Modelling the Logistics of Mantzikert

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Chapter 1 – Introduction

An organised military has always been a key feature of an organised state, and whether the military succeeds or fails can have a massive impact on societies in general. For this reason, a key part of state bureaucracy, particularly in pre-modern states, is the organisation of the military for offensive and defensive action. Yet despite its importance as a key method by which states can be maintained, the study of the mechanisms by which armies are raised, moved, fed and equipped has attracted less attention than the study of strategy and tactics and the personalities of generals and political leaders. Military logistics is a term that covers the organisations and methods that ensure sufficient people are in the right place at the right time and in the right condition to threaten or achieve military supremacy. Strategy and tactics are important in achieving military supremacy but if armies cannot be moved or fed then strategic and tactical ability become moot points. Armies can be destroyed without fighting and armies that are moved and fed effectively can have a critically important advantage in battle.

The historical focus on battles and leaders is partly because far more of the primary sources focus on these topics,[1] but also because the relationships between the systems included within military logistics are complex and the evidence for these systems is often inaccurate and/or incomplete. Raising an army requires resources and organisation, and moving it is dependent on transport infrastructure and, especially in the pre-modern world before effective food preservation and railways, the amount and location of food surpluses. Surplus food is dependent on agricultural productivity and demography, both of which also affect tax income. Military campaigns can have extensive effects on the availability of food surpluses, even if those campaigns are fought away from home soil. If enemy action impacts on home territories then this can have drastic effects on demography, agricultural productivity and therefore also on tax income. With such an interrelated web of complex systems, it's unsurprising that historians, both ancient and modern, have focused on the character of famous generals and the turning points of decisive battles. These stories have clearer narratives and more exciting plot twists than can usually be found in a description of the organisation of a baggage train or a list of required foodstuffs.

However, gaining a more complete understanding of military logistics, including the mechanisms that support it and the effects of moving large groups of people across a pre-industrial landscape is not only important in researching the significant military campaigns of history but also a way of gaining new insights into other aspects of society. If we can quantify the amount of food required to sustain an army in a campaign we are able to say something about the agricultural productivity, demography and transport networks of the lands they travel through. Each of these aspects of society are complex systems, with complex relationships between them. The complexity inherent in the systems that underpin military logistics has its pros and cons. It makes understanding these systems a more difficult task, but it also means that work on one piece of the puzzle can maybe help us with the other pieces too.[2] As Gotthold Ephraim Lessing, along with many students of esoteric, environmental and sociological topics may contend, 'everything is connected'.[3] This statement does not just hold for nature, as Lessing originally intended, but also applies to this book, in which Byzantine history, computer science, graph search algorithms, the spread of the railroads, Microsoft, the 19th-century British Army and the Roman roads of Anatolia all play a role.

In 2007, the *Medieval Warfare on the Grid* project commenced at the University of Birmingham, with funding from a joint AHRC-EPSRC-Jisc e-Science research grant. Its aim was to find some way of reaching beyond the limits of the historical sources by using new technology to try and access this interrelated network of complex systems underpinning pre-modern military logistics. Research into complexity in the second half of the 20th century had resulted in computer simulation techniques that had been profitably used to research the behaviour of complex systems. If these could be used on the systems that constitute the elements of military logistics in a pre-modern state, then we could not only approach military campaigns from a bold new direction but also use this to understand more about the societies that supported the armies that protected them. The work undertaken during the *Medieval Warfare on the Grid* project forms the basis of this book, though much has been added since then to incorporate new sources of information on military logistics.

1 Luttwak 1993, 5–6

2 Haldon 2006a

3 Lessing 1889, 399

What is military logistics?

According to the United Kingdom Ministry of Defence,

> *Logistics is the science of planning and carrying out the movement and maintenance of forces. Logistics comprises the development, acquisition, storage, movement, distribution, maintenance, recovery and disposal of materiel; transport of personnel, acquisition and construction; maintenance, operation and disposal of facilities; acquisition or furnishing of services; and medical and health services.*[4]

The above quote is the definition of logistics from the 2017 UK tactical doctrine for land operating environments, but it is sufficiently generic to apply to military logistics of any era. It is designed, along with administrative support, to be the means by which armies can be sustained for as long as operationally necessary. The word itself is derived from the Greek, *logistikos*, meaning 'skilled in calculation', and has been used in its current form since at least 1838 when Jomini used it to refer rather vaguely to essential tasks for warfare that are not strategy or tactics.[5]

The importance of logistics

The areas covered by our definition of logistics are key factors in the ability to keep an army in the field. George Armand Furse, writing in the 19th century and drawing from examples in which the British Army had campaigned against nations with less developed logistical infrastructures in Africa and Asia, stated that local forces which can travel light and are highly mobile pay 'an enormous price, which is the impossibility of carrying on protracted operations'.[6] The implication here is that the British Army's logistics infrastructure made their forces less mobile. Nevertheless, the British army's support structures, expensive and complicated as they were, allowed forces to be kept in the field longer than their opponents, thus securing a critical advantage.

This trade-off between mobility and endurance is just one of a series of complex relationships and factors involved with moving and feeding an army. Although there are methods of organising an army that are more, or less, effective than others, the individual circumstances of each campaign are important and undermine any attempt to define a 'one size fits all' idealised approach to military logistics.

> *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.*[7]

Mantzikert - our case study

In 1071, the Byzantine Emperor, Romanos IV Diogenes, marched an army of native soldiers and foreign mercenaries from west to east across Anatolia in order to decisively engage the Seljuk Turk Sultan, Alp Arslan, in battle. We have writings regarding the character of the leaders and the events of the battle but, in common with most pre-modern campaigns, we cannot say precisely how large the armies were nor do we possess all the information we would like in order to say exactly how they were organized, fed or moved, what effect they had on the communities that will have supplied them or what life on the road was like for the vast majority of the combatants in a battle that would have significant effects for the Byzantine Empire and the whole of the Middle East.

The march of the Byzantine army across medieval Anatolia to the Battle of Mantzikert in 1071 was chosen as a case study for the *Medieval Warfare on the Grid* project as it is recorded in a number of contemporary and near-contemporary historical accounts and takes place across a reasonably well-researched landscape and yet there are crucial details missing from our knowledge of the campaign and the areas through which it passed. The sources of our knowledge of this campaign have been thoroughly discussed by many researchers and, absent new data, all we can do is revisit the same accounts and reargue the same points, *ad infinitum*. Carole Hillenbrand in her study of the Muslim historical writing about the battle suggests 'the only way to shed any really new light on the 'event' lies within the discipline of military archaeology'[8], but we hope to demonstrate that archaeology, history and computer science can combine to provide an approach to the Mantzikert campaign that gives a radical new perspective. We also hope to demonstrate that this approach is applicable to a wide variety of pre-modern military campaigns, and even to some from more recent history.

The historical context

In 1068 the Byzantine Empire was in a more precarious military position than it had been for almost a century.

[4] Land Warfare Development Centre 2017
[5] Leighton and Coakley 1955, 11
[6] Furse 1882, 34
[7] Furse 1901, 4
[8] Hillenbrand 2007, 4

Figure 1: Byzantine Anatolia at the time of the Turkish raids.

Basil II (976-1025) left Byzantium with an expanded empire, a strong successful army and a healthy treasury when he died, childless, leaving his brother Constantine VIII as head of the Empire. From the 1040s in particular, Byzantine military strength had been jeopardised by civil wars, rebellions and a preponderance of bureaucratic emperors who favoured the metropolitan elites above the provincial military aristocracy.[9] Basil II's successes ensured that the Bulgars in the west no longer presented a threat, 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, citizen soldiers recruited from the Empire's own provinces, had been unused and in some cases disbanded in favour of regionally recruited field armies, known as tagmata, whereas the existing field armies had been partially replaced by foreign mercenaries.[10] Nevertheless, there is evidence to suggest that properly led Byzantine armies had some measure of success up to the 1060s.[11]

By 1068 the reduction in defences protecting the east had led to a series of raids by Turkish nomads[12] (Figure 1). The nomads were encouraged by the Seljuk Turk rulers to prey on Byzantine Anatolia instead of Seljuk-controlled areas further east.[13] 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 strong 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.[14]

Romanos IV Diogenes, as he then became, established as his first priority the need to stop the Turkish 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 to engage the nomads in battle. The nomads themselves consisted of a series of mobile bands which were elusive and difficult to commit to an engagement. Romanos reasoned that if he were to engage them in pitched battle then superior Byzantine organisation, numbers and heavy troops would triumph over Turkish mobility. During 1068, Romanos chased the nomads across Anatolia without ever being able to decisively engage them. A similar campaign took place in 1069.[15] 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.[16] At least there was now a more hostile environment in Anatolia for the nomadic raiders.

[9] Angold 2004; Cheynet 1990; Holmes 2008; Lauxtermann and Whittow 2017
[10] Haldon 2008, 165
[11] Haldon 2003
[12] Attaleiates 2012
[13] Haldon 2008, 168
[14] Holmes 2008
[15] Vratimos-Chatzopoulos 2005
[16] Attaleiates 2012, 253

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'[17], although he was hardly a neutral observer and his description of the size of the army probably reflects his sympathies, which were most likely with the Turks, or at least against the Byzantines. 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 that this army was much larger 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'[18], although, like Matthew of Edessa, al-Husayni had no reason to downplay the size of the Byzantine force. The emperor's aim was to engage the Seljuk Turk Sultan in battle and destroy Seljuk military strength on the eastern borders. Alp Arslan had in 1070 taken the border fortress of Mantzikert 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 ambassadors 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.[19] Alp Arslan reacted by hastily assembling a force to resist the Byzantine army, although 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 Byzantine Empire long before Romanos had expected him to be able to do so. There are suggestions from some later Byzantine historians that this was the result of a secret arrangement with Romanos' political enemies as part of a plan to use the Seljuks to remove the emperor.[20] By the time Romanos reached Mantzikert and recaptured the fortress without a fight, Alp Arslan was in the area with a sizeable force.[21]

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 bands of nomads, who used 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 quarters and were prepared to retreat back to the fortress and try again the following day. It was at this point that a fatal political 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.[22] 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 rear guard. When Romanos reversed his banner to signal the retreat, the rear guard 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 Doukai took advantage of the situation and siezed control of the empire.[23] 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.

The importance of Mantzikert

Mantzikert is a pivotal moment in medieval history and affected areas far removed from Eastern Anatolia. Runciman called it 'the most decisive disaster in Byzantine history'.[24] The Byzantine Empire was afflicted by a period of civil wars from the defeat at Mantzikert until Alexios I Komnenos took the throne in 1081.[25] It was this unrest more than the military defeat at Mantzikert that weakened the empire[26] but the usurping of the throne by the Doukas family marked 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 Mantzikert also stoked European fears of the Muslim world and was in small part a catalyst of the First Crusade.[27] The Ottomans in their turn gave way to the modern Republic of Turkey, with Mantzikert being the

[17] Dostourian 1972, 231
[18] Hillenbrand 2007, 53
[19] Haldon 2008, 169
[20] Vratimos 2018
[21] Friendly 1981, 173
[22] Haldon 2008, 170
[23] Angold 2004; Holmes 2008
[24] Runciman 1951, 61
[25] Cheynet 1980
[26] Haldon 2008, 165
[27] Hillenbrand 2007, 1

first major military victory of Turkic peoples within the borders of what is today the modern state of Turkey. As such it is a well-established event in the modern Turkish historical tradition and in Turkish popular ideology. Within the town of Malazgirt, the modern name for Mantzikert, there is a statue to the Seljuk Sultan Alp Arslan. Mantzikert occupies a similar status as a pivotal event for the modern state of Turkey as the Battle of Hastings does for England.[28] As the Byzantine Empire was a direct continuation of the Eastern part of the Roman Empire the Battle of Mantzikert resonates through the ancient, medieval and modern worlds.

The campaign

Of the actual campaign, we know relatively little. Contemporary Byzantine sources include Michael Psellus, an anti-military bureaucrat and scholar, who disliked Romanos and stayed behind in Constantinople,[29] and Michael Attaleiates, a military nobleman who accompanied the emperor on the campaign.[30] A few decades after the battle, Nikephoros Bryennios, the grandson of a general of the same name who was on the Mantzikert campaign, wrote an account.[31] From contemporary sources, we know that the emperor left Constantinople for Mantzikert in either late February or early March, crossed the River Halys (the modern Kızılırmak River) near a place called Krya Pege where he expelled some German mercenaries from the army,[32] travelled via Sebastea (modern Sivas) and Theodosiopolis (modern Erzurum) and split his army into two parts not far from Lake Van and ordered half his forces to take the fortress at Khliat (modern Ahlat).[33] 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[34] 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 where this happened or for how long this arrangement lasted.

What is missing?

The historical records have very different priorities than providing a practical account of the Byzantine army's logistical requirements. Michael Psellus was 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, although he would undoubtedly have had contact with survivors of the campaign on their return. 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 Mantzikert 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[35] along with the *Taktika* of Leo the VI,[36] originally written in the late 9th or early 10th century but subsequently expanded in around 1000 by Nikephoros Ouranos. The three military treatises translated by Dennis[37] also belong to the 10th century, as does the *Sylloge Tacticorum*,[38] but only the *Strategikon* of Kekaumenos remains as a major military work from the pre-Mantzikert 11th century. That is not to say that these works are of no use at all. Even the *Strategikon* of Maurice,[39] written in the late sixth century, carries useful organisational detail that may well have remained current until the 11th century. The 10th century treatise translated by Dennis as *Campaign Organisation and Tactics* for instance[40] 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 evening's camp site. More detailed discussion of the 10th century Byzantine military context is available in the works of McGeer[41] and Chatzelis and Harris.[42]

However certain key facts are missing from the historical record. The size of the Byzantine army on the Mantzikert campaign is a matter of conjecture, discussed by Haldon[43] and Cheynet[44] among others, although it is possible to make estimates based on the recorded detail of specific units. Modern estimates ranging from 40-60,000 are considered reasonable but lack conclusive evidence.[45] No numbers are given by Byzantine sources at all, although not because Byzantine historians were reticent to exaggerate numbers on principle. Leo the Deacon claimed a total of 400,000 for the army of Nikephoros II Phokas which was almost certainly much

[28] Hillenbrand 2007, 205
[29] Psellus 1966
[30] Attaleiates 2012
[31] Bryennios and Gautier 1975
[32] Friendly 1981, 168
[33] Cheynet 1980, 424
[34] Attaleiates 2012, 267
[35] Constantine Porphyrogenitus 1990
[36] Dennis 2010
[37] Dennis 1985
[38] Chatzelis and Harris 2017
[39] Dennis 2001
[40] Dennis 1985
[41] McGeer 1995
[42] Chatzelis and Harris 2017
[43] Haldon 2008, 172
[44] Cheynet 1980
[45] Haldon 2006b, 13

too large for a field army of the time, to such an extent that there is uncertainty regarding whether he ever meant it to be taken literally.[46]

Some Arabic sources give numbers of soldiers for the Byzantine army at Mantzikert, 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). When plotted on a graph against the date of death of the historian, used in the absence of reliable data regarding when each source was written, it reveals an unexpected pattern. Interestingly, it seems the size of the Byzantine army in the Arabic literature tends to get smaller over time (Figure 2), the tale shrinks in the telling.

Table 1: Size of the Byzantine army from Arabic sources

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

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 via other, often contradictory, historical sources. Existing theories based on historical research suffer from a lack of testability.[47] 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 quantified data also applies to the military treatises, indeed there is a lack of quantifiable evidence throughout all areas of the historical debate.[48] No systematic survey has been recorded in which 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 a comprehensive 'how to' guide to moving and supplying an army.

The need to model

Much of archaeology consists of the discovery of patterns, whether they are the patterns of finds on an excavation site or the distribution of sites in a landscape. Interpreting these patterns involves creating hypothetical processes to explain how these patterns came to be created and discovered. Why are the sites we research or the objects we find located where they are? Is it an artefact of our recording methods or does it reflect past behaviours? If we are seeing evidence of human activity, what form did it take? What processes can explain the patterns? Archaeologists can create mental models of these processes, but these mental models remain theoretical and untestable. One area of archaeology, experimental archaeology, seeks to work the other way around. These explanatory processes are reattempted in order to determine whether they actually do create the patterns seen in the archaeological record. Hence, people have worked iron to try to associate patterns of hammerscale with different metalworking tasks and conditions.[49] They have knapped flint to compare the results to excavated assemblages.[50] They have dragged a replica *ahu* across Easter Island and erected it with primitive tools and equipment.[51] However, some processes are more amenable to this kind of physical, real world simulation than others.

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. The impracticality of marching tens of thousands of people across hundreds of miles in varying conditions

[46] Talbot and Sullivan 2005, 104
[47] Haldon 2006b, 4
[48] Haldon 2006b, 2
[49] Dungworth and Wilkes 2007
[50] Aubry *et al.* 2008
[51] Van Tilburg and Ralston 2005

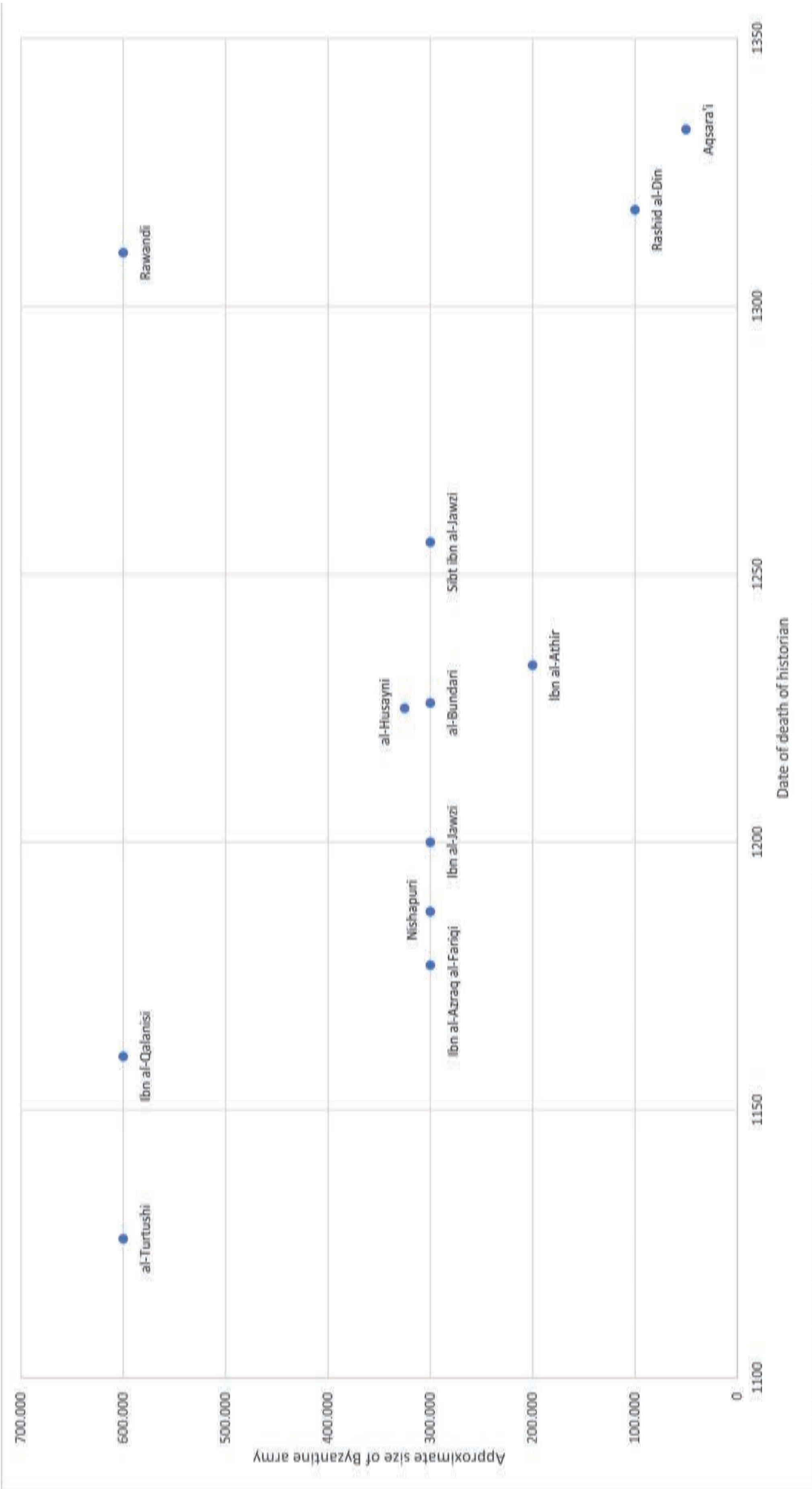

Figure 2: Estimates of the size of the Byzantine army at Mantzikert from Muslim sources.

and with varying types of organization should be obvious. Much more practical is the option of creating a model of the Byzantine army within a computer. Rules can be created in order to simulate an army on the march which can then be modified and altered, and the results compared with each other and with the historical facts as we know them.

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 often hypothetical values, but these can be rooted in real world metrics in order to provide an element of testability. The models can be used to express hypotheses and run simulations over time, producing results which we can compare with both the historical record and the results of other, slightly different, models. Simulation is not re-creation, and the objective is not to build an exact model of the Byzantine army on the march, with the exact number of participants moving in the exact way that they did in 1071. Instead, we are seeking to examine the processes involved with moving the army and how they interact to create the large-scale behaviours of the army as a whole. For this reason, several models must be created and run multiple times with differing parameters in order to provide comparative data. The hypotheses can then 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 debate over the events of the Mantzikert campaign.

If the results of the models agree with the historical data, it does not necessarily follow that the model is an exact representation of our research target, different processes may produce the same end 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 image of what *did* happen, but they will be able to indicate what *could* have happened and may allow us to eliminate certain hypotheses that *could not* have happened.

Why can this not be filled with conventional research?

Although much work has been done on Byzantine military organisation and logistics,[52] 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 does not necessarily follow that this was adhered to.

In the case of Mantzikert, 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 counterclaim. No new evidence is likely to appear unless a previously undocumented account is discovered. However, 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.[53] 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 since Mantzikert, or even within the last 10,000 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 outside of a computer environment by, among others, Jonathan Roth[54] in his work on the Roman army, Donald Engels[55] on the Macedonian army of Alexander the Great, John Lazenby[56] and Stephen O'Connor[57] on the soldiers and sailors of Ancient Greece, John Pryor[58] and Bernard Bachrach[59] on the times of the Crusades and John Haldon on the Byzantine Empire.[60]

The model-based approach

Just such a system utilising fairly simple maths and no computing power beyond that of a calculator was used by Donald Engels in his book about the logistics of the army of Alexander the Great. Although top-down, statistical modelling of an army's logistical arrangements had been attempted for modern defence situations,[61] Engels' book was the first comprehensive attempt to do so with the aim of researching a pre-modern campaign. 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 per day he was able to calculate

52 McGeer 1995

53 Carpenter 1921
54 Roth 1999
55 Engels 1978
56 Lazenby 1994
57 O'Connor 2013; 2015
58 Pryor 2006
59 Bachrach 2006
60 e.g. Haldon 2006a
61 e.g. Holliday and Gurfield 1968

a total weight of the food and drink requirements of 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 available for the food of others as increased capacity was taken by its own food. 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.[62]

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 the same approach slightly differently, to examine the journey of Bohemond and his troops on their march to Thessaloniki in 1096.[63] He used 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 used 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.

Yuval Harari constructed a hypothetical medieval army of 10,000 combatants in order to examine the practical implications of supply on strategy, and vice versa.[64] Like Engels, he worked with averages for food consumption and the calorie content of foodstuffs in a top-down model with fairly simple maths that can be done with pencil and paper. Like Engels, his model is a useful step beyond the majority of work that has gone before, but is too simple to explore some of the implications of the results that it delivers.

The problem of complexity

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 of the army along the same route on subsequent 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, though not necessarily by a predictable amount. This all indicates that the system at work when an army moves is more complex than can be adequately modelled by the approach taken by Engels, Pryor, Harari and others.

But if we are to model the movement and provisioning of an army to a greater level of detail that that used by Engels and others, we would require more detail on these aspects of logistics than is contained in the Byzantine military treatises. Comparative data for our models is supplied by 19th-century military writing, particularly the work of George Armand Furse, which is a largely untapped source of information regarding the movement of armies in conditions comparable to those of the Mantzikert campaign. These more modern sources can be used to fill in detail entirely absent from medieval sources, with caution, enabling plausible models to be created which have details of small interactions between agents and large-scale validation of data.

A system in which the overall behaviour depends on a series of much smaller interactions between its constituent parts and in which this overall behaviour cannot be predicted by examining the constituent parts individually is known as a complex system. Complex systems consist of many small, simple interactions and are evidenced in the forming of snowflakes, the flocking of birds and the behaviour of an ant colony.[65] Complex systems with emergent behaviour, behaviour

[62] Engels 1978, 19
[63] Pryor 2006
[64] Harari 2000
[65] Gilbert and Troitzsch 2005, 11

that emerges from a mass of simple interactions, 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 maximum possible speed of one car will not be enough information to help determine its arrival time at its destination. This is because its progress is also affected by 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 estimate its arrival time. The whole system however has no overall controller determining how each car behaves. Each vehicle has 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.

Agent-based modelling (ABM) is a computer modelling technique whose structure replicates complex systems such as these.[66] ABM 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 their 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 it replicates the structure created by large numbers of individuals travelling across, and interacting with, a landscape.

A brief history of ABM

The concept of agent-based modelling has been around since the middle of the 20th century, but it was not until the 1990s that computing power had advanced to the point where it became widely adopted. Prior to that, Conway's 'Game of Life'[67] and the cellular automata of von Neumann and Ulam[68] had laid the theoretical underpinnings while remaining low technology, with Ulam's cellular automata being worked out on sheets of paper. Craig Reynolds' models of the flocking behaviours of birds were among the first that would be recognisable as modern computerised agent-based models and were an early example of how a group of individuals with simple internal rules could replicate real world phenomena.[69] 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. OOP 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[70] to more abstract applications in social science.[71]

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 computing's ability to explore general systems theory,[72] 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 ABM for exploring the interactions involved in socionatural systems, systems that incorporate both human society and culture as well as natural, environmental factors. 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,[73] the emergence of states in Central Asia[74] and the link between ecology and observed settlement patterns in the American south west.[75] State-level ABMs dealing with societal complexity typically require data from many different fields as these systems are affected by many variables. This typically results in large, multidisciplinary projects which are comprised of a wide range of specialists.

The Village Ecodynamics Project (VEP) ran from 2001-2014 and involved archaeologists, geologists, geographers, computer scientists and economists among others in seeking to explain key aspects of

[66] Gilbert and Troitzsch 2005, 172
[67] Gardner 1970
[68] Von Neumann 1951
[69] Reynolds 1987
[70] Thompson and Marchant 1995
[71] Epstein and Axtell 1996
[72] Doran 1970
[73] Wilkinson *et al.* 2007
[74] Cioffi-Revilla *et al.* 2007
[75] Kohler 2010

the societies inhabiting the area around south west Colorado between 600-1300.[76] It coupled detailed modelling of terrain and weather with human societies, plant and animal resources and water availability. By treating these elements as one socionatural system 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,[77] the VEP were able to add detail to this work by incorporating it into an environment that simulated temperature and rainfall. The series of models developed as part of the project allowed archaeologists to investigate aspects of the landscape and its use by its inhabitants, including use of resources, location of settlements, societal complexity and possible reasons for the study area's apparent depopulation in the 13th century AD.[78]

Archaeological ABMs do not just consist of large interdisciplinary projects such as the VEP, that amass large quantities of data in order to research a specific subject. 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[79] and Shawn Graham's NetLogo models of Roman civic violence[80] being 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, commonly 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 OOP, 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.

[76] Kohler and Varien 2012
[77] Van West 1994
[78] Kohler *et al.* 2012
[79] Smith and Choi 2007
[80] Graham 2009

Military historical simulation

ABM's architecture of agents within an environment has lent itself to examining interactions between individuals and their surroundings. Socionatural systems,[81] systems in which both social and natural factors have an effect, are common research topics for ABM within archaeology. Military applications have been less common, despite the long history of simulation use within modern military environments. The solution of military problems was a significant driver in the development of electronic digital computing[82] and the use of simulation for strategic planning, logistical organisation and tactical training has a much older pedigree than computing itself. Kriegsspiel, a proto-wargame developed for the Prussian army in 1812, though leaning on even earlier work, was a battle simulation system that was used to train Prussian army officers in generalship and battlefield tactics.[83] It used a table with modular terrain tiles and wooden blocks to represent forces but allowed replaying of historical battles and the development of 'what if?' scenarios to enable officers to run through possible future engagements without the organisation and expense involved with full-scale military manoeuvres. Its rules were initially very complex, being designed to be as accurate as possible, resulting in simulated battles that often took longer than the real thing. As this was inconvenient and somewhat removed the need to quickly react to the kind of surprising circumstances that crop up on the battlefield, a sleeker version, 'free Kriegsspiel', was developed. Although free Kriegsspiel was more immediate and took less time, it sacrificed some of the earlier version's complex rule system in favour of snap judgments by experienced referees. It took until the development of digital computing for military simulation to develop the ability to maintain complexity whilst allowing fast-paced simulations.

By the 1960s, computing power had advanced to the level where state-supported organisations could use simulation to provide effective training simulators and also to be able to examine the systems used in military organisations and suggest improvements. Computers could now calculate events based on real world data and feed the results back in real time. Mainframe-based software was being used to solve problems of logistics,[84] command and communications,[85] deployment by air,[86] and equipment maintenance,[87] with 200-300 simulation projects being carried out over 3 years in the United

[81] Kohler and van der Leeuw 2007
[82] Copeland 2004
[83] Wintjes 2015
[84] Davis 1967
[85] Tiede and Leake 1971
[86] Sharpe 1965
[87] Conway 1964

States alone by the mid-1960s.[88] More recently, there are enough modern military simulation papers for academic journals to be dedicated to the subject (e.g. The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology), with subjects ranging from the strategy of guerrilla warfare[89] to the damage caused to equipment by IEDs.[90] The focus has moved from the systems-based equations of the 1960s to ABMs such as the U.S Marine Corps' ISAAC [91] and Project Albert.[92]

Although ABMs are used extensively within modern military environments, their use for studying military activity in the past is much rarer. With the exceptions of a game-theory examination of the World War II U-boat campaign in the Bay of Biscay,[93] a brief simulation of Roman military communications along Hadrian's Wall[94] and several models regarding military tactics published with the involvement of Xavier Rubio Campillo,[95] there is very little impact of ABM in military history or archaeology. The majority of recent work on pre-modern military logistics[96] uses technology available in the 19th century and therefore cannot examine the complex systems and emergent behaviours accessible to agent-based approaches.

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? Our answer is yes! Complexity theory shows that where emergent behaviours occur, our knowledge of an individual's state and behaviours will not allow us to predict the behaviour of the system as a whole.[97] 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 eloquently described 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.*[98]

The limitations of ABM

> *All models are wrong but some are useful*[99]

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 a reproduction of the events of the Mantzikert campaign. A model is a hypothesis to be tested, ready to be refuted or upheld until a better model comes along that more plausibly describes reality. In modelling the march of the Byzantine army, it is accepted that it is not possible to model all aspects of every individual in the marching column, or even just all aspects thought to be relevant. It is, however, 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 Mantzikert 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.[100] 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, and it will fall to other, possibly more traditional, sources of data to be able to determine when this is happening. Simulation is an addition to other methods of research, rather than a replacement for them.

Archaeology presents many specific problems to ABM. Unlike other topics such as medicine or physics, archaeological modelling generally starts with only a

[88] Dalkey 1967
[89] Doran 2005
[90] Gabrovsek *et al.* 2016
[91] Ilachinski 2000
[92] Horne and Leonardi 2001
[93] Hill *et al.* 2004
[94] Gotts 2017
[95] e.g. Rubio-Campillo *et al.* 2013; 2015; Wittek and Rubio-Campillo 2012
[96] e.g. Bachrach 2006; France 2006
[97] Gilbert and Troitzsch 2005, 10
[98] Furse 1901, 206
[99] Box 1979, 2
[100] Premo 2010

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 largely unknown.

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, however, 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.[101] Mathematical equations can be easily represented and resolved allowing data to be calculated reliably and quickly. The ability of modern computers to handle large 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 as 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.[102]

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 varied in order to compare with results from other models. It is this characteristic that makes them so suitable to OOP languages, whose own approach is that of a series of modular entities with their own rules and characteristics. 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, with only the inputs and outputs needing to be specified beforehand. The hierarchical and modular nature of OOP 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.

Summary

Despite good work by Engels and others, there are still a lot of unanswered questions regarding how pre-modern armies move and how their practical requirements impact the states which raise and direct them and the lands through which they move. We now have access to tools such as ABM which are suitable for examining the complex interactions between individuals that exist in an army on the march, yet little work has so far been attempted using such methods to research military logistics. By using the case study of Mantzikert, a significant turning point in history with supporting historic accounts which largely ignore logistical concerns, we can demonstrate how ABM can complement traditional historical methods of research. This approach can then be used to provide a new angle with which to approach age old questions regarding other military campaigns.

A note on names and dates

All dates are AD, unless specified. Names have been rendered as closely as possible to their Greek usage at the time of the Mantzikert campaign, except where individuals or places are more well known by their anglicised equivalent.

101 Roth 1999, 1
102 Aldenderfer 1981