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Chapter 1: Introduction

The road system is one of the most essential components of cities. It supports the daily traffic of residents and reduces human moving track from vast space to regular line segments. The road system in cities can be developed and reformed for reasons including but not limited to urban expansion, regeneration, or improvement of user experience. Therefore, the road system can be considered a mirror that reflects the accumulated activities of urban life. The archaeologically remaining structure of the road system can be even more valuable, as it provides a window on the internal dynamics of the past cities, through which the knowledge, engineering, aesthetics, and the strength of the dominating power can be observed.

Urban roads have been mentioned in extensive archaeological research yet in a basic and intuitive way. To determine whether a city is created following a top-down conception, its road structure would be observed for the presence of the gridiron pattern, which is often used to achieve an orderly appearance and to simplify the city management. And cities with an organic pattern (irregular layout) are considered merged bottom-up.

Despite being used as a standard, the city's road pattern had drawn less interest in archaeology for a long time. Since the 70s, archaeological research on the roads started appearing (Collis, 1976). The developing Geographic Information System (GIS) technology enables the study that employed 5600 km roads (ca. 23,139 km intersecting roads) of the Inka road system (Hyslop, 1984). In addition to GIS, photogrammetry plays an important role in urban streets, as it is more accurate than the traditional hand measurements (Spero, 1983). Sophisticated data are incorporated into archaeological projects, and details of cities can be engaged in current studies.

More researchers have recognized the importance of archaeology in urban studies. However, it is considered the heritage resource for the humanistic decoration of the present-day city (Guttormsen, 2019). The potential contribution that archaeology can make has been seldom addressed. Archaeology is one of the best repositories for urban development. The archaeological city remains are readable time-capsules for today's urban planners and researchers, demonstrating how cities were developed under different power relations and in which situation an urban design would be adopted or abandoned. Certain urban developing patterns and strategies from the past must still be practical nowadays.

Observing the urban road system of ancient cities is a supplemental approach to studying urban development. Previous research has been focusing on mapping possibly detailed and correct road systems through different methods, and some research has been trying to interpret the urban infrastructure based on the road network (Jansen, 1989). Capturing the non-static urban dynamic was challenging.

However, in recent decades as computer power undergoes exponential growth and the research interest in complex adaptive systems increased, Agent-based modeling (ABM) has been drawing increasing attention. Chen (2012, pp. 168) defined ABM as a type of model in which the agents contain autonomy and social ability so that each agent is able to operate, carry out instructions and make decisions independently while being able to interact with other agents as part of the community. It is a research method that has been applied to social science since the 1990s (Drogoul & Ferber, 1992) and later to urban analysis (Benenson, 1998). Nowadays, the variety of ABM software further lowered the barrier for non-computer-science researchers to apply this method to projects in different disciplines.

Current ABM models in urban road system studies are concerned with issues such as walking behavior (Yang et al., 2011), transport efficiency (Liu et al., 2014), and the design of pedestrian zone (Duc et al., 2020). As for pedestrian studies, ancient cities could be the perfect reference. They contained no modern interference from motor vehicles, which require distinguished traffic lanes due to the speed difference. Besides, the roads of archaeological sites could have been running continuously for ages. Unfortunately, urban researchers seldom address archaeological information.

This thesis aims to investigate the urban road system in ancient cities developed under different formation concepts. An ABM model would be built to simulate the pedestrian behavior of ancient urban roads based on the GIS data of archaeological sites. By running the same model with the data from sites with different urban formation modes, the pedestrian traffic of the urban road system can be visualized and discussed.

1.1 Prior studies on the road system

As one of the essential structures of human's daily activities, the road system did not draw much research interest for a long time. And for people who lived in the pre-digital age, the record of roads could not have the same accuracy as today. Waterman explained why his map of the studied area contained little information on roads "because I did not travel the trails myself" (1920, p. 220). His study's description and analysis of roads were based on field trips and could not be comprehensive and objective. They were biased as his access to geographical and archaeological/anthropological information was highly limited in the early 20th.

At that time, roads were not treated as archaeological objects. Unlike research on potteries or architectures, a systematic way to describe, investigate, and understand the road system was lacking. In the second half of the 20th century, the importance of spatial distribution in archaeology became recognized. Regional interaction and its influence on cultural development were focused on (in the old world: Lamberg-Karlovsy 1975; Kohl, 1978; Alden, 1982; and in the new world: Price 1977). The demand for language and methods to describe space appeared in archaeology.

Terminology and methods for spatial description were borrowed from other disciplines. Conolly and Lake (2006, p. 4) summarized the two most commonly used types of spatial description for archaeologists: topology or Euclidean geometry. The topology focus on the object's relative relation to its neighbors, and the Euclidean geometry contains more precise measurements such as distance and area. Both types of spatial data could be recorded for a single archaeological object or activity. As the data grew massive, the traditional way of managing spatial information was considered unsatisfying.

1.2 GIS data for studying urban roads

During the 1960s, GIS was proposed to process spatial information. With the development of computer technology, it was adopted into commercial software by the 1980s (Waters, 2017). In 1984, exploration of the Inka roads still required a combination of archaeological survey evidence and the regional infrastructure historical documents (Hyslop, 1984). However, in 1999, archaeologists could map the Roman city Carnuntum using archaeological data, photogrammetry, and GIS (Doneus & Scharrer, 1999). It could be observed that spatial information can be collected, processed, and visualized more efficiently with GIS than with traditional methods. Therefore, the completeness of the GIS data was one of the most critical factors for choosing archaeological sites as case studies in this thesis. Despite the existence of graphic maps, only the accessible GIS data of the case studies were used for modeling.

Although in this thesis, only the location information was needed for modeling, the GIS data could offer more. Conolly (2006) noted that the early archaeological GIS research was limited by the traditional 'common-sense' approach and lacked inferential rigor. As post-processual archaeology and theories introduced from anthropology became influential, archaeological spatial studies were no longer restrained to data integration. Cultural exploration became the main focus of the studies on road systems in ancient cities. Van Tilburg (2007) explored the road user and the traffic congestion in the Roman cities. Moreover, Kaiser (2011) compared different types of urban road-system to demonstrate their influences on Roman urban space.

1.3 Urban road patterns and their corresponding urban formation mode

Nowadays, the GIS data of most countries are openly accessible. For researchers who would like to observe urban road systems, the road map of cities can be downloaded from governmental or commercial platforms. In urban studies, the road system can be characterized by various patterns (gridiron, organic, radial grid, dendritic, loop and lollipop). This thesis selected the most commonly used characteristics, gridiron and organic, as they were considered formed through contradictory urban formation modes.

The grid plan of urban planning resulted in the gridiron road pattern. In this type of city, roads are aligned parallel to each other and intersect perpendicularly, forming a regular grid layout. The gridiron pattern has a long history and was not rare among ancient cities. The oldest grid-based design could be the cities Mohenjo-Daro and Harappa of the Indus Valley Civilization in the 3rd millennium BC. In ancient Greek, the Hippodamus of Miletus (498-408 BC) planned the new city of Thurium with gridiron streets, and the design was adopted later in other cities, for example, Alexandaria. In ancient Rome, this planning method was known as Centuriation (Roman grid system) and was widely applied in Roman cities. The grid patterns of streets were often related to highly concentrated political power. Kostof (1991, pp. 99) listed the gridiron cities that absolute governments ruled. Generally speaking, the gridiron pattern of roads is considered formed through the top-down urban formation mode, in which the city was built according to a master plan decided by the central governing power.

Besides the gridiron cities, another road pattern often observed is organic. The organic road system contains irregular street arrangements with curves and cul-de-sacs. Although this type of city seems disorganized, Kostof (1991, pp. 52) pointed out that they are not necessarily unplanned. The organic pattern could result from a continuous design process and comprehensive considerations of topography, prior occupation, and social convention instead of a totalitarian master plan. In general, the organic pattern was considered a result of the bottom-up urban formation mode.

1.4 The traffic influence of different urban road patterns

Since Renaissance, the gridiron design has been widely applied in Europe (ex. Mannheim, the new district of Copenhagen, and the center of Glasgow) and its colonies (pueblos in New Spain, New Haven in the English colonies). Numerous metropolis nowadays still follow the grid design, for instance, Los Angeles, Mexico City, Johannesburg, and Turin. In urban traffic planning, the gridiron pattern represents a high level of connectivity, which is evaluated by the multiple routes to and from a destination in the street network.

As time passed, the inadequacy of the grid design became apparent. The gridiron streets are an egalitarian system that does not cohere with the uneven traffic caused by the distribution of amenities, public services, and the social hierarchies. Moreover, the gridiron road system may have lower traffic efficiency as it has more intersections than other patterns. Besides, a modern urban study (Ben-Joseph, 1995) suggested a higher frequency of accidents in the gridiron residential neighborhood than the irregular neighborhood, which could also impact the traffic performance. In the modern city, where grid and organic patterns coexist, the organic urban form was considered more appropriate for pedestrians (Yoo & Lee, 2017).

The organic road system, however, could be more advantaged in traffic efficiency. First, the organic system follows the natural arrangement of the topography. For example, the pedestrian of a hilly city could prevent unnecessary traverse through steep streets. Secondly, the road system could be more flexible, as the intersections are not limited to the right angle. Some streets in the organic system have been built according to the pre-existed desire-line paths, which were the shortest or the most easily navigated route to the destination.

Furthermore, the seemly natural arrangement of the organic street system is self-conscious and rational (Kostof, 1991, pp. 64-70). Topologically, each node is connected with four street segments in the grid system. However, the number of connected street segments in an organic system is flexible. Therefore, roads could form convergence onto places like markets or city gates. Besides, the density of roads would also vary. Roads would be dense in the residential area and sparse at the edge of cities, matching the prospective traffic volume. Considering these characteristics of the organic road pattern, modern urban studies suggested that it could lead to better traffic performance than the gridiron pattern.

1.5 ABM simulating the urban traffic

The research on road patterns mentioned above contained data mainly acquired from two sources: the field measurement in chosen areas, and the simulated data from traffic modeling.

Modeling is a common approach to urban studies, in which ABM is one of the models that are widely used. This method is practical for studying complex and dynamic processes and has become popular for urban analysis. Moreover, the exponential growth of computer power in recent decades lowered the threshold for non-computer-science researchers to use programmable ABM in their projects.

Most urban ABM studies have been based on the modern urban environment. From the most famous model of segregation (Schelling, 1971) to the more recent land-use and transport model (Kii & Doi, 2005), ABM has been considered a reliable tool that can combine the rigorous argumentation of computer science and the profound understanding of social science.

Roads in cities belong to the essential urban structure. The road system has been an inevitable factor that could directly influence the urban pedestrian environment. Prior studies investigate the basic parameters of pedestrians, including walking speed, start-up time (Knoblauch et al., 1996), and energy expenditure (Zarrugh, 1976). In more recent urban studies, audits have been set to comprehensively evaluate the pedestrian environment (Clifton et al., 2007).

Moreover, a series of ABM studies have indicated that pedestrian behavior is highly related to city configuration and the location of attractions (Schelhorn et al. 1999, and Daamen and Hoogendoorn 2003). Kitazawa and Batty (2004) indicated that pedestrian behavior is under the utility-maximization theory. Although models using the shortest path algorithm cannot contour realistic trajectories in detail, their simulation is still relatively proper and reliable.

For a better understanding of the urban road system, ABM provides the possibility of setting multiple parameters of agents and the simulating environment to imitate more realistic pedestrian movement. By importing archaeological geo-spatial data, the simulation of past urban traffic could be particularly interesting for archaeologists.

Archaeological pedestrian studies have employed ABM as one of the most fruitful methods. In cities with thorough geo-spatial surveys, for example, Kerkenes, the full-scaled remote sensing data (aerial photography, satellite imagery, and geophysical surveys) enabled the development of a detailed topographical map of this ancient urban center. Combining the available data with ABM modeling, Branting conducted a series of studies, including pedestrian movement (Branting et al., 2007), route selection (Branting, 2012a), and transportation model (Branting, 2012b). Altaweel and Wu (2010) explained the model used for this approach in detail and demonstrated how to investigate pedestrian movement by measuring the passing traffic volume of roads in Kerkenes. These researchers ran the ABM model under different scenarios with specific age and gender groups of pedestrians.

Interestingly, the roads with the highest volume of pedestrians in the results generated from different scenarios were similar, although the intensity level among these roads differed. Although this model provided valuable results, it could be improved. The agents in the model were distributed evenly, one per architecture, without considering the actual size of the building compound. Besides, many details of the workflow were not given in the description.

Furthermore, these previous archaeological pedestrian studies on the road system cannot be considered conclusive. They have exclusively focused on route choice and neglected the possible impact of pedestrian interaction. Therefore, a new approach to integrating both factors is needed and will be discussed in this thesis.

1.6 Research goals and questions

This thesis aims to explore the urban road system of ancient cities by modeling their pedestrian traffic behavior. First, a reflexive overview of previous studies on the ABM method will be presented. In the next part, Kerkenes and Pompeii, the cities whose geospatial data is invoked in this research, will be introduced to represent different types of urban formations. Afterward, a new approach to using ABM to simulate pedestrian traffic in an archaeological environment will be proposed. Finally, the results will be generated from the data of the archaeological sites used as case studies and discussed. With this thesis, I wish to offer a more comprehensive approach to designing the ABM model for archaeological pedestrian studies and contributing to urban archaeology by investigating the potential relationship between pedestrian traffic and the formation mode of the city and its urban road system.

Therefore, my research questions were:

Is there a significant difference in the traffic effectiveness in ancient cities with different urban formation modes (top-down or bottom-up)?

- How should the pedestrian traffic of ancient cities be simulated in an agent-based model combining the route selection and the pedestrian interaction?
- Is it possible to gain statistically reliable simulation data to correlate the pedestrian effectiveness with urban road patterns through this agent-based model?

1.7 Thesis structure

To answer the research questions listed above, this thesis will be started with the history of agent-based modeling and its current development in Chapter 2. In this chapter, the explicit definition of ABM will be given, and its commonly used software will be listed. Next, ABM's advantages and disadvantages compared to another common modeling method, Cellular Automata, will be discussed. A brief overview of the application of ABM in archaeological studies will be presented and followed by a discussion of the previous ABM research on pedestrian behavior.

In Chapter 3, the research of the archaeological sites involved in this paper will be reviewed. Its historical background and current state of archaeology are the foundation for understanding its urban system so that the archaeological context of the urban road system can be better understood.

The methodological component of this paper is in Chapter 4. The invoked dataset and software in this thesis will be presented, and the workflow for combining route selection and pedestrian interaction in the ABM model will be described. In this model, the archaeological spatial data can be imported as the model environment, and agents are allowed to have autonomy and social ability to interact. The pattern of pedestrian traffic between different urban formation modes can be revealed by imputing data from the selected archaeological sites.

In chapter 5, the results generated from the model will be presented and evaluated to see whether they answered the research questions.

In Chapter 6, the workflow and results will be discussed in a broader context. The advantages and disadvantages will be noted compared with other pedestrian studies. Moreover, the way power structure affects urban planning will be explored. The factor that was most important for ancient traffic effectiveness will be interpreted. In addition to the comparison between cities, the varied pedestrian traffic volume in areas within each city will also be presented, and its archaeological potential will be discussed. Finally, this paper will be ended with a discussion of the idea of open science, wishing to contribute my effort to a better future for archaeological science.

Chapter 2: Agent-based Model

2.1 Defining ABM

In the 1960s, Schelling (1969) developed one of the essential models in sociology, the segregation model, which simulated the relocation process of people based on the racial ratio of their immediate neighborhood. This model has drawn not only interest from sociologists but also researchers from other disciplines, as they could not find the mathematical certainty between the segregation degree and the tolerance of racial ratio. The segregation model demonstrated a non-linear dynamical system that required a new study approach. This model has developed many computational variants, and the segregation model has become one of the most representative ABM models.

Agent-based modeling (ABM) has been a practical approach to studying complex and dynamic processes (Chang et al., 2020, Silva et al., 2020, Truszkowska et al., 2021). Traditionally simulation models are based on mathematical equations that describe the relation between variate and output. This abstract approach enables the researcher to observe a discrete system from a macroscopic level. However, many complex systems contain more than one sub-system, and the decentralized interaction among sub-systems is generally unpredictable in classic models. In this case, ABM provides a different structure in which every agent can be endowed with its own attributes. The interaction among agents can be recorded under each corresponding agent. This unique feature empowers researchers to observe complex systems from a bottom-up viewing angle and analyze the non-linear behavior within. Crooks and Heppenstall (2012) presented an overview of ABM and introduced its basic features. Wilensky and Rand (2015) combined the introduction of the ABM with practical coding information, which helped the reader understand this approach's computational aspect. And for archaeological studies of ABM, Lake (2015) discussed the general archaeological ABM simulation.

2.2 ABM software development

Since ABM has become one of the most potent simulation tools, various software has been developed for researchers. The most commonly named ABM software/toolkits include (but are not limited to) AnyLogic, NetLogo, MESA (Python), SARL, and SWARM. These mainstream software/toolkits support standard operating systems such as Windows, macOS, and Linux, allowing researchers in different disciplines to develop simulation models.

The mainstream ABM software/toolkits use popular computer language, JAVA or Python (JAVA for AnyLogic, SARL, and SWARM, Python for MESA). Having relevant knowledge of a specific language certainly decreases the learning cost of ABM software. However, not all researchers command high-level programming skills, especially in social science. Therefore, NetLogo becomes the best choice, as it is designed to be "low threshold and no ceiling"(Wilensky & Rand, 2015, p. XV). Uri Wilensky developed this software in 1999, and its latest version was released in December 2021 (retrieved in April 2022).

Although NetLogo uses its own language, the similarity between this programming language and natural language has reduced the requirement for previous coding experience. Numerous scientific articles in various domains have been published using NetLogo (NetLogo references from the official NetLogo website, retrieved in April 2022). It is also handy for archaeologists as it has specific teaching material targeting archaeological research (Romanowska et al., 2021), which is infrequent for other software/toolkits. Moreover, as this paper focuses on archaeological research, NetLogo is used for the simulation.

2.3 ABM vs Cellular Automata

ABM has been referred to as a powerful approach to complex systems, as its agents contain autonomy and can interact with each other independently. In this case, another simulation method, cellular automata (CA), is often compared to ABM. Literature of ABM often mentioned CA, as they could be used as an alternative or addition to each other (Crooks & Heppenstall, 2012). The idea of cellular automata was proposed in the 1940s as an analogy for self-replication and became well known through the Game of Life board game by John Conway in the 1970s.

CA model usually contains a cellular lattice, in which the value (or state) of each individual cell "is taken from a finite set and varies with time.... The state of a cell at the time t + dt (the derivate time from time t) is only determined by states of its neighbouring cells at the time t" (Liu et al., 1996, p. 1679). The transition between states follows predefined rules. CA has been widely employed in urban studies since its regular lattice affinities to the pixel arrays of remote sensing and the raster data of geographic information systems (Torrens & O'Sullivan, 2001; Santé et al., 2010; and Liu et al., 2021).

CA and ABM have a few characteristics in common. Both are considered decentralized, bottom-up approaches, and their patterns are connected with the process, mimicking the real-world systems dynamically. In some cases, these two methods can hardly be differentiated if the agents in an ABM model are located in cells and act to change the state of its cell based on the neighboring agents (in neighboring cells). For example, the forest fire model (https://ccl.northwestern.edu/netlogo/models/Fire) fits the definition of both CA and ABM modeling.

Both CA and ABM are popular approaches to exploring bottom-up disaggregate systems. Compared to ABM modeling, the cells in CA models only follow one set of predefined rules and do not contain autonomy. CA models have the characteristic of relative simplicity to simulate the emerging process of urban patterns. However, they are also considered "constrained by their simplicity, and their ability to represent real-world phenomena is often diluted by their abstract characteristics" (Torrens & O'Sullivan, 2001, p. 163). Nevertheless, in more recent studies, the individual behavior of human in urban studies has somewhat been simplified to conceptualizations of stochasticity (De Almeida et al., 2003) regarding the complexity of the urban interaction.

Unlike CA modeling, ABM modeling can incorporate more complicated interactions among agents and between agents and the environment and explicitly express the modeling feedback of shifting properties of agents and the environment, providing more possibilities to represent human decision behaviors. However, CA or ABM method is not an either-or proposition. Some researchers have driven the future development of combining CA and ABM modeling (Nainggolan et al., 2012; Wang et al.,2021). This kind of modeling containing coexisting methods still needs a more systematic and theoretical analysis.

Although CA has been proven beneficial in studying urban road networks and urban formation (Esser & Schreckenberg, 1997; Moghadam et al., 2013; and Wahyudi & Liu, 2016), the simulation model in this thesis applied the AMB approach without combining CA, as the agents' autonomy was required and their location kept changing during the simulation process. The roads in the model were similar to the cells in CA. However, they were static in this model, so CA was unnecessary. For future development of the simulation model, CA could be helpful to generate real-time features of roads, for instance, crowdedness or the upcoming traffic condition.

2.4 ABM in archaeological research

Before the term “agent-based modeling” was introduced into the archaeological domain in the 1990s, there was already computational simulation showing the characteristic of ABM (Lake, 2015). Since ABM modeling has been shedding light on the study of complex systems by exhibiting how macro patterns could emerge from micro parts, a series of previous and current archaeological ABM research has focused on the bottom-up growth of social phenomena.

From the most basic Sugarscape model in 1996 (Epstein et al., 1996) to the Long House Valley model in 2002 (Axtell et al., 2002), archaeological ABM studies have aimed at constructing artificial society to re-enact human behavior. For instance, this approach has been applied to several studies to understand the prehistoric evolution of social behavior (Premo, 2007; Janssen & Hill, 2016; Gravel-Miguel et al., 2022). ABM “enable us to examine the possibility of the emergence of new structures (for example, institutions, alliances, and communities) out of the basal units and their interactions”(Kohler & van der Leeuw, 2007, p. 6).

Most archaeological ABM studies have been based on the null model (random network) and rational agents (agents know all the information and only make the rational choice based on the given rules). Lake (2015, p. 15) suggested that this perspective could have come from the Santa Fe Institute. Its ABM textbook, grounded on the Complex Adaptive Systems approach, has a strong influence on archaeologists.

Bentley and Ormerod (2011, p. 205-6) stated that, unlike the computer, humans do not have the capacity and the access to all the information to make optimal decisions. Hence, the rationality of agents in ABM is nonhuman. The ABM modeling can not fully mimic human behavior, and it is also difficult to quantitatively evaluate it. Therefore, a new approach that can contain the most appropriate agents and elevate the existing constraints is still one of the tough challenges for all researchers in this domain.

The controversial issue of archaeological ABM studies is ineluctable, but the obstacle cannot refrain researchers from using ABM. Costopoulos summarized the existing approaches in archaeological simulation, in which the abstract-generalist form “focuses on modeling high-level processes and is concerned with the specific case as an instance that illustrates the operation of the process” (Costopoulos, 2015, p. 265). This approach uses generative models to model a few processes and must not be connected to an actual particular case. The realist approach, which tries to portray a context with possibly many processes and features, is generally infeasible in archaeological studies. The abstract-generalist is, although controversial, the preferable approach for current research. Additionally, Bentley and Ormerod (2012, p. 205) themselves also mentioned that many complex social phenomena need not require complex behavior on the part of individuals.

This thesis followed the abstract-generalist approach and only focused on the simplified route selection and pedestrian interaction process. The traditionally preferred rational agents were replaced by agents with bounded rationality, and their knowledge would be metabolic based on the real-time situation.

2.5 ABM in pedestrian studies

Since 2000 ABM modeling started to be seen in pedestrian studies (Dijkstra et al., 2000). As one of the bottom-up modeling paradigms, ABM is particularly useful in simulating pedestrian behavior, as its decentralized nature is challenging to be present by traditional methods. In contrast to Cellular Automata, the ABM modeling could contain various types of agents. Moreover, different features of the pedestrian group have been proven to influence macro behavior (Toyama et al., 2006). Hence, ABM modeling has become the more preferred method in pedestrian studies.

A large and growing body of literature has focused on assessing urban or architectural design performance using simulated pedestrian dynamics (Godara et al., 2007; Lujak & Ossowski, 2017). Rosenman and Wang (2001) developed a CAD system combined with ABM. Maher et al. (2005) further Incorporated the 3D virtual environment into this kind of CAD system and indicated that ABM is a basis of design reasoning that facilitates synchronous collaboration.

More recent attention has been paid to optimizing the simulation of individual pedestrian trajectories, which is highly dependent on agents' autonomy in the ABM modeling. Dijkstra et al. (2011) discussed that the shopping agenda of pedestrians could guide their movement and time spent. Furthermore, "culture" as dependence in the ABM modeling was introduced by Kaminka and Fridman (2018) to simulate more realistic pedestrian crowds. Filomena et al. (2020) explored the influence of the information difference about urban subdivisions on agents' behavior. However, all these studies have been done in the modern context, where the traffic system is much more complicated (coexisting pedestrian and vehicle circulation and three-dimensional transportation) than in the ancient environment.

Despite the traffic change over time, considering the above-mentioned pedestrian models, the pedestrian behavior could be influenced by their personal background and travel plans. Papadimitriou et al. (2009) distinguished two types of dependence in pedestrian route choice, the tactical and the operational decision. The former is based on activity scheduling, activity area choice, and route choice; the latter is on road-crossing, obstacle avoidance, and interaction with other pedestrians.

In brief, the behavior of agents is developed on the previous endowed knowledge of agents and their real-time reaction to traffic and other agents. The ABM model needed to be designed with autonomous agents for a better simulation result. Therefore, although the agents' cultural backgrounds were ignored to prevent cultural bias in simulating different cities, all agents in the model of this thesis could make individual decisions based on real-time information acquired from their surroundings.

Overall, the ABM pedestrian studies focused on developing a more realistic pedestrian flow by optimizing the attributes and dependence of agents. On the contrary, studies on the assessment of urban design performance are limited. The research potential between pedestrian traffic and urban planning is neglected.

The road system is deeply related to the urban emerging process and directly influences pedestrian behavior. The urban study with a non-ABM approach proved that pedestrian behavior would vary in areas with different street patterns (Yoo & Lee, 2017). However, the potential of ABM in researching pedestrian traffic related to urban road patterns has not been explored, and the related studies are inadequate. This thesis would attempt to narrow the gap in pedestrian traffic behavior and further explore its relation with the urban formation modes represented by the road patterns.

Chapter 3: The archaeological sites: Kerkenes and Pompeii

In this thesis, two archaeological sites, Kerkenes and Pompeii, are concerned with applying the ABM modeling. Based on their geo-spatial data, the ABM model can simulate pedestrian behavior to better understand the relationship between different types of urban emerging processes and pedestrian traffic.

3.1 Kerkenes

3.1.1 The research history of Kerkenes

The archaeological site Kerkenes locates in central Turkey. As a walled city, it contained more than 270 Ha and was occupied for a relatively short period before being abandoned in mid 6th century BC. This site was preliminarily investigated by Anderson (1903) and later by von der Osten (1928) in 1926 and 1927. At the end of the 1920s, the first excavation took place by E. Schmidt (1928) from the Oriental Institute of Chicago. With the survey of the enclosure of Kerkenes, Kerkenes amazed archaeologists with its vast coverage area. It is considered the largest pre-Hellenistic site in Anatolia. Although this site was hoped to be constructed during the Hittite Empire, the pottery yielded during excavation dated Iron Age.

From 1993 to 2012, the international Kerkenes Project was led by G. Summers and F. Summers. A series of studies were published, in which considerable evidence such as inscriptions, graffiti, and architecture indicated that Kerkenes was involved with the Phrygian culture (Summers, 2006; Summers & Summers, 2008).

Although there was controversy, Kerkenes has been identified as the ancient city Pteria (Branting, 2004a; Summers & Summers, 2021). Since the city had been inhabited briefly between the 7th to 6th centuries BC and destructed afterward, its structure was preserved relatively well, and today part of the city is still visible. One of its most famous architecture discovered by the team of Summers is the Cappadocia Gate (one of the seven city gates). It contained a monumental stone structure, shedding light on the age of turbulence and the threat Kerkenes was facing.

3.1.2 Geo-spatial studies and simulations

Since the Iron Age urban structure in Kerkenes was relatively well preserved and easily accessed, in the last two decades, studies of Kerkenes have been focused on applying geo-spatial technologies to understand its city structure better. Aerial photography, satellite imagery, resistivity survey, and magnetometry survey was conducted over the once occupied area. Branting (2004) reconstructed a detailed plan of Kerkenes by combining the collected geo-spatial data. Moreover, he continued to work on mapping the residential area of the city and identifying individual buildings and rooms of urban blocks and compounds (Branting, 2012a).

With the comprehensive geo-spatial data, in particular the digital plan of Kerkenes, new approaches could be introduced into the research of the city. Several studies containing ABM or Transportation GIS modeling have been published (Branting et al., 2007; Branting 2004a, 2012a). Previous studies on pedestrian traffic in Kerkenes have almost exclusively emphasized creating a realistic human pedestrian model using real-world geographical configuration. The relationship between pedestrian behavior and the urban road system has never been addressed.

3.1.3 Roads in Kerkenes

Despite the adequate geo-spatial studies, the roads in Kerkenes were seldom mentioned in excavations. Branting (2004b) noted that most of the roads in Kerkenes were likely unpaved. Moreover, Altaweel and Wu (2010) mentioned that there were soil samples collected from six road trenches, and their varied soil particle sizes evidenced an uneven distribution of traffic in Kerkenes, albeit the location of the road trenches was not given in the paper.

In brief, the known information about the roads in Kerkenes has mainly been the geographical location, the elevation, and the building compounds surrounding them. Some areas in the road system of Kerkenes contained the pattern similar to loose grids. However, the roads could be generally characterized as the organic pattern. As mentioned in chapter 1.3: Urban road patterns and their corresponding urban formation mode, the organic pattern is not necessarily equivalent to “unplanned”. Its planning process could be continuous and decentralized. According to the road pattern, Kerkenes could be considered a result of the bottom-up urban formation process. Nevertheless, in Kerkenes, a certain traffic hierarchy existed between the roads.

3.2 Pompeii

3.2.1 The research history of Pompeii

The other archaeological site to be explored in this paper is Pompeii. This ancient city emerged from a settlement in about 6th century BC and extended northeastwards. Kaiser (2011, pp. 67-71) suggested that Pompeii was transformed into a Roman city around 80 BC, as the Roman general and dictator Sulla governed the city and implemented the regeneration work.

However, Poehler (2017, pp. 43) was convinced that there was a single master plan for Pompeian urban planning since the beginning of the 4th century BC. Despite the disagreement, most of the city’s layout was preserved by the destruction of Pompeii and rediscovered through the last centuries' excavations.

Albeit the digging in the past, the modern archaeological work of Pompeii started in the 1920s (Moormann, 2015). A. Maiuri directed the excavation from the 1920s to the 1950s. The city wall and some of the city area were uncovered through extensive excavations. Unfortunately, these large-scale excavations were not documented scientifically.

After the Second World War break, large-scale excavations had been continued in Pompeii. The excavated area was expanding quickly. However, some areas had not been exposed for scientific purposes but for selling the pumice from the archaeological layer, and the mining damaged the archaeological remains in Pompeii (De Caro, 2015, p. 24). Nevertheless, the earthquake in 1980 and the subsequent watershed also caused severe destruction.

Today the excavations of Pompeii have been continuing. More architectures and findings have been discovered in the previously unexcavated area. The modern, scientific and sustainable excavation method and the extraordinarily preserved remains provide numerous research potential to understand Pompeii better.

3.2.2 Pompeian street network

As archaeologists and historians have continuously studied Pompeii for centuries, the archaeological knowledge of this city has reached an enormous quantity and is highly specialized. The intensive excavations in the past broadly exposed the streets, which have become the foundation for creating the topographic map of the ancient city. The more recent research interest in the Pompeian street network appeared in the 1990s. The streets have been used as the context to interpret the ancient urban life and to explore the social dynamic. The change in economy and society can be observed by discussing the distribution of commercial and production centers and showing the spatial boundary between private and public life embedded in the street network (Laurence, 1994; Wallace-Hadrill, 1994; Zanker, 1998).

According to Geertman (2007), Pompeii's street network was developed in three phases. In his urban growth model, the city was first expanded from the southwestern Altstadt in the north along the via di Mercurio shortly before 300 BC and bounded by via del Vesuvio and via Stabiana (phase 1). And the construction of the next phase (phase 2) started from the newly formed boundary of phase 1 and continued northeastward. Moreover, the eastern part of Pompeii was formed in phase 3. The urban area increased in these three phases were generally long, rectangular blocks.

Although Geertman did not further explore how the shape of city blocks varies according to the construction phases, his model demonstrated that the growth of Pompeii was a series of planned events. Poehler (2017, chapter 2) pointed out that the ground slope influenced the shape of Pompeian urban blocks, and the city was formed based on a master plan designed by the end of the 4th century BC, which could suggest that an even more concentrated power planned Pompeii.

In comparison to Kerkenes, Pompeii has been excavated to a fairly extensive degree. Therefore geophysical methods were not the primary approach for completing the city map. Malfitana et al. (2018) conducted surveys with ground-penetrating radar and electrical resistivity tomography investigating the necropolis of Porta Nocera, which is outside of the city wall of Pompeii. The geo-spatial data of the urban area is mainly based on the findings of excavations.

Chapter 4: Methods

4.1 Introduction

This research is grounded on an ABM simulation model to understand how the urban road system could influence pedestrian effectiveness in ancient cities. The ABM model generated corresponding pedestrian traffic behavior and produced quantitative data for evaluation based on individual urban geospatial data.

Since this research emphasized different urban growth patterns (bottom-up or top-down) and their influence on traffic behavior, the pedestrian traffic would be generated based on two archaeological sites, Kerkenes and Pompeii. Each of them represented one type of urban growth pattern. The pedestrian efficiency with the formation mode could be qualitatively correlated by statistically comparing the simulation data of these two different types of cities.

4.2 Dataset

The dataset used for this research included the GIS data of Kerkenes and Pompeii. The data of the urban road network is isolated from the geospatial data collection of Kerkenes in the form of a shapefile.

Furthermore, the data on Pompeii is collected from the Pompeii: Navigation Map 2 of the Pompeii Bibliography and Mapping Project directed by E. Poehler (Pompeii: Navigation Map 2, 2017). A shapefile of the isolated urban road network was drawn according to the street information on the map. Moreover, the Street Evidence published on ArcGIS Online also by Poehler (Street Evidence, 2017) was used for reference.

In comparison to Poehler's Street Evidence, the drawn road network of

Pompeii added the missing intersection of roads (the intersection of Via Consolare, Vicolo del Farmacista, and Via delle Terme) shown on the Navigation Map 2. The Forum was not being treated as a traffic-isolated island. The streets attached to it were connected across the Forum.

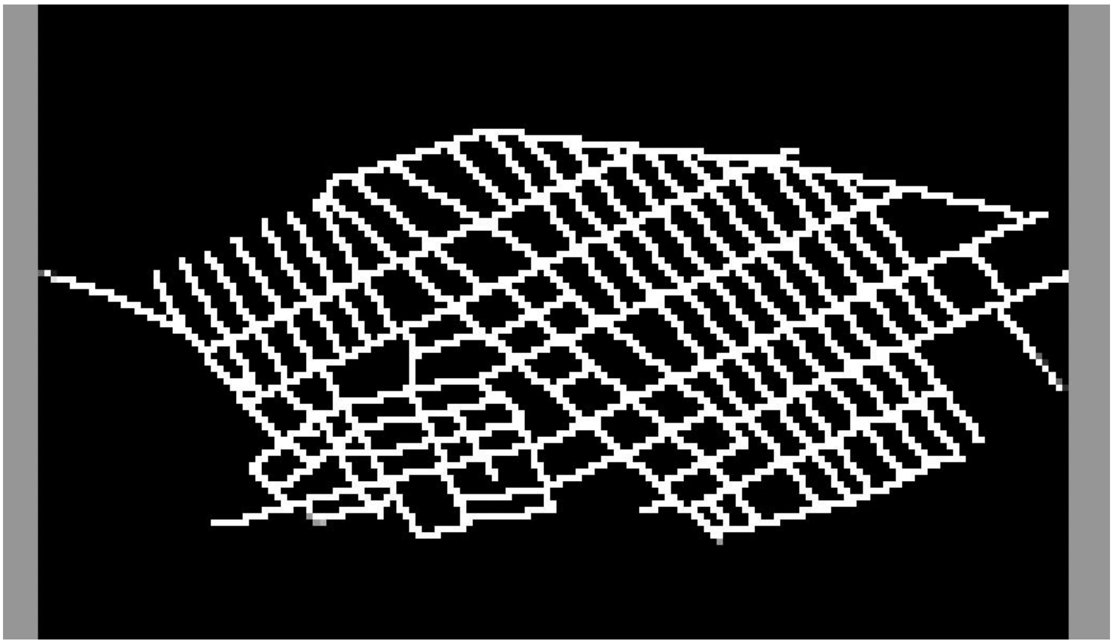

Figure 1 The shapefile of Pompeian road system

4.3 Software

The software used in this research was QGIS and NetLogo, and both of them are free and open-source.

Although the referencing data of Pompeii was processed and published by ArcGIS (a commercial GIS software), to support the idea of open science and to avoid the black box associated with commercial software, the digital data of the urban road system used for simulation is viewed and prepared using QGIS. It is also a commonly used GIS software for analyzing and editing geospatial data. This software was previously named Quantum GIS and developed by Gary Sherman in 2002. In 2007, Open Source Geospatial

Foundation adopted it and renamed it QGIS in 2013.

It is generally noted that QGIS is less user-friendly, as it has a relatively confusing interface and inadequate tech support compared to ArcGIS (a personal judgment from the author, and other QGIS-users may disagree). However, in this research, only the essential functions of GIS software were required. Therefore the disadvantages of QGIS were not significant. The version used in this research is QGIS 3.20.1-Odense, released in June 2021.

The software used for simulation in this research is NetLogo, one of the most frequently used ABM modeling software. And the version used in this paper is NetLogo 6.2.2 (released in December 2021).

Although NetLogo uses its own coding language, it is known as easy to learn and has less threshold. These advantages became the primary cause of choosing this software, as the author only had limited coding experience. Most of the knowledge the author acquired was from the free online course of Santa Fe Institute and the ABM textbook for archaeology (Romanowska et al., 2021). These open accessed materials further reduced the obstacle of using this software. Moreover, NetLogo also provides users with many sample models and a continuously updated collection of published references, empowering researchers to create and improve their own ABM models. More details on comparing NetLogo and other mainstream ABM software could be found in chapter 2.2: ABM software development.

4.4 The ABM Model

For this research, an ABM model was built using NetLogo. ABM modeling has been increasingly used for pedestrian simulation. In archaeology, it has also been considered a promising research method.

A series of studies of pedestrian transportation in Kerkenes has been conducted (Branting et al., 2007; Altaweel & Wu, 2010; Branting, 2012b). The

ABM model SHULGI was built to investigate the traffic volume. In this model, the agents have a fixed starting location and return to it after reaching the goal location through the least-cost route. Since the research focuses on identifying the most traversed area, each agent would be reassigned with a new goal once they arrive at their starting point until all the structure in Kerkenes has been visited.

The model built for this paper followed the abstract-generalist approach that "focuses on modeling high-level processes and is concerned with the specific case as an instance that illustrates the operation of the process" (Costopoulos, 2015, pp. 265) and aims to explore the pedestrian traffic effectiveness of ancient cities. This model attempted to simulate pedestrian behavior and applied comparatively realistic human data when possible. Since Kerkenes was chosen to be one of the case studies in this research, the SHULGI model had been used as the most important reference.

To study the pedestrian traffic of ancient cities, the pedestrian movement was simulated based on two types of parameters. The first type was the parameter used to set the "world", which was the stage where agents behaved themselves. The world was formed based on the GIS data imported into this model. The shapefile of the real-world road network information from Kerkenes and Pompeii archaeological sites was used.

To lower the threshold of this model, the computing power required had to be limited. Therefore, the model followed two basic assumptions: the first one is the "isotropic plain", which means the "world" formed in this model was idealized in a uniform standard that there were no slopes, rivers, or other land-forms. The other assumption was the "isotropic road system", that all the roads in this model have the same "walkability". The width of each road and the presence of other agents on the road would not affect the agents' behavior. Based on the archaeological evidence of the prevalence of one-lane narrow streets in Pompeii, the roads in this model were set to one-lane. These settings lower the realistic degree of the simulation. However, it compromised the computing power required by the model and the workload.

The second type was the parameter of agents. Each agent was set with two random locations as "home" and "work", and commuted between these two locations through the shortest path. There were six-speed categories among the agents representing young men, young women, middle-aged men, middle-aged women, older men, and older women, which are references to the pedestrian division of SHULGI model. Each category was assigned with a corresponding average speed limitation that would be reached in ordinary walking. The speed setting in SHULGI was used as a reference to build this model (Altaweel and Wu, 2010, Tab.1). However, instead of the exact number from the relevant real-world data, the speed limit was set according to the ratio between different sex and age groups, as the real-world velocity could not be used directly in the patched surface of NetLogo. The agents in this model were in a closed environment. Unlike the real world, the pedestrians would not leave the city, and no outsider would enter through the city gates.

The average velocity on the horizontal layer of young men, young women, middle-aged men, middle-age women, older men, and older women was 8.61 km/h, 8.10 km/h, 7.81 km/h,7.16 km/h, 6.85 km/h, and 6.16 km/h respectively. The ratio were 1:0.94:0.91:0.83:0.80:0.72. The reference point was the velocity of the young men group as it was the highest, which helped to fit all the velocities with slide bars in the NetLogo interface.

In the simulation of pedestrian traffic, the interaction between passengers should not be ignored. The agents needed to make real-time reactions to the changing traffic condition caused by pedestrian interaction to mimic more realistic behavior. In this case, the following rules were set in the model.

The initial velocity of all agents was 0. Once the agents started to move, their velocity varied according to the real-time situation of each agent. The environmental information of each agent (next patch to move, the velocity of the agent ahead) would be collected as the metabolic information at each tick and replaced by the new information by the next tick. For each agent, if there were no other agents ahead of it, its velocity would accelerate till its speed limit was reached. If there were an agent ahead of it and walked in the same direction, the agent's velocity would be set to the same as the agent ahead and decelerate. These rules used the model Traffic Basic from the Model Library in NetLogo as a reference.

Based on the more realistic traffic in the road system based on archaeological sites, a rule for the situation of the agent ahead walking in a different direction (crossing) was added. Initially, the author set the agent to stop when its agent ahead was in a different direction. However, the simulated traffic would clog from the very beginning stage. After several attempts, it was found out that the agents needed to keep a relatively slow speed so that the simulation could run appropriately. Therefore, the agent's velocity would reduce to 0.1 in this situation. So the rule is: If the agent ahead were in a different direction, the agent would almost stop walking (velocity = 0.1) until the traffic condition changed.

Zębala et al. (2012) stated that the acceleration between different age groups is not decisive. Furthermore, in the scene of ordinary walking, the range of acceleration of males and females are largely overlapped. Therefore, all agents were set with the same acceleration in this model.

As this model's simulation process could be demonstrated on its interface, the general traffic condition was visualized through the aggregated agents. Moreover, this model also gave a live report counting agents in congestion (velocity = 0). It also presented the changing percentage of roads currently occupied by agents and the level of agents' dispersion, indicating the road system's efficiency. Nevertheless, this model recorded the number of visits in each patch and normalized and visualized the data into a color scale.

By the end of the simulation (5000 ticks), the number of agents in congestion (at the last tick) would be given, along with the road occupancy rate and the dispersion rate of the agents. The road occupancy rate was calculated by dividing the number of occupied road patches by the total number of road patches. Furthermore, the dispersion rate of the agents was calculated by dividing the number of occupied road patches by the total number of agents. Besides, the aggregated traffic volume of each road patch would also be given. After the simulation, the total visit of agents (per tick) would be counted and normalized. In the NetLogo interface, the road patches could be rendered according to the normalized traffic volume for instant visual assessment. Moreover, the normalized traffic volume could be exported in an ASC file for further process in GIS software.

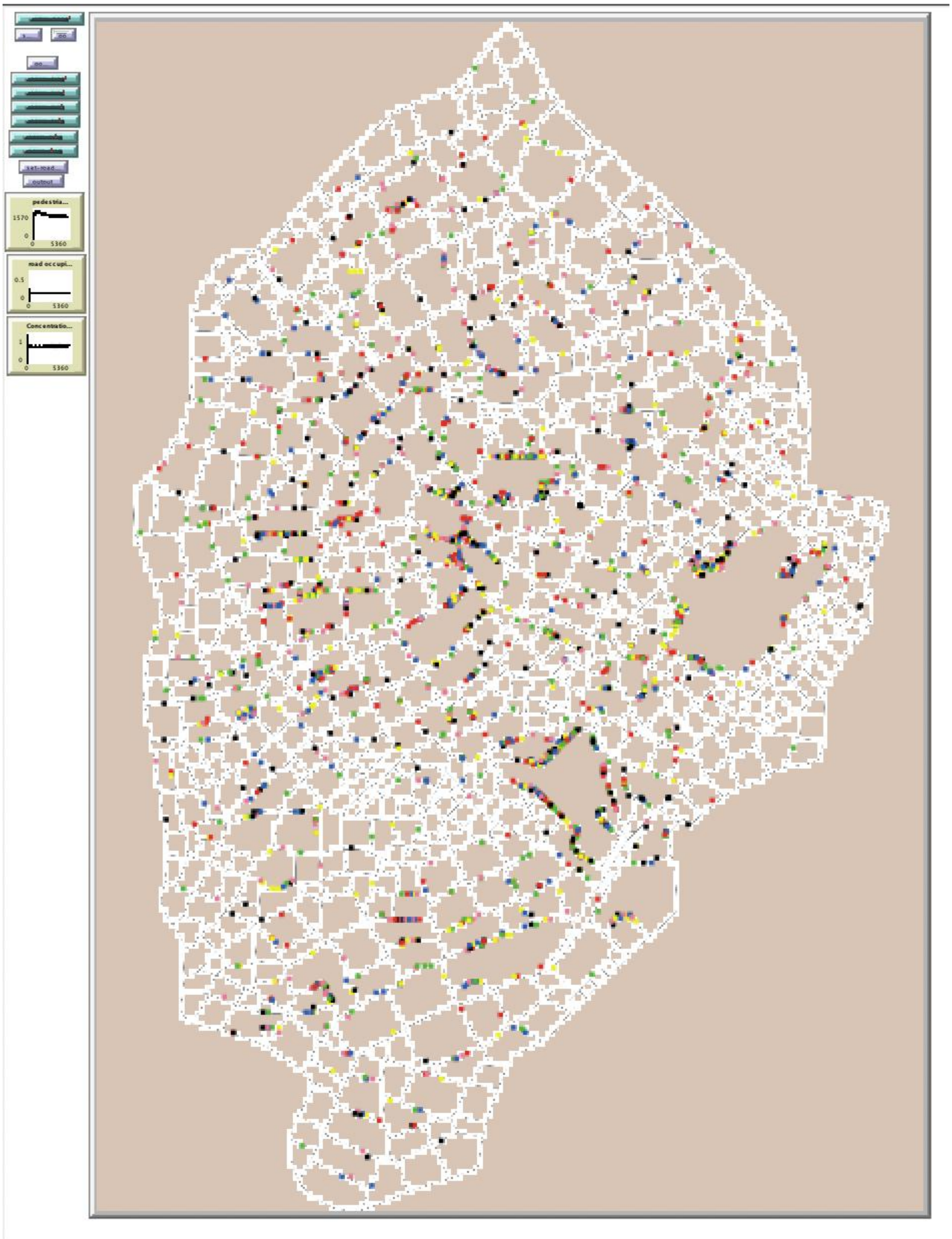

Figure 2 NetLogo interface with the simulation of Kerkenes

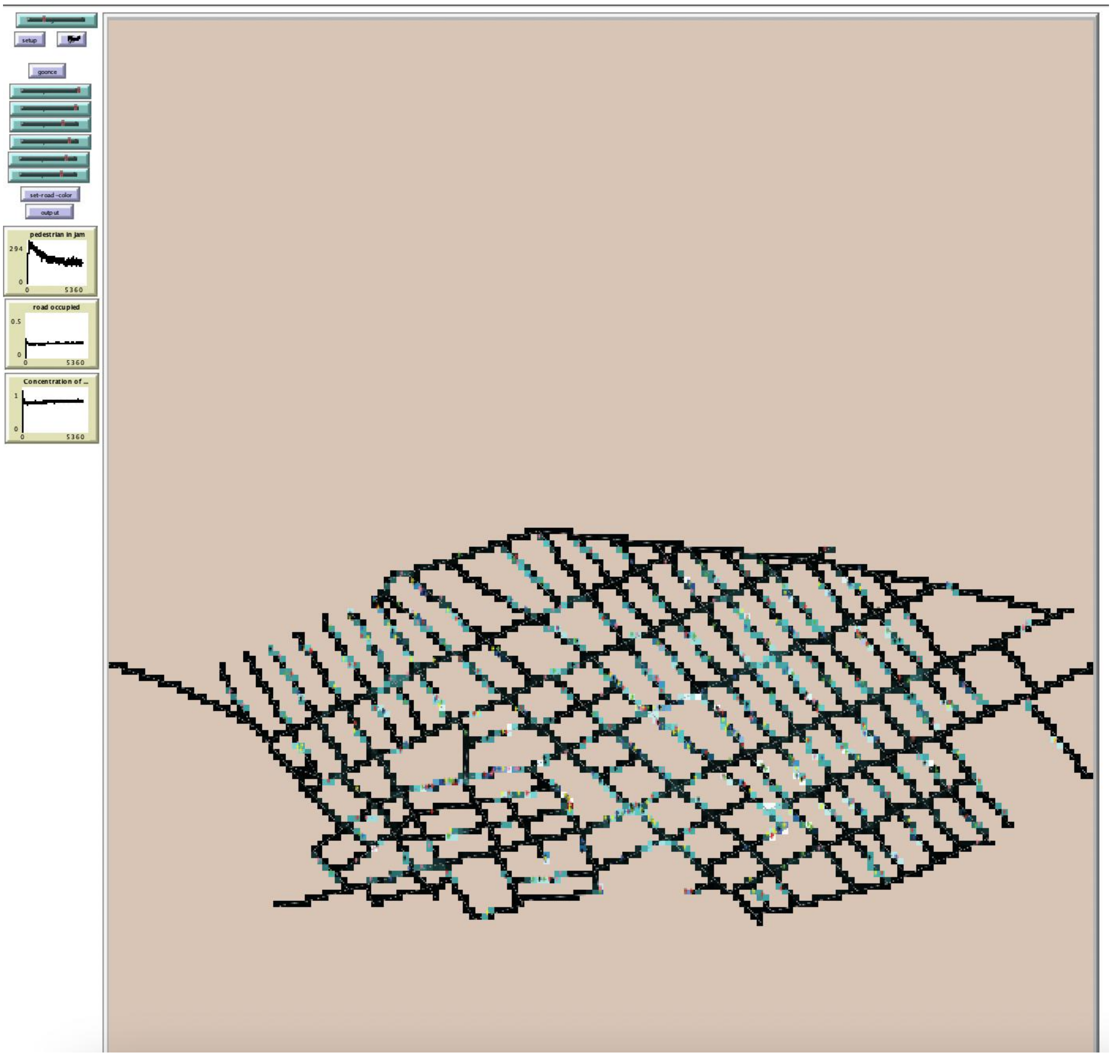

Figure 3 The rendered traffic volume in the NetLogo interface at the end of one simulation of Pompeii

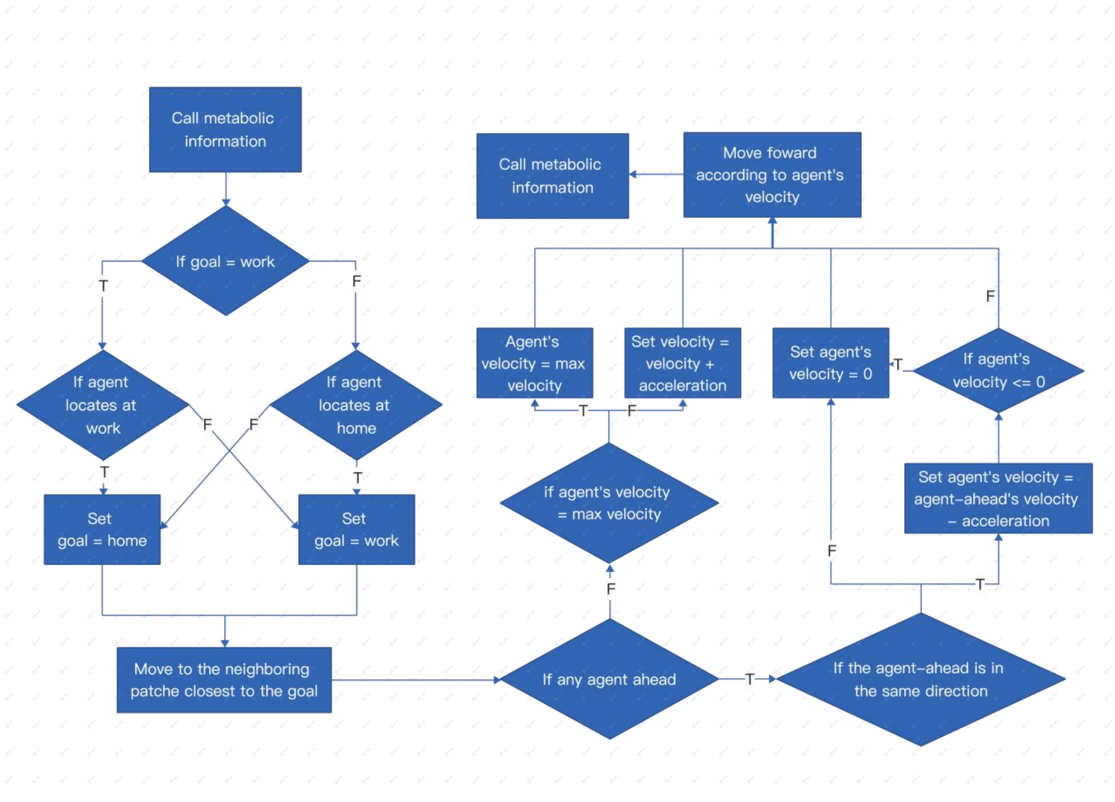

Figure 4 Flow chart summarized how agent moved in each tick

4.5 Workflow

4.5.1 Preparing the road network data

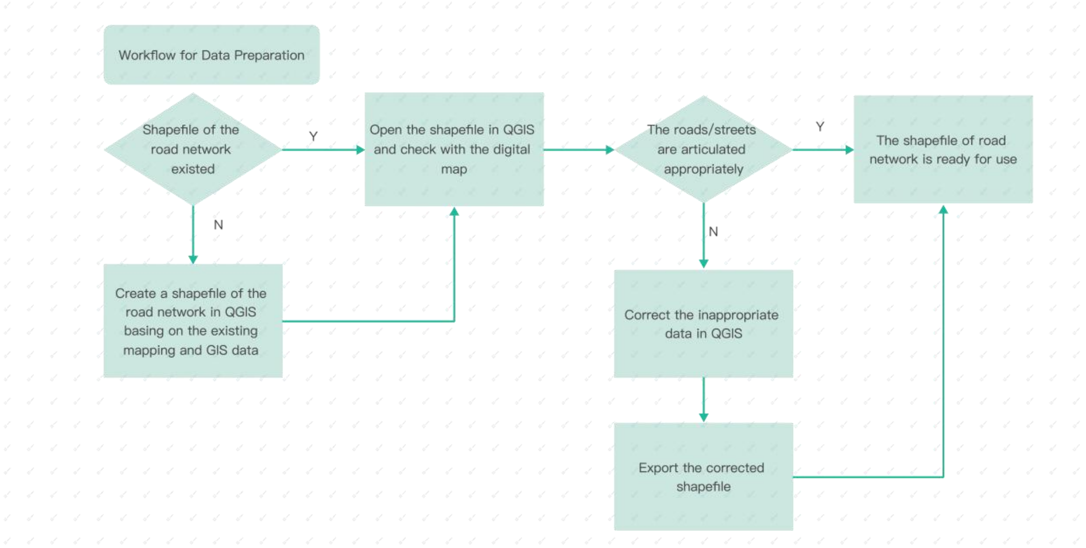

Figure 5 Workflow of data preparation

The ABM model required the appropriate GIS data of the urban road system to be imported. In this thesis, two archaeological sites, Kerkenes and Pompeii, were used as case studies, and their GIS data on the road network is an essential factor for simulation.

The data (shapefile) was opened in QGIS and examined whether the roads in the shapefile were correctly drawn and articulated. Despite the method used, the urban area of the archaeological sites chosen for this study was fully mapped. Without a known area of traffic isolation, the road system of each site should only form one topology. Thanks to the elaborate work of the Kerkenes Project, there was no necessary modification to the data. Once all the errors are cleared, the data is ready for modeling.

For the other site, Pompeii, more procedures were needed. In preparation for the Pompeian street network data, the Navigation Map 2 of the Pompeii Bibliography and Mapping Project was used as a reference. The director of this project, E. Poehler, also published some related GIS data in ArcGIS Online, in which the Street Evidence contained a layer of the street network. It had become a valuable reference to complete the data of the road system of Pompeii. A new shapefile is created, including the reconstructed road network of Pompeii. Compared to Poehler’s street network, the Forum in the city is not treated as an end of articulated streets. It is embedded in the network as the traffic could go through.

Once the data of Pompeii was completed, it was examined through the same process as the data of Kerkenes had until it was ready.

4.5.2 Modeling

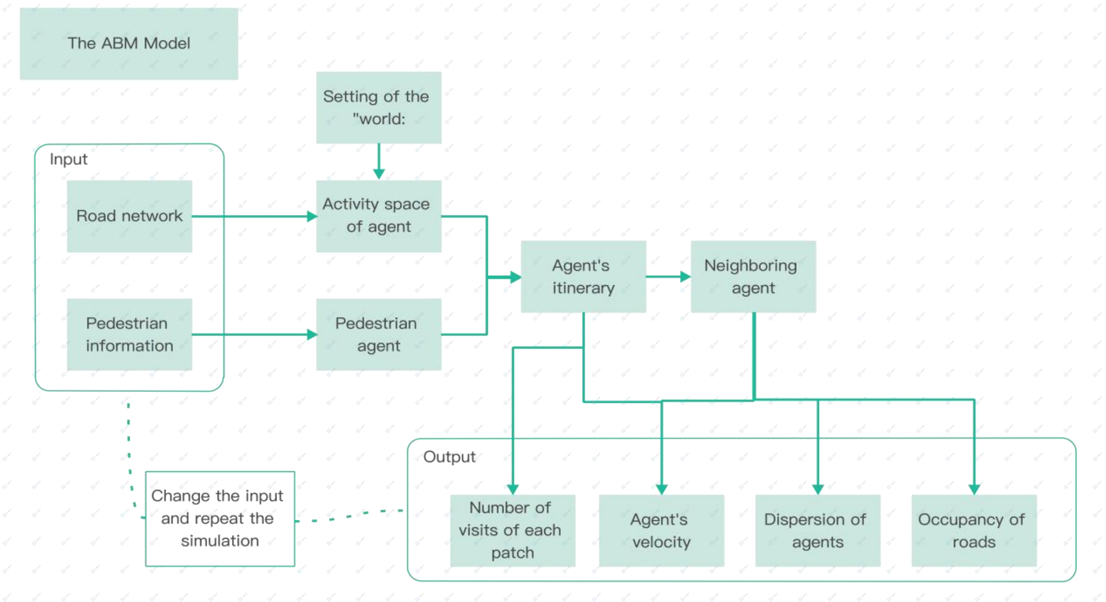

Figure 6 Workflow of ABM modeling

In this section, the ABM model built for this research was in use, which required to be opened by the software NetLogo. Moreover, the modeling process started with importing the GIS data of the first archaeological site. The agents should be set to the desired number (the default number is 600 in this model), with six different speed limitations representing the pedestrian's six age and sex groups. The corresponding data of speed limitation used in this research was set as the default numbers for each group in the model.

Besides the parameters mentioned above, it was important to check the setting of the "world" and make sure the road system was demonstrated with appropriate resolution. In this thesis the coordinates were set to max-pxcor = 160 and max-pycor = 230, creating a 160 x 230 coordinate system for the imported road system.

To generate a more reliable result, the model ran simulation separately with three different numbers of agents (600, 900, and 1200 agents) for each archaeological site. The demography estimation of archaeological sites is usually from100-150 per Ha (Kramer, 1982) to 250-1200 per Ha (Postgate, 1994). Storey (1997) suggested that Pompeii (66 Ha) had11,000 residents.

With this population to surface area ratio, the population of Kerkenes (270 Ha) could be about 45,000. Therefore the assumed portion of people who were moving to the city at the same time would be between 1.3% (600 agents in Kerkenes) to 10.9% (1200 agents in Pompeii). Unfortunately, there was no reference indicating the portion of urban residents transporting simultaneously.

Furthermore, the simulation was repeated 30 times for each number of agents. Each simulation ended with 5000 ticks. The number of agents in congestion, the road occupancy rate, the dispersion rate of the agents, and the normalized data of visits to each patch would be exported.

Chapter 5: Results and Analysis

5.1 The modification in the workflow of modeling

In chapter 4.5.2 the workflow of the modeling process was described. The GIS data of the archaeological sites, Kerkenes and Pompeii, was imported into the ABM model to generate the “world”. The road systems of these two ancient cities were demonstrated as patches in which agents could traverse.

In this process, the built-in extension “GIS” of NetLogo was used to convert the GIS data from the imported shapefile to the road system that was formed by individual patches. Unfortunately, it was unable to predict the number of patches of the road system before it was generated. As the patches were generated automatically based on the shapefile and the set resolution (in this thesis, 160 x 230), fine-tuning the number of patches was also impossible.

In the ABM model, the road system of Kerkenes consisted of 8877 road patches and the road system of Pompeii 2549 patches. The road system of Kerkenes had a considerably higher capacity for pedestrians. To avoid the deviation in the number of patches, for Kerkenes, three extra groups of simulations were added and set with 2090, 3134, and 4179 agents to compare with the simulation of Pompeii with 600, 900, 1200 agents, which was in accordance with the ratio of the patches number 8877:2549. Therefore the portion of transporting urban population used was 5.5%, 8.2%, and 10.9%.

5.2 Results

5.2.1 Kerkenes

The simulation of Kerkenes was run a total of 180 times with agent numbers

600, 900, 1200, 2090, 3134, and 4179. The average value and the standard deviation of the simulation can be seen in Table 1. All the data was collected by the last tick (the 5000 tick) in the scenario with evenly proportioned age and sex groups of pedestrians.

Agents	Average number of agents in congestion	SD of number of agents in congestion	Average dispersion	SD of dispersion	Average road-occupy-rate	SD of road-occupy-rate
600	42.2000	7.3924	0.7749	0.0144	0.0524	0.0010
900	96.1667	9.2962	0.7084	0.0117	0.0718	0.0012
1200	155.9000	9.6145	0.6669	0.0111	0.0902	0.0015
2090	382.7333	18.9899	0.5705	0.0078	0.1343	0.0018
3134	2099.3333	37.9358	0.5015	0.0049	0.1771	0.0017
4179	3104.3000	34.4455	0.4587	0.0066	0.2160	0.0031

Table 1 Simulation results of Kerkenes

Figure 7-9 presents an overview of the simulation result of Kerkenes. The correlation between the varied agent number and the exported data was tested using Pearson's correlation coefficient. As the number of agents increased, the ratio of agent in congestion rose (r = .9863, p = 0.014). Road patches were occupied by agents (r = .9956, p < .001). Meanwhile, the dispersion rate of agents dropped when more agents were released into the road system (r = -.9670, p < .001).

Furthermore, Figure 10 provides the cumulative result of the traffic volume with 2090 agents in the road system, with the indication of the road patches that were most frequently traversed. Since the origin and the destination of agents were designated randomly, it was possible these two locations of one agent were close to each other, resulting in unusually high traffic volume in a localized area. To decrease this type of interference, the traffic volume of ten simulations was merged together.

It could be observed that the traffic in Kerkenes was unevenly distributed. There were arterial streets that bore higher traffic volume in the center, and the streets at the edge of the city tended to have less traffic. Moreover, topographic features were surrounded by road segments with high traffic volume. And some building compounds also drew the traffic volume to them.

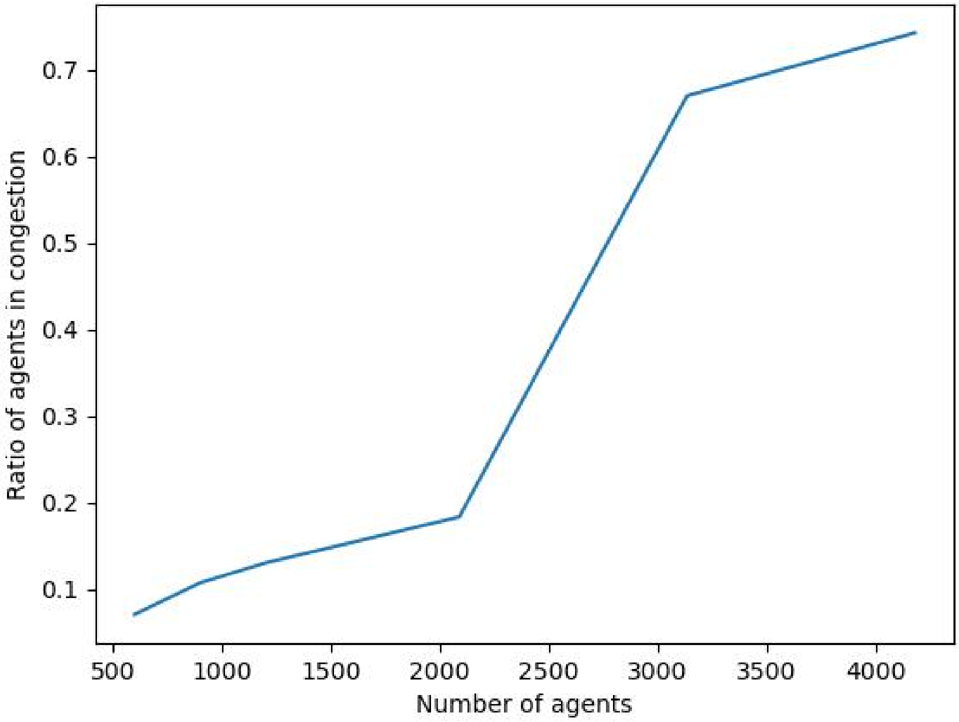

Figure 7 Ratio of agents in congestion in the simulation of Kerkenes

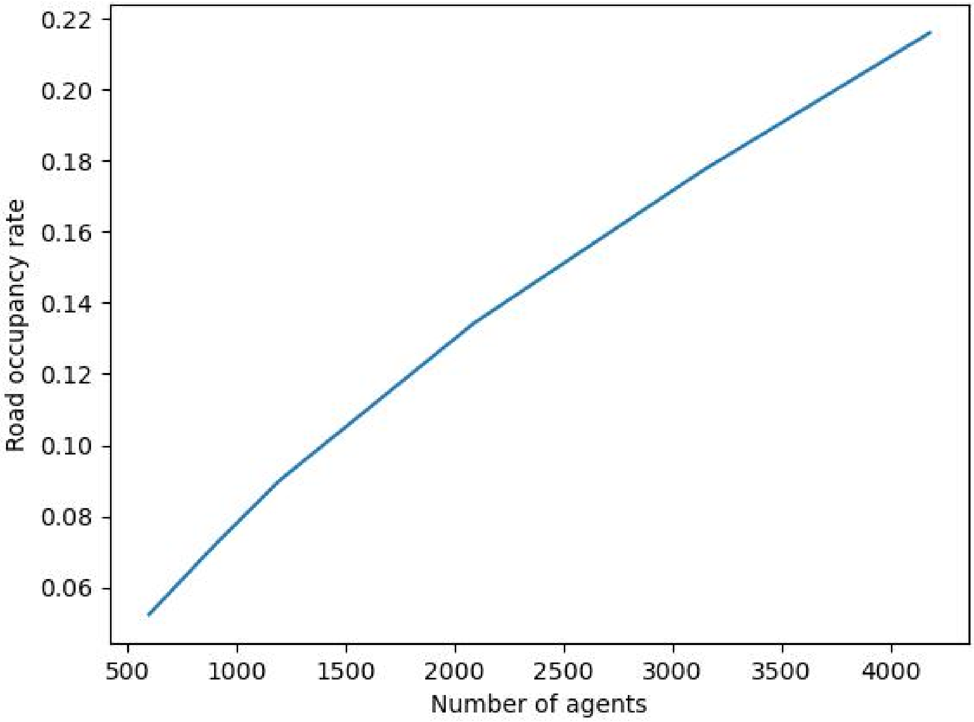

Figure 8 Road occupancy rate in the simulation of Kerkenes

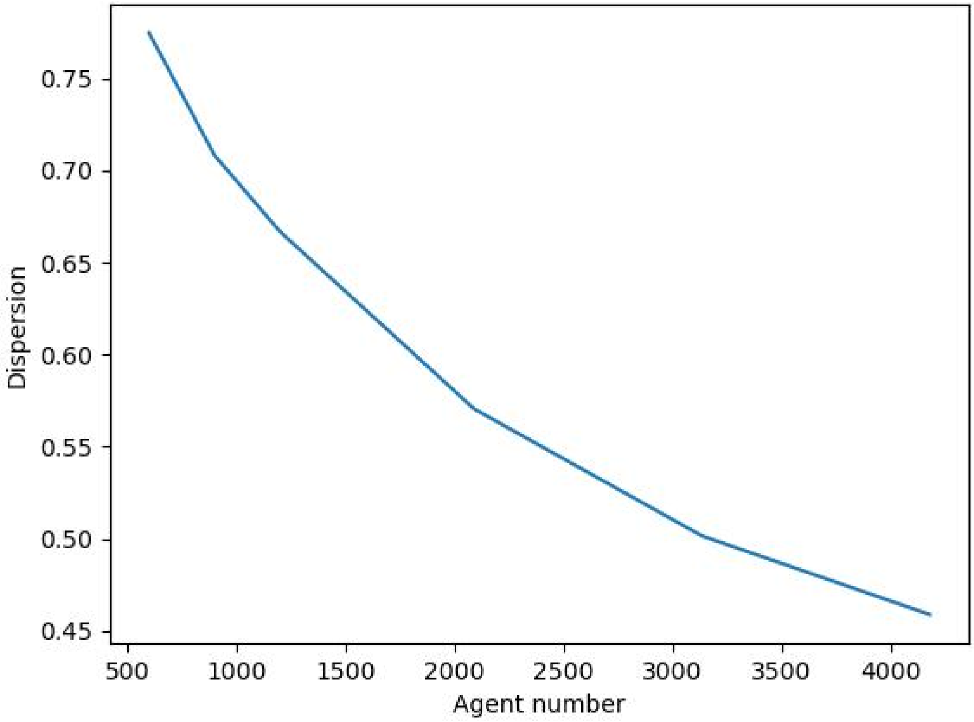

Figure 9 Dispersion rate in the simulation of Kerkenes

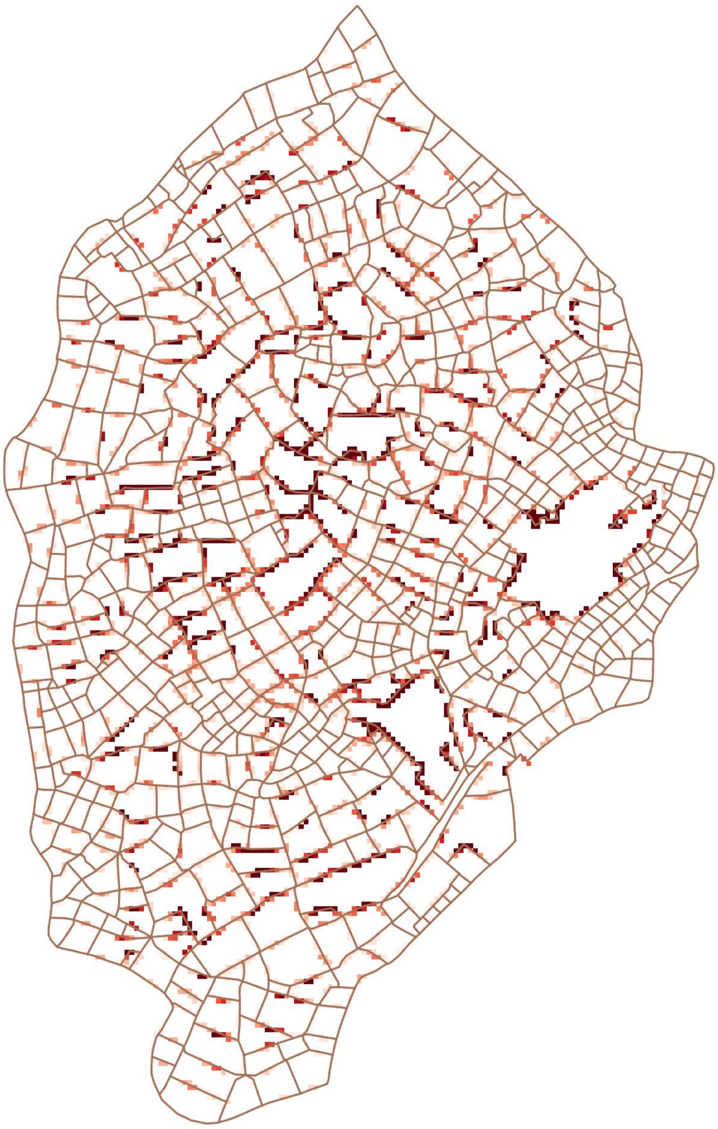

Figure 10 Aggregate traffic volume of 10 simulation showing the traffic volume in Kerkenes (2090 agents)

5.2.2 Pompeii

Using the GIS data of Pompeii, the simulation was run with 600, 900, and 1200 agents a total of 90 times. The results of the simulation were in accordance with those demonstrated by Kerkenes.

Agents	Average number of agents in congestion	SD of number of agents in congestion	Average dispersion	SD of dispersion	Average road-occupy-rate	SD of road-occupy-rate
600	49.4000	7.3747	0.6912	0.0170	0.1627	0.0040
900	110.6000	8.6247	0.6054	0.0118	0.2138	0.0042
1200	185.1000	15.9857	0.5515	0.0105	0.2596	0.0049

Table 2 Simulation results of Pompeii

A strong positive correlation could be found between the set agent number and the ratio of agents in congestion ($r = .9972$, $p = 0.047$). As an increasing number of agents were distributed into the road system, the occupancy of road patches grew visibly ($r = .9936$, $p < .001$). Nevertheless, the traffic of the road system was in a more crowded condition, resulting in a decrease in the dispersion rate ($r = -.9663$, $p < .001$).

Besides, the traffic volume of each road patch with 600 agents traversing Pompeii was recorded. The aggregation of ten simulations demonstrated an uneven distribution of traffic in Pompeii. However, the degree of unevenness is lower than Kerkenes. In the areas with strictly aligned streets, the traffic volume was almost the same in the road segments parallel to each other.

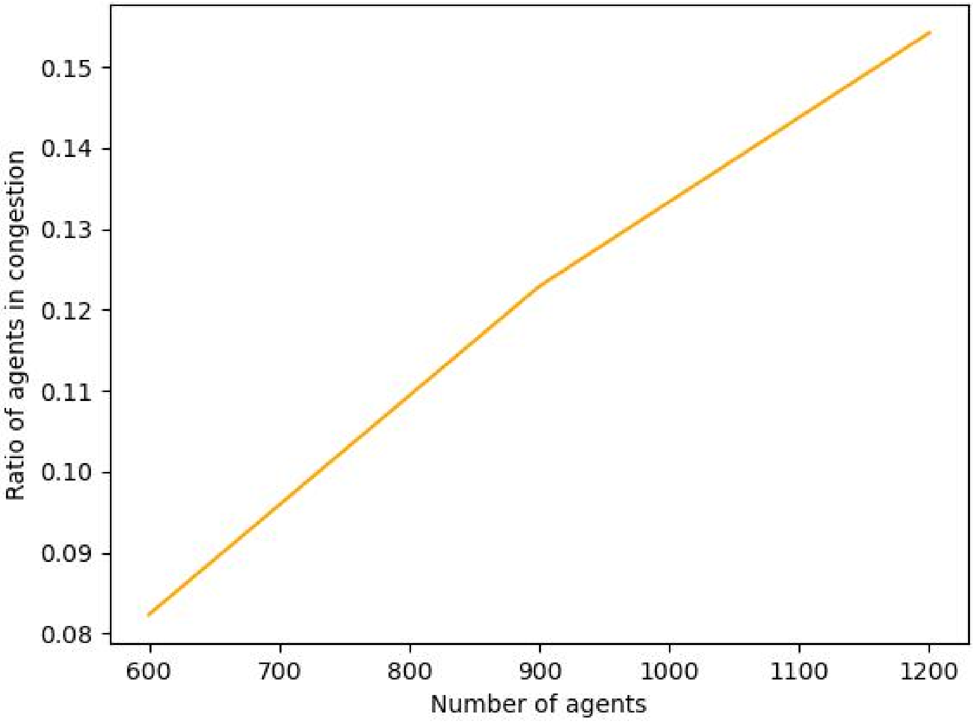

Figure 11 Ratio of agents in congestion in the simulation of Pompeii

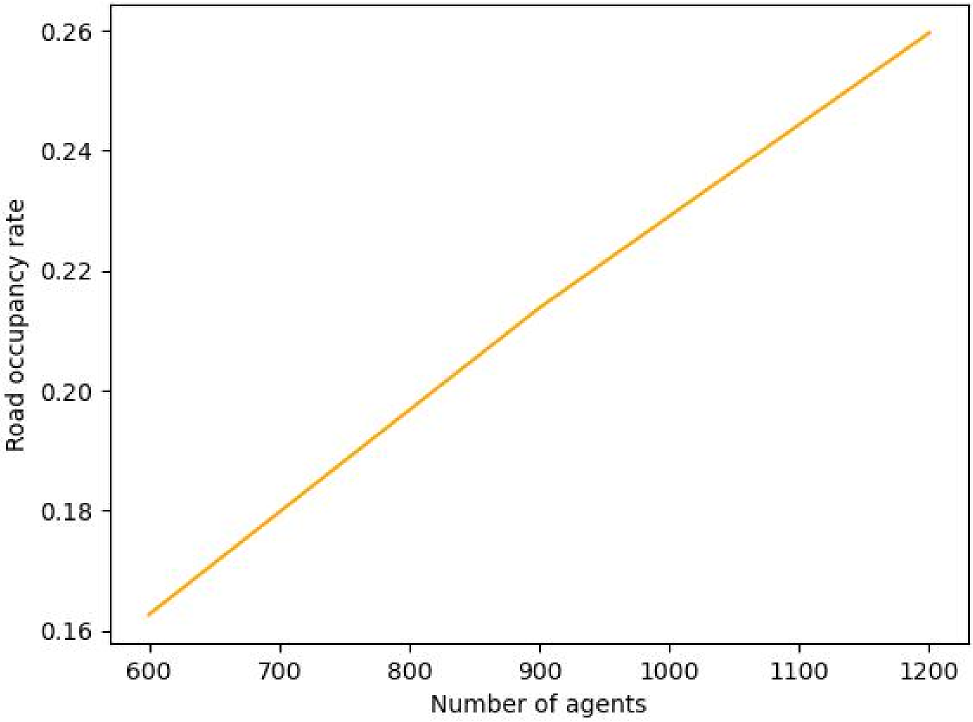

Figure 12 Road occupancy rate in the simulation of Pompeii

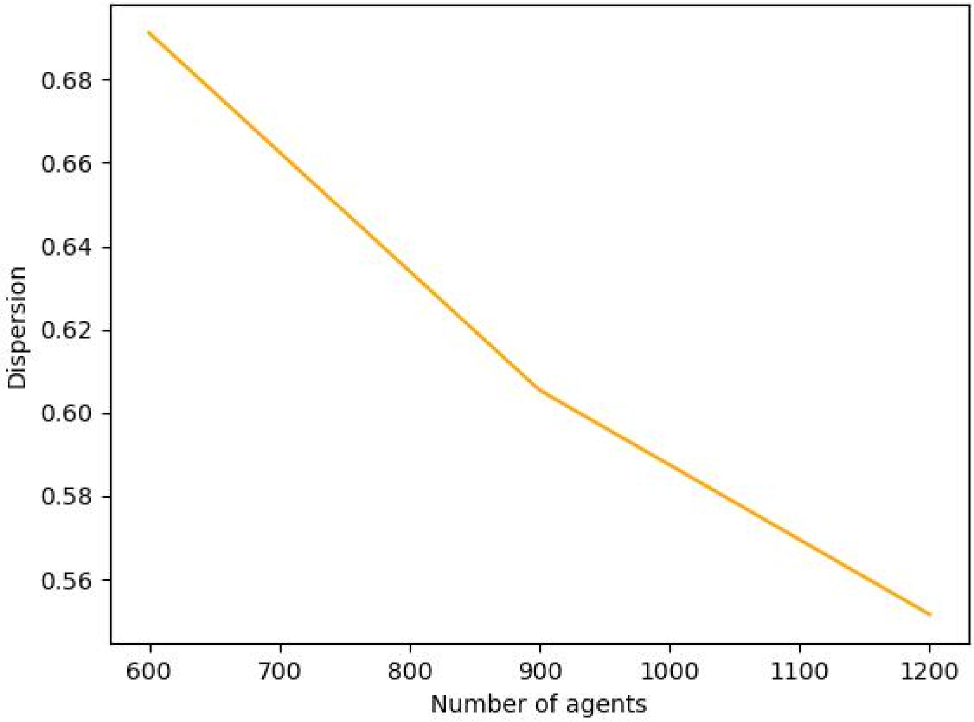

Figure 13 Dispersion rate in the simulation of Pompeii

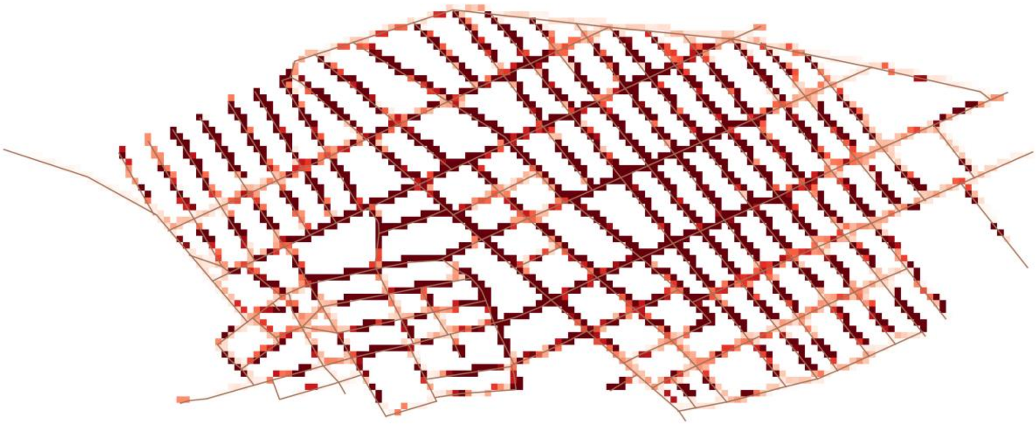

Figure 14 aggregate traffic volume of 10 simulation showing the traffic volume in Pompeii (600 agents)

5.3 Analysis

5.3.1 The simulated traffic

For both archaeological sites, Kerkenes and Pompeii, the simulated traffic was sensitive to the change in pedestrian volume. By enhancing the volume, the road system could be effectively pressured. The three indicators used to describe the traffic effectiveness all showed strong correlation with the traffic pressure in the simulation of Kerkenes and Pompeii.

(1) The congestion: the ratio of agents in congestion was in strong positive correlation with the set total number of agents.

(2) The crowdedness: the dispersion of agents was in strong negative correlation with the set total number of agents.

(3) The utilization of the road system: the occupancy rate of the road patches was in strong positive correlation with the set total number of agents.

Despite the decline in the dispersion level of agents, the occupancy rate continued to grow as more agents were placed in the model. This indicated that the boundary of the capacity of both road systems had not yet been reached by the number of agents that were set in the simulation.

5.3.2 The urban formation mode and the traffic efficiency

The GIS data used in the simulation were from two archaeological sites representing different urban formation modes. Kerkenes was one of the examples of bottom-up urban growth, and Pompeii was designed top-down and built based on one or more master plans.

In this model, the pedestrian traffic effectiveness was evaluated in three dimensions: the congestion, the crowdedness, and the utilization of the road system. During the simulation, when the traffic allowed, the agents would continue to accelerate until they reached their speed limitation. They would only lose their velocity when they were blocked by other agents (congestion). Once the agent's velocity was equal to or lower than 0.1, this agent would be counted as "in congestion" in this tick. Since each road patch in the simulation could hold more than one agent (imitating the congestion in one-lane narrow streets in the realistic), the dispersion rate of agents represented the degree of crowding of the traffic.

Moreover, the level of road occupancy indicated the degree to which the entire road system was utilized. From the simulation result, it could be seen that the line graphs of the occupancy rate were similar to linear growth. However, the dispersion rate could be characterized by a logarithmic decrease and may reach a limit value. The author supposed that the corresponding agent number of this limit value should be the boundary capacity of the road system under the set modeling resolution (160 x 230).

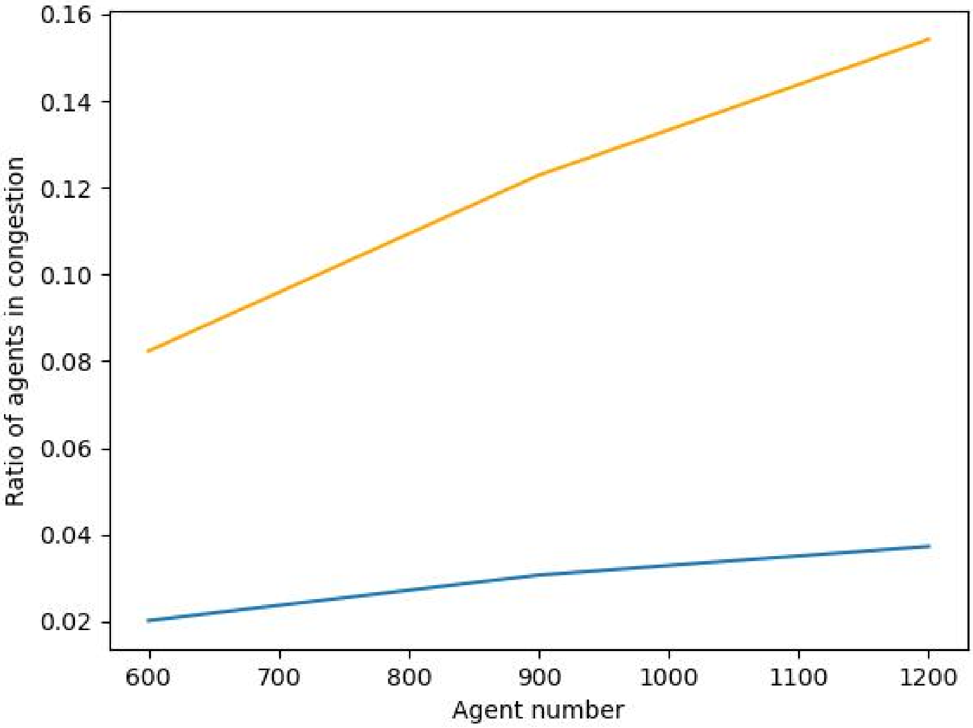

Figure 15 Ratio of agents in congestion in the simulation of Kerkenes (blue) and Pompeii

(orange)

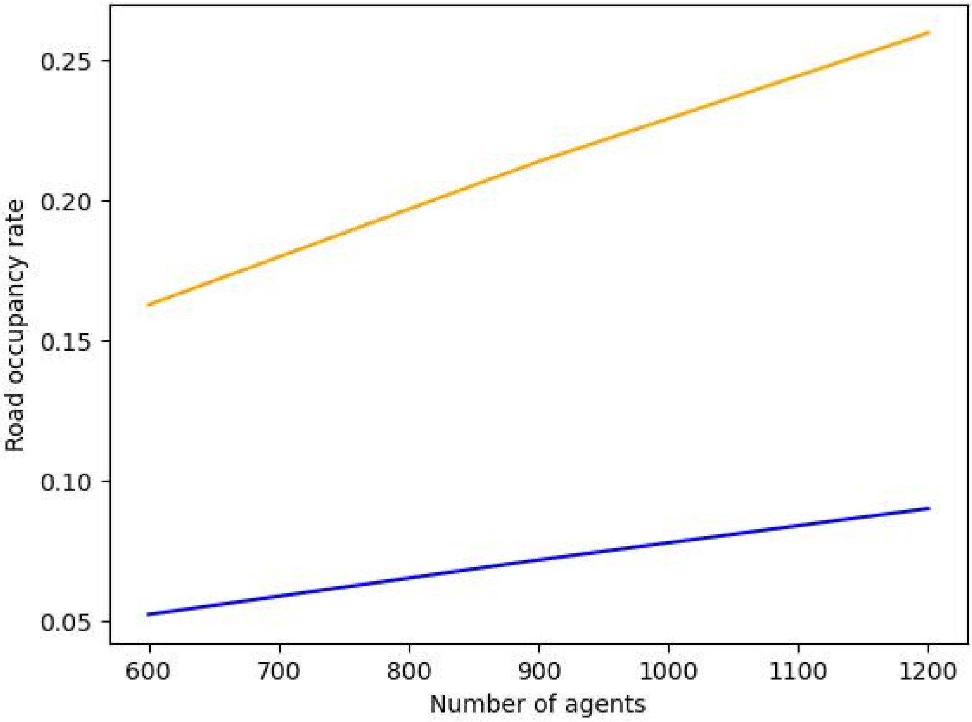

Figure 16 Road occupancy rate in the simulation of Kerkenes (blue) and Pompeii (orange)

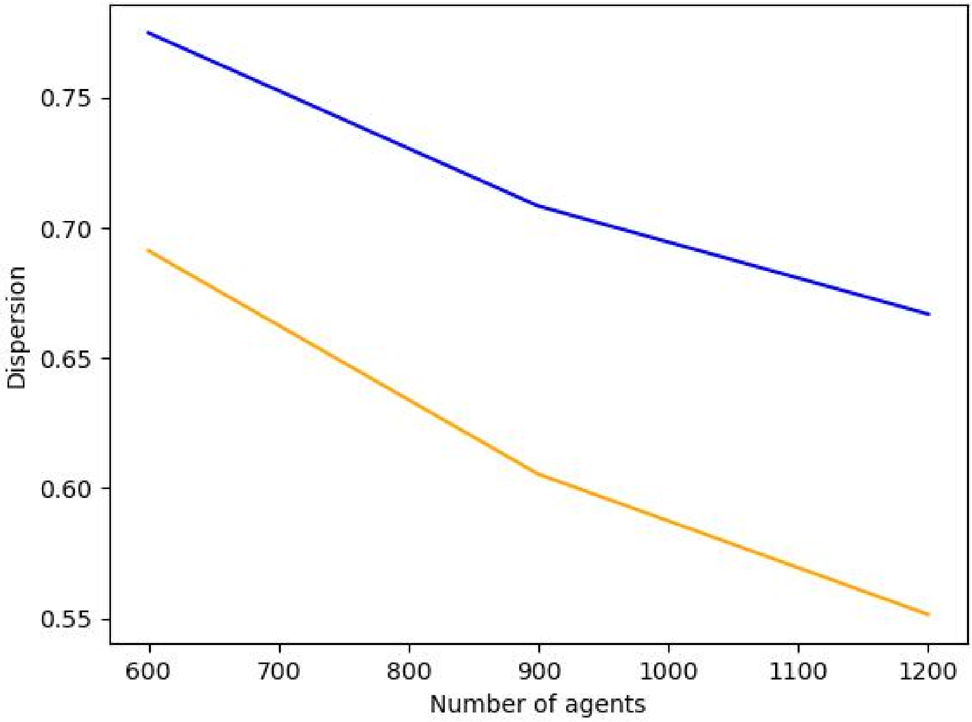

Figure 17 Dispersion rate in the simulation of Kerkenes (blue) and Pompeii (orange)

From the illustrated diagram, it can be seen that with the same number of agents, the simulated traffic was significantly different in Kerkenes and Pompeii. The result demonstrated significantly better utilisation of the road system in Pompeii (t = 31.0, p < 0.001). However, Pompeii also demonstrated a higher level of the crowding of agents, as the agents were less dispersed in the road system (t = -12.7, p < 0.001). More agents in Pompeii were stopped due to congestion compared to Kerkenes (t = 2.2, p = 0.03).

As mentioned in Chapter 5.1, the automatic generation of the road system in the ABM model caused an unequal number of road patches in the simulations of both Kerkenes and Pompeii. The road system of Kerkenes contained 8877 patches, which was about 3.48 times the patches contained in the Pompeian road system. Three different groups of simulations (Kerkenes with 2090, 3134, and 4179 agents) were added to facilitate comparison with the simulation of Pompeii (600, 900, and 1200 agents) to explore the behavior of traffic under the same ratio of agents to road patches.

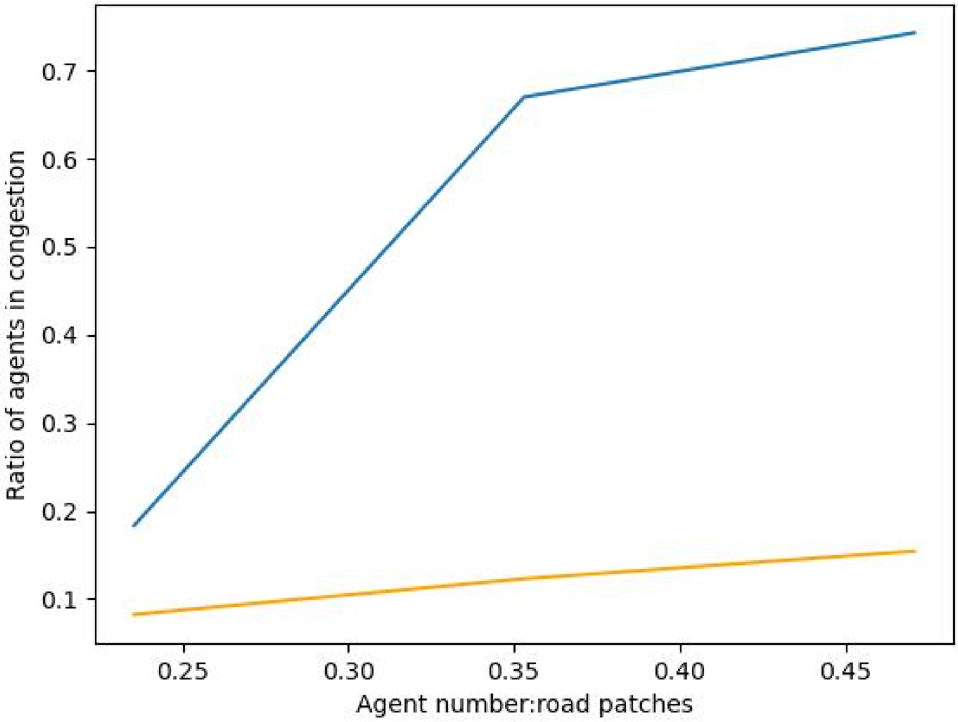

Figure 18 Ratio of agents in congestion in the simulation of Pompeii (orange) and Kerkenes (blue) with the same agents to road patches ratio

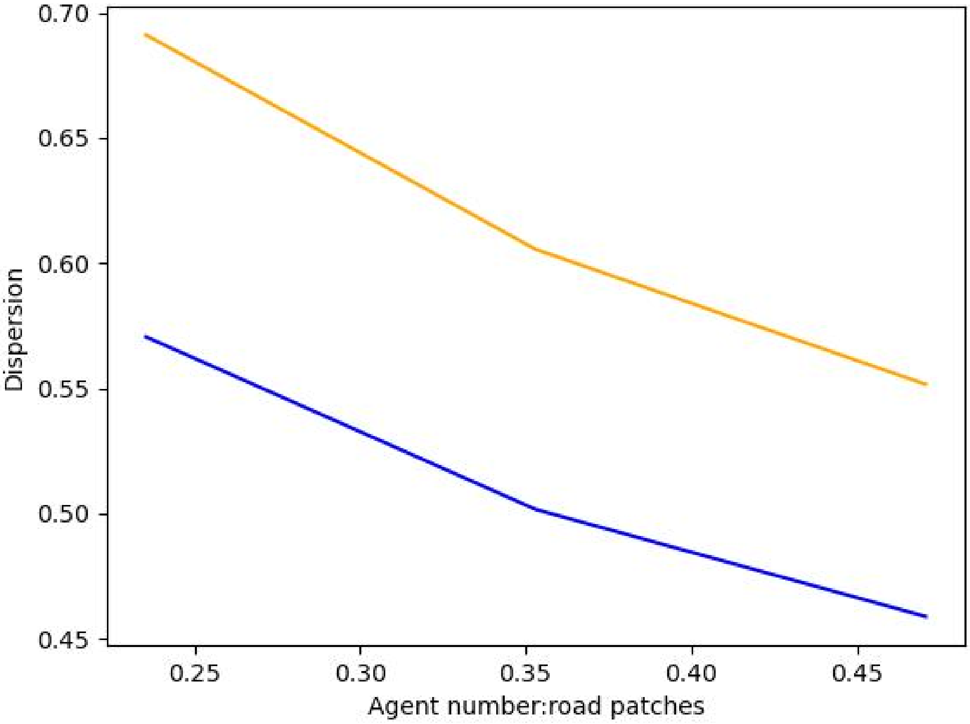

Figure 19 Road occupancy rate in the simulation of Kerkenes (blue) and Pompeii (orange) with the same agents to road patches ratio

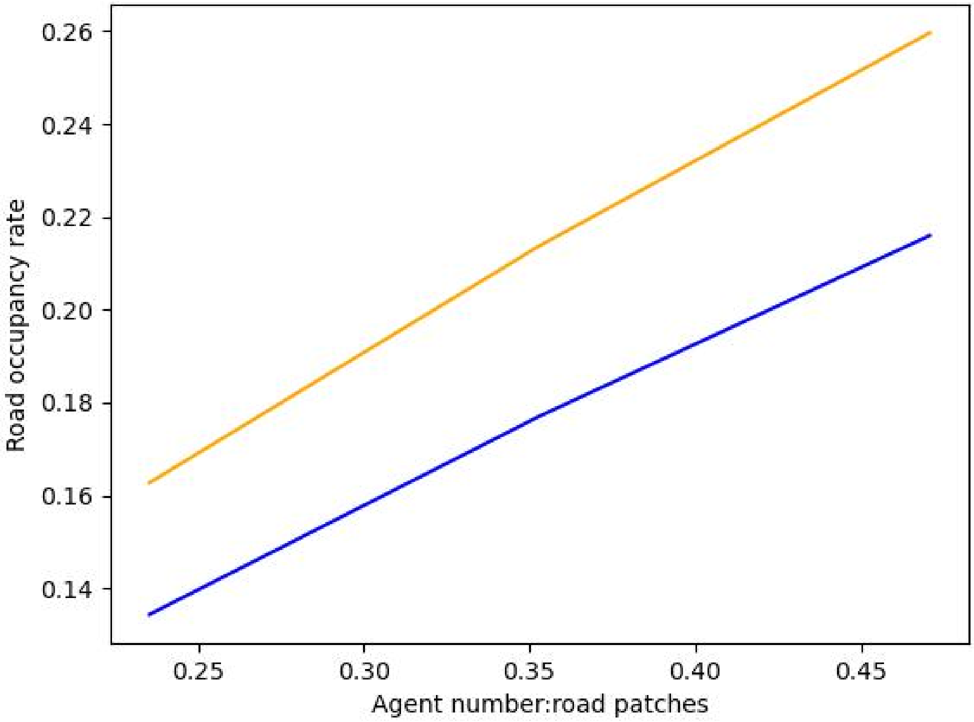

Figure 20 Dispersion rate in the simulation of Kerkenes (blue) and Pompeii (orange) with the same agents to road patches ratio

As shown in Figure 18-20, the road system of Pompeii demonstrated higher traffic efficiency under the same ratio of agents to road patches. In Kerkenes, the pedestrians were more concentrated ($t = 13.3$, $p < .001$), and fewer road patches were in use ($t = 6.6$, $p < .001$). And the ratio of agents in congestion indicated that fewer Pompeian agents were stopped in congestion compared to the data of Kerkenes ($t = -15.5$, $p < 0.001$).

5.4 Conclusion

In this study, simulated pedestrian traffic of Kerkenes and Pompeii, two archaeological sites representing different urban formation processes, was obtained using the ABM model. Through comparison of the simulation data, it can be seen that the pedestrian behavior simulated in the ABM model was sensitive to the traffic pressure, which was in accordance with the real-world traffic pattern. The exported data of the simulation revealed the difference in traffic effectiveness based on the road system of these two cities.

As the simulation was set with the same number of agents, the road system of Kerkenes showed higher traffic efficiency with less congested agents, and Pompeii had higher road occupancy. This combination indicated that instead of the formation mode, the size of the road system was the dominant factor causing differences in pedestrian behavior.

To investigate the relationship between urban formation mode and pedestrian traffic, the bias of varied sizes of road systems needed to be excluded. The comparison based on the same ratio of the number of agents to road patches provided compelling evidence to suggest that Pompeii, the city representing the top-down formation mode, showed higher performance regarding pedestrian traffic. The road system of Kerkenes, which features a bottom-up formation mode, had less effectiveness when facing the same traffic pressure. Besides, despite the difference in road patterns between these two cities, their simulated traffic was unevenly distributed. With detailed observation, it could be seen that the distribution of the traffic volume followed different patterns inside these two cities.

Chapter 6: Discussion

6.1 Limitations of the workflow

6.1.1 Data limitation

As mentioned above, this thesis studied the influence of road patterns on traffic effectiveness. Through simulating the pedestrian behavior based on GIS data of Kerkenes and Pompeii, better traffic performance could be observed in the simulation of Pompeii, which contained the gridiron road network.

Kerkenes and Pompeii were highly representative of bottom-up and top-down urban formation modes. Both contained relatively complete GIS information, as they were fully surveyed or excavated. Although the discrepancy in surface area of these two cities was apparent (for Kerkenes 270 Ha and Pompeii 66 Ha), the simulation overcame it by comparing the traffic behavior based on the ratio of agents to road patches. This measure ensured that the road systems were facing the same level of traffic pressure, despite their varied size.

The results of the simulation were promising. However, some issues could be noticed concerning the data used in this study. First, although the simulation was repeated multiple times to gain statistically reliable results, it was only based on two archaeological sites. Moreover, the sites chosen as case studies in this research were not from the same time period and were dispersed on different continents. The limited choice of archaeological sites compromised the workload and the completeness of the GIS information. Further simulations involving more ancient cities with top-down and bottom-up formation modes would be beneficial in enhancing the persuasiveness of the results.

6.1.2 Modeling limitation

The ABM model was the core of this study. It applied the real-world pedestrian parameters, the decision-making of route selection, and the real-time interaction, resulting in the sensitive response to the proportionally increased traffic pressure in the simulation.

The model converted the GIS information of the archaeological sites into road networks composed of single patches through the bundled extension “GIS”. This extension transformed the GIS data space to NetLogo space with a certain projection, and the vector dataset of the road network would be shifted into a raster dataset. Combined with the set resolution of the “world”, the consecutive road system could be disassembled into countable patches, which enabled the calculation of the road occupancy rate and the dispersion of agents. In this model, the “GIS’ extension was useful but limited. Although one could change the projection while loading the GIS data, there was no way to estimate the number of road patches before they were generated. With the limited programming knowledge, the author could not generate a road system with an expected number of patches through the built-in functions.

Furthermore, the randomly designated origin and destination of agents resulted in different average walking distances in Kerkenes and Pompeii. Kerkenes was a much larger site compared to Pompeii, and therefore, the agents were most probably designated with an averagely longer route, which could influence the pedestrian behavior.

By the end of each simulation, the traffic volume of each location could be recorded by counting the total visits of each patch and demonstrated with scaled color. The recorded data had to be exported as an ASC file manually and could not be batch processed in the BehaviorSpace of NetLogo.

Therefore the traffic volume data was not from the same simulation from which other data was recorded, even though they were set with the same parameters.

Nevertheless, subject to the computing power, more attributes of the roads were not integrated into the modeling. The roads network in the ABM model were generated following the “isotropic plain” assumption (see chapter 4.4: The ABM Model). There was no applicable reference to the age and sex ratio in the constitution of pedestrians. Hence, the pedestrians were divided equally into the six age and sex groups, which also limited the realistic degree of this model.

The factors contributing to the pedestrian traffic in this ABM model were limited. As mentioned in the literature review, two types of dependence influence pedestrian behavior: the tactical and the operational decision (Papadimitriou et al., 2009). The tactical includes activity scheduling, area choice, and route choice; the operational consists of real-time decision-making based on the road crossing, obstacle avoidance, and interaction with other pedestrians. This model focused on the route choice and the fundamental interaction between agents.

Despite the factors this model had taken in, in reality, the pedestrians could have planned their route based on the agenda and local attractions and changed their itinerary based on the number and speed of agents in sight. Invoking such dependence requires greater computing power and highly detailed archaeological GIS and cultural information, which might be accomplished someday.

6.2 Comparison with other pedestrian ABM workflows/models

The ABM model of this research used the SHULGI model as the primary reference, which was designed for studying the transportation of Kerkenes (Branting et al., 2007; Altaweel & Wu, 2010; Branting, 2012b). The SHULGI model calculated the least-cost path between the home location and the destination of agents as determined by physical energy expenditures. Moreover, after finishing each round-trip, the agents would be given a new destination. Besides, in each simulation, only one group of agents (same-sex and same-age) moved with their loaded static velocity in the city and did not interact with other agents.

The SHULGI model was one of the prior studies of the archaeological pedestrians model. Although its agents' behavior seemed relatively rigid, it had great potential for further development. The model of this thesis improved the workflow of the ABM simulation by allowing the agents to have more autonomy and interact. The simulated individual behavior merged into macroscopic traffic changes, demonstrating uneven traffic volume distribution.

Compared to the ABM model of this research, the SHULGI model introduced the elevation variation of Kerkenes. The physical energy expenditure could be calculated by combining the agent's weight and the elevation change along the route. Instead of the shortest path, the route choice in the SHULGI model was made based on the physical cost of transportation. However, it is questionable whether the pedestrian in Kerkenes would consider the energy expenditure as the primary factor for route selection, as it requires a relatively high level of spatial knowledge of Kerkenes. Moreover, the maximal slope in Kerkenes is 0.71 (rise/run). It could not form a significant obstacle to the pedestrian traffic, especially with the steps that could be built in such a location. Hence, in the ABM model of this thesis, the elevation was not included as a parameter.

In the SHULGI model, the traffic volume was simulated in different scenarios, and each scenario only contained one sex and age group of pedestrians. As this thesis's model aimed to simulate more realistic pedestrian behavior, the interaction of agents with different velocities was necessary. Therefore, each simulation of this thesis was run with all groups of pedestrians.

Besides the changes in the design and the simulation procedures, the model of this thesis was specifically coded to be generally applicable. Its application range was not limited to Kerkenes and Pompeii. The pedestrian traffic could be simulated with the road network data in any ancient city. Moreover, the choice of coding language (NetLogo) and the relatively low requirement of computing capacity also lower the threshold for potential researchers who would use or improve this model.

6.3 The urban formation mode that led to better urban traffic

As described in previous chapters, this thesis focused on comparing the traffic based on different road patterns. Two archaeological sites that were typical to the representing road pattern were selected and analyzed. From the simulation result, it could be seen that the pedestrian traffic in Pompeii had better performance than in Kerkenes. Its road system was less congested, more roads were in use simultaneously, and the pedestrians were less crowded.

Pompeii was built through the top-down formation mode following a master plan, resulting in the roads being extensively designed in the gridiron pattern. Modern urban studies rated the gridiron design of top-down urban formation less for pedestrian traffic for its high frequency of intersection, rigidness, and lack of centrality. However, the simulation result could suggest that the connectivity of the road system was the key to traffic effectiveness. Although the organic road system was topographically refined, topologically flexible, and (partly) followed the pre-existed desire-line path, its traffic showed statistically significant deficiency compared to the gridiron system. The gridiron pattern had the highest connectivity among all road patterns. The grid-like roads provided various alternative options for pedestrians to travel between their origin and destination, reducing the traffic volume on arterial streets. Furthermore, a study on modern traffic simulated the traffic volume and noted that the gridiron network could decrease the vehicle trip length and travel time more than the curvilinear network (McNally & Ryan, 1992), indicating that the higher connectivity improved the traffic effectiveness.

In comparison to cities of the bottom-up formation mode, the top-down formed cities were built according to their master plan, which often demonstrated high orderliness. The road system in this type of city often had a rectangular or radial gridiron pattern. Traffic effectiveness might not have been the primary factor of the urban planners' consideration. However, this design did improve the traffic performance.

Besides, archaeological evidence proved that a traffic system in Pompeii existed and once governed Pompeian cart drivers' behaviors (Poehler, 2017, pp. 139-189). Poehler (2017, pp. 140) mentioned that by the second and first century BC, the shape of most of the intersections in this city limited the movement of vehicles, suggesting a conscious design and management of the traffic system from the centralized governing power to further enhance the traffic effectiveness in Pompeii.

From the modeling and the archaeological evidence, it could be concluded that the top-down cities had better traffic than those formed bottom-up. The orderly road network preferred by the governor was characterized by high connectivity. Moreover, a traffic system consisting of rules and infrastructure would possibly require the decision of the authority and was more likely to appear in cities administrated by centralized power. Furthermore, the gridiron road system could be considered the foundation of the urban traffic, which requires maintenance of the collective control. For instance, the gridiron road system in the Roman colony Aosta was deregulated after the fall of the Roman Empire and gradually became irregular (Crawford, 2005).

6.4 Influence of road patterns on pedestrian traffic inside a city

Although in this thesis, Pompeii was the case study representing the top-down urban formation mode, Its road system was not entirely gridiron planned. The Altstadt of Pompeii in the southwest was relatively irregular, and its pattern could be described as organic. In Figure 14, it could be observed that the traffic volume in this area was lower than the area with the gridiron pattern. An architectural study (Laurence, 2005) of Pompeii showed that the frequency of doorways in the Altstadt of Pompeii was higher than in the streets with grid patterns. The mean number of spaces within the adjacent building of these irregular streets was lower, and the buildings were shallower, indicating a stronger integration of the residents and the streets.

Nevertheless, a study on the ruts in Pompeii indicated that the ruts in the Altstadt were less deep than the gridiron streets, suggesting the traffic in this area could be less dependent on wheeled traffic or was less intensive (van Tilburg 2007, pp. 141). The integration and blocking of wheeled traffic might not be the reason for reducing the pedestrian traffic volume. However, it would appear that all of them were correlated to the road pattern.

In Kerkenes, the simulated traffic demonstrated an uneven distribution of traffic volume. Arterial roads with higher traffic volume could be found in the center and around closed areas of prominent topographical features or building compounds, suggesting the existence of traffic hierarchy in Kerkenes. The modeling result of Kerkenes in this thesis was in general agreement with a previous study (Altaweel & Wu, 2010, Fig. 4). Moreover, since the unit of the traffic volume measurement was each patch, the distribution of traffic volume could be observed with higher resolution. Instead of calculating the roads with the highest traffic, the result of this thesis narrowed the range to road segments. In Figure 10, it could be seen that in the same street, the traffic was uneven in each segment. Besides, around notable buildings, Megaron and the Palace Complex, and the reservoirs, Büyük Göl and Sülüklü Göl, road segments were frequently found with higher traffic volume.

Although there were areas in Kerkenes whose pattern could be categorized as the loose grid, their traffic volume was not showing a significant difference compared to areas containing the organic pattern. Unlike in Pompeii, the distribution of traffic volume in Kerkenes was probably related to the traffic hierarchy, which was a complete result of topography and the function of the surrounding buildings (amenities, public service, or monumental architectures). Hence it was reasonable to interpret that the building compounds enclosed by high traffic volume could be worth further archaeological investigation. Albeit the modeling in this thesis was restrained with limited parameters, the simulation result of Kerkenes could assist archaeologists in determining new excavation areas. Moreover, the simulation result of Kerkenes was encouraging. It should be compared with fieldwork data and validated in a larger cohort of cities with a bottom-up formation mode (organic pattern).

6.5 Potential traffic system in Kerkenes

A series of research published by Tsujimura (1991), van Tilburg (2007, 2011), Laurence (2008), Kaiser (2011), and Poehler (2017) revealed the traffic system in Pompeii by analyzing the archaeological evidence, for instance, ruts, the shape of corners, and width of streets. The road network in Pompeii mainly consisted of one-lane, one-way streets (84% of the named streets) and a few wide streets (two-lane and two-way), and the traces of wear evidenced that the Roman road-users drove on the right side of the road (Poehler 2017, pp. 150). The road segments of intersection with designed variation in width had indicated that Vicolo di Mercurio was designed with the eastbound direction. Later it was changed to westbound, as shown by the traces of wear on stepping-stones, curb stones, and corners (van Tilburg, 2011), demonstrating that the traffic system was not static but evolving to improve its effectiveness. Despite the lack of record of the consequence of blocking the traffic in Pompeii, the Roman city law of Urso in southern Spain, dated 1st century CE, indicated that there would be fines for offenders (van Tilburg, 2007, pp. 131-132). In general, the traffic in Pompeii followed specific rules and was under the control of the local government.

According to the simulation result, the pedestrian traffic in Kerkenes was less efficient than in Pompeii. Under the same agents to road patches ratio, in Kerkenes, there was more congestion, and the pedestrians were more crowded than in Pompeii. Based on the archaeological demography study of Wiessner (1974), the urban population increases exponentially instead of linearly. In other words, the residents in Kerkenes were denser than in Pompeii. Subsequently, the traffic flow would also increase exponentially. Combined with the less effective road network, the traffic in Kerkenes must have been challenged with severe pressure.

In this case, a traffic system should have been necessary to keep the traffic circulation in Kerkenes. Some narrow roads might serve one-way only, and the arterial streets could be two-way and with multiple lanes. Nevertheless, it is unclear whether the road users in Kerkenes drove on a particular side of the road. The ruts were one of the essential pieces of evidence of the Roman traffic system. Unfortunately, most of the roads in Kerkenes were likely unpaved (Branting, 2004b). However, the area leading to the Palace Complex Entrance was found with stone pavement (Branting, 2005), where potential traces of wear could exist. Despite the lack of pavement, the shape of corners and the width of roads, especially the width difference at intersections, could bear information about the traffic system. This potential archaeological evidence would deserve further investigation.

6.6 Open Science

At the end of this chapter, it is necessary to mention that this thesis followed the principles of Open Science. During the coding phase for this thesis, finding the source code of the ABM model used in the referencing publications was challenging. The coding process of this thesis primarily relied on browsing the NetLogo Models Library and trying out possible codes from the NetLogo Dictionary. In this case, the source code of the ABM model used in this thesis was uploaded to a GitHub repository (https://github.com/lga0/Pedestrian-traffic-in-ancient-city), along with the road system data of Pompeii drawn by the author (for the data of Kerkenes, please contact the Kerkenes Project). GitHub is a commonly used platform for open-source projects, and this repository would be open-accessible. Furthermore, the license of this repository was set to GNU General Public License v3.0, which allows users to run, share, and modify this model, and restricts the distribution of the closed source version of it. Under this license, this model could be more transparent and reproducible.

Besides source code and the data, all the software used in this thesis is open source. The software used in this thesis was QGIS, and NetLogo, both of which have at least one commercial competitor that is commonly used in scientific studies. This thesis intentionally excluded the usage of commercial software to ensure the source code's transparency. Moreover, QGIS and NetLogo are free software and are publicly accessible, which was also essential to researchers with a limited budget.

Overall, this thesis provided an approach to studying pedestrian traffic in ancient cities and discussed the influence of the urban formation mode and its representing road pattern. Considering the limited number of case studies, the reliability of this study should be validated by reusing this model with other archaeological data. Hence this thesis should be as open and reusable as possible to facilitate future research.

Chapter 7: Conclusion

This thesis set out to investigate the relationship between pedestrian traffic and the urban formation modes. The Agent-based Modeling approach was applied to explore the complex, non-linear pedestrian traffic. An ABM model was designed combining route choice and pedestrian interaction to simulate pedestrian traffic based on the urban road system from archaeological sites. The workflow and the limitation of this model were discussed separately. The data produced by simulations evidenced the sensitivity of this model under varied traffic pressure.

The result of simulations indicated that the city with the top-down formation mode (Pompeii) had higher traffic effectiveness than the bottom-up formation mode (Kerkenes). By comparing the ratio of agents that were in congestion, the crowdedness of agents on the road (dispersion rate), and the utilization of the roads (occupancy rate), Pompeii had better traffic performance when facing the same traffic pressure (agents to road patches ratio) than Kerkenes. Moreover, cities with the top-down design concept built their road system with conscious planning, embodied in the gridiron roads constructed according to a master plan. The gridiron road pattern has the highest connectivity among all patterns. Compared with the factors influencing traffic effectiveness from the modern urban studies, the connectivity of the urban road system was considered the primary factor affecting the pedestrian traffic in the ancient urban environment.

Moreover, although the simulated traffic volume was distributed unevenly in both cities, the cause was not the same. As a whole, Pompeii and Kerkenes were both highly characterized by one type of road pattern. However, in both cities, the gridiron and organic patterns coexisted. In the city characterized by the gridiron pattern, the traffic behavior was influenced by the local road patterns. The gridiron streets in Pompeii had higher traffic volume than the organic areas. In Kerkenes, where the organic streets were the majority, the traffic was distributed according to the traffic hierarchy in this city. The road segments of arterial streets and around notable buildings and locations would have higher traffic volume, and the other roads would receive less pedestrian traffic. Besides, the simulated distribution of traffic in Kerkenes was largely in accordance with previous studies.

Considering the less effective road system and the higher population density in Kerkenes, the traffic pressure in Kerkenes was assumed to be higher than in Pompeii. The archaeological evidence of Pompeii indicated the existence of a traffic system, which could improve the general urban traffic performance. Based on the more intensive traffic pressure, it is logical to infer that a traffic system was more necessary for Kerkenes. The archaeological features related to the traffic system in Kerkenes deserve further investigation.

This thesis attempted to explore the traffic influence of urban formation modes. However, only two cities were involved in the research, and the generalisability of these results was subject to this significant limitation. The ABM model was designed following the abstract-generalist approach, and only limited parameters were taken into account. Features of urban roads that were not included in this model, for instance, road width and multi-lane traffic, could also directly impact pedestrian behavior. The real-world pedestrian would have a more complicated decision process than the agents in the model. Moreover, between Kerkenes and Pompeii, there were considerable differences in location, climate, dating, and cultural background. These could not be embodied in the modeling.

Further studies could assess the pedestrian traffic of different urban formation modes with the data from other archaeological sites, which would help to gain more generalizable conclusions. Moreover, for future development of the ABM model, new attributes could be added to the road patches to generate a road system with multi-lane traffic. Nevertheless, the route selection and the interaction could also be optimized with more complex rules and higher autonomy of the agents.

The application of ABM modeling to research questions of archaeological urban studies was promising. However, the programming ability of archaeologists has been limited. The author had taken programming courses as part of the Master's curricula and spent extra efforts learning ABM coding from open-accessed internet platforms. However, many technical programming difficulties were unsolvable for the author, and some features of the model had to be canceled. Therefore, training in programming and modeling would never be enough. Besides, finding the source code of the published ABM studies of pedestrian traffic and urban road pattern was not easy. The author hoped that with the open-source and reproducible model in this thesis, future archaeological traffic simulation and urban studies researchers could gain some inspiration and reference for applying the ABM approach.

Abstract

Roads are essential to urban planning as they directly impact traffic effectiveness. By observing the road system of a city, the formation concept could be interpreted through specific road patterns. Modern urban studies have proven that the road pattern could influence pedestrian traffic. However, it was seldom correlated with the urban formation process. Urban road systems, including their pattern and traffic, have drawn archaeological interests. However, the urban studies commonly applied approach, Agent-based Modeling (ABM), has been less extensively used to study the archaeological urban roads.

This thesis provides an ABM model to simulate pedestrian traffic in ancient cities and discuss the relation between traffic effectiveness and the urban formation modes in the archaeological context. Two archaeological sites, Pompeii and Kerkenes, are chosen to represent the top-down and the bottom-up urban formation mode, and their GIS data will be used for simulations. The simulated traffic performance of the archaeological sites will be assessed with the degree of congestion, the crowdedness, and the utilization of the road system. And a conclusion of which urban formation mode could lead to better traffic will be drawn from the assessment. The primary factor causing different traffic effectiveness will be interpreted. This model will also demonstrate the road system's traffic volume distribution, which could be helpful for further archaeological investigation.

The GitHub link for the ABM model and the GIS data

https://github.com/lga0/Pedestrian-traffic-in-ancient-city

Internet sources

NetLogo references : https://ccl.northwestern.edu/netlogo/references.shtml, accessed on June, 2022.

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Navigation Map 2, 2017:

https://digitalhumanities.umass.edu/pbmp/?page_id=1258, accessed on June, 2022.

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Appendix 1: Simulation result of Kerkenes with agent number of 600, 900, and 1200

[run number]	num_agent	velocity-limit1	velocity-limit2	velocity-limit3	velocity-limit4	velocity-limit5	velocity-limit6	step	count_turtles_with_0_velocity	concentration	road_occupy_rate
1	600	1	0.94	0.91	0.83	0.8	0.72	5000	36	0.793333333	0.053621719
2	600	1	0.94	0.91	0.83	0.8	0.72	5000	39	0.761666667	0.051481356
3	600	1	0.94	0.91	0.83	0.8	0.72	5000	51	0.783333333	0.052945815
4	600	1	0.94	0.91	0.83	0.8	0.72	5000	35	0.791666667	0.053509068
5	600	1	0.94	0.91	0.83	0.8	0.72	5000	46	0.761666667	0.051481356
6	600	1	0.94	0.91	0.83	0.8	0.72	5000	42	0.783333333	0.052945815
7	600	1	0.94	0.91	0.83	0.8	0.72	5000	39	0.78166	0.05283316

											6667	4
8	600	1	0.94	0.91	0.83	0.8	0.72	5000		54	0.79	0.053396418
9	600	1	0.94	0.91	0.83	0.8	0.72	5000		40	0.773333333	0.052269911
10	600	1	0.94	0.91	0.83	0.8	0.72	5000		34	0.806666667	0.054522924
11	600	1	0.94	0.91	0.83	0.8	0.72	5000		42	0.761666667	0.051481356
12	600	1	0.94	0.91	0.83	0.8	0.72	5000		43	0.79	0.053396418
13	600	1	0.94	0.91	0.83	0.8	0.72	5000		52	0.746666667	0.0504675
14	600	1	0.94	0.91	0.83	0.8	0.72	5000		53	0.756666667	0.051143404
15	600	1	0.94	0.91	0.83	0.8	0.72	5000		48	0.763333333	0.051594007

16	600	1	0.94	0.91	0.83	0.8	0.72	5000		58	0.788333333	0.053283767
17	600	1	0.94	0.91	0.83	0.8	0.72	5000		46	0.77	0.05204461
18	600	1	0.94	0.91	0.83	0.8	0.72	5000		34	0.77	0.05204461
19	600	1	0.94	0.91	0.83	0.8	0.72	5000		30	0.788333333	0.053283767
20	600	1	0.94	0.91	0.83	0.8	0.72	5000		42	0.781666667	0.052833164
21	600	1	0.94	0.91	0.83	0.8	0.72	5000		47	0.761666667	0.051481356
22	600	1	0.94	0.91	0.83	0.8	0.72	5000		39	0.776666667	0.052495212
23	600	1	0.94	0.91	0.83	0.8	0.72	5000		37	0.786666667	0.053171116
24	600	1	0.94	0.91	0.83	0.8	0.72	5000		45	0.773333333	0.052269911
25	600	1	0.94	0.91	0.83	0.8	0.72	5000		43	0.76333	0.05159400

										3333	7
26	600	1	0.94	0.91	0.83	0.8	0.72	5000	42	0.761666667	0.051481356
27	600	1	0.94	0.91	0.83	0.8	0.72	5000	51	0.763333333	0.051594007
28	600	1	0.94	0.91	0.83	0.8	0.72	5000	36	0.773333333	0.052269911
29	600	1	0.94	0.91	0.83	0.8	0.72	5000	29	0.79	0.053396418
30	600	1	0.94	0.91	0.83	0.8	0.72	5000	33	0.753333333	0.050918103
31	900	1	0.94	0.91	0.83	0.8	0.72	5000	103	0.687777778	0.069730765
32	900	1	0.94	0.91	0.83	0.8	0.72	5000	92	0.704444444	0.071420525
33	900	1	0.94	0.91	0.83	0.8	0.72	5000	88	0.702222222	0.071195224

34	900	1	0.94	0.91	0.83	0.8	0.72	5000	103	0.697777778	0.070744621
35	900	1	0.94	0.91	0.83	0.8	0.72	5000	90	0.715555556	0.072547032
36	900	1	0.94	0.91	0.83	0.8	0.72	5000	88	0.702222222	0.071195224
37	900	1	0.94	0.91	0.83	0.8	0.72	5000	109	0.716666667	0.072659682
38	900	1	0.94	0.91	0.83	0.8	0.72	5000	76	0.724444444	0.073448237
39	900	1	0.94	0.91	0.83	0.8	0.72	5000	102	0.705555556	0.071533176
40	900	1	0.94	0.91	0.83	0.8	0.72	5000	101	0.698888889	0.070857272
41	900	1	0.94	0.91	0.83	0.8	0.72	5000	92	0.701111111	0.071082573
42	900	1	0.94	0.91	0.83	0.8	0.72	5000	95	0.71777	0.07277233

											7778	3
43	900	1	0.94	0.91	0.83	0.8	0.72	5000		98	0.707777778	0.071758477
44	900	1	0.94	0.91	0.83	0.8	0.72	5000		93	0.711111111	0.072096429
45	900	1	0.94	0.91	0.83	0.8	0.72	5000		113	0.688888889	0.069843416
46	900	1	0.94	0.91	0.83	0.8	0.72	5000		92	0.717777778	0.072772333
47	900	1	0.94	0.91	0.83	0.8	0.72	5000		95	0.693333333	0.070294018
48	900	1	0.94	0.91	0.83	0.8	0.72	5000		106	0.704444444	0.071420525
49	900	1	0.94	0.91	0.83	0.8	0.72	5000		98	0.725555556	0.073560888
50	900	1	0.94	0.91	0.83	0.8	0.72	5000		88	0.716666667	0.072659682

51	900	1	0.94	0.91	0.83	0.8	0.72	5000	98	0.707777778	0.071758477
52	900	1	0.94	0.91	0.83	0.8	0.72	5000	88	0.705555556	0.071533176
53	900	1	0.94	0.91	0.83	0.8	0.72	5000	94	0.71	0.071983778
54	900	1	0.94	0.91	0.83	0.8	0.72	5000	113	0.724444444	0.073448237
55	900	1	0.94	0.91	0.83	0.8	0.72	5000	82	0.706666667	0.071645826
56	900	1	0.94	0.91	0.83	0.8	0.72	5000	94	0.722222222	0.073222936
57	900	1	0.94	0.91	0.83	0.8	0.72	5000	98	0.707777778	0.071758477
58	900	1	0.94	0.91	0.83	0.8	0.72	5000	88	0.731111111	0.074124141
59	900	1	0.94	0.91	0.83	0.8	0.72	5000	91	0.71222	0.07220908

											2222	
60	900	1	0.94	0.91	0.83	0.8	0.72	5000		117	0.683333333	0.069280162
61	1200	1	0.94	0.91	0.83	0.8	0.72	5000		169	0.660833333	0.089331982
62	1200	1	0.94	0.91	0.83	0.8	0.72	5000		155	0.6475	0.087529571
63	1200	1	0.94	0.91	0.83	0.8	0.72	5000		150	0.6675	0.090233187
64	1200	1	0.94	0.91	0.83	0.8	0.72	5000		157	0.673333333	0.091021742
65	1200	1	0.94	0.91	0.83	0.8	0.72	5000		151	0.653333333	0.088318125
66	1200	1	0.94	0.91	0.83	0.8	0.72	5000		164	0.67	0.090571139
67	1200	1	0.94	0.91	0.83	0.8	0.72	5000		152	0.7025	0.094964515

68	1200	1	0.94	0.91	0.83	0.8	0.72	5000	173	0.663333333	0.089669934
69	1200	1	0.94	0.91	0.83	0.8	0.72	5000	158	0.664166667	0.089782584
70	1200	1	0.94	0.91	0.83	0.8	0.72	5000	173	0.660833333	0.089331982
71	1200	1	0.94	0.91	0.83	0.8	0.72	5000	163	0.663333333	0.089669934
72	1200	1	0.94	0.91	0.83	0.8	0.72	5000	157	0.654166667	0.088430776
73	1200	1	0.94	0.91	0.83	0.8	0.72	5000	151	0.668333333	0.090345838
74	1200	1	0.94	0.91	0.83	0.8	0.72	5000	145	0.671666667	0.09079644
75	1200	1	0.94	0.91	0.83	0.8	0.72	5000	172	0.674166667	0.091134392
76	1200	1	0.94	0.91	0.83	0.8	0.72	5000	159	0.65416	0.08843077

											6667	6
77	1200	1	0.94	0.91	0.83	0.8	0.72	5000		153	0.663333333	0.089669934
78	1200	1	0.94	0.91	0.83	0.8	0.72	5000		138	0.67	0.090571139
79	1200	1	0.94	0.91	0.83	0.8	0.72	5000		164	0.67	0.090571139
80	1200	1	0.94	0.91	0.83	0.8	0.72	5000		138	0.685	0.092598851
81	1200	1	0.94	0.91	0.83	0.8	0.72	5000		155	0.659166667	0.08910668
82	1200	1	0.94	0.91	0.83	0.8	0.72	5000		149	0.669166667	0.090458488
83	1200	1	0.94	0.91	0.83	0.8	0.72	5000		154	0.669166667	0.090458488
84	1200	1	0.94	0.91	0.83	0.8	0.72	5000		150	0.666666667	0.090120536

85	1200	1	0.94	0.91	0.83	0.8	0.72	5000		172	0.661666667	0.089444632
86	1200	1	0.94	0.91	0.83	0.8	0.72	5000		160	0.675833333	0.091359694
87	1200	1	0.94	0.91	0.83	0.8	0.72	5000		152	0.673333333	0.091021742
88	1200	1	0.94	0.91	0.83	0.8	0.72	5000		147	0.650833333	0.087980173
89	1200	1	0.94	0.91	0.83	0.8	0.72	5000		151	0.683333333	0.09237355
90	1200	1	0.94	0.91	0.83	0.8	0.72	5000		145	0.66	0.089219331

Appendix 2: Simulation result of Kerkenes with agent number of 2090, 3134, and 4179

[run number]	num_agent	velocity-limit1	velocity-limit2	velocity-limit3	velocity-limit4	velocity-limit5	velocity-limit6	step	count_turtles_with_0_velocity	concentration	road_occupy_rate	comparison
1	2090	1	0.94	0.91	0.83	0.8	0.72	5000	382	0.577033493	0.135856708	600
2	2090	1	0.94	0.91	0.83	0.8	0.72	5000	433	0.553110048	0.130224175	600
3	2090	1	0.94	0.91	0.83	0.8	0.72	5000	375	0.574162679	0.135180804	600
4	2090	1	0.94	0.91	0.83	0.8	0.72	5000	359	0.575598086	0.135518756	600
5	2090	1	0.94	0.91	0.83	0.8	0.72	5000	400	0.570813397	0.13439225	600
6	2090	1	0.94	0.91	0.83	0.8	0.72	5000	388	0.562200957	0.132364538	600
7	2090	1	0.94	0.91	0.83	0.8	0.72	5000	413	0.56746	0.1336036	600

										4115	95	
8	2090	1	0.94	0.91	0.83	0.8	0.72	5000	369	0.566985646	0.133491044	600
9	2090	1	0.94	0.91	0.83	0.8	0.72	5000	378	0.559330144	0.131688634	600
10	2090	1	0.94	0.91	0.83	0.8	0.72	5000	377	0.571770335	0.134617551	600
11	2090	1	0.94	0.91	0.83	0.8	0.72	5000	399	0.577033493	0.135856708	600
12	2090	1	0.94	0.91	0.83	0.8	0.72	5000	371	0.577511962	0.135969359	600
13	2090	1	0.94	0.91	0.83	0.8	0.72	5000	370	0.558851675	0.131575983	600
14	2090	1	0.94	0.91	0.83	0.8	0.72	5000	379	0.572727273	0.134842852	600
15	2090	1	0.94	0.91	0.83	0.8	0.72	5000	386	0.561722488	0.132251887	600

16	2090	1	0.94	0.91	0.83	0.8	0.72	5000	364	0.566985646	0.133491044	600
17	2090	1	0.94	0.91	0.83	0.8	0.72	5000	370	0.56507177	0.133040442	600
18	2090	1	0.94	0.91	0.83	0.8	0.72	5000	383	0.585645933	0.13788442	600
19	2090	1	0.94	0.91	0.83	0.8	0.72	5000	349	0.574641148	0.135293455	600
20	2090	1	0.94	0.91	0.83	0.8	0.72	5000	395	0.559330144	0.131688634	600
21	2090	1	0.94	0.91	0.83	0.8	0.72	5000	384	0.575598086	0.135518756	600
22	2090	1	0.94	0.91	0.83	0.8	0.72	5000	373	0.563636364	0.13270249	600
23	2090	1	0.94	0.91	0.83	0.8	0.72	5000	359	0.56937799	0.134054298	600
24	2090	1	0.94	0.91	0.83	0.8	0.72	5000	392	0.58038	0.1366452	600

										2775	63	
25	2090	1	0.94	0.91	0.83	0.8	0.72	5000	379	0.573205742	0.134955503	600
26	2090	1	0.94	0.91	0.83	0.8	0.72	5000	377	0.571291866	0.1345049	600
27	2090	1	0.94	0.91	0.83	0.8	0.72	5000	356	0.573205742	0.134955503	600
28	2090	1	0.94	0.91	0.83	0.8	0.72	5000	413	0.57846889	0.13619466	600
29	2090	1	0.94	0.91	0.83	0.8	0.72	5000	410	0.568421053	0.13382896	600
30	2090	1	0.94	0.91	0.83	0.8	0.72	5000	399	0.584210526	0.137546468	600

Appendix 3: Simulation result of Pompeii with agent number 600, 900, and 1200

[run number]	num_agent	velocity-limit1	velocity-limit2	velocity-limit3	velocity-limit4	velocity-limit5	velocity-limit6	step	count_turtles_with_0_velocity	concentration	road_occupy_rate
1	600	1	0.94	0.91	0.83	0.8	0.72	5000	50	0.718333333	0.169085916
2	600	1	0.94	0.91	0.83	0.8	0.72	5000	57	0.688333333	0.162024323
3	600	1	0.94	0.91	0.83	0.8	0.72	5000	43	0.665	0.156531973
4	600	1	0.94	0.91	0.83	0.8	0.72	5000	43	0.688333333	0.162024323
5	600	1	0.94	0.91	0.83	0.8	0.72	5000	52	0.688333333	0.162024323
6	600	1	0.94	0.91	0.83	0.8	0.72	5000	45	0.706666667	0.166339741
7	600	1	0.94	0.91	0.83	0.8	0.72	5000	61	0.695	0.16359356

											6
8	600	1	0.94	0.91	0.83	0.8	0.72	5000	57	0.68	0.16006277
9	600	1	0.94	0.91	0.83	0.8	0.72	5000	61	0.688333333	0.162024323
10	600	1	0.94	0.91	0.83	0.8	0.72	5000	54	0.681666667	0.16045508
11	600	1	0.94	0.91	0.83	0.8	0.72	5000	47	0.67	0.157708905
12	600	1	0.94	0.91	0.83	0.8	0.72	5000	56	0.665	0.156531973
13	600	1	0.94	0.91	0.83	0.8	0.72	5000	44	0.715	0.168301295
14	600	1	0.94	0.91	0.83	0.8	0.72	5000	53	0.665	0.156531973
15	600	1	0.94	0.91	0.83	0.8	0.72	5000	56	0.7	0.164770498
16	600	1	0.94	0.91	0.83	0.8	0.72	5000	53	0.69166	0.16280894

											6667	5
17	600	1	0.94	0.91	0.83	0.8	0.72	5000		34	0.696666667	0.163985877
18	600	1	0.94	0.91	0.83	0.8	0.72	5000		50	0.683333333	0.160847391
19	600	1	0.94	0.91	0.83	0.8	0.72	5000		49	0.683333333	0.160847391
20	600	1	0.94	0.91	0.83	0.8	0.72	5000		49	0.688333333	0.162024323
21	600	1	0.94	0.91	0.83	0.8	0.72	5000		31	0.72	0.169478227
22	600	1	0.94	0.91	0.83	0.8	0.72	5000		51	0.701666667	0.165162809
23	600	1	0.94	0.91	0.83	0.8	0.72	5000		47	0.685	0.161239702
24	600	1	0.94	0.91	0.83	0.8	0.72	5000		40	0.701666667	0.165162809

25	600	1	0.94	0.91	0.83	0.8	0.72	5000	40	0.731666667	0.172224402
26	600	1	0.94	0.91	0.83	0.8	0.72	5000	53	0.706666667	0.166339741
27	600	1	0.94	0.91	0.83	0.8	0.72	5000	45	0.69	0.162416634
28	600	1	0.94	0.91	0.83	0.8	0.72	5000	57	0.698333333	0.164378188
29	600	1	0.94	0.91	0.83	0.8	0.72	5000	47	0.678333333	0.159670459
30	600	1	0.94	0.91	0.83	0.8	0.72	5000	57	0.665	0.156531973
31	900	1	0.94	0.91	0.83	0.8	0.72	5000	121	0.613333333	0.216555512
32	900	1	0.94	0.91	0.83	0.8	0.72	5000	109	0.607777778	0.214593958
33	900	1	0.94	0.91	0.83	0.8	0.72	5000	103	0.59222	0.20910160

											2222	8
34	900	1	0.94	0.91	0.83	0.8	0.72	5000		120	0.6	0.211847783
35	900	1	0.94	0.91	0.83	0.8	0.72	5000		106	0.613333333	0.216555512
36	900	1	0.94	0.91	0.83	0.8	0.72	5000		111	0.592222222	0.209101608
37	900	1	0.94	0.91	0.83	0.8	0.72	5000		114	0.595555556	0.210278541
38	900	1	0.94	0.91	0.83	0.8	0.72	5000		109	0.612222222	0.216163201
39	900	1	0.94	0.91	0.83	0.8	0.72	5000		103	0.615555556	0.217340133
40	900	1	0.94	0.91	0.83	0.8	0.72	5000		124	0.606666667	0.214201648
41	900	1	0.94	0.91	0.83	0.8	0.72	5000		102	0.6	0.211847783

42	900	1	0.94	0.91	0.83	0.8	0.72	5000	98	0.605555556	0.213809337
43	900	1	0.94	0.91	0.83	0.8	0.72	5000	109	0.606666667	0.214201648
44	900	1	0.94	0.91	0.83	0.8	0.72	5000	116	0.603333333	0.213024716
45	900	1	0.94	0.91	0.83	0.8	0.72	5000	124	0.603333333	0.213024716
46	900	1	0.94	0.91	0.83	0.8	0.72	5000	128	0.602222222	0.212632405
47	900	1	0.94	0.91	0.83	0.8	0.72	5000	93	0.612222222	0.216163201
48	900	1	0.94	0.91	0.83	0.8	0.72	5000	117	0.606666667	0.214201648
49	900	1	0.94	0.91	0.83	0.8	0.72	5000	118	0.623333333	0.220086308
50	900	1	0.94	0.91	0.83	0.8	0.72	5000	105	0.63222	0.22322479

										2222	4
51	900	1	0.94	0.91	0.83	0.8	0.72	5000	110	0.594444444	0.20988623
52	900	1	0.94	0.91	0.83	0.8	0.72	5000	118	0.585555556	0.206747744
53	900	1	0.94	0.91	0.83	0.8	0.72	5000	103	0.594444444	0.20988623
54	900	1	0.94	0.91	0.83	0.8	0.72	5000	100	0.585555556	0.206747744
55	900	1	0.94	0.91	0.83	0.8	0.72	5000	110	0.594444444	0.20988623
56	900	1	0.94	0.91	0.83	0.8	0.72	5000	105	0.601111111	0.212240094
57	900	1	0.94	0.91	0.83	0.8	0.72	5000	114	0.623333333	0.220086308
58	900	1	0.94	0.91	0.83	0.8	0.72	5000	120	0.595555556	0.210278541

59	900	1	0.94	0.91	0.83	0.8	0.72	5000	104	0.62	0.218909376
60	900	1	0.94	0.91	0.83	0.8	0.72	5000	104	0.624444444	0.220478619
61	1200	1	0.94	0.91	0.83	0.8	0.72	5000	167	0.561666667	0.264417419
62	1200	1	0.94	0.91	0.83	0.8	0.72	5000	161	0.558333333	0.262848176
63	1200	1	0.94	0.91	0.83	0.8	0.72	5000	186	0.554166667	0.260886622
64	1200	1	0.94	0.91	0.83	0.8	0.72	5000	175	0.551666667	0.25970969
65	1200	1	0.94	0.91	0.83	0.8	0.72	5000	182	0.523333333	0.246371126
66	1200	1	0.94	0.91	0.83	0.8	0.72	5000	202	0.5525	0.260102001
67	1200	1	0.94	0.91	0.83	0.8	0.72	5000	168	0.56	0.26363279

											7
68	1200	1	0.94	0.91	0.83	0.8	0.72	5000	219	0.541666667	0.255001962
69	1200	1	0.94	0.91	0.83	0.8	0.72	5000	206	0.55	0.258925069
70	1200	1	0.94	0.91	0.83	0.8	0.72	5000	184	0.561666667	0.264417419
71	1200	1	0.94	0.91	0.83	0.8	0.72	5000	174	0.549166667	0.258532758
72	1200	1	0.94	0.91	0.83	0.8	0.72	5000	192	0.549166667	0.258532758
73	1200	1	0.94	0.91	0.83	0.8	0.72	5000	173	0.569166667	0.267948215
74	1200	1	0.94	0.91	0.83	0.8	0.72	5000	196	0.541666667	0.255001962
75	1200	1	0.94	0.91	0.83	0.8	0.72	5000	200	0.543333333	0.255786583

76	1200	1	0.94	0.91	0.83	0.8	0.72	5000		194	0.555833333	0.261671244
77	1200	1	0.94	0.91	0.83	0.8	0.72	5000		192	0.5675	0.267163594
78	1200	1	0.94	0.91	0.83	0.8	0.72	5000		194	0.54	0.25421734
79	1200	1	0.94	0.91	0.83	0.8	0.72	5000		162	0.545833333	0.256963515
80	1200	1	0.94	0.91	0.83	0.8	0.72	5000		184	0.56	0.263632797
81	1200	1	0.94	0.91	0.83	0.8	0.72	5000		168	0.531666667	0.250294233
82	1200	1	0.94	0.91	0.83	0.8	0.72	5000		172	0.5575	0.262455865
83	1200	1	0.94	0.91	0.83	0.8	0.72	5000		180	0.556666667	0.262063554
84	1200	1	0.94	0.91	0.83	0.8	0.72	5000		186	0.561666667	0.264417419

85	1200	1	0.94	0.91	0.83	0.8	0.72	5000		200	0.555833333	0.261671244
86	1200	1	0.94	0.91	0.83	0.8	0.72	5000		217	0.5425	0.255394272
87	1200	1	0.94	0.91	0.83	0.8	0.72	5000		160	0.563333333	0.26520204
88	1200	1	0.94	0.91	0.83	0.8	0.72	5000		189	0.539166667	0.253825029
89	1200	1	0.94	0.91	0.83	0.8	0.72	5000		170	0.551666667	0.25970969
90	1200	1	0.94	0.91	0.83	0.8	0.72	5000		200	0.549166667	0.258532758