modern data finishes approximately 50km west of the edge of the simulated area is not factored into the calculations, depopulation due to Seljuk raids would have made up for any inaccuracy this introduces. Obviously the presence of a modern settlement should not imply the presence of one in the Byzantine era but using modern data should at least reflect general areas of high population density and ensure settlements are not placed in lakes or in impassable terrain. The modern data is also considerably more complete than the TIB data, which partially reflects patterns of archaeological research as well as patterns of settlement.

The process of creating the data consisted of five phases:

- Digitising the TIB data (Figure 18)
- Importing the modern data (Figure 19)
- Determining the modern settlement density (Table 9)
- Extrapolating settlements in the West and East areas based on the TIB data (Table 10)
- Random selection of modern points to generate an appropriate settlement density and composition in the West and East areas (Figure 20)

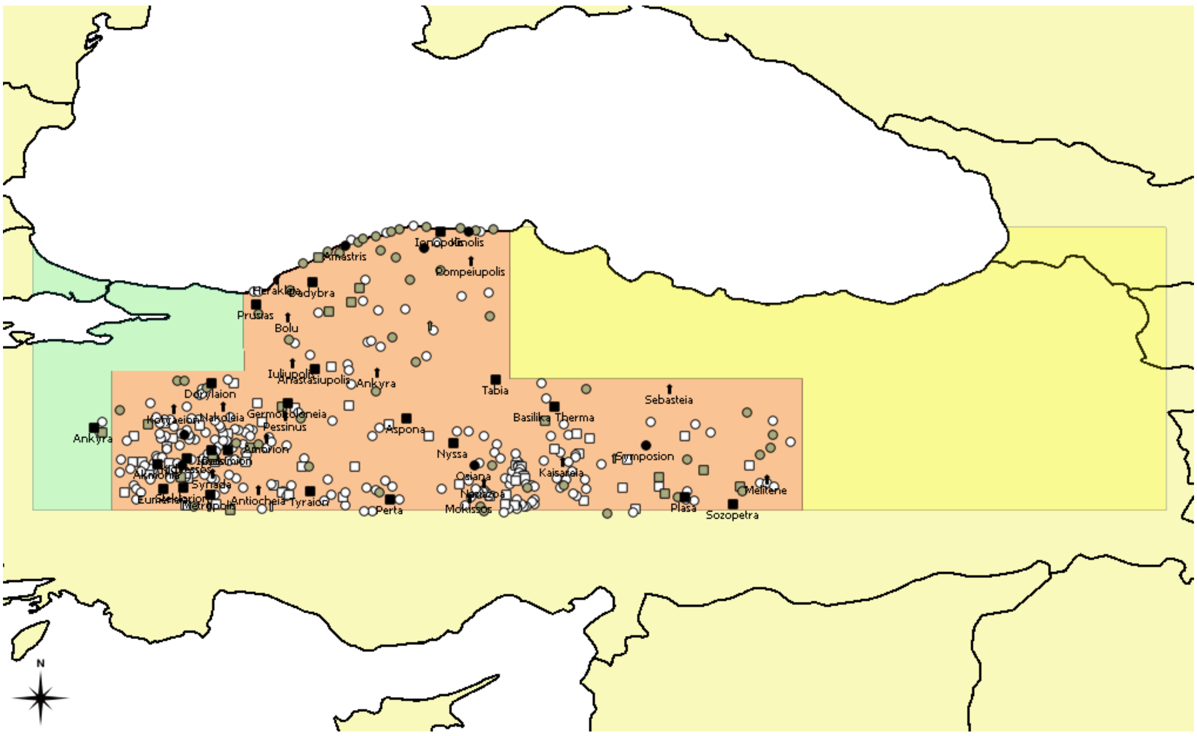


Figure 18: Settlement data derived from TIB maps

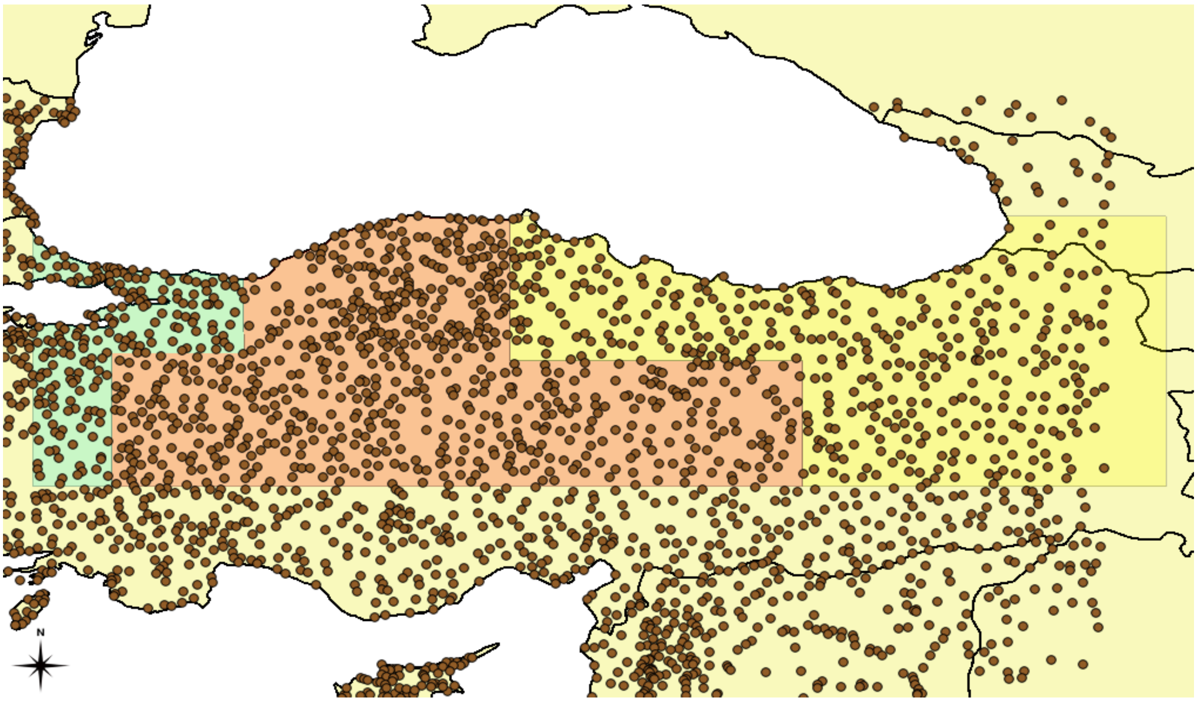


Figure 19: Modern settlement data

Area Name	Area (km2)	# of modern settlements	km2/settlements
West	45520	166	274
TIB	242152	649	373
East	228340	386	592

Table 9: Modern settlement density in the three areas

Type of settlement	# in TIB area	extrapolated # in West TIB * 166 / 649	extrapolated # in East TIB * 386 / 649
Walled city - archbishopric	16	4	10
Walled city - bishopric	22	6	13
Walled city - other	7	2	4
Citadel city - archbishopric	3	1	2
Citadel city - bishopric	16	4	10
Citadel city - other	46	12	27
Unfortified settlement - archbishopric	2	1	1
Unfortified settlement - bishopric	53	14	32
Unfortified settlement - other	210	54	125
Total	**375**	**98**	**224**

Table 10: Extrapolation of settlement numbers and types

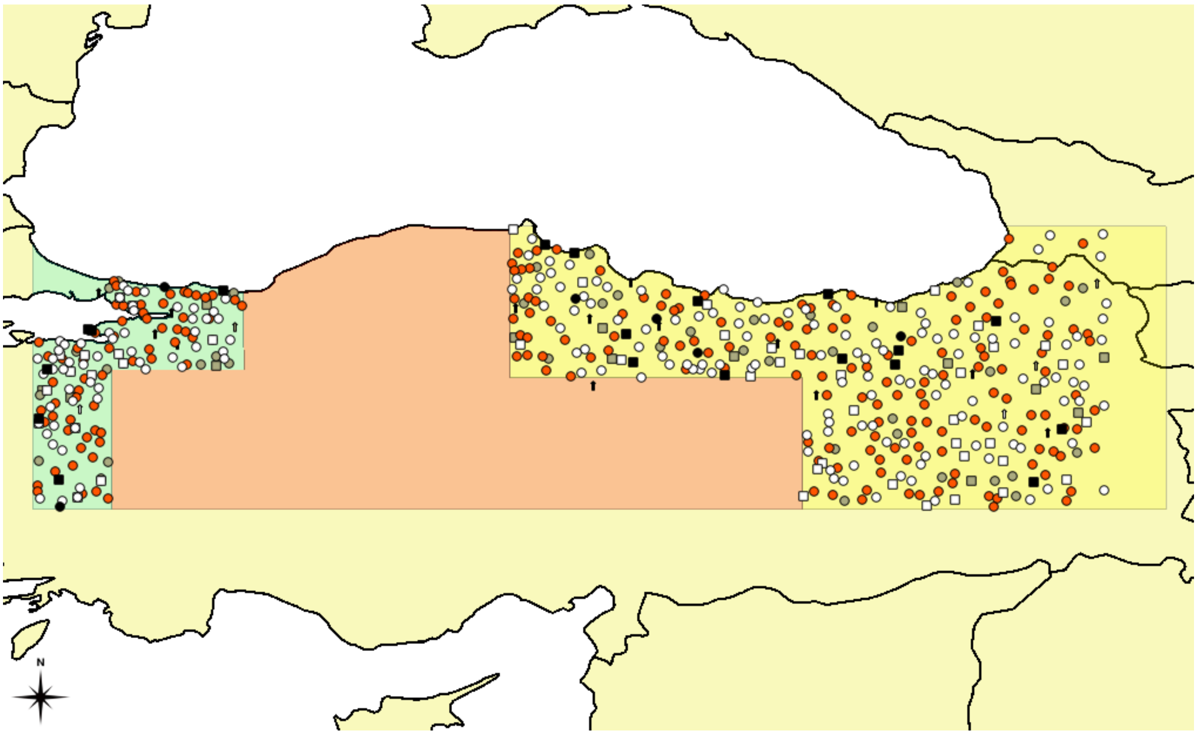


Figure 20: Modern settlements split into TIB categories. Orange dots are discarded points

As can be seen, the number of settlements recorded in the TIB is just over half that of the number of modern settlements. Obviously not all settlements are recorded so the number of settlements in the Byzantine era would likely be closer to that in the modern era, taking into account the opposing modifiers of greater modern population and lower Byzantine urbanism. Despite this, the majority of small rural settlement would have been too small and/or poor to have enough supplies to significantly affect the provisioning of the army, their surplus having been already transported to the nearest main settlement anyway. For this reason the model keeps the settlement density recorded in the TIB maps and removes unwanted settlements at random.

2.9.2.2.4 Effect

Each category of site cab be assigned a number of inhabitants representing the population of the settlement and it's immediate hinterland (Table 11). These were derived from 16th century data (Dagron 2002, 394) however historical demography can be imprecise at the best of times and these figures are intended only as a guide. The number of inhabitants will be used in conjunction with the ESA Globcover data to produce two values for each resource, a total amount and a surplus amount. The total amount is the amount in that settlement for use by the inhabitants in addition to the surplus. The surplus is the amount over and above what the inhabitants need to survive. The surplus amount is the amount normally available to the army, however in times of shortage the army may force the settlement to hand over any extra, up to the total. It should be noted that the values for settlement size and the accompanying amounts of supplies represent a highly speculative hypothetical model. The MWGrid ABM can be used as a tool to provide some kind of framing evidence for these figures, possibly indicating the practical limits of food surplus.

TIB category	Assumed population size
Walled settlement (archbishopric)	30000
Walled settlement (bishopric)	15000
Walled settlement (no bishop)	10000
Citadel settlement (archbishopric)	10000
Citadel settlement (bishopric)	5000
Citadel settlement (no bishop)	4000
Unfortified settlement (archbishopric)	4000
Unfortified settlement (bishopric)	3000
Unfortified settlement (no bishop)	2000

Table 11: Assumed population size for each TIB category

2.9.2.3 ***Globcover*** *– The European Space Agency's Vegetation Cover Database.*

2.9.2.3.1 Resolution

Low

2.9.2.3.2 Source

The ESA's Globcover 2009 land cover map (http://ionia1.esrin.esa.int/). Due to the difficulties in recreating the ecology of the whole of the ABM study area, modern land use data is used. This obviously creates inaccuracy as changes in agricultural technology and settlement patterns will result in different land uses. The GlobCover categories have been used as the basis for coarsely derived values for food, fodder and firewood as an indication of resources available.

Figure 21: ESA Globcover data

2.9.2.3.3 Format

An integer indicating the type of agricultural terrain of an area.

2.9.2.3.4 Effect

The Globcover categories are used to determine the amount of animal fodder, food from arable agriculture and firewood that are available to each settlement (Table 12). These values are estimated on a scale of 0 – 3. The ABM can perform a range query on all land within a certain radius of a settlement in order to determine how much of each resource the settlement has available to it. This can also be performed by the army in rural areas to determine how much firewood or fodder can be foraged.

Globcover type	Description	Fodder amount	Food production	Firewood amount
11	Post-flooding or irrigated croplands (or aquatic)	1	3	0
14	Rainfed croplands	1	3	1
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	3	2	2
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	3	2	3
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	1	1	2
50	Closed (>40%) broadleaved deciduous forest (>5m)	1	1	3
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	2	2	2
70	Closed (>40%) needle leaved evergreen forest (>5m)	1	1	3
90	Open (15-40%) needle leaved deciduous or evergreen forest (>5m)	2	2	2
100	Closed to open (>15%) mixed broadleaved and needle leaved forest (>5m)	1	1	2
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	3	1	3
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	3	2	2
130	Closed to open (>15%) (broadleaved or needle leaved, evergreen or deciduous) shrubland (<5m)	1	1	2
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	3	2	1
150	Sparse (<15%) vegetation	0	0	1
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	1	1	2
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water	0	1	3
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	1	2	1
190	Artificial surfaces and associated areas (Urban areas >50%)	0	0	0

200	Bare areas	0	0	0
210	Water bodies	0	0	0
220	Permanent snow and ice	0	0	0
230	No data (burnt areas, clouds)	0	0	0

Table 12: Globcover categories with associated resource values

2.9.2.4 **Transport** – *Presence of Roads*

2.9.2.4.1 Resolution

Medium

2.9.2.4.2 Source

Digitised from the *Tabula Imperii Byzantini* maps, inserted from ancient sources and extrapolated from known data.

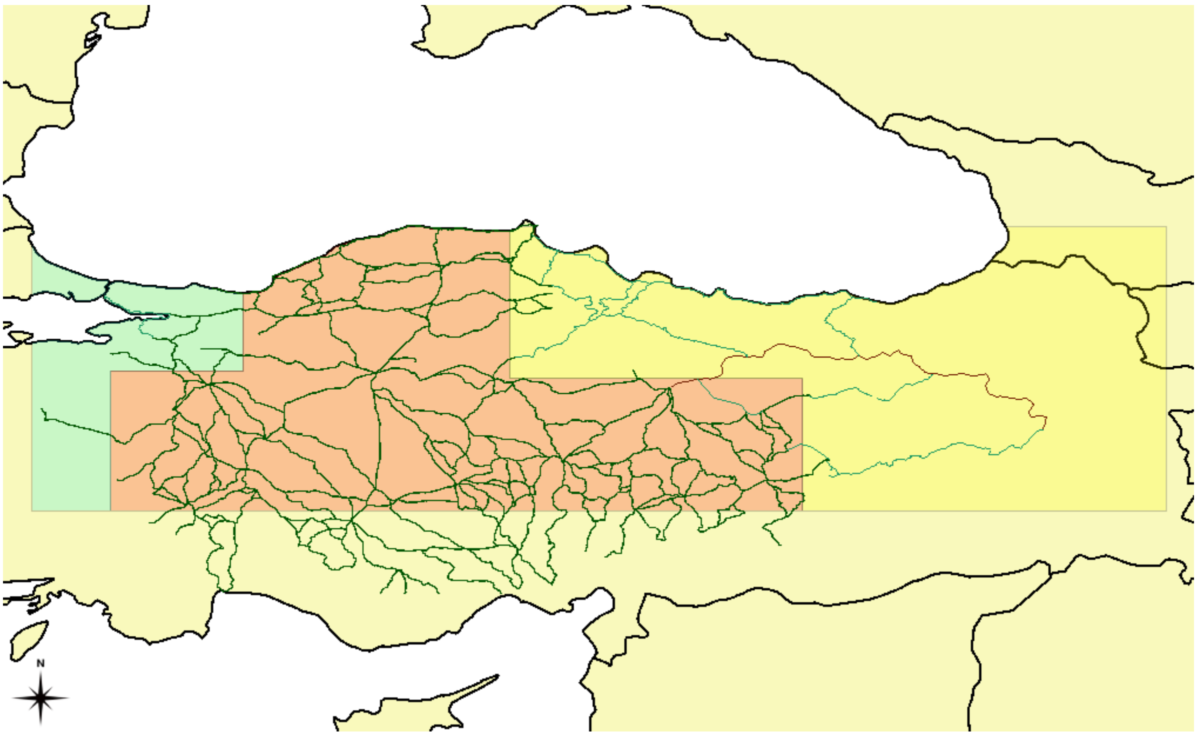


Figure 22: The roads represented in the ABM

A similar process was followed with the road data as for the settlement data. Unfortunately roads are less amenable to the approach followed with settlements as, unlike settlements which can look plausible when randomly selected, roads have a pattern to their path. They usually start somewhere and end somewhere and, in between, follow a reasonable path. With this being the case a much more minimal approach was taken to expanding the data outside the area covered by the TIB maps. Only roads between major settlements (walled settlements with archbishoprics) were added. The routes themselves were taken from whichever modern routes most aligned with the routes from John Haldon's 1999 map (Figure 23).

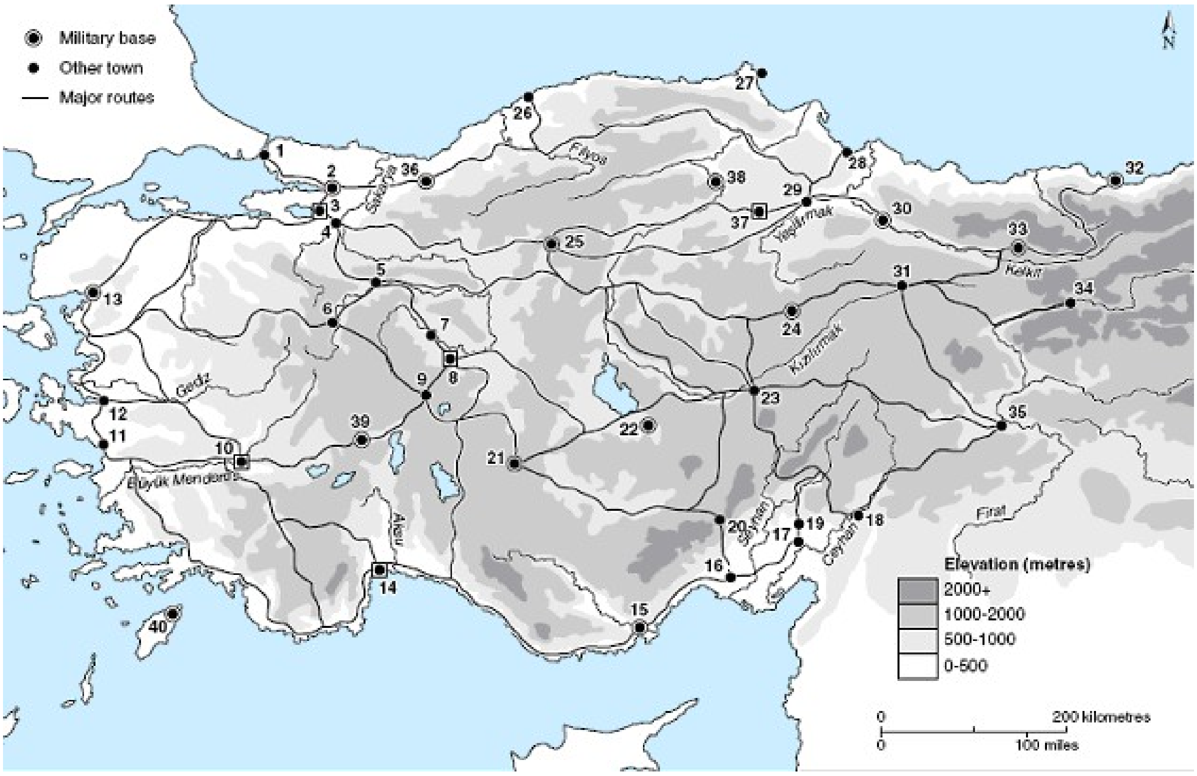


Figure 23: Map of Anatolia from Haldon (1999)

Within the area covered by the TIB maps, roads were more difficult to align between different maps than settlement data. In these cases the roads were tidied up as much as possible, the new roads being created in between where the TIB maps indicate them. On some occasions there were roads marked on some maps that weren't present on others. As a result some roads do not appear to go anywhere. Ultimately there are no easy answers to this problem. The roads themselves are only approximate not having been proofed along their whole length. Dating roads is also notoriously difficult (French 1981) so some roads present in the TIB maps may not have been in use in AD1071.

2.9.2.4.3 Format

Each pixel contains either 0 (no road present) or 1 (road present)

2.9.2.4.4 Effect

Roads are primary factors in macro route planning for the whole army. Where a route exists which follows a major road it will be taken due to its positive effects on movement speed and army coherence. It also affects movement, with agents travelling faster on roads and following them whenever practical.

2.9.2.5 **Water** *– Presence and Type of Water*

2.9.2.5.1 Source

http://www.diva-gis.org/gdata

2.9.2.5.2 Format

An integer identifying the type of water (Table 13).

2.9.2.5.3 Effect

Acts as a water source for humans and animals. Acts as a barrier to movement.

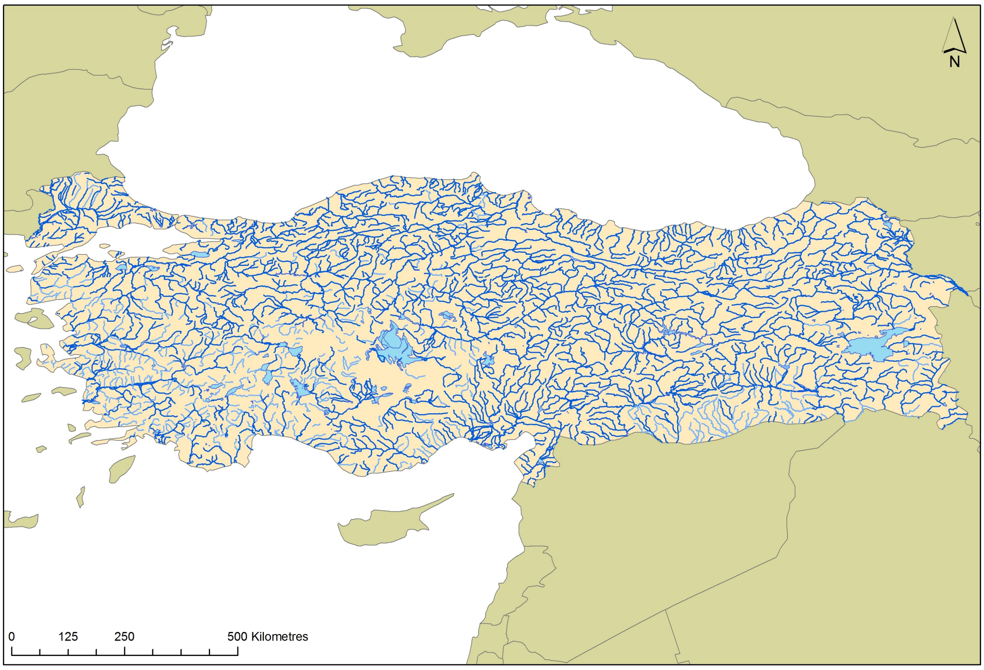


Figure 24: Water data

Data type	Type of water
0	Land subject to inundation
1	Lake
2	Intermittent streams
3	Perennial streams or rivers

Table 13: Water data types

2.9.3 Weather Data

The climate of Anatolia in the late 11th century was not significantly different to that of recent years (England et al. 2008). This being the case, modern data can be used to provide hypothetical weather schemes for Byzantine Anatolia that can affect movement and the amount of water and food consumed.

Three years will be selected from the data available, one year much hotter than average, one much cooler and one as close to average as possible. These three different sets of data, one hot, one average and one cool, can be used to assess the effects of weather on energy and water consumption of the agents.

Hourly temperature data will be extrapolated from the daily maximum and minimums by using a typical curve of temperature change throughout the day. This will produce an hourly temperature for each weather station in each of the three sample years. When an agent needs to determine the temperature of the location he is at the ABM can perform a simple calculation to extrapolate a temperature from the 3 nearest weather stations.

Weather data is available via the internet (http://climexp.knmi.nl), however daily coverage of Anatolia is relatively sparse. The following weather stations were found to have sufficient daily data to be useful.

- Istanbul
- Rize
- Kastamonu
- Sivas
- Gumri
- Van

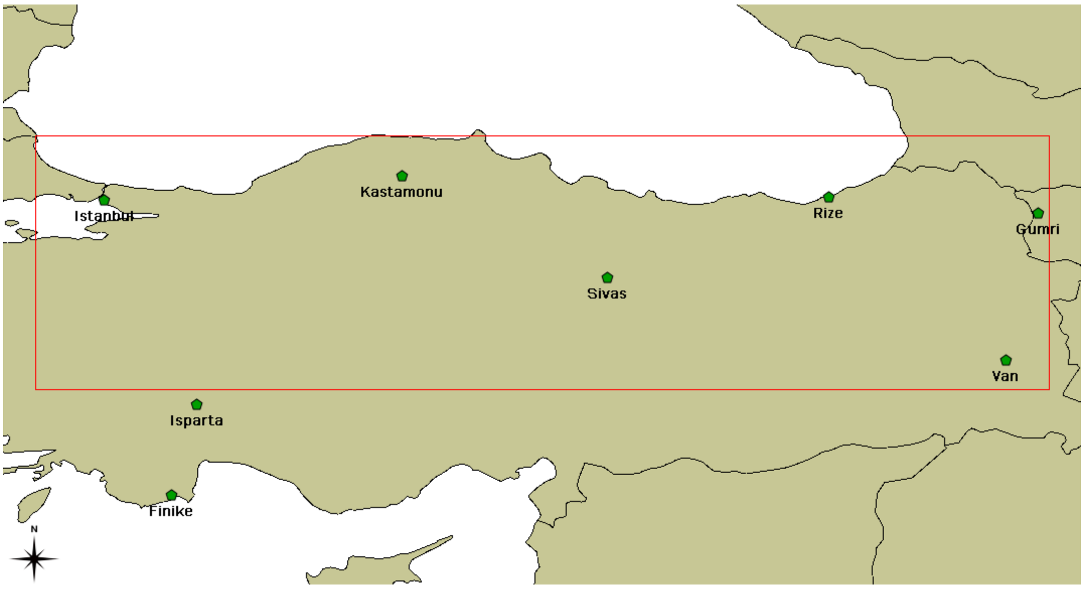


Figure 25: Location of weather station with the ABM area

The only data common to all stations that were substantially complete were between 1957 and 1992. In order to narrow down the amount of data so that a hot, cold and average year could be chosen, only data from 1980 - 1992 inclusive were used. As not all stations had the same hottest year, coolest year or average year a system was introduced whereby the years were ranked by average mean temperature. The hottest two years were separated for each station, along with the coolest two years and the median year. From this, the hottest year was chosen as 1989, the coolest as 1992 and the average year was 1984 as it was the median year twice and never appeared in either the hottest or coolest years for any weather station.

Now that these years are selected, the daily maximum and minimum temperatures can be downloaded and applied to a standard temperature curve over the course of the day. Whenever an agent requires the temperature at its current location it can request the temperature from each of the three nearest weather stations and average them, weighted by distance.

2.10 Conclusion

Just as there were a variety of levels on which campaign organisation worked in the Byzantine army so there are a variety of levels on which this simulation is modelled. The macro decisions regarding the overall route can be either pre-scripted or based on criteria built into the route planning network. This creates waypoints that are navigated between using the grid-based A* route planner. The route is then subdivided based on the length of the daily march and a series of camps specified. These can be altered at the end of each day based on the experiences of the previous day's march. Each day the army makes and breaks camp according to a set routine.

The ABM design detailed here is constrained by three main factors; the types of data available in a suitable format, the behaviours that can be plausibly modelled and the aspects of the Byzantine army and the Anatolian landscape that are necessary to produce the output required. As in most archaeological contexts, the data required is incomplete, unreliable and varies in spatial and temporal resolution. These problems are not insurmountable however. Where data is absent, plausible hypotheses can be introduced. Where multiple plausible hypotheses exist and the choice makes an appreciable difference to the output then multiple hypotheses can be modelled. Historical data can be used not only to create the model but also to calibrate the results. The following chapter describes the implementation of the model, including how it was developed and the choices made regarding which factors were important enough to ensure the output was useful.

The result of the technical efforts will be an agent-based model that incorporates the terrain and weather of Anatolia with hypothetical supply levels and distribution into an environment over which our agents can travel. By creating and running a series of 'what if?' scenarios with armies of different sizes and compositions travelling in a landscape with different levels of supply and water availability. The results of these scenarios will allow us to draw conclusions about how armies behave in ideal circumstances. We can then compare this with the historical record and attempt to explain any differences.

Finally, whilst appreciating that all models are wrong (Box and Draper 1987, 424), the project attempts to make a break with traditional historic analysis in the manner in which it incorporates individual action within an interpretative framework that can add to our understanding of a historic event or process. While small glimpses into individual behaviours can be found in the work of Attaleiates and modern research tools such as the online Prosopography of the Byzantine World (http://www.pbw.kcl.ac.uk), these do not allow us to examine the interactions common in complex systems. With the emergent behaviour modelled in the ABM the project seeks to add new evidence to existing debates about the movement of large numbers of troops across a pre-industrial landscape. We can examine the relationship between human and animal stamina, unit organisation and how this impacts on army speed in ways previously unavailable. To the movement model will be added modelling of the use and transport of food and supplies. Levels of supplies can be varied to investigate the impact on the army as a whole. With its modular nature, Agent-based Modelling can test different hypotheses regarding agricultural productivity and settlement by ensuring that the route planning decision making remains constant while varying the resource levels. The differences this creates between otherwise identical runs of the model can help inform our interpretations of how Byzantine military operations were planned and executed.

3 Implementation

3.1 Introduction

Once the model has been designed, implementation can begin. The scale of the project and the process of development require multiple models to be created. This enables features to be added sequentially and tested individually while still using the model to create useful data. Some aspects of the ABM require others to be complete beforehand and some do not. For instance, when dealing with crowding and movement it is unnecessary to include energy expenditure data. In contrast, when examining energy expenditure the crowding and movement mechanisms must be in place as these will affect the number of calories burned. For this reason a basic model was created which focussed on the movement aspects of the army and then subsequently changed and expanded in order to focus on such areas as army composition, size and calorie expenditure during the Manzikert campaign.

In this chapter I will detail the process of translating the design described in the previous chapter into a series of functioning agent-based models. I will describe the technical details of how it was implemented and explain how and why the models deviate from the design as so far described. I will explain the limitations of the software and how these are affected by the hardware that was made available. Any technical terms will be explained in the glossary.

3.2 Temporal and Spatial Resolution

The micro-scale movement described in the previous chapter is essential in our model of the movement of the Byzantine army. It is this level that is accessible to agent-based modelling yet is below the level of the work of Pryor and Engels' attempts to look at the movement of the Crusaders and Macedonians respectively (Pryor 2006; Engels 1978). If we are to add the complexity possible with ABM to these techniques we must be able to simulate the phenomena that would make the movement of the army as a whole more than just the sum of the speed and size of its individual elements. For this reason, the resolution of the model needs to be appropriate to simulate phenomena such as crowding and the concertina effect, emergent behaviours from individual movements. In order to achieve the granularity required to plausibly simulate these behaviours the ABM uses one agent to represent one member of the Byzantine army. This will increase the processing time of the model as the number of agents will be greater than if each agent represented a unit but it is in the interactions between these agents that the overall movement of the army will come from. Sacrificing resolution at this level will compromise the plausibility of the model.

This 1:1 ratio extends to the human members of the army but not the animals. On the march cavalry horses will either be ridden or, in the case of spare horses tethered to their owner's mount so there is no need to separately model horses. The baggage train and baggage handling procedures for individual squads is not modelled but they will be taken into account in the concluding chapter.

3.3 Building the Model

The MWGrid ABM is written in Java. Java is an object-oriented programming language and is well suited for the creation of agent-based models (Gilbert and Troitzsch 2005, 22). It is relatively easy to learn, powerful and most importantly it is portable, it can be run on many types of computer architecture with no change in the code (Gosling 2000). This ability to be written once then recompiled to run on various systems was seen as an important characteristic given the project's initial aim to run the model in a distributed environment. It allowed the project to be flexible regarding which distributed computer cluster that the model would run on while still allowing it to be run on desktop machines for development and debugging.

As multiple individuals needed access to the code of both the models and the distributed infrastructure being developed to run them, the ABM was stored on an SVN repository on the servers of the University of Birmingham's Computer Science department. This ensured that the software could be accessed from anywhere with an internet connection and enabled some measure of version control to be exercised. This meant that two programmers could not change the same section of code at the same time without an explicit resolution of any problems caused. Eclipse was used as a development environment due to its easy integration with Java, its ability to seamlessly work with SVN repositories, its industry standard nature and the fact that, being open source, it was free.

3.3.1 Focussing on the Micro-Scale

Due to the scale of the model as it was designed, a distributed agent-based model infrastructure, PDES-MAS, was developed by the MWGrid project members from the Computer Science department of the University of Birmingham. This consisted of the software required to run the model on multiple machines at once, vastly increasing the computing resources available to the model. As PDES-MAS was written in C++, an intermediate layer of software, the middleware, was created to provide an API that the model could use (Figure 26). This was necessary to convert the Java software calls into instructions the C++ code could handle as well as providing helpful classes for the model and constraining its behaviour to avoid actions that the PDES-MAS software would not be able to handle.

Due to the experimental nature of the infrastructure (Lees et al. 2005) and the departure of the original Computer Science Research Fellow, the infrastructure was not completed in time to be used in this research. As the model was being developed to use the API of the middleware operating between the ABM and the distributed infrastructure the need to abandon the distributed element of the ABM caused some rewriting. As some of the functionality of the middleware provided classes that were useful to the ABM these were kept in. This included the Location class, the Message class and the Value class used to extract values from Environmental slices. The basic handling of environment slices, the first Python script to produce Blender animations and the basic core of the A* route planner were also developed by the MWGrid Computer Science Research Fellows, Bart Craenen and Rob Minson. All other software used in this project including all the rest of the ABM, the second Blender Python script and the file processing tools in both Java and OpenOffice Calc were written by Philip Murgatroyd. The Java ABM consists of nearly 6500 lines of code.

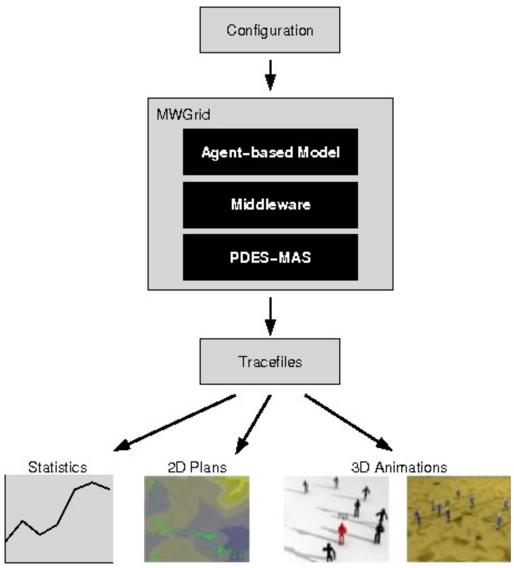


Figure 26: The intended MWGrid infrastructure (from Murgatroyd et al. 2011)

As the distributed software infrastructure was a parallel development, to be described in future work, a separate version of the ABM was required to run on a single PC-compatible computer. The reduction in computing power meant either the scale or the resolution of the model would have to be reduced. This resulted in the decision to reduce the scale of the model and focus on the effects of a day's march. A day's march is a discrete unit of time on a military campaign, especially in the pre-industrial era. The lack of artificial lighting in addition to security issues meant that the aim was to have all troops in the camp before sunset, preferably with enough time to set up camp and make food. By modelling a day's march it is still possible to examine the effects of crowding on the overall speed of the army. Individual elements such as the speed and composition of the army can still be varied to determine their effects on overall speed. In order to examine macro-scale movement a series of day's marches can be run over different terrain in different conditions. Nine different sets of scenarios have been run with a different version of the MWGrid ABM in each case. The scenarios are run with a specific goal in mind and as such, different models are required to best reach that goal. The basic functionality of the whole system including the ABM, the input files, the output files and the intermediate processing steps is detailed in this chapter. The specific modifications carried out for each of the nine sets of scenarios are detailed in Chapter 4, along with the results and analysis.

3.4 The Simulation Process

When running a simulation, a series of steps are followed (Figure 27). The ABM takes the parameters of its scenario from an initialisation file. This file specifies the size and composition of the army, the starting and finishing points of the army's march, the route planning and flocking parameters, the camp layout and the speed of the cavalry in various modes. This file is loaded by the ABM in order to set its parameters. Having these parameters in a text file ensures that the Java code does not need to be recompiled if changes are needed to the scenario. The MWGrid ABM sets up a scenario based on the contents of the initialisation file and processes the simulation over a sequence of consecutive timesteps known as 'ticks'. These ticks represent a set period of real world time, within the MWGrid ABM this is usually about 3.7 seconds, as explained on page 151. The ABM outputs two files: the tickfile which records the location and status of each agent on every tick of the simulation and the dayfile that records aggregated data about the whole day's march for each agent. Each of these files are used to access different types of data. In order to process this data, the tickfile is processed by a Python script in Blender to produce animations and the dayfile is loaded into an OpenOffice Calc template to produce statistical data. Each step of the process is described in further detail below.

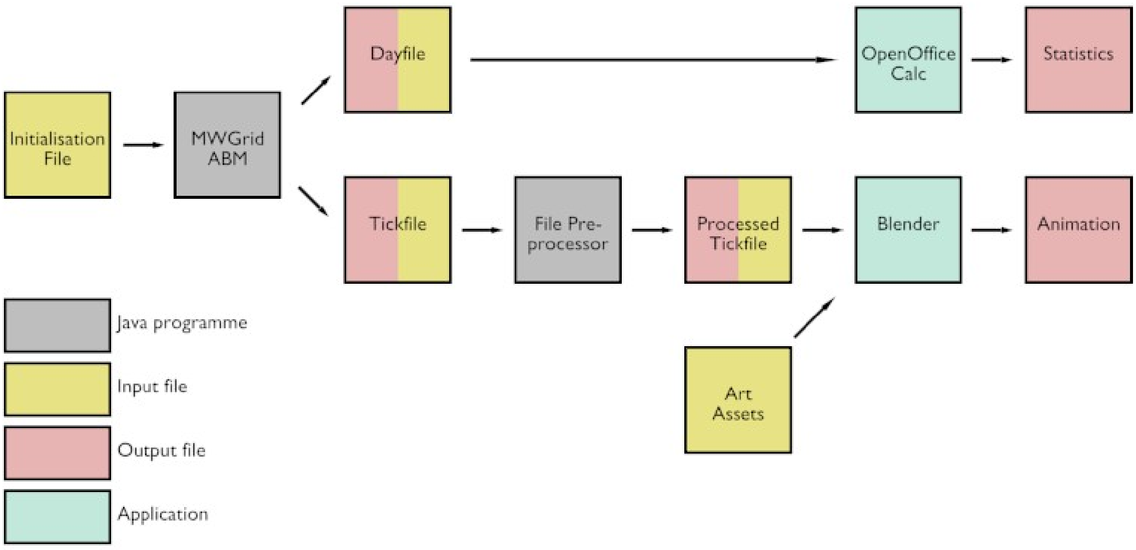


Figure 27: The simulation process

3.4.1 The Initialisation File

The initialisation file contains text parameters that can be used to change the behaviour of the simulation. If these parameters were within the Java code the software would have to be recompiled with every change. This would require more effort and time and be more susceptible to errors. Although the contents of the initialisation file have altered as the needs of each set of scenarios has changed it has always contained all the parameters that have needed to be changed between scenarios. The initialisation file is in ASCII text and can be altered with any text editor.

Each line contains a parameter name followed by a space, then the value associated with that parameter (Figure 28). Any entry that does not conform to the correct format is ignored so text comments can be added to the initialisation file without causing errors. Also, as a value will be ignored if the parameter name is not exactly as it should be, a line can be commented out simply by placing unrecognised characters at the front of the parameter name, as can be seen from the example. If a value that the ABM is expecting is missing from the initialisation file or it refers to a value of the wrong type it will cause a crash in the ABM. The information in Table 14 contains all the parameters used by the ABM in its final form.

```
OFFICERS 6
OFFICER_CAVALRY_SQUADS 6
CAVALRY_SQUADS 4
INFANTRY_SQUADS 2

OFFICER_CAVALRY_SQUAD_SIZE 4
CAVALRY_SQUAD_SIZE 4
INFANTRY_SQUAD_SIZE 9
CAMP_SPACE_BETWEEN_SQUADS 2
GAP_BETWEEN_SECTORS 5

COLUMN_LEADERS 1
TEXT_ID MPtest

SECONDARY_UNIT_SIZE 10
SETOFF_SPACING 2
SECONDARY_SETOFF_SPACING 5
SECTION_SETOFF_SPACING 200

OUTPUT_TICK_FILENAME SPtickfile.txt
OUTPUT_DAY_FILENAME SPdayfile.txt
START_LOCATION 34600,27200
#####DESTINATION_lOCATION 30100,34500
DESTINATION_lOCATION 30000,34500
RESOURCE_LOCATION D:/Manzikert/branches/ManzikertSP/environment/src/resources/environment/
START_TIME 0
END_TIME 10877
REST true

ContextSingleton
MAX_AGENT_SIZE_IN_CELL 20
```

Figure 28: Sample initialisation file data

Parameter	Type of value	Notes
OFFICERS	Integer	The number of Officer agents with no subordinate troops. These camp in the central sector of the camp and represent Generals, Bureaucrats and others close to the Emperor but outside the regular chain of command.
OFFICER_CAVALRY_SQUADS	Integer	The number of squads of cavalry agents camping in the central sector of the camp with the Emperor. These represent the household units and bodyguards.
CAVALRY_SQUADS	Integer	The number of Cavalry squads occupying the outer 4 sectors of the camp. These represent the regular cavalry units of the army.
INFANTRY_SQUADS	Integer	The number of Infantry squads occupying the outer 4 sectors of the camp. These represent the infantry units of the army.
OFFICER_CAVALRY_SQUAD_SIZE	Integer	The number of Cavalry agents in each Officer Cavalry Squad, not including the Officer.
CAVALRY_SQUAD_SIZE	Integer	The number of agents in each Cavalry squad, not including the Officer.
INFANTRY_SQUAD_SIZE	Integer	The number of agents in each Infantry squad, not including the Officer.
CAMP_SPACE_BETWEEN_SQUADS	Integer	The amount of space in environment cells between the starting and destination locations in camp.
GAP_BETWEEN_SECTORS	Integer	The amount of space in environment cells between each of the outer sectors and the central sector in camp.
COLUMN_LEADERS	Integer	The number of columns that the army splits its movement into. This does not create more than one Column Leader agent but will result in some Officer agents acting like Column Leaders if necessary.
TEXT_ID	String	A text string that is included in the dayfile and tickfile names. Used to add to the parameters that occur in these filenames by default, something set within the Java class.
SECONDARY_UNIT_SIZE	Integer	The number of units that constitute a secondary unit for the purposes of setting off gaps only.
SETOFF_SPACING	Integer	The default number of ticks between each unit setting off.
SECONDARY_SETOFF_SPACING	Integer	The number of ticks between each secondary unit setting off. This is inserted every X units where X is the SECONDARY_UNIT_SIZE. This replaces the default SETOFF_SPACING.
SECTION_SETOFF_SPACING	Integer	The number of ticks between each sector setting off. This replaces the default SETOFF_SPACING.
OUTPUT_TICK_FILENAME	String	This is the final part of the filename of the tickfile.

Parameter	Type of value	Notes
OUTPUT_DAY_FILENAME	String	This is the final part of the filename of the dayfile.
START_LOCATION	Location	This is the location of the starting camp. Refers specifically to the centre location of the central sector of the camp.
DESTINATION_LOCATION	Location	This is the centre location of the central sector of the destination camp.
RESOURCE_LOCATION	String	This is the path of the directory in which the environment files are found. This directory is also where the dayfile and tickfile will be saved.
START_TIME	Integer	The tick number of the first tick of the simulation.
END_TIME	Integer	The tick number of the last tick of the simulation. After this tick the simulation ends.
REST	Boolean	Whether the agents rest during the march according to the built-in rules.
MAX_AGENT_SIZE_IN_CELL	Integer	The maximum total size of agents in each cell.
INIT_HEURISTIC_MOD	Double	The initial value of the A* heuristic modifier.
MIN_HEURISTIC_MOD	Double	The minimum value of the A* heuristic modifier.
INIT_ROADTEST_HEURISTIC_MOD	Double	The initial value of the A* heuristic modifier when used only along the road network.
INIT_MAXSTEPS	Integer	The base number of steps before the A* route planner determines that a plan has failed to reach its destination.
INIT_ROADTEST_MAXSTEPS	Integer	The base number of steps before the roads-only A* route planner determines that a plan has failed to reach its destination.
HM_STEP	Double	The value by which the A* heuristic modifier is reduced if the previous value was successful.
DIAGONAL_MOD	Double	The multiplier that is applied to the cost of diagonal moves. If set to 0, the cost of a diagonal move is calculated using Pythagoras' theorem.
CUTOFF_MED_STEEP	Integer	The maximum height difference that is categorised as a 'medium' slope.
CUTOFF_SHALLOW_MED	Integer	The maximum height difference that is categorised as a 'shallow' slope.
CUTOFF_LEVEL	Integer	The maximum height difference that is categorised as 'level'.
COST_LEVEL	Double	The cost the A* route planner attributes to a level move.
COST_UP_SHALLOW	Double	The cost the A* route planner attributes to a shallow upward move.
COST_UP_MED	Double	The cost the A* route planner attributes to a medium upward

Parameter	Type of value	Notes
		move.
COST_UP_STEEP	Double	The cost the A* route planner attributes to a steep upward move.
COST_DOWN_SHALLOW	Double	The cost the A* route planner attributes to a shallow downward move.
COST_DOWN_MED	Double	The cost the A* route planner attributes to a medium downward move.
COST_DOWN_STEEP	Double	The cost the A* route planner attributes to a steep downward move.
COST_ROAD_LEVEL	Double	The cost the A* route planner attributes to a level move along a road.
DEFAULT_HEURISTIC_MOD	Double	The heuristic modifier used when no starting modifier is specified or when producing macro route plans.
NUMBER_OF_X_PARTS	Integer	The size of each environment tile in cells along the X axis.
NUMBER_OF_Y_PARTS	Integer	The size of each environment tile in cells along the Y axis.
SIZE_OF_PART_LIST	Integer	The maximum number of environment tiles kept in memory at any one time.
MAX_STUCK_TICKS	Integer	The maximum number of ticks an agent can fail an action before it activates its 'failed action' procedures.
FLOCKING_DISTANCE	Integer	The maximum distance a Soldier can be from its Officer before it will attempt to move closer.
MARCH_SPACING	Integer	The maximum distance an Officer can be from its preceding Officer before it will attempt to move closer.
CAVALRY_LEAD	Double	The speed in metres per tick of a cavalry agent when leading its horse.
CAVALRY_WALK	Double	The speed in metres per tick of a cavalry agent when riding its horse at the walk.
CAVALRY_TROT	Double	The speed in metres per tick of a cavalry agent when riding its horse at the trot.
MARCH_CUTOFF_TEMP	Integer	The temperature at or above which the agents will rest instead of marching.
HEIGHTCRAWLER	Boolean	If true, this writes the height above sea level in metres of each agent in the tickfile. Used to produce height maps of the day's march.
AGENT_WEIGHT	Double	The agent's weight in kilograms. Used in DM009 to simulate agents carrying supplies

Table 14: Initialisation file parameters

3.4.2 The MWGrid ABM

3.4.2.1 The Main Programme

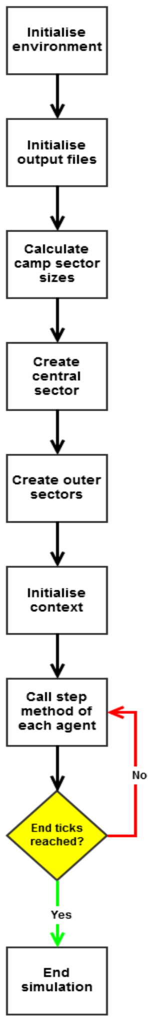


Figure 29: Flow of the main programme

`ManzikertDaysMarchSP` is the main class, the one that is run in order to start the ABM (Figure 29). It takes just one command line argument, the filename and path of the initialisation file. The final version of this file is included in this document as Appendix 1. It goes through the following steps:

3.4.2.1.1 Initialise Environment

As the class that processes the initialisation file is a Singleton, a class of which there is only ever allowed to be one instance, the filename and path used as a command line argument must be passed to it on its first call so that it can find the initialisation file and read its values. In order to simplify programming it is called here in order to initialise it so that any subsequent calls in the software no longer need to specify the filename and path. The Singleton handling the weather information is also first called here so that the correct weather values can be initialised if multiple options are present.

3.4.2.1.2 Initialise Output Files

The dayfile and tickfile are created here and opened, ready to accept data as it is created by the model.

3.4.2.1.3 Calculate Camp Sector Sizes

The layout of the camp depends on the size of the largest camp sector. Each sector is given enough space to fit the largest sector, regardless of how many agents are in it. This prevents sectors being created that overlap each other.

3.4.2.1.4 Create Central Sector

The agents within each camp sector are created in the order that they leave the camp so that the march order can be set when the agents are created. As the central sector is always first and always starts with the Column Leader, it is always created first.

3.4.2.1.5 Create Outer Sectors

The order of the creation of the outer sectors depends on the direction of travel from the camp and the number of columns the march will be split into. The creation of the agents in the outer sectors is done here.

3.4.2.1.6 Initialise Context

The agents share a single pool of data regarding the environment, including which environment cells are already full of agents. This is also a Singleton as all agents need to access the same information and having only one copy of this information removes the possibility of errors transmitting this information from agent to agent. The class handling the context needs to have the details of all the agents in the ABM in order to find their location so this needs to be initialised after the agents are created.

3.4.2.1.7 Call Step Method of Each Agent

The model functions by calling the step method of every agent in turn for each tick of the simulation. At the start of each tick the context is updated to refresh the locations of every agent. This continues until the number of ticks reaches the maximum number specified in the initialisation file.

3.4.2.2 The Agents

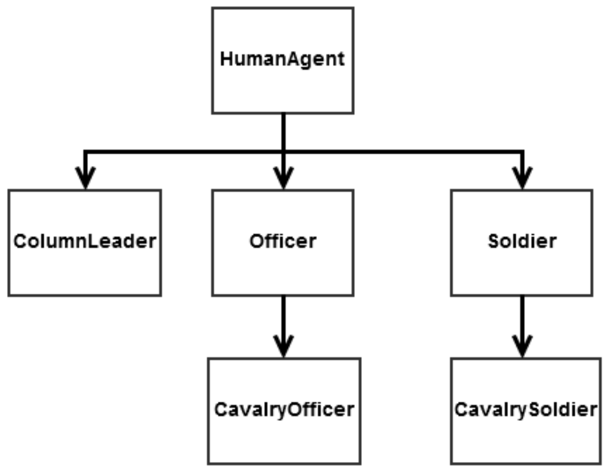


Figure 30: Agent Java class hierarchy

Due to Java's support for inheritance between classes all the characteristics and behaviours common to human agents can be placed in a single class, `HumanAgent` (Figure 30). `HumanAgent` is never instantiated itself, it is an abstract Java class and therefore all agents are members of subclasses of `HumanAgent`.

3.4.2.2.1 HumanAgent

`HumanAgent` contains all characteristics common to the agents of the ABM. The final version is included in this document as Appendix 2. It serves as a description of the default agent behaviours. The main methods within HumanAgent are `step`, `processMessage` and `report`. The `step` method (Figure 31) is the one called by the main programme each tick. It contains the basic plan and message handling logic.

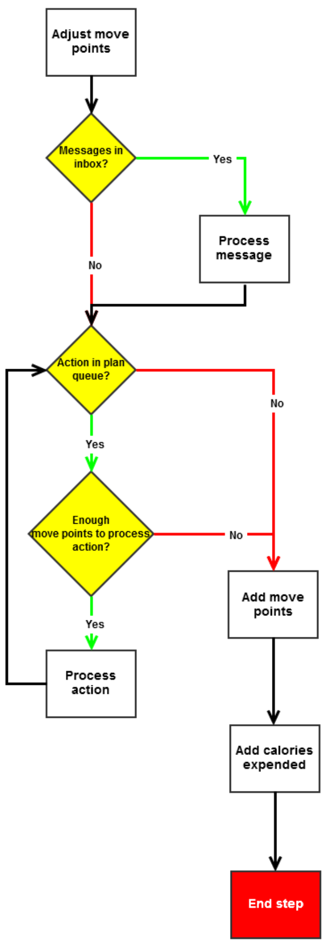


Figure 31: The HumanAgent step method

Each agent collects a certain number of move points each tick, based on the maximum speed of the agent. At the start of each agent's step method the number of move points is reduced if over an upper threshold or increased if under a lower threshold. This ensures that agents that are stationary for any period of time do not accumulate a large number of move points, only odd numbers of move points insufficient for a complete move are supposed to carry over between ticks. Then the agent's message inbox is checked to see if there are any messages in it. If so the `processMessage` method is called (see below). Only one message may be processed per turn. If there are any unprocessed actions in the agent's plan queue and the agent has the required number of move points then the `processAction` method of the action is called. Once all possible actions have been processed the `step` method adds the appropriate number of move points and calculates any calories expended.

The `HumanAgent`'s report method is called by the main programme every tick. It provides the data that is written to the tickfile and, on the final tick of the simulation, the dayfile. As each agent gives the same data this is never superseded by `HumanAgent`'s subclasses.

The `processMessage` method handles the messages that are dealt with in the same manner by all classes. This is dealt with in greater detail in the section on Messages (see below).

3.4.2.2.2 ColumnLeader

The `Emperor` agent described in chapter 2 has been renamed the `ColumnLeader` due to it referring to the agent that heads the army column. In practice this may not have been the Emperor. The `ColumnLeader` agent has a method called `firstTick` which only runs on the first tick of the simulation. It adds the plans to its plan list that cause it to plan a route to the destination location specified in the initialisation file. The `step` method sets the speed of the agent to the appropriate cavalry speed as the `ColumnLeader` is always classed as cavalry. It also checks to see if the tick is a rest tick if resting is set to 'on' in the initialisation file.

3.4.2.2.3 Officer

The basic `Officer` agent represents an infantry officer, if a cavalry officer is required the subclass `CavalryOfficer` is used. The `Officer`'s `step` method checks to see whether the `Officer` is supposed to be following another unit on the middle section of the march. If so a `TravelTo` action is added, with the destination location as the preceding unit's `Officer`. The `processMessage` method calls the `HumanAgent` method but also adds the functionality to deal with the `Follow` order.

3.4.2.2.4 CavalryOfficer

The `CavalryOfficer` class only differs from the `Officer` in order to ensure the size is different and that the speed is set correctly for the type of cavalry movement.

3.4.2.2.5 Soldier

`Soldiers` do not route plan to the same degree as either the `ColumnLeader` or the `Officers`. They flock towards the `Officer` of their squad, if they are outside of a set distance from their `Officer` they will add a `TravelTo` plan to their plan list with the location of the `Officer` as the destination.

3.4.2.2.6 CavalrySoldier

`CavalrySoldiers` use exactly the same methods as `Soldiers` except they are larger and they take their current speed from their superior `Officer`.

3.4.2.3 Plans and Actions

Each agent has a plan queue in which an agent's designated tasks are stored in the order in which they need to be performed. Each plan consists of a series of actions. A plan initially starts as a single symbolic action. When it reaches the top of the queue and becomes the current plan it is expanded into a series of appropriate actions upon execution (Figure 32). If these subsequent actions need revising then the action queue can be cleared back to the original first action and then expanded again. This is useful if an agent has a plan to move to a location, creates a route plan, then finds halfway towards its destination that the route is blocked. In this case all remaining moves are cleared and the route plan is recalculated, avoiding blocked cells.

This planning process works well with the limited number of actions required. Due to its highly logistical nature, the majority of the tasks involve moving somewhere and interacting with another agent. To handle errors or situations in which actions cannot successfully be completed, each type of agent has a stuck method which is activated if an action is unsuccessfully attempted for more times than the value of maximum stuck ticks as defined in the initialisation file. This ensures that plans can fail gracefully. The scenarios modelled as part of the Byzantine army's march across Anatolia can be modelled with relatively basic movement and message passing plans. The limited number of actions required and the restricted set of circumstances in which they will be used means that this approach, in which the process of performing tasks is largely hardcoded, does not increase the time involved with programming the model unreasonably.

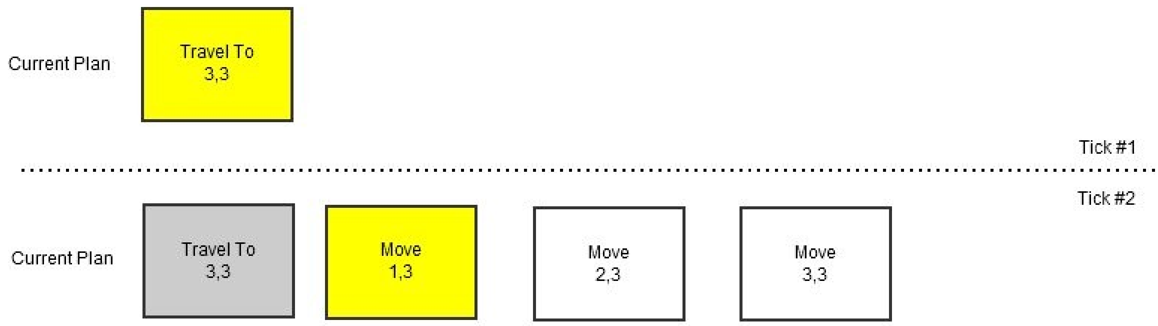


Figure 32: A TravelTo symbolic action expands into a series of Moves

Each action consists of an action type and a value or series of values that act as parameters for the action (Table 15).

Action Name	Parameters	Description
GiveOrder	Order, Value, Recipient	Inserts a message into the recipient's inbox. The value is dependent on the order (see below)
Move	Destination location	Causes the agent to try to move to the destination location
PlanMacroRouteTo	Destination location, point?, order before?, follow?	Plans a macro-scale route to the destination location
TravelTo	Destination location	Plans a micro-scale route to the destination

Table 15: The actions and their parameters

`GiveOrder` contains an order and a value. These are used by the recipient to create plans and are detailed in the section on messages below.

`Move` actions are usually created by route planning actions and instruct an agent to move to an adjacent location. If the location specified is not adjacent then the move is ignored. If subsequent move actions are also not adjacent the route plan will fail and be collapsed back to the symbolic action where it will be replanned. This should never happen but introduces some resilience to errors. `Move` actions calculate the amount of energy used and the distance travelled and add them to the appropriate variables in the agent.

`PlanMacroRouteTo` actions create a route plan from height data point to height data point. As the height data is at a resolution 10 times coarser than the environment itself, the route planner needs to visit 10 times fewer locations to arrive at its destination. It creates a route plan that it made up of `TravelTo` actions which are then added to the plan list as individual plans waiting to be expanded into `Move` actions. It will also add a `GiveOrder` plan that communicates the destination to the succeeding officer. This results in the original `PlanMacroRouteTo` destination calculated by the `ColumnLeader` agent is passed down the order of march from `Officer` to `Officer` until it reaches the unit at the end of the column. The extra parameters on the `PlanMacroRouteTo` action are:

Point? - This is a boolean value specifying whether the destination location is a point or a camp location. The difference between these is discussed in the messages section below.

Orderbefore? - This is a boolean value specifying whether the agent passes this order to its succeeding officer agent before it processes its own route plan or after. This is to allow an agent to expand a route plan and travel to the destination location before sending the order to follow.

Follow? - During the main section of the march officers do not plan their own route to the destination, they just follow their preceding officer until they reach the destination. This boolean value is used to specify that the `GiveOrder` action used in this plan will use the Follow order.

3.4.2.4 Messages

The `GiveOrder` action is used to send messages and is usually created as part of a `PlanMacroRouteTo` action. The orders used in the `GiveOrder` action are:

GO_TO_CAMP_LOCATION

GO_TO_POINT

FOLLOW

These all have a `Location` as a value included in the message. *GO_TO_POINT* makes the recipient go to the precise location specified in the order. *GO_TO_CAMP_LOCATION* has as its value the location at the centre of the destination camp. Each agent can work out from this its own camp location. *FOLLOW* causes the agent to follow its preceding officer until it reaches the destination location, then it will process any further messages that by then should have arrived.

3.4.2.5 Route Planning

Several serious problems were overcome in the development of the route planning behaviours of the agents. The route planning algorithm has to be reliable enough to ensure that if agents leave the marching army it is because of legitimate behaviour of the agents and not an error of the model. It also has to be robust enough to cope with any problems that may occur on the way. Troops that encounter problems should attempt to resolve them in plausible ways. The movement system must be able to cope with the macro-level decisions that the Emperor makes regarding the overall route as well as the micro-level decisions made by a single soldier making his way around the camp. The behaviour emerges from how the movements of individual agents on a day to day basis affect the army's performance and speed as a whole. The speed of the army cannot be extrapolated from the speed of its individual components and we do not know how increasing the number of men and animals in the army will reduce the overall speed. Modelling the movement of the army in a detailed and plausible manner can help us understand these factors in a way impossible through other methods.

The core of the movement system is route planning. A route plan is a series of individual moves that each agent will have to make in order to reach its destination. The army needed to have an overall route decided in advance in order to ensure that the settlements on the route could have supplies ready. Supplies sufficient to feed and equip the army would be inconvenient and expensive to move over land and changes in this macro route, while possible, would be difficult to effect. But it is not just the army as a whole that needs a route plan; each individual agent will need one in order to move anywhere. A route plan must be worked out in advance but can be changed at any time if circumstances render the initial route invalid. Any time an agent needs to move it takes its current location and intended destination and passes these to a route planning algorithm which formulates a series of individual moves that will get the agent from point A to point B.

Route planning is a very well documented branch of computer science from Dijkstra (1959) onwards. Several methods exist to allow an agent to select between different possible routes and manoeuvre itself across a landscape. The movement system needs to cope with the planning of the route of the army as a whole as well as the everyday movement of each agent. Any solution that treats both strategic route planning and micro-level movement in the same way risks either overloading itself when planning macro routes or missing out on the detail required to plan plausible micro routes.

3.5 A Route Planning*

One of the most popular algorithms used for route planning is the A* algorithm (Russell and Norvig 2010, 97). A* (pronounced "A star") is a graph search algorithm that is used for route planning by representing each possible destination as nodes in a graph. The algorithm then searches through the nodes to find the route to the destination with the least 'cost': cost here can represent anything including distance, energy expended, time taken or any other method of differentiating between routes. The presence of terrain and weather within the environment means we can model the energy expenditure of each individual in the army, the mechanisms for which will be dealt with in future publications. At each step of its search the algorithm combines the cost to get to this node with an estimate of the cost to get from this node to the destination. If the cost of each move is represented by the energy expended to make the move then the search algorithm will attempt to find the route that uses the least energy.

The estimated part of the equation, or heuristic, is based on the distance to the destination, and its presence allows us to prioritise routes that get us closer to our goal. Therefore the nodes first searched are the ones that cost less energy to reach and that reduce the distance to the destination. This ensures the search procedure prioritises more likely routes in order to speed up the process.

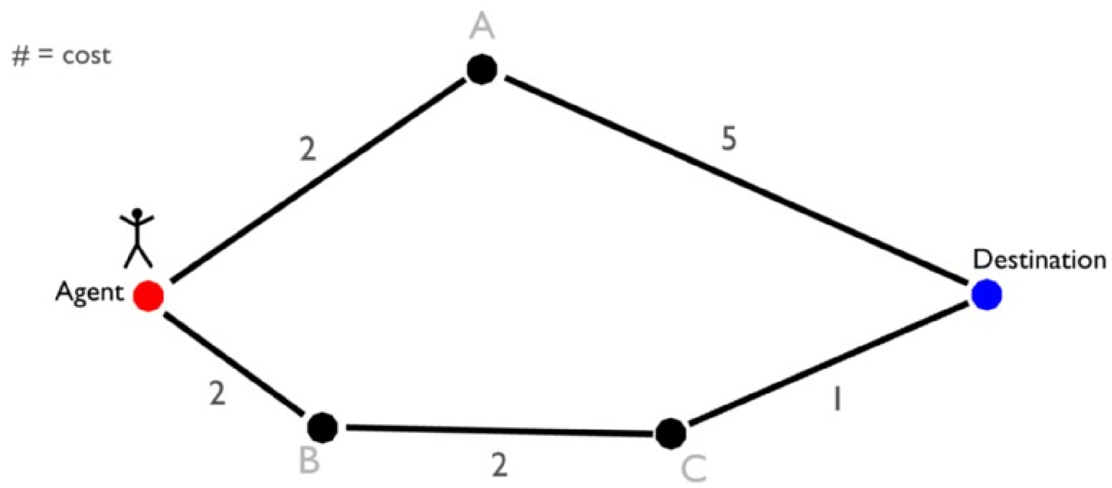


Figure 33: An example of A in action*

In the example in Figure 33, the agent has two possible routes to its destination. In order to prioritise its search towards the route likely to be the most efficient it examines each node based on the cost to reach it plus an estimate of the cost to get from that node to the destination. For ease of calculation this estimate is the distance between the node and the destination, equivalent to assuming the cost of each move will be 1 from there onwards (Table 16).

Node	Cost to reach	Estimated cost to destination	Total
A	2	1	3
B	2	2	4

Table 16: A first planning move*

In this case the cost to reach nodes A and B is the same, 2; however when estimating the cost to get from each of these nodes to the destination the estimate for A is 1 being 1 node away from the destination, whereas the estimate for B is 2, giving a total estimated cost of 3 for node A versus 4 for node B. This means that from where the agent starts, the move to node A seems the most attractive. Now the route planner expands node A and sees that the cost to move to its destination is an extra 5 making a total of 7 (Table 17).

Node	Cost to reach	Estimated cost to destination	Total
A	2 + 5 = 7	-	7
B	2	2	4

Table 17: A second planning move*

This exceeds the estimated total of moving via node B; so, with node B now looking the most attractive option; the route planner backtracks to node B and goes from there. Following the same procedure, the cost via this route will never exceed the cost via node A so the route planner will complete its plan and return to the agent a route plan of 3 moves; starting location to B, B to C, C to destination. In this example the route planner ended up expanding all possible nodes to return the most efficient plan; but if the cost of moving from A to the destination had been more in line with the estimate then the best route would have been planned in 2 moves with no need to further examine nodes B or C, saving much processing time.

In order to use A*, which is a very simple, efficient and effective search algorithm when properly used, the environment must be represented in a way that can be represented in graph form. During the development of the model, two main approaches were tried.

3.5.1 Grid Movement

Grid movement (Figure 34), moving each agent from one cell of the environment to another, has the advantage of being both easy to process conceptually and also to program. Each agent occupies a square of the environment, the number of agents in each cell is limited based on the size of the cell and the size of the agents (cavalry taking up more space than infantry, for example). Agents move from their cell to an adjacent cell, with each move having a cost associated with it. This cost can be used to plan routes based on the A* planning algorithm. Disadvantages with this approach arise when the route being planned results in a large number of cells of diverse costs being visited. Short distances are resolved quickly but long distances face an ever increasing trade-off between lengthy processing time and sub-optimal routes. A key factor in A* planning performance is tree depth, a measure of the minimum number of nodes needed to reach any given destination. Each cell further away from the start that the destination is, the greater the tree depth. Unless the heuristic involved is very accurate, each increase in tree depth also increases the tree width, the number of nodes visited per step closer to the destination. This rapidly increases the number of nodes to be visited by the planner.

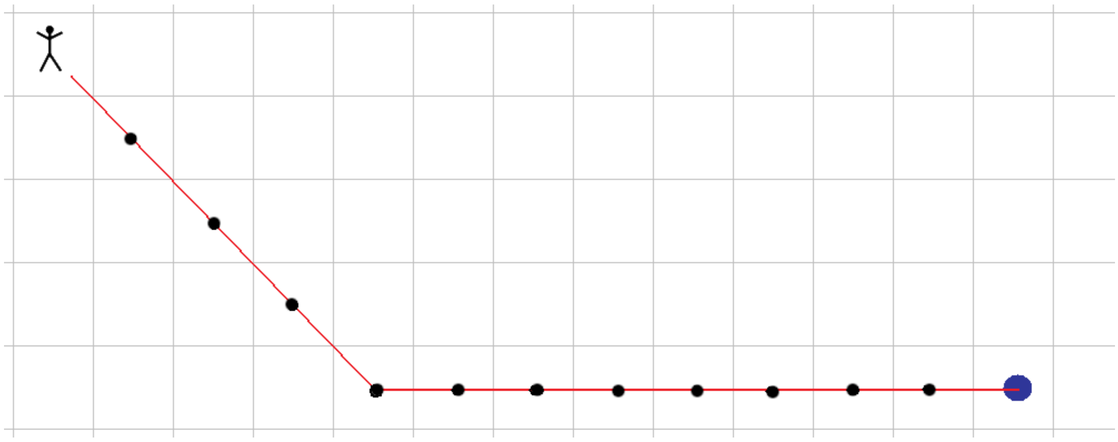


Figure 34: Grid movement

3.5.2 Probabilistic RoadMap Movement

Probabilistic RoadMap (PRM) movement (Figure 35) relies on a series of nodes to be created over the environment. These nodes are linked by edges which are the paths that an agent can move between nodes. Therefore an agent can move from node to node instead of from cell to cell, aggregating a whole series of movement costs into a single cost of moving from one node to another. This decreases the processing time of A* route planning because the number of steps required to traverse large numbers of cells is reduced. Disadvantages with this method arise when the nodes or edges are not created in places that would enable agents to access certain resources. This could render an agent unable to perform tasks that it would be able to do in real life, because of the ABM's design, a situation that is clearly to be avoided.

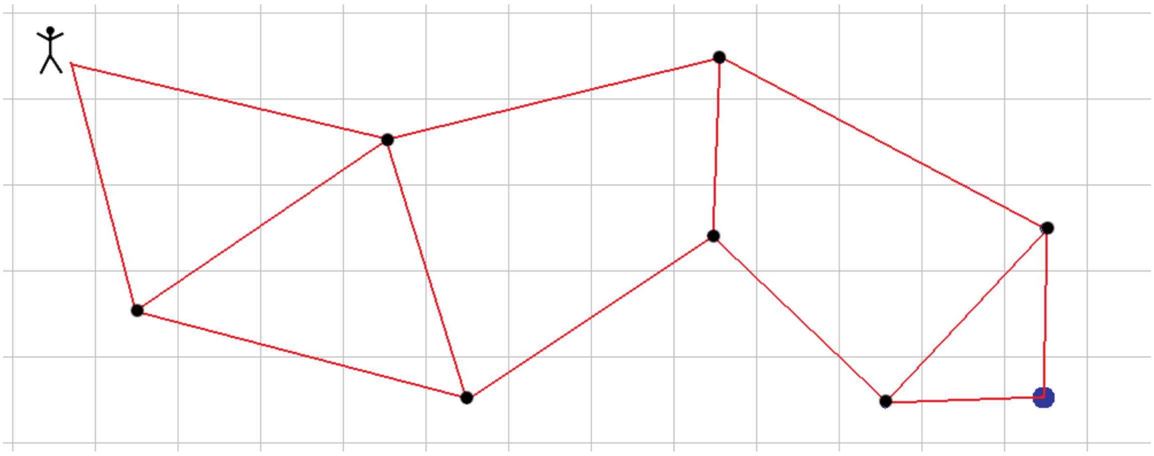


Figure 35: PRM movement

3.5.3 Why Not Just A*?

A* graph search algorithms are both admissible and complete when properly implemented. The term 'complete' means that a solution will always be found if one exists; if an algorithm is 'admissible' then it returns the optimal solution as long as the heuristic does not overestimate the cost of reaching the goal. The closer the heuristic is to the actual cost of movement, the quicker and more optimally the algorithm will run, as seen in Table 18.

Comparison of heuristic to actual cost	Result
Heuristic overestimates cost of remaining moves	Algorithm runs fast but result may be sub-optimal
Heuristic estimates cost accurately	Algorithm runs fast, result is optimal
Heuristic underestimates cost of remaining moves	Result is optimal but algorithm runs inefficiently, expanding more nodes than necessary

Table 18: Effects of heuristic values on the running of the A algorithm*

A* route planning over an environment consisting of discrete cells works most rapidly when the distance covered is small. When the distance covered is considerable, matching the heuristic to the actual movement cost becomes more important. Using cells of 5m x 5m, the area covered by the ABM results in a grid of 280,700 x 88,900 cells. Planning a route across the whole of this area presents an insurmountable problem for the A* algorithm unless the heuristic estimates the remaining cost precisely. Finding a plausible route, however, relies on a variety of movement costs, making any estimate inaccurate. The difference in desirability between a smooth, flat road and a hike over a hilltop is considerable. The specific movement values are not important but the relationship between them is. For a steep movement uphill to be twice as undesirable as a smooth level movement the movement cost must be twice as much. As the minimum and maximum movement values diverge, so the heuristic is more likely to be further from the actual cost of movement. So with straight A* we're stuck in a situation with two undesirable options:

- Ensure the distances are never long by having more preset waypoints.
- Ensure the movement costs are more predictable by making the costs differ by smaller amounts

The first option is undesirable because it reduces the autonomy of the agents, which ideally should be able to choose their own route based on our defined rules, not have it preordained from the start. The second option is likewise undesirable because the agents should make sensible route planning choices, not be more likely to select an unreasonable route because of a design decision.

3.5.4 What is the Solution?

Our A* route planning can be set up to work well over either long or short distances. Thankfully these can be combined by using a mixture of grid-based and PRM movement. Supplies would have been concentrated at settlements which in turn tend to be linked by roads. Therefore the army would have tended to move from settlement to settlement along the road network. This makes the army's macro level route planning ideally suited for PRM movement. Whereas true PRM creates a random series of nodes spread over the environment, our node network can be created using settlements as nodes. Edges can be automatically created between neighbouring nodes and costs assigned to each edge will be based on the likely supply level of each settlement and the presence of a road linking them. The A* route planner can be run on this node network to create a macro route, which is then converted to a series of waypoints over which the grid-based A* planner can work. If a specific route needs to be tested then these waypoints could be specified in advance and this step skipped.

Even chopping the route into discrete sections, an unmodified A* route planner will not do everything needed in a reasonable timescale. One way in which performance can be improved is to have a dynamic method of calculating the heuristic modifier. The heuristic calculates how many steps it takes to reach our destination and assigns a cost of 1 per cell. If movement costs are 1 or higher per cell this means the result will be the lowest cost route. It can be assumed that the average cost of movement will be greater than 1 per cell and increase the heuristic cost accordingly. This will speed up the route planning but if the heuristic cost exceeds the actual cost then the route may not be the one with least cost.

There is clearly a trade-off between performance and quality. In order to test this, an arbitrary measurement of energy expended during movement was created. An agent used more units of energy when moving uphill and along longer routes than level or downhill on shorter routes. This gave a coarse measure of a given route's easiness: the lower the energy expended the more the route planner avoided going uphill or on long detours. Tests reveal there will be a point of reasonable compromise where the route planned is near optimal and the processing time is acceptable (Figure 36).

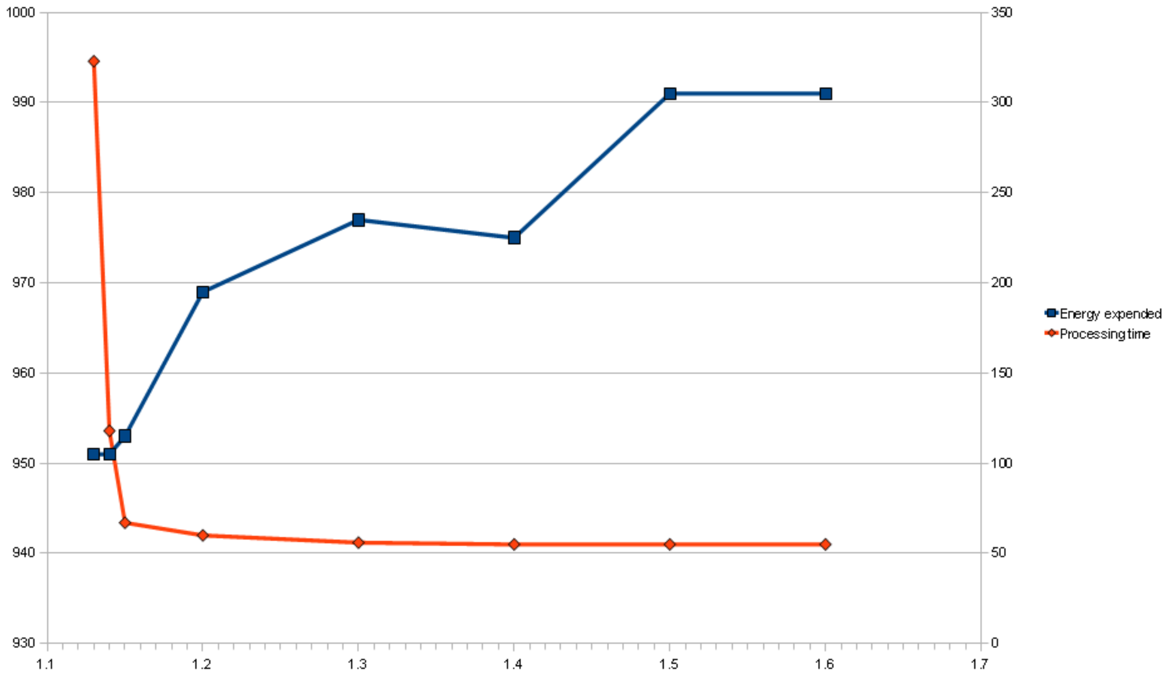


Figure 36: Graph showing relationship between heuristic modifier and performance

As can be seen, when the heuristic cost per cell is between 1.14 and 1.15 the processing time is acceptable and the route is very close to being optimal. Our dynamic method of calculating this point assumes a deliberately high heuristic modifier and calculates the route. It repeats this process with decreasing values for the heuristic modifier until it exceeds a set time limit for the route planning process. It then takes the route calculated by the last successfully completed run and uses that as the route. This method ensures all routes fall within an acceptable area of accuracy and performance.

A separate step can be added which attempts to find a route along a road from the start location to the destination. If such a route exists then this route will be taken, working on the assumption that a road route is preferable to an off road route even if the road route is longer (Figure 37). This would have the effect of further optimising any road routes as the number of possible locations are drastically reduced.

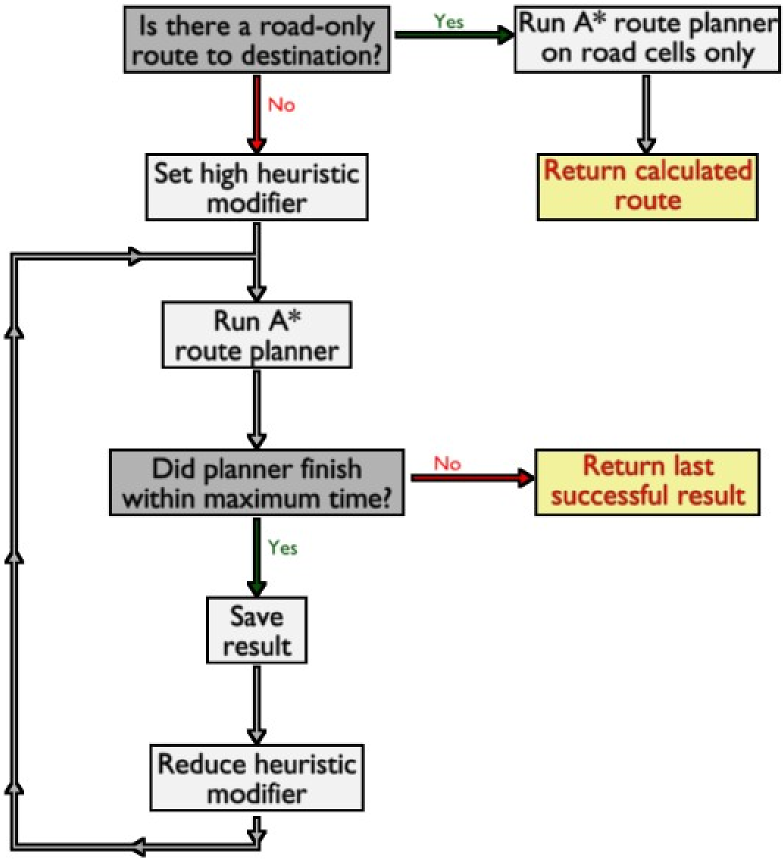


Figure 37: Flowchart detailing dynamic route planning logic

3.5.4.1 Shuffling

The movement system needs to be robust enough to enable any number of agents to move across any terrain without having that movement fail due to any feature of the model. The system as it stands may result in a situation whereby an `Officer` is attempting to move to a cell that has no space. This is not a problem if these agents blocking the path are subsequently going to move on, however this is not always the case. A cell may be blocked by a unit whose movement has finished or, in some cases, a unit further back in the order of march. This results in a deadlock whereby each unit is blocking the destination of the other and therefore neither they or any subsequent units will continue their movement. The system needs a mechanism to avoid deadlocks such as these.

Whichever mechanism is chosen has to be relatively plausible so as not to effect the plausibility of the whole model and as effective as possible so as to minimise the number of model runs unsuccesfully completed due to movement deadlocks. Care must also be taken that any system does not contain within itself a mechanism whereby new deadlocks are created. One way of minimising this risk is to add a random component to the behaviour. This will add a random element to the results of the models, possibly necessitating mutiple runs of individual models to ensure the random effect is not significant however it will minimise the possibility of the system itself being stuck in a loop from which it cannot break out.

The mechanism chosen for DM001-007 was a process whereby if an agent found itself in a cell with no space for incoming agents then it would move to a random empty neighbouring cell, a process referred to within the ABM as 'shuffling'. This ensures that no cell is blocked for long and that the system reduced the prospect of deadlocks being intrinsic to the system itself, having within it a random component. This worked well for the majority of models however when a large number of agents attempted to move into a small area it could lead to never ending shuffling as agents tried to avoid full cells while still remaining in flocking distance of their officers. Blockages tended to clear eventually and the concept of having too many agents in too small a space causing movement problems is not implausible however the agents themselves tended to create an unrealistic large swirling blob. The reality of an army on the march being stuck would probably result in a condensed and slightly widened queue, behaviour not seen when more than a few agents get stuck with random empty neighbour shuffling.

The solution incorporated into the DM008 and DM009 scenarios was to restrict shuffling to `Officer` agents and/or only one `Soldier` agent. Instead of shuffling randomly, the agent would shuffle either backwards to the last location occupied or back and to the side. This resulted in a slightly fattened queue of agents rather than the amorphous swirling blob created by random shuffling.

3.5.4.2 The Environment

The environment is handled by a Singleton to ensure only one copy of it exists as all agents must be certain they are accessing the same data. All access to environment data is handled by the `EnvironmentImplementation`, which provides the `getEnvironmentVariable` method. The `getEnvironmentVariable` method can be called by any part of the ABM and needs the location and the environment slice to be queried. This method returns a `Value<?>`, a bespoke class which can carry a value of any type, specified inside the angle brackets. The type of value returned from each environment slice is specified in the class `EnvironmentVariables`. The environment slices themselves are accessed as either a `PartitionedSliceArray`, a `SliceArray` or a `SliceMap` (Figure 38).

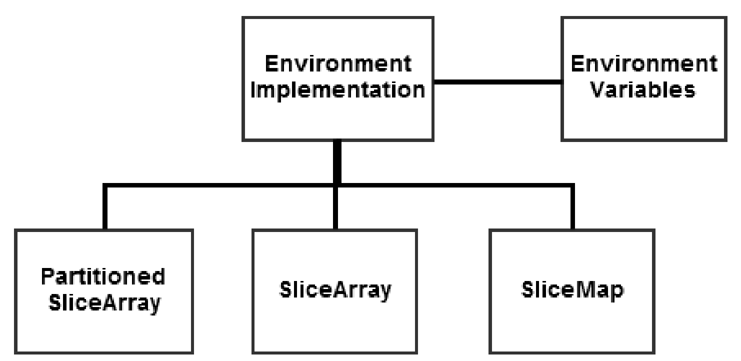


Figure 38: Environment class organisation

3.5.4.2.1 SliceMap

A `SliceMap` takes the form of a list of `Location`s along with the value represented in each of them. When a call is made on a location in this slice, the `EnvironmentImplementation` checks the list of locations for the location queried. If an entry exists the associated value is returned. If not a null value or 0 is returned depending on the data type. This is used for sparse data such as roads or settlements where there are insufficient data points to merit a complete raster array.

3.5.4.2.2 SliceArray

A `SliceArray` is a raster data layer covering the whole of the ABMs area. It can be of any resolution and contains data for every cell in the array. It is used for continuous data such as the GlobCover environmental data.

3.5.4.2.3 PartitionedSliceArray

As the height data needs to cover the whole of the ABM area it needs to be a raster array. The height data needs to be of sufficient resolution to have a real effect on route planning which sometimes occurs over fairly short distances. This requires a raster data file of over 1Gb in order to cover the whole ABM area. It is inefficient and unnecessary to have this entire file loaded into memory at all times. For this reason `PartitionedSliceArray` was created. The height data is stored in a zipped file and is loaded in a slice at a time. The size of each slice and the number of slices held in memory at any one time are specified in the initialisation file. This results in a processing overhead compared to the `SliceArray` class but drastically reduces the memory resources required for the environment.

These types of slice are transparent to the ABM which calls the `getEnvironmentVariable` method and casts the returned `Value<?>` to the appropriate data type.

3.6 Overall Army Behaviour

So in an army with one column the procedure is as follows:

- The `ColumnLeader` reads the destination location from the initialisation file and determines the two appropriate waypoints, one outside the starting camp and one outside the destination camp (Figure 39). He then adds three *PlanMacroRouteTo* plans to his plan queue.

- He processes the first *PlanMacroRouteTo* action which expands the plan into a *GiveOrder* action to its succeeding officer and a series of *TravelTo* plans.
- He gives the order to travel to the first waypoint outside the start camp and moves on to expanding the first *TravelTo* into a series of *Move* actions.
- Meanwhile the *ColumnLeader's* succeeding officer receives a *GO_TO_POINT* order with the first waypoint as the destination location.
- He adds a *PlanMacroRouteTo* action to his plan queue, this cascades down the line of march.
- When the *ColumnLeader* arrives at waypoint 1 he processes the second *PlanMacroRouteTo* action. This results in him planning a route to waypoint 2 then messaging his succeeding officer with a *FOLLOW* order.
- The *ColumnLeader* sets off for waypoint 2. His succeeding officer processes the *FOLLOW* order and starts following, passing the *FOLLOW* order down the line of march.
- When the *ColumnLeader* arrives at waypoint 2 he processes the final *PlanMacroRouteTo* action which results in him passing a *GiveOrder* down the line of march with the order *GO_TO_CAMP_LOCATION* and the destination location being the centre of the camp.
- When each of the succeeding officers arrives at waypoint 2 they process the *GO_TO_CAMP_LOCATION* order, work out their camp location and add a

`PlanMacroRouteTo` plan with the destination location as the centre of camp and the Point? Parameter set to false.

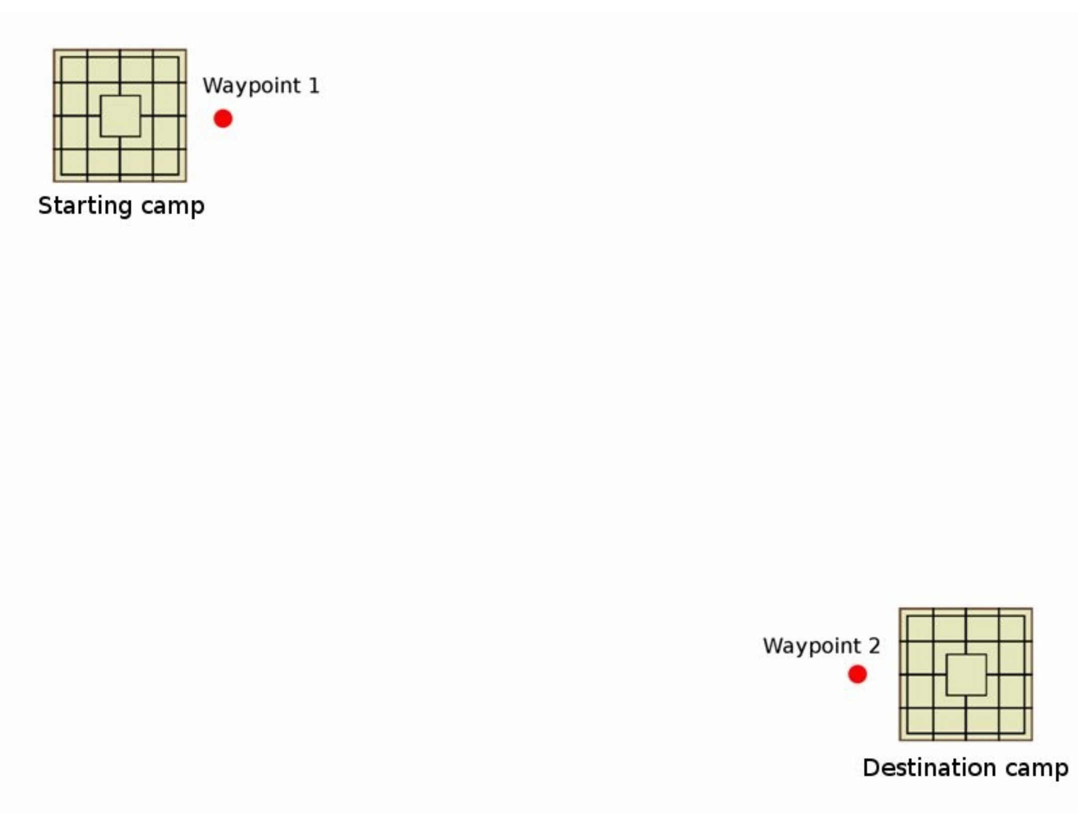


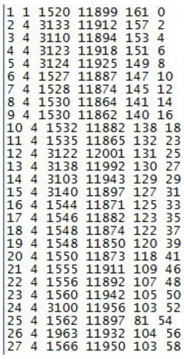
Figure 39: Sample camp layout with single column waypoints marked

3.6.1 The Dayfile

The dayfile contains one line of data for each agent (Figure 40). This is the aggregated data for the agent over the course of the simulation's run. Its contents have been added to over the development of the ABM, Table 19 lists the values contained in the dayfile and the simulations in which they appeared.

Data field	Data type	Description	DM versions
Agent number	Integer	The agent's unique ID	001-008
Agent type	Integer	An integer indicating the type of agent (see Table 20)	001-008
Arrival tick	Integer	The tick number that the agent last moved, if the simulation has completed this will be the tick at which it arrives at its destination	001-008
Total distance moved	Integer	The total distance moved by the agent in metres.	001-008
Rest ticks	Integer	The total number of ticks that the agent has not moved due to resting. Only recorded for Officers and Column Leaders	002-007
Start tick	Integer	The tick that the agent started moving from the start camp	007-008
Calories Expended	Double	The total number of calories expended during movement	008

Table 19: Dayfile data fields



```
1 1 1520 11899 161 0
2 4 3133 11912 157 2
3 4 3110 11894 153 4
4 4 3123 11918 151 6
5 4 3124 11925 149 8
6 4 1527 11887 147 10
7 4 1528 11874 145 12
8 4 1530 11864 141 14
9 4 1530 11862 140 16
10 4 1532 11882 138 18
11 4 1535 11865 132 23
12 4 3122 12001 131 25
13 4 3138 11992 130 27
14 4 3103 11943 129 29
15 4 3140 11897 127 31
16 4 1544 11871 125 33
17 4 1546 11882 123 35
18 4 1548 11874 122 37
19 4 1548 11850 120 39
20 4 1550 11873 118 41
21 4 1555 11911 109 46
22 4 1556 11892 107 48
23 4 1560 11942 105 50
24 4 3100 11956 103 52
25 4 1562 11897 81 54
26 4 1963 11932 104 56
27 4 1566 11950 103 58
```

Figure 40: Part of a dayfile from DM007

Agent type number	Agent type
1	Column Leader
2	Infantry Officer
3	Infantry Soldier
4	Cavalry Officer
5	Cavalry Soldier

Table 20: Agent types

3.6.2 The Tickfile

The tickfile contains a line of data for every agent on every tick of the simulation (Figure 41). This can result in large files in simulations with sufficiently large numbers of agents or lengths of run. The categories of data in the tickfile have remained constant throughout the Day's March scenarios.

Data Field	Description
Tick number	The number of the tick
Agent number	The agent's unique ID
Agent type	An integer indicating the type of agent (see Table 20)
Location X	The X value of the environment cell in which the agent is this tick
Location Y	The Y value of the environment cell in which the agent is this tick

Table 21: Tickfile data fields

```
1 1 2 30000 34495
1 2 2 29999 34495
1 3 2 29999 34495
1 4 2 29998 34495
1 5 2 29998 34495
1 6 2 29997 34495
1 7 2 29997 34495
1 8 2 29996 34495
1 9 2 29996 34495
1 10 3 30000 34495
1 11 2 29995 34500
1 12 2 29994 34500
1 13 2 29994 34500
1 14 2 29993 34500
1 15 2 29993 34500
1 16 2 29992 34500
1 17 2 29992 34500
1 18 2 29991 34500
1 19 2 29991 34500
1 20 3 29995 34500
1 21 2 30020 34500
```

Figure 41: Section of a tickfile

3.6.3 Blender

In order to visualise the behaviours of the ABM it was decided to use Blender, an open source 3D graphics and animation package. Blender is tightly integrated with the Python programming language, enabling an import script to be created which would convert a tickfile into an animation of the agents. Two Python scripts were produced.

3.6.3.1 First Python Script

The first was written by the project's first Computer Science Research Fellow, Rob Minson and used separately created models of agents to produce detailed animated agents. The script loaded art assets from a separate file, created by Philip Murgatroyd, that were able to portray individual agents performing tasks, carrying objects and displaying the intention to perform tasks in their plan queue. These agents had animations set for different actions and activities and could show which objects they were carrying and which tasks they were waiting to perform. Providing the names of the models and animations conformed to those expected by the script, any models could be used. This had the advantage of enabling differently detailed models to be automatically imported depending on how many agents were in each model. It would even be possible to obtain bespoke models from a specialist 3D artist and produce professional quality animations and stills. Figure 42 shows the same frame of animation with the more realistic, high polygon models on the left and the less resource intensive lower polygon output on the right. This was useful for early versions of the ABM which dealt with small numbers of agents. It allowed a detailed visualisation of the state of each agent and the tasks that it intended to do in the future. It was also planned as an attractive way to illustrate some elements of the model to non-specialist audiences. Unfortunately as the numbers of agents in each model increased the processing time and file sizes became impractical, even with the low polygon models. As this is a separate process from the running of the ABM, tickfiles from previous ABM runs can be saved and used to produce animations at any time afterwards.

Figure 42: Output from the first python script showing both sets of art assets

3.6.3.2 Second Python Script

For larger scale models a simpler script was written by Philip Murgatroyd. This script created a simple shape for each agent and set it to a particular colour depending on the type of agent (Figure 43). Infantry are represented by triangles and cavalry by squares, officers are lighter than soldiers, the `ColumnLeader` is dark red. This resulted in faster processing times and smaller Blender file sizes. Once the tickfile had been processed by the Python script, the Blender file could be saved for future use. For debugging the model the actions of the agents could be seen in Blender with time being moved backwards and forwards at will. For presentation to others an animation can be produced in any standard video format. This involved a certain amount of directorial control as the focus of the camera depends on the particular activity to be shown and is therefore not a totally automatic procedure. This does, however, enable the focus to be either large scale movement or small scale behaviours. Unlike the first Python script, the second is designed to be best seen directly from the top in orthographic mode.

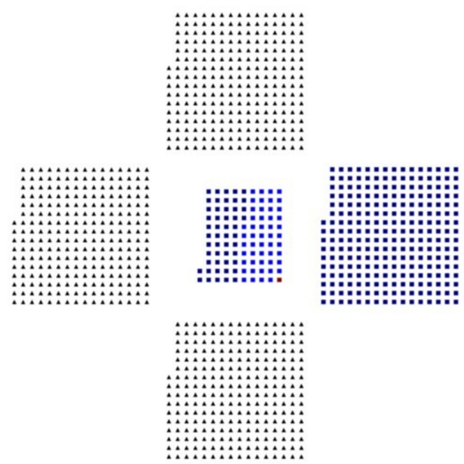


Figure 43: Output from the second python script

3.6.4 Blender pre-processing

In order to produce a visual representation of the actions of the ABM it was necessary to create a graphical representation of the agents and their behaviours. As the size of the tickfile increased, the Blender processing (described above) took increasing lengths of time. This was partly because the Blender Python script created a keyframe for every agent on every tick whether the agent had moved or not. This not only increased the processing time but also the size of the saved Blender file. As a keyframe is only required if the agent moves, a Java programme was written which read in a tickfile and outputted the same data with all the data removed for ticks in which the agent doesn't move. This results in reduced tickfile sizes, reduced Blender processing time and reduced Blender file sizes.

3.6.5 OpenOffice Calc

In order to process the data from the dayfile, it is pasted into an OpenOffice Calc template (Figure 44). This template extracts aggregated data from the dayfile.

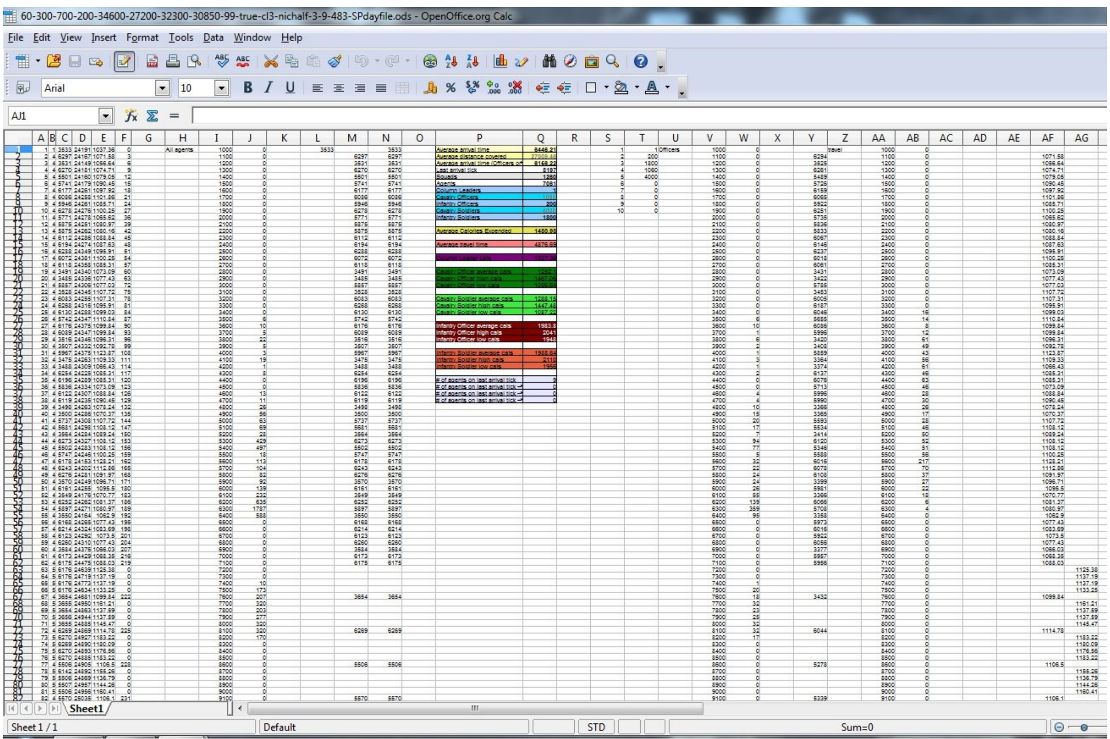


Figure 44: The dayfile spreadsheet for aggregated data

This spreadsheet not only produces averaged data for the whole run of the simulation (Figure 45) but also creates frequency tables that allow the plotting of arrival times at the destination camp (many examples in the following chapter).

Average arrival time	**6446.21**
Average distance covered	27009.46
Average arrival time (Officers only	**6156.22**
Last arrival tick	**8197**
Squads	**1260**
Agents	**7061**
Column Leaders	**1**
Cavalry Officers	1060
Infantry Officers	**200**
Cavalry Soldiers	4000
Infantry Soldiers	**1800**
Average Calories Expended	**1480.98**
Average travel time	4876.69
Column Leader cals	1037.36
Cavalry Officer average cals	1252.1
Cavalry Officer high cals	1467.06
Cavalry Officer low cals	1056.64
Cavalry Soldier average cals	1288.15
Cavalry Soldier high cals	1447.48
Cavalry Soldier low cals	1087.22
Infantry Officer average cals	1983.8
Infantry Officer high cals	2041
Infantry Officer low cals	1948
Infantry Soldier average cals	1988.64
Infantry Soldier high cals	2110
Infantry Soldier low cals	1956
# of agents on last arrival tick	9
# of agents on last arrival tick – 1	0
# of agents on last arrival tick – 2	0
# of agents on last arrival tick – 3	0

Figure 45: Sample tabulated aggregate data from the spreadsheet

3.7 Summary

So in summary, the decisions made regarding which elements of the ABM design to implement were primarily made with regards to the limitations of the hardware available to run the task. In order to accomplish this, a novel ABM design has been implemented that incorporates a substantial alteration of standard A* route planning. This work takes advantage of existing procedures but increases the flexibility and applicability to the unique route planning problems associated with moving tens of thousands of agents over both large and small distances. By focussing on a day's march the army's movement can be split up into discrete chunks in order to make the processing time short enough to be able to produce the many different outputs required. This also allows development to progress incrementally with each new model allowing different hypotheses to be tested. This will reduce the vast numbers of necessary scenarios required to test every permutation of parameters. The following chapter details the each of these sets of scenarios along with their results and the new information gained from each model.

4 The Day's March Scenarios

4.1 Introduction

Having implemented the agent-based model, it can be used to try and answer the research questions described in chapter 2. These are:

- How did the army organisation affect the overall speed?
- How do size and composition of the army affect the overall speed?
- What effect did the supply of the army have on the settlements through which it passed?

Given the lack of prior ABM work in the modelling of military logistics the use of the model will demonstrate that it is a useful technique that will add new evidence to existing debates. Due to development considerations the models will increase in the complexity of their design and implementation as new factors are examined. This also allows the tailoring of the model to the question being asked of it, as appropriate abstraction is important in the modelling process. In this chapter I will introduce the background to the scenarios before describing each of the nine sets of scenarios in turn. They were implemented in chronological order and the increasing complexity can be seen through this chapter.

The first agent-based models (ABMs) of the march of the Byzantine army to Manzikert in AD1071 were limited in scope to a single day. This was done for a variety of reasons:

- To simplify development and debugging of the software.
- To enable the models to be easily run on a single machine.
- To enable spatial resolution to stay fine enough to create a plausible movement model.

Starting on a small scale allows development and debugging of the software to progress via incremental steps. The models could start small with few agents moving over short distances over the course of a day and gradually build up the complexity and scale of the models in order to meet more ambitious goals. This also allowed elements of the model to be tested in sparser models in order to debug their behaviours, with extra functionality added a bit at a time. The modular nature of Java, an object-oriented language, actively encourages this approach.

The lack of a functional distributed infrastructure required a single computer version to be developed in order for testing of the code and behaviours involved in the model. Due to the restrictions of using only one machine, the ABM had to be able to be run within an acceptable time frame especially during the development and debugging phase. While a set of scenarios may require tens of different processing runs, debugging the software in order to test that the model works as intended can require hundreds of runs. If the processing time of the model is too great, the development phase will be unacceptably long.

With this in mind, the ABM has to have suitable spatial and temporal resolution. As the interactions between individual agents and their effect on the overall movement of the army is one of the key goals of using ABM, the spatial resolution has to stay fine enough to examine this. This means that the temporal scope needs to be reduced to ensure timely processing. The choice of setting the time scale at one day was driven by the fact that it represents a sensible and discrete time for marching, every attempt would have been made to arrive at the destination camp before nightfall in order to avoid the problems of marching and setting up camp in the dark.

The sets of scenarios are referred to by the prefix "Day's March" then a sequentially assigned three digit number, therefore the first is referred to as Day's March 001 or DM001 for short.

4.1.1 Units of Measurement

The ABM represents its whole environment with reference to a grid system 280,700 cells wide and 88,900 cells high. This covers the area between 38° - 42°N and 28° - 44°E. Due to the curvature of the earth this does not result in a uniform cell size, nor are the cells exactly square however for the purposes of our model they can be considered approximately 5m x 5m. This gives us approximately 200 cells to the km or around 321 cells to the mile when measuring orthogonal distances. The length of a tick was initially set to reflect the speed of agents over the ground. By setting the length of a tick to be the amount of time needed for an average human to walk 5 metres it will simplify movement calculations. I have assumed a human marching speed of 3mph which equates to:

4828.032 metres per hour

80.46 metres per minute

0.0124285 minutes per metre

0.0621425 minutes per 5m

3.72855 seconds per 5m

Due to the multiple speeds required by both infantry and cavalry agents and the conversion between the Imperial system commonly used in historical documents (mph for publications such as *The Art of Marching*) there is no simple system that will result in round numbers for both the spatial and temporal parameters.

4.2 Initial Setup

In order to provide an initial sample length of scenario, sunrise and sunset data from Ankara for April 15th 2010 was used, giving sunrise and sunset times of 06:11 and 19:27 respectively at

UTC +3. This gives a day of 13 hours 16 minutes which equates to 12809 ticks per day at 3.72855s/tick. Each day is taken to consist of 12809 ticks for all scenarios up until DM008.

For both technical and modelling purposes it is advisable to start small and increase in complexity. A day's march will be modelled with a variety of lengths and a variety of army sizes, escalating initially to the lower estimates of the army's size and the lower estimates of the distance covered. Although marches of over 30 miles per day are recorded (Furse 1901, 237) these can be considered in excess of what the Byzantine army would typically have achieved considering the less professional nature of some of its combatants and the deteriorated state of the Byzantine roads. *The Art of Marching* indicates this is far in excess of the distances usually considered to be a reasonable day's march (Furse 1901, 217). Table 22 gives some representative distances to be attempted in miles, metres and ABM cells. These will be measured as the crow flies, allowing us to measure the difference between the nominal distance covered in a day's march and the actual ground covered by each agent. March distances during scenarios DM001 - DM007 increase in increments of 3 miles, an arbitrary distance initially thought large enough to make a difference to the result but small enough to enable multiple plausible data points. Miles were chosen as a unit to make the distances easier to relate to previously published research.

Miles	Metres	Cells
6	9656	1931
9	14484	2897
12	19312	3862
15	24140	4828
18	28968	5794
21	33796	6759
24	38624	7725

Table 22:Sample march distances in miles, metres and ABM environment cells

Figure 46: Anatolia with the ABM extent marked in red

4.3 Start and Finish Locations

We have no historical accounts of a plausible day's march for the Byzantine army during the Manzikert campaign. We do however have an account of the army of the 1st Crusade marching from Nikaia to Malagina on what was commonly taken to be a reasonable day's march (Bachrach 2006). As our hypothetical Manzikert route went through Nikaia and Malagina this is a plausible initial scenario for our model. The presumed size of the crusading army, 50,000, neatly fits in with our hypothesised Byzantine force of around 32,000 (as detailed on page 234). Working from our data we can see that the distance from Nikaia to Malagina in our model is 6397 cells as the crow flies. This makes it about 20 miles, an initially plausible distance for a one off day's march if the crusaders were being resupplied in Malagina and so wouldn't have had to move for maybe a few days afterwards. We can start our Byzantine army at Nikaia (Location 30000, 34500) and send it towards (and possibly beyond) Malagina at 3 mile intervals. These are:

6 miles: 31830,35352

9 miles: 32745,35778

12 miles: 33660,36204

15 miles: 34575,36630

18 miles: 35490,37056

21 miles: 36405,37482

24 miles: 37320,37908

Day's March scenarios 001-007 all start at Nikaia and have as their destination a point directly towards or beyond Malagina. Due to the area between Nikaia and Malagina being fairly flat, terrain plays a minimal role in route planning, the army will be marched over different terrain in DM008 with its effects on energy expenditure examined in DM009. Aspects such as water courses and roads will not be initially implemented, although the way each column marches ensures it is usually less than 10m wide and as such could plausibly fit on the major roads of Byzantine Anatolia (French 1981). Each Day's March set of scenarios will be presented below with an introduction and a description of the modelling and software development work required to enable the ABM to run. The results will then be presented in tabular format with a discussion on these results and any conclusions to be drawn.

4.4 Hardware Overview

The hardware and operating system specifications are listed in Table 23. The UNI desktop and laptop have radically different hardware and software setups to the cluster nodes and were also being used for other purposes during some of the scenarios. The same version of the model was run each time, with only the initialisation file being changed to determine each setup. Data was collected either from Eclipse (processing time), the ABM trace files (distance travelled and time to camp) or a separate Java post-processing programme written specially for the purpose (length of column).

PC name	Description	Processor	Cores	Memory (Gb)	Operating System
UNI	University desktop	Intel Xeon 3.60GHz	2	16	Windows 7 64-bit
CN21	Cluster node 21	Intel Xeon 2.67GHz	4	16	Windows Server HPC edition
CN22	Cluster node 22	Intel Xeon 2.67GHz	4	16	Windows Server HPC edition
CN23	Cluster node 23	Intel Xeon 2.67GHz	4	16	Windows Server HPC edition
CN24	Cluster node 24	Intel Xeon 2.67GHz	4	16	Windows Server HPC edition
CN25	Cluster node 25	Intel Xeon 2.67GHz	4	32	Windows Server HPC edition
CN29	Cluster node 29	Intel Xeon 2.67GHz	4	4	Windows Server HPC edition
HOME	Home desktop	AMD Athlon64 X2 2.2Ghz	2	12	Windows 7 64-bit
LAP	Laptop	Intel Core i7 M620 2.67GHz	2	8	Windows 7 64-bit

Table 23: PC Hardware and OS specifications

The performance of the model is an important factor in its usefulness. The processing time has been recorded for each run of the simulation. This only applies to the actual Java ABM, processing the subsequent tickfiles for Blender or running statistical analysis on the dayfiles is not included in this although it is analysed as part of DM004. If any pattern shows up in the processing time of the model it may be possible to improve the model's performance, allowing more scenarios to be run in the time available.

4.5 The Day's March Scenarios

4.5.1 DM001

From a development point of view, DM001 examines how the software responds to a variety of values for the number of agents per cell. Various sizes of army are modelled over a variety of lengths of march with different values of agents per cell. Some scenarios are expected to result in heavy crowding, enabling an assessment to be made of how the model deals with extreme situations. From a modelling perspective it allows us to examine how crowding affects the length of the column and the distance travelled by each agent.

4.5.2 DM002

DM002 introduces changes suggested by *The Art of Marching*, along with fixing a couple of model errors from DM001. A rest period is introduced every hour between waypoints 1 & 2 and the effects of this on column length and travel time assessed.

4.5.3 DM003

DM003 is an attempt to find out the practical limits of the ABM on a single computer. This provides valuable information that will inform all subsequent models, especially regarding the size of future scenarios and their projected finish time. It involves scenarios in which a steadily increasing number of agents is introduced into the ABM and the processing times recorded. This also includes post-processing steps such as the processing of tickfiles in Java and their visualisation in Blender.

4.5.4 DM004

DM004 uses scenarios with different environment variables to examine whether the efficiency of the model can be improved. The environment is stored as a series of tiles and the size and number of these tiles in memory at any one time can have an effect on the performance of the model.

4.5.5 DM005

DM005 introduces variable sizes and speeds of agent in an attempt to examine how the presence and percentage of cavalry affect the speed and size of the column. Various scenarios are run over different lengths of march with varying quantities of cavalry and the effect on average arrival and latest arrival is measured. The individual arrival time of agents is compared in order to see the effects more accurately than relying on average times.

4.5.6 DM006 & DM006a

DM006 and 006a are a set of scenarios designed to investigate the practical limits of marching an army in a single column over a variety of lengths of march during a day. Various sizes of army and length of march are used, with a set 25% of the main force of the army consisting of cavalry.

4.5.7 DM007

DM007 examines the implications of splitting the army into separate column. It compares the arrival time and travel distance of identical armies split into 1, 2 or 3 columns.

4.5.8 DM008

DM008 creates a hypothetical army and marches it across Anatolia, attempting to provide representative day's marches in order to show how the model can help us understand the conditions of the Manzikert campaign.

4.5.9 DM009

DM009 examines the supply situation of the army as it relates to the carrying of equipment by the infantry. It takes a more in depth look at the food requirements of the army under different loads and assesses the impact of having food carried by humans instead of baggage animals.

4.6 DM001 - Crowding

4.6.1 Introduction

During the process of implementation (detailed in Chapter 3) basic movement rules were developed. In order for this basic infrastructure to be turned into a useful tool for the study of medieval military logistics, two main processes needed to be completed:

- Calibration of the model so that it uses the most plausible parameters
- Running of the model over several scenarios, the output of which can be compared to useful effect

4.6.2 Calibration of the Model

The basic ABM software allows us to move agents around in plausible ways and seems robust in its handling of basic movement situations. The user can can input an army size and destination and the model will automatically ensure all agents get to their destination. Each unit has a start and end point in both the starting and destination camps and there exists the capability for the units to march in any order they wish. Before DM001 there were several parameters in the model that weren't yet tied to real world measurements (Table 24). The parameters that couldn't yet be resolved to real world metrics were represented by placeholder values, often derived from arbitrary values or values useful for other purposes than the calculation of useful statistics.

Real world parameters	Placeholder parameters
Time	Army hierarchy
Distance moved	Agents per cell
	Energy expenditure

Table 24: Parameters

Human energy expenditure data is needed in order to be able to calculate the calorie requirements of the army and therefore the food supplies required en route to Manzikert. The number of agents per cell affects the length of the army column and the delay caused by crowding. The environment cells are 5m x 5m and the model determines how full a cell is by comparing the maximum size of agents per cell with the totals of the sizes of the agents in each cell. During the development of the model up to this point the maximum size of agents per cell has been 3 and the size of each agent has been 1, therefore there had been a maximum of 3 agents per cell. This was obviously unrealistically sparse considering a cell size of 5m x 5m but had been chosen in order to exaggerate the effects of crowding to ensure the mechanism worked satisfactorily.

The hierarchy of the army had until this point been based on a system whereby each officer has a maximum of 4 subordinate officers. This works well as the square shape of the camp lends itself to splitting the force into north, south, east and west areas. This also works as far as the organisation on the march is concerned as the army is split into vanguard, left wing, right wing and rearguard. Although this is artificially regular when compared to the actual Byzantine organisational chart, the differences shouldn't alter the behaviour of the model in any significant way and as such it may not be necessary to make this system more "realistic".

4.6.3 Running of the Model

The Day's March scenarios need to be run in order to examine the effects of the parameters as described above. Maximal and minimal values of 'Maximum Agent Size Per Cell' were run to determine the effects of this parameter. This experimentation has been done at an early stage in the model's development when there are minimal other factors affecting movement. Running a series of these scenarios should give us an idea about the relationship between density of agents, movement speed and length of marching column. Obviously there are no right answers for these questions however future modelling will be made easier if plausible and useful values can be decided upon at this point.

4.6.4 Setup

A combination of 10, 100 and 200 squads were marched over 6, 12 & 21 miles with either 3, 10 or 25 agents per cell. Due to the model's automatic creation of intermediate Officer agents between the Column Leader and the squads, scenarios with 10, 100 and 200 squads have a total of 103, 1033 and 2067 agents respectively. Maximum column length, average time to arrival in camp, average distance travelled per agent and processing time were all recorded. Tick file sizes for each experiment were 29Mb for 10 squads, 310Mb for 100 squads and 635Mb for 200 squads. Each scenario was run over 12,809 ticks, equating to a total time of 13 hours and 16 minutes at around 3.73 seconds per tick. This gives all the agents a movement speed of 3 mph.

The size of each scenario was specified in the initialisation file, and is recorded here, in squads and not agents. Until DM005 each squad contains nine soldiers and an officer. Extra officers are added between the squad level and the Column Leader to fill up the heirarchy to ensure no one has more than 4 subordinate officers. For this reason the total number of agents is generally the number of squads multiplied by 10, plus about 5% for the extra officers. From DM006 onwards, where the total number of agents is more important and less easily calculated, the number of agents is specified. Until then the size of the scenario is specified by number of squads.

Lines on Figures 47 - 50 are labelled with the length of march, then the maximum numbers of agents per cell. '6 3' therefore refers to a scenario run over 6 miles with 3 agents per cell.

4.6.5 Results

PC	Length of march (miles / metres)	# of squads / agents	Max Agent Size per cell	Max column length (metres)	Average time to camp (ticks)	Processing time (minutes)	Tick# of maximum column length	Average distance travelled (metres)
UNI	6 / 9656	10 / 103	3	789	2460	8	1294	12285
UNI	12 / 19312	10 / 103	3	1535	4658	32	4304	24442
CN25	21 / 33796	10 / 103	3	2019	8030	611	7603	42749
UNI	6 / 9656	100 / 1033	3	8046	4553	58	1767	15906
CN22	12 / 19312	100 / 1033	3	8385	6518	80	3624	28403
CN25	21 / 33796	100 / 1033	3	8230	9405	661	6910	45721
CN22	6 / 9656	200 / 2067	3	10938	6663	1503	2654	20454
CN22	12 / 19312	200 / 2067	3	17227	8119	1533	3815	32139
CN25	21 / 33796	200 / 2067	3	18368	10632	1561	3809	48442
CN24	6 / 9656	10 / 103	10	491	2325	5	1231	11942
CN24	12 / 19312	10 / 103	10	615	4488	17	3605	23801
CN24	21 / 33796	10 / 103	10	2507	7850	546	7442	41834
CN25	6 / 9656	100 / 1033	10	5511	2944	42	1692	12020
CN25	12 / 19312	100 / 1033	10	4925	5087	167	3623	23955
CN24	21 / 33796	100 / 1033	10	5640	8438	866	6913	42028
CN25	6 / 9656	200 / 2067	10	9705	4313	99	2131	13865
CN25	12 / 19312	200 / 2067	10	9254	5642	329	3625	23964
CN25	21 / 33796	200 / 2067	10	9950	9003	1067	6906	42033
LAP	6 / 9656	10 / 103	25	428	2321	7	1006	11934
CN23	12 / 19312	10 / 103	25	350	4457	7	1752	23813
CN24	21 / 33796	10 / 103	25	350	7749	546	1751	41843
CN24	6 / 9656	100 / 1033	25	5494	2921	27	1685	11975
CN24	12 / 19312	100 / 1033	25	4620	4964	35	2734	23933
CN24	21 / 33796	100 / 1033	25	4635	8237	626	6255	41993
UNI	6 / 9656	200 / 2067	25	9736	3480	133	2137	12014
CN24	12 / 19312	200 / 2067	25	9177	5451	72	3624	23943
CN24	21 / 33796	200 / 2067	25	9286	8729	621	6646	42006

Table 25: Data from all runs of the DM001 simulation

4.6.5.1 Processing Times

Processing times ranged from 5 to 1561 minutes (Table 34). Due to the differences in hardware and software of the PCs used, the processing times give little information regarding the interaction between model performance and hardware and software configuration. It can clearly be seen from the graph (Figure 47) however that route planning over 21 miles has a drastic effect on model performance. 546 minutes was the fastest run over 21 miles, with only 10 squads. Compared to this, 200 squads were run over 6 miles at 25 agents per cell in 72 minutes. As only 1 agent, the Column Leader, produced this route plan and all other agents exhibited some kind of flocking behaviour we can say that the majority of the nearly 10 hour running time was spent on this one route plan. 6 and 12 miles were much more efficient though, with the only excessive times being due to crowding problems and errors that resulted from this. Runs of 200 squads at 3 agents per cell gave artificially high processing times due to an error in the model. With realistic values of agents per cell the current model performs acceptably.

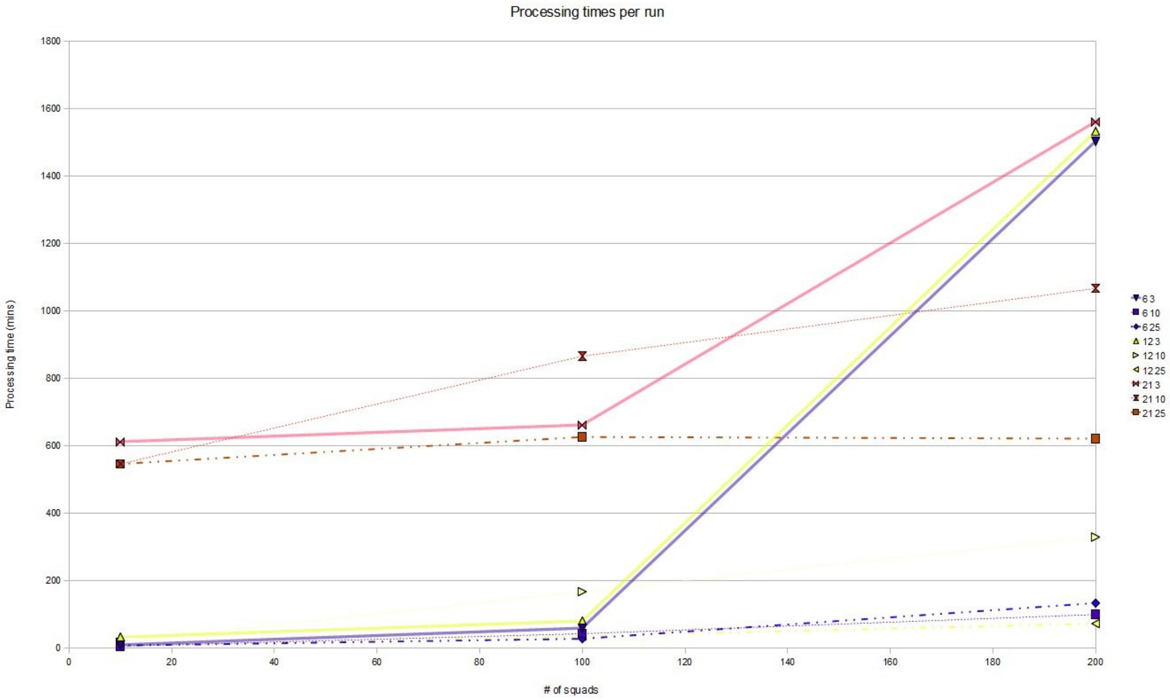


Figure 47: Processing time per run

4.6.5.2 Distance Travelled

The total distance travelled by each agent will depend on the movement rules that handle crowding and organisation on the march. If the model dictates that each unit should wait for the unit ahead to move then the total distance travelled should stay fairly static as the number of agents increases. This will be at the expense of average time of arrival which should increase. If, however, units have a certain amount of flexibility in their approach to blockages then they will find less congested but longer routes to their destination that will save time but increase the distance travelled. As the rules in DM001 dictate a reasonable gap between units with no breaks, pauses or slackening of pace we can expect the distance travelled to behave in a relatively stable fashion as blockages will be rare. This is reflected in the graphs (Figure 48), however the values of runs where only 3 agents per cell were allowed show that the movement caused by shuffling of position when crowded increases the distance travelled. This also occurs during the run with 10 agents per cell and 200 squads over 6 miles. This can be expected to be the next most crowded scenario.

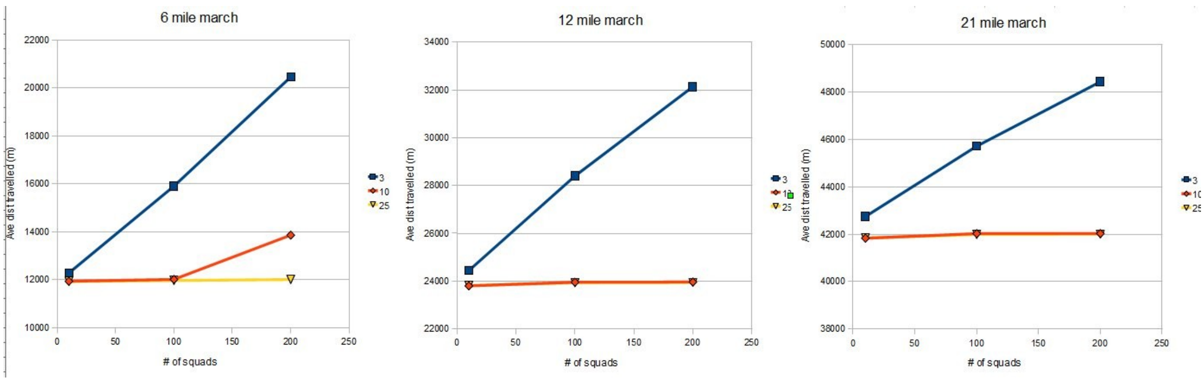


Figure 48: Distance travelled per run

4.6.5.3 Average Arrival Time in Camp

The average arrival time in camp should be affected by the number of units as each unit waits for its preceding unit to start before setting off. As stated above, delays caused by crowding will transmit themselves more visibly in arrival time than in distance travelled. This can be seen in the graph (Figure 49), the difference between 10 and 25 agents per cell being more pronounced than in the graphs showing distance travelled. The steady increase of arrival time is to be expected, although the lack of data points make the data appear more regular than it would be in reality.

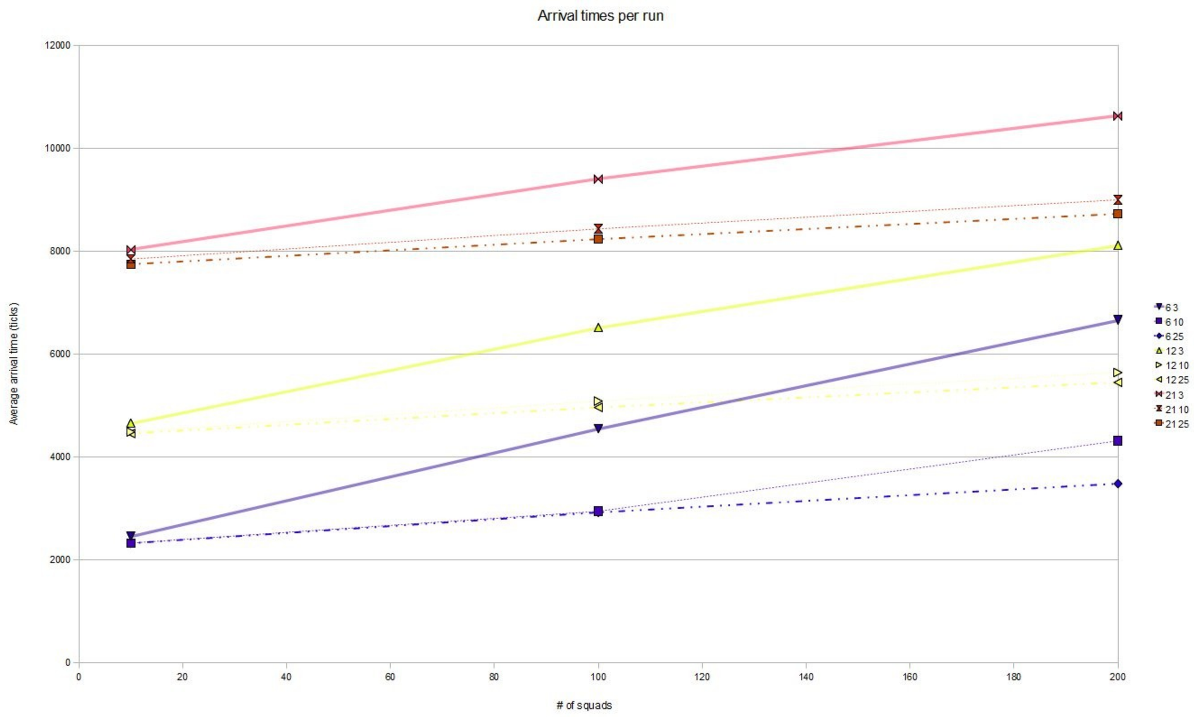


Figure 49: Arrival times per run

4.6.5.1 Maximum Column Length

We would expect that the more agents that there are in the army, the greater the distance between the first and last members of the column. This was clearly a factor but the distance over which the march was conducted turned out to also be important (Figure 50). Runs over 6 miles tend to exhibit longer columns than those over 12 or 21. One explanation for this is that the 6 mile run involved using a different point outside the first camp, one less in line with the overall direction of movement. Another factor is that this camp may be less in alignment with the order in which the units commenced movement, thus leading to a longer column. As with arrival time, the limited number of data points results in an overly simplified graph, presenting not much information about the relationship between size of army, length of march and size of column.

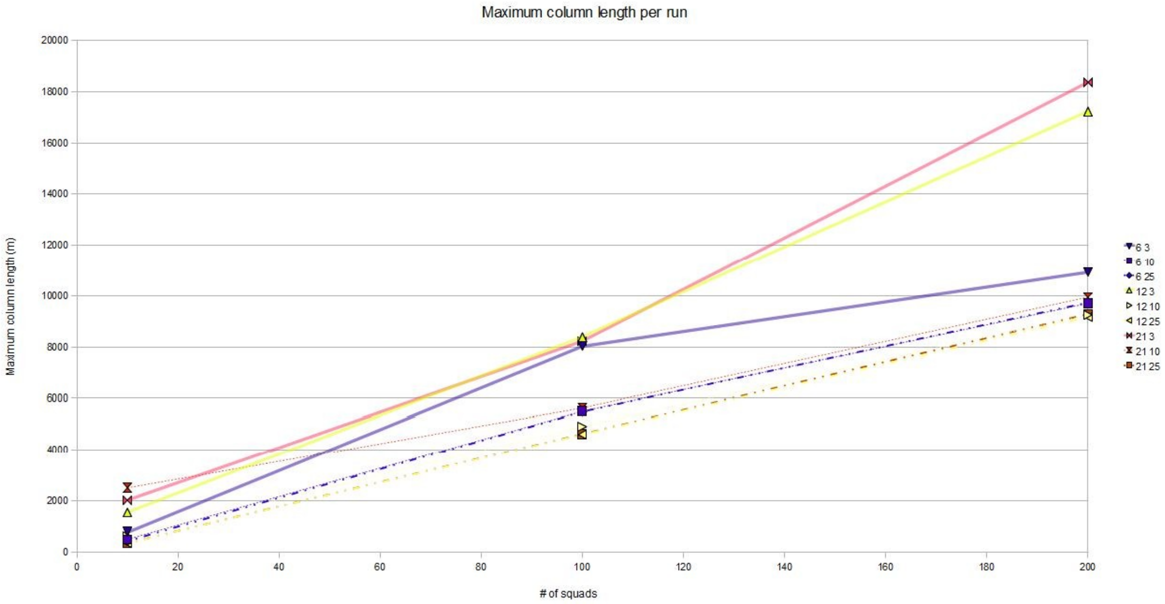


Figure 50: Maximum column length by run

4.6.6 DM001 Conclusions

As can be seen, our model struggles with performance using 3 agents per cell and over 21 miles. There were also problems within the model relating to messaging and route planning using 3 agents per cell. These increased processing time. Also, with reference to Furse's *The Art of Marching*, it is clear that the Byzantine army at its largest during the Manzikert campaign would probably not have travelled 21 miles in a day. This lies comfortably within values described as forced marching (Furse 1901, 218) and is neither recommended by military writers nor is it probably necessary on the Manzikert campaign. We can therefore discount these values from future scenarios involving large numbers of agents, the breaking point of our software exceeds the values within which it needs to operate.

It is clear from even this unrealistic movement model that crowding can cause either severe delays, longer march routes or both, depending on how delays are handled. If units are given autonomy to move round delays then march lengths are increased as they do this. If they wait in line for their preceding unit to start moving then journey times are increased. The level of autonomy is unknown for the Byzantine army but Furse (1901, 21) recommends the order of march is kept as much as possible. This means the arrival time in camp would be a more reliable indicator of how army size affects movement than distance travelled. Distance travelled will still be a useful value to measure as this affects the condition of the agents and the level of supplies they require.

4.7 DM002 – Resting on the March

4.7.1 Introduction

The main input into the design of DM002 will be the information contained within *The Art of Marching* (Furse 1901). It is clear that a constant march of largely uniform pace is unrealistic and creates a partially false dichotomy between having units crowd each other and ensuring they are adequately spaced out. For the concertina effect of delay and slow catch up to be modelled, breaks in marching of variable length must occur. Furse's suggestion of 5 - 10 minutes rest per hour is a useful starting point (1901, 202). The exact amount of rest can be modified by proximity to the unit in front. If there is a significant gap then 5 minutes rest can be taken rather than the 10 that is allowed if a unit is within an acceptable distance of the unit in front. This will allow gaps to be partially closed up.

As values including a maximum of 3 agents per cell and a march length of 21 miles are unlikely, it is suggested a series of scenarios are run as follows.

March distance (miles)	# of squads	Maximum agents per cell
6, 9, 12, 15	10, 100, 200	5, 10, 25

Table 26: Variables in DM002

The above scenarios were run twice, once with no resting (as in DM001) and once with rests of at least 5 minutes per hour, going up to 10 when available. The ABM will record how many ticks were spent resting for each agent, allowing us to have a crude measure of how “easy” the march was for agents in different parts of the column. We would expect the march to take longer but have a shorter column with these rests in place. With the elimination of the 3 agents per cell and 21 miles march distance the scenarios should run much quicker than those for DM001.

4.7.2 Work Required

In order to run the above scenarios, certain changes must be made to the model.

4.7.2.1 Fixing Order Problems from DM001

The DM001 scenarios highlighted a problem with ordering, Officers towards the rear of the column on particularly congested runs would receive the final order to move to their camping location before they had commenced their "follow" order and would plot a separate path from waypoint 1 rather than follow their preceder to waypoint 2. This had initially been sorted by allowing units to requeue messages that weren't ready to be processed. This method was unsatisfactory as it resulted in agents continually removing messages from and then adding them back into their message queues. In order to simplify this process and maintain consistency within the model, the message process was rewritten to use the same basic procedure as the action planning structure. Previously a message would be removed from the message queue and passed to the processMessage method. This method would have to reinsert the message back into the message queue if it had not been successfully processed. processMessage would not return a value so there was no explicit indication whether the message had successfully been dealt with. In DM002, when a message is received by an agent it takes a copy of it and tries to process it but only if it is processed successfully is it removed from the message queue. The processMessage method now returns a boolean value, if it returns the value 'false', the message is left where it is to be rechecked on the following tick.

4.7.2.2 New Time Handling Procedures

In order for an agent to determine when the rest periods are on the march it needs to have a way of determining the time of day. Officers need to know when they have been marching for 50 minutes in order to determine when the earliest point they can stop for a rest is, and also to know when the 55 minute point has been reached so they can rest even if not close enough to their preceding unit. This requires a complete remodelling of the `TimeHandling` class as it was initially constructed to split continuous time ticks into days, daylight hours and periods of darkness. To this end a new class has been created, `DMTimeHandling`, that will be able to classify each tick into 3 categories:

Marching tick

Optional rest tick

Mandatory rest tick

During marching ticks all agents will behave as in the previous DM001 model. During optional rest ticks, Officers will rest only if they are close enough to their preceding unit to not need to make up the distance between them. During mandatory rest ticks they will rest regardless of the gap between them and their preceding unit. The Emperor will always rest for 10 minutes per hour. This will require the `DMTimeHandling` class to be able to translate tick numbers into actual times of the day.

The length of a tick has been fixed at 3.72855 seconds. This is done to ensure agents move at 3mph. The start time of the day has been set at 06:11 and the end time at 19:27 which is 796 minutes long, giving 12,809 ticks per day. Each hour contains roughly 966 ticks which means the 50 minute mark comes at around tick 805 and the 55 minute mark at tick 886.

These rests will only happen if the units are on the main part of the march between waypoints

1 & 2, when exiting or entering camp no rests are taken as the troops should be fully rested or be just about to set up camp. In addition to all the values recorded in DM001, DM002 records the number of rest ticks for each `Officer` and the `ColumnLeader`. `Soldiers` do not rest as such, their flocking behaviour means they are never far from their `Officer` and will rest when they do. These scenarios will measure the effect of this method of resting on column length and arrival time. We will also be able to assess whether the effect increases or decreases in effectiveness as the numbers of agents increases.

4.7.2.3 Better Flocking

There had been a flocking problem introduced at a previous stage of the modelling process. This caused flocking soldiers to be slightly offset when following the line of march. This has been corrected for DM002 but is thought not to have introduced significant error into DM001.

4.7.2.4 Changes to the Initfile

A new boolean variable, *`REST`*, has been introduced to the initfile. Only when set to true will the army stop for rests.

Lines on some graphs are labelled with the length of march, the maximum numbers of agents per cell and whether agents rest every hour. '6 5 Yes' therefore refers to a scenario run over 6 miles with 5 agents per cell and resting turned on.

The following key (Figure 51) applies to all graphs in this document.

Figure 51: Key for the graphs of DM002

4.7.3 Results

PC	Length of march (miles)	# of squads	Max Agent Size per cell	Resting every hour?	Max column length (metres)	Average time to camp (ticks)	Processing time (minutes)	Tick# of maximum column length	Average distance travelled (metres)	Average rest ticks
LAP	6	10	5	Yes	619	2637	7	684	12148	246
LAP	9	10	5	Yes	755	3835	25	2728	17344	359
LAP	12	10	5	Yes	763	5135	19	4847	24408	489
LAP	15	10	5	Yes	1199	6457	42	6172	30222	657
LAP	6	100	5	Yes	4858	3119	63	1757	12259	152
CN24	9	100	5	Yes	4381	4370	67	3880	18153	233
CN22	12	100	5	Yes	4511	5662	82	5062	24827	339
CN23	15	100	5	Yes	4768	7007	95	6388	31176	470
CN25	6	200	5	Yes	8563	3682	73	2180	12298	142
CN25	9	200	5	Yes	7751	4810	134	3877	17899	225
CN22	12	200	5	Yes	8103	6153	161	1770	25052	340
CN25	15	200	5	Yes	8103	7474	172	1808	31184	451
HOME	6	10	10	Yes	594	2624	5	674	12026	253
CN24	9	10	10	Yes	500	3824	13	2730	16962	399
HOME	12	10	10	Yes	772	5097	11	4827	23937	557
CN22	15	10	10	Yes	732	6366	25	5793	29538	680
HOME	6	100	10	Yes	4818	3100	52	1758	12031	146
CN23	9	100	10	Yes	4216	4210	114	887	17180	226
HOME	12	100	10	Yes	4216	5543	124	884	24128	352
CN24	15	100	10	Yes	4216	6835	158	886	29955	442
CN24	6	200	10	Yes	8452	3639	81	2152	12078	142
CN22	9	200	10	Yes	7731	4680	219	1833	17262	216
CN24	12	200	10	Yes	8104	5974	243	1837	24074	332
CN23	15	200	10	Yes	8104	7244	318	1834	29942	428
HOME	6	10	25	Yes	555	2623	4	667	11987	263
CN22	9	10	25	Yes	472	3815	5	3810	16897	447
HOME	12	10	25	Yes	763	5095	8	4847	23815	591
CN22	15	10	25	Yes	732	6320	12	5793	29428	743
HOME	6	100	25	Yes	4846	3107	34	1750	12119	147
CN22	9	100	25	Yes	4216	4110	34	887	17149	231
HOME	12	100	25	Yes	4216	5402	42	886	23930	359
CN23	15	100	25	Yes	4216	6630	37	888	29673	466
CN25	6	200	25	Yes	8452	3632	58	2620	12184	141
CN24	9	200	25	Yes	7731	4544	70	1843	17098	211
CN22	12	200	25	Yes	8104	5790	68	1841	23926	322
CN23	15	200	25	Yes	8104	6992	74	1832	29633	426
LAP	6	10	5	No	591	2342	6	1242	12046	
LAP	9	10	5	No	1054	3439	13	3118	17302	
LAP	12	10	5	No	1195	4580	24	4280	24215	
LAP	15	10	5	No	1510	5672	35	5405	29913	
CN25	6	100	5	No	5265	2943	30	1685	12285	
CN25	9	100	5	No	5010	3995	75	3288	17737	
CN25	12	100	5	No	5484	5200	75	4400	24626	
CN25	15	100	5	No	5817	6325	83	5462	30707	
CN25	6	200	5	No	9544	3461	68	2082	12297	
CN24	9	200	5	No	8985	4555	127	2501	18063	
CN23	12	200	5	No	9274	5667	151	3622	24709	
CN22	15	200	5	No	9880	6836	153	4681	30848	
LAP	6	10	10	No	576	2333	7	1235	11963	
LAP	9	10	10	No	555	3363	22	2613	16899	
LAP	12	10	10	No	825	4530	38	4188	23883	
LAP	15	10	10	No	572	5546	20	5371	29429	
CN25	6	100	10	No	5611	2975	44	1709	12137	
CN24	9	100	10	No	4948	3973	154	3288	17178	
CN23	12	100	10	No	5030	5078	162	3622	23959	
CN22	15	100	10	No	5300	6185	218	4684	29720	
CN25	6	200	10	No	9807	3496	94	2144	12151	
CN24	9	200	10	No	9023	4442	240	2502	17192	
CN23	12	200	10	No	9259	5584	334	3620	23981	
CN22	15	200	10	No	9680	6723	554	4677	29951	
CN25	6	10	25	No	537	2333	3	1218	11963	
CN25	9	10	25	No	450	3350	5	2479	16892	
CN25	12	10	25	No	461	4467	7	3983	23839	
CN25	15	10	25	No	500	5536	11	5337	29434	
CN25	6	100	25	No	5467	2930	26	1709	11992	
CN24	9	100	25	No	4770	3858	31	2479	17152	
CN23	12	100	25	No	4735	4973	36	2748	23951	
CN22	15	100	25	No	4800	6042	38	3607	29684	
CN25	6	200	25	No	9897	3503	54	2164	12212	
CN24	9	200	25	No	8989	4336	68	2503	17187	
CN23	12	200	25	No	9280	5435	71	3621	23951	
CN22	15	200	25	No	9550	6536	73	4557	29863	

Table 27: Data from the DM002 scenarios

4.7.3.1 Processing Times

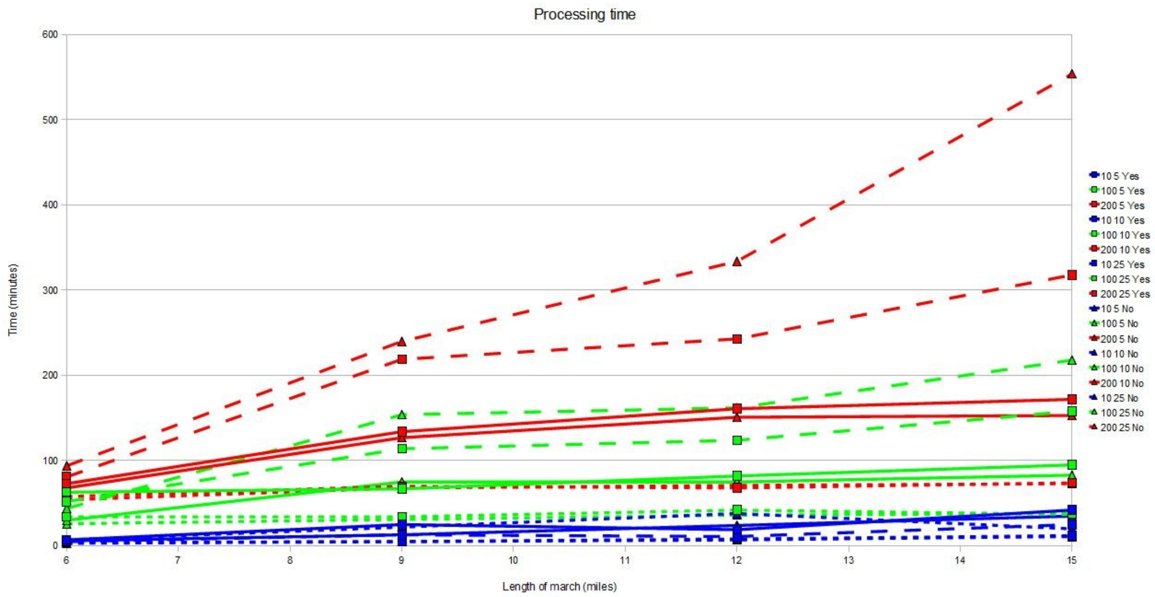


Figure 52: DM002 processing times

There seems to be no significant differences in processing time between scenarios where troops rest every hour and those where they don't (Figure 52). This is to be expected as the resting mechanism itself does nothing more than skip each agent's step method so that no processing is done. Obviously the scenarios tend to take longer the more agents there are. Interestingly, it seems that scenarios using 10 agents per cell tend to take longer than those with either 5 or 25 agents per cell. The relationship between processing time, hardware and software configuration and ABM parameters is not obvious from the scenarios run so far. A series of scenarios run specifically to investigate this would be a good investment of time, especially if it allows us to reduce the time of future experiments significantly.

4.7.3.2 Distance Travelled

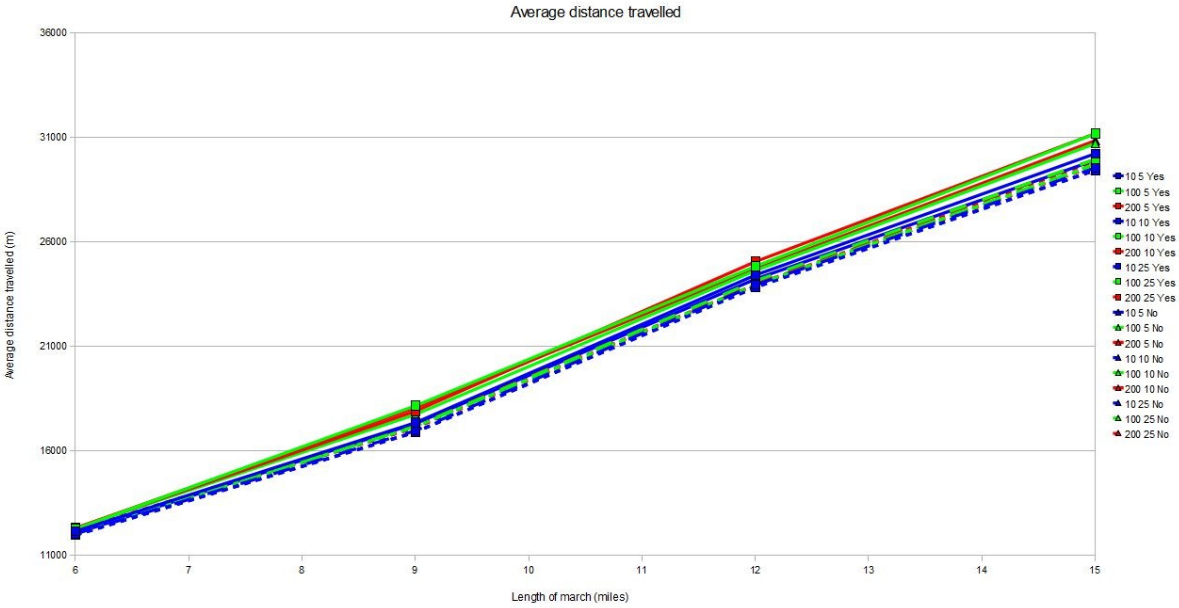


Figure 53: DM002 average distances travelled

Resting seems to have no significant effect on distance travelled.

4.7.3.3 Average Arrival Time in Camp

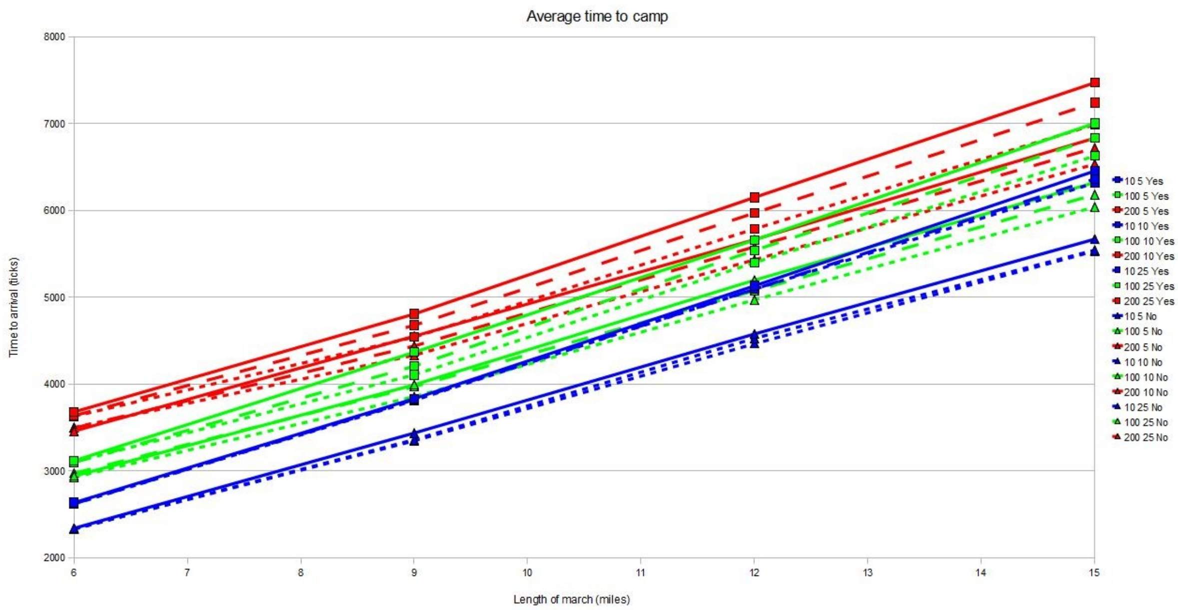


Figure 54: DM002 average arrival time at destination camp

As expected, the runs in which units rest every hour have the latest times of arrival (Figure 54). Resting also seems to slightly exacerbate the effects of crowding, with slightly more difference between runs with different values of agents per cell than their equivalents where resting does not take place. This is probably due to the bunching that occurs during the time between the 50 and 55 minute marks. This is the beginning of the concertina effect as units bunch up when coming to rest and take some time to get going again as they set off. If random rests to cope with equipment failure or unforeseen delays were to be introduced in a future model then it would be expected that this effect would increase even more.

4.7.3.4 Maximum Column Length

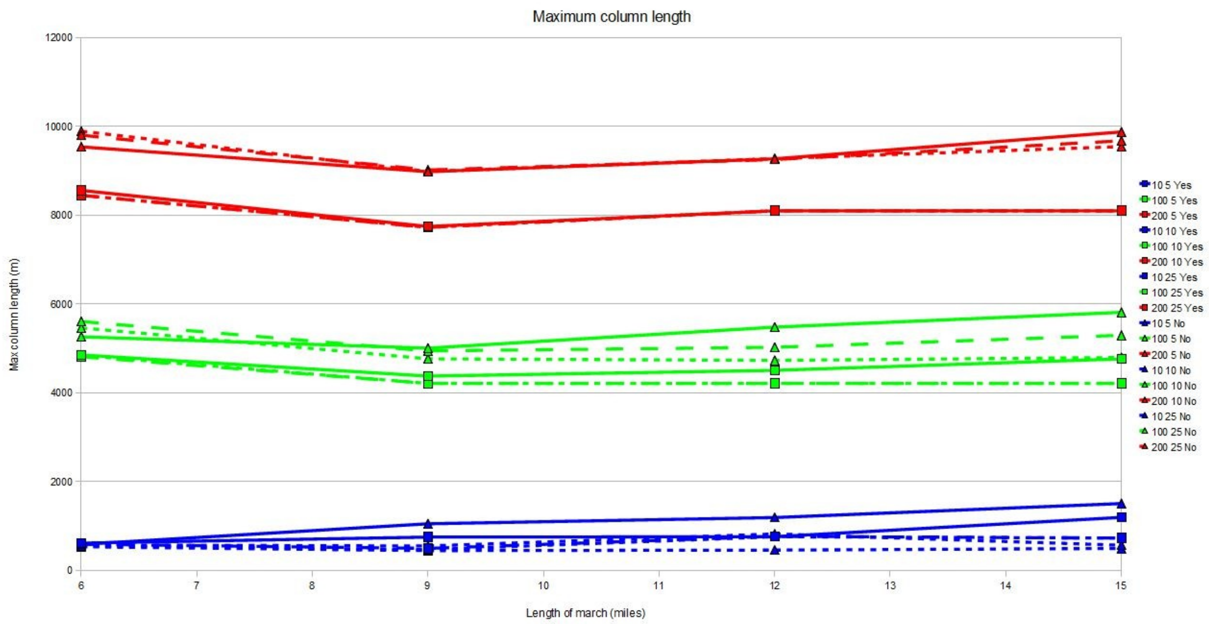


Figure 55: DM002 maximum column length

As can be seen (Figure 55), the effects of resting on maximum column length get more pronounced with increasing numbers of agents. With 10 squads, crowding is still the largest factor in maximum column length. With 100 squads, a mixture of crowding and the effects of resting can be seen. With 200 squads a clear gap can be seen between the maximum column length in scenarios with resting compared to those without.

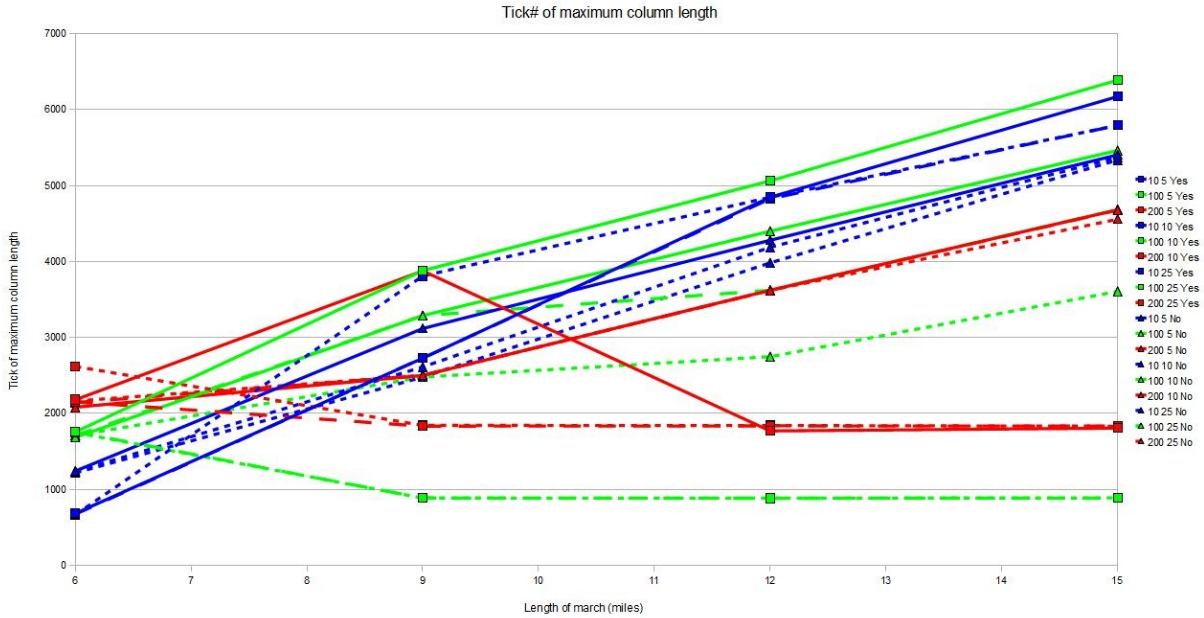


Figure 56: DM002 tick of maximum column length

When we look at the tick on which the maximum column length occurs we see that, in scenarios with 100 and 200 squads, the longer marches give more chance for the column to bunch up (Figure 56). In scenarios where no resting occurs the column gets longer the more the day's march goes on. When resting is introduced, 100 squad and 200 squad scenarios with 10 and 25 agents per cell show that the maximum column length occurs as the camp is broken. Once all squads are on the move resting ensures that the column bunches up. This pattern is complicated slightly by crowding as can be seen by the time it takes the 200 squad, 5 agents per cell results to stabilise and the fact that the 100 squad, 5 agents per cell run doesn't bunch up in the expected way.

4.7.3.5 Rest Ticks

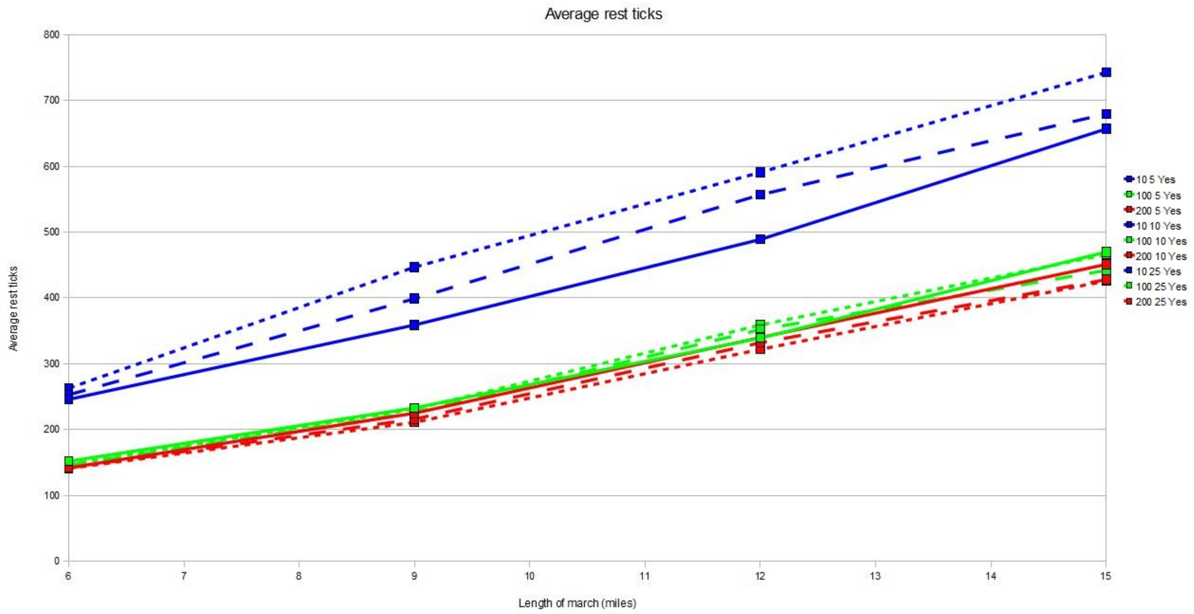


Figure 57: DM002 average rest ticks

As can be seen in Figure 57, and as expected, the average number of rest ticks increases with the length of march. The average number of rest ticks is higher in the 10 squad scenarios as the column is less spread out and therefore less catching up needs to be done.

4.7.4 DM002 Conclusions

Resting clearly helps with column length, as seen in the graphs. The effects are not inconsiderable (over 10% shorter column of march with 200 squads) and seem to increase with army size. Although the concepts behind this model were detailed in a 20th century military manual, they were implementable to the Byzantine army of the 11th century. Although time keeping may not have been precise, the use of trumpets or other loud musical instruments could be used to relay the signals for the start of each rest period down the army column. Some method of reducing the otherwise inevitable lengthening of the column would have been highly advantageous to the Byzantine army. As increasing speed to close the gap with the unit ahead was cautioned against by Wellington among others due to the way it quickly fatigues the soldiers, this seems the most likely mechanism for keeping the column relatively compact. That of course presumes the Byzantine army of Romanos IV Diogenes enacted any technique to reduce the length of the column, however the results of these scenarios indicate that it was at least highly beneficial.

Remaining concerns from this set of scenarios include the variable performance of the ABM and the practical limits regarding army size. With this in mind, the next couple of tests deal with these aspects. These tests were used to save time in the planning and execution of future tests.

4.8 DM003 - The Practical Limits of the Day's March Model

4.8.1 Introduction

Once a robust ABM had been created, a brief test was run to determine the upper practical limits of the system with regards to army size. To this end, a series of scenarios were run with minimal numbers of different parameters but a steadily increasing number of agents. These also include Blender pre-processing, construction of the Blender file and rendering of the results, along with processing of the dayfile with Java and Excel. The focus of this test is the processing times and file sizes and it also tests the practical limits of the ABM setup and reliability of the software.

A series of 8 scenarios were run on the cluster nodes. The first 4 each contained 2,000 squads and had slightly different parameters. The second 4 increased the number of squads from 3,000 to 4,500 in increments of 500. The processing time of the ABM was recorded, along with the time taken to process the tickfile for use in Blender, the time taken to build the Blender file and the size of the processed tickfile and completed Blender file.

4.8.2 Work Required

The ABM produces a tickfile which contains an entry for every agent on every tick of the simulation. Although Blender can process this file directly to produce a visualisation of the model's results, this produces a much larger file than needed as it creates IPO keyframes for every tick, even when the agent is not moving. In order to reduce processing times and Blender file sizes a pre-processing step was introduced where the raw tickfile can be used by a Java programme to create a tickfile with all ticks removed that involve an agent standing still. This processed tickfile is read into Blender via a Python script where the omission of stationary ticks results in the same output being produced with reduced processing time and file size.

4.8.3 Results

PC	March length (miles)	Number of Squads	Number of agents	Agents per cell	Resting?	Processing time (mins)	Blender PreProcessing time (mins)	Processed tickfile size (Mb)	Blender processing time	Blend file size (Mb)
CN22	6	2000	20667	5	Yes	1644	7	718	<48hrs	4700
CN23	6	2000	20667	5	No	2111	7	767	<48hrs	5000
CN24	6	2000	20667	25	Yes	1170	6	397	<48hrs	2600
CN25	6	2000	20667	25	No	1231	7	398	<48hrs	2600
CN22	9	3000	31000	25	No	4207	9	734		
CN23	9	3500	36166	25	Yes	6606	11	718	>7days	
CN24	9	4000	41333	25	Yes	8983	13	711	>6days	
CN25	12	4500	46499	25	Yes	13006	14	731		

Table 28: DM003 data from all scenarios

The data here is incomplete due to the excessive processing times within Blender.

4.8.3.1 Processing Times

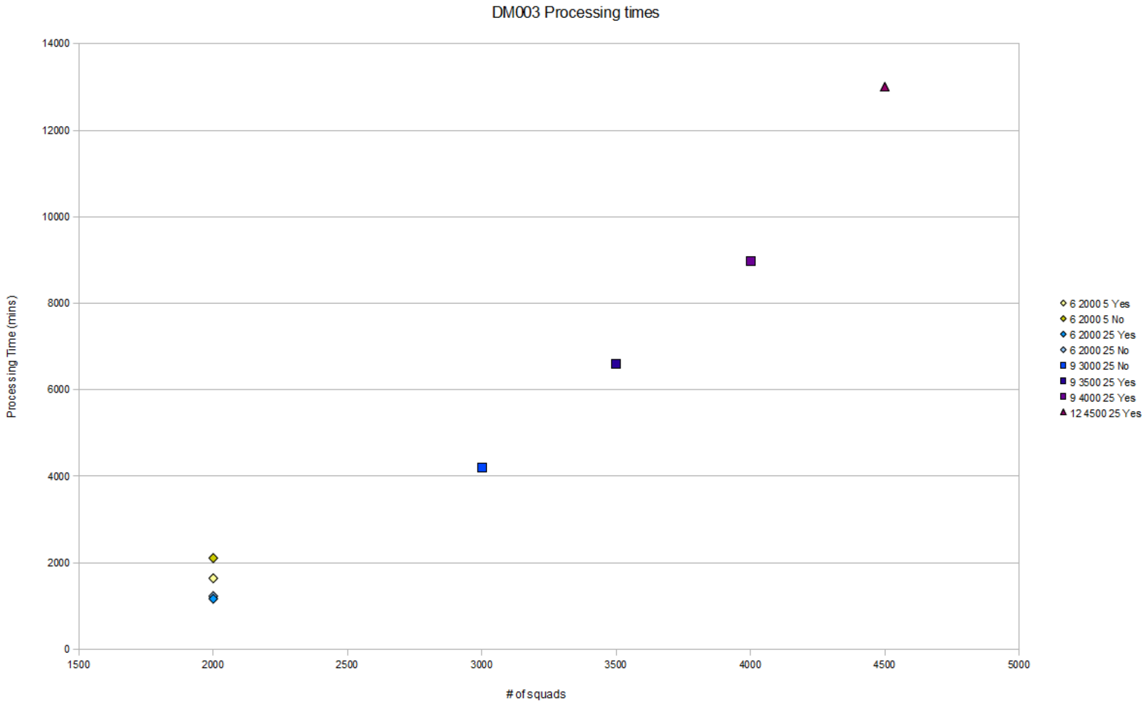


Figure 58: DM003 processing times

Each data point on the graph (Figure 58) is labelled with the number of miles marched, the number of squads, the number of agents per cell and whether resting occurred. As can be seen, the increase in processing time is not directly proportional to the number of squads. 4000 squads require over four times the amount of processing time as 2000 squads. Due to the high number of agents per cell allowed in most scenarios, crowding can be excluded as a factor in this increase. This leaves system constraints as the most likely source, the ABM being unable to keep all required data in memory at the same time.

4.8.4 DM003 Conclusions

As can be seen, certain parts of the whole procedure scale up well and certain parts were at this point unable to process the numbers of agents required by the model in a timely manner. The size of the initial tickfile produced by the ABM (not recorded in this test but running at around 1Gb per 300 squads) and the Blender pre-processing time both scale up in a linear fashion, however neither of these aspects need cause any problems to our workflow.

The processing of the tickfile results in an interesting pattern regarding the increase in model size. As the number of squads increases so does the crowding in the model. More agents spend their time standing still instead of moving, reducing the size of the processed tickfile. The end result is that, whatever the size of the model, the processed tickfile never exceeds 800Mb. Even if the number of squads is increased, the amount of movement allowed by the model remains the same.

The two bottlenecks in the workflow at this point were the running time of the ABM and the time needed for Blender processing. In a model where the required maximum number of agents is around 100,000 the sharp rise in processing time beyond 20,000 agents is worrying. The main area of concern is in debugging the model. A runtime of a week or two is not necessarily useless but only as long as the results are valid. Requiring this to be run 4 or 5 times in order to remove bugs and produce a functional result will obviously be a problem and past experience indicates that movement models that function perfectly well for small numbers of agents do not necessarily work for larger numbers.

It is possible that improvements can be made to the model's efficiency in order to reduce the processing time of larger numbers of agents. Faster hardware will also obviously improve processing times. This will be discussed in the report of DM004.

4.9 DM004 - Effects of Environment Variables on ABM performance

4.9.1 Introduction

The Day's March 004 scenarios were designed to further investigate the relationship between environment variables, hardware and ABM processing times.

4.9.2 Brief Overview

DM002 demonstrated that the relationship between ABM parameters and processing time was not a simple one. Certain scenarios ran much faster than other, similar scenarios. In this set of scenarios a restricted number of ABM setups was run with different environment settings on different machines. Different machines were used to determine whether hardware or environment variables had a significant impact on processing times.

4.9.3 Results

				6-100-10-false			12-100-25-false	6-10-10-false
				OLD	UNI	CN22	CN22	CN23
Scenario number	X parts	Y parts	List size	Processing time (mins)	Processing time (mins)	Processing time (mins)	Processing time (mins)	Processing time (mins)
1	100	100	100	115	75	40	35	4
2	100	100	500	104	75	41	34	5
3	100	100	1000	115	78	49	35	4
4	100	100	2000	99	74	46	33	5
5	100	100	5000	104	76	44	35	4
6	100	100	10000	104	79	40	35	6
7	1830	852	4	109	76	41	33	4
8	1830	852	2	106	69	41	32	4
9	3660	1704	1	112	83	42	35	5
10	3660	1704	4	106	76	46	35	4
11	50	50	100	101	75	47	36	5
12	50	50	1000	101	79	42	35	4
13	50	50	10000	110	76	44	36	5

Table 29: DM004 data from all scenarios

4.9.3.1 Processing Times

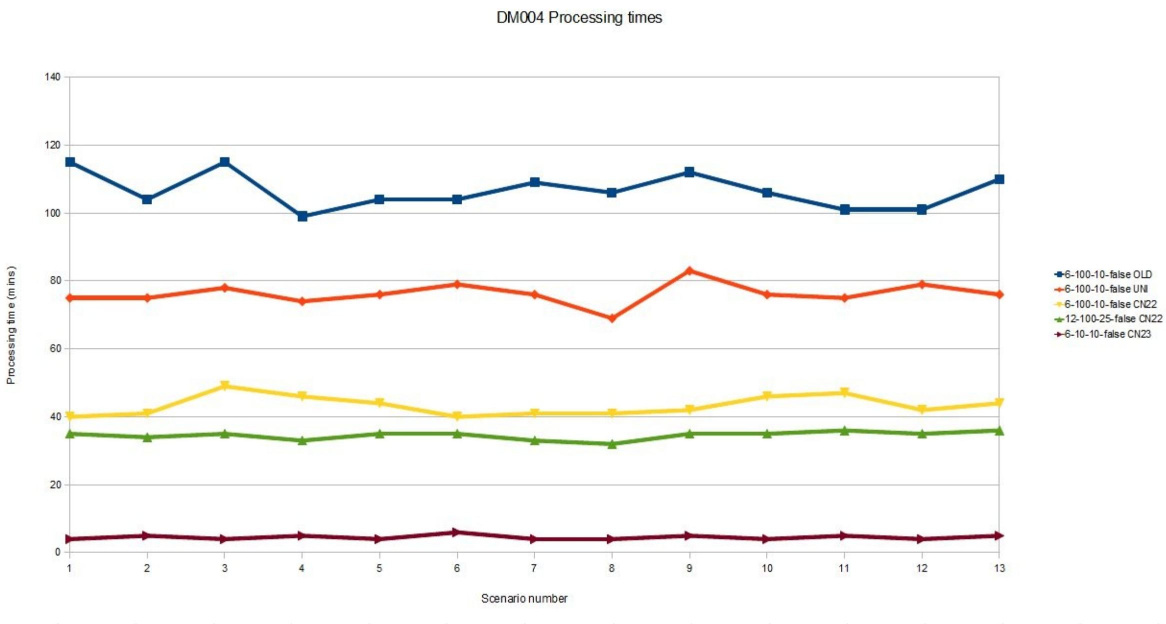


Figure 59: DM004 processing times

As can be seen from the graph (Figure 59), there seems to be no clear correlation between environment setup and processing time across all scenarios. Environment parameters that seem to improve processing times in certain circumstances do not have the same effect in others. The only clear conclusion is that hardware and crowding have more effect than environment settings. Crowding even has more effect than distance travelled as evidenced by the scenarios run over 12 miles with 25 agents per cell all taking less time than any run on the same machine over 6 miles but with 10 agents per cell. This means that crowding involves procedures that are either slow or inefficient. DM002 tells us that the difference is not caused by crowding ensuring a longer journey time.

4.9.4 DM004 Conclusions

Environment parameters, although having an effect on processing time, do not cause an effect that is either predictable enough to mitigate or significant enough to warrant further investigation. Hardware and crowding have a far greater effect on processing times. Subsequent testing on other VISTA centre PCs indicated that no available computers were able to significantly improve on these results.

4.10 DM005 – Cavalry

4.10.1 Introduction

The Byzantine army on the Manzikert campaign consisted of a mix of cavalry and infantry. *The Art of Marching* makes it clear that these forces move differently to each other in pace, organisation and physical needs. In order to simulate this our model needs to be able to move agents of different sizes, speeds and modes of movement. In the previous Day's March scenarios the agents have been homogeneous in all three areas. The ability to simulate both cavalry and infantry will allow the examination of how the two interact on the march and determine the kinds of organisational structures that are required to be able to move the whole army efficiently.

4.10.2 Work Required

In order to run the above scenarios the following certain changes were made to the model.

4.10.2.1 Agent Size

Infantry and cavalry take up different amounts of space. In order to reflect this, the model needed to move away from the existing system of a set number of agents per cell and instead have a number representing the maximum total size of agents within a cell with each agent having its own size. *The Art of Marching* suggests that each cavalry soldier should be allowed 5 sq.m. (Furse 1901, 193). This slightly contrasts with Pryor's (2006, 7) work on estimating the length of Bohemund's forces during the march across the Balkans to Constantinople during the first crusade. He assigns a length of 2.5m for each horse and presumes there would need to be 2.5m of space at the rear of each horse to ensure that in the event of a trip or fall subsequent horses aren't affected. This fits nicely into our 5m x 5m environment cells but his estimate of the width required by each horse assumes 2 horsemen riding abreast on a road 3m wide. As the work of Furse is based on actual experience on the march I have used Furse's figures. This equates to 20% of a 5m x 5m environment cell. No figure is given for a single infantryman but if we assume a value of a little over $1m^2$ then we can give a maximum total agent size per cell of 20, with cavalry having a size of 4 and infantry having a size of 1. This allows 5 cavalry or 20 infantry per cell or any suitable mixture of the two. The changes involved with this were problematic as the existing system assumed a size of 1 per agent, allowing any agent to move to a cell with a total agent size of 19 in it regardless of whether it was infantry or cavalry.

4.10.2.2 Agent Speed

The existing movement system assumed a steady agent speed of 3mph which would result in an orthogonally moving agent moving at 1 cell per 3.729 second tick. Changing this to allow the faster movement required by cavalry meant choosing one of two technical solutions. The first would be to keep the one move per tick maximum move by decreasing the amount of time represented by each tick. This would be simpler from a programming perspective but increase the number of ticks required to represent a day's march. The second option would be to allow an agent to process multiple actions per tick. This would require rewriting the step method of the HumanAgent Java class but would maintain the size of the output tickfiles. As tickfile size and post-processing times were already considerable when dealing with large models (see DM004) it was decided to take the second option. This also had the benefit of being able to improve the design of a method that had become unwieldy and confusing as modifications had been added.

From this point each Move action has a cost equal to the distance moved, with each agent being able to process as many moved as required depending on the speed it was travelling at. Infantry still travel at 3mph and therefore are able to move 5m per tick. Cavalry speed is variable.

In *The Art of Marching* (Furse 1901, 195) it is suggested that cavalry spend part of their time walking and part of their time trotting. Walking speed is 4mph and trotting speed is described as either 6-7mph or 8 mph (192, 193). It is also recommended that cavalry occasionally spend time out of the saddle leading their horses (195). The speed at which this occurs has been set at 2.5mph as this is the maximum speed given for wagons. As the speeds given for cavalry on the trot vary between 6-8mph we have chosen the middle value of 7mph. The agent's speed in miles per hour needs to be converted into metres per tick, the measurement used within the ABM (Table 30).

Agent Type	Speed (mph)	Speed (m/tick)
Infantry	3	5
Cavalry – Leading horses	2.5	4.16
Cavalry - Walking	4	6.66
Cavalry - Trotting	7	11.66

Table 30: Agent speed

Different cavalry speeds also require a method of determining which speed an agent should move at in any given tick. To do this, a system was developed whereby a cyclical rota could be set where, over a period of a certain number of minutes the cavalry would spend a certain amount of time walking, a certain amount trotting and a certain amount leading their horses. This operates independently of the cycle of marching and resting as implemented in DM002. This rota only applies once the agent has moved out of the previous day's camp. In these scenarios a 60 minute rota is set with the cavalry trotting for 30 minutes, walking for 20 then being led for the last 10 (Figure 60). This last 10 minutes overlaps the optional rest period so some cavalry such as the Column Leader may never end up leading their horse depending on how strung out the column is. This rota only applies during once the cavalry have exited the camp, they move at the trot until then.

Figure 60: Amount of each hour cavalry spend at each speed

4.10.2.3 Army Organisation

The current army organisational hierarchy is based on each officer having no more than four subordinates and will need to be replaced with a more flexible alternative. When examining the relationship between army composition and speed we will need to compare armies with different ratios of cavalry to infantry. The model setup process must be able to create armies with any number of officers, cavalry and infantry. These should be able to be organised in any manner. Actual army organisation is unimportant to the model because, for the purposes of movement, the army consists of a series of units who only need to know which unit precedes them in the column.

4.10.2.4 *Camp Setup*

The previous method of determining camping location resulted in multiple units camping in the same location, in addition to giving the whole camp a diamond-shaped plan (Figure 61). There was also a disconnect between the order of march and the camping locations, meaning that there were often large gaps between units that were supposed to be following each other on the march. A new camp setup was designed that more closely emulated the plans described in military treatises, ensured units were camped near their preceding unit and that no units occupied the same space. This necessitated a change in the initialisation procedures and the way that the component parts of the army are specified.

The units in the army are split into five categories for the purposes of the initialisation file.

Column Leader – This agent was previously called the Emperor but has been renamed due to it more accurately representing whichever agent is at the front of the army. This also will make more sense in future when the ability to split the army into different columns is added.

Officer – This is a cavalry agent representing a General or other official that has no subordinate troops. They camp in the centre area of the camp with the *`ColumnLeader`*

Officer Cavalry Squad – This is a cavalry squad consisting of a *`CavalryOfficer`* and 4 *`CavalrySoldiers`*. These also camp in the centre of the camp and represent the Emperor's household troops.

Cavalry Squad – These are regular cavalry squads consisting of a *`CavalryOfficer`* and 4 *`CavalrySoldiers`*. They camp in the outer areas of the camp and always precede the Infantry.

Infantry Squads – These consist of an Infantry *`Officer`* and 9 Infantry *`Soldiers`*. They camp in the outer areas of the camp and always march at the rear of the army.

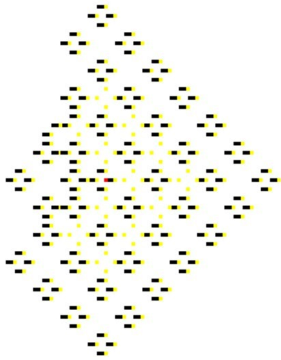


Figure 61: Old camp layout, 200 squads

As can be seen from the illustrations (Figure 61, Figure 62, both of which are at the same scale), the new camp is much more orderly, compact and faithful to the Byzantine military treatises.

Figure 62: New camp layout, 200 squads

The number of squads of each of these categories (except the `ColumnLeader`, at the moment only 1 of these is allowed) can be specified in the initialisation file, as can the number of soldiers in each unit. The area taken up by the central sector is equal to the area needed to accommodate the units contained within or the area required for one of the outside sectors, whichever is the larger. This prevents the sectors overlapping. The initialisation file specifies the gap round the central sector, set to 5 cells in these scenarios. This simulates the road running round the central area as described in military treatises (Dennis 1985). As there is commonly a choke point outside the camp as the units form up for the main part of the march, it is necessary to introduce delays between units setting off in order to avoid overcrowding. The initialisation file specifies the gap between individual units setting off, the gap between camp sectors (to simulate the gap between army corps) and an intermediate level where a medium sized gap is inserted between each group of units, the size of which is also specified in the initialisation file. For DM005, the gap between each unit was set at 2 cells, the gap between each sector at 50 cells and an intermediate gap of 10 cells was set every 10 units.

4.10.2.1 Weather

As there is at this point no system for determining energy usage, the only function of the weather system is to determine when the temperature is too hot to march and impose an enforced rest on agents until the temperature has cooled. This takes the form of a cutoff temperature, set in the initialisation file. The temperature changes every hour, depending on the date and which of the three temperature settings is chosen. Data will be chosen to represent an average temperature over the course of a day, with options for either hotter or cooler than average temperatures. For the purposes of this set of scenarios only one set of temperatures have been used, those for April 15th 2010 at Ankara as retrieved from Weather Underground (www.wunderground.com). These are given in Table 26.

Time of day	Tick Number	Temperature (°C)
06:11	1	3
07:00	788	2
08:00	1753	5
09:00	2718	8
10:00	3683	11
11:00	4648	13
12:00	5613	15
13:00	6578	16
14:00	7543	17
15:00	8508	17
16:00	9473	17
17:00	10438	17
18:00	11403	16
19:00	12368	16
19:27	12809	16

Table 31: Temperatures, times and tick numbers

The cutoff temperature was set to 17°C, meaning the agents would not march between 14:00 and 18:00 (ticks 7543 – 11403) in scenarios where the weather is set to affect resting.

The same data will be recorded as that in DM002. In addition, graphs will be produced showing the arrival times of individual units for each scenario.

4.10.3 Results

PC	Distance	Resting	Weather breaks	Officers	Officer Cav Squads	Cav Squads	Inf Squads	Average time to camp (ticks)	Processing time (minutes)	Average distance travelled (metres)	Average rest ticks
CN22	6	Yes	Yes	10	10	0	180	2847	70	11971	113
CN23	6	Yes	Yes	10	10	45	135	2569	56	11931	108
CN24	6	Yes	Yes	10	10	90	90	2253	53	11962	107
CN25	6	Yes	Yes	10	10	135	45	1903	58	11935	102
LAP	6	Yes	Yes	10	10	180	0	1468	39	12098	74
CN22	6	Yes	No	10	10	0	180	2827	68	12000	116
CN23	6	Yes	No	10	10	45	135	2561	38	11988	110
CN24	6	Yes	No	10	10	90	90	2251	58	11936	102
CN25	6	Yes	No	10	10	135	45	1917	60	11995	102
LAP	6	Yes	No	10	10	180	0	1488	38	12137	79
LAP	6	No	Yes	10	10	0	180	2712	48	11921	
CN23	6	No	Yes	10	10	45	135	2494	42	12053	
CN24	6	No	Yes	10	10	90	90	2200	58	11886	
CN25	6	No	Yes	10	10	135	45	1826	53	11928	
CN22	6	No	Yes	10	10	180	0	1443	49	12141	
CN22	6	No	No	10	10	0	180	2687	67	11884	
CN23	6	No	No	10	10	45	135	2430	53	11797	
CN24	6	No	No	10	10	90	90	2183	55	11955	
CN25	6	No	No	10	10	135	45	1826	54	11932	
LAP	6	No	No	10	10	180	0	1439	70	12137	
CN23	12	Yes	Yes	10	10	0	180	4988	99	23754	271
CN23	12	Yes	Yes	10	10	45	135	4594	168	23803	250
CN23	12	Yes	Yes	10	10	90	90	4146	89	23847	231
CN23	12	Yes	Yes	10	10	135	45	3590	88	24093	207
CN23	12	Yes	Yes	10	10	180	0	2831	84	24439	186
CN24	12	Yes	No	10	10	0	180	4987	99	23799	271
CN24	12	Yes	No	10	10	45	135	4587	178	23645	253
CN24	12	Yes	No	10	10	90	90	4150	91	23837	226
CN24	12	Yes	No	10	10	135	45	3596	97	24079	208
CN25	12	Yes	No	10	10	180	0	2834	82	24343	185
CN25	12	No	Yes	10	10	0	180	4682	144	23647	
CN25	12	No	Yes	10	10	45	135	4332	207	23763	
CN25	12	No	Yes	10	10	90	90	3916	92	23754	
CN25	12	No	Yes	10	10	135	45	3391	93	23948	
CN25	12	No	Yes	10	10	180	0	2662	85	24262	
CN22	12	No	No	10	10	0	180	4693	112	23655	
CN22	12	No	No	10	10	45	135	4329	184	23758	
CN22	12	No	No	10	10	90	90	3912	91	23768	
CN22	12	No	No	10	10	135	45	3386	97	23931	
CN23	12	No	No	10	10	180	0	2665	83	24256	

Table 32: DM005 data from all scenarios

4.10.3.1 Processing Times

For some reason the 12 mile experiments with 45 cavalry squads and 135 infantry squads required more processing time than any others. There is no obvious reason for this but it echoes similar situations in DM002 that were unable to be cleared up by the work done in DM003.

4.10.3.2 Distance Travelled and Average Rest Ticks

As the percentage of cavalry increases the average distance travelled also increases and the average number of rest ticks decreases. This is due to the increased amount of crowding encountered in models with more cavalry. Even taking into account the smaller size of cavalry units, 4 cavalry soldiers per squad compared with 9 infantry soldiers, the cavalry squad takes up more space and results in more crowding, necessitating more movement in order to avoid cells with no space.

4.10.3.3 Individual Arrival Time in Camp

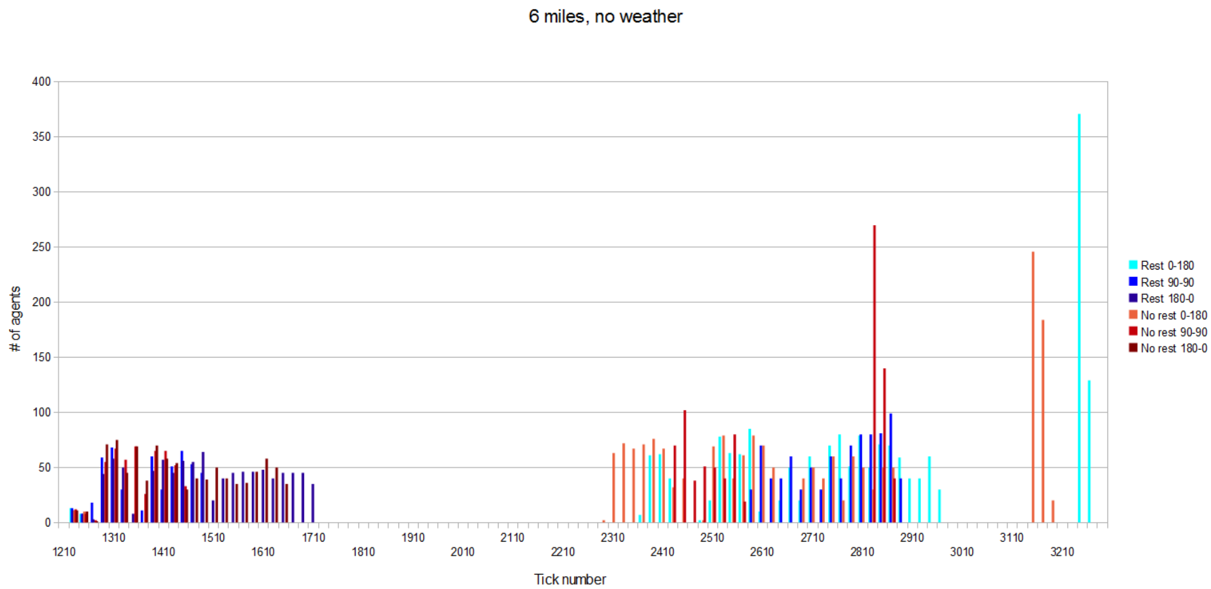


Figure 63: DM005 arrival time in camp, 6 miles, no weather

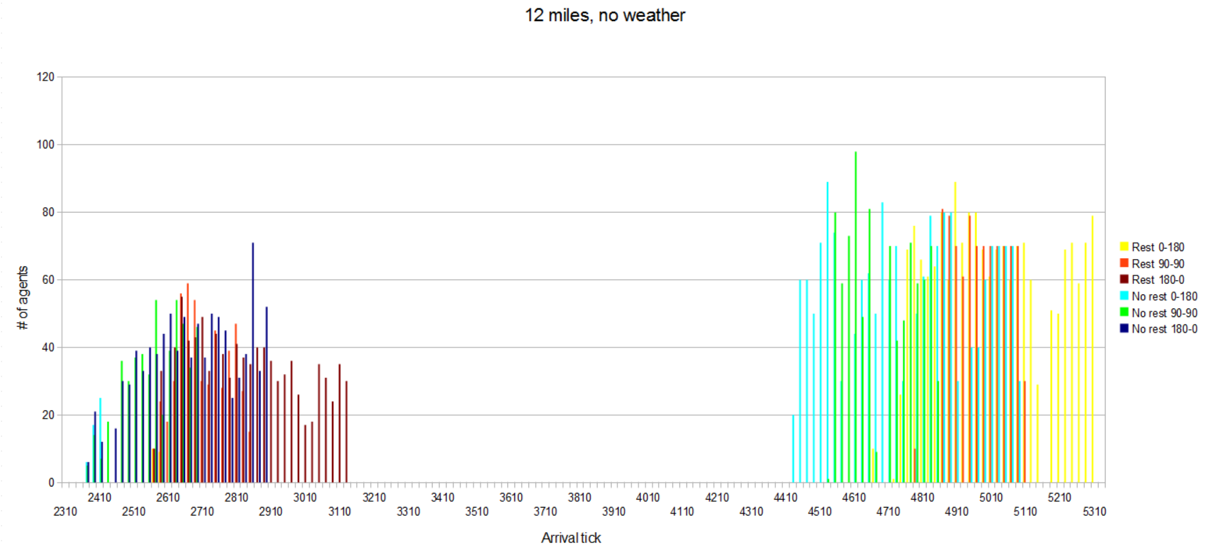


Figure 64: DM005 arrival time in camp, 12 miles, no weather

The gap between the earlier and later units is a result of the faster movement of the cavalry. As can be seen the infantry lag quite some way behind, even over 6 miles. If this is a reflection of the actual situation on the march then there will definitely have to have been some mechanism for indicating the correct route, either via "military police" stationed at locations where routes diverge or via signs as mentioned in *The Art of* Marching (Furse 1901, 357).

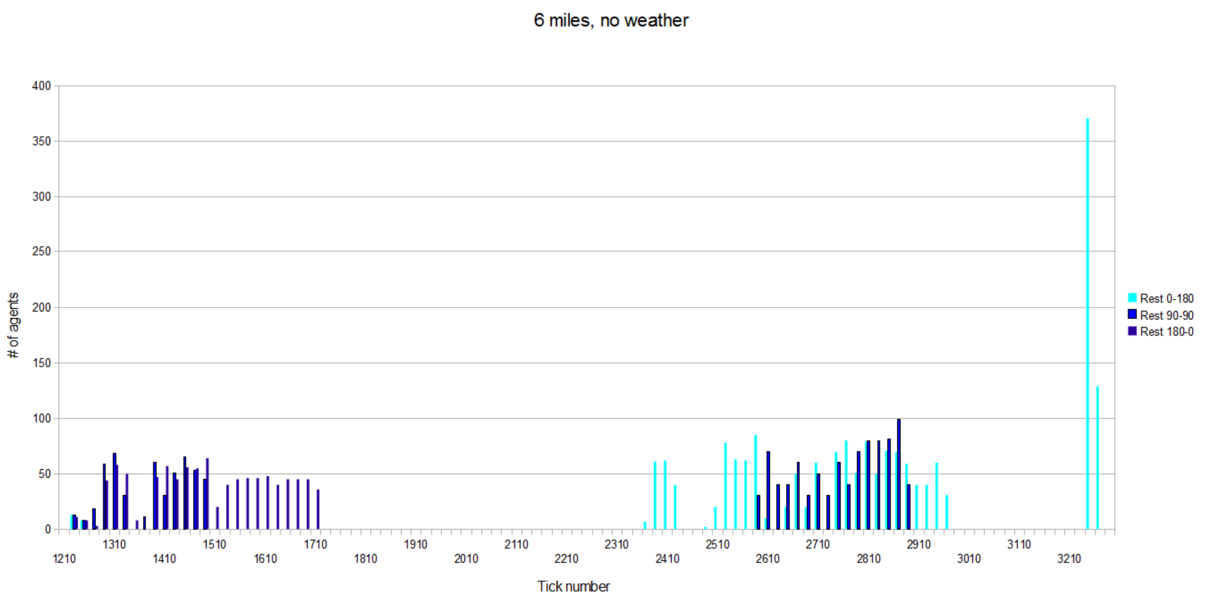


Figure 65: DM005 arrival time in camp, 6 miles, no weather, rest only

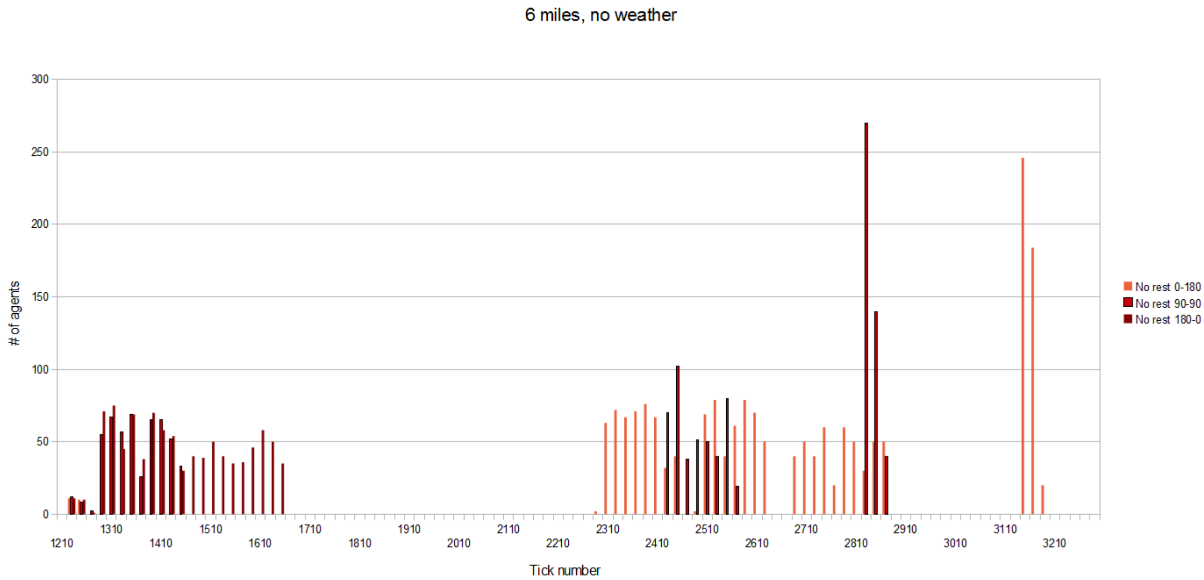


Figure 66: DM005 arrival time in camp, 6 miles, no weather, no rest only

Over 6 miles if resting is set on, the arrival of agents, particularly infantry, is less spread out. As can be seen from the graphs, with resting on there is a peak of over 400 agents in a single 20 tick slot but no others over 100, whereas there are 5 between 100 and 275 with no resting.

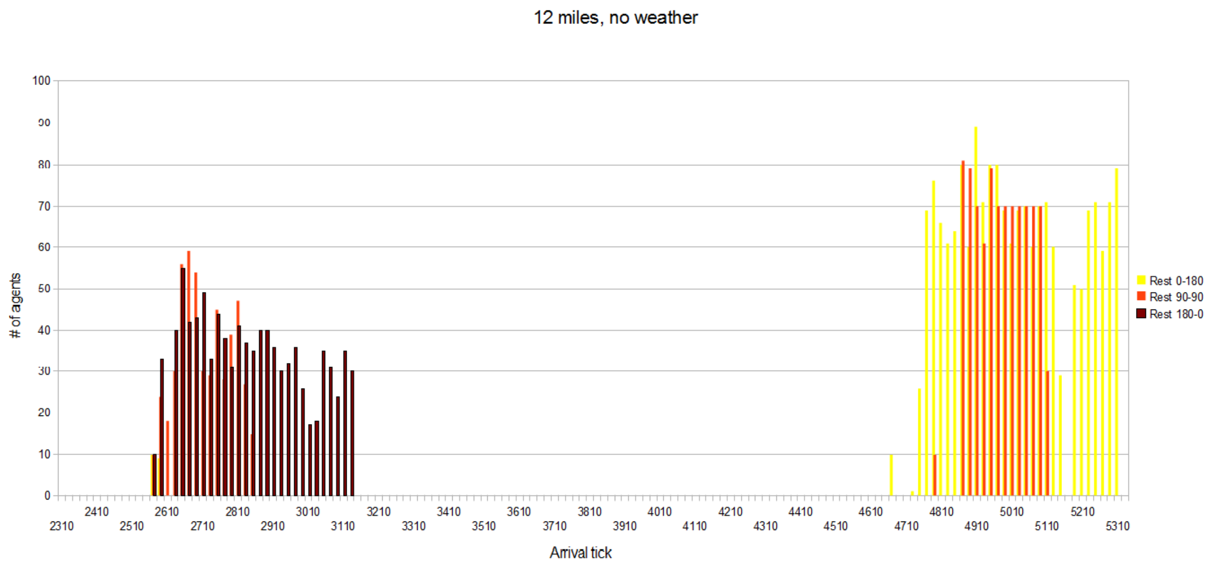


Figure 67: DM005 arrival time in camp, 12 miles, no weather, rest only

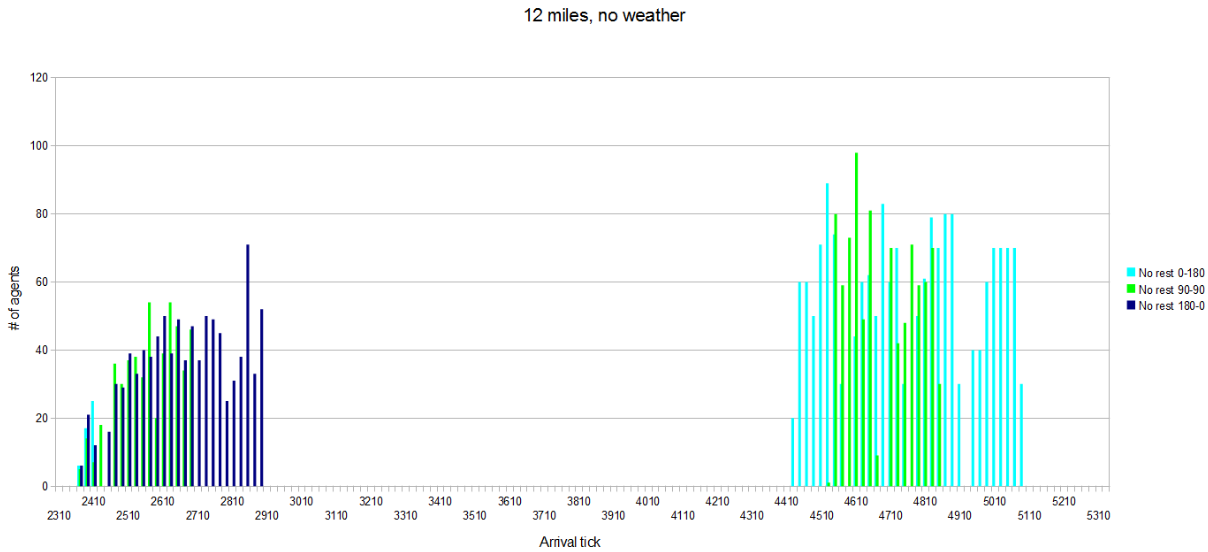


Figure 68: DM005 arrival time in camp, 12 miles, no weather, no rest only

Over 12 miles this pattern is less noticeable, however the delay in arrival caused by resting is more clearly seen.

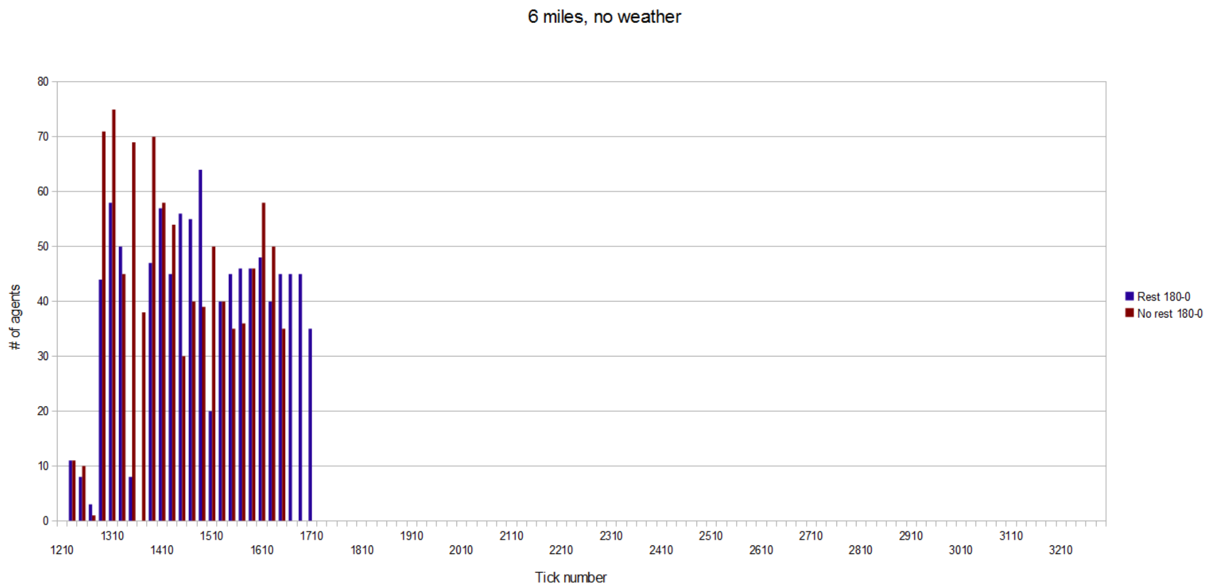


Figure 69: DM005 arrival time in camp, 6 miles, no weather, 180-0 only

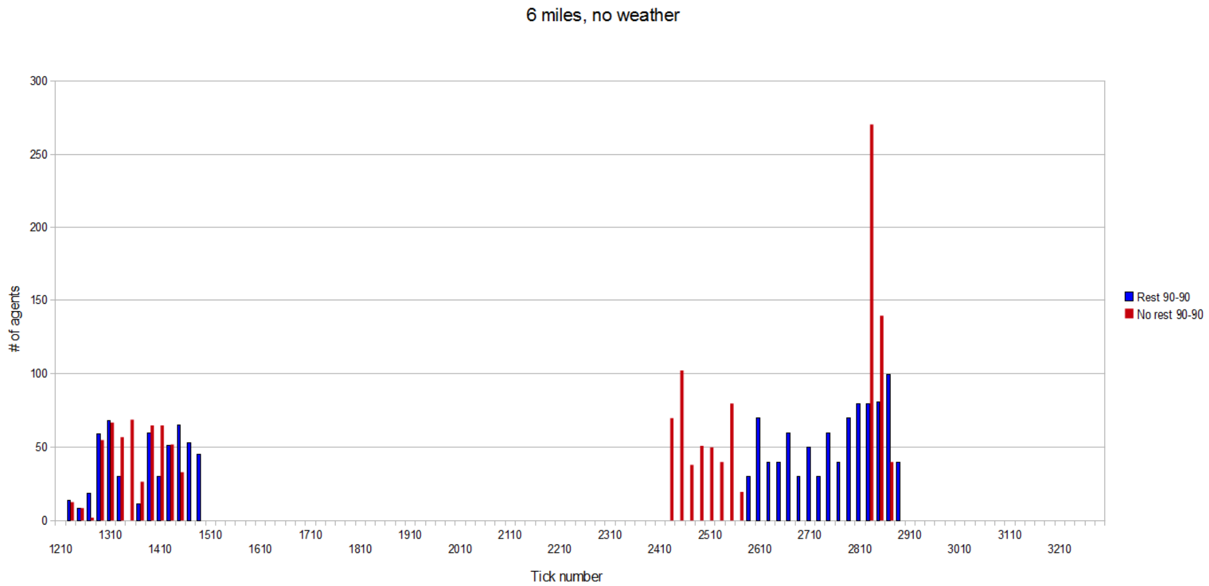


Figure 70: DM005 arrival time in camp, 6 miles, no weather, 90-90 only

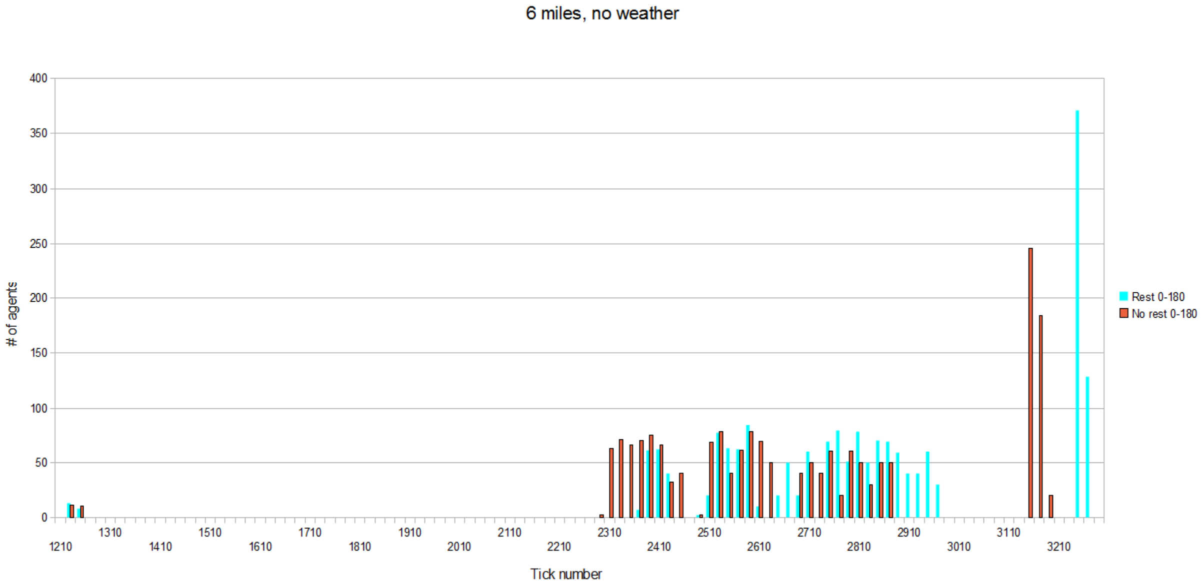


Figure 71: DM005 arrival time in camp, 6 miles, no weather, 0-180 only

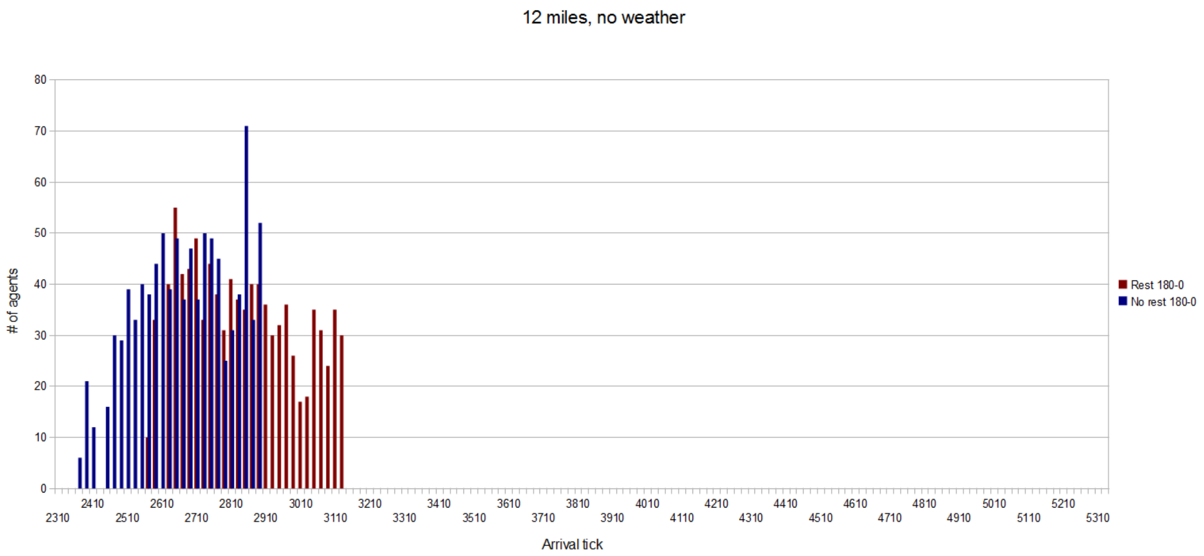


Figure 72: DM005 arrival time in camp, 12 miles, no weather, 180-0 only

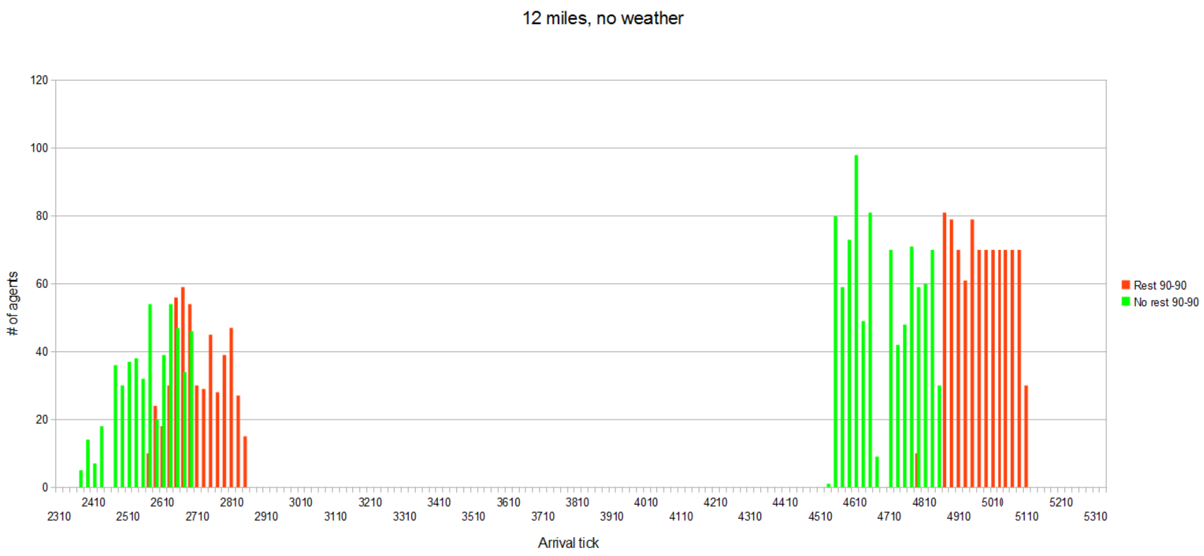


Figure 73: DM005 arrival time in camp, 12 miles, no weather, 90-90 only

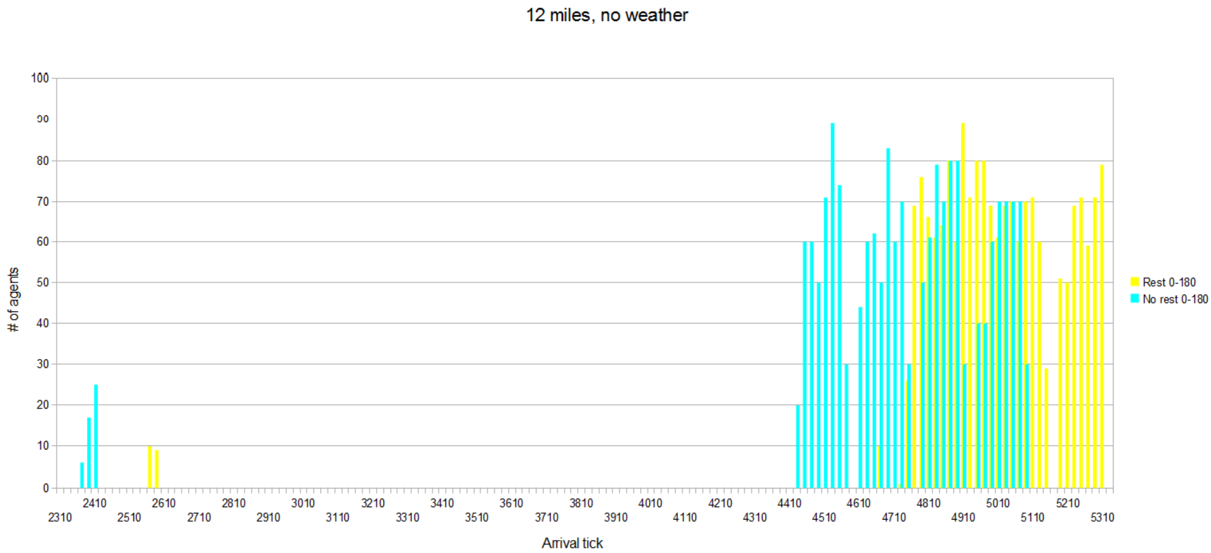


Figure 74: DM005 arrival time in camp, 12 miles, no weather, 0-180 only

4.10.4 DM005 Conclusions

In many ways the DM005 scenarios have provided little useful data. The end result however is a model with more functionality and the same robust nature as that used in previous tests. Although the model has been run here with less than 2000 agents, it scales up with no functional problems. As the speed of the agents and the time of day are all translatable to real world units and the shape of the camp and organisation of the army's movement are more in line with the information provided in the military treatises we can now use the ABM to investigate real world scenarios.

4.11 DM006 – The Limits of a Single Column

4.11.1 Introduction

Having grounded the ABM in real world measurements and ensured there is a plausible movement model, the model can be used to determine at what point the limits of single column marching can be reached. It is clear from *The Art of Marching* that the benefits of marching an army over multiple routes were well known to military planners. Using the plausible movement speed, organisation and behaviours of the agents we can determine at what point the last agent arriving at camp gets there too late. “Too late” is of course dependent on a variety of variables. Although we can calculate the amount of daylight on any particular day at any point in Anatolia, the total amount of daylight is not necessarily the total amount of march time. The Art of Marching makes clear the ideal situation, that soldiers should have enough sleep and then enough time both before and after a march to feed themselves and their animals and take care of their equipment. Nevertheless, for these experiments the maximum time has remained at that of the previous Day's March scenarios, 12809 ticks representing 13 hours and 16 minutes.

All scenarios were run over either 6 or 12 miles with a variety of numbers of agents from 5301 to 30901. Several aspects were varied for the DM006 scenarios.

4.11.1.1 Army Composition

Initial scenarios were run with all cavalry forces, all infantry (except the central camp sector's troops representing the Emperor's household), and with cavalry as 20%, 25% and 30% of the main force.

4.11.1.2 Setting Off Delays

Most scenarios were run with gaps between units setting off of 3, 9 and 483 ticks as described above. 4 scenarios were run with gaps of 1, 1 and 10 respectively to investigate the effects of these gaps compared to a situation with virtually no delays between units setting off.

4.11.1.3 Cavalry Speed

In most scenarios the cavalry speed varied with cavalry units alternating between trotting, walking and leading their horses. 8 scenarios were run in which cavalry units always travelled at the trot.

4.11.1.4 March Spacing

In most scenarios, unit leader's attempt to leave a gap of 2 cells (10m) between themselves and the leader of the unit in front. As infantry squads take up less room than cavalry squads it is possible to reduce this gap to 1 cell (5m) for infantry units. This was done in 4 scenarios.

4.11.2 Work Required

4.11.2.1 Setting Off

In DM005 each unit waited until the preceding unit was closer to the first waypoint by a set distance before setting off itself. This served to stagger the setting off of the units in order to avoid crowding outside the camp. In reality this is an unrealistic way of handling the initial movement of units. In DM006 a unit sets off a set number of ticks after its preceding unit. There are 3 different delays able to be set, as in DM005. Each of the 5 sectors of the camp have a delay between the setting off of the last unit and the setting off of the first unit of the next sector. Each unit itself will have a much smaller gap between it and the unit ahead. In between there is an intermediate gap that is inserted every X units where X is a number assigned in the initialisation file. For DM006, each unit sets off 3 ticks after the preceding unit, a delay of around 10 seconds. The first unit of each of the 4 sectors following the central sector will wait 483 ticks after the last unit of the preceding sector has set off, a delay of 30 minutes. In between these there is a gap of 9 ticks every 10 units, a gap of about a minute.

4.11.3 Results

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	S1	S2	S3	Cavalry Speed	Infantry March Spacing	Agents	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average rest ticks
CN22	6	100	100	2000	0	3	9	483	Variable	2	10601	11320			17:54	1014	6804	6683	12080	76
CN23	6	50	50	1000	0	3	9	483	Variable	2	5301	7337			13:46	418	4680	4605	11833	76
CN24	6	150	150	3000	0	3	9	483	Variable	2	15901		12668	2654		1543	7590	7459	12114	76
CN25	6	200	200	4000	0	3	9	483	Variable	2	21201		13122	2785		1913	7839	7728	11804	75
CN22	6	100	100	500	1500	3	9	483	Variable	2	18101	12293			18:55	836	8131	7329	12162	99
CN23	6	50	50	250	750	3	9	483	Variable	2	9051	8224			14:42	523	5750	5207	11728	92
CN24	6	150	150	750	2250	3	9	483	Variable	2	27151		19402	2526		3577	8648	7698	11715	97
CN25	6	100	100	0	2000	3	9	483	Variable	2	20601	12226			18:50	1607	7756	7426	11874	101
CN22	6	50	50	0	1000	3	9	483	Variable	2	10301	8177			14:39	593	5617	5377	11737	97
CN23	6	150	150	0	3000	3	9	483	Variable	2	30901		22902	2501		5740	8256	7780	12224	102
CN25	6	100	100	400	1600	3	9	483	Variable	2	18601	12314			18:56	1418	8082	7382	12073	96
CN22	6	50	50	200	800	3	9	483	Variable	2	9301	8235			14:42	535	5800	5322	12072	97
CN22	6	150	150	600	2400	3	9	483	Variable	2	27901		19982	2509		3873	8627	7732	12144	101
CN24	6	100	100	600	1400	3	9	483	Variable	2	17601	12272			18:53	1351	8130	7259	11941	98
CN22	6	50	50	300	700	3	9	483	Variable	2	8801	8212			14:41	521	5822	5224	12149	96
CN24	6	150	150	900	2100	3	9	483	Variable	2	26401		18513	2512		3425	8676	7638	12032	95
CN22	12	50	50	250	750	3	9	483	Variable	2	9051	10599			17:09	644	7939	7206	23965	229
CN25	12	100	100	500	1500	3	9	483	Variable	2	18101		13512	1742		1575	9088	8065	24010	230
CN24	12	50	50	200	800	3	9	483	Variable	2	9301	10569			17:07	655	7988	7337	24003	234
CN23	12	100	100	400	1600	3	9	483	Variable	2	18601		14061	1746		1540	9116	8170	23871	235
CN22	12	50	50	300	700	3	9	483	Variable	2	8801	10665			17:13	654	7911	7138	24001	224
CN24	12	100	100	600	1400	3	9	483	Variable	2	17601		13002	1741		1577	9052	8007	23976	220
CN25	6	50	50	250	750	1	1	10	Variable	2	9051									
CN23	6	100	100	500	1500	1	1	10	Variable	2	18101									
CN24	12	50	50	250	750	1	1	10	Variable	2	9051	8414			14:53	715	6396	5901	27627	412
CN22	12	100	100	500	1500	1	1	10	Variable	2	18101									
CN24	6	50	50	250	750	3	9	483	11.66	2	9051	8184			14:39	521	5711	5096	11932	96
CN21	6	100	100	500	1500	3	9	483	11.66	2	18101	12257			18:52	1464	8015	7165	11822	91
CN22	6	50	50	1000	0	3	9	483	11.66	2	5301	6819			13:14	454	4260	4181	11903	75
CN24	6	100	100	2000	0	3	9	483	11.66	2	10601	10771			17:20	1181	6363	6249	11945	74
CN21	12	50	50	250	750	3	9	483	11.66	2	9051	10572			17:08	634	7832	7076	23773	215
CN21	12	100	100	500	1500	3	9	483	11.66	2	18101		13521	1742		1656	8917	7807	23791	203
CN22	12	50	50	1000	0	3	9	483	11.66	2	5301	7834			14:17	605	5267	5152	23799	110
CN24	12	100	100	2000	0	3	9	483	11.66	2	10601	11808			18:24	1229	7370	7191	23890	110
CN21	6	50	50	250	750	3	9	483	Variable	1	9051	8343			14:49	529	5799	5245	12077	94
CN22	6	100	100	500	1500	3	9	483	Variable	1	18101	12235			18:51	1347	8102	7310	12022	94
CN23	12	50	50	250	750	3	9	483	Variable	1	9051	10558			17:07	652	7933	7205	23804	224
CN24	12	100	100	500	1500	3	9	483	Variable	1	18101		13551			1711	9083	8058	23931	228

Table 33: DM006 scenario data

Comparing different scenarios is made more complicated due to the difference in squad size between cavalry and infantry. Cavalry squads consist of an `CavalryOfficer` and four `CavalrySoldiers` whereas infantry squads contain an `Officer` and nine `Soldiers`. This is partly practical as the increased space taken up by cavalry mean that squads with similar numbers of men would need different flocking parameters for cavalry and infantry. The fact that 100 squads of infantry will consist of twice as many agents as the same number of squads of cavalry means that another way of comparing arrival times rather than just the average of all agents was needed. For this reason the average arrival time of officers only was added. As flocking rules are quite tight this can be taken as an average arrival time of each squad. This compensates for the increased numbers of agents in infantry squads.

4.11.3.1 Army Composition

Excluding the scenarios dealing with the two extremes of all cavalry and all infantry, it is clear that the maxim of an army marching as quickly as the speed of its slowest element appears to be true on a macro scale. Over the course of a day the final arrival time of a force where 25% of the squads of the main army is comprised of cavalry differs very little from forces composed of 20% or 30% cavalry.

% of squads of main force are cavalry	Last arrival tick	Last arrival time	Average Officer arrival time
20	12314	18:56	7382
25	12293	18:55	7329
30	12272	18:53	7259

Table 34: Last arrivals in a force of 2000 squads over 6 miles

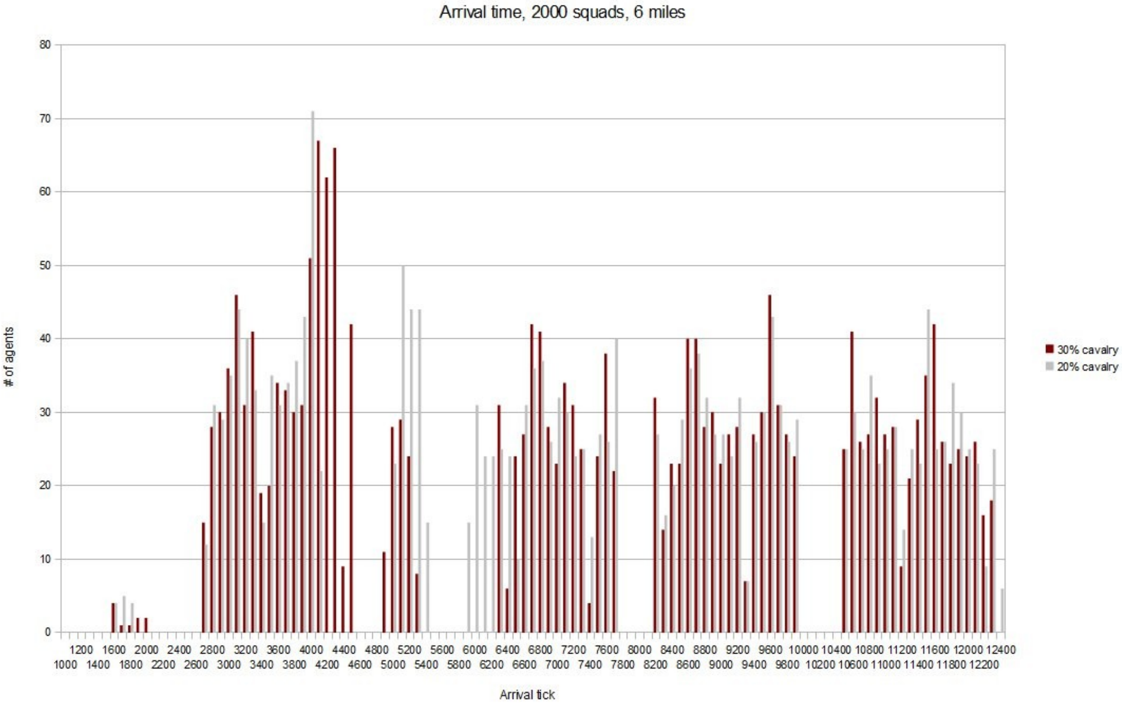


Figure 75: Officer arrival time with 20% cavalry vs 30% cavalry

As the number of squads is the same and the setting off delay between each squad is the same in each scenario the only difference will be due to the speed difference between cavalry and infantry and will determine how many squads arrive earlier and how many arrive later. This is illustrated in Figure 75.

4.11.3.2 Setting Off Delays

As part of DM006 some scenarios have been run with reasonable sounding delays between each unit setting off and some with hardly any. The ones with hardly any delay result in massive crowding and consequently take quite a while to run, one having been left running for over three weeks before being cancelled. This is a quick comparison between the one scenario that finished compared to the one that's otherwise identical but with a more staggered start.

As part of the regular DM006 scenarios, each unit waits for 3 ticks (10 seconds) after its preceding unit sets out of camp before it sets out itself. Every 10 units this delay is increased to 9 ticks (30 seconds) to indicate a slightly longer gap between larger organisations of units. Between each of the 5 sectors of the camp there is a gap of 483 ticks (30 minutes), representing the gap between the largest organisation of units. This results in an orderly withdrawal from camp with plenty of space for the delays and holdups expected in an actual army column. By way of comparison some scenarios were started where the gap between units setting off was 1 tick, except between the 5 sectors where it was 10 ticks. The results are below.

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	S1	S2	S3	Cavalry Speed	Agents	Time of Last Arrival	Last Agent to arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average rest ticks
CN22	12	50	50	250	750	3	9	483	Variable	9051	10599		17:09	644	7939	7206	23965	229
CN24	12	50	50	250	750	1	1	10	Variable	9051	8414		14:53	715	6396	5901	27627	412

Table 35: DM006 setting off delays

As can be seen, the scenario with the larger gaps between units arrives later, both on average and when comparing the last unit to arrive. Looking at the arrival times of the individual agents we can see a significant difference, even the crowding that resulted is not enough to stop the agents arriving earlier when there are much smaller gaps between units setting off (red bars = larger gaps).

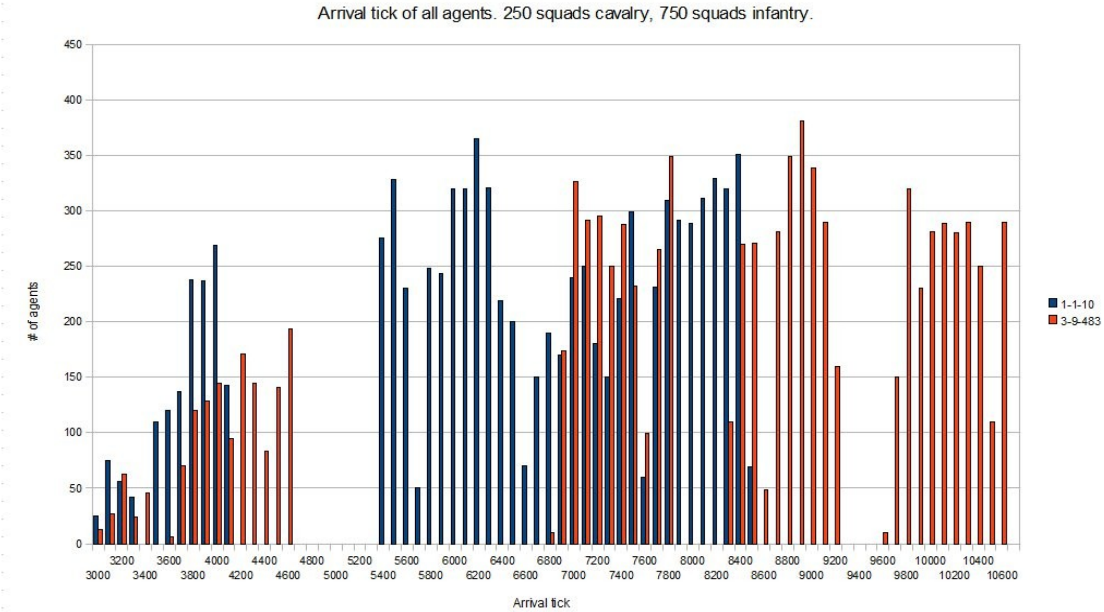


Figure 76: DM006 arrival tick of all agents, different setting off delays

The down side to setting off with smaller gaps between the units can be seen in both the average distance travelled and the average rest ticks. The units are actually on the road for longer in scenarios with smaller gaps between units. Crowding makes them cover more ground and, as they're on the road for longer they accumulate more rest ticks, the 5-10 minutes in every hour's marching that they spend resting. So reducing the gap between units setting out does mean they arrive at the following camp earlier, but results in a longer day on the march and more ground covered. That's all time that could be better spend having a leisurely breakfast, as George Armand Furse is keen to point out in *The Art of Marching*.

It is clear from the DM006 scenarios though that once the setting off delays reach the level where they drastically reduce crowding, particularly just outside the starting camp, then any extra is for the purposes of the model superfluous and add to the average arrival time in a fairly linear way. The difference between the model and the real world is that ensuring the army's column was punctuated by gaps did not just work to avoid crowding but also to cope with any unexpected delays, something not modelled in DM006.

4.11.3.3 Cavalry Speed

As part of the DM006 scenarios, the movement speed of cavalry is determined by a rota whereby they spend a certain amount of every hour moving at the trot, a certain amount at the walk and a certain amount out of the saddle leading their horses. In order to investigate the effects that movement speed has on the speed of the army as a whole some scenarios have been run in which the cavalry spend all their time moving at the trot. The agents still spend 5-10 minutes every hour resting in each set of scenarios.

4.11.4 Data

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	S1	S2	S3	Cavalry Speed	Agents	Time of Last Arrival	Last Agent to arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average rest ticks
CN24	6	50	50	250	750	3	9	483	11.66	9051	8184		14:39	521	5711	5096	11932	96
CN21	6	100	100	500	1500	3	9	483	11.66	18101	12257		18:52	1464	8015	7165	11822	91
CN22	6	50	50	1000	0	3	9	483	11.66	5301	6819		13:14	454	4260	4181	11903	75
CN24	6	100	100	2000	0	3	9	483	11.66	10601	10771		17:20	1181	6363	6249	11945	74
CN21	12	50	50	250	750	3	9	483	11.66	9051	10572		17:08	634	7832	7076	23773	215
CN21	12	100	100	500	1500	3	9	483	11.66	18101		13521		1656	8917	7807	23791	203
CN22	12	50	50	1000	0	3	9	483	11.66	5301	7834		14:17	605	5267	5152	23799	110
CN24	12	100	100	2000	0	3	9	483	11.66	10601	11808		18:24	1229	7370	7191	23890	110
CN23	6	50	50	250	750	3	9	483	Variable	9051	8224		14:42	523	5750	5207	11728	92
CN22	6	100	100	500	1500	3	9	483	Variable	18101	12293		18:55	836	8131	7329	12162	99
CN23	6	50	50	1000	0	3	9	483	Variable	5301	7337		13:46	418	4680	4605	11833	76
CN22	6	100	100	2000	0	3	9	483	Variable	10601	11320		17:54	1014	6804	6683	12080	76
CN22	12	50	50	250	750	3	9	483	Variable	9051	10599		17:09	644	7939	7206	23965	229
CN25	12	100	100	500	1500	3	9	483	Variable	18101		13512		1575	9088	8065	24010	230

Table 36: DM006 total scenario data

4.11.4.1 The Effects of Increased Cavalry Speed in Cavalry-Only Forces

Increasing the speed of cavalry agents in a cavalry-only force has the expected effect on both the average and last arrival time of the agents. Over 6 miles, a force of 5301 cavalry agents will arrive on average about 420 ticks before agents moving at variable speed. The last agent arrives 518 ticks earlier, just over half an hour. The average arrival time improves by about 10% even though the average speed increases by much more than this as some of the time is spent resting and some is spent waiting to set off.

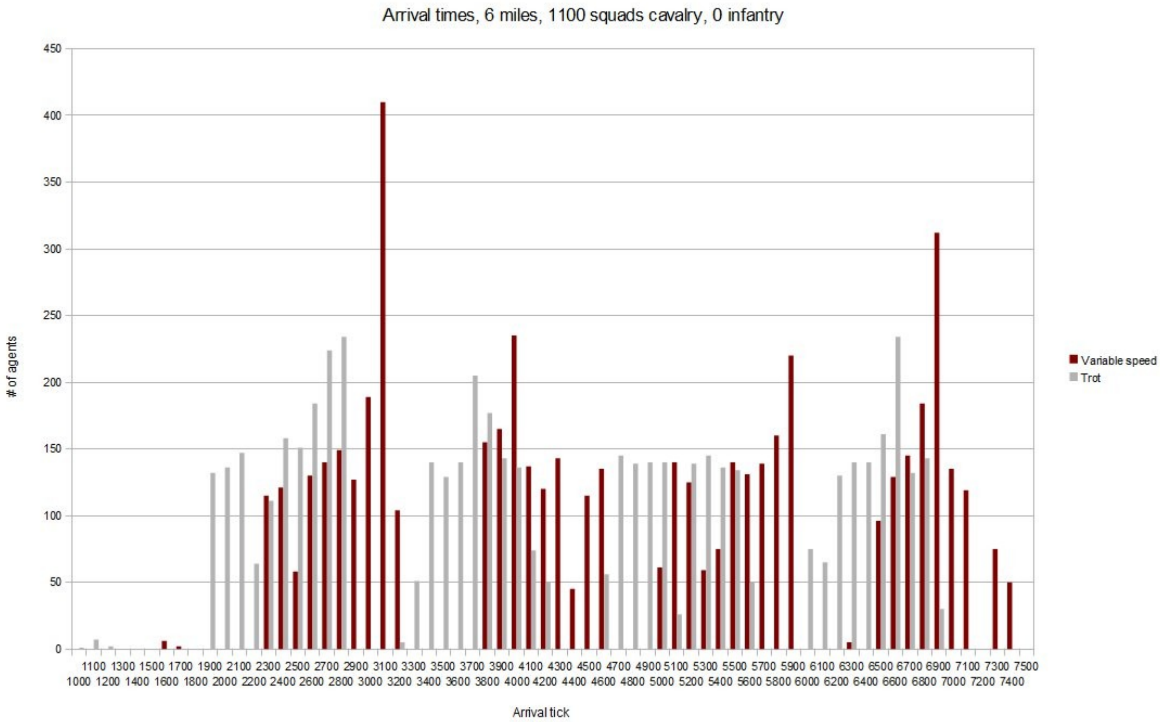


Figure 77: DM006 effects of increased speed on cavalry-only forces

As we can see from the arrival graph, the pattern is much the same, just shifted to the left when all agents move at the trot all the time. Negative factors that may result from increased speed such as increased chance of injury and increased energy expenditure are not modelled in this scenario.

4.11.5 The Effects of Increased Cavalry Speed in Mixed Forces

Less immediately obvious is the difference in movement that increased cavalry speed makes on forces combining cavalry and infantry. As the cavalry lead the column and the time that units set off is dependant on the setting off time of the preceding unit and not the progress made, the arrival of the infantry units is substantially unchanged by the speed of the cavalry.

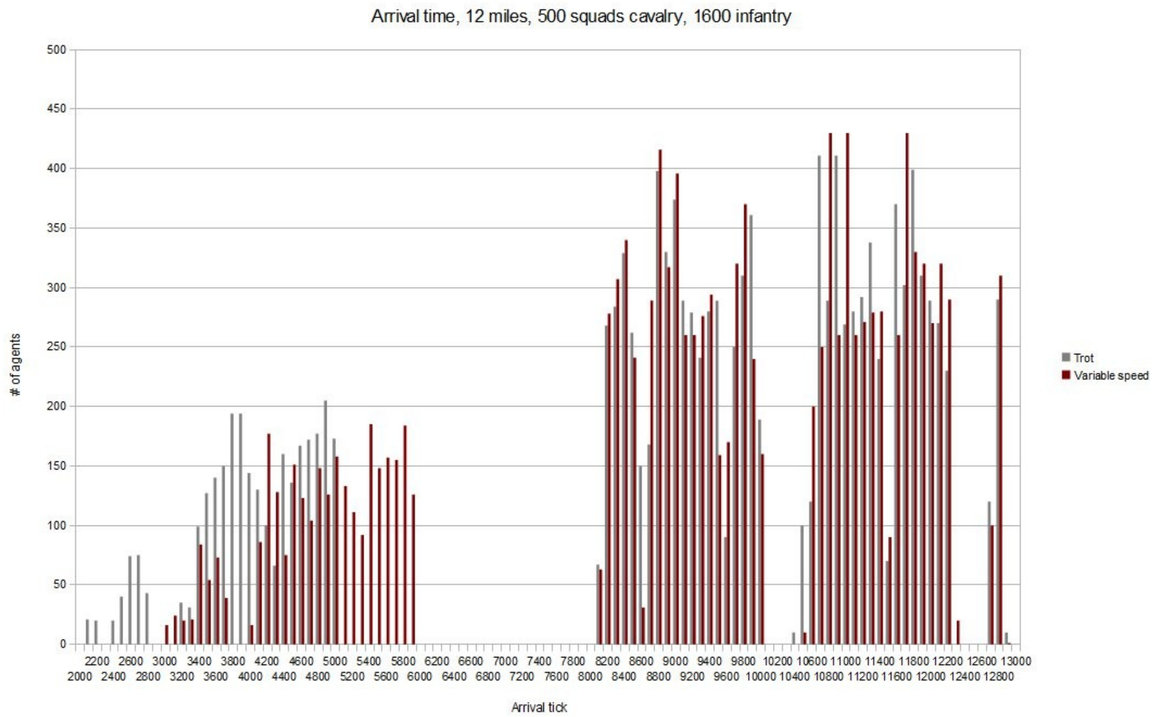


Figure 78: DM006 effects of cavalry speed in mixed forces

As before, the cavalry arrive earlier but the infantry arrive at pretty much the same time. In terms of overall army movement speed no benefit is gained. The increased gap between the cavalry and infantry may allow more time for problems in the cavalry part of the army to be sorted out before the infantry are held up but the increased speed will probably result in a higher chance of delays due to horse or rider injury. The only net gain is that the cavalry spend more time resting at the destination. This has to be factored against the fatiguing effects of moving constantly at the trot as mentioned in *The Art of Marching*.

By way of summary, it's said that an army moves at the speed of its slowest element. This is true at the macro scale but as far as individual agents in a mixed force are concerned, as long as the order of march is properly organised an army marches at a variety of speeds. The speed of the foremost elements, providing they are faster than those at the rear, is probably dictated more by comfort the desired speed of the army as a whole.

4.11.5.1 *March Spacing*

The parameter that specifies the distance between `Officer`s on the march is referred to as march spacing. On the main part of the march where each unit is merely following the one on front, each officer checks whether the distance between himself and the preceding `Officer` exceeds the march spacing value. If it does, the `Officer` moves towards the preceding `Officer` until he is within the march spacing value (subject to speed constraints, obviously). In all scenarios prior to DM006 the march spacing value has been set to 2, corresponding to 10m. This is a reasonable value where cavalry is concerned as a cavalry squad will usually be spread over 2 cells. Infantry however can comfortably fit in 1 cell and so some scenarios were run in which infantry used a value of 1 for march spacing, ensuring each infantry `Officer` attempts to stay 5m from the preceding `Officer`. The differences caused by this change were not obvious from the tabulated data so arrival time graphs were produced (figures 79 & 80).

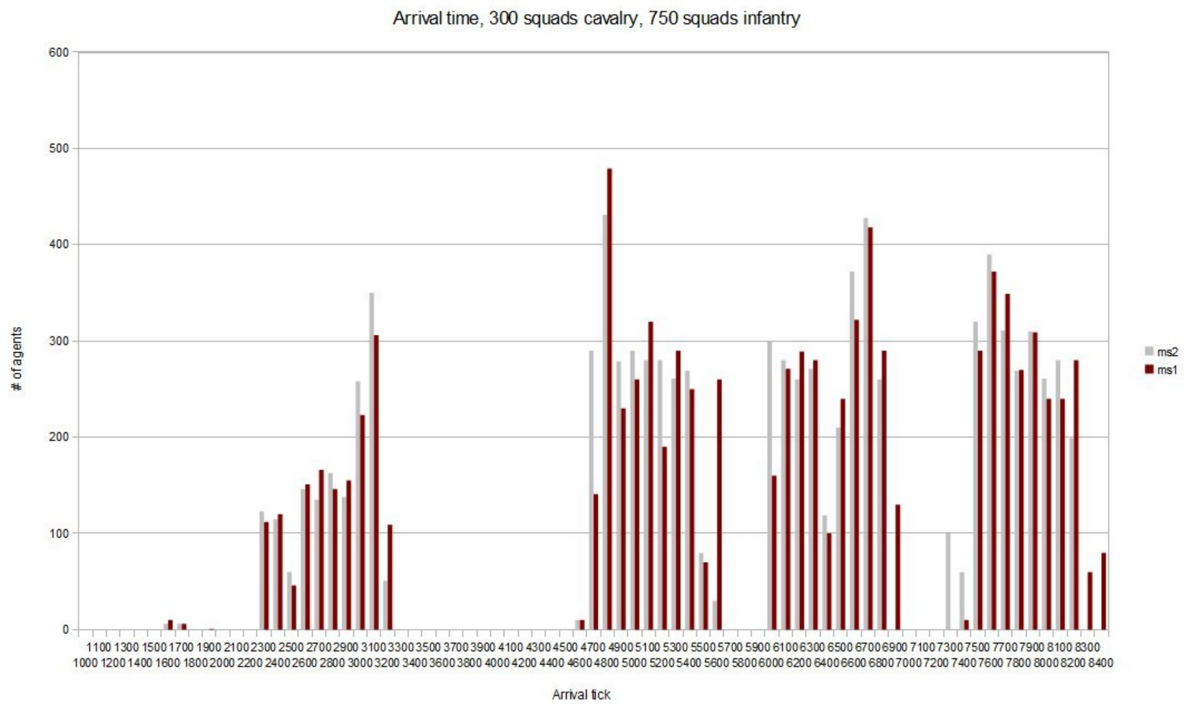


Figure 79: DM006 arrival time over 6 miles

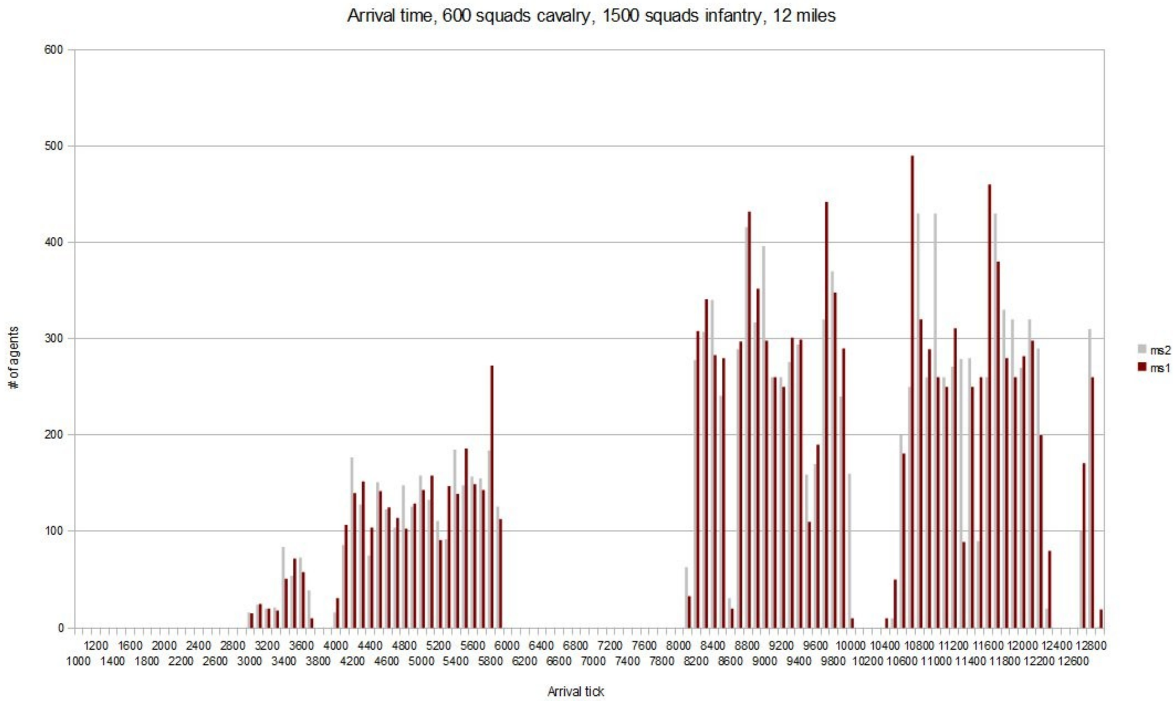


Figure 80: DM006 arrival time over 12 miles

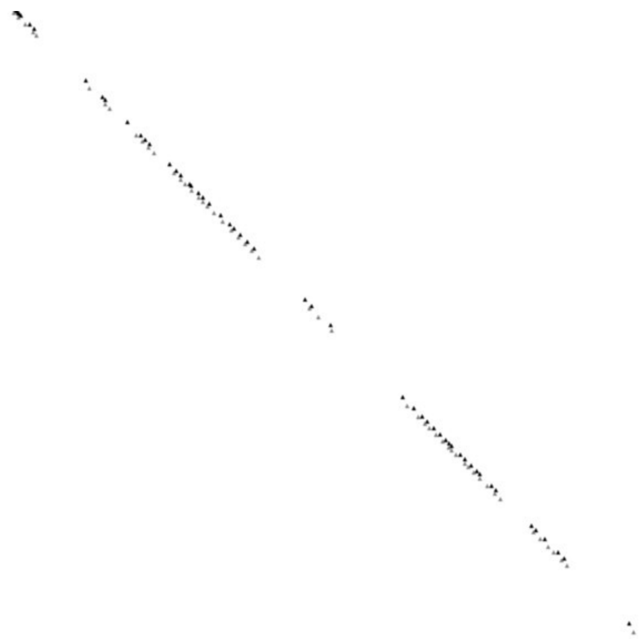


Figure 81: DM006 column of infantry units with march spacing = 1

As can be seen, no significant difference exists between the two results, either with 1050 or 2100 squads or over 6 or 12 miles. This can be explained by the generous nature of the setting off delays. As the gaps between units ensure there is no significant crowding, the reduction in march spacing manifests itself mainly as a desire for each `Officer` to be closer to the one in front. Without the ability to alter its speed, however, all the `Officer` can do is keep pace with the preceding unit until a rest period. As each rest period allows each `Officer` to catch up with the `Officer` in front (providing that `Officer` is not also doing the same and ends up taking the minimum amount of rest) this then causes problems for the `Officer` behind. Looking at the Blender files created by these scenarios it seems that reducing the march spacing without also reducing the setting off delays results in more clumping of the army column but no increase in throughput (figures 81 & 82).

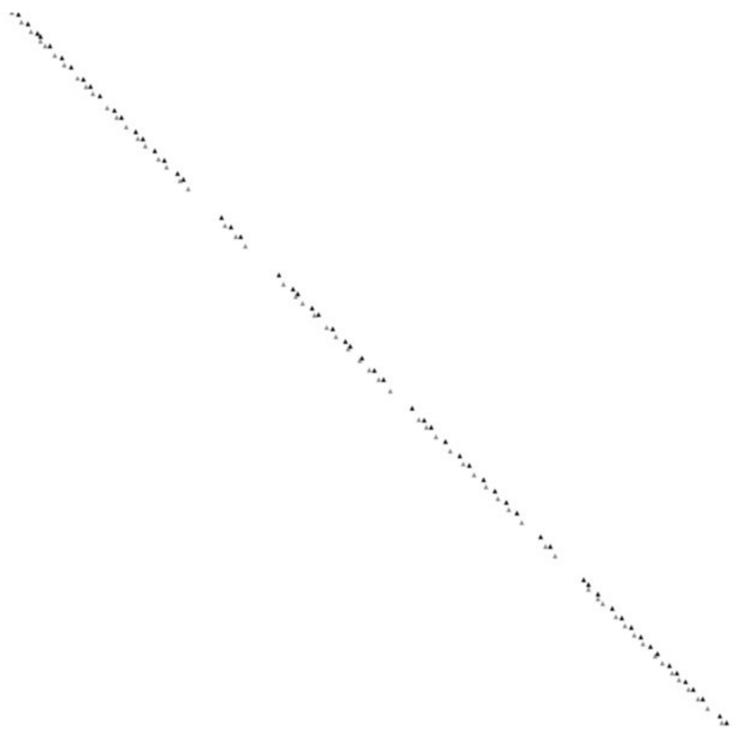


Figure 82: DM006 The same tick with the same parameters except march spacing = 2

Looking at both these columns it seems that if the units set out with smaller gaps between them then more units should be able to be marched in a single column in a day under the conditions of the DM006 scenarios.

4.11.6 DM006 Conclusion

Under the conditions of the DM006 scenarios the army composition, providing it is within historically plausible values, will have an insignificant effect on the overall speed of the army. This is because the last units to arrive will, providing sufficient gap is left to cope with crowding or holdups, only be able to move at a certain speed, not constrained by preceding, faster, units. Obviously this is provided the slowest units will be at the rear of the column but the benefits of this approach seem so obvious that it must have been the norm where practically possible. The composition of the army merely dictates how many units arrive earlier than the infantry. This raises a broader point regarding historical accounts, when a writer mentions that an army arrives at a particular time or even on a particular day, who exactly are they talking about? It is not hard to envisage from the results so far that a Byzantine army of 40,000 - 70,000 will have spent a certain amount with some sections travelling a day or two (or even three or four) behind the head of the column. Taking stragglers into account, the tail of the army may well have stretched some way behind on the route.

From a technical point of view, the scenarios run with virtually no gaps between the units didn't perform well. One crashed, two ran so slowly that one had to be cancelled to make room for other scenarios, the other was left running and just over halfway to completion 17 days after it was started. It's clear that the model doesn't cope with extreme crowding well. The one scenario that did run emphasised the point that in a situation where the army moves as a single column, one unit abreast, some sort of system to introduce gaps between units is essential. Further scenarios are needed in order to distinguish some variation between the apparently generous gaps of the majority of DM006 scenarios and the unworkable free for all that results from having hardly any gaps at all.

The stated aim of DM006 was to find the maximum number of agents able to travel in a single column on a single day. What has actually been achieved is a more complete understanding of the factors involved in moving the maximum number of people in a single day. It is clear that the gaps between units setting off has a clear effect on the arrival time of units. March spacing is only important if the gaps between units are small enough for there to be enough of a backlog to enable units to march closely to each other. We have seen from previous sets of scenarios though that the closer the units are to each other the more chance of crowding and the resulting increase in travel time and distance. So there is a direct tradeoff between the number of troops able to travel in a single column on a single day and the ease of that journey. A subsequent set of scenarios is planned to establish an absolute theoretical maximum for a day's march in a single column, using the maximum amount of daylight found on the route.

4.12 DM006a – The Limits of a Single Column

4.12.1 Introduction

This document details the planned experiments for DM006, the Day's March scenarios that will attempt to determine at which point in the model the limits of the single column method of marching are reached. This is a supplement to the scenarios in DM006 as, while being informative in many areas, they did not highlight the specific limits of the single column over a number of march distances with variable army sizes. Where all agents arrived in camp before sunset in our 13 hour and 16 minute day, the amount of excess time represents the amount of time between sunrise and the first agent setting out plus the amount of time between the final agent arriving and sunset.

4.12.2 Data

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	S1	S2	S3	Cavalry Speed	Cavalry March Spacing	Infantry March Spacing	Agents	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average rest ticks
CN21	6	50	50	250	750	2	5	200	Variable	2	1	9051	5713			12:06	543	4219	3854	11995	104
CN22	6	100	100	500	1500	2	5	200	Variable	2	1	18101	8316			14:47	1460	5725	5188	12187	99
CN23	6	50	50	250	750	1	5	100	Variable	2	1	9051	4914			11:16	526	3545	3257	12585	112
CN24	6	100	100	500	1500	1	5	100	Variable	2	1	18101									
CN21	6	50	50	250	750	2	5	200	Variable	1	1	9051	5766			12:09	547	4293	3913	12350	102
CN22	6	100	100	500	1500	2	5	200	Variable	1	1	18101	8202			14:40	1492	5717	5190	12119	93
CN23	6	50	50	250	750	1	5	100	Variable	1	1	9051	5244			11:36	555	3647	3349	12900	116
CN24	6	100	100	500	1500	1	5	100	Variable	1	1	18101									
CN25	6	150	150	750	2250	2	5	200	Variable	1	1	27151	10768			17:20	3846	7223	6524	12291	99
CN21	12	50	50	250	750	2	5	200	Variable	1	1	9051	7935			14:24	776	6344	5845	24052	226
CN22	12	100	100	500	1500	2	5	200	Variable	1	1	18101	10548			17:06	1562	7864	7182	24011	233
CN23	12	50	50	250	750	1	5	100	Variable	1	1	9051	6763			13:11	654	5626	5242	24133	253
CN21	12	150	150	750	2250	2	5	200	Variable	1	1	27151		26211	3206		4203	9204	8360	24196	242
CN23	15	50	50	250	750	2	5	200	Variable	1	1	9051	9156			15:40	649	7487	6920	29972	309
CN24	15	50	50	250	750	2	5	200	Variable	2	1	9051	9129			15:38	618	7501	6948	30064	325
CN22	15	100	100	500	1500	2	5	200	Variable	1	1	18101	11738			18:20	1706	9030	8302	30089	329
CN23	15	100	100	500	1500	2	5	200	Variable	2	1	18101	11731			18:20	1734	9041	8337	30147	340
CN24	15	150	150	750	2250	2	5	200	Variable	1	1	27151		20771	2662			9545	8645	30189	319
CN24	15	150	150	750	2250	2	5	200	Variable	1	1	27151	14189			20:52	5032	10475	9584	30103	325

Table 37: DM006a total scenario data

4.12.3 Results

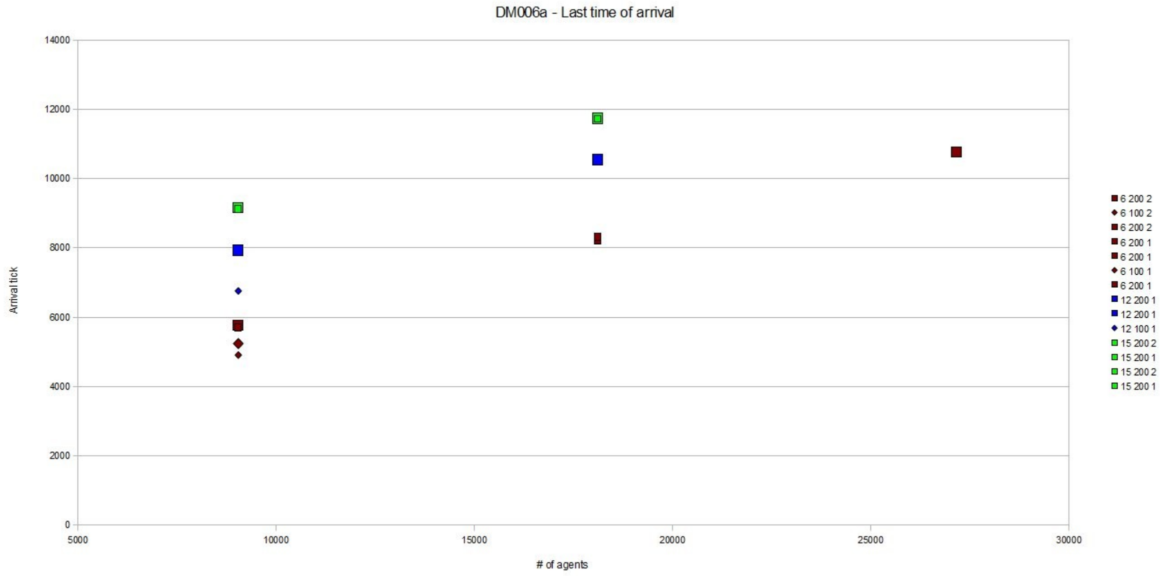


Figure 83: DM006a last time of arrival

4.12.3.1 6 Miles

Once again the value given to cavalry spacing had little effect on the results of the model. Over 6 miles, all sizes of armies finished well within the allotted time. 27151 agents completed the 6 mile march with 2041 ticks to spare, representing about 2 hours and 6 minutes. Given that some time would be required before and after the march of the army to allow the first units to have breakfast and the final units to set up their tents and cook food, this represents the practical limits of moving the modelled army via a single column over 6 miles.

4.12.3.2 12 Miles

Over 12 miles, the last arrival in the model with 18101 agents was at a similar time to that of the 6 mile march with 27151 agents. 18101 agents marched 12 miles in a single column with 2 hours and 20 minutes to spare, a similarly plausible amount of spare time during our typical 13 hour 16 minute day. Taking things to their absolute maximum, 26211 agents were able to make it to their camping locations before sunset although this assumes a daybreak start and an arrival at sunset.

4.12.3.3 15 Miles

Over 15 miles, 18101 agents were able to make it to camp, but with only 1071 ticks to spare. This represents 1 hour and 6 minutes, just within the limits of plausibility for the total spare time in a day's march. It is more likely that, unless circumstances dictated otherwise, a longer gap was required and 18101 agents would be above the number commonly attempted to be marched on a single column during a day. A special run of the model was completed with 27151 agents over 15 miles with a maximum number of ticks representing the amount of daylight at Sebastea in the middle of June, 14449 ticks. The army in this model finished with 260 ticks to spare, just 16 minutes. This represents a good theoretical maximum for an army marching using our rules over 15 miles.

4.12.4 DM006a Conclusions

There are significant differences between our model and an actual army on the march. There are no mules or pack animals in this series of scenarios. The single column movement represented here does not allow for two units walking abreast, a situation that may have been possible in open ground or on major roads. There is also no account made for the bank and ditch that would have surrounded the camp. These factors must be taken into account when interpreting these results. Nevertheless, these scenarios give a rough indication of how many agents could be moved within a single day under different circumstances.

4.13 DM007 – Multiple Columns

4.13.1 Introduction

The DM007 scenarios will model a system whereby the army is split into two or three columns and require these to use separate routes to march to the next camp. This will allow us to examine the circumstances in which splitting the army may be beneficial to the army as a whole. All multiple column scenarios were processed with cavalry spacing set to 2 and with gaps of 2, 5 and 200 as per most of the DM006a scenarios.

4.13.2 Work Required

The only differences between this model and the DM006a model is that it is possible to set the number of columns that the army can split itself into. When the number of columns is set at 1 the model behaves exactly the same as DM006a. When the number of columns is set to two or three then the model separates the army into two or three different columns. The first column will have the `ColumnLeader` agent at its head, the other one or two will have an ordinary *`Officer`* agent who, for the purposes of route planning, behaves like a `ColumnLeader`. The army is broken down by sector with each sector heading for a waypoint outside camp depending on the overall direction of travel and the number of columns. The second waypoint is always closer to the destination camp than the third so the new routes become longer as the number of columns increases. As can be seen from the following figures, having five sectors to the camp does not result in an even number of squads in each column but this is likely to have been the case in reality as the organisational structure would have been kept in place and the columns built around that, rather than the other way round. As they use different waypoints outside the camp, each column can set off at the start of the day, it does not have to wait until any of the other columns has moved out before it moves itself. Within each column the same movement rules apply as in previous models, where each unit, collection of units and sector has a gap set between its own setoff time and that of the unit preceding it.

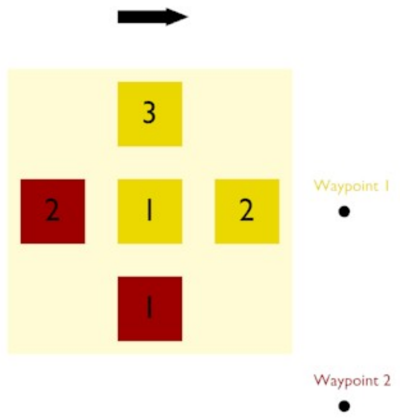


Figure 84: 2 columns with the overall direction of travel being east. The numbers indicate the order in which the sectors set out.

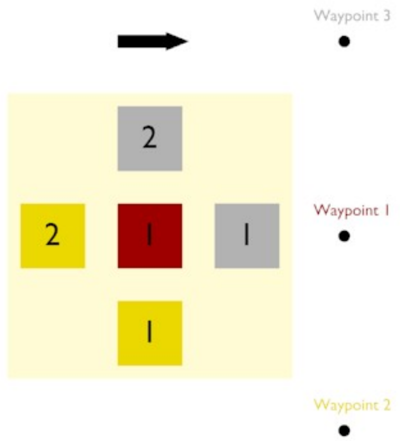


Figure 85: 3 columns travelling East

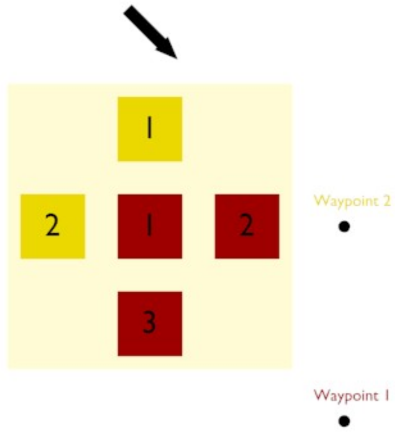


Figure 86: 2 columns travelling South East

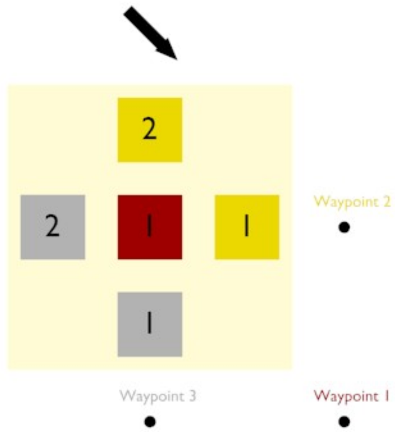


Figure 87: 3 columns travelling South East

The leader of each column plans a route to the corresponding waypoint outside the destination camp, as seen in Figure 88.

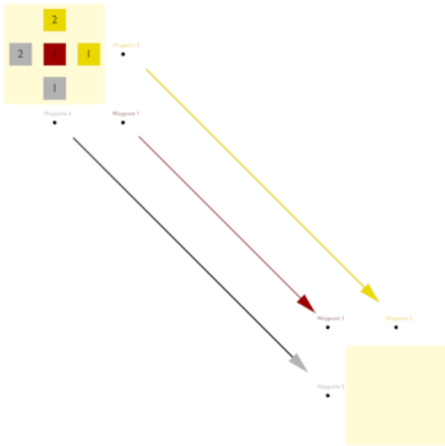


Figure 88: The selection of destination waypoints

This selection of waypoints helps ensure that the separate columns do not cross each other unless the terrain forces columns to use the same route. Due to the relatively flat terrain between Nikaia and Malagina no such situation exists in the DM007 scenarios. The same distribution of units was used as in DM006a, with the central sector of the camp consisting of the `ColumnLeader`, a number of `Officer`s equal to 5% of the total squads in the main part of the army and a number of `Officer` cavalry squads also equal to 5% of the total squads of the main part of the army. The numbers of agents corresponds to the following numbers of squads.

Total number of squads	Number of agents
1100	9051
2200	18101
3300	27151

Table 38: Conversion between number of squads and number of agents

4.13.3 Data

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN21	6	50	50	250	750	9051	1	5713			12:06	543	4219	3854	11995	
CN23	6	50	50	250	750	9051	2	4138			10:28	572	3446	3234	12863	2325
CN29	6	50	50	250	750	9051	3	4344			10:40	839	3567	3334	14259	2531
CN22	6	100	100	500	1500	18101	1	8316			14:47	1460	5725	5188	12187	
CN21	6	100	100	500	1500	18101	2	5564			11:56	1447	4142	3909	12774	2363
CN25	6	100	100	500	1500	18101	3	5457			11:50	1520	4189	3927	14051	2590
CN25	6	150	150	750	2250	27151	1	10768			17:20	3846	7223	6524	12291	
CN22	6	150	150	750	2250	27151	2	6851			13:16	3564	4918	4674	12717	2489
CN24	6	150	150	750	2250	27151	3	7939			14:24	4818	5266	5018	15242	3147
CN21	12	50	50	250	750	9051	1	7935			14:24	776	6344	5845	24052	
CN23	12	50	50	250	750	9051	2	6534			12:57	624	5675	5314	24997	4407
CN25	12	50	50	250	750	9051	3	6665			13:05	664	5800	5467	25807	4665
CN22	12	100	100	500	1500	18101	1	10548			17:06	1562	7864	7182	24011	
CN29	12	100	100	500	1500	18101	2	8246			14:43	4760	6539	6213	25259	4667
CN23	12	100	100	500	1500	18101	3	7797			14:15	1580	6417	6093	25571	4756
CN21	12	150	150	750	2250	27151	1		26211	3206		4203	9204	8360	24196	
CN21	12	150	150	750	2250	27151	2	9690			16:13	5979	7492	7182	25292	4999
CN25	12	150	150	750	2250	27151	3	8937			15:26	3753	7102	6790	25685	4919
CN24	15	50	50	250	750	9051	1	9129			15:38	618	7501	6948	30064	
CN22	15	50	50	250	750	9051	2	7767			14:13	612	6908	6571	30820	5663
CN21	15	50	50	250	750	9051	3	7830			14:17	664	6866	6516	31349	5713
CN23	15	100	100	500	1500	18101	1	11731			18:20	1734	9041	8337	30147	
CN23	15	100	100	500	1500	18101	2	9015			15:31	1766	7671	7334	30789	5788
CN21	15	100	100	500	1500	18101	3	9388			15:54	2162	7701	7343	31992	6006
CN24	15	150	150	750	2250	27151	1		20771	2662			9545	8645	30189	
CN22	15	150	150	750	2250	27151	2	10423			16:58	4464	8529	8226	30963	6042
CN23	15	150	150	750	2250	27151	3	10106			16:39	5651	8250	7900	31732	6030

Table 39: DM007 total scenario data

The scenarios with multiple columns within this data were all run for DM007. The scenarios with a single column are all taken from DM006 and DM006a. Some of the single column scenarios were run with cavalry spacing set to 1 but this does not significantly effect the results as shown in the report for DM006a.

4.13.4 Results

4.13.4.1 6 Miles

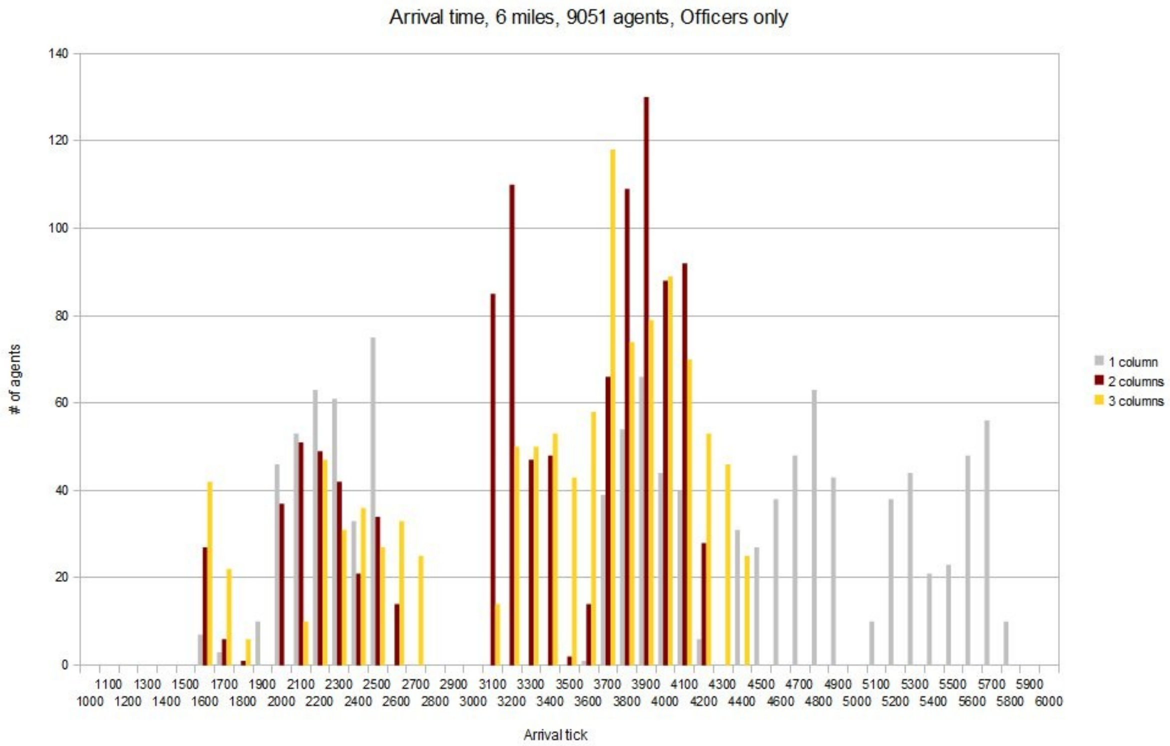


Figure 89: DM007 arrival times, 6 miles, 9051 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN21	6	50	50	250	750	9051	1	5713			12:06	543	4219	3854	11995	
CN23	6	50	50	250	750	9051	2	4138			10:28	572	3446	3234	12863	2325
CN29	6	50	50	250	750	9051	3	4344			10:40	839	3567	3334	14259	2531

Table 40: DM007 data, 6 miles, 9051 agents

As can be seen from the arrival time with 9051 agents over 6 miles (Figure 89), using both two and three columns have advantages over just one column. They both result in the last agent arriving before the last agent in the single column model. With only one column the whole force still arrives at the destination camp before half of the available daylight is gone though. With this amount of wiggle room, it would be down to the individual commander to decide whether the extra complication of using two or three columns was worth any benefits to be gained from the earlier arrival time. As can be seen from the graph, splitting the army into two columns results in a faster overall arrival than splitting into three columns. This is a result of more agents taking a suboptimal route and therefore travelling further. The extra distance travelled by the third column pushes the average distance travelled up by over a kilometre.

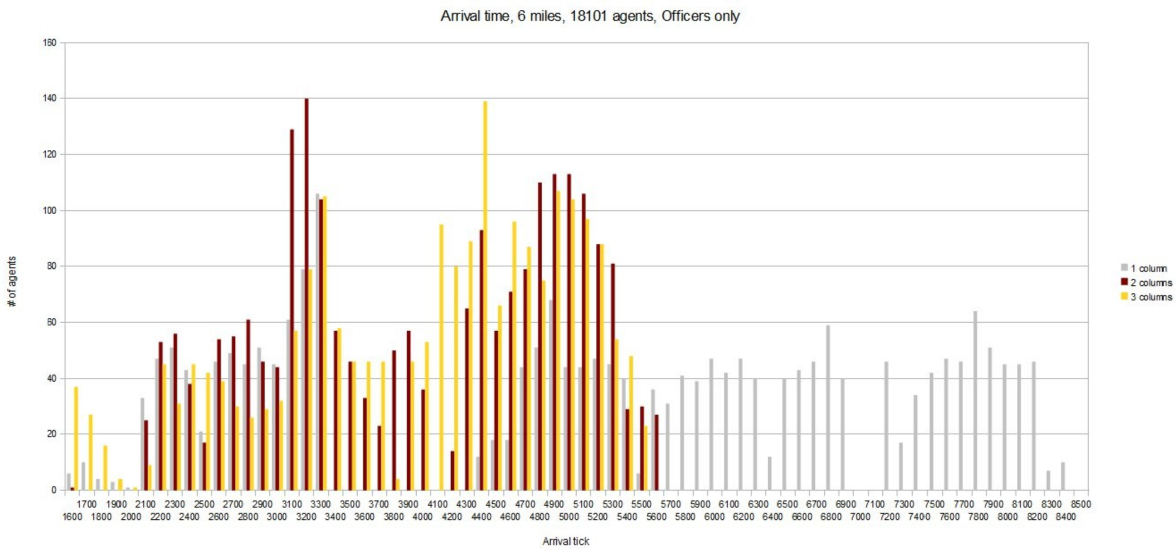


Figure 90: DM007 arrival times, 6 miles, 18101 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN22	6	100	100	500	1500	18101	1	8316			14:47	1460	5725	5188	12187	
CN21	6	100	100	500	1500	18101	2	5564			11:56	1447	4142	3909	12774	2363
CN25	6	100	100	500	1500	18101	3	5457			11:50	1520	4189	3927	14051	2590

Table 41: DM007 data, 6 miles, 18101 agents

If the number of agents is doubled then we see real benefits towards splitting the army into separate columns (Figure 90). The final agent arrives in around two thirds the time as if one column was used, more than two and a half hours' difference. In this set of scenarios the difference between 2 and 3 columns is less that with 9051 agents, the added size of the army making splitting into more columns more worthwhile. The one column army still arrives in plenty of time though, although it would take fewer unforeseen holdups along the way to cause the final few agents to arrive close to sunset.

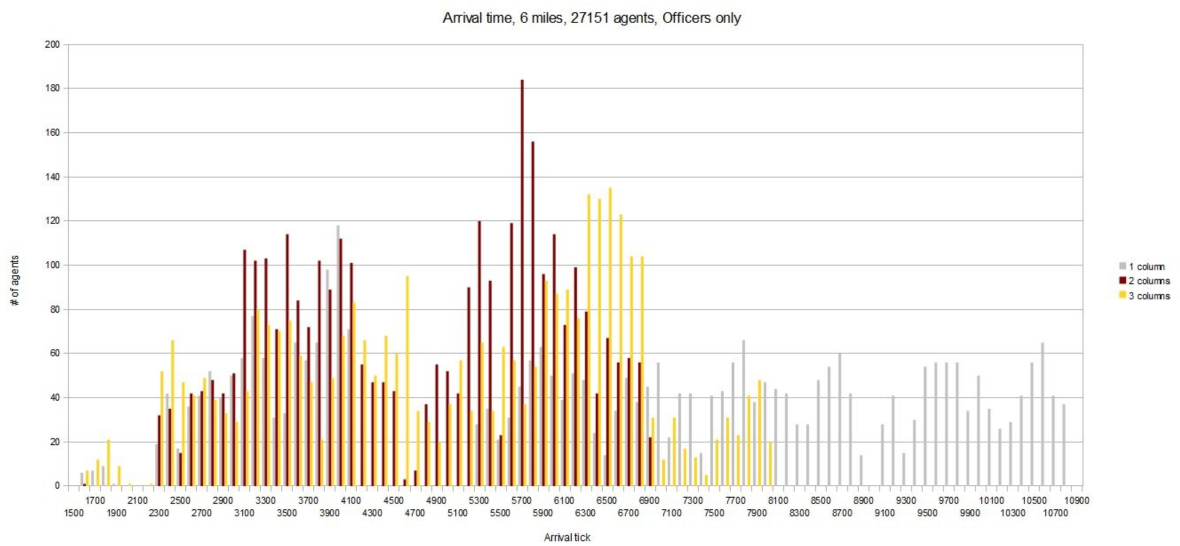


Figure 91: DM007 arrival times, 6 miles, 27151 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN25	6	150	150	750	2250	27151	1	10768			17:20	3846	7223	6524	12291	
CN22	6	150	150	750	2250	27151	2	6851			13:16	3564	4918	4674	12717	2489
CN24	6	150	150	750	2250	27151	3	7939			14:24	4818	5266	5018	15242	3147

Table 42: DM007 data, 6 miles, 27151 agents

With 27151 agents the situation becomes more complicated (Figure 91). The scenario with two columns has a much earlier last time of arrival than the three column force, something unexpected if the overall pattern were to be that the larger the force the more useful three columns would become. The reason for this is clearly seen in the tabular data. There is a large increase in the average distance travelled with three columns. There may be something about the third route that makes it prone to crowding once a certain number of agents is sent down it. One benefit of this is that there is less of a concentration of squads arriving at the same time, as seen in the massive spike of the two column data around tick number 5700.

4.13.4.2 12 Miles

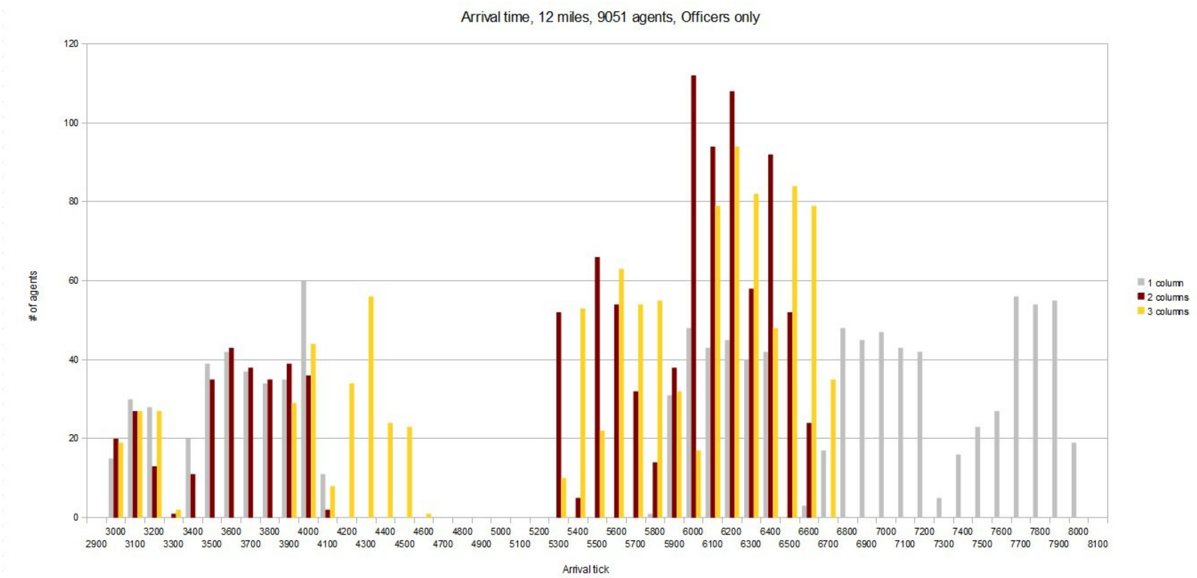


Figure 92: DM007 arrival times, 12 miles, 9051 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN21	12	50	50	250	750	9051	1	7935			14:24	776	6344	5845	24052	
CN23	12	50	50	250	750	9051	2	6534			12:57	624	5675	5314	24997	4407
CN25	12	50	50	250	750	9051	3	6665			13:05	664	5800	5467	25807	4665

Table 43: DM007 data, 12 miles, 9051 agents

Over 12 miles we see a similar pattern to that over 6 miles (Figure 92), having two columns shows an improvement over having 3 columns. Due to the increased time taken to march 12 miles the benefits of splitting the army into multiple columns starts to be felt even with smaller numbers of troops. Over 12 miles there is less difference between the second and third routes in length. This can be explained by the 12 mile camps being more aligned with the diagonal organisation of the waypoints than the 6 mile camps which are off centre.

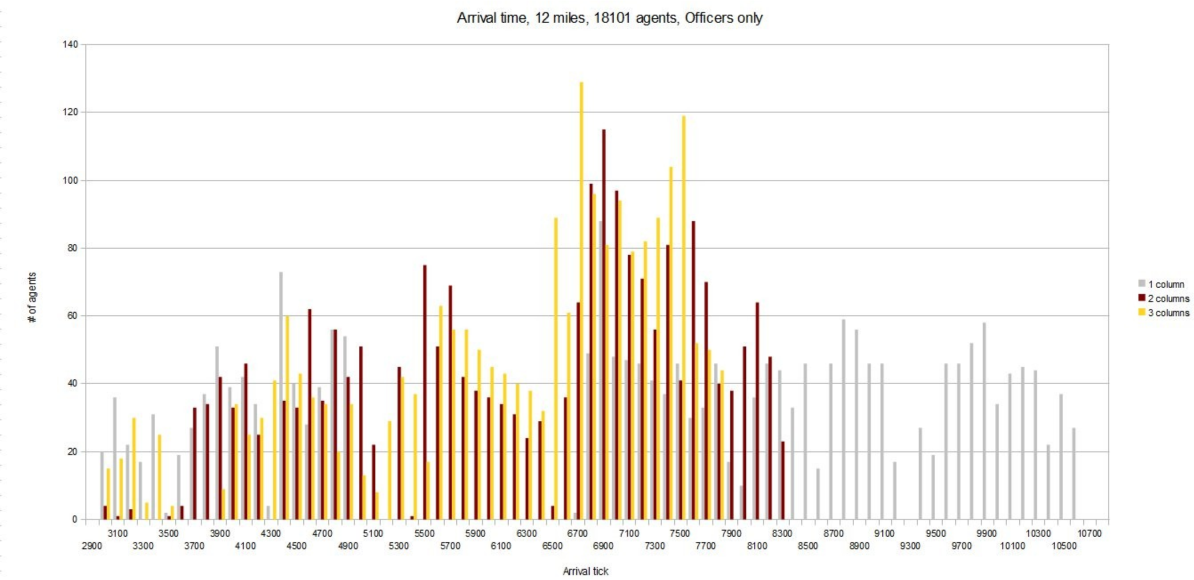


Figure 93: DM007 arrival times, 12 miles, 18101 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN22	12	100	100	500	1500	18101	1	10548			17:06	1562	7864	7182	24011	
CN29	12	100	100	500	1500	18101	2	8246			14:43	4760	6539	6213	25259	4667
CN23	12	100	100	500	1500	18101	3	7797			14:15	1580	6417	6093	25571	4756

Table 44: DM007 data, 12 miles, 18101 agents

Over 12 miles, 18101 agents show a distinct preference for three columns with 449 ticks between the last agent to arrive in the three column model compared to the two column model (Figure 93). That's still only around 28 minutes but as arrival times are approaching the end of the day the possibility of hold ups making those minutes more important increases.

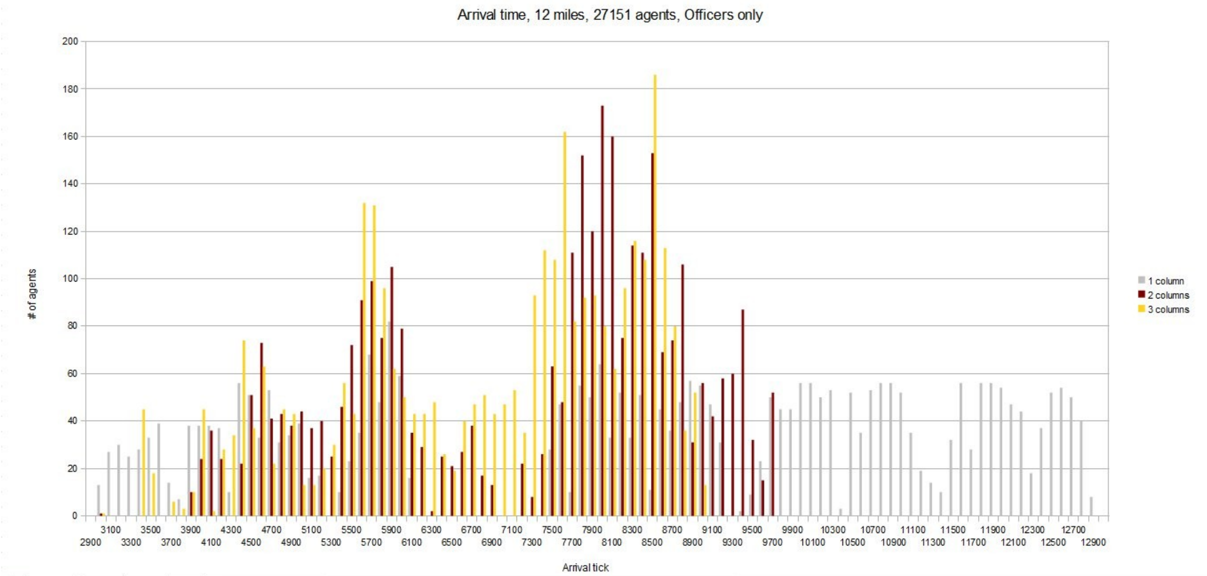


Figure 94: DM007 arrival times, 12 miles, 27151 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN21	12	150	150	750	2250	27151	1		26211	3206		4203	9204	8360	24196	
CN21	12	150	150	750	2250	27151	2	9690			16:13	5979	7492	7182	25292	4999
CN25	12	150	150	750	2250	27151	3	8937			15:26	3753	7102	6790	25685	4919

Table 45: DM007 data, 12 miles, 27151 agents

When 3300 squads are used, multiple columns become the only way all agents can arrive at the destination camp before sunset (Figure 94). The difference between the last arrivals of the two and three column scenarios is 753 ticks (nearly 47 minutes). Also noticeable are the peaks where at times over 160 squads are arriving in camp in a 100 tick period. That equates to 1600 infantry agents within six minutes, surely causing some organisational problems within camp.

4.13.4.3 15 miles

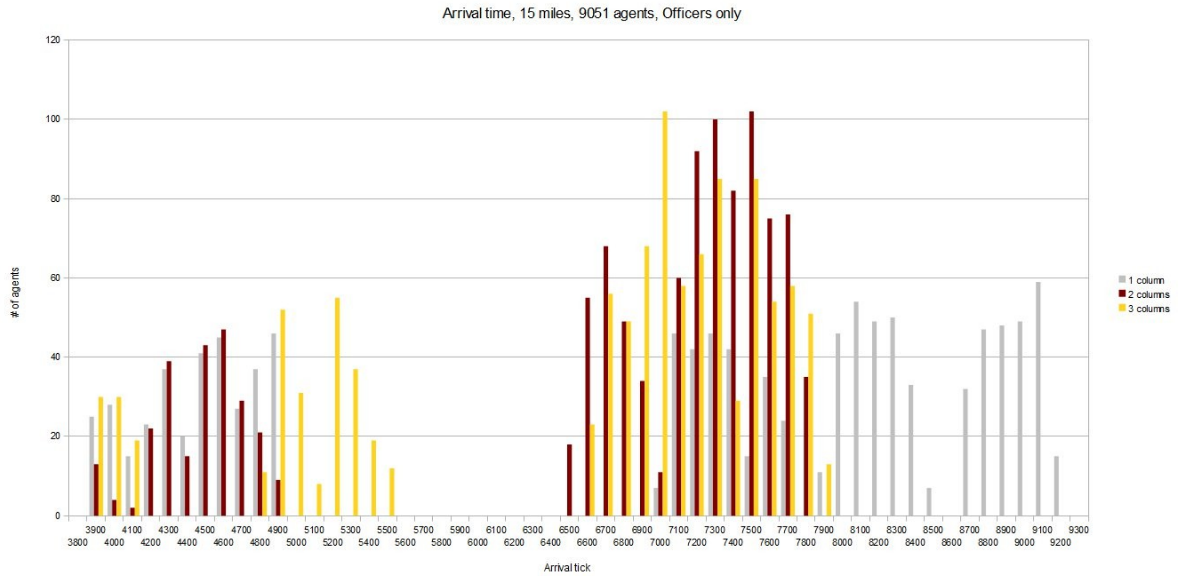


Figure 95: DM007 arrival times, 15 miles, 9051 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN24	15	50	50	250	750	9051	1	9129			15:38	618	7501	6948	30064	
CN22	15	50	50	250	750	9051	2	7767			14:13	612	6908	6571	30820	5663
CN21	15	50	50	250	750	9051	3	7830			14:17	664	6866	6516	31349	5713

Table 46: DM007 data, 15 miles, 9051 agents

Over 15 miles with 9051 agents the difference in speed between cavalry and infantry shows itself almost as clearly with multiple columns as it does with a single column (Figure 95). The longer the march, the more capacity there is for route planning to extend the difference in journey lengths. All agents are still arriving well within the available daylight for marching, whichever model is used 15 miles seems a perfectly reasonable marching distance for a force of this size given the conditions within the model.

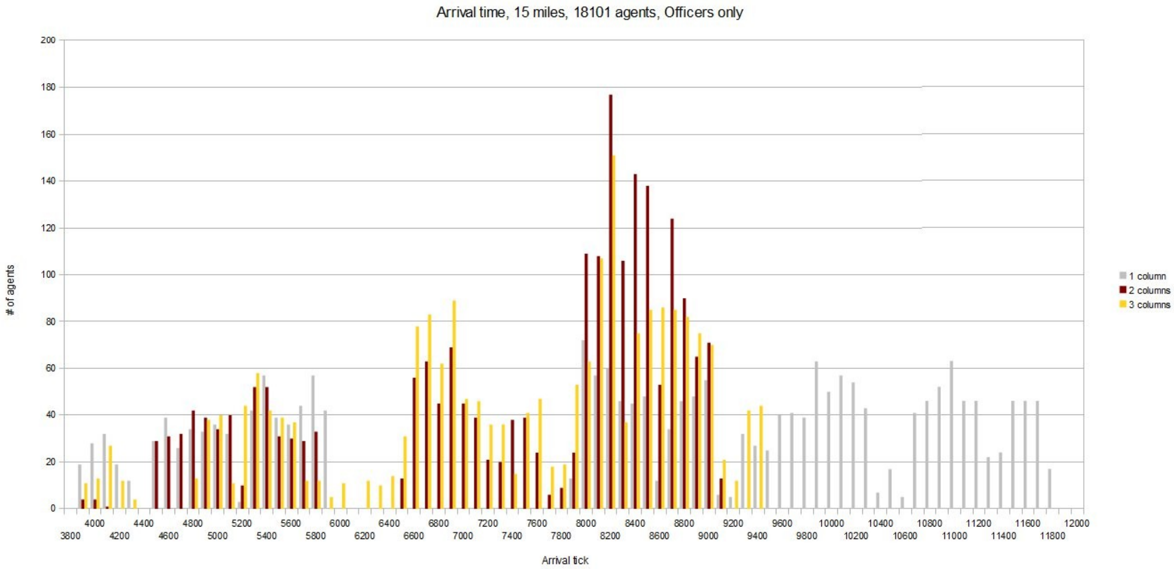


Figure 96: DM007 arrival times, 15 miles, 18101 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN23	15	100	100	500	1500	18101	1	11731			18:20	1734	9041	8337	30147	
CN23	15	100	100	500	1500	18101	2	9015			15:31	1766	7671	7334	30789	5788
CN21	15	100	100	500	1500	18101	3	9388			15:54	2162	7701	7343	31992	6006

Table 47: DM007 data, 15 miles, 18101 agents

A similar situation exists within this set of scenarios as in the largest scenarios with a 6 mile march (Figure 96), some crowding exists in the three column model that increases the average distance travelled and final arrival time. Once again the three column scenario exhibits a more regular pattern of arrival, possibly leading to fewer crowding problems in the destination camp.

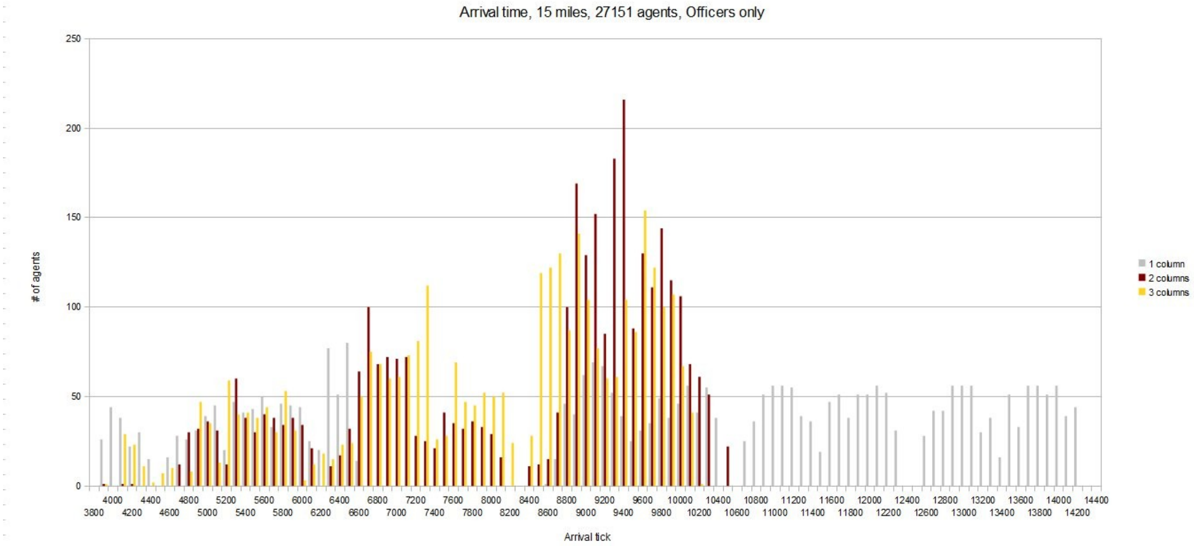


Figure 97: DM007 arrival times, 15 miles, 27151 agents

PC	Distance (miles)	Officers	Officer Cavalry	Cavalry	Infantry	Agents	Column Leaders	Time of Last Arrival	Last Agent to arrive	Last Officer to Arrive	Time (UTC + 3)	Proc Time	Average arrival time	Average arrival time (officers only)	Average distance travelled	Average Travel Time
CN24	15	150	150	750	2250	27151	1		20771	2662			9545	8645	30189	
CN22	15	150	150	750	2250	27151	2	10423			16:58	4464	8529	8226	30963	6042
CN23	15	150	150	750	2250	27151	3	10106			16:39	5651	8250	7900	31732	6030

Table 48: DM007 data, 15 miles, 27151 agents

Whatever crowding problems there are with the third route they aren't severe enough to make up for the lack of bandwidth in the two column scenario (Figure 97). The average distance increases with three columns but the time of last arrival is still earlier, albeit only by 19 minutes. By this point it is clear that splitting the army into separate columns is the only way to get 27151 agents over 15 miles in our representative day. Barring unforeseen events it would just be possible to move such a force with enough time to make breakfast in the morning and set up camp in the evening.

4.13.5 DM007 Conclusions

While the army is still modelled at a fairly abstract level, the DM007 scenarios allow us to draw conclusions regarding the movement of the army in separate columns. There is clearly a benefit to splitting the army into columns when looking at the last agent to arrive in the following day's camp. Only if the second or third routes were much longer or more arduous would the last agent arrive later than it would with a single column. This may be the case in mountainous areas but not in the relatively flat terrain between Nikaia and Malagina. The time of arrival of the last agent, while important, is not the only factor to be considered when deciding how many columns to split the army into.

Marching in a single column may result in later arrival times but it also ensures that excessive numbers of agents do not arrive at the destination camp at the same time. There is a real density about the arrival times of both the two and three column models that is absent from the single column scenarios. Properly organised this would not necessarily cause problems at the destination camp as the camping locations would be suited to the direction from which the units are arriving. However this would make actions within camp such as watering the horses and digging the surrounding bank and ditch more difficult with arriving units possibly getting in the way. The single column model with agents arriving via a single direction would make organisation of tasks within camp simpler. One of the other advantages of splitting the army into separate columns is that the army is quicker at forming up into battle order. That this is likely to be the case can be seen quite easily from the arrival graphs. This however is not a factor on the Manzikert march as the Seljuks were thought to be too far away to pose a threat even up to the Byzantines' arrival at Manzikert.

Another pattern apparent from the results is that with the army split into multiple columns the gap between the cavalry and infantry's arrival is less pronounced. This is due to the infantry not having to wait in the starting camp until the cavalry set off. This may manifest itself in a greater feeling of equality between the cavalry and infantry units. In the MWGrid ABM the cavalry head the column, this is to ensure the slower moving infantry do not unduly hold up the cavalry. When marching in a single column this may generate a certain amount of bad feeling within the infantry units, especially the ones arriving in camp earliest, when they see the cavalry already camped, fed and rested. This feeling will no doubt be magnified if the infantry have had to march through the heat of the day because they had to wait for the cavalry to leave. It is also likely that it is the infantry that will have to dig the bank and ditch surrounding the camp, the cavalry being of generally higher status. The earliest infantry units to arrive are more likely to have to bear the greatest burden in constructing the camp.

This gap between cavalry and infantry is less pronounced in the scenarios with multiple columns as the infantry can start straight away, the only gap being caused by the difference in speeds and the length of route. Furse notes in *The Art of Marching* (Furse 1901) that when splitting columns the infantry should go via the shortest route and the cavalry by the longer. This is not modelled here but would cut the gap between the cavalry and infantry even further, maybe even ensuring the infantry arrive first if the difference between route lengths is enough. Although this may increase any crowding issues with arriving at camp it would surely improve the morale of the infantry.

In reality, splitting the army can happen over the course of a day or for much longer. Splitting the army for more than a day would create a series of parallel single column armies that would have to join up at some later point on the route. This will be considered in the DM008 scenarios.

In addition to the historical factors, one significant technological aspect of splitting the army into camps is worth mentioning. The size of the processed tickfile is increased as more agents can be on the move at the same time. Whereas with a single column it is unlikely to have a processed tickfile of over 800Mb, the ones containing multiple columns are all over 1Gb. This not only increases required storage space but also results in longer Blender processing times and larger Blend file sizes (see DM003).

4.14 DM008 – The March to Manzikert

4.14.1 Introduction

The Day's March 008 scenarios deal with the specific context of the Byzantine army's march across Anatolia to the fortress at Manzikert in AD 1071. In order to use the model to examine the specific circumstances of the army's march to Manzikert the relatively generic models used so far will have to deal with specific information about the campaign. As detailed in chapter 1, we do not know the size of the Byzantine army but a plausible hypothetical force and route of march have been supplied by John Haldon and detailed below. It is this force that will be used for the DM008 scenarios. These scenarios will provide new evidence of the organisation required to move the army over 700 miles as the crow flies in around 6 months. Although there is insufficient time to model the army on each day of it's march, three sample points of the route are used to illustrate the issues faced by the army at different points along the route. The model still lacks some important factors, the army is modelled without any baggage or baggage handling mechanisms for example. This will, however, give an optimistic estimate, a null hypothesis against which we can compare reality. If the hypothetical army without baggage cannot reach its destination in time, what hope for the real-world Byzantine army with mules, extra horses and the like?

The setting off delays between units have been set to the reasonably generous 3/9/483 ticks used in DM006.

4.14.2 Work Required

4.14.2.1 Route

A hypothetical route for the Manzikert campaign based on the fragments of information contained in historical accounts, the *Tabula Imperii Byzantini* maps and other relevant sources has already been produced (Haldon 2006, 9). This is the route that will be assumed for the purposes of our model. It starts at Nicomedia based on an assumption that sea travel would have been used from Constantinople up until that point. It then passes through Nikaia, Malagina, Dorylaion, Ankyra, Charsianon, Sebastea and Theodosiopolis before arriving at Manzikert (Figure 98). This route totals around 1,110 miles in length and encompasses a wide variety of elevations (Table 51).

Figure 98: The hypothetical route of the Byzantine army to Manzikert

4.14.2.2 Army Composition

The Byzantine army was made up of a variety of different troop types in differing proportions and any attempt to produce precise numbers will necessarily be highly speculative. Working from data provided by John Haldon a hypothetical army has been produced, consisting of different types of troops joining the campaign at different locations (Table 49).

Within this hypothetical army, the following units join at the following locations:

Constantinople - The units from the palace leave Constantinople with the Emperor. These are the Hetaireia, Scholai, Stratelatai and the Varangians.

Nicomedia - Pecheneg mercenaries and Balkan allies.

Malagina - Frankish mercenaries under Roussel de Bailleul, German and Oghuz mercenaries, units from Bulgaria the thematic tagmata from Bithynia and the five tagmata of the west.

Dorylaion - Thematic tagmata from the Anatolikon theme.

Charsianon - Thematic tagmata from Cilicia.

Sebastea - Thematic tagmata from Cappadocia, Koloneia, Charsianon, Armeniakon along with the Armenian infantry.

Theodosiopolis - Thematic tagmata of Chaldia plus the tagmata from Syria.

In addition to this, the German mercenaries were sent back at Krya Pege, between Dorylaion and Charsianon, and the army was split in two between Theodosiopolis and Manzikert with half the force being sent to Khliat.

Leg of route	Distance (km)	Cavalry	Infantry
Constantinople - Nicomedia	boat	3,000	-
Nicomedia - Malagina	90	5,000	2,000
Malagina - Dorylaion	114	9,000	10,000
Dorylaion - Charsianon	699	9,250	10,750
Charsianon - Sebastea	128	9,500	11,500
Sebastea - Theodosiopolis	552	10,500	16,500
Theodosiopolis - Manzikert	204	11,250	20,750

Table 49: DM008 hypothetical army with route distances

Nomadic and Frankish mercenaries would have differed from Byzantine units with the

Emperor's household being of a different character than the thematic tagmata. Within the model we have assumed that Frankish and nomadic troops are represented solely by cavalry along with the Emperor's household. Other Byzantine troops have 25% cavalry and 75% infantry. Armenian and Balkan troops comprise solely of infantry. The number of `Officer`s in the central sector is represented by 5% of the number of squads in the army as a whole. This covers high ranking officers and bureaucratic elements along with their servants.

4.14.2.3 Weather and Daylight

The amount of daylight within which the army had to move would have differed as it crossed Anatolia. Although the differences in latitude are fairly minor, the march took almost 6 months and would have resulted in considerable variation in the number of daylight hours. The values recorded in Table 50 are based on data from the Australian Government (http://www.ga.gov.au/geodesy/astro/sunrise.jsp) and are for dates in AD 2010.

4.14.2.4 Timing

There are few fixed temporal points on the Manzikert campaign. We know that the Emperor left Constantinople in late February or early March, had reached Theodosiopolis by late June and fought the battle at Manzikert on August 26th, very soon after arrival. If we take the 1st of March as the start date and the 30th June to represent late June we have 122 days from leaving Constantinople to arriving at Theodosiopolis and 56 days from that point to arriving at Manzikert on the day before the battle. It seems almost certain that the army spent some time at Theodosiopolis as Skylitzes Continuatus records a major strategic discussion at which the decision to move on to Manzikert was made (Friendly 1981, 171). He also records that the order was given to gather 3 months worth of supplies. Engels' work shows (1978, 20) that this cannot have included food for the whole three months but it does at least indicate that the stop at Theodosiopolis was more than just a flying visit.

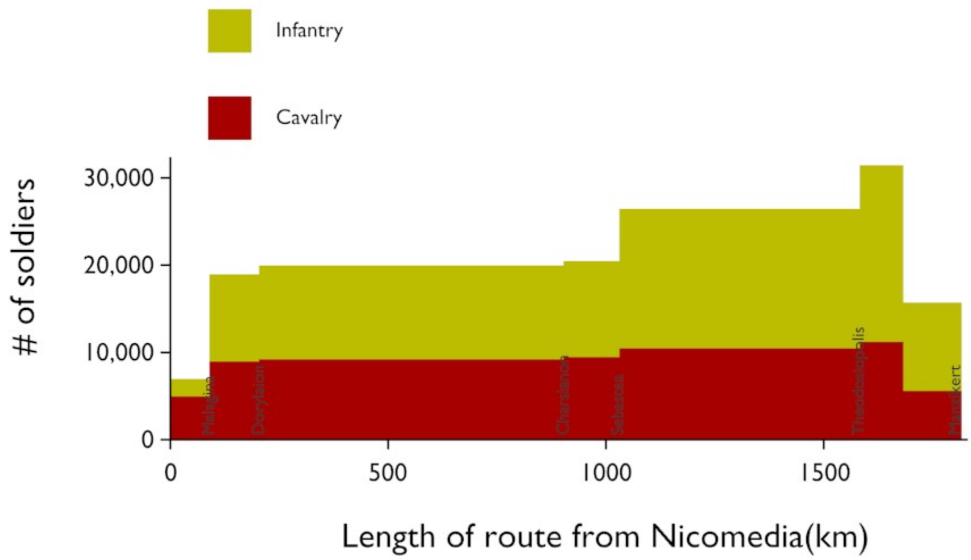


Figure 99: The size of the hypothetical army as it progresses towards Manzikert

Location	Co-ordinates	Date	Sunrise (UTC +3)	Sunset (UTC +3)	Minutes of daylight	Ticks @ 3.729 secs/tick
Nicomedia (Izmit)	40° 46'N, 29° 55'E	01/03/10	07:35:00	18:51:00	676	10877
Ankyra (Ankara)	39° 52'N, 32° 52'E	15/04/10	06:11:00	19:27:00	796	12809
Ankyra (Ankara)	39° 52'N, 32° 52'E	15/05/10	05:34:00	19:57:00	863	13886
Sebastea (Sivas)	39° 45'N, 37° 01'E	01/06/10	05:06:00	19:54:00	888	14288
Sebastea (Sivas)	39° 45'N, 37° 01'E	15/06/10	05:04:00	20:02:00	898	14449
Theodosiopolis (Erzurum)	39° 54'N, 41° 16'E	01/07/10	04:51:00	19:48:00	890	14320
Theodosiopolis (Erzurum)	39° 54'N, 41° 16'E	01/08/10	05:14:00	19:29:00	855	13757
Manzikert (Malazgirt)	39° 48'N, 42° 19'E	26/08/10	05:34:00	18:53:00	799	12856

Table 50: Sunrise and sunset times used in DM008

Location	Environment Co-ordinates	Elevation (m above sea level)
Nicomedia	34600,27200	6
Nikaia	30000,34500	74
Malagina	35800,37200	221
Dorylaion	44200,49400	799
Ankyra	85400,45600	964
Charsianon	139000,49900	1166
Sebastea	155800,50500	1244
Theodosiopolis	232900,46400	1885
Manzikert	250000,63900	1478

Table 51: The location of settlements visited by the army using the ABM's environmental co-ordinate system

4.14.2.5 Movement Costs

Up until now the cost of moving was calculated based on the 2D distance between two points, even though the actual distance travelled was calculated in three dimensions. This had the effect that agents would travel comparatively quicker on slopes than they did on flat terrain. This would not have caused significant inaccuracy in scenarios run up until this point due to the flat nature of the terrain between Nikaia and Malagina, although it certainly would do in the more undulating areas to be modelled.

4.14.2.6 Health

The number of kilocalories expended by movement during the model is now being calculated for each agent. This is updated every minute of simulation time as the equations used to calculate this are based on millilitres of O_2 per kilogram of body weight per minute. Each minute the ABM calculates the distance travelled within that minute. It also compares the current height with the previous height. It applies these to the equation detailed in chapter 2. The calculations for infantry are exactly as described previously. A further step was required to remove a source of variability in the data for riding horses.

Rider	Walk - VO_2 (litres per minute)	Trot - VO_2 (litres per minute)	Weight (kg)	Walk (ml per kg per min)	Trot (ml per kg per min)
1	1	1.85	77	12.99	24.03
2	0.56	1.4	54	10.37	25.93
3	0.72	1.55	58	12.41	26.72
4	0.6	1.17	48	12.5	24.38
5	0.64	1.43	54	11.85	26.48
Mean	**0.7**	**1.48**	**58.2**	**12.02**	**25.51**

Table 52: Energy expenditure of horse riders and the conversion to ml/kg/min (after Devienne and Guezennec 2000)

These values specified in chapter 2 are in litres of O_2 per minute and already have the weight of the rider taken into account. The weight of the rider does make a difference though. As can be seen in Table 52, considerable variability exists between riders. I have added the weights of the individual riders and from this, calculated VO_2 in millilitres per kilogramme of rider weight per minute. By extracting ml/kg/min figures from the l/min averages given in the paper, it is possible to remove the variability caused by the rider's weight. For this reason the mean of the ml/kg/min figures will be used instead of the mean of litres per minute.

Within the source data there also exists considerable variability between horses with some requiring more energy to be expended by the rider than others (Devienne and Guezennec 2000, 501). As there is no study which allows us to estimate the implications of this to the MWGrid ABM it has been omitted but is noted here for completeness.

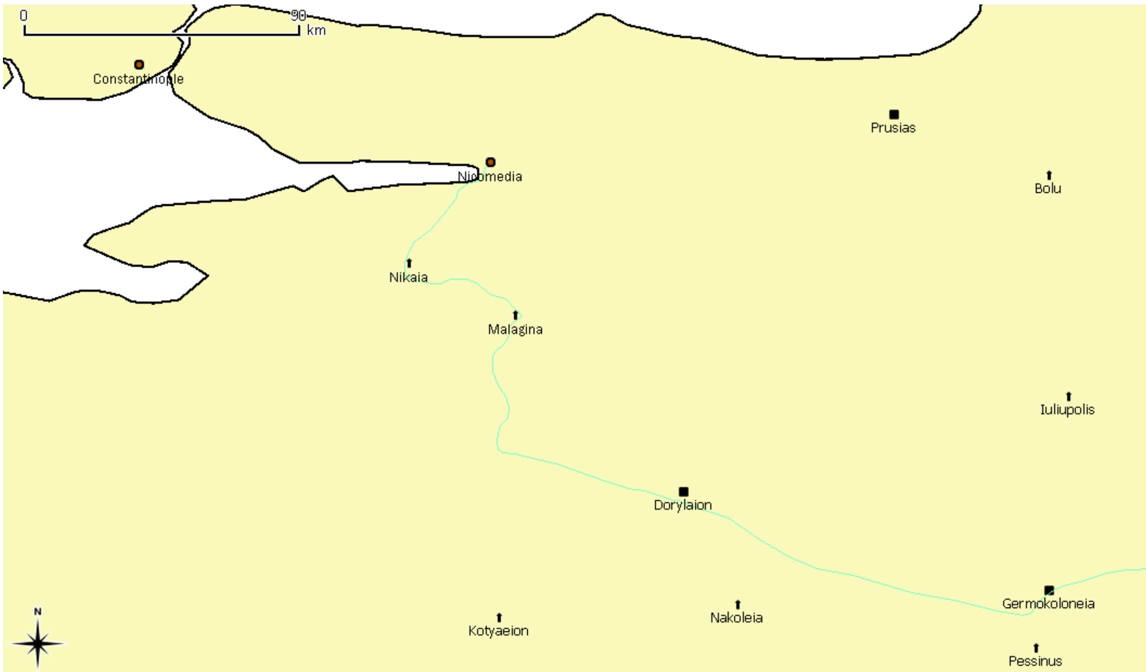


Figure 100: North West Anatolia, with the hypothetical route marked in blue

4.14.2.7 Nicomedia to Malagina

The journey between Nicomedia and Malagina would only have been around 55 miles (90 km) and would have been broken into two sections at Nikaia, "one of the greatest Byzantine cities" (Kazhdan et al. 1991, 1463). It is obviously impractical to travel all the way from Nicomedia to Malagina in a day, but our model indicates that even Nicomedia to Nikaia, a distance of 27 miles along the road, would have been a challenge for our hypothetical army. The army of 7061 agents was marched from Nicomedia to a point halfway between it and Nikaia. Both 1 column and 3 columns were tried and the data recorded below.

	1 column	3 columns	1 column without unfinished
Average arrival time	7792.2	6446.21	6581.8
Average distance covered	24823.62	27009.46	25761.91
Average arrival time (Officers only)	7166.73	6156.22	6471.52
Last arrival tick	10877	8197	10797
Squads	1260	1260	1061
Agents	7061	7061	5071
Column Leaders	1	1	1
Cavalry Officers	1060	1060	1060
Infantry Officers	200	200	1
Cavalry Soldiers	4000	4000	4000
Infantry Soldiers	1800	1800	9
Average Calories Expended	1423.32	1480.98	1394.4
Average travel time	4038.72	4876.69	3902.28
Column Leader cals	1225	1037.36	1225
Cavalry Officer average cals	1354.1	1252.1	1354.1
Cavalry Officer high cals	1508	1467.06	1508
Cavalry Officer low cals	1193	1056.64	1193
Cavalry Soldier average cals	1404.23	1288.15	1404.23
Cavalry Soldier high cals	1598	1447.48	1598
Cavalry Soldier low cals	1191	1087.22	1191
Infantry Officer average cals	1496.13	1983.8	1749
Infantry Officer high cals	1749	2041	1749
Infantry Officer low cals	1260	1948	1749
Infantry Soldier average cals	1498.53	1988.64	1750
Infantry Soldier high cals	1750	2110	1750
Infantry Soldier low cals	1271	1956	1750
# of agents on last arrival tick	1287	9	9
# of agents on last arrival tick – 1	624	0	0
# of agents on last arrival tick – 2	60	0	0
# of agents on last arrival tick – 3	19	0	0

Table 53: Aggregate data from Nicomedia heading towards Nikaia

As can be seen, the last agent in the three column army reaches its destination at tick number 8197, approximately three quarters of the way through the available daylight. This represents a sensible movement distance given the need for some time at the start of the march to ensure everyone gets packed up and has something to eat. With only one column, likely considering the probability of a good road between Nicomedia and Nikaia, the infantry are just arriving at the destination camp as the sun sets. As this is the first day's march of the whole Manzikert campaign the distance attempted may have contained more than a measure of guesswork although the size of the force at this point will most likely have been one which the Emperor would have had experience dealing with.

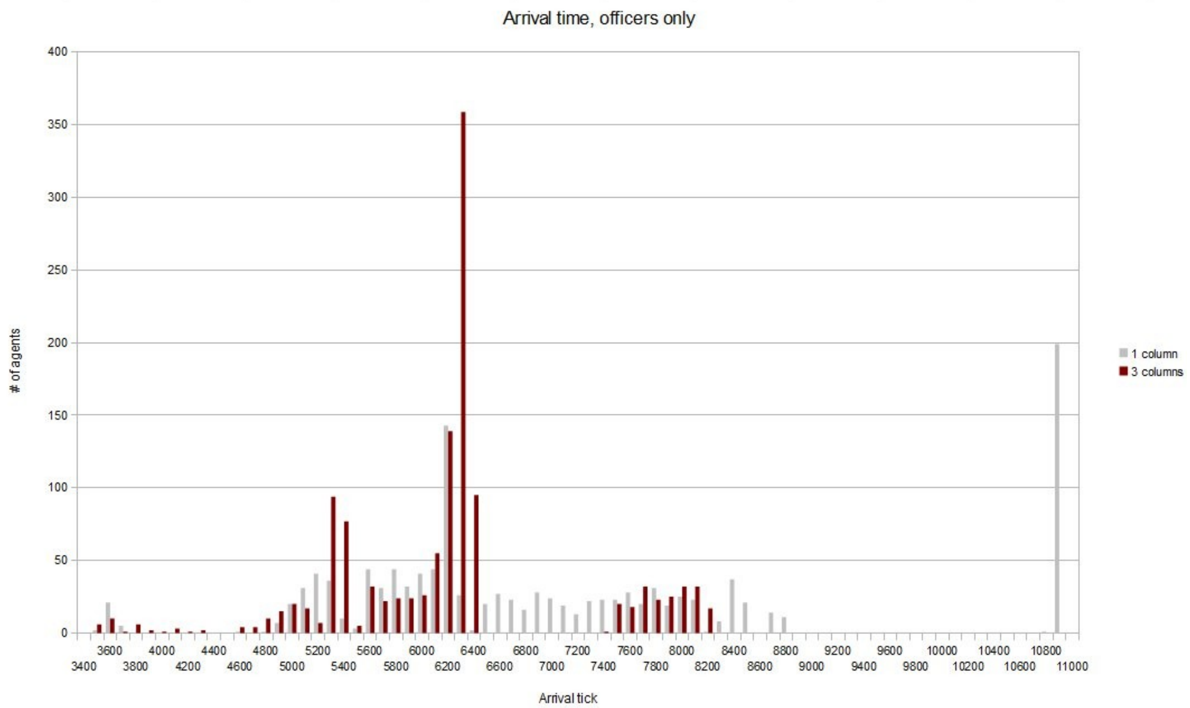


Figure 101: DM008 Nicomedia - Nikaia arrival time, Officers only

So although the three column model provides the army with plenty of time to arrive at a camp halfway between Nicomedia and Nikaia comfortably before sunset it is more likely that either three days were taken to reach Nikaia or the infantry had to put up their tents in the dark. Figure 102 shows that even if 3 columns were practical, it would have resulted in around 3000 agents arriving in camp within 300 ticks, less than 20 minutes of real time. The three column model also represents a much increased average travel time (Figure 103) even without taking into account the fact that the Sea of Marmara would have effectively blocked one of the routes taken in this model requiring an even longer route to be taken.

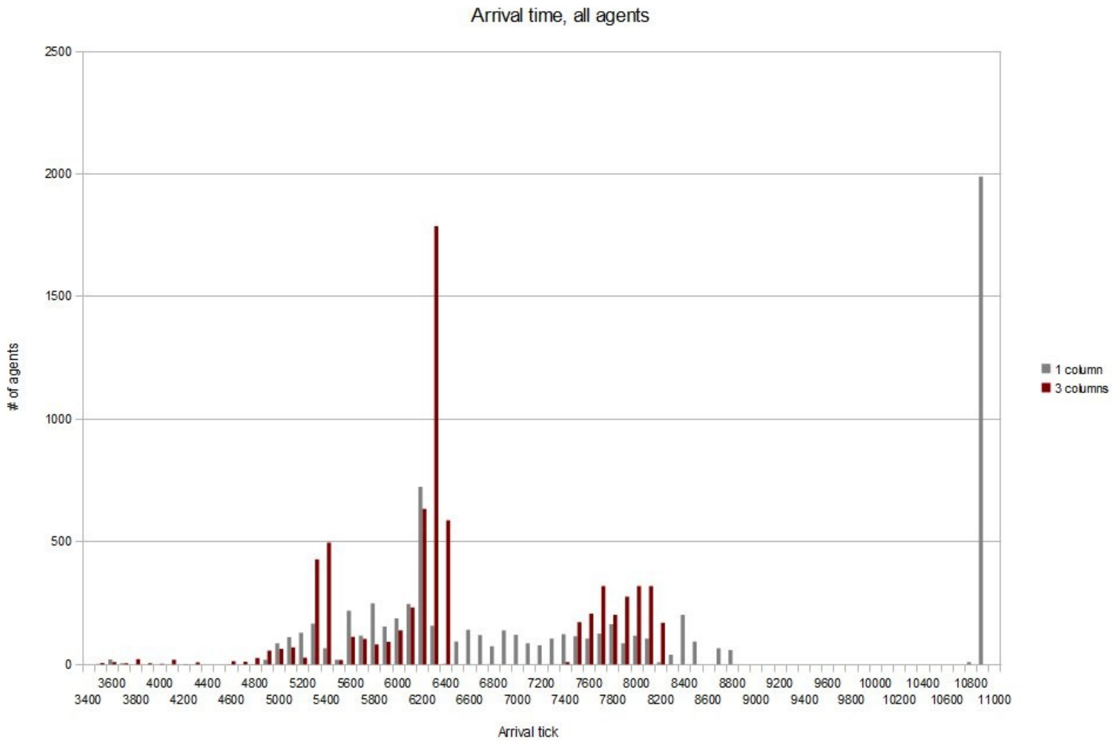


Figure 102: DM008 Nicomedia - Nikaia arrival time, all agents

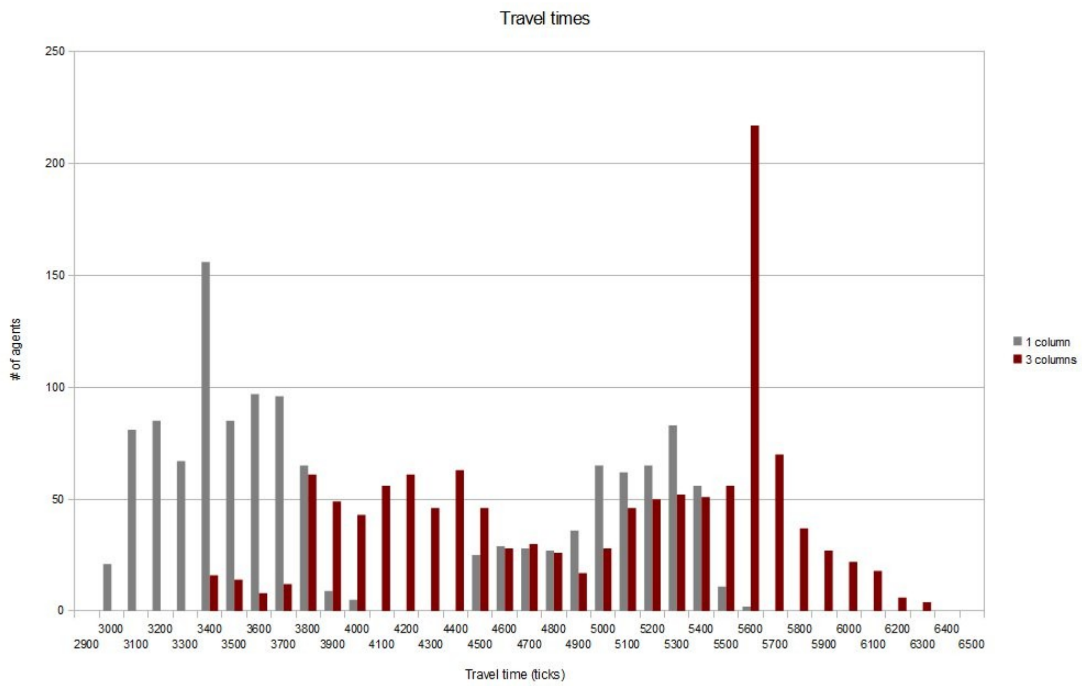


Figure 103: DM008 Nicomedia - Nikaia travel time, Officers only

With this in mind, and considering the likelihood of picking up supplies at Nikaia, it seems reasonable to assign 3 days for the journey from Nicomedia to Nikaia, a day of rest and resupply, then another 3 days from Nikaia to Malagina where, in our model, new troops would have been waiting. This seven day travel time actually coincides with that taken by First Crusade forces between Nikaia and Dorylaion (Bachrach 2006, 59), albeit for a force of unknown size.

It is interesting to note that the distance as the crow flies from Nicomedia to Nikaia is 43km and the distance via the hypothetical route is 44.5km yet the average travel distance for this half journey is 27km for the 3 column model and 25.7km for the single column. This represents the actual distance moved when taking into account exiting the camp, entering the destination camp and any increase from crowding and is an increase of 15% over the distance of the hypothetical route in the single column model and 21% in the three column model. Expanded over the course of the route, this would make a large distance to the actual distance travelled by the agents. Nicomedia to Manzikert as the crow flies is around 700 miles, our hypothetical route is around 1,110 miles but the actual distance covered on the march way well include the extra 15-21% implied in this scenario.

Although the average calories expended is higher for the infantry of the 3 column model reflecting the longer and possibly less optimal route of the second and third columns the average calorie expenditure for the cavalry is less. This can be explained by a reduction in the amount of crowding, a mechanism that can cause unnecessary movement in the cavalry agents. This may indicate a tendency to overestimate the number of calories used by cavalry agents within the model.

4.14.2.8 Malagina to Dorylaion

The journey from Malagina to Dorylaion along our hypothetical route covers a distance of 71 miles or 114 km (Figure 100) and involves travelling from 221m above sea level up to 799m. At Malagina the hypothetical force increases from around 7,000 troops to around 19,000 with the addition of the Frankish, German and Oghuz mercenaries and the five tagmata of the west, among others. There would have to have been at least a day for these forces to be introduced into the army's organisational structure. The supply situation at Malagina will almost certainly have been affected by how long the troops joining here will have been in the area. Initially the route between Malagina and Dorylaion was broken into four day's march but this proved to be beyond the capabilities of the modelled army completely, regardless of organisation. Splitting the route into eight resulted in more success.

4.14.2.8.1 *Cross Section of the Day's March*

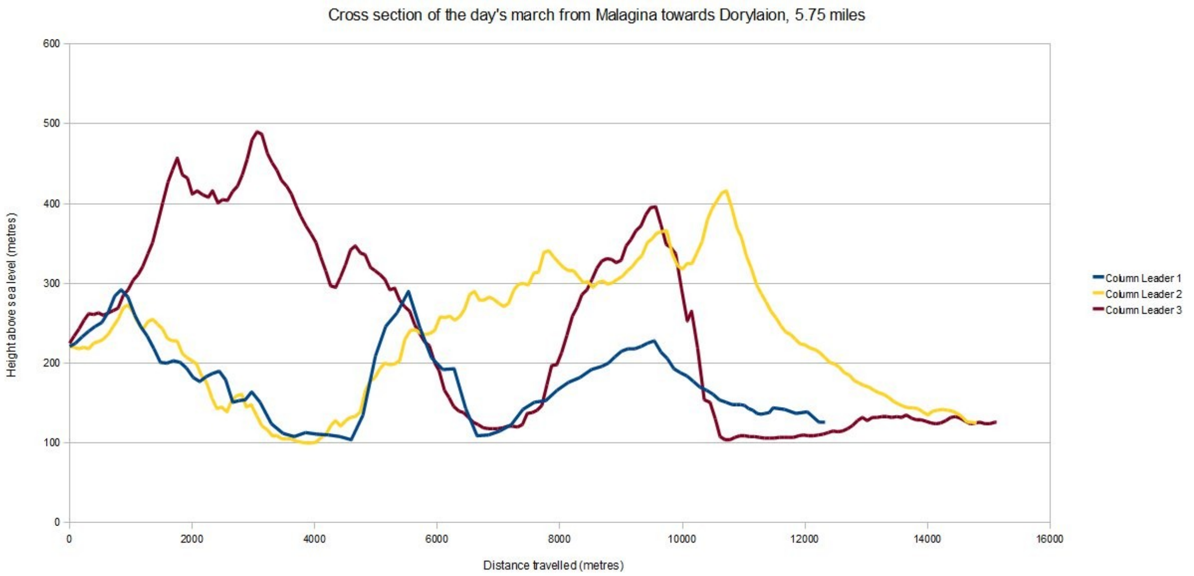


Figure 104: Malagina towards Dorylaion for 5.75 miles

As can be seen from the cross section of the day's march (Figure 104), the route to the first day's camp out of Malagina is uneven but does not contain any extreme increases of height.

4.14.2.8.2 Data

	1 column	2 columns	3 columns
Average arrival time	7206.3	8581.43	5570.6
Average distance covered	7334.61	15693.9	15252.78
Average arrival time (Officers only)	8380.17	9118.54	5272.97
Last arrival tick	10877	12809	9725
Squads	2940	2940	2940
Agents	19141	19141	19141
Column Leaders	1	1	1
Cavalry Officers	1940	1940	1940
Infantry Officers	1000	1000	1000
Cavalry Soldiers	7200	7200	7200
Infantry Soldiers	9000	9000	9000
Average Calories Expended	423.54	1241.83	1012.6
Average travel time	3110.95	5765.98	2915.84
Column Leader cals	628	647	628
Cavalry Officer average cals	657.52	1615.52	886.19
Cavalry Officer high cals	835	2593	1540
Cavalry Officer low cals	528	642	609
Cavalry Soldier average cals	675.65	1617.1	920.51
Cavalry Soldier high cals	903	2564	1593
Cavalry Soldier low cals	530	643	603
Infantry Officer average cals	189.74	883.72	1095.66
Infantry Officer high cals	563	1084	1386
Infantry Officer low cals	0	788	1008
Infantry Soldier average cals	197.39	900.93	1104.33
Infantry Soldier high cals	595	1134	1262
Infantry Soldier low cals	0	807	1004
# of agents on last arrival tick	2474	1338	2
# of agents on last arrival tick – 1	1641	988	5
# of agents on last arrival tick – 2	567	620	4
# of agents on last arrival tick – 3	28	540	4

Table 54: DM009, Malagina to camp #1

Although the one and two column scenarios do not result in all agents arriving in camp before nightfall, the three column model does, with just over an hour to spare. Although this would indicate that the army could march from Malagina to Dorylaion in eight days, horses and baggage animals would need at least one day's rest during that journey. As there would have been a day or two's rest at Malagina to incorporate the new troops into the army and another day to pick up supplies and new troops at Dorylaion only one day should be required. This would also provide a valuable opportunity to allow any stragglers to catch up to the main body of the army. This indicates a total of nine days from leaving Malagina to arriving at Dorylaion is a sensible time period for our hypothetical force.

4.14.2.9 Charsianon to Sebastea

By the time the army arrived at Charsianon, around halfway between Nicomedia and Manzikert, it had climbed in total over 1km from sea level to the Central Anatolian Plateau.

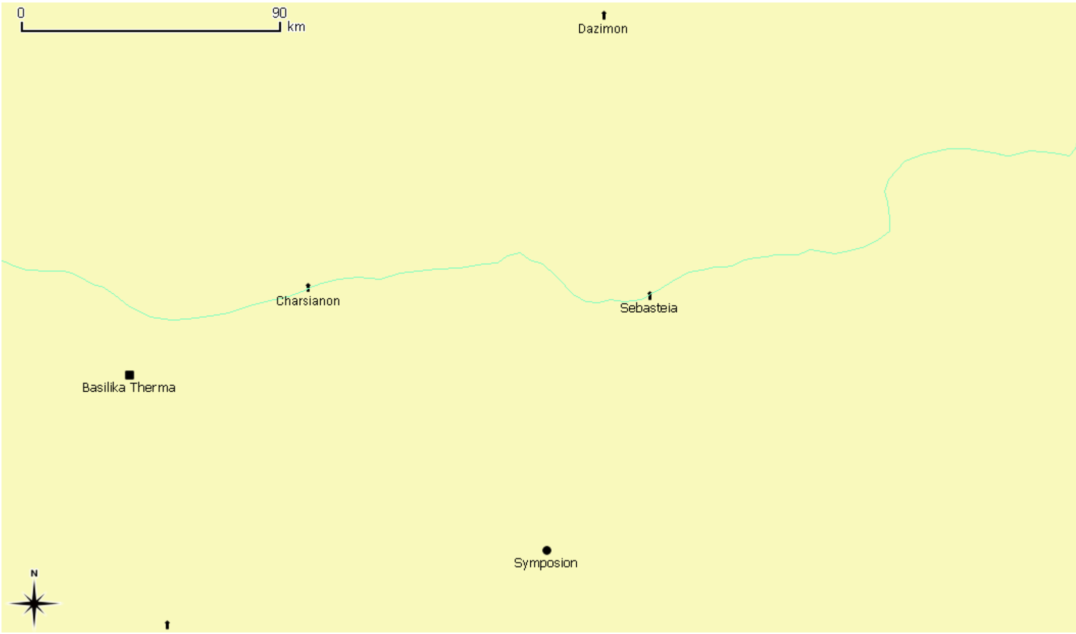


Figure 105: The route between Charsianon and Sebastea

The army size is similar to that between Malagina and Dorylaion as, although thematic tagmata from the Anatolikon and Cilician themes had joined, the German mercenaries had been sent back between Dorylaion and Charsianon. This leaves our hypothetical army at 20,000 agents.

4.14.2.9.1 Cross Section of the Day's March

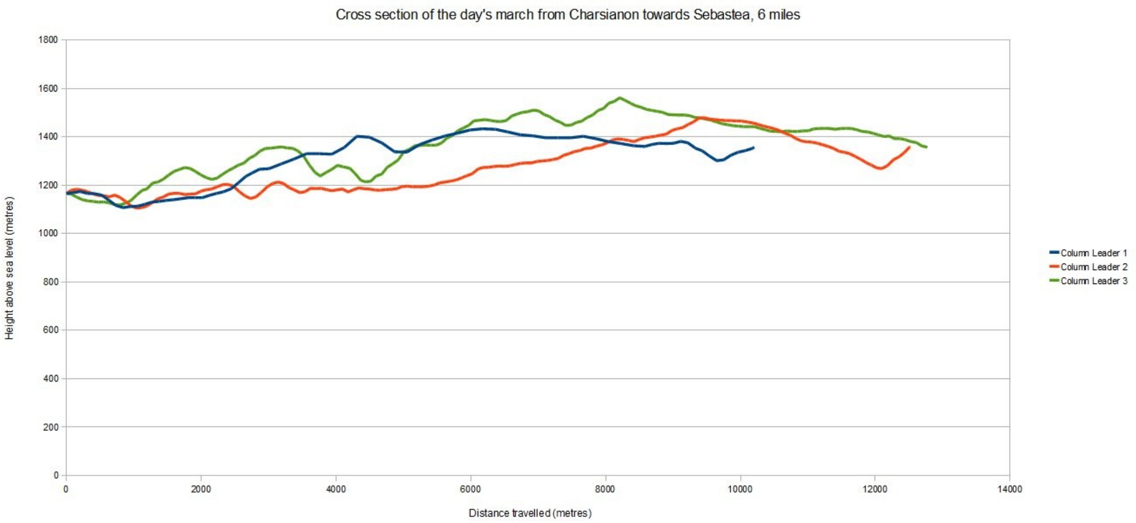


Figure 106: Cross section of the march out from Charsianon

The day's march modelled here heads straight out of Charsianon eastwards toward Sebastea. As can be seen, the march is undulating but contains no steep changes of altitude.

4.14.2.9.2 Data

	1 column	2 columns	3 columns
Average arrival time	10242.07	6101.19	5300.78
Average distance covered	9551.88	11884.35	12819.29
Average arrival time (Officers only)	9075	6240.32	4898.34
Last arrival tick	13886	9531	8315
Squads	3200	3200	3200
Agents	21133	21133	21133
Column Leaders	1	1	1
Cavalry Officers	2052	2052	2052
Infantry Officers	1148	1148	1148
Cavalry Soldiers	7600	7600	7600
Infantry Soldiers	10332	10332	10332
Average Calories Expended	602.1	807.04	873.49
Average travel time	2392.11	2647.9	2340.46
Column Leader kcals	531	536	554
Cavalry Officer average kcals	581.97	604.33	685.63
Cavalry Officer high kcals	760	852	869
Cavalry Officer low kcals	525	524	524
Cavalry Soldier average kcals	591.39	600.28	694.22
Cavalry Soldier high kcals	806	836	838
Cavalry Soldier low kcals	518	530	523
Infantry Officer average kcals	608.76	970.68	1023.6
Infantry Officer high kcals	769	1026	1191
Infantry Officer low kcals	87	919	948
Infantry Soldier average kcals	613.25	981.24	1026.01
Infantry Soldier high kcals	778	1043	1186
Infantry Soldier low kcals	88	936	948
# of agents on last arrival tick	2709	4	9
# of agents on last arrival tick – 1	1951	1	0
# of agents on last arrival tick – 2	174	0	0
# of agents on last arrival tick – 3	43	0	0

Table 55: Day's march east from Charsianon, 6 miles

The maximum number of ticks has been set to 13886, representing the amount of daylight available on the 15th of May at Ankyra, the nearest reference point. As can be seen (Table 55), the single column model failed to arrive in time while the double and triple column models arrived with over 4,000 ticks to spare. This represents a comfortable amount of daylight in which to break and set up camp, around 4 hours. With this in mind it is likely that longer marches could be considered, especially where suitable camp locations were available. The army would of course by now be well practiced in breaking and making camp. The Imperial party may also have split itself off as mentioned by Attaleiates (1853, 146).

Considering the circumstances and the fact that the army increased in size at Sebastea by over 25%, it may well have been that this section of the march across the relatively flat plains between Charsianon and Sebastea was among the most efficient on the march, where the 6 miles per day typical of previous sections could be increased for a time.

4.14.2.10 Theodosiopolis to Manzikert

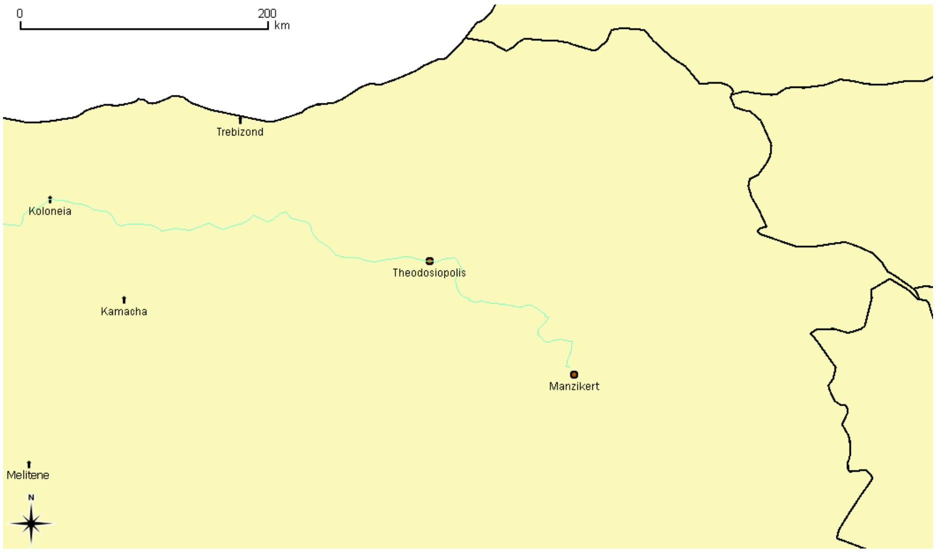


Figure 107: The route between Theodosiopolis and Manzikert

The journey from Theodosiopolis to Manzikert (Figure 107) represents one of the most interesting parts of the journey across Anatolia. In the ABM's hypothetical army, as in the real army, the time between leaving Theodosiopolis and the split of the army into two parts represents the army at its largest.

	1 column	1 column without unfinished
Average arrival time	6751.23	8908.84
Average distance covered	6063.76	10885.98
Average arrival time (Officers only)	9115.55	8082.56
Last arrival tick	13757	13757
Squads	4540	2798
Agents	32207	14787
Column Leaders	1	1
Cavalry Officers	2466	2466
Infantry Officers	2074	332
Cavalry Soldiers	9000	9000
Infantry Soldiers	18666	2988
Average Calories Expended	437.39	737.1
Average travel time	2255.83	2508.01
Column Leader kcals	602	602
Cavalry Officer average kcals	632.54	632.54
Cavalry Officer high kcals	730	730
Cavalry Officer low kcals	555	555
Cavalry Soldier average kcals	629.83	629.83
Cavalry Soldier high kcals	753	753
Cavalry Soldier low kcals	567	567
Infantry Officer average kcals	328.44	1095.12
Infantry Officer high kcals	1148	1148
Infantry Officer low kcals	0	1031
Infantry Soldier average kcals	330.92	1106.77
Infantry Soldier high kcals	1165	1165
Infantry Soldier low kcals	0	1029
# of agents on last arrival tick	3023	9
# of agents on last arrival tick – 1	2322	19
# of agents on last arrival tick – 2	851	10
# of agents on last arrival tick – 3	72	1

Figure 108: DM008 first march out of Theodosiopolis

Figure 108 shows the aggregated data from the single column model, with all agents in the left hand spreadsheet column and only those who arrived in camp before the end of the day in the right hand. The length of day was set to 13757 ticks as per the amount of daylight on the 1st August. This reflects the uncertainty regarding the amount of time spent at Theodosiopolis, a topic dealt with in Chapter 5. As can be seen, just under half the force was able to arrive at the camp before sunset. Energy expenditure seems within reasonable limits, a fact maybe reflecting that the Theodosiopolis - Manzikert leg of the campaign is the only one in which the destination is lower than the starting point. The failure of the second half of the army to arrive would seem to rule out a single column march over 6 miles. Some of the agents had not even set off from their starting camp outside Theodosiopolis by the end of the day.

The choices for the Emperor are limited in this situation. He can shorten the daily march even further, marches of around 3 miles are recorded for other campaigns in history (Furse 1901, 237). He can split the army into different columns, an organisational mechanism discussed above. He can also split the army along the same route with one group travelling a day behind the other. This may well have been the case as, although close to the Seljuk army by this point, this was a fact unknown to Romanos IV Diogenes. The column did in fact split at some point on the road to Manzikert with half the army heading off to Khliat, after which point it seems a 6 mile march per day is not unreasonable. This was widely claimed to be for strategic reasons though, (Friendly 1981, 173) and there is no suggestion that logistical considerations played a part in the decision. If the army was still travelling in a single group it must have been a relief to both portions of the army to be suddenly much easier in their day to day movements. If there were two sections travelling one a day behind the other then the diversion of one section to Khliat would have made movement no easier and the rear group would have been responsible for their own fortification each day again.

4.14.3 DM008 Conclusions

It can clearly be seen from the results that the infantry used more calories on the march than the cavalry, even without taking into account tasks involved in setting up the camp, a burden likely to have fallen heavier upon the infantry. Of course demonstrating that cavalry used less calories on the march does not prove that they had access to or ate less food. The reverse may even be the case, food is not merely a tally of calories inwards but a source of pleasure and a denoter of status. Certainly officers, bureaucrats and other high status persons were likely to have had access to more, richer food than those further down the hierarchy who actually expended more energy.

Even taking into account the mountainous terrain and the size of the army, 56 days to travel from Theodosiopolis to Manzikert is excessive. This must have included quite a stay at Theodosiopolis and may even add evidence to the claim that large amounts of supplies were collected. Even though it would be impractical to move the 3 months worth of supplies claimed, there may still have been a significant amount of food collected. The time possibly spent at Theodosiopolis indicates that maybe these supplies were gathered from an extended area around the town. This storing of supplies for the rest of the campaign added to the time the army stayed in the area during which they had to be fed, all on top of any losses to Turkish raiders which would have left the town denuded of resources in a way not likely to have been experienced by any other settlement on the route.

4.15 DM009 - Supply

4.15.1 Introduction

The purpose of DM009 is to investigate the relationship between the conditions of the march and the calories consumed during its course. This will also enable the modelling of the effects of the army's march on the settlements through which it passed in greater detail. The equation used to calculate energy expenditure is easily modified to accomodate the carrying of supplies by infantry troops. The weight specified for each individual is their body weight combined with any clothing and carried objects. In DM008 the weight of each agent plus their clothing was assumed to be 70kg. If this is taken to still be the case, any carried supplies can be added to this value to determine a total weight for each agent. The model has been modified so that the weight of each agent is specified in the initialisation file, allowing scenarios in which the same group of agents can traverse the same terrain carrying different weights of supplies.

In the DM009 scenarios we return to the area around Nikaia, as used in DM001 - DM007. Clark & Haswell (1970, 202 – 205) give 80lbs (36kg) as the maximum amount of weight in excess of ordinary clothing that a human can comfortably carry for a long distance. This is taken as the maximum extra supplies that an agent will carry in these scenarios. In addition to the standard 70kg of our hypothetical infantryman plus clothing, an intermediate value of 18kg of extra supplies has also been calculated. Armies of 3 different compositions are marched over either 6 miles or 9 miles with either no extra supplies, 18kg of extra supplies or 36kg of extra supplies. The hypothetical force from the DM008 scenarios is marched in both single column and double column configurations to assess any difference that the splitting of the army may create. The differences in calorie expenditure are noted and compared with the extra amount of food that the extra carrying capacity allows. This only applies to infantry troops. Although there exists in the equation the capability of doing the same thing for cavalry, that would assume any extra supplies were carried by the rider and not the horse, an unlikely situation. The ability to calculate animal energy expenditure has not yet been programmed into the model.

Troop Type	Small	Medium	'Historical'
Officers	25	50	60
Officer Cavalry Squads	25	50	300
Cavalry Squads	100	250	700
Infantry Squads	100	750	200

Table 56: DM009 army sizes

4.15.2 Data

6 miles, Small			
Agent weight	70kg	88kg	106kg
Average arrival time	3926.71	3931.61	3939.11
Average distance covered	11927.65	11923.71	11930.21
Average arrival time (Officers only	3391.8	3405.78	3412.47
Last arrival tick	5296	5297	5307
Squads	250	250	250
Agents	1651	1651	1651
Column Leaders	1	1	1
Cavalry Officers	150	150	150
Infantry Officers	100	100	100
Cavalry Soldiers	500	500	500
Infantry Soldiers	900	900	900
Average Calories Expended	794.66	941.08	1097.41
Average travel time	1986.05	2000.1	2006.82
Column Leader cals	630	625	625
Cavalry Officer average cals	644.33	643.31	642.85
Cavalry Officer high cals	674	690	672
Cavalry Officer low cals	616	614	622
Cavalry Soldier average cals	643.3	639.36	640.48
Cavalry Soldier high cals	681	686	677
Cavalry Soldier low cals	594	606	606
Infantry Officer average cals	888.87	1132.05	1387.85
Infantry Officer high cals	930	1181	1443
Infantry Officer low cals	865	1100	1337
Infantry Soldier average cals	893.51	1137.46	1395.28
Infantry Soldier high cals	926	1175	1442
Infantry Soldier low cals	866	1108	1346
# of agents on last arrival tick	9	9	9
# of agents on last arrival tick – 1	9	0	0
# of agents on last arrival tick – 2	0	0	9
# of agents on last arrival tick – 3	0	0	0

6 miles, Medium			
Agent weight	70kg	88kg	106kg
Average arrival time	5942.79	5984.58	6000.29
Average distance covered	12022.44	12089.77	12097.75
Average arrival time (Officers only	5381.94	5421.43	5434.28
Last arrival tick	8580	8581	8689
Squads	1100	1100	1100
Agents	9051	9051	9051
Column Leaders	1	1	1
Cavalry Officers	350	350	350
Infantry Officers	750	750	750
Cavalry Soldiers	1200	1200	1200
Infantry Soldiers	6750	6750	6750
Average Calories Expended	873.61	1101.34	1322.54
Average travel time	2311	2350.53	2363.39
Column Leader cals	619	614	619
Cavalry Officer average cals	647.51	647.76	647.57
Cavalry Officer high cals	694	703	689
Cavalry Officer low cals	609	613	617
Cavalry Soldier average cals	642.26	642.52	644.26
Cavalry Soldier high cals	714	695	696
Cavalry Soldier low cals	604	602	603
Infantry Officer average cals	917.54	1189.62	1454.53
Infantry Officer high cals	1043	1450	1666
Infantry Officer low cals	831	1054	1293
Infantry Soldier average cals	921.62	1196.69	1463.56
Infantry Soldier high cals	1029	1603	1817
Infantry Soldier low cals	833	1061	1300
# of agents on last arrival tick	18	9	9
# of agents on last arrival tick – 1	0	0	9
# of agents on last arrival tick – 2	1	1	10
# of agents on last arrival tick – 3	9	9	1

6 miles, Historical						
Agent weight	70kg	88kg	106kg	70kg – CL2	88kg – CL2	106kg – CL2
Average arrival time	5712.1	5720.55	5717.96	4028.26	4109.12	4074.34
Average distance covered	12021.76	12121.9	12026.34	12450.13	12630.05	12692.7
Average arrival time (Officers only	5170.8	5186.32	5193.12	3922.2	3992.87	3948.41
Last arrival tick	9189	9221	9107	5607	5735	5435
Squads	1260	1260	1260	1260	1260	1260
Agents	7061	7061	7061	7061	7061	7061
Column Leaders	1	1	1	1	1	1
Cavalry Officers	1060	1060	1060	1060	1060	1060
Infantry Officers	200	200	200	200	200	200
Cavalry Soldiers	4000	4000	4000	4000	4000	4000
Infantry Soldiers	1800	1800	1800	1800	1800	1800
Average Calories Expended	721.84	802.33	867.07	715.57	815.73	908.8
Average travel time	2042.74	2058.27	2065.07	2179.57	2250.3	2205.8
Column Leader cals	630	620	614	624	624	614
Cavalry Officer average cals	643.47	654.29	645.85	680.44	679.65	677.33
Cavalry Officer high cals	738	755	756	828	819	858
Cavalry Officer low cals	591	597	597	607	598	602
Cavalry Soldier average cals	637.72	647.59	641.9	677.78	679.54	677.78
Cavalry Soldier high cals	723	764	768	840	840	880
Cavalry Soldier low cals	572	582	583	594	586	595
Infantry Officer average cals	928.9	1184.26	1425.23	802.23	1143.48	1476.63
Infantry Officer high cals	1037	1332	1537	844	1360	1545
Infantry Officer low cals	850	1102	1331	772	1037	1410
Infantry Soldier average cals	931.97	1191.05	1435.86	810.68	1162.22	1495.54
Infantry Soldier high cals	1077	1391	1616	860	1472	1607
Infantry Soldier low cals	859	1105	1347	769	1049	1435
# of agents on last arrival tick	9	9	9	4	4	4
# of agents on last arrival tick – 1	0	0	0	1	0	1
# of agents on last arrival tick – 2	0	0	0	0	1	0
# of agents on last arrival tick – 3	1	0	1	0	0	0

Table 57: DM009 6 miles march data

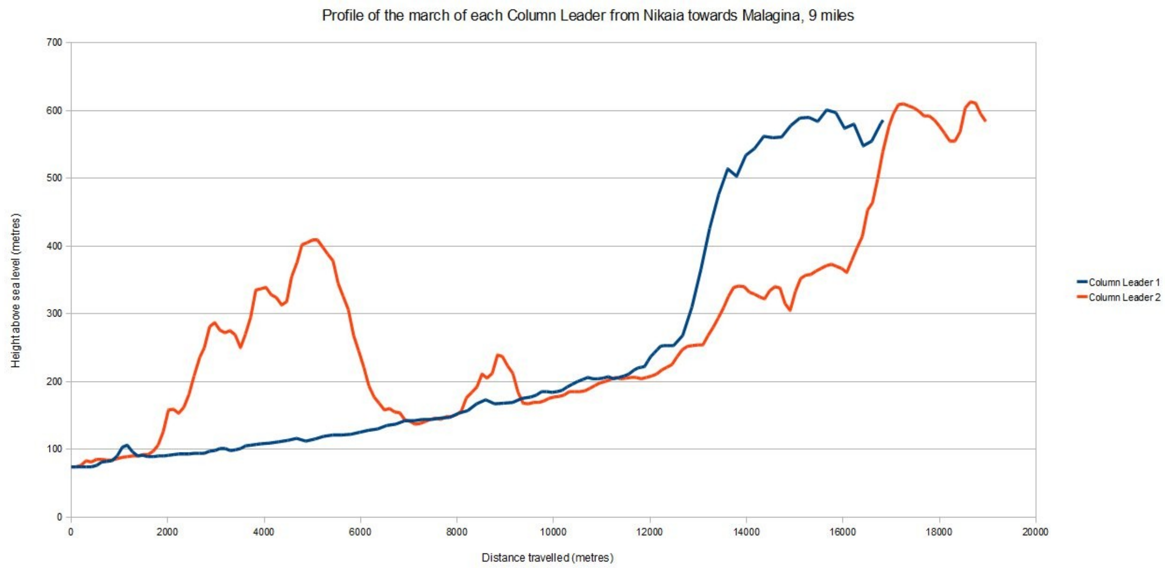
9 miles, Small			
Agent weight	70kg	88kg	106kg
Average arrival time	4809.38	4801.69	4807.92
Average distance covered	17045.37	17017.06	17012.21
Average arrival time (Officers on▸	4155.02	4141.57	4162.52
Last arrival tick	6399	6390	6377
Squads	250	250	250
Agents	1651	1651	1651
Column Leaders	1	1	1
Cavalry Officers	150	150	150
Infantry Officers	100	100	100
Cavalry Soldiers	500	500	500
Infantry Soldiers	900	900	900
Average Calories Expended	1083.48	1277.09	1475.13
Average travel time	2750.08	2736.61	2757.64
Column Leader cals	840	835	840
Cavalry Officer average cals	857.25	858.43	858.31
Cavalry Officer high cals	895	916	916
Cavalry Officer low cals	823	824	828
Cavalry Soldier average cals	877.47	877.75	877.57
Cavalry Soldier high cals	933	959	943
Cavalry Soldier low cals	823	809	832
Infantry Officer average cals	1211.04	1531.61	1853.67
Infantry Officer high cals	1234	1564	1889
Infantry Officer low cals	1186	1488	1817
Infantry Soldier average cals	1221.73	1540.92	1868.56
Infantry Soldier high cals	1244	1609	1936
Infantry Soldier low cals	1198	1500	1835

9 miles, Medium			
Agent weight	70kg	88kg	106kg
Average arrival time	7026.81	7005.46	7012.55
Average distance covered	17439.39	17412.59	17501.5
Average arrival time (Officers on▸	6404.41	6375.27	6376.26
Last arrival tick	9593	9664	9661
Squads	1100	1100	1100
Agents	9051	9051	9051
Column Leaders	1	1	1
Cavalry Officers	350	350	350
Infantry Officers	750	750	750
Cavalry Soldiers	1200	1200	1200
Infantry Soldiers	6750	6750	6750
Average Calories Expended	1282.72	1580.77	1949.7
Average travel time	3333.91	3304.73	3305.73
Column Leader cals	835	845	835
Cavalry Officer average cals	895.09	893.97	899.43
Cavalry Officer high cals	961	961	966
Cavalry Officer low cals	839	833	833
Cavalry Soldier average cals	917.41	915.76	922.48
Cavalry Soldier high cals	992	1003	995
Cavalry Soldier low cals	855	850	855
Infantry Officer average cals	1343.79	1692.62	2133.47
Infantry Officer high cals	1666	1888	2317
Infantry Officer low cals	1269	1598	1954
Infantry Soldier average cals	1361.04	1722.29	2166.53
Infantry Soldier high cals	1835	2112	2564
Infantry Soldier low cals	1274	1654	1991

9 miles, Historical						
Agent weight	70kg	88kg	106kg	70kg – CL2	88kg – CL2	106kg – CL2
Average arrival time	6556.36	6512.14	6517.67	4977.16	4968.28	4887.03
Average distance covered	17504.83	17409.66	17389.8	18048.1	18086.35	18089.6
Average arrival time (Officers on▸	5982.72	5938.28	5910.61	4773.08	4776.92	4668.26
Last arrival tick	10134	10096	10266	6504	6486	6639
Squads	1260	1260	1260	1260	1260	1260
Agents	7061	7061	7061	7061	7061	7061
Column Leaders	1	1	1	1	1	1
Cavalry Officers	1060	1060	1060	1060	1060	1060
Infantry Officers	200	200	200	200	200	200
Cavalry Soldiers	4000	4000	4000	4000	4000	4000
Infantry Soldiers	1800	1800	1800	1800	1800	1800
Average Calories Expended	1051.54	1134.67	1214.99	1110.47	1224.07	1347.15
Average travel time	2854.87	2810.38	2782.7	3030.69	3034.53	2925.79
Column Leader cals	836	830	840	835	835	840
Cavalry Officer average cals	917.61	914.12	905.6	963.3	962.95	958.58
Cavalry Officer high cals	993	997	983	1218	1230	1203
Cavalry Officer low cals	840	832	834	836	825	840
Cavalry Soldier average cals	935.78	932.37	923.79	976.92	975.94	972.86
Cavalry Soldier high cals	1030	1036	1017	1163	1159	1170
Cavalry Soldier low cals	841	839	849	848	857	854
Infantry Officer average cals	1347.3	1644.39	1951.34	1447.59	1841.68	2278.15
Infantry Officer high cals	1405	1705	2048	1496	1917	2394
Infantry Officer low cals	1294	1594	1887	1415	1797	2212
Infantry Soldier average cals	1354.89	1657.63	1962.69	1456.6	1860.81	2304.58
Infantry Soldier high cals	1406	1709	2092	1500	1911	2481
Infantry Soldier low cals	1317	1609	1880	1426	1812	2240

Table 58: DM009 9 miles march data

4.15.3 Cross Section of the March



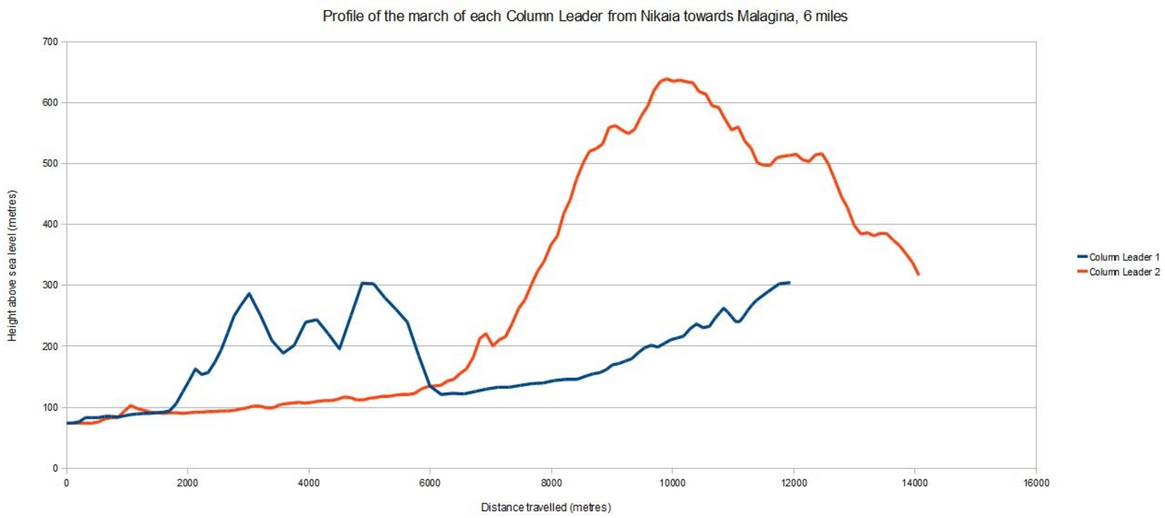


Figure 109: DM009 6 mile cross section

As can be seen from the profile of the march, the 6 mile march is largely flat (Figure 109), climbing only just over 200 metres over the course of around 12km. The second column takes a much less optimal route, rising almost 600m at one point. Over 9 miles the two routes are more similar in character (Figure 110).

4.15.4 Supplies

Engels states that 1kg of wheat ultimately provides 2025 kcals of digestable energy (1978, 123). Within the 'historical' army size, the 2000 infantry would therefore be able to carry a combined total of 145,800,000 kcals of wheat between them. This would cost them an extra 1,006,270 kcals to transport over 6 miles and 1,214,849 kcals to transport over 9 miles (Table 59). As these calories are merely the calories expended on the march, these values ignore any calories spent on any activities in camp or indeed the calories needed to keep the body functioning when idle. If these are added to the equation then moving 2 days at 9 miles per day will become more efficient than moving 3 days at 6 miles per day. The energy expended in digging the ditch around the camp or even just lounging around on that extra third day is all energy that would not have been expended if two days had been taken instead.

Nevertheless, taking the value for the 9 mile march with no extra load carried by the infantry, the energy expended on the march by our hypothetical army would have equated to over 1337 kg of wheat for the infantry alone. If the number of calories used by each agent for all non-marching activities is set at 2000 kcals per day, the whole army on this day would use 19,218,912 kcals. It would take 9490 kg of wheat to make enough bread to replace these calories at just over 1.3kg of wheat consumed per person. This equals pretty much exactly Donald Engels' estimate of 3lbs (1978, 125). If each infantryman carries 36kg of supplies the total energy expenditure of the army over a 9 mile march increases to 20,244,381 kcals. This adds an extra 506kg to the weight of the wheat required and would have a knock-on effect on the weight carried the following day. Obviously wheat is not the only food available to the Byzantine army, it is used here merely as an indicator of the complexity of the relationship between energy in and energy out.

	Total Infantry kcals						1 column		2 columns		Increase in kcals by splitting into 2 columns		
	70kg	88kg	106kg	70kg – CL2	88kg – CL2	106kg – CL2	Increased kcals by carrying 18kg	Increased kcals by carrying 36kg	Increased kcals by carrying 18kg	Increased kcals by carrying 36kg	70kg	88kg	106kg
6 miles	**1863318**	**2380740**	**2869588**	**1619678**	**2320685**	**2987298**	**517422**	**1006270**	**701007**	**1367620**	**-243640**	**-60055**	**117710**
9 miles	2708263	3312614	3923112	2911391	3717792	4603881	604351	1214849	806401	1692490	203128	405178	680769

Table 59: DM009 Calories consumed on the march

When looking at the effect that the passage of the army might have had on the settlements through which it passed, the start of the march from Nicomedia to Malagina would seem to be the area of least concern. Large settlements such as Nicomedia, Nikaia, Malagina and Dorylaion would all have had access to ample food stocks to feed their own population and the army at this point would have been comparatively small and fast moving. The timing of the march is important though, the march from Nicomedia to Dorylaion would probably have taken place in March, just after the winter and long before the harvest. There may also have been the need to start collecting extra food in order to have some spare for when the much larger army arrives at the less hospitable areas further east.

4.15.5 DM009 Conclusions

As can be seen, the relationship between supplies and the carrying capacity of the army is a complex one. The single computer ABM used here is only able to run a day's march in a reasonable timescale but supply issues are more longer term than that. The Byzantine army on the march to Manzikert will be constantly consuming and collecting resources, both at variable rates. To add further complexity, meat can be brought along on the hoof. This will cause crowding and organisational problems but will remove the need for the members and baggage animals of the army to carry this valuable source of food. When required the baggage animals themselves can be used to feed the members of the army.

The movement of an army over a day will affect the food required to keep them healthy which will in turn affect the amount of supplies carried which will feed back into the movement of the following day. The army is not just a complex system, it layers complex systems on top of complex systems. The daily total of energy expended is a result of the interactions of the agents on the march, the terrain to be crossed and the distance marched. The food expended then affects the calories expended on the following day's march so both the micro and macro level movement introduce complexity into the system. As can be seen from chapters 2 and 3, mechanisms exist for this to be modelled but a single computer lacks the processing resources to run the model within a practical timescale. The distributed infrastructure currently under development will allow larger scale models of more than a single day's duration in order to investigate this complex set of interdependancies.

4.16 Summary

The 244 scenarios used in DM001 - DM007 have taken 196,720 processing minutes which equals over 3278 hours, over 136 days, over 19 and a half weeks or over 4 months. This represents a mammoth processing task and highlights the need for a distributed infrastructure to spread the load from individual PCs to clusters or even cloud computing resources. As can be seen from these scenarios, by comparing the results of models in which only limited factors having changed, we can draw conclusions regarding the march of the Byzantine army across Anatolia to the Battle of Manzikert. The effects of crowding on overall speed and the comfort of the individual participants can be shown. The implications of different organisational mechanisms can be demonstrated along with the effects of differing army sizes and compositions. Some of these conclusions can also be applied to other pre-industrial armies on the march. The majority of work done in scenarios DM001 to DM007 is applicable to similarly sized armies in similar conditions and highlights the model's ability to be used in other situations. In the following chapter we will review the project, determine any new evidence it has brought to the subject and suggest further work.

5 Conclusions

5.1 Introduction

The differences between the work presented here and previous attempts to examine the practicalities of pre-modern military logistics are profound. Whereas top-down systemic approaches have done much to introduce quantitative values to the subject of military logistics, ABM can provide much finer detail while examining the complexity of moving large numbers of people. An army on the march is a complex system and should be treated as such, to do otherwise is to ignore important details that can dramatically affect any conclusions. ABM provides a method for creating 'what if?' scenarios that can allow hypotheses to be tested and actual quantitative data to be produced. This can then be used to add detail to debates that have previously relied on historical sources alone, sources that often give misleading quantitative values or simply omit them altogether. The replicable nature of computer modelling then allows these hypotheses to be modified, expanded and retested by others, all while being able to be visualised in a variety of forms to specialists and non-specialists alike.

This chapter contains a summary of the project and its results, demonstrating that the project does deliver new evidence and new insights into the movement of pre-industrial armies. Ways are suggested in which the model can be improved to be both more accurate and more expansive. Situations are identified in which the modelling principles could be used in other places and in eras across the pre-industrial world. The conclusions of the research, both intended and unintended, are outlined with specific attention given to new evidence created by the models for the march of the Byzantine army across Anatolia to Manzikert.

5.2 The Art of Marching

One of the biggest helps to the project has been the discovery, via the kind advice of

Professor Gary Sheffield, of Colonel Furse's book, *The Art of Marching*. Where there existed gaps in the historical records and no framework could be found to provide a plausible model, Furse would have an answer and a series of historical examples. It seems clear from conducting the highly practical task of modelling an army on the march that the information contained within *The Art of Marching* is derived from personal experience and/or the sound study of the records of others with personal experience of moving large bodies of people on a military campaign. Although it cannot be demonstrated that the Byzantine army used such methods as regular rests to compact the column or sending the cavalry ahead of the infantry, their utility can be demonstrated by modelling.

In general, the assumptions made during the making of the model are reinforced, or at least not contradicted by *The Art of Marching*. The current Day's March model's assumption that the troops will exit the camp to form up at the start of the day's march, then commence is borne out by Furse (1901, 333). He was well aware of the principal of the performance of the system being the result of the interactions between its individual elements long before ABM became a computer simulation technique. It may well be that the lessons learned on the Manzikert campaign were new to the people in charge but it surely would not have taken long for procedures to be put into place to avoid the chaos that might result from disorganised movement.

5.3 Reuse

Although the modularity of ABM and the portable nature of Java allow the model to be used by other researchers the practicality of this must be addressed. There is a reasonable library of archaeological ABMs produced since the 1970s yet only rarely are they rechecked, despite this being one of the supposed main advantages of computer modelling, Janssen's (2009) reevaluation of the modelling of Anasazi settlements (Dean et al. 2000) being a rare case. The structure of the MWGrid ABM lends itself to some minimal reuse, any start or end location in Central and Northern Anatolia can be specified in the initialisation file along with any size of army. To alter any agent behaviour requires access to the source code and a level of Java programming knowledge. The agents remain generic enough to represent any pre-industrial army but this generic nature reduces their application in specific instances. Any new types of agent or behaviours would require alterations to the source code. To facilitate any reuse of the project's code, the entire Java source code will be archived at the Archaeology Data Service and will be freely available for download.

5.4 Applicability of the Project to Other Places and Times

Reusing the model for other military campaigns would be possible due to the generic nature of the movement rules and the agent characteristics. The height data would be directly reusable in any simulation that dealt with the same geographic area such as the first Crusade or the journey to Myriokephalon in 1080. To a certain extent the results of the Day's March scenarios can be used to provide a quantitative framework for other military expeditions, or even movement of civilian populations. Generic models have their limitations though, and context is still important in agent-based modelling (Edmonds 2011).

5.5 Class Warfare

Within the structure of ABM, with its multiplicity of autonomous agents creating emergent behaviours, lies the ability to shed some light on the lives of people who were not considered important enough to have them recorded at the time. Although the agents within the model do not correspond to any actual individuals, the path of an agent through the model can tell us something about the experiences of individuals within the Byzantine army. Care must be taken to avoid over extrapolation, but differences in experience between individuals with different roles within the army can be plausibly detected.

We have seen in the results of DM007 that there exists the strong possibility of a disparity in comfort between cavalry and infantry within the Byzantine army. Attaleiates identifies certain events that hint of a lack of concord on the march, the hostility towards the Armenians at Sebastea and the harsh punishment of a soldier for stealing a donkey being two instances (Norwich 1991, 347). It is also noted that the Emperor split his baggage train off from the main body of the army just beyond the Halys, although this is not modelled within the scenarios. Clearly things were not going well. It is easy to see from the results obtained how the organisation of the army on the march can either promote unity or increase division. Some parts of the column will have had easier times under certain circumstances than others. In dry conditions, being at the head of the column has the advantage of not having the dust of the road kicked into your face by preceding troops (Rogers 2007, 76). If the overall length of the march is short enough, being at the back leaves time for a good breakfast yet raises the possibility that arrival at the destination camp will be when the majority of the surrounding ditch is dug. The disparity of experiences available means that an astute commander will give everyone a share of the benefits whereas an inconsiderate or malicious commander may put the same burdens on the same, steadily more disillusioned, troops.

One problem with measuring marching efficiency under ideal conditions is that the people making the decisions regarding march length and organisation are not the ones at the rear of the column. It is possible to assume everything is working acceptably simply because the people at the top of the hierarchy arrive at the following day's camp in plenty of time. Either the information regarding the arrival of later members of the army may not filter all the way up to the leaders or they may simply not care. We have tended to assume during the Day's March scenarios that the goal is to get everyone into the destination camp with enough time to set up before nightfall. This is not necessarily a sound assumption, however the models are there to act as a null hypothesis against which we can compare theories. We cannot prove that the people making the decisions regarding the length of march cared whether those at the rear arrived in camp before sunset but we can say something about the conditions in which that might happen. Modelling is an aid to historical analysis, not a substitute for it.

5.6 What Effect Did the Supply of the Army Have on the Settlements Through Which it Passed?

When examining the design, implementation and results of the MWGrid ABM it is important to remember the project's main research questions.

- What effect did the supply of the army have on the settlements through which it passed?
- How did the army organisation affect the overall speed?
- How do the size and composition of the army affect the overall speed?

In order to summarise the success or otherwise of the project it will be necessary to review the progress made towards answering these questions. If ABM has been able to provide new evidence and insight into a historical problem such as the Manzikert campaign it would be possible to suggest that the technique is applicable to other times, places and conflicts.

Work on the food requirements of an army on the march needs more fine detail but an important first step has been made to provide the complexity needed to understand the relationship between movement and supplies. Engels assumed a daily calorie intake of 3600 (1978, 123), Roth sets the daily allowance at 3000 kcals per day (1999, 67) while Rogers records a generous food allowance of 4300 kcals for a Frankish force (2007, 11). There is enough data from the Day's March models to show that this kind of static assumption of calorie usage can be improved upon with ABM. The DM009 scenarios provide an appreciation of the factors involved, specifying the energy expended in a variety of situations. Engels says "the army's consumption rate (the weight of food and water consumed per individual per day) ... remains constant" (1978, 3), a conclusion that is a product of his top-down systemic approach. It is apparent from the model that, even without taking into account calories burned when resting or setting up camp or digging the camp's surrounding ditch, an infantryman can quite easily burn 2000 kcals on a relatively short march. The role of the gradient of march in the energy calculations makes it easy to see how soldiers can become exhausted in difficult terrain, as was recorded by Leo the Deacon in the 10th century (Talbot and Sullivan 2005, 41:105). With this in mind, previous work on the supplies required by the army must be called into question. Did the army reduce speed and increase rest days in difficult terrain in order to keep supply levels reasonably constant or did they increase the amount of food they carried, with the associated increase in carrying capacity? Certainly Romanos IV Diogenes had pushed his men to exhaustion before, marching them through difficult terrain to the point where men and beasts died during the campaigns of the late 1060s (Attaleiates 1853, 119).

The lack of an accurate way to calculate an individual's complete calorie usage in any given day, not just that burned on the march, introduces uncertainty over food requirements. Along with the number of variables that could possibly contribute to determining a settlement's surplus food stocks, this means that any conclusions regarding the effect of the army on the settlements passed through can only be comparative at this stage. If anywhere felt the effects of the army it would have been Theodosiopolis where the army was at its largest and where it was likely to have stayed the longest. It was here that the army were supposedly told to store up on food for the coming part of the campaign too, so it may well have resulted in a very hard winter for the residents of the town and its hinterland compounded by the increase in Turkish raiding that would probably have accompanied the collapse of the Byzantine military presence in Anatolia. The gaps in our knowledge can be partially filled with further modelling though, the model provides the ability to start modelling historical food consumption and overall nutrition from a bottom-up basis focussed on individuals rather than using a top-down systemic approach.

5.7 How Did the Army Organisation Affect the Overall Speed?

It is clear from the Day's March scenarios that the organisational mechanisms used in the march of the army can dramatically affect both the overall speed and the ease with which the march is conducted. In fact the results of the scenarios run so far show that the way the army's movement is organised influences the total speed more than the size or composition of the army itself. Factors such as the gap between each unit setting off and the number of columns can have a massive effect on total movement during a day. For instance, DM006 and DM007 show that with reasonable setting off delays, 18,000 - 27,000 agents can march 15 miles in a day depending on number of columns and amount of daylight. With the larger but still plausible setting off delays in DM008 a force of just over 7,000 agents can only march the 13.5 miles from Nicomedia to the halfway point to Nikaia if it is split into multiple columns, as a single column unit it fails. Setting off delays, number of columns and amount of daylight can all play as large a part in the speed of the overall army as size does. The composition of the army, providing it is a mix of cavalry and infantry, may affect the soldier's experience of life on the march but it will not affect the overall speed of the army.

Although organisation has more of an effect on movement speed than size does, it's important to remember that these two aspects are inextricably linked. As Furse states, “The march of a division conducted with little order and discipline may result disastrously, but the march of an army corps under similar conditions would not be brought to a completion at all" (1901, 206). One of the main mechanisms by which the march can be made more orderly is that of introducing a delay between the setting off of individual units. The model only simulated three levels of organisation, the sector, the individual unit and an arbitrary intermediate number of units, which represents fewer levels of organisational hierarchy than the Byzantine army would have possessed. Nevertheless this mechanism introduced an order and robustness in the column that would have been valuable in the event of unforeseen stoppages. The gaps between units would serve as a buffer when any one unit had to stop unexpectedly. As the models did not introduce unexpected stoppages it was the setting off delay that had the most effect on the arrival time of the final unit in a single column march. The shorter these delays, the sooner the army arrived but the less tolerance for stoppages there would have been. This would have been a balancing act in which there were no correct answers, with trial and error probably being the rule.

Another organisational mechanism with a potentially large effect on overall speed is the splitting of the army into separate columns. On the campaign the practicality of this measure would have depended on the terrain and transport infrastructure. In mountainous regions it may have been the case that only one practical route existed. Nevertheless, despite the increase in numbers of units arriving at the destination camp at the same time, the splitting of the army when it might otherwise not arrive before sunset has showed itself to be a very valuable tool. When this was not possible it was possible that the army split into several columns and either travelled completely separate routes for a number of days or even weeks as the Muscovites often did when travelling large distances over poorly supplied terrain (D. L. Smith 1993, 37). They may also have travelled the same route separated by a day or two. This has been recorded within similar contexts, Frederik Barbarossa's army of the Third Crusade being extended over 3 days

(Nesbitt 1963, 178). Multiple columns sharing the same route and using the previous day's camp of the column in front has the advantage that only the first unit needs to fortify the camp each night. Maurice's Strategikon recommends that the rearguard travel 15-20 miles behind the main body of the army. Unless the army was very small this would make it at least a day behind (Dennis 2001, 100). Furse's sample army corps occupies a column of over 27 miles (1901, 298–302), a distance it would have no hope of covering within a day. The main problem with this approach is the increased time taken to form up the army in the event of a threat but this possibility may well have been discounted on the Manzikert campaign due to the Emperor's ignorance of the proximity of the Turkish force.

5.8 How Our Results Compare With Records of Armies Marching

Ultimately we cannot know how many days were spent without marching at all as these may well be motivated by factors outside the scope of logistics. Nesbitt records a march of the Crusades where only 59 out of 89 days were spent on the road (1963, 172). As can be seen from the model's results, size makes a big difference to the distance an army can travel each day and the sizes of historic forces is not usually known. Context is incredibly important and the information required to understand the events is sometimes completely absent. For instance Furse notes how Napoleon marched 120 miles in 4 days to Dresden in 1813 on bad roads in heavy rain (1901, 228). He also states that the cavalry of Charles XII in the early 18th century marched from the Vistula to the Oder in pursuit of the Saxon army, doing 30 miles a day for nine consecutive days. The force was numerous, and the roads were bad (Furse 1901, 226). Yet there are also situations in which much slower progress was made with insufficient information to be able to explain the difference in the situation. Warren's division in the Boer War took six days to cross a ford, unopposed by the enemy, and to accomplish marches that should have been done in two, by not marching far enough in a day and by having slow transports (Furse 1901, 115). Wellington states in a letter, " The order for the march yesterday was sent by Reynett who reported that he had delivered it at 20 minutes to 11 ; the whole distance to be marched was not five miles, and yet the head of the column did not reach its ground till sunset" (Furse 1901, 117). A table of sample march lengths shows great variation, with marches as short as 2.3 miles in a day recorded (Figure 111). Yet it is obvious that much more impressive feats could be accomplished with proper organisation, "Wellington marched with 100,000 men 600 miles in 6 weeks, passed six great rivers, gained one decisive battle, invested two fortresses, and drove 120,000 veteran troops out of Spain" (Furse 1901, 14). It is clear that, although the MWGrid ABM has provided new evidence into the kind of situations that might create these situations, more work is required.

Designation.	Number of marches.	Greatest march in one day.	Shortest march in one day.	Average length of march per day.
		miles.	miles.	miles.
Campaign of 1796	203	33·5	5	15·5
„ 1800	135	23·6	2·3	10·6
„ 1805	267	29·8	7·4	16·1
„ 1806	94	30·4	3	15·5
„ 1815	20	19·8	6·2	13·7
„ 1859	130	19·2	5	9·6
„ 1866	459	26·0	2·5	14·0

Figure 111: Analysis of 7 campaigns and their marches (from Furse 1901, p237)

5.9 How Do the Size and Composition of the Army Affect the Overall Speed?

It is clear from our preliminary investigation that the question "How big was the Byzantine army?" can very easily be answered with the statement "It depends on when you mean". The army fluctuated in size as it moved across Anatolia, usually increasing in size but sometimes decreasing as at Krya Pege and between Theodosiopolis and Manzikert. As can be seen from the Days March scenarios, the size of the army has a significant effect on the overall speed of the army. The main effect of the size of the army was felt when leaving the starting camp and gathering outside prior to embarking on the main leg of the march. This was another area in which the size of the setting off delays were directly inversely proportional to the problems caused by crowding. These were mitigated by splitting the army into separate columns but in certain circumstances it may not have been possible to have these columns exiting the camp in different directions. In this case the benefit of splitting the army would have been drastically reduced.

In comparison the composition of the army has much less of an effect on the overall speed of the army. The army as a whole marches at the speed of its slowest element so increasing the percentage of cavalry compared to infantry would not make the army as a whole move any quicker. It would, however, affect the provisioning required for the army. Cavalry use fewer calories on the march compared to infantry and therefore would have required less food to stay in healthy condition. This would however been offset by the requirements of the horses.

A common feature of the early stages of model development was that the rules used to move small numbers of agents often broke down when larger numbers were applied. This may well be a true reflection of the real problems with moving large numbers of people. The mechanisms that work with small numbers of agents needed alteration when scaled up. Once the basic model showed problems with crowding, the mechanism introducing setting off delays had to be added. In many ways the problems encountered in scaling up the model would have been encountered scaling up the army. Romanos IV Diogenes had been a successful general but had probably not commanded an army as large as the one on the Manzikert campaign, even during the 1068-9 campaigns against the Turks. It would have been a learning experience for him and his generals as well as for the inexperienced members of the army. In this respect, the steady build up of forces along the route would have eased the army into the routine of movement.

As can be seen from the earlier comparison of this work to that of Engels and Pryor, using ABM to examine military logistics represents a significant increase in complexity and flexibility on what has gone before. This is not solely true of the study of military logistics, no other ABM project has tried to simulate organised human movement at such a small spatial scale over such long durations. Previous use has focussed on hazard situations of limited duration or crowds with no overall goal. Previous historical ABM work has modelled movement in quite a crude or small scale manner, either dealing with low numbers of agents or avoiding situations such as crowding. As a consequence, novel methods for simulating movement were required. Due to the unique challenges presented, requiring plausible movement over long and short distances, a whole new way of using a standard tool, A* route planning, was developed. The result is that this project is of interest to agent-based modellers and computer scientists as well as military historians.

As can be seen from the results, the movement of an army in a single column has real limits and those limits can be found with ABM. There are a maximum number of personnel able to travel a single route within a single day. When the size of an army increases to a certain point, the length of a day's march drops to under reasonable levels. The models show that armies of around 10,000 struggle to march 10 miles in a day. DM008 had 5,000 agents struggling to march around 13 miles. Once the size reaches the plausible values for the most difficult parts of the Manzikert campaign then 2 or 3 miles becomes a problem unless measures are taken to ease the issues of crowding.

5.10 Problems Encountered

In the early stages of the project a design was produced that involved a single simulation of the whole march to Manzikert. Modelling a duration of almost 6 months with each tick representing about 5 seconds and including night time patrols, foraging and the language differences between the various mercenary contingents, it managed to be both technically impossible given the time constraints and needlessly complex given the project's aims. Some time was spent preparing the way for this gargantuan model and mechanisms for modelling and manipulating individual objects such as tents, hand mills and firewood were developed and tested. Such a model could not have been completed on time and may well have taken more time to run than the actual campaign itself. Thankfully the majority of the behaviours contained within it could be abstracted out without affecting the goals of the project. Some useful work still remains to be done however, and the ABM can be extended to examine other aspects of the Manzikert campaign.

5.11 Future Work

There are still important aspects of the Manzikert campaign that can be modelled within the MWGrid ABM. The baggage carrying capacity of the army is dependent on how many beasts of burden are available and to what extent the human and animal members of the army are willing and able to also carry food and equipment. As can be seen in the DM009 scenarios, the amount of food carried and the energy used to carry that food is a relationship best examined by modelling subsequent day's marches to see how changing loads affect calorie requirements and vice versa. Many new elements could be added to the ABM, such as differing agent weights, animal health and wider or narrower marching columns. The advantage of the modular nature of the model is that each of these can be introduced separately and the results compared with the same model absent them.

Running the model in a distributed computing environment is intended via the PDES-MAS infrastructure but another form of distribution such as that used by the SETI@Home project ((Anderson et al. 2002)) would allow members of the public to download the ABM and run individual day's marches with parameters fed from a central server. Although each run of the model would be no faster than using a dedicated machine, if enough people were to participate many parallel Manzikert campaigns could be run simultaneously on machines around the world with the end state of a day's march fed back to a central server and used as the start data of the following day's march. It would take months at the ABM's current speed to run a whole campaign but with a sufficient number of different campaigns running at the same time they could exceed the throughput of a high speed dedicated cluster over time.

5.12 Summary

To conclude, a new tool has been created which can offer valuable and unique insights into the movement of armies across the pre-industrial landscape. Agent-based modelling offers real benefits to the study of military logistics by providing new evidence and testing hypotheses that were untestable by less technologically advanced techniques. The scope of the technique is currently limited, both by the data available to be modelled and the hardware available to run the models on. Nevertheless it is already providing quantitative data and testable hypotheses regarding military logistics. Maybe more importantly it is providing retestable hypotheses by being based on a portable piece of software.

The models themselves will become more robust with reuse by testing them in other locations and eras. The models represented here will hopefully be surpassed by more accurate, accessible and complex models capable of taking into account many more factors than have been described here. This will enable the conclusions drawn here to be themselves tested with other models and further refined so that the actions of individuals and their effect on the actions of systems can be better understood.

6 Glossary

Double - A double precision 64-bit floating point number.

Integer - A whole number between -2,147,483,648 and 2,147,483,647 inclusive.

Location - A class defined in the middleware. Consists of two integers, the first giving the x co-ordinate in environment cells and the second giving the y co-ordinate in environment cells. 0,0 is at the top left of the ABM environment area.

Singleton - A Singleton is an object that is restricted to only one instantiation across a system. It is used in the MWGrid ABM to ensure that all users of a data source are using the same copy.

String - A series of text characters.

Tagmata - The field armies of the Byzantine Empire, consisting mainly of professional soldiers and mercenaries.

Thematic troops - Troops levied from the individual themes of the Byzantine Empire.

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8 Appendix 1

8.1 *ManzikertDaysMarchSP*

ManzikertDaysMarchSP is the main class of the MWGrid ABM, the class that starts and runs the simulation. It is described in detail in Chapter 2.

```
package mwgrid.manzikert;
import java.io.BufferedWriter;
import java.io.File;
import java.io.FileWriter;
import java.io.IOException;
import java.util.ArrayList;
import java.util.List;
import java.util.logging.Logger;
import mwgrid.environment.ExpandedSingletonInitFile;
import mwgrid.environment.Weather;
import mwgrid.environment.Weather.WeatherType;
import mwgrid.manzikert.ContextSingleton.CampNeighbours;
import mwgrid.manzikert.agent.HumanAgent;
import mwgrid.middleware.distributedobject.Location;

public class ManzikertDaysMarchSP {
        private static final Logger LOG = Logger
        .getLogger(ManzikertDaysMarchSP.class.getPackage()
                        .getName());
        private BufferedWriter fOutputTickFile;
        private BufferedWriter fOutputDayFile;
        private List<HumanAgent> fAllAgents;
        public static ExpandedSingletonInitFile initFile = null;
        public static ContextSingleton initContext = null;
        public static Weather weather = null;
        public int radiusOfLargestSquare;
        public int radiusOfOuterSectors;
        public int radiusOfOfficerSector;
        public int agentObjectID;
        public int unitID;
        public int largestSector;
        public int colLdrNumber;


        public ManzikertDaysMarchSP(final String pInitFile) {

                LOG.info("Read init file");
                initFile = ExpandedSingletonInitFile.getInstance(pInitFile);
                weather = Weather.getInstance(WeatherType.HOT);

                LOG.info("Initialising output files");
                try {
                        this.fOutputTickFile =
                                new BufferedWriter(new FileWriter(new File(
                                                initFile.getResourceLoc()
                                                +
ExpandedSingletonInitFile.getOutputTickFilename())));
                        this.fOutputDayFile =
                                new BufferedWriter(new FileWriter(new File(
                                                initFile.getResourceLoc()
                                                +
ExpandedSingletonInitFile.getOutputDayFilename())));
                } catch (final IOException e) {
                        LOG.severe("IOException caught while initialising output file");
                        e.printStackTrace();
                        System.exit(1);
```

```
		}


		final int officers = ExpandedSingletonInitFile.getOfficers();
		final int officersquads= ExpandedSingletonInitFile.getOfficerCavalrySquads();
		final int officersquadsize =
ExpandedSingletonInitFile.getOfficerCavalrySquadSize();
		final int campspacebetweensquads =
ExpandedSingletonInitFile.getCampSpaceBetweenSquads();

		int officerCount = 0;
		int officerSquadCount = 0;
		int spacing = 0;

		int outsideTotal = ExpandedSingletonInitFile.getCavalrySquads() +
ExpandedSingletonInitFile.getInfantrySquads();

		LOG.info("Creating agents");
		this.fAllAgents = new ArrayList<HumanAgent>();
		agentObjectID = 1;
		unitID = 1;

		LOG.info("Calculating largest sector");
		if (officers + officersquads > (outsideTotal / 4)) {
			largestSector = (int) (officers + officersquads);
		} else {
			largestSector = (outsideTotal / 4);
		}

		radiusOfLargestSquare = (int) ((0.5 * Math.sqrt(largestSector)) *
campspacebetweensquads);
		radiusOfOuterSectors = (int) ((0.5 * Math.sqrt((outsideTotal / 4))) *
campspacebetweensquads);
		LOG.info("Radius of each camp spot is "+ radiusOfLargestSquare);

		LOG.info("Creating Officer Sector");
		int radiusOfOfficerSector = (int) ((0.5 * Math.sqrt(officers + officersquads +
1)) * campspacebetweensquads);
		LOG.info("Radius of Officer sector is " + radiusOfOfficerSector);
		int startX = ExpandedSingletonInitFile.getStartLocation().getX();
		int startY = ExpandedSingletonInitFile.getStartLocation().getY();

		LOG.info("Creating Officer agents");
		for (int locX = startX + radiusOfOfficerSector; locX >= startX -
radiusOfOfficerSector; locX = locX - (int) campspacebetweensquads) {
			for (int locY = startY + radiusOfOfficerSector; locY >= startY -
radiusOfOfficerSector; locY = locY - (int) campspacebetweensquads) {
				if (agentObjectID == 1) {
					LOG.info("Adding ColumnLeader at loc " + locX + ":" +
locY);

	this.fAllAgents.add(LocalObjectFactory.createColumnLeader(new Location(locX, locY),

	ExpandedSingletonInitFile.getDestinationLocation(), agentObjectID));
					agentObjectID++;
				} else {
					if (officerCount < officers) {
						LOG.finest("Adding Officer at loc " + locX + ":" +
locY);
						if (unitID %
ExpandedSingletonInitFile.getSecondaryUnitSize() == 0) {
							spacing =
ExpandedSingletonInitFile.getSecondarySetoffSpacing();
						} else {
							spacing =
ExpandedSingletonInitFile.getSetoffSpacing();
						}

	this.fAllAgents.add(LocalObjectFactory.createCavalryOfficer(new Location(locX, locY),
unitID, agentObjectID, spacing, 0));
						agentObjectID++;
```

```
                                        unitID++;
                                        officerCount++;
                                } else if (officerSquadCount < officersquads) {
                                        LOG.finest("Adding Cavalry Squad Officer at loc "
+ locX + ":" + locY);
                                        if (unitID %
ExpandedSingletonInitFile.getSecondaryUnitSize() == 0) {
                                                spacing =
ExpandedSingletonInitFile.getSecondarySetoffSpacing();
                                        } else {
                                                spacing =
ExpandedSingletonInitFile.getSetoffSpacing();
                                        }


        this.fAllAgents.add(LocalObjectFactory.createCavalryOfficer(new Location(locX, locY),
unitID, agentObjectID, spacing, 0));
                                        agentObjectID++;
                                        for (int j = 1; j <= officersquadsize; j++) {
                                                LOG.finest("Adding Officer Cavalry Squad
Soldier at loc " + locX + ":" + locY);

        this.fAllAgents.add(LocalObjectFactory.createCavalrySoldier(
                                                                new Location(locX, locY),
unitID, agentObjectID));
                                                agentObjectID++;
                                        }
                                        officerSquadCount++;
                                        unitID++;
                                }
                        }
                }
        }

        CampNeighbours direction =
ContextSingleton.getCampDirection(ExpandedSingletonInitFile.getStartLocation(),
ExpandedSingletonInitFile.getDestinationLocation());
        colLdrNumber = 2;

        int sectorTot = outsideTotal / 4;
        int[] inf = new int[4];
        int[] cav = new int[4];
        int cavsofar = 0;

        for (int i = 0; i < 4; i++) {
                inf[i] = 0;
                cav[i] = 0;
                if (cavsofar < ExpandedSingletonInitFile.getCavalrySquads()) {
                        if (cavsofar + sectorTot <=
ExpandedSingletonInitFile.getCavalrySquads()) {
                                cav[i] = sectorTot;
                                cavsofar = cavsofar + sectorTot;
                        } else {
                                cav[i] = ExpandedSingletonInitFile.getCavalrySquads() -
cavsofar;
                                inf[i] = sectorTot - cav[i];
                                cavsofar = ExpandedSingletonInitFile.getCavalrySquads();
                        }
                } else {
                        inf[i] = sectorTot;
                }
        }


        if (direction == CampNeighbours.RIGHT) {
                if (ExpandedSingletonInitFile.getColumns() == 1) {
                        createSector(0, cav[0], inf[0], 3);
                        createSector(0, cav[1], inf[1], 4);
                        createSector(0, cav[2], inf[2], 1);
                        createSector(0, cav[3], inf[3], 2);
                } else if (ExpandedSingletonInitFile.getColumns() == 2) {
```

```
                createSector(0, cav[0], inf[0], 3);
                createSector(0, cav[1], inf[1], 1);
                createSector(1, cav[2], inf[2], 4);
                createSector(0, cav[3], inf[3], 2);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 2);
                createSector(1, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 1);
            }
        } else if (direction == CampNeighbours.DOWN_RIGHT) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 3);
                createSector(0, cav[1], inf[1], 4);
                createSector(0, cav[2], inf[2], 1);
                createSector(0, cav[3], inf[3], 2);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 3);
                createSector(0, cav[1], inf[1], 4);
                createSector(1, cav[2], inf[2], 1);
                createSector(0, cav[3], inf[3], 2);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 3);
                createSector(0, cav[1], inf[1], 1);
                createSector(1, cav[2], inf[2], 4);
                createSector(0, cav[3], inf[3], 2);
            }
        } else if (direction == CampNeighbours.DOWN) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 3);
                createSector(0, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 1);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 3);
                createSector(1, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 1);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 3);
                createSector(1, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 1);
            }
        } else if (direction == CampNeighbours.DOWN_LEFT) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 2);
                createSector(0, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 1);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 3);
                createSector(1, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 1);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 4);
                createSector(0, cav[1], inf[1], 3);
                createSector(1, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 1);
            }
        } else if (direction == CampNeighbours.LEFT) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 1);
                createSector(0, cav[2], inf[2], 4);
                createSector(0, cav[3], inf[3], 3);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 1);
                createSector(1, cav[2], inf[2], 4);
```

```
                createSector(0, cav[3], inf[3], 3);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 1);
                createSector(0, cav[1], inf[1], 3);
                createSector(1, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 4);
            }
        } else if (direction == CampNeighbours.UP_LEFT) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 1);
                createSector(0, cav[2], inf[2], 4);
                createSector(0, cav[3], inf[3], 3);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 4);
                createSector(1, cav[2], inf[2], 1);
                createSector(0, cav[3], inf[3], 3);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 4);
                createSector(1, cav[2], inf[2], 1);
                createSector(0, cav[3], inf[3], 3);
            }
        } else if (direction == CampNeighbours.UP) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 1);
                createSector(0, cav[1], inf[1], 2);
                createSector(0, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 4);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 4);
                createSector(1, cav[2], inf[2], 1);
                createSector(0, cav[3], inf[3], 3);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 1);
                createSector(0, cav[1], inf[1], 2);
                createSector(1, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 4);
            }
        } else if (direction == CampNeighbours.UP_RIGHT) {
            if (ExpandedSingletonInitFile.getColumns() == 1) {
                createSector(0, cav[0], inf[0], 1);
                createSector(0, cav[1], inf[1], 3);
                createSector(0, cav[2], inf[2], 2);
                createSector(0, cav[3], inf[3], 4);
            } else if (ExpandedSingletonInitFile.getColumns() == 2) {
                createSector(0, cav[0], inf[0], 2);
                createSector(0, cav[1], inf[1], 4);
                createSector(1, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 1);
            } else if (ExpandedSingletonInitFile.getColumns() == 3) {
                createSector(1, cav[0], inf[0], 1);
                createSector(0, cav[1], inf[1], 2);
                createSector(1, cav[2], inf[2], 3);
                createSector(0, cav[3], inf[3], 4);
            }
        } else {
            LOG.info("Direction ERROR!");
        }


        initContext = ContextSingleton.getInstance(fAllAgents);

        LOG.info("Starting simulation");
        for (int i = 1; i <= ExpandedSingletonInitFile.getEndTime(); i++) {
            LOG.info("Starting step " + i);
            ContextSingleton.step(i);
            for (HumanAgent thisAgent : fAllAgents) {
                thisAgent.step(i);
```

```
                        }
                        for (HumanAgent thisAgent : fAllAgents) {
                                collectReport(thisAgent);
                        }
                }
                LOG.info("End of simulation");
        }


        private void createSector(final int pColLdrs, final int pCavSquads, final int
pInfSquads, final int pSector) {
                int startX;
                int startY;
                int cavcount = 0;
                int infcount = 0;
                int spacing = 0;
                int columnleaders = pColLdrs;
                final int gapbetweensectors = ExpandedSingletonInitFile.getGapBetweenSectors();
                final int campspacebetweensquads =
ExpandedSingletonInitFile.getCampSpaceBetweenSquads();

                switch (pSector) {
                case 1:
                        LOG.info("Creating Sector1 (North)");
                        startX = ExpandedSingletonInitFile.getStartLocation().getX();
                        startY = (int) (ExpandedSingletonInitFile.getStartLocation().getY() -
radiusOfLargestSquare - gapbetweensectors - radiusOfOuterSectors);
                        break;
                case 2:
                        LOG.info("Creating Sector2 (West)");
                        startX = (int) (ExpandedSingletonInitFile.getStartLocation().getX() -
radiusOfLargestSquare - gapbetweensectors - radiusOfOuterSectors);
                        startY = ExpandedSingletonInitFile.getStartLocation().getY();
                        break;
                case 3:
                        LOG.info("Creating Sector1 (East)");
                        startX = (int) (ExpandedSingletonInitFile.getStartLocation().getX() +
radiusOfLargestSquare + gapbetweensectors + radiusOfOuterSectors);
                        startY = ExpandedSingletonInitFile.getStartLocation().getY();
                        break;
                case 4:
                        LOG.info("Creating Sector4 (South)");
                        startX = ExpandedSingletonInitFile.getStartLocation().getX();
                        startY = (int) (ExpandedSingletonInitFile.getStartLocation().getY() +
radiusOfLargestSquare + gapbetweensectors + radiusOfOuterSectors);
                        break;
                default:
                        startX = 0;
                        startY = 0;
                }

                LOG.info("Creating sector " + pSector + " agents");
                for (int locX = startX + radiusOfOuterSectors; locX >= startX -
radiusOfOuterSectors; locX = locX - (int) campspacebetweensquads) {
                        for (int locY = startY + radiusOfOuterSectors; locY >= startY -
radiusOfOuterSectors; locY = locY - (int) campspacebetweensquads) {
                                if (cavcount < pCavSquads) {
                                        LOG.finest("Adding Cavalry Squad Officer at loc " + locX
+ ":" + locY);

                                        if (cavcount == 0) {
                                                spacing =
ExpandedSingletonInitFile.getSectionSetoffSpacing();
                                        } else if (cavcount %
ExpandedSingletonInitFile.getSecondaryUnitSize() == 1) {
                                                spacing =
ExpandedSingletonInitFile.getSecondarySetoffSpacing();
                                        } else {
                                                spacing =
ExpandedSingletonInitFile.getSetoffSpacing();
                                        }
```

```
                                    if (columnleaders != 0) {

        this.fAllAgents.add(LocalObjectFactory.createCavalryOfficer(new Location(locX, locY),
unitID, agentObjectID, spacing, colLdrNumber));
                                            agentObjectID++;
                                            colLdrNumber++;
                                            columnleaders = 0;
                                    } else {

        this.fAllAgents.add(LocalObjectFactory.createCavalryOfficer(new Location(locX, locY),
unitID, agentObjectID, spacing, columnleaders));
                                            agentObjectID++;
                                    }

                                    for (int j = 1; j <=
ExpandedSingletonInitFile.getCavalrySquadSize(); j++) {
                                            LOG.finest("Adding Officer Cavalry Squad Soldier
at loc " + locX + ":" + locY);

        this.fAllAgents.add(LocalObjectFactory.createCavalrySoldier(
                                                          new Location(locX, locY), unitID,
agentObjectID));
                                            agentObjectID++;
                                    }
                                    cavcount++;
                                    unitID++;

                            } else if (infcount < pInfSquads){
                                    LOG.finest("Adding Infantry Officer at loc " + locX + ":"
+ locY);
                                    if (pCavSquads == 0 && infcount == 0) {
                                            spacing =
ExpandedSingletonInitFile.getSectionSetoffSpacing();
                                    } else if ((pCavSquads + infcount) %
ExpandedSingletonInitFile.getSecondaryUnitSize() == 1) {
                                            spacing =
ExpandedSingletonInitFile.getSecondarySetoffSpacing();
                                    } else {
                                            spacing =
ExpandedSingletonInitFile.getSetoffSpacing();
                                    }

                                    if (columnleaders != 0) {

        this.fAllAgents.add(LocalObjectFactory.createOfficer(new Location(locX, locY), unitID,
agentObjectID, spacing, colLdrNumber));
                                            agentObjectID++;
                                            colLdrNumber++;
                                            columnleaders = 0;
                                    } else {

        this.fAllAgents.add(LocalObjectFactory.createOfficer(new Location(locX, locY), unitID,
agentObjectID, spacing, columnleaders));
                                            agentObjectID++;
                                    }


                                    for (int j = 1; j <=
ExpandedSingletonInitFile.getInfantrySquadSize(); j++) {
                                            LOG.finest("Adding Infantry Squad Soldier at loc "
+ locX + ":" + locY);

        this.fAllAgents.add(LocalObjectFactory.createSoldier(
                                                          new Location(locX, locY), unitID,
agentObjectID));
                                            agentObjectID++;
                                    }
                                    infcount++;
                                    unitID++;
                            }
```

```
                }
            }
        }

        public static void main(final String[] pArguments) {
                new ManzikertDaysMarchSP(pArguments[0]);
        }

        public void collectReport(final HumanAgent pAgent) {
                final String[] splitReport = pAgent.report().split(NullHandling.SEPARATOR);
                try {
                        this.fOutputTickFile.write(splitReport[0]);
                        this.fOutputTickFile.newLine();
                        this.fOutputTickFile.flush();
                } catch (final IOException e) {
                        LOG.severe("IOException caught while writing to output file");
                        e.printStackTrace();
                        System.exit(1);
                }
                if (DMTimeHandling.isLastTickOfSimulation(pAgent.getTime())) {
                        try {
                                this.fOutputDayFile.write(splitReport[1]);
                                this.fOutputDayFile.newLine();
                                this.fOutputDayFile.flush();
                        } catch (final IOException e) {
                                LOG.severe("IOException caught while writing to output file");
                                e.printStackTrace();
                                System.exit(1);
                        }
                }
        }
}
```

9 Appendix 2

9.1 HumanAgent

HumanAgent contains all the basic behaviours for each agent in the simulation. It is described in detail in Chapter 2.

```
package mwgrid.manzikert.agent;

import java.util.ArrayList;
import java.util.List;
import java.util.logging.Logger;


import mwgrid.environment.Environment;
import mwgrid.environment.EnvironmentVariables;
import mwgrid.environment.ExpandedSingletonInitFile;
import mwgrid.environment.PartEnvHeightOnlyImplementation;
import mwgrid.manzikert.CampHandling;
import mwgrid.manzikert.ContextSingleton;
import mwgrid.manzikert.DMTimeHandling;
import mwgrid.manzikert.NullHandling;
import mwgrid.manzikert.ClassType;
import mwgrid.manzikert.action.Action;
import mwgrid.manzikert.action.Move;
import mwgrid.manzikert.action.GiveOrder.Order;
import mwgrid.manzikert.action.PlanMacroRouteTo;
import mwgrid.manzikert.messages.OrderLocationMessage;
import mwgrid.manzikert.planning.PlanStructure;
import mwgrid.middleware.distributedobject.Location;
import mwgrid.middleware.distributedobject.Message;
import mwgrid.middleware.distributedobject.Value;
import mwgrid.middleware.distributedobject.Location.Neighbours;


public abstract class HumanAgent {

        private static final Logger LOG = Logger.getLogger(HumanAgent.class
                        .getPackage().getName());
        protected Location fLocation;
        public Location fStartLocation;
        public PlanStructure fPlanStructure;
        private ClassType fClass;
        private int fStuckTicks;
        protected int fRestTicks;
        private HumanAgent fSuperior;
        public HumanAgent fPreceder;
        public HumanAgent fSuccessor;
        private List<Message> fMessageInbox;
        protected int fSize;
        protected int fUnitID;
        public long fLastTickMoved;
        private long fObjectID;
        private long fTime;
        protected Location fDestination;
        protected double fDistTravelled;
        public double fMovePoints;
        public double fMaxSpeed;
        public long fStartOfMarchTick;
        public int fCampOffsetX;
        public int fCampOffsetY;
        public long fFirstTickMoved;
        public int fColumnLeader;
```

```
	public double fCaloriesExpended;
	public int lastMinHeight;
	public double lastMinDistance;
	private static final Environment ENVIRONMENT =
		PartEnvHeightOnlyImplementation.getInstance();



	public HumanAgent(final ClassType pClassType, final int pCampId,
			final Location pLocation, final PlanStructure pPlanStructure,
			final int pSize, final int pObjectID) {
		HumanAgent.LOG.finest("Constructor");
		this.fClass = pClassType;
		this.fSize = pSize;
		this.fLastTickMoved = 0;
		this.fTime = 0;
		this.fLocation = pLocation;
		this.fStartLocation = pLocation;
		this.fPlanStructure = pPlanStructure;
		this.fMessageInbox = new ArrayList<Message>();
		this.fSuperior = null;
		this.fObjectID = pObjectID;
		this.fUnitID = pCampId;
		this.fDestination = Location.NULL_LOCATION;
		this.fDistTravelled = 0;
		this.fRestTicks = 0;
		this.fStartOfMarchTick = 0;
		this.fMovePoints = 0;
		this.fCampOffsetX = pLocation.getX() -
ExpandedSingletonInitFile.getStartLocation().getX();
		this.fCampOffsetY = pLocation.getY() -
ExpandedSingletonInitFile.getStartLocation().getY();
		this.fFirstTickMoved = 0;
		this.fColumnLeader = 0;
		this.lastMinDistance = 0;
		final Value<?> thisHeightVal =
			ENVIRONMENT.getEnvironmentValue(this.getLocation(),
					EnvironmentVariables.HEIGHT);
		this.lastMinHeight = (Integer) thisHeightVal.get();
	}

	public ClassType getClassType() {
		return fClass;
	}

	public int getClassTypeID() {
		return fClass.ordinal();
	}


	public int getUnitID() {
		return fUnitID;
	}

	public String getUnitIDString() {
		return Integer.toString(this.getUnitID(), 5);
	}

	public void setUnitID(final int pUnitID) {
		this.fUnitID = pUnitID;
	}


	public int getSize() {
		return fSize;
	}

	public Message getMessage() {
		if (fMessageInbox.size() > 0) {
			return fMessageInbox.remove(0);
		}
```

```
		else {
			return NullHandling.NULL_MESSAGE;
		}
	}


	public void receiveMessage(final Message pMessage) {
		fMessageInbox.add(pMessage);
	}

	public Message viewMessage() {
		if (fMessageInbox.size() > 0) {
			return fMessageInbox.get(0);
		}
		else {
			return NullHandling.NULL_MESSAGE;
		}
	}

	public void setDistTravelled(double pDistTravelled) {
		fDistTravelled = pDistTravelled;
	}

	public double getDistTravelled() {
		return fDistTravelled;
	}

	public int getStuckTicks() {
		return fStuckTicks;
	}

	public void setStuckTicks(final int pStuckTicks) {
		this.fStuckTicks = pStuckTicks;
	}

	public long getObjectId() {
		return fObjectID;
	}

	public void setObjectId(long pObjectID) {
		this.fObjectID = pObjectID;
	}

	public void setTime(final long pTime) {
		this.fTime = pTime;
	}

	public long getTime() {
		return fTime;
	}

	public boolean isCavalry() {
		if (this instanceof CavalryOfficer || this instanceof CavalrySoldier || this
instanceof ColumnLeader) {
			return true;
		}
		return false;
	}

	public Location getDestination() {
		return fDestination;
	}

	public void setDestination(final Location pDestination) {
		LOG.fine("Destination of agent " + this.getObjectId() + " is being set to " +
pDestination);
		this.fDestination = pDestination;
	}

	public void resetStuckTicks() {
		setStuckTicks(0);
```

```
	}

	public HumanAgent getSuperior() {
		return fSuperior;
	}

	public void setSuperior(final HumanAgent pSuperior) {
		this.fSuperior = pSuperior;
	}

	public Location getLocation() {
		return fLocation;
	}

	public void setLocation(final Location pLocation) {
		this.fLocation = pLocation;
	}


	protected Location randomEmptyNeighbour() {
		List<Location> usedneighbours = new ArrayList<Location>();
		while (usedneighbours.size() < 8) {
			Location thisneighbour = CampHandling.randomNeighbour(getLocation());
			if (ContextSingleton.hasSpace(thisneighbour, this.isCavalry())) {
				return thisneighbour;
			} else {
				usedneighbours.add(thisneighbour);
			}
		}
		return Location.NULL_LOCATION;
	}

	protected void shuffle() {
		LOG.finest("On step " + this.getTime() + " Agent " + this.getObjectId() + " is 
shuffling");
		Location shuffleloc = this.randomEmptyNeighbour();
		if (!shuffleloc.equals(Location.NULL_LOCATION)) {
			fPlanStructure.addActionPlanToPlanList(new Move(shuffleloc));
			LOG.finer("Shuffling from " + this.getLocation() + "to " + shuffleloc);
		}
	}


	public void insertShuffle() {
		LOG.finest("On step " + this.getTime() + " Agent " + this.getObjectId() + " is 
shuffling");
		Location shuffleloc = this.randomEmptyNeighbour();
		if (!shuffleloc.equals(Location.NULL_LOCATION)) {


fPlanStructure.insertActionPlanToPlanList(fPlanStructure.getCurrentPlan().getSymbolic());
			fPlanStructure.insertActionPlanToPlanList(new Move(shuffleloc));
			fPlanStructure.clearCurrentPlan();
			LOG.finer("Shuffling from " + this.getLocation() + "to " + shuffleloc);
		}
	}

	protected Location getNearestNeighbour(final Location pLocation) {
		List<Location> emptylocs = ContextSingleton.getEmptyNeighbours(pLocation, 
this.isCavalry());
		Location nearestloc = Location.NULL_LOCATION;
		double nearestdist = 99999999;
		for (Location thisloc : emptylocs) {
			if (thisloc.distanceTo(pLocation) < nearestdist) {
				nearestloc = thisloc;
				nearestdist = thisloc.distanceTo(pLocation);
			}
		}
		return nearestloc;
	}
```

```
	protected Location flockNeighbour(final Location pLocation) {
		final int FLOCKFACTOR = 4;
		Location tl = this.getLocation();
		Location fl = pLocation;
		boolean xbigger = false;
		boolean ybigger = false;
		Neighbours neighbour;
		int xdiff = tl.getX() - fl.getX();
		LOG.finest("xdiff = " + xdiff);
		int ydiff = tl.getY() - fl.getY();
		LOG.finest("ydiff = " + ydiff);
		int absx = Math.abs(xdiff);
		int absy = Math.abs(ydiff);
		if (xdiff > 0) {
			xbigger = true;
			LOG.finest("so xbigger = " + xbigger);
		}
		if (ydiff > 0) {
			ybigger = true;
			LOG.finest("so ybigger = " + ybigger);
		}
		if (ybigger && absx * FLOCKFACTOR < absy) {
			LOG.finest("Setting UP");
			neighbour = Neighbours.UP;
		} else if (!ybigger && absx * FLOCKFACTOR < absy) {
			LOG.finest("Setting DOWN");
			neighbour = Neighbours.DOWN;
		} else if (xbigger && absy * FLOCKFACTOR < absx) {
			LOG.finest("Setting LEFT");
			neighbour = Neighbours.LEFT;
		} else if (!xbigger && absy * FLOCKFACTOR < absx) {
			LOG.finest("Setting RIGHT");
			neighbour = Neighbours.RIGHT;
		} else if (xbigger && ybigger) {
			LOG.finest("Setting UPLEFT");
			neighbour = Neighbours.UP_LEFT;
		} else if (!xbigger && ybigger) {
			LOG.finest("Setting UPRIGHT");
			neighbour = Neighbours.UP_RIGHT;
		} else if (xbigger && !ybigger) {
			LOG.finest("Setting DOWNLEFT");
			neighbour = Neighbours.DOWN_LEFT;
		} else {
			LOG.finest("Setting DOWNRIGHT");
			neighbour = Neighbours.DOWN_RIGHT;
		}
		LOG.finest("Agent " + this.getObjectId() + " loc = " + tl + " and officerloc = 
" + fl + " so dest = " + neighbour);
		return neighbour.getLocation(tl);
	}

	protected Location flockNeighbour(final Location pStartLocation, final Location 
pDestLocation) {
		final int FLOCKFACTOR = 4;
		Location tl = pStartLocation;
		Location fl = pDestLocation;
		boolean xbigger = false;
		boolean ybigger = false;
		Neighbours neighbour;
		int xdiff = tl.getX() - fl.getX();
		LOG.finest("xdiff = " + xdiff);
		int ydiff = tl.getY() - fl.getY();
		LOG.finest("ydiff = " + ydiff);
		int absx = Math.abs(xdiff);
		int absy = Math.abs(ydiff);
		if (xdiff > 0) {
			xbigger = true;
			LOG.finest("so xbigger = " + xbigger);
		}
		if (ydiff > 0) {
			ybigger = true;
```

```
                LOG.finest("so ybigger = " + ybigger);
            }
            if (ybigger && absx * FLOCKFACTOR < absy) {
                LOG.finest("Setting UP");
                neighbour = Neighbours.UP;
            } else if (!ybigger && absx * FLOCKFACTOR < absy) {
                LOG.finest("Setting DOWN");
                neighbour = Neighbours.DOWN;
            } else if (xbigger && absy * FLOCKFACTOR < absx) {
                LOG.finest("Setting LEFT");
                neighbour = Neighbours.LEFT;
            } else if (!xbigger && absy * FLOCKFACTOR < absx) {
                LOG.finest("Setting RIGHT");
                neighbour = Neighbours.RIGHT;
            } else if (xbigger && ybigger) {
                LOG.finest("Setting UPLEFT");
                neighbour = Neighbours.UP_LEFT;
            } else if (!xbigger && ybigger) {
                LOG.finest("Setting UPRIGHT");
                neighbour = Neighbours.UP_RIGHT;
            } else if (xbigger && !ybigger) {
                LOG.finest("Setting DOWNLEFT");
                neighbour = Neighbours.DOWN_LEFT;
            } else {
                LOG.finest("Setting DOWNRIGHT");
                neighbour = Neighbours.DOWN_RIGHT;
            }
            LOG.finest("Agent " + this.getObjectId() + " loc = " + tl + " and officerloc =
" + fl + " so dest = " + neighbour);
            return neighbour.getLocation(tl);
        }


        public void stuck(Action pAction) {
            resetStuckTicks();
        }

        protected Location getSoldiersOfficerLocation() {
            return getSuperior().getLocation();
        }

        public void step(final long pTime) {
            HumanAgent.LOG.finest("Tick is " + this.getTime());
            if (fMovePoints > fMaxSpeed * 2) {
                fMovePoints = fMaxSpeed * 2;
            } else if (fMovePoints < 0 - (fMaxSpeed * 2)) {
                fMovePoints = 0 - (fMaxSpeed * 2);
            }
            // Handle messages
            Message message = NullHandling.NULL_MESSAGE;
            message = this.viewMessage();
            if (message != NullHandling.NULL_MESSAGE) {
                LOG.fine("Agent " + this.getObjectId() + " has a message on tick " +
this.getTime());
                if (this.processMessage(message)) {
                    message = this.getMessage();
                }
            }

            boolean actionSuccessful = true;

            while (fMovePoints >= 0 && actionSuccessful && !fPlanStructure.isEmpty()) {
                if (fPlanStructure.getCurrentPlan().isEmpty() ||
fPlanStructure.getPosition() >= fPlanStructure.getCurrentPlan().size()) {
                    fPlanStructure.getNextPlanFromPlanList();
                }

                if (!fPlanStructure.getCurrentPlan().isEmpty()) {
                    Action action =
fPlanStructure.getCurrentPlan().get(fPlanStructure.getPosition());
                    actionSuccessful = this.processAction(action);
```

```
                        if (actionSuccessful) {
                                fPlanStructure.setPosition(fPlanStructure.getPosition() +
1);
                                this.resetStuckTicks();
                        } else {
                                this.fStuckTicks++;
                                if (fStuckTicks >=
ExpandedSingletonInitFile.getMaxStuckTicks()) {
                                        this.stuck(action);
                                }
                        }
                }
        }
        fMovePoints = fMovePoints + fMaxSpeed;

        //work out cals expended
        if (this.getTime() % DMTimeHandling.ticksPerMinute() == 0) {
                if (fDistTravelled != lastMinDistance) {
                        double dist = fDistTravelled - lastMinDistance;
                        if (!isCavalry()) {
                                final Value<?> thisHeightVal =

        ENVIRONMENT.getEnvironmentValue(this.getLocation(),
                                                        EnvironmentVariables.HEIGHT);
                                final Integer thisHeight = (Integer) thisHeightVal.get();
                                int heightdiff = thisHeight - lastMinHeight;
                                fCaloriesExpended += caloriesExpended(dist, heightdiff,
70);
                                lastMinHeight = thisHeight;
                        } else {
                                fCaloriesExpended += cavCaloriesExpended(dist);
                        }
                        lastMinDistance = fDistTravelled;
                }
        }
}


        public double cavCaloriesExpended(final double dist) {
                double vo2;
                if (dist > (ExpandedSingletonInitFile.getCavalryWalk() *
DMTimeHandling.ticksPerMinute())) {
                        LOG.finest("Cavalry trotting");
                        vo2 = 25.51;
                } else {
                        LOG.finest("Cavalry walking");
                        vo2 = 12.02;
                }
                return vo2ToCals(vo2, 70);
        }

        public double caloriesExpended(final double pDist, final int pHeightM, final int
pWeightKg) {
                double R = 3.5;
                double H = 0.1 * pDist;
                double length = Math.sqrt((Math.pow(pDist, 2)) - Math.pow(pHeightM, 2));
                double grade = pHeightM / length;
                if (grade < 0) {
                        grade = 0;
                }
                double V = 1.8 * pDist * grade;
                double vo2 = (int) (R + H + V);
                LOG.finest("pDist=" + pDist + " height = " + pHeightM + " weight=" + pWeightKg
+ " H="
                                + H + " R=" + R + " V=" + V + " grade=" + grade + " vo2=" +
vo2);
                return vo2ToCals(vo2, pWeightKg);
        }

        public double vo2ToCals(final double vo2, final int pWeightKg) {
                double vo2weight = vo2 * pWeightKg;
```

```
            double vo2l = vo2weight / 1000;
            double cals = (int) (vo2l * 5.047);
            LOG.info("Weight=" + pWeightKg + " vo2=" + vo2 + " vo2w=" + vo2weight + "
vo2l="
                    + vo2l + " cals=" + cals);
            return cals;
        }

        public String report() {
            final StringBuilder report = new StringBuilder();
            final long time = this.getTime();
            report.append(time);
            report.append(" ");
            final long objectId = this.getObjectId();
            report.append(objectId);
            report.append(" ");
            final int classTypeId = this.getClassTypeID();
            report.append(classTypeId);
            report.append(" ");
            final Location location = this.getLocation();
            report.append(location.getX());
            report.append(" ");
            report.append(location.getY());
            report.append(NullHandling.SEPARATOR);
            if (DMTimeHandling.isLastTickOfSimulation(time)) {
                report.append(objectId);
                report.append(" ");
                report.append(classTypeId);
                report.append(" ");
                final long timeArrived = this.fLastTickMoved;
                report.append(timeArrived);
                report.append(" ");
                final int distTravelled = (int) this.getDistTravelled();
                report.append(distTravelled);
                report.append(" ");
                report.append(fCaloriesExpended);
                report.append(" ");
                report.append(fFirstTickMoved);
            }
            return report.toString();
        }

        protected boolean processAction(final Action pAction) {
            return pAction.performAction(this);
        }

        protected boolean processMessage(final Message pMessage) {
            LOG.info("Agent number " + getObjectId()
                    + " is processing a message");
            if (pMessage.getType().equals(
                    OrderLocationMessage.class)) {
                LOG.info("Processing OrderLocationMessage. String = "
                        + pMessage.convertToString());
                final OrderLocationMessage thisOLMessage =
                        (OrderLocationMessage) pMessage;
                if (thisOLMessage.getOrder().equals(Order.GO_TO_CAMP_LOCATION)) {
                    LOG.info("Agent " + this.getObjectId()
                            + " processing GTCL order.");
                    fPlanStructure.addActionPlanToPlanList(new PlanMacroRouteTo(
                            thisOLMessage.getLocation(), false, true, false));
                    LOG.info("Going to " + thisOLMessage.getLocation());
                } else if (thisOLMessage.getOrder().equals(Order.GO_TO_POINT)) {
                    LOG.info("Agent " + this.getObjectId()
                            + " processing GTP order.");
                    fPlanStructure.addActionPlanToPlanList(new PlanMacroRouteTo(
                            thisOLMessage.getLocation(), true, true, false));
                    LOG.info("Going to " + thisOLMessage.getLocation());
                }
            } else {
                LOG.info("Didn't process message. Type = " + pMessage.getType());
                LOG.info("Message = " + pMessage.convertToString());
```

```
                return false;
            }
            return true;
        }
    }
```