From the Highlands of Lyktos to the Coast of Hersonissos: Walking on the Early Iron Age Cretan Landscape through a Computational Perspective

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Preface

This thesis is the culmination of two years marked by chaos, paranoia, and numerous enriching experiences. It stands as a testament to the diverse interests I pursued during my Master's program in Leiden, and throughout the various challenges and adventures of my early twenties.

Acknowledgments

Regarding the people I would like to thank, I should start with my parents, Elpida and Phidias. Without their support I would not have been able to study in, the field of archaeology and especially leave my hometown, Piraeus in Athens to study abroad and chase new opportunities. Second in command my grandma Litsa, and my auntie Pagona who have been my day-one supporters as well as my sister, Zoi , my uncle Dimitris, and the rest of my family. Their help has played a significant role in the completion of this work.

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May we live long and prosper and may we be blessed through eternity

"Wow! What a Ride!"

-Hunter S. Thompson

In Loving Memory of my Grandma Popi and my Grandpa Vouvoulis

1. Introduction

1.1 A General Introduction

In the last decades, Landscape Archaeology met significant developments in both its theoretical and methodological aspects. The concept of the landscape has been reconsidered numerous times since the 1980s, and the simultaneous technological evolution has allowed the development of new frameworks for the study of the relationship between people and their environment in an archaeological context. Regarding the theoretical aspect, an important question, besides the landscape level is to explore how people experience their surrounding space. However, a question that emerged from this interest is how we, as archaeologists, can study this issue besides theoretical reviews, and what methodologies can be employed for this study.

The philosophical ideas of Phenomenology, which were heavily discussed by the philosophers Martin Heidegger, Edmund Husserl, and Maurice Merleau-Ponty, during the first half of the 20th century, have played a foundational role in the field of archaeology (Brück, 2005; p. 46). Their ideas on human perception have helped the emergence of a school of thought inside the archaeological field that tries to understand how people perceive the multi-modal aspects of the past. This interest covers a large spectrum of human life, ranging from material aspects to sociocultural dimensions.

Human existence and perception are deeply connected and an individual is in a constant and intertwined relationship with the environment they live in. Perception is not just a mental process, but it is heavily affected by our relationship with the world and space. Space, even if it is artificial (an urban environment) or natural (a landscape) is foundational for our bodily experiences and our perceptual processes, meaning that our bodies are not passive and that space is not merely a container of actions.

In Archaeology, the ideas of phenomenology started appealing to the interest of scholars during the 1990s (Brück, 2005, p. 46-47). Christopher Tilley, with his book "*A Phenomenology of the Landscape*" (1994) was one of the first archaeologists to incorporate phenomenological ideologies for the study of the past, with a focus on a landscape context (Brück, 2005; p. 47). Tilley was one of the first scholars to denounce the role of the landscape as it was formed by capitalist ideologies, as a product available for trade (Brück, 2005; p. 47). Instead, he proposes that the landscape is an entity of our world, with an embodied role, deeply connected to the human experience, memory, and perception (Tilley, 1994).

Tilley's critique against the previous understanding of the term led to the recognizing of the landscape as an important archaeological artifact and its influence on society. His main proposal was that an archaeologist, besides the main part of their work, should also explore how ancient sites interact with themselves, as a means to understand the site from a phenomenological perspective (Tilley, 1994). This understanding is heavily affected by the chronological and cultural context, however, a possible scenario is that certain things can affect the spiritual and mental world of an individual in similar ways.

Another influential scholar that has helped on the development of these ideas is the Anthropologist Tim Ingold. Ingold, inspired by the ideas of Merelau-Ponty, has made significant contributions in the understanding of the relationship between humans and their environment (Ingold, 1993; 2000). Ingold's work emphasizes that the landscape is a medium that both shapes and is shaped by human perception. These ideas have provided an adequate theoretical framework for studying such issues, however, a question that persists is how to explore them through a methodological perspective.

From a methodological standpoint, landscape issues are often studied through the use of Geographical Information Systems (GIS). GIS is an important cartographic tool, used in a variety of fields and for different purposes, while it is often exploited by archaeologists for its map-making potential and for analyzing landscape and settlement patterns in a past context. The use of GIS for archaeological research has been the subject of intense theoretical debates among scholars (Van Leusen, 2000, p. 225; Gillings, 2012; Witcher, 1999; Gaffney and Van Leusen, 1995).

The main critique lies on the fact that these tools are mostly used for obtaining a quantitative perspective of a landscape and its features (Brück, 2005, p. 52-53). These systems are based on Data, which from their nature are solely quantitative. This seems only logical, considering that spatial information need to be converted to a language that the machines can understand. However, archaeologists disagree with the fact that GIS-based studies do not take into consideration the experiential aspect of a landscape and they treat it as a mere product, or a unit (Brück, 2005, p. 54; Van Leusen, 2000, p. 225; Gillings, 2012). This quantitative treatment of the landscape results to its use as a static object. On the contrary, a landscape is a dynamic entity heavily affected by social development and actions taking place in it (Tilley, 1994). This misconception of space and landscape has only been recently reconsidered in the field of archaeology (Tilley, 1994; Brück, 2005).

An important action that highlights and conceptualizes the dynamic nature of the landscape is the movement of people. The importance of movement for Archaeology is a result of the introduction of phenomenological ideas in the field (Tilley, 1994; Brück, 2005, p. 47). Movement and mobility are important factors for human life and that applies to both ancient and contemporary times. By studying movement, one can comprehend a spectrum of social behaviors, ranging from understanding individual and social perception processes to grasping regional and social relations between communities and settlements and human-landscape relations (Verhagen & Jeneson, 2012; Herzog, 2013). Moreover, examining human and product mobility provides insights into trade patterns, whether regional or occurring on a larger scale. These concepts are important for the field of archaeology, while the study of movement can additionally lead to the discovery of new sites.

Focusing on Archaeology, the interest in the specific subject started flourishing with the development of geospatial applications and Geoinformatics systems (Polla & Verhagen, 2014). Movement-related questions are a primary example of the introduction of phenomenology in the use of GIS. Movement has been fundamental for overcoming the quantitative perspective of GIS to obtain qualitative results that can be more beneficial for understanding space and time (Gkiasta, 2008). The tools of Cost Surface and Least Cost Path analysis. available in modern GIS, have been the two most used options for understanding mobility patterns and the ways that people move on the landscape (Polla & Verhagen, 2014). These methodologies consider environmental, or other types of costs and are beneficial for studying settlement patterns and path-routing issues.

These tools can be exploited for a variety of purposes but regarding Archaeology, these applications have been quite beneficial for trying to understand path and communication networks. Their main advantage is that they help test hypotheses regarding path networks that can be found in the archaeological and historical records and not so much for recreating paths with no evidence. An important issue with these technologies is that archaeologists tend to use them without paying attention to the software-provided algorithms and with little to no interest in their computational processes. This leads to a neglection of their true potential and in a holistic acceptance of the software results as scientifically accurate.

Based on these issues, this thesis aims to provide a methodological framework for overcoming these technological misunderstandings. By avoiding the reliance on ready-made tools provided by available software, the goal is to deepen into the processes behind the methodology of Least Cost Paths. Instead of a GIS, the Python programming language will be utilized to evaluate its potential for investigating such matters. An expectation of this research is to provide a methodological workflow applicable to various case studies for examining path networks, while also giving insight on the background processes of Path analysis without simply producing outputs that are not adequately understood by the user. The results of the Python methodology will be compared to those produced by the open-source geospatial software, QGIS. This way, a methodology that prioritizes the principles of Open Science will be employed, while also serving as a model for similar types of analysis.

From an archaeological standpoint, this research is focused on movement in the landscape of the Greek island of Crete, particularly in its Central region. The primary objective is to delve through a computational perspective into the path network of Central Crete during the Early Iron Age (EIA) period. However, instead of relying on established workflows, this study seeks to employ a novel methodology by harnessing the potential of programming languages.

The results of the methodology will be evaluated not only from a computational standpoint but also through an archaeological and phenomenological lens. To overcome the deterministic nature of geospatial analysis and GIS, the interpretative process will be crucial. After assessing the methodology's validity by comparing its outcomes with those produced by QGIS, the results will be further examined against the archaeological record of Central Crete. This comparison aims to understand their relationship to the Early Iron Age path network and what they can reveal about the social relations between sites in the area. By incorporating a hint of phenomenological ideas, the analysis will also consider the experiential aspect of these paths as they might have been perceived by a traveler. This multidisciplinary approach seeks to bridge the gap between the quantitative and qualitative aspects of path analysis, offering insights that can enhance archaeological research overall.

1.2 On Crete

Crete (Fig. 1), one of the largest islands of the Mediterranean and the largest of Greece, boasts a rich history from the Neolithic to the present day. The island is mostly famous for its Bronze Age with the Minoan Civilization, known for its palatial system and maritime prowess. After the Minoan collapse, Crete retained its significance, transitioning to city-states in the Iron Age, such as Lyktos and Hersonissos which are located inside the study area of this thesis. These city-states continued to influence Crete's history through the Classical, Hellenistic, and Roman periods. Archaeological exploration of Crete has been ongoing since the 19th century, predating the island's official incorporation into the Greek nation, with an emphasis on landscape archaeology (Gkiasta, 2008).

While this thesis focuses on understanding movement and settlement connectivity between key sites of Central Crete such as Lyktos and Hersonissos, the main objective is still to address the methodological challenges of analyzing ancient pathways and understanding human-landscape relations. Nevertheless, attention will be given to the EIA period of the island, a period that drew academic interest in recent decades, after the intense archaeological activity on the Minoan and Roman periods (Kotsonas, 2022). This period set the foundation for the social development of Crete which took its primary shape in the Archaic period and flourished from the Classical to the Roman times. A hypothesis that will be tested is whether the results of this thesis can offer any insight into whether Hersonissos was part of the social network of the area of focus during the EIA period.

Figure 1 Map of Greece showing Crete's location

1.3 Research Questions

This thesis examines the application of computational approaches for studying ancient movement in the context of Crete. The central research question is whether code-based geospatial analysis, through the use of Python, can produce comparable results to those obtained from traditional GIS tools like QGIS. This question will be further explored compared to the archaeological record of the study area and based on phenomenological ideas to see if the computational results can provide information regarding the socio-cultural context of the area under study and the human experience of landscape movement.

The exact research questions are the following:

1. Can LCP analysis through Python provide results that match the QGIS outputs and provide an alternative methodological workflow and what is the potential of programming approaches for such purposes?
2. Can LCP results, enhanced by archaeological data and a phenomenological perspective, provide a deeper understanding of the path network, movement, social interactions, and human-landscape relationships in Early Iron Age Central Crete?

   Sub-Question:

   - Can the resulting path network provide insights on the case of Hersonissos and if it was part of the social network of the area earlier than the Classical period?

1.4 Chapters' Overview

Following the *Introduction* chapter, the theoretical and methodological ideas that shaped this thesis will be discussed. In the *Theoretical Background* chapter, the main theoretical frameworks will be explored, explaining concepts concerning human perception and movement in archaeology. Then, in the *Methodological Background* chapter, the methodological frameworks employed will be presented along with a brief history of research on similar issues in the Cretan context and an explanation of the implemented methodology.

Before delving into the study of the paths, an *Archaeological Background* chapter will provide the social and chronological context of the study area. The *Methodology* chapter will discuss the applied approaches to address the project's research questions. This will be succeeded by presenting the outcome in the *Results* chapter. Subsequently, the results will be evaluated from computational and archaeological perspectives to explore their significance for the research in the *Discussion* chapter. Considerations regarding the experiential aspect of the paths will also be discussed. Finally, a *Conclusion* chapter will critically examine the entire process of this thesis and its outcomes from a broader perspective.

1.5 On the use of ChatGPT

This thesis greatly benefited from the AI-language model ChatGPT, developed by OpenAI in 2022. Its capabilities in scripting and code generation were essential in avoiding conventional GIS software and adapting scripts into Python for this project. ChatGPT's guidance on methodology was invaluable, especially given my limited coding experience, and my strictly archaeological background.

Utilizing AI ethically can enhance research across disciplines, particularly in areas with limited online documentation like GIS and geospatial analysis. However, it's important to recognize that these tools, shaped by human training, may carry biases affecting their objectivity, thus they should be used carefully. Nevertheless, the potential of ChatGPT proved to be great for academic purposes

2. Theoretical Background

2.1 Archaeology and the Concept of Human Perception

The study of the human sensorium has been integral to archaeological research, shedding light on decision-making processes and past experiences within the environment. Frieman and Gillings (2007) highlight perception as the link between sensing and cognition, while Pollock (1967) describes how all senses contribute to our awareness of objects and spaces (Landeschi and Betts, 2023, p. 2). In their volume "Capturing the Senses: Digital Methods for Sensory Archaeologies" Landeschi and Betts explore the potential benefits of computational methods in understanding the senses within archaeology. They propose that understanding the stimuli that shape perception can provide valuable insights into the behaviors of ancient peoples (Landeschi and Betts, 2023, p. 1). However, these ideas are based on modern ideologies regarding space and its perception and they might have not been the same for past communities (Wheatley, 2014, p. 119-120).

Phenomenological approaches in archaeology have mostly appeared in theoretical contexts (Tilley, 1994; Bruck, 2005), defined by a first-hand/experiential examination of archaeological remains by a contemporary individual (for instance, the archaeologist) (Landeschi and Betts, 2023, p. 2). With the introduction of quantitative methods in archaeology, there is a trend of exploring phenomenological concepts through a more scientific perspective to enhance subjectivity (Landeschi and Betts, 2023, p. 3). However, as stated by Floyd Allport (1955) the quantification of real events can lead to abstract measurements that if they are not contextualized, have neglectable research value (Allport, 1955, p. 31).

The influence of post-processualism and the emergence of cognitive archaeology were pivotal for phenomenological archaeology and it owes a lot to scholars like Wheatley, Llobera, and Renfrew (e.g., Wheatley & Gillings, 2000; Wheatley, 2004; Llobera, 1996; Llobera, 2002; Renfrew & Zubrow, 1994; Renfrew, 2008). The first introduction of such ideas in archaeology can be observed in the 1980s by researchers that focused on vision and its role in human perception (Lake et. al, 1998). However, the use of computational methods to explore such phenomena developed in the 1990s (Landeschi and Betts, 2023, p. 3)

Tilley's work on landscape archaeology (1994) has been foundational for the development of phenomenological ideas in the study of ancient landscapes. His work has been significant for the establishment of methodologies for data collection and interpretation that overcome the solely deterministic nature of scientific approaches. It also led to the concept of landscape being perceived differently than just an abstract and quantified term (Gillings, 2012, p. 602).

GIS is one of the tools that has helped produce methodologies that can help academics form a stable methodological framework for examining human perception of the past. Computational methods have been used to investigate landscape issues on a large number of occasions, expanding beyond the spectrum of vision (Landeschi and Betts, 2023, p. 3). Mobility is another important subject that is studied for exploring the relationship of an individual with their environment and it is commonly studied through GIS (e.g. Van Leusen 1999; Verhagen and Jeneson 2012; Herzog, 2013)

The use of GIS for phenomenology-related questions has been criticized in the past (Witcher, 1999; Gaffney and Van Leusen, 1995). Gillings and Goodrick (1996) have mentioned that GIS is not a tool that can help with such issues, as integrating social parameters is a difficult task, as is true at least for the potential of computer systems of their time. In the same paper, they argue that GIS approaches will not be the sole methods for exploring the landscape, due to its complex nature and the new ideologies that appeared later. The strictly deterministic character of GIS studies has been described as not considering socio-cultural parameters for their interpretations (Gillings & Goodrick, 1996).

As Gaffney and Van Leusen (1995) discuss, early applications of GIS were mostly focused on the technological aspect, which enhanced environmental determinism. Phenomenological approaches are described as too subjective, deviating from a solid scientific foundation. A balance between objectivity and subjectivity is proposed to enhance the interpretative aspect of these methods (Gaffney & Van Leusen, 1995, p. 375). Nevertheless, this combination can lead to a nuanced understanding of the human-landscape relationship (Gaffney & Van Leusen, 1995, p. 379). Witcher (1999) proposes the incorporation of qualitative data for "humanizing" GIS analysis and gaining a better perspective on the socio-cultural aspects of past human life.

The debate between GIS applications and the phenomenological approaches in archaeology has been evident for decades (Van Leusen, 2000, p. 225; Gillings, 2012). Despite numerous discussions and conferences aimed at integrating these ideas, minimal effort has been made to combine them into a common theoretical framework (e.g., Bender, 1993; Tilley, 1994; Lock & Stancic, 1995). Gillings (2012) describes the relationship between spatial technologies and phenomenology as dysfunctional due to unresolved tension between their representatives. He suggests that instead of forcing spatial technologies into existing theoretical discussions, they should be used as innovative media interpreted through new theoretical approaches (Gillings, 2012, p. 604).

GIS practitioners have shown significant interest in researching the experiential aspects of landscapes, but theorists have been less interested, contributing to the dysfunctional relationship mentioned by Gillings. Efforts to create a common conceptual basis mainly come from GIS practitioners. According to Gillings (2012), this schism originated from the early focus on exploring GIS potential and developing new tools. In the early 1990s, the term "landscape" was adopted as an abstract, quantitative concept, leading to methods such as predictive modeling (e.g., Judge and Sebastian, 1988). This methodological focus led to the characterization of GIS practitioners as technicians (Gillings, 2012, p. 603), which alienated them from landscape theorists. The main issue was that GIS users were criticized for merely applying existing theoretical ideas rather than developing new approaches to advance the field (Gillings, 2012, p. 604).

A way to bridge GIS analysis with a stable theoretical background was the concept of affordances, created by psychologist J.J. Gibson, who focused on the issue of visual perception. Gibson proposed that the environment is perceived by an agent through the mental translation of meanings occurring through the sensing mechanisms of the agent (Gibson, 1979). Gillings suggests that we should neglect the effort to reunite these two schools of thought (phenomenologists and GIS practitioners), and instead proceed by changing the focus of spatial technologies by advocating for the concept of affordances.

The exact definition of the term is still discussed mainly in the discipline of psychology specifically Ecological Psychology. Gibson's definition has been characterized as abstract (Gillings, 2012, p. 606). Gibson discusses the affordances of animal movement and perception and defines them as the parameters and conditions of a landscape that influence the perceptive mechanisms. Affordances are the relationship that exists between these parameters and an individual agent. Generally, the term has led to heavy debates about its definition, drawing the attention of scholars from various disciplines (Gillings, 2012, p. 606-607).

Llobera's research (1996) on prehistoric ditches with the use of viewsheds was one of the first applications of Gibson's ideas in an archaeological context (Gillings, 2012, p. 607). Gillings, drawing on Webster's critique of Llobera's work (Webster, 1999), argues that archaeologists using GIS approaches must account for the subjective nature of affordances and how individuals perceive them, making them difficult to record and interpret (Gillings, 2012, p. 605).

Don Norman's work on the role of affordances in the field of design has been important for how affordances are perceived in the field of archaeology. Affordances for humans are heavily connected with the environment and the natural and social conditions defining it (Norman, 1988). Despite this huge debate on the definition of affordances and how they affect perception, it is important enough to simply apply them in GIS-based research. The ideas of researchers such as Gibson should be used as a background for archaeological studies, but affordances should be considered based on their context and not according to the thoughts of a scholar applying them in a different framework (Gillings, 2012, p. 606-607).

Gillings argues that instead of aiming to model the human experience through traditional mapping techniques with computational spatial tools, the goal should be to explore the experiential aspect of a landscape based on the desired context of the researcher (Gillings, 2012, p. 608). To do that he proposes avoiding complex layers typically used in GIS systems, such as soil coverage and vegetation, and alternatively exploring relational issues between humans and landscape (Gillings, 2012, p. 608). Chemero has suggested that affordances can be explored through an objective perspective, however, it is a difficult task to achieve (Chemero, 2003, p. 191). Based on this, Gillings advocates for creating new analytical frameworks that can help us understand relations, for example between a community and its environment (Gillings, 2012, p. 606).

In recent years, there has been a significant evolution in understanding sensory perception and movement in archaeology. For example, Visibility and Cost Surface analysis are two techniques that can be significantly influenced by the incorporation of perceptual theories to reach stable interpretations that avoid the software's determinism, considering that the data are explored from their sociocultural context as well (Van Leusen, 2000, p. 215; Gaffney & Van Leusen, 1995, p. 380).

These aspects offer valuable insights into how past societies interacted with their environment. Movement, in particular, has emerged as a key influence on human consciousness (Murrieta-Flores, 2010), highlighting the importance of exploring these dynamics in archaeological research. In this thesis that studies LCPs from a computational perspective in the Cretan landscape, with a particular focus on the action of walking, these ideas are instrumental.

By using the concept of affordances, the aim is to interpret geospatial analysis results based on the lived experiences of ancient Cretan societies. Understanding how past communities interacted with their environment, guided by the concept of affordances, allows a more nuanced interpretation of ancient movement and landscape use. This approach enriches the computational analysis with an experiential perspective, offering deeper insights into the socio-environmental context of ancient Crete.

2.2 Theoretical Review of Movement in Archaeology

2.2.1 Affordances of Movement

Affordances of movement can be recognized by considering the geographical and cultural characteristics of an area, as well as the potential of the medium, meaning the body, on the physical and social spectrum (Verhagen et al., 2019, p. 218). The advancement of computational tools has been crucial for studying archaeological movement as can be observed by the results of a variety of studies that have been conducted in the last two decades. Geoinformatics systems and the establishment of the methodologies of Cost Surface Analysis (CSA) and Least Cost Paths (LCP) have provided the means to understand movement by exploring a variety of environmental and social parameters (Murrieta-Flores, 2010). The effort to reconstruct ancient pathways with computational methods has started to appear ever since the early 1990s, through the use of GIS systems (e.g. Van Leusen, 1993). Since then, the main issue has been to accurately replicate pathway networks of the past by trying to incorporate as many parameters that would impact landscape movement as possible (Verhagen et al., 2019, p. 225-226).

Terrain topography is the most preferred environmental parameter for studies adopting these methodologies. The problem of GIS replicating more complex conditions such as socio-cultural variables has been an issue of heavy criticism. This critique has led to a huge debate and an ongoing effort to recognize and list the different influences that might affect human movement. So, in each case study, the socio-cultural context of an area under study should be taken into consideration (Murrieta-Flores, 2010, p. 258).

Affordances lead to actions that are sometimes easy to predict, while not refuting the possibility for an alternate scenario to take place. This could be translated by the fact that the actions of humans will most likely follow a normal behavioral pattern, but different patterns can also occur (Wheatley and Gillings, 2000). What can be said with certainty is that humans perceive and learn about their environment by walking and traveling in it. Sites and features are used as landmarks for navigation (Verhagen et al., 2019, p. 224). These can be either natural or artificial. Territoriality and safety are also of major concern. People can travel within boundaries where they can feel safe (Verhagen et al., 2019, p. 223). Walking outside of these borders can make them face a variety of dangers, such as the hostility of an enemy's territorial expansion.

2.2.2 Movement Reconstruction of the Past, based on Affordances

The modeling of movement has been a subject of major interest for archaeologists. As noted by Llobera, a key issue for reconstructing path networks is exploiting current environmental parameters to provide a possible scenario for how movement happened in a specific terrain (Llobera, 2000, p. 70-71). There are two main components for the study of movement; Orientation and Direction. Both are heavily influenced by traverse costs. The accessibility of a site also needs to be considered, meaning how easy it is to approach it from different directions (Verhagen et al., 2019, p. 219). However, the subject of movement is quite complex and landscape costs are not the only explanatory forces. The combination of socio-cultural and natural parameters and the understanding of their influence is significant for eventually understanding movement (Fábrega-Álvarez & Parcero-Oubiña, 2007, p. 121).

Movement is therefore directed by various variables, and the purposes are not solely economy-related. Murrieta-Flores (2010) distinguishes between two main categories of variables affecting movement. The first category are factors that are beyond an individual's abilities and they could be characterized as applicable to any agent, human or animal (Murrieta-Flores, 2010, p. 252). This set of parameters includes topography and natural features and conditions of an area, as well as factors that influence the kinetic mechanisms of an agent. These factors could be considered as universal and they would affect all people the same, no matter the sociocultural context (Murrieta-Flores, 2010, p. 251). Landscape features can be separated into three main categories; those that "attract movement", those that "repel movement", and "neutral" ones (Llobera, 2000, p. 72; Murrieta-Flores, 2010, p. 259).

The second category is variables connected to the individual's social background, and they will differ according to the chronological and geographical period. Territorial boundaries, trading networks, and general factors that belong to a community's general ideology are some examples of this category (Murrieta-Flores, 2010, p. 258-259). Both of these categories form the concept of "landscape affordances".

This means that individuals will pay attention to specific parameters when doing an action (Verhagen et al., 2019, p. 219). Relating to movement, affordances are separated into two spectrums. The first is their movement potential, which is origin-oriented and can either be conceived, or not by an individual while moving from point A to a point B. The second is accessibility, which relates to movement based on the destination (Verhagen et al., 2019, p. 219). This idea needs to be considered in two scenarios. In a total isotropic context, movement potential and accessibility are the same, but in reality, affordances are affected by direction (Verhagen et al., 2019, p. 219).

According to affordance theory, the foundation for the study of movement with limited evidence is the relationship between the physicality of an individual and their movement potential with the archaeological remains of a landscape, which can be either cultural monuments or settlements (Fábrega-Álvarez & Parcero-Oubiña, 2007, p. 121). Two key points need to be considered when trying to reconstruct movement networks of past affordances. The first one is the condition and physical potential of an individual, and the second is the movement potential and accessibility, which can be computed through cost surfaces (Verhagen et al., 2019, p. 226-227).

1. Landscape constraints

Llobera (2000), makes a separation between landscape constraints. The first are those related to capability issues, such as slope, types of soil, and vegetation and their impact on the traveler (Llobera, 2000, p. 68). Then, there are "coupling constraints" that refer to changes and shifts in the shape of a landscape (Llobera, 2000, p. 68). An example would be atmospheric and seasonal changes, as well as works that alter the initial form of the environment. Finally, there are "authoritarian constraints" that relate to social boundaries, such as territorial limits (Llobera, 2000, p. 68). As Helbing et al. (1997) suggest, social behavior is the foundation for understanding the structure of society.

In an archaeological context, paths and roads should also be considered as artifacts of the archaeological record (Snead et al., 2009, p. 1-2; Tilley & Cameron-Daum, 2017). From a phenomenological perspective, paths are an important means to explore their impact on society, as well as the relationship between individuals and their environment (Llobera, 2000, p. 68-69; Murrieta-Flores, 2010, p. 249). The spatial structure of a landscape, or even of a cityscape, is foundational to the development of social behavior (Llobera, 2000, p. 69). Hillier & Hanson (1984) suggest that movement dynamics need to be seen from every aspect so that they can be understood better. Their work focuses on urban environments, however, their main ideas can still be applied on a landscape level (Llobera, 2000, p. 69).

Landscape features heavily affect social behavior, and they can interact with an individual's physical or mental spectrum (Llobera, 2000, p. 71-72). A good example of this is the existence of monuments or other archaeological remains and their influence on human beings (Llobera, 2000, p. 72). On a given landscape that is empty, movement from one point to another is directed mainly by the natural characteristics of an area. Environmental factors, including topography, slope, climatic conditions, land cover, and vegetation, are crucial considerations for understanding ancient movement patterns (Verhagen et al., 2019, p. 221-222; Murrieta-Flores, 2014, p. 100). Water bodies are another natural factor that is considered by individuals besides slope. The need to access resources is a constant one (Murrieta-Flores, 2014, p. 100). Also, water bodies can direct movement (Herzog, 2014a, s. 5.5). People need to cross rivers so appropriate locations to cross them are needed. The remains of bridges show the actions of people in such cases (Lewis, 2017; p.6). The incorporation of these parameters is dependent on the data availability. Nevertheless, besides these natural factors, there are, also, those that are determined by the society one lives in (Llobera, 2000, p. 75).

2. Social/cultural constraints

Movement is a social activity that can be understood from the fact that people are active agents engaging with their environment and not passively existing in it. In a geographical context, people develop habits that affect their behavior in their niche environment. Social and behavioral rules are developed that are mutually followed by individuals, leading to the creation of a social identity. The results of these rules are observed in the actions of people (Murrieta-Flores, 2010, p. 258).

As stated by Murrieta-Flores (2010), movement, and networks of mobility are developed based on a community's knowledge and perception of their surrounding environment. The factors that influence movement can be either part of the conscious or unconscious processes of the individuals forming a social structure. The practicality of movement as well as the purposes behind an action should be taken into account when trying to understand mobility in an archaeological context (Murrieta-Flores, 2010, p. 250).

Navigation is another important component of movement, and it is heavily connected with the cognitive mechanisms of the human mind. Navigation means finding your way in the landscape, while it develops based on the sequence and the vision of natural or artificial landmarks of the environment that help reach point B from point A. Navigational markers are landscape features of two categories. They can be either natural (those that relate to natural features) or anthropogenic (architectural remains) (Verhagen et al., 2019, p. 224). Infrastructural remains are important to be considered (Verhagen et al., 2019, p. 222).

Safety, for example, is important for navigating the terrain. People used to move inside the territorial borders of the society they belonged to. Territorial borders and social relationships are significant for social development, and they define the behavioral acts of the people occupying an area (Verhagen et al., 2019, p. 223-224; Murrieta-Flores, 2014, p. 100). Territoriality is often represented through natural or artificial landmarks that signify different areas (Murrieta-Flores, 2010, p. 261). Cases of landmarks can be found in many different cultures (Murrieta-Flores, 2010, p. 262). By understanding the borders and the settlement pattern in an area, archaeologists can implement more robust frameworks to develop computational methodologies (Lewis, 2017, p. 6). Aspects of territorial expansion and control are usually studied through the use of CSA and LCP analysis, which is also apparent in the case of Crete (e.g. Bevan, 2011, Drillat, 2022).

When trying to model human movement, an important thing to understand is the goals of the action as well as the cognitive and social processes that are relevant to the development of pathways and street networks (Verhagen et al., 2019, p. 219). These dependent variables are formed due to the complexity of a social environment and differ chronologically, geographically, and culturally. People perceive parts of the landscape differently according to these variables; for example, sacred sites might exist, that people may try to avoid when traveling in the terrain. These ideas occur based on the social identity of a community and how it perceives its surroundings (Murrieta-Flores, 2014, p. 100). In the same sense, navigational skills also develop based on the knowledge of the community.

3. Individual constraints

Besides the aforementioned affordances, movement is also heavily connected with individual perception. While we move the senses are constantly working. For example, optical stimuli are constantly changing while an individual is on the move. This change is significant to the individual's experience (Verhagen et al., 2019, p. 224). Humans rely on sequential and visual cues when navigating the landscape (Verhagen et al., 2019, p. 224). This relates to an individual's cognitive capabilities, which can also be shared by the members of the same community, and they are part of social knowledge (Verhagen et al., 2019, p. 224).

The physicality of an individual is another important parameter for movement. Physiological studies on human movement have managed to show that the speed of a human being might differ according to the purposes of the movement and their body mass, considering it is dependent on energy expenditure (Murrieta-Flores, 2010, p. 253). Activities that will minimize energy costs are often preferred by an agent as kinetic studies have shown. Speed and energy are the two most commonly used parameters to compute the cost of walking to an individual (Murrieta-Flores, 2010, p. 253).

For measuring speed a variety of factors are considered, such as age, physical condition, and whether an individual carries a load and how heavy that load could be (Murrieta-Flores, 2010, p. 253). Energy is calculated by addressing environmental factors such as slope, aspect, and direction of movement, as well as the types of soil and vegetation of an area (Murrieta-Flores, 2010, p. 253-254). Slope has been heavily connected with energy, as is apparent in studies by Minetti (1995) and Llobera (2000). The direction of the slope is of major interest. Energy expenditure differs depending on the uphill or downhill direction of movement. According to Llobera and Sluckin (2007), a traveler will most likely follow a path that already exists from previous walkers, even if a new path could be more economical in energy expenditure, to avoid unknown conditions, because it is easier to walk into the already established one. Means of transport also need to be considered (Bevan, 2011, p. 4; Verhagen et al., 2019, p. 220) but this thesis focuses solely on the action of walking across a landscape. The case of individuals carrying baggage is a scenario that needs to be considered (Murrieta-Flores, 2014, p. 100) as the feasibility of transporting products by foot from one location to another (Herzog, 2014a, s. 5.2).

Therefore, movement analysis typically relies on energy loss or speed calculations, often using average human agents (Murrieta-Flores, 2014, p. 101). However, this approach doesn't fully reflect real-life variability in movement rhythms and physical conditions due to factors like sex, age, and other physical parameters of an individual (Verhagen et al., 2019, p. 229). The combination of these two methods for the creation of cost surfaces is common.

2.3 Conclusion

These theoretical frameworks are integral to this thesis, shaping its methodology and interpretative process. The main objective is to utilize landscape affordances and constraints for creating the path model, with a special emphasis on slope. Other landscape constraints, such as water bodies, will be considered in the interpretation process. Social and cultural constraints will be drawn from the archaeological and historical data for interpreting the model.

3. Methodological Background

3.1 Introduction

The primary objective of this chapter is to elucidate the rationale behind the methodology while providing a concise overview of the historical application of movement-based geospatial analysis in Cretan archaeology. The main concepts of LCP analysis will be discussed focusing on the application of algorithms and the necessary parameters for this purpose. Emphasis will be placed on extant studies that center on connectivity issues through LCP analysis and those that integrate ideas derived from the *Theoretical Background* chapter.

The initial section will provide a comprehensive backdrop of LCPs by conducting a literature review of different aspects of the selected methodology, based on studies that parallel the thematic scope of this thesis. The main objective is to establish a contextual framework for the methodological discussion. A brief mention of studies focusing on the application of LCPs in the Cretan context will be briefly discussed to provide a history of research. By systematically delineating the historical trajectory of movement-based geospatial applications in Cretan archaeology and surveying analogous research, this chapter aims to underscore the significance of the methodology within the broader academic discourse.

3.2 General Overview of Movement Analysis for Archaeology

The focus on archaeological research of the Cretan Landscape is apparent in many studies (Gkiasta, 2008). Applications of geospatial technologies in the Mediterranean landscape are well-established (Carroll & Carroll, 2022) as is the case for the island of Crete, with the island's distinct topography often utilized for geospatial research. This type of research is significant in understanding the connectivity between archaeological sites across Crete (Megarry, 2012). However, this thesis will focus on issues of movement and path networks, limiting its scope to research with a similar focus and excluding general GIS studies. Various methodologies exist for modeling movement and paths such as ABM (Agent-Based Modeling) or techniques based on hydrology modeling (e.g. Bellavia, 2001). This thesis will focus on the LCP approach.

Movement is a continuous-dynamic activity, thus it is hard to visualize through the mere process of cartography, which represents a disconnected view, as the viewer of the map has a godlike view, which is not how the landscape is experienced by an agent (Mlekuž, 2014, p. 5-6). However, that does not constitute that maps have no value. Visualization of results is a key principle in archaeology. Maps and modeling outcomes should be viewed accordingly, and the results of GIS analyses should be used to formulate new ideas and theories that will enhance the interpretative process (Mlekuž, 2014, p. 6). As Mlekuž (2014) states, the concept of “time geography”, meaning the relationship between time and space, is crucial for understanding movement. This is a hard task to apply in archaeological research considering the difficulty of imagining the spatiotemporal aspect of the life of past people (Mlekuž, 2014, p. 6-8).

The use of GIS-provided tools such as LCP and CSA has helped a lot with the study of settlement patterns and mobility in archaeological landscapes (Mlekuž, 2014, p. 9). In the Mediterranean context, the study of movement has been in the scope of academics and several methodologies exist for its analysis (Bevan, 2011). The concept of LCP suggests that people focus mostly on energy expenditure and costs while crossing a landscape, however, what can be said for sure is that movement is affected by a variety of factors and constitutes a more complex and abstract action ((Mlekuž, 2014, p. 9). The importance of a location as a destination was determined not only by energy costs but also by sociocultural and natural conditions as extensively discussed in the *Theoretical Background* chapter.

As Polla and Verhagen (2014) suggest, path formation and their relation to the development of social networks between different communities in an archaeological context are quite abstract and can be studied through the formation of hypotheses and their testing. Modeling technologies are indeed an important framework within which new theories and methodologies can be established for researching such issues (Polla and Verhagen, 2014, p. 1-2). With computational techniques, we can adjust research by setting and experimenting with numerous parameters, testing different results, and exploring how well they could predict reality (Polla and Verhagen, 2014, p. 1-2).

A notable point is that the effort of replicating and modeling path networks should not be used for reconstructing them, but instead to explore speculated networks that either still exist or we know of their existence (Polla and Verhagen, 2014, p. 2). Computational methods are nothing more than tools to test these hypotheses, and that is their key characteristic. The thesis's theoretical and methodological frameworks are designed based on these notions.

3.3 Least-Cost Paths: Literature Review

3.3.1 On Least Cost Paths (LCP)

Least Cost Paths (LCPs) have been established as a commonly used method for modeling path networks in GIS-oriented archaeology. LCPs are based on the concept of the Principle of Least Effort. They are a part of predictive modeling applications, used to investigate path networks and identify possible locations of archaeological settlements (Herzog, 2013, p. 1). This technology is beneficial for exploring possible scenarios of paths between sites, and for examining the differences and similarities between a generated network and an existing, recorded, or hypothesized one (Herzog, 2021, p. 132). Their main utility is their ability to model movement across landscapes and form hypotheses regarding possible networks (Carroll and Carroll, 2022, p. 36; Surface-Evans & White, 2012, p. 1).

LCPs follow the minimum cost of moving from one location to another, on top of a cost surface (Conolly & Lake, 2006, p. 252). The main concept behind the theory of LCPs is the belief that people prefer to economically coordinate their behavior in their daily activities (Surface-Evans & White, 2012, p. 2). The optimization of the cost needed to traverse an area is a motivational factor that is taken into consideration by individuals (Herzog, 2013, p. 1-2). The importance of LCPs is not apparent only in archaeology. These algorithms can be beneficial for environmental, urban, infrastructural planning, and military purposes (Herzog, 2013, p. 1; e.g. Lebeck et al., 2014). Generally, LCPs can be useful for either small or large-scale studies, however, they are not appropriate for studying one-time journeys, as the selection of optimal paths is not a main parameter for this instance (Herzog, 2013, p. 2; Lewis, 2017; p. 3).

The appearance of LCP analysis for archaeological purposes dates back to the 1980s with a study by Ericsson and Goldstein, however, it was after a decade that this form of analysis took its basic form in a study by Gaffney and Stancic (1991) (Schild, 2016, p. 4-5). The decade of the 1990s was significant for the study of movement and pathways. Reconstruction of networks using GIS started taking place during this period (Verhagen et al., 2019, p. 225; e.g. Van Leussen, 1993; Verhagen et al., 1995).

An important problem with the use of LCPs is their extensive use by scholars that do not aim to understand how the algorithms and the different parameters that affect modeling interact, and they are just focusing on the produced results of the tools of the GIS. According to Kantner (2012), the ready-made packages provided by GIS undermine the true potential of LCP algorithms. These systems operate like a black box, concealing the essentials of their operation background processes (Carroll and Carroll, 2022; p. 36). Archaeologists belong to this category of scholars (Herzog, 2014b, p. 237).

One thing that needs to be considered is the quality of the LCP analysis results. People do not always choose the path of least energy expenditure, as the LCP algorithms generate, but various conditions affect decision-making (Verhagen et al., 2019, p. 221-222). Understanding the process that LCP analysis operates is crucial if we as researchers aim to produce better interpretations that can be more realistic (Herzog and Posluschny, 2011, p. 236-237).

3.3.2 On the creation of LCPs

In general, five components are needed when conducting a cost-path analysis (Fig. 2) (Kantner, 2012, p. 225). The first and most foundational component is a 3-D raster surface that represents real-world topography. A set of vector objects indicating the points of the analysis is also required. Additionally, a cost surface is necessary for implementing the path-finding algorithm. Finally, statistical analysis of the results is needed (Kantner, 2012, p. 225).

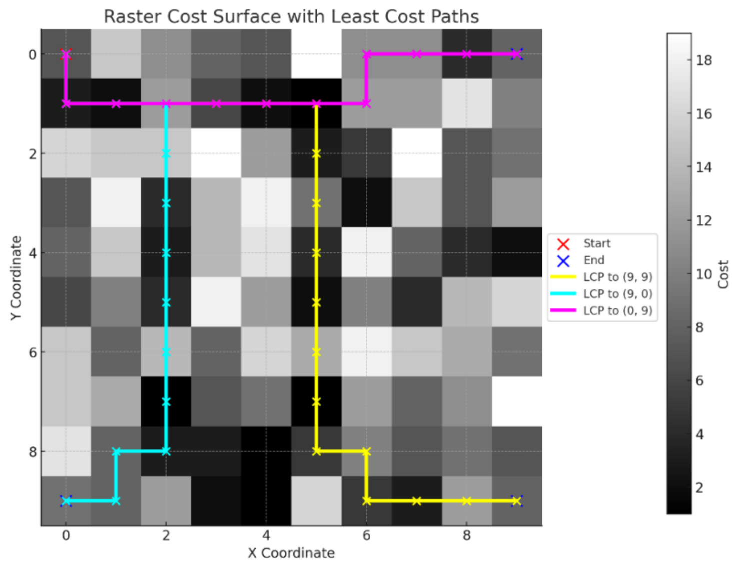


Figure 2 Example of Least Cost Paths. From a single starting point to three different end-points (Figure by Theo Andreopoulos)

Component 1: DEM

Environmental data, particularly topography, are crucial for calculating LCPs. Digital Elevation Models (DEMs) are essential for examining topographical features and variations (Bell et al., 2002). DEMs (Fig. 3) serve as the primary data source for LCP studies due to their role in slope calculation, a key parameter in LCP modeling (Lewis, 2021, p. 912; Herzog, 2021, p. 132). DEM raster data is the primary type of data used in archaeological studies exploiting LCP modeling (Herzog & Yepez, 2015, p. 1). However, the quality of DEMs and their preprocessing are often overlooked (Herzog & Yepez, 2015, p. 2-4; Herzog, 2014a, s. 5.1.1; Herzog, 2021, p. 133; Herzog, 2022, p. 132). Herzog and Posluschny (2011) suggest a 15 cm elevation point separation for accuracy, but such high-resolution DEMs are rare and computationally expensive. According to Kantner (2012), DEMs with over 30-meter resolution are too coarse, leading to inaccurate results, though they reduce computational time. Resolution remains a critical factor for effective LCP analysis (Verhagen et al., 2019, p. 227).

Researchers have also proposed that a lower definition DEM can produce results that match the actual perception of the landscape by humans, however, this subject has not been thoroughly explored (Lewis, 2017, p. 72). Experiments with different resolutions have been conducted in many case studies and sometimes the results heavily differ between different resolutions. Modifications of a DEM are being applied to try and create a version of the landscape that matches its ancient structure. However, the past form of a landscape is hard to reconstruct (Herzog, 2014a, s. 5.1.1). DEMs provide a perspective of topography based on the modern landscape (Verhagen et al., 2019, p. 227).

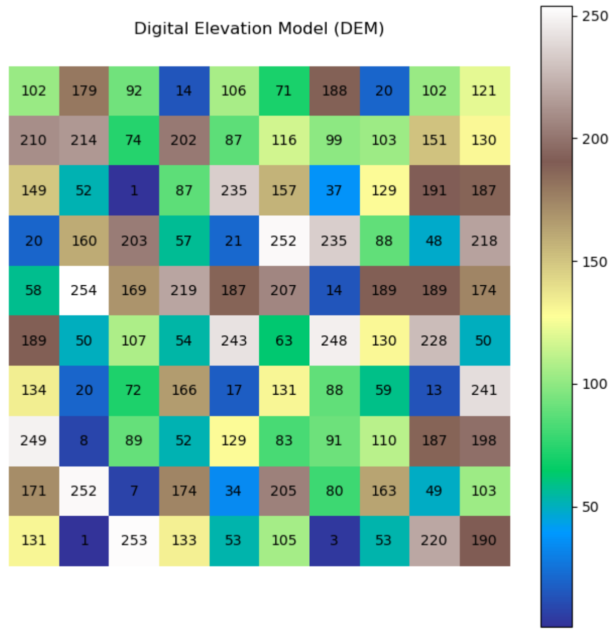


Figure 3 Example of a simple DEM dataset (Figure by Theo Andreopoulos)

Component 2: Cost Surface

When generating LCPs two necessary categories of data need to be taken into consideration; cultural and natural (Surface-Evans & White, 2012, p. 5). The first is the data relating to cultural conditions. Cultural features could be the territorial limits of sites, or sites with a ritualistic character (Herzog, 2013, p. 6-7). Another cultural feature is visibility (Herzog, 2013, p. 7). For example, urban roads are often built based on their visual properties (Lee and Stucky, 1993, p. 904). Lee and Stucky (1993) differentiate between different types of paths based on their visual properties, making distinctions between strategically hidden paths and scenic ones with high visual properties. Cultural data are harder to acquire in an archaeological context, considering the availability of relevant data (Herzog, 2014a, s. 5.7). Studies using visibility to understand movement are quite common (e.g. Turchetto & Salemi, 2017; Lock et. al, 2014; Murietta-Flores, 2014; Zakšek et al., 2007)

On the other hand, natural data include any type of environmental data, which is also easier to obtain compared to cultural ones. These include topographical features, such as slope, elevation, energy expenditure, hydrology, etc. (Lewis, 2017, p. 5-8). Natural data are easier to be converted numerically and be utilized for the creation of cost surfaces. The most commonly used however is slope (Herzog, 2014a, s. 5.1; Herzog & Yepez, 2015, p. 1).

A combination of cultural and natural data is an important step for LCP analysis. Llobera was one of the first researchers to incorporate both landscape and cultural features as the main cost parameters for the modeling of paths (Lock et al., 2014, p. 23). However, due to the nature of archaeology and the lack of data, the main socio-cultural factor that is taken into account in the creation of LCPs are costs that relate to visibility issues (Lock et al., 2014). According to Bevan (2011), the incorporation of a variety of factors might be suitable for creating more realistic scenarios, but they enhance the complexity of the model, thus leading to a loss of explanatory potential. Simple models that can be compared to the archaeological record are better and easier to provide some basic results that can be quite close to reality (Bevan, 2011, p. 3). Kantner (2012) argues with this statement and suggests complex models that integrate a variety of data suggesting that they are more realistic. For this thesis, Bevan’s approach will be applied. A slope-based cost surface will be utilized, considering that slope is an important parameter for movement in the mountainous terrain of Crete. Then, the results will be assessed based on the archaeological record of the area of focus.

An important thing to note is that most studies of movement, mainly focus on the natural parameters of the environment. As mentioned before, the physicality of the human body is also influential. A large majority of research focuses on healthy individuals of average height. However, that is not always the case. Besides that, movement speed is also important to consider as well as the energy expenditure of an individual when walking on a terrain (Verhagen et al., 2019, p. 225). These data are utilized for the creation and calculation of the Cost Surfaces, on top of which the LCP algorithm will operate to identify optimal paths. A variety of Cost Surfaces can be created based on most of the data that were presented before. The most commonly used natural parameter is the slope of the terrain.

For the computation of slope, many algorithms exist. Slope algorithms used to not be discussed in archaeological papers, however, in recent years they have drawn the interest of scholars. Each of these algorithms can produce different results. To compute the cost of slope the means and direction of movement need to be considered. The slope is commonly calculated based on the mathematical equation of “rise over run”. “Rise over Run” means that Slope equals the change between two points in a vertical direction divided by the change of these points in a horizontal direction (Lewis, 2017, p. 8). In GIS slope is calculated based on the average value of slope in a grid cell, with its 8 surrounding cells in each direction (Verhagen et al., 2019, p. 227). It also needs to be noted that each software can produce different slope maps from the same DEM due to the computation process of each method. Zakšek et al. (2007) discuss the importance of considering slope direction in path modeling. They propose recalculating the slope value based on the approximate direction of movement, differentiating the energy cost of moving up or down a slope.

$$Rise\ over\ Run:\ m\ = \frac{y2\ -\ y1}{x2\ -\ x1}$$

m: $slope$
$x1, y1$: $coordinates\ of\ the\ 1st\ point$
$x2, y2$: $coordinates\ of\ the\ 2nd\ point$
X: $Horizontal\ Distance\ along\ the\ ground$
Y: $Elevation\ or\ height\ at\ a\ point$

Once the necessary data such as slope are computed, then a cost function is needed to create a cost surface (Lewis, 2017, p. 4). There are different cost functions used that are based on slope. The cost function is the most important parameter influencing the resulting cost surface and eventually the produced path (Herzog, 2010, p. 375; Kantner, 2012, p. 226). There is a large variety of available cost functions, but the problem is that there has been no significant effort to inspect which one can better model human movement (Herzog, 2010, p. 375-376). They can be related to a variety of possible costs of traversing a terrain, such as slope, soil, vegetation, or waterbodies (Herzog, 2020, p. 2). Nevertheless, a main issue for pedestrian movement is the accurate estimation of travel time. Walking on foot is a complicated process that is affected by a variety of parameters that relate both to the landscape and an individual's characteristics, such as age, physical condition, gender, etc. (Marquez-Perez et al, 2017, p. 54). However, these traits are difficult to model.

The list of cost functions is quite big, but the most common one is the Hiking function proposed by Waldo Tobler, which is based on empirical data provided by research that was executed by Eduard Imhof (1950) (Herzog, 2010, p. 376). Tobler's hiking function calculates the speed of a walker/hiker based on slope, thereby determining the time needed to cross a terrain. Tobler's function considers slope as a percentage (Tobler, 1993). Functions based on energy expenditure also exist like the one developed by Llobera and Sluckin in 2007 and by Minetti on 2002, based on research on energy costs and human metabolism (Herzog, 2010, p. 378).

There are two categories of cost functions, Isotropic and Anisotropic. Isotropic costs are independent of direction and they include water bodies, soil and vegetation cover, landscapes and sites of different characters, visibility, etc. (Herzog, 2010, p. 376). Anisotropic costs are natural parameters such as slope which are affected by the orientation of mobility (Herzog, 2010, p. 376). An example would be the different cost values between walking a slope upwards or downwards.

Tobler's function is the most frequently used cost function for archaeological studies (Herzog, 2010, p. 376). The specific function assesses the time that is needed to traverse a surface by taking into account the direction of the slope (Marquez-Perez et al., 2017, p. 57). This function is based on empirical data, but Herzog (2010) notes that despite it not being based on scientific data, its results are quite fair when used for LCP calculation (e.g. Verhagen & Jeneson, 2012). Tobler's function was proposed for archaeological purposes in the 1990s (Gorenflo & Gale, 1990).

$$V(S) = 6 * e^{-3.5 * |S + 0.05|}$$

V: $Velocity\ of\ walking\ in\ km/h$
S: $Slope\ of\ the\ terrain\ as\ a\ percentage$
e: $Base\ of\ the\ natural\ logarithm\ (approximately\ 2.718)$

Formula to calculate velocity of walking

S is the slope, calculated as the ratio of vertical to horizontal change, and is expressed as a percentage (Vertical change/Horizontal). The function is based on a diagram created by Imhof, that visualizes hiking time based on gradients and map distances (Herzog, 2010, p. 376). Nevertheless, the collection of contemporary empirical data is an issue that needs further exploration (Kantner, 2012, p. 234).

A newer approach to cost functions is the one proposed in the research by Marquez-Perez et al. (2017). This new approach suggests the combination of the MIDE (Método de Información de Excursiones: Excursion Information Method) method (París Roche, 2002) function, which computes an individual's walking hours carrying a modest cargo with them, with the Tobler's Hiking function (Lewis, 2017, p. 11-12). The results of this function seem to be better than previous approaches (Lewis, 2017, p. 11-12). This Modified Hiking function belongs to the anisotropic ones as the simple Tobler's (Kantner, 2012, p. 234) and it is further explained in the *Methodology* Chapter.

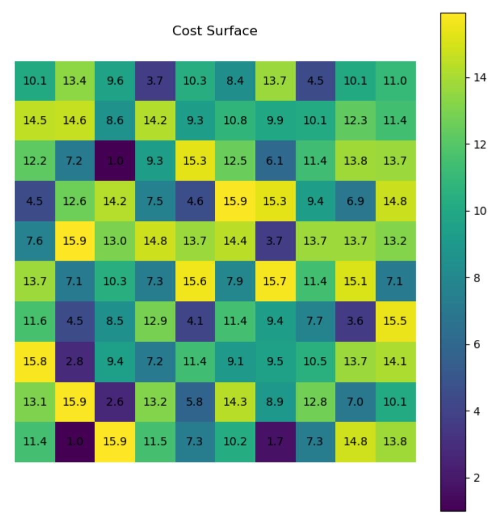


Figure 4 Example of a Cost Surface derived simple DEM of Figure 3 (Figure by Theo Andreopoulos)

Once the cost for each cell has been calculated based on the researcher's desired parameters, they are combined to create the cost surface (Fig. 4). This surface typically involves the numerical representation of how hard it is to cross each cell in the resulting raster grid. On top of this surface, the spreading algorithm operates (Lewis, 2017, p. 4). Then, a spreading algorithm is used, most commonly Dijkstra's algorithm, that computes the sum of cost from the selected origin point to all other cells of the cost surface. Once this is executed the path-finding algorithm can trace the past of least cost (Lewis, 2017, p. 12).

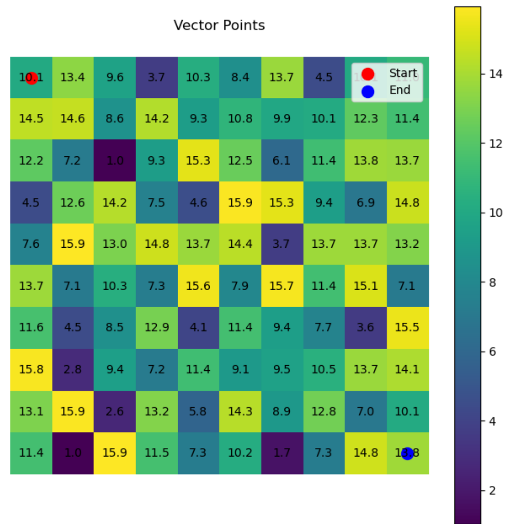


Figure 5 Vector Points on top of the Cost Surface (Figure by Theo Andreopoulos)

Component 3: Vector-Points

The third component that is required is a list of vector points (Fig. 5) that represent the geospatial location of the sites that will be used for the computation of the paths. Usually, this type of data consists of geographical coordinates. The importance of the way-points lies in the fact that they can dictate the trajectory of the path-finding algorithm.

Component 4: Path Finding Algorithm

Path-finding algorithms in Geoinformatics systems are based on the research conducted by Dijkstra and other computer scientists such as Robert Floyd and Stephen Wharshall, that tried to explore the shortest paths between multiple unevenly-spaced nodes on a graph environment (Madkour et al., 2017; Verhagen et al., 2019, p. 230). However, the case of an actual landscape that is represented digitally as a grid is a special case considering that all nodes are evenly spaced in a natural environment (Verhagen et al., 2019, p. 230). A variety of LCP algorithms exist with Dijkstra's algorithm and the A* algorithm being the most commonly used (Herzog, 2013, p. 8; Herzog 2014a, s. 3.3). The results of the cost-path analysis are heavily dependent on the algorithm that is used (Kantner, 2012, p. 234; Mlekuž, 2014, p. 9).

The most commonly used LCP algorithm in archaeological studies has been the one developed by Dijkstra (Herzog & Posluschny, 2011, p. 237; Verhagen et al., 2019, p. 230). Dijkstra's algorithm has been available as a tool in GIS ever since the 2000s (Herzog & Posluschny, 2011, p. 237). Variations of LCP algorithms based on Dijkstra's can be found in most GIS systems (Kantner, 2012, p. 227; Verhagen & Jeneson, 2012, p. 127).

Cost of traveling and walking needs to include positive values which are an important parameter for running the LCP algorithm (Fig. 6). Dijkstra's algorithm (1959) is an algorithm that is based on finding the shortest path on a graph environment and needs weights of a positive value so that the path between point A and point B can be computed (Herzog & Posluschny, 2011, p. 237). The algorithm operates on a cost surface following the same principle as on a graph (Tang & Dou, 2023, p. 1-2). Thus, the cost function used must be able to provide positive values.

Dijkstra's algorithm can operate only when there is a known value for the cost of a subpath (Herzog and Posluschny, 2011, p. 237). The specific algorithm has as a main requirement the existence of only positive cost values. The cost of a path is computed based on the total cost of the subpaths (Herzog and Posluschny, 2011, p. 237). One raster cell is connected with its neighboring cells, and in the end the data are converted to the vector format. The number of neighboring cells is significant for the LCP computation. The more neighboring cells, the smaller the error rate of the LCP, thus it can match better with the scenario of the optimal path (Herzog and Posluschny, 2011, p. 237). These neighboring cells also indicate the direction the path will follow. These differences rely on the selection of neighboring cells. Although a recommended range of 16 to 24 cells is considered optimal for producing accurate results while remaining computationally efficient (Lewis, 2017, p. 14, p. 76), most available software provides an option of either 4 or 8 cells. An exception is the algorithm developed by Herzog (2020) that considers 48 neighboring cells. In my research, using 8 cells was justified as it struck a balance between computational feasibility and achieving satisfactory accuracy.

Paths and their networks often result after a long time of occurring activities on a landscape (Verhagen et al., 2019, p. 219). The process of least-cost path analysis is similar to this phenomenon. The algorithms develop the path step by step and at the end, they produce an optimal, suggested path. Researchers are often neglecting the different parameters between the various path-finding algorithms and they simply focus on using the ready-made tools provided by a GIS (Herzog, 2010). It needs to be noted that each software presents differences between the available algorithms they provide meaning that results as well as background processes might differ on different platforms (Herzog and Posluschny, 2011, p. 237).

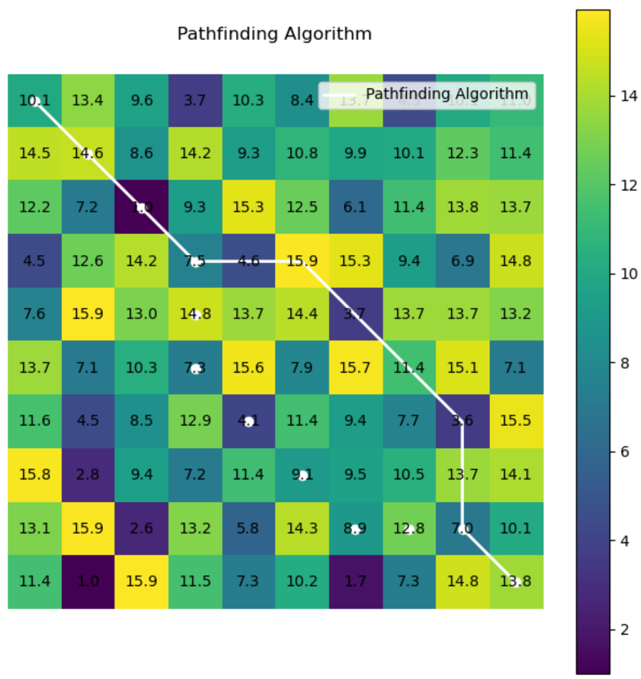


Figure 6 Example of the Path-Finding Algorithm's Operation (Figure by Theo Andreopoulos)

Component 5: Statistical analysis and validation of the results

As is true for most predictive modeling applications, the final result (Fig. 7) needs to be validated, and not simply accept the output provided by the machine (Lewis, 2017, p. 14). Vermeulen (2006) notes that the majority of archaeological predictive models do not take into consideration the examination and validation of the results produced. Due to the exploratory nature of LCP analysis, validation of the results is a practice that needs to be considered (Herzog, 2014). Even a simple visual inspection and a comparison with the archaeological record or historical data and maps can be a starting point for checking the quality of the results (Herzog, 2014; Herzog, 2012). It needs to be noted that the best way to identify ancient roads is through fieldwork, but LCP analysis can provide a general view of possible route scenarios (Ejstrud, 2005). For this thesis, the produced LCPs will be compared to a hypothesized path network of the study area from older research, as well as to their proximity to identified archaeological sites. Personal visits to the area will also be exploited for the evaluation of the produced results. The key point is that the results of the Python-based methodology will be compared to the QGIS-produced ones to explore their validity.

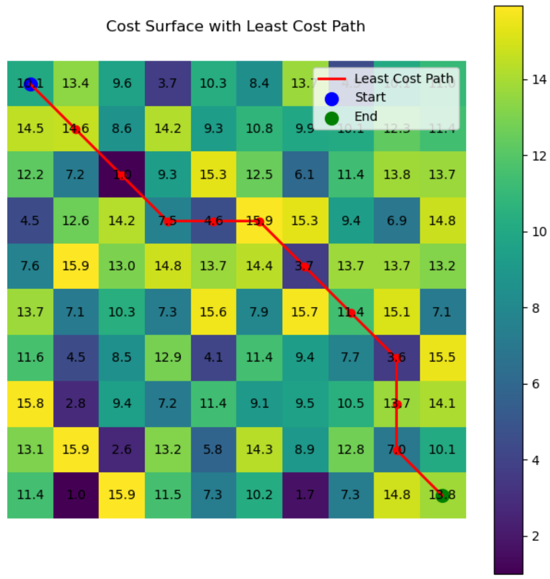


Figure 7 Final Result with the LCP overlayed on the Cost Surface (Figure by Theo Andreopoulos)

3.4 A Brief History of GIS and path-modeling in Crete

There is a large body of research focusing on the use of least-cost paths (LCPs) and Cost Surface Analysis (CSA) for modeling paths and landscape movement in archaeology. Mentioning all of them would be a difficult task. However, it is important to note that, as is the case for Crete, LCPs are a good approach for studying movement in mountainous terrains, such as the study area. Examples of the use of these techniques can be found across different locations from all over the world (e.g., Lewis, 2017; Kantner, 2012) and especially in the Mediterranean context (e.g., Mascarello, 2023; Ejstrud, 2005; Bevan, 2003; Bevan, 2011a). Some of them have already been mentioned in the previous section. This subsection aims to cover the research on ancient Cretan paths from a methodological perspective. General interest in the specific subject is provided in the *Archaeological Background* chapter.

The use of these modeling techniques has been exploited for different research purposes in Cretan archaeology. However, they are most often employed for the study of the Minoan period, which has drawn the majority of academic interest. The primary focus is to study the connectivity and relationships between sites and settlements in nearby locations across the island's surface, as well as the role of important socio-cultural centers and their influence (Paliou & Bevan, 2017, p. 268). Understanding the island's urban development and its connection to the surrounding landscape is a common issue (Megarry, 2012, p. 39).

In most studies where these methodologies are exploited, they are used in combination with other techniques, such as remote sensing and visibility analysis (e.g. Siart et al., 2008; Siart & Eitel, 2008; Bitsakaki, 2020). In these examples, CSA and LCP analysis are used to complement other methodologies to study connectivity between settlements and sites of different types, such as the Minoan peak sanctuaries or harbor installations and their relationships to palaces and settlements. Most of these studies focus on south-central/west-central Crete and central Crete and follow the general pattern of focus on the Minoan period of the island. Aspects of territorial expansion and control are also studied through the use of cost surfaces and least cost paths (e.g., Bevan, 2011; Bevan, 2010; Drillat, 2022). Historical documents of journeys, such as the ones recorded by John Pendlebury (1939) on the Cretan landscape have also been used for comparing them to applications of LCPs (e.g. Bevan, 2011; 2013)

The study by Drillat (2022) is exceptional as it studies a city-state of the Classical era, the city of Lato, and its surrounding landscape and territorial expansion. Another study that focuses beyond the Minoan era is the thesis by Pollard (2022), which focuses on connectivity and movement between settlements and funerary landscapes in the Late Bronze Age (LBA) and Early Archaic periods of the island. The focus on sites of funerary character is a common phenomenon, often combining LCP analysis with issues of visibility (e.g., Déderix, 2015; 2017). The use of these techniques for site catchment and predictive modeling purposes is also observed (e.g., Fernandes et al., 2012; Drillat, 2022). Studies on older periods also exist, such as the Final Neolithic (FN) period, for understanding settlement patterns in the Sitia region (e.g., Tomkins et al., 2004).

Most of the mentioned studies use the LCP methodology to complement other approaches, often employing GIS software to conduct the analysis. The methodological aspect is typically not elaborated upon, with the main discussion focusing on the results generated by the software. In contrast, this thesis emphasizes the computational processes of the methodology and their archaeological relevance.

4. Archaeological Background

4.1 On the chronological, geographical, and social context of EIA Crete:

The archaeological background of this thesis stems from a keen academic interest in the archaeology of Crete. The Mediterranean island has captivated scholars worldwide for its Bronze Age period. Recently, there has been a growing interest in the less studied but equally important periods of its history. While the island's significance during the Bronze Age is well-documented, Crete continued to be a cultural center through the Classical period and beyond.

Age	Period	Ceramic Phase		Years BCE
Bronze Age	Neopalatial	Middle Minoan (MM) III	MM III	1750-1670
		Late Minoan (LM) I	LM IA	1670-1550
			LM IB	1550-1460
	Final Palatial	LM II	LM II	1460-1410
		LM IIIA	LM IIIA1	1410-1350
			LM IIIA2	1350-1310
	Post-Palatial	LM IIIB	LM IIIB	1310-1190
		LM IIIC	LM IIIC	1190-1070/970
Iron Age			(Subminoan (SM))	(1070-970)
	Early Iron Age/ Dark Age	Protogeometric (PG)	Early Protogeometric (EPG)	970-920
			Middle Protogeometric (MPG)	920-875
			Late Protogeometric (LPG)	875-840
			Protogeometric B (PGB)	840-810
		Geometric (G)	Early Geometric (EG)	810-790
			Middle Geometric (MG)	790-745
			Late Geometric (LG)	745-710
		Protoarchaic (PA) (Orientalising (O))	Early Protoarchaic (EPA)	710-670
	Classical Greece		Late Protoarchaic (EPA)	670-600
		Archaic (A)	A	600-480
		Classical (CL)	CL	480-323

Figure 8 Table with the chronology from LBA to Classical Crete with pottery phases, dates and abbreviations used in the text (Pollard, 2022, Table 1.1, p. 19).

A period that has been drawing the interest of academics in recent times is the transition from the Minoan Era to the Iron Age (For an explanation of the chronologies and their abbreviations used in the text see Fig. 8). The development of the city-states that set their foundations during the Geometric and Archaic eras and later flourished during the Classical period and afterward, remains a mystery and only in the last two decades did archaeologists start focusing on this period more thoroughly (Kotsonas, 2009; Kotsonas, 2022; Wallace, 2010; Prent, 2014). References to the Early Iron Age (EIA) have been fragmentary since the 1960s. However, it wasn't until the late 1990s that researchers began to focus on understanding the island's history during this period. Despite this increased interest, the material available to them remained limited (Nowicki, 2002, p. 150). An important question for the specific era is how the sociopolitical changes that affected almost all of the Mediterranean cultures during the end of the Late Bronze Age (LBA) affected the island of Crete.

Crete was one of the most affected areas by the Orientalization, while it kept having contact with South-West Asia before, during, and after the collapse of the palace centers of the LBA (Prent, 2014, p. 651; Pollard, 2022, p. 22). During the shift from LBA to EIA period in Crete, international trade kept on going. The relations of the island with other cultures in the Mediterranean have been foundational for the ongoing interest in the EIA period (Kotsonas, 2009; Kotsonas, 2022, p. 135)

Imported goods can still be found in many archaeological sites from the transitional period after the 12th century BCE both in the island, as well as other Mediterranean areas (Kotsonas, 2022, p. 135). Based on Wallace's claims (2007), one can suggest most of these imported products were found in Crete in gateway or coastal sites. Peoples of the period would have traveled from the citadel-centers located on the mountains to the lower sites for trading and other purposes (Wallace, 2007, p. 6).

Crete is notable for its mountainous landscape (Megarry, 2012, p. 79), a typical characteristic of almost all Mediterranean islands (Mannion & Vogiatzakis, 2007). The island, surrounded by the sea, was partially isolated, developing distinct social structures within its boundaries (Nowicki, 2000, p. 19). The connection between the sea and the mountains has been significant in Crete's history (Pollard, 2022, p. 77). Mountains are the most important topographical features in the Cretan landscape, playing a vital role in shaping the island's culture and defining the means for moving across its surface (Nowicki, 2000, p. 22; Nowicki, 2022, p. 491-492; Pollard, 2022, p. 84). The most important mountain ranges (Fig. 9) are the White Mountains (Lefka Ori) on the west, the Psiloritis mountain (Mount Ida) on the central part, the

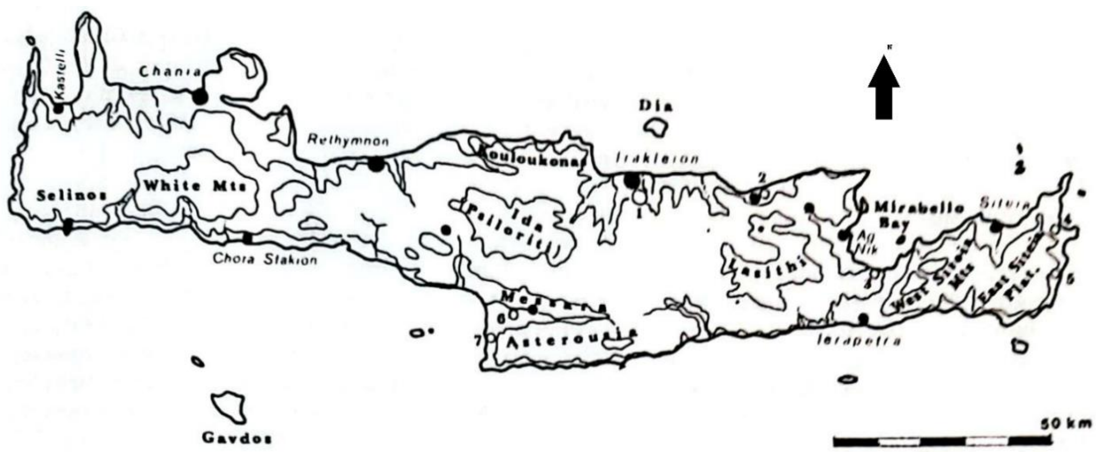


Figure 9 Map of Crete with the important Mountain ranges, Plateaus and Cities of the island (Nowicki, 2000, fig. 2, p. 23).

Asterousia mountains on the North, the Dikte mountains on the central-east part, surrounding the Lasithi plateau and the Siteian mountains on the east (Nowicki, 2000, p. 24). Elevations on the island exceed 2000 meters (Fig. 10) (Mannion & Vogiatzakis, 2007, p. 27)

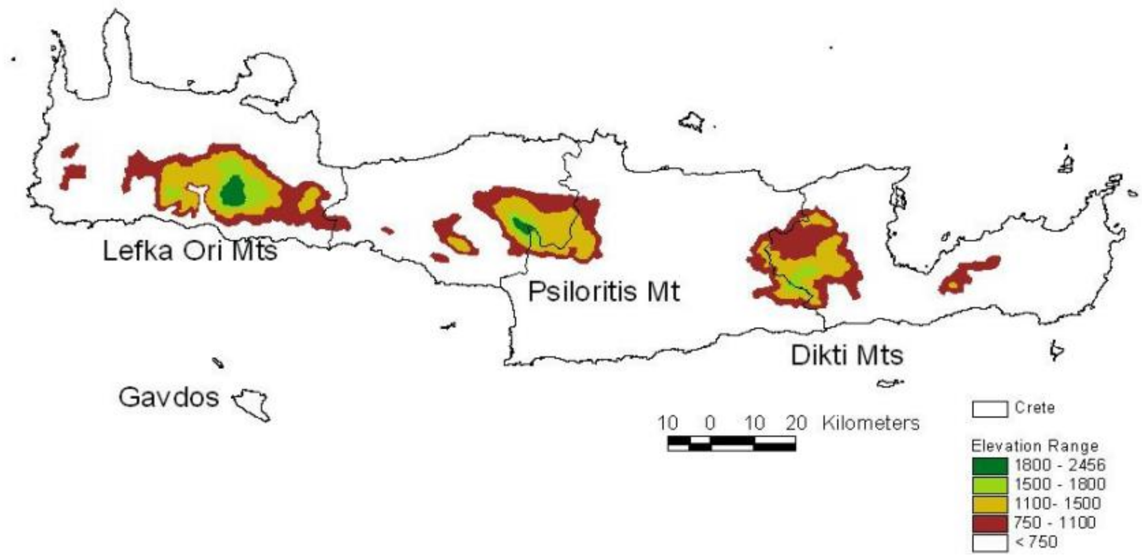


Figure 10 Elevation Ranges of Crete. Copyright retained by I N Vogiatzakis. (Mannion & Vogiatzakis, 2007, fig. 6)

Natural parameters, including water resources and vegetation, influenced settlement establishment on the island (Nowicki, 2000, p. 24). The island's diverse flora, including pine, oak, carob, and cypress trees, likely played a crucial role for settlers in mountainous areas during the island's history. However, deforestation has significantly impacted Crete's landscape over time. The varied vegetation may have contributed to defense and protection strategies for settlements and territories (Nowicki, 2000, p. 25). Regarding the climate of the island, it is characterized as the typical Mediterranean climate, with mild rain periods during the winter and warm and dry summer periods (Mannion & Vogiatzakis, 2007, p. 26). Nevertheless, environmental issues are not the only parameter to consider when trying to understand the development of a civilization. Other issues also exist such as territorial boundaries, and general conflicts between communities, things that play an important role in how humans interact with their surrounding space (Nowicki, 2000, p. 23)

A lot of archaeologists have been referring to the period between the Bronze Age and the EIA as the Dark Age, due to the missing knowledge and visibility in the historical and archaeological record (The term has been refuted by modern scholars, however, it is used with the purpose to address the period under study) (Nowicki, 2000, p. 15). Material evidence testifies the intense socio-political changes of the period across Mediterranean cultures and the same applies for Crete (Kotsonas, 2009, p. 1051). The term EIA refers to the early Geometric (G) period also known as the Protogeometric (PG) period. Other terms have been provided, such as Post-Minoan or Doric, but they have been refuted (Kotsonas, 2022, p. 133).

Moreover, foreign threats appear (Nowicki, 2002, p. 155). The Dark Age period shows a lot of similarities with the Byzantine and Venetian eras when the island's locals were pushed to the inlands, so that foreign settlers, who occupied the coastal areas by force, could control the fertile lands for agricultural purposes. Dark Age sites are often located close to villages that appeared during the Byzantine and Venetian periods (Nowicki, 2000; p. 16). These factors are foundational for the changes that the island went through during this period.

The issue of ritual and cult practices is important for the study of EIA Crete. New cult practices appear during the 1st Millennium B.C.. However, the Minoan past is not abandoned (D'Agata, 2006, p. 399). Minoan sacred places and settlements are embodied in the memory of the Cretans. Their meaning is different but their role is still part of the new cultural changes happening on the island (Prent, 2014, p. 651). Cult spaces of the Minoan period, such as caves have remained in use for the majority of Crete's history (Wallace, 2003a, p. 260). One example is the cave of Psychro on the Dikte mountain (D'Agata, 2006, 402). The cave of Phaneromeni close to the villages of Avdou and Gonies is a similar example (Wallace, 2007, p. 262). The continuation of LBA traditions is apparent in the EIA Crete. New settlements appear, however, elements of the past in the landscape, continue to be in use during the EIA period (Prent, 2014, p. 653). Scholars propose continuity from the Late Minoan (LM) to the EIA in Crete, primarily seen as "spatial repurposing" (D'Agata, 2006, p. 406). This transition, starting from the LM-IIIC and Subminoan periods, is crucial for understanding how the Classical city-states expanded their influence and territories.

Understanding the evolution of ancient Greek city-states that played an important role during the Classical and Hellenistic periods of the island, especially during their early stages from the Geometric to the Archaic Period, presents various challenges due to the limited archaeological knowledge (Kotsonas, 2022, p. 134; Haggis, 2015, p. 220). These periods are quite under-studied compared to the Minoan, Classical, and Roman (Wallace, 2003b, p. 604). Material evidence from this period poses significant issues for reconstructing ancient cities' physical form and developmental trajectory. Despite being considered as materially poorer periods, the EIA and Archaic Periods have gained scholarly attention due to the complex nature of urbanization as a cultural process (Haggis, 2015, p. 220). Based on these obstacles, the understanding of the image of EIA Crete is a task hard to achieve. Until today the evidence is mostly limited to pottery assemblages. The sudden evolution of the poleis, and their form during the Classical period, led to an overwriting and neglect of their previous stages (Nowicki, 2002, p. 150).

New economic systems appear indicating the changes that had already been settled by the 8th Century BCE (Wallace, 2003a, p. 258). Haggis (2015) challenges Wallace's view on Cretan Poleis' formation, suggesting that urban development in the EIA was a gradual process driven by sociopolitical changes. He notes the emergence of identities and political powers as necessities, that had already been established and reached their final form in the 7th century B.C. While acknowledging urbanization during the PG and G periods, Haggis highlights their limited archaeological evidence (Haggis, 2015, p. 225-226).

4.2 On the formation of settlements in the Post-Minoan Era

During the twelfth century, new sites emerged in Crete through rapid procedures by its residents, who possessed extensive knowledge of the island's landscape and cultivation techniques (Nowicki, 2002). Most of these sites developed in the northern part of the island, which benefited from more favorable conditions for development compared to the south, owing to the presence of main plains and extensive coastal areas (Nowicki, 2000). A key characteristic of these sites was their familiarity with the surrounding landscape and pathways (Wallace, 2007, p. 252).

Settlement patterns in Crete shifted after 1200 B.C.E., with LM-IIIC sites declining and giving way to simple farming communities during the PG (Nowicki, 2000; Wallace, 2003b). By the 11th and 10th centuries, regional changes in settlement patterns prompted the need for individual case studies (Nowicki, 2000, p. 14-15). Surviving LM-IIIC settlements laid the foundation for later city-states (Nowicki, 2000, p. 14-15). The G period witnessed the rapid evolution of former rural settlements like Lyktos into large urban centers, suggesting significant population movements (Nowicki, 2002, p. 170). This transition was marked by a focus on strategic positioning for defense and exploiting the landscape, termed a "social revolution" by Nowicki (2002, p. 152). Especially in the PG, the defense was a primary need for settlements, thus strategic locations of the LM-IIIC period continued their development (Nowicki, 2000, p. 14-15). Society is influenced during this period by new and more complex social factors. The changes occurring in the PG set the base for the city-states that controlled the island's different areas during the Archaic period and afterward (Nowicki, 2002, p. 170).

According to Wallace (2003a), EIA Crete underwent two significant phases of change. The first, around 1200 BC, saw a shift from low-level settlements to elevated locations for natural defense. The second phase involved abandoning over half of LM-IIIC founded sites, with surviving settlements expanding and a few new ones appearing in the PG period (Wallace, 2003a, p. 256-257). These new settlements were strategically positioned to offer visual control of surrounding areas, often located on flat-topped hills with high visibility (Wallace, 2003a, p. 257). A shift is also noted regarding paths and routes, with settlements of the PG being located close to pathways offering better advantages for transportation (Wallace, 2003a, p. 257-258)

Prent (2014) discusses the radical shifts noted in the literature regarding the transitional period from LBA to EIA in Crete and the shift from coastal areas to the hinterlands to high, defensible, and highly visible locations. The dangers from the sea, due to the invasion of foreign settlers heavily influenced the population movements towards the inner and harder-to-access parts of the island, due to its geomorphology and topography (Borgna, 2003, p. 156; Nowicki, 2000, p. 15). The re-occupation of coastal areas is observed during the PG period (Nowicki, 2000, p. 17). In the PG and G, besides a return to the coast, areas of lower elevation are also starting to get occupied, in contrast to the situation and the settlements that developed in the LM-IIIC period (Nowicki, 2002, p. 169).

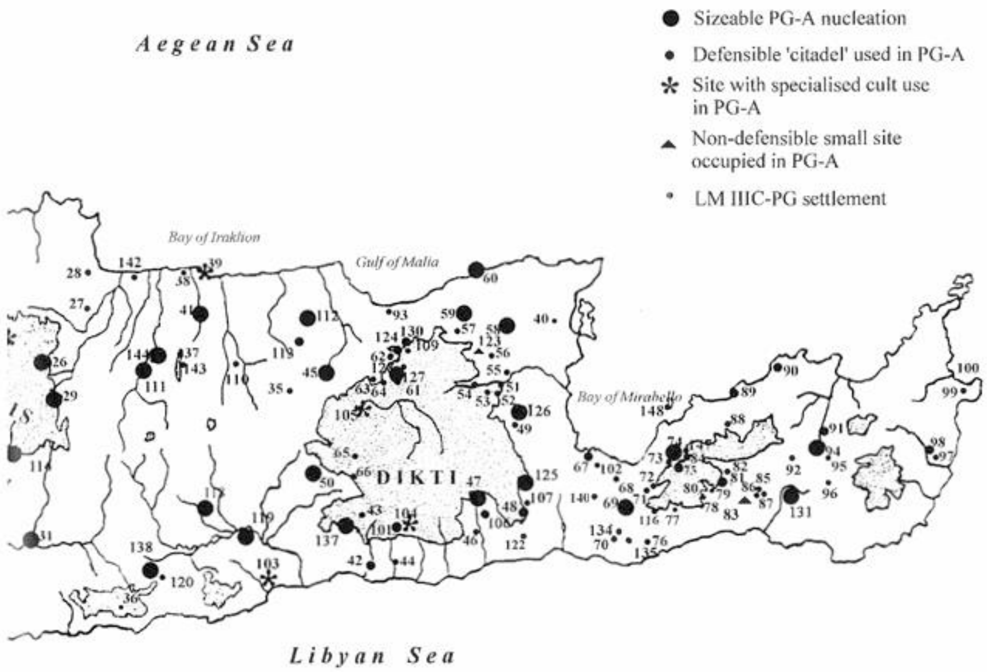
The hypothesis for the role of intervisibility in site formation during the EIA is easy to understand considering the need for locations that can be easily protected from “foreign” threats (Prent, 2014, p. 651). This hypothesis is foundational for the research questions that this thesis aims to explore. The establishment of sites located in relatively more accessible locations working as mediators for trade between the low and high-elevation sites, as suggested by Wallace (2007) is also important to consider in the identification of the path network and its analysis. These sites are not located randomly but in strategically significant areas visible from hilltop settlements, providing advantages for defense and control. The establishment of these sites signifies a shift in settlement patterns during the period, reflecting new needs for trade, defense, and communication, while their role was important for the sites up in the mountains. (Wallace, 2007, p. 263). An example would be the sites and settlements located in the Aposelemis valley, that can be directly seen from the settlements that lie on the surrounding mountain tops, such as Karfi. This network will be elaborated in the Study Area subsection.

The theory of nucleation in EIA Crete is not universally accepted, but evidence from sites like Lato, Dreros, and Kavousi suggests its presence (Wallace, 2003a, p. 262). These sites later developed into important city-states (Fig. 12), indicating a nucleation effect. Similarly, Papoura, located east of Lyktos, displays nucleated settlement patterns (Wallace, 2003a, p. 258). However, autonomous locations that did not nucleate, such as the Acropolis of Smari, Profitis Ilias, also existed. Founded during the Late Bronze Age, Smari continued to be occupied into the PG and Archaic periods, albeit reduced in size (Wallace, 2003a, p. 265). These sites disappeared during the Archaic Period, coinciding with the creation of Cretan poleis.

Regarding the continuity of existence of LM settlements, the abandoned LM-IIIC sites, which were located in highly visible locations, could be seen during the PG and G periods by the newly founded settlements. Probably, they were integrated in the social memory, and they had a role in the social perception of the surrounding landscapes (Wallace, 2003a, p. 274). They could also have been used as possible landmarks helpful for navigation across the mountainous terrains of the island.

LBA sites retained their significance in the social memory of Crete during the EIA, often repurposed for various functions, including cult practices. For instance, the acropolis of Smari, later hosting a temple dedicated to Athena during the Archaic period, exemplifies this trend (Wallace, 2003a; p. 265). The enduring role of ancient monuments, particularly Minoan remains, influenced urban development in the EIA, showcasing a continuity in their use and sacred significance (Prent, 2014, p. 654). These sanctuaries and ritual spaces, maintained over extended periods, significantly shaped the islanders' perception of their surroundings (Cucuzza, 2013, p. 31). However, an important question is how these old structures appeared during the later periods and how exactly they were perceived by the locals (Cucuzza, 2013, p. 33).

Wallace (2003a) states that the use of extra-settlement sanctuaries was a form of display by the PG and Geometric cities. The past of the landscape was recognized and older sites were used as places of cult and ritual. These sanctuaries helped showcase the political power and the expansion of the new settlements. The importance of these extra-urban sanctuaries is also noted by Chaniotis (2009). Sacred places of the Bronze Age were recognized and treated as important cultural elements up until the Classical period (Chaniotis, 2009).



109. Krasi Armi
110. Astritsi Kefala
111. Profitis Elias Rokka
112. Kalo Chorio Maza
113. Smari Profitis Elias
114. Kourtes Kefala
115. Orne Kastello
116. Ayios Ioannis Katalimata
117. Patsos Cave
118. Ligortinos Kefala
119. Kasteliana Kastello
120. Rotasi Korifi
121. Prasies Kastri
122. Anatoli Elliniki Korifi
123. Drasi Xeli
124. Kera Kastello
125. Kalamafka Kastello
126. Lato
127. Kera Papoura
128. Kera Vigla
129. Sellia Kastri
130. Krasi Kastello
131. Lithines Adromyloi Anginares
132. Lappa
133. Traxilos Selli
134. Vainia Charakas
135. Vainia sto Skouro
136. Aptera
137. Viannos Korakias
138. Rotasi Kefala
139 Idaian Cave
140. Ayia Triada
141. Gazi
142. Kommos
143. Archanes town
144. Profitis Elias Korifi
145. Elyros
146. Irtakina
147. Avgo Trapeza
148. Pseira town

Figure 11 List of Sites from LM-IIIC, PG and Archaic period from Central-East Crete. It shows the results of nucleation and includes sites that are mentioned in the text (Wallace, 2003a, fig. 2, p. 255)

The fact that the EIA sites are a continuation of LM-IIIC sites, or that they appear in similar regional contexts, shows a continuation in regional identity, that existed through the PG and Geometric period until the Archaic, while it was also heavily affected by the new social developments that evolved during these periods (Wallace, 2003a, p. 272). Wallace (2003) supports the theory that the newly founded settlements that evolved during the PG were formed due to the nucleation of LM-IIIC settlements in a short area (Fig. 11). Settlement patterns in the post-LM-IIIC Crete were subdued to many changes and it is a subject that has recently attracted the interest of scholars (Nowicki 2000; 2002)

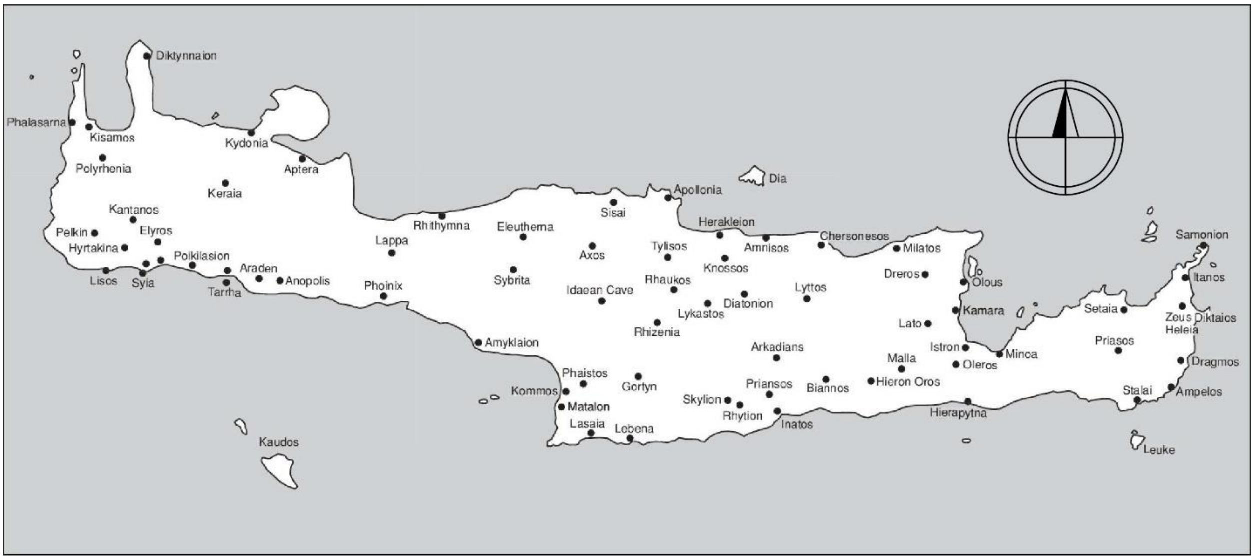


Figure 12 Classical and Hellenistic Cities of Crete with sites that are mentioned in the text (Chaniotis, 2005, Map 2, p. 10)

4.3 On the Paths of Crete

Since the early years of archaeological research on the island of Crete, one question that has always baffled scholars is the development and the structure of the road network of ancient Crete (e.g. Mavraki-Mpalanou, et. al, 2016; Tzedakis et al., 1989; 1990; 1989-1990; Beckmann 2012; 2019). The road system during the Minoan times, especially, has been the main concern of academics. The Minoan Roads project by Tzedakis (1989-1990) is an important example. Due to the island's topography, one must note that the road network in Crete is predefined. The steep slopes, and generally the area's mountainous landscape have played a significant role in the creation of transportation habits on the island.

With that in mind, it is easy to understand that the network of the Minoan roads must have remained the same for the largest part of the island's history, until the Roman period. Natural pathways existed even in Roman times, but the biggest impact of their abandonment was the creation of the modern road network. Sir Arthur Evans was the first to initiate the discussions for the Cretan road network, while he focused on trying to reconstruct the road that started from Knossos to the inland island (Mavraki-Mpalanou et al., 2016, p. 2). During his work on Crete, Evans discussed the possible scenario of a connected network expanding across the island with constructed roads that formed it. However, Evans' idea cannot be proved by the existing evidence (Nowicki, 2000, p. 23). Later, John Pendlebury (1939) studied the main road arteries passing from important sites of the island (Mavraki-Mpalanou et al., 2016, p. 2)

It is generally accepted that for the Minoan Civilization, the existence of a road network would be substantial as it would help improve the connectivity between palaces, settlements, and other types of sites, especially during the Neopalatial period. Top-down transportation infrastructure may have occurred only in the case of main roads connecting sites of high hierarchy, with little to no architectural evidence supporting their existence. Secondary routes must have only remained on the level of natural pathways across the landscape, connecting settlements with a variety of different sites (Nowicki, 2000, p. 24).

Despite the fall of the Minoan Civilization, the main structure of the communication network that developed during prehistoric times must have remained in use in the periods that followed. This can be testified especially when considering the mountainous terrain of Crete, where transportation routes were constrained by the natural landscape, but not completely nor in a way that negates this study. Traces of the Minoan paths (Fig. 13, 14) could be traced even during the time of Evans (Mavraki-Mpalanou et al., 2016, p. 2). People during the Dark Age did not change their residential locus, rather than moved to different locations that were used mostly by shepherds (Nowicki, 2000, p. 16). Thus, roads and paths were preserved by the newly-founded communities, while their condition must have depended on sociopolitical factors, such as the social power of a settlement or its territorial boundaries (Nowicki, 2000, p. 24).

Figure 13 Example of Minoan road with enclosure walls (Beckmann, 2019, fig. 12, p. 12)

Nowicki (2000) provides a hypothesized description of what roads in LBA and EIA Crete might have looked like based on ethnographic and historical studies. The first type is natural paths that are defined by the topography of the island, with no traces of engineering applied to their case. The second is the fully or partially paved tracks which were defined by natural routes, and which are known as Kalderimia (Fig. 15)(from the Turkish word "kaldırım"(Singular: Kalderimi= Cobbled Path) (Nowicki, 2000, p. 24-25). The term, which is of Ottoman origin, refers to the paths formed during the Ottoman period in Greece and especially in Crete (Baldwin Bowsky et al. 2006; Moudopoulos-Athanasiou & Sklavounos, 2022), but in the text, it is used more generally to describe similar paths. Such roads are a bit wider than the natural paths, and their role was to connect settlements of small size such as villages (Nowicki, 2000, p. 24-25).

The Kalderimia demanded some type of conservation due to the overgrowth of plants making it inaccessible (Nowicki, 2000, p. 24). The third type is well-paved roads, which are wider than the previous two categories. These three types of roads focus on pedestrian and not wheeled transportation. The difference between each road type is mainly focused on the engineering skill that is needed to develop them. During the period that is examined, the first two types would be more likely to exist, as newly founded communities, during such a transitional period, would not have been able to create roads that demand a lot of energy to build (Nowicki, 2000, p. 25). Actual evidence of transportation infrastructure can be observed mostly inside the settlements, with stone paved roads connecting the different buildings of a settlement (Mavraki-Mpalanou et al., 2016, p. 3). Landscape routes, which connected villages and towns, were usually natural paths with small efforts to provide a safer foundation for transportation (Mavraki-Mpalanou et al., 2016; p. 3).

Figure 14 Architectural plan of simple-paved Minoan Road (Tzedakis et al., 1989, fig. 2, p. 46)

Figure 15 Example of Kalderimi from the Aposelemis Valley area (Mavraki-Mpalanou et al., 2016, fig. 19, p. 15)

During the EIA the safety of the streets was an important parameter for the connectivity between settlements. As is known from inscriptions of the Classical period and afterward, such as the ones between Lyttos and Olous, the importance of protecting the routes belonging to a city-state's territory, as well as the passages that were intersecting between the territories of two cities, can be testified (Chaniotis, 1999, p. 201). Roads that connected different territorial entities were described as "Xenikai Odoi" which translates to "Routes of Aliens", meaning the people from other cities (Chaniotis, 1999, p. 201). Wallace notes that communication between different settlements and sites was easier to achieve during the EIA period in contrast to the LBA when relationships were fixed based on palatial territories, a situation similar to the one of the Classical Period with the Cretan Poleis.

In conclusion, all these suggest, that exploring the connectivity of settlements in a specific period can provide valuable information for the general structure of the road networks of the island for a larger chronological context. This thesis aims to understand the paths connecting sites in a specific period and a specific area, however, basic ideas could be applied to understand different chronological eras of the same area, while, also, helping to get a perspective on how paths might have developed in general on the island. This section aims to explore the theoretical interest in Cretan paths from an archaeological perspective. Examples of studies that focus on the computational study of this subject have been provided in the *Methodological Background* chapter.

4.4 Study Area

The primary objective of this thesis is to evaluate the potential of code-based geospatial analysis in producing results comparable to those obtained through traditional GIS software. This will be tested on a specific region of Crete to analyze the path network and connectivity between settlements, thereby gaining insight into the social network of the island during the EIA. A subsequent aim is to obtain an archaeological and phenomenological perspective on the paths and their significance for the area and the people.

To be more specific, the area of interest (Fig. 16) lies in the areas of the Minoa Pediada, the Northern Lasithi area, and the Aposelemis Valley, and reaches up to the northern coast of Hersonissos (see Appendix A for a detailed map with sites mentioned in the text). These areas used to belong in the territorial control of Lyktos (Fig. 18) during the Classical period and later, and the main goal is to explore their relationship during the EIA (Kotsonas, 2019, p. 434-435).

Archaeological inquiry into the area of Central Crete reveals urban development dating back to the Minoan era. During the Bronze Age, settlements were strategically situated on hills, while nowadays, contemporary villages have been established nearby. During the transition to the EIA, many ancient locations continued to be inhabited, while in other areas, people relocated to elevated terrains for better

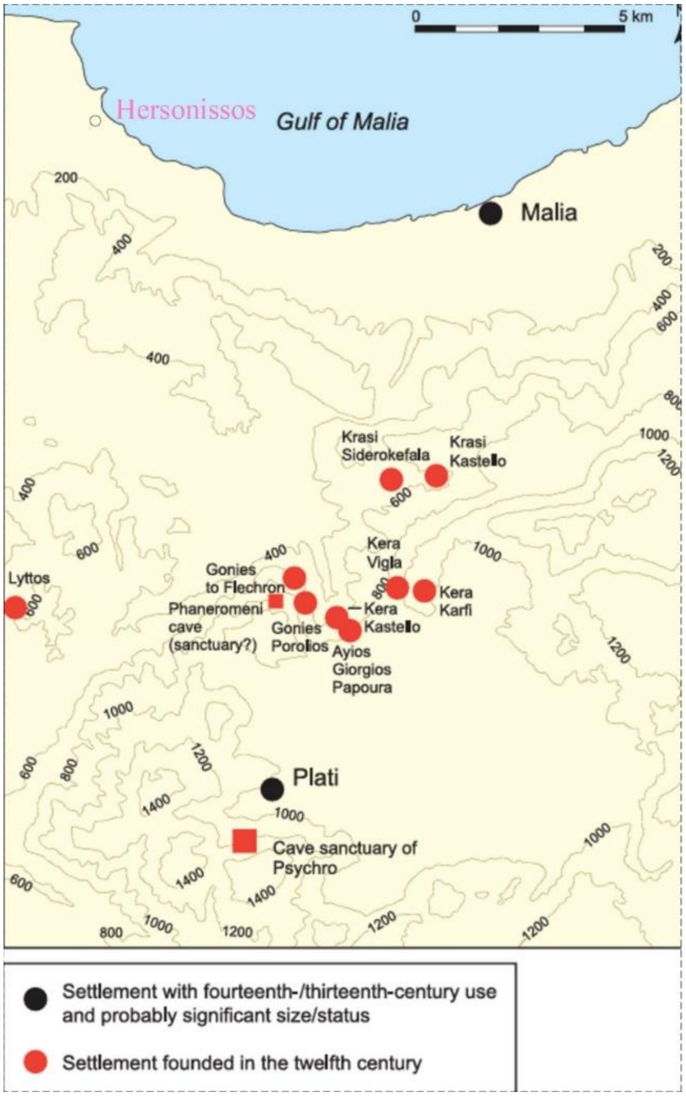


Figure 16 Study area with Late Minoan and EIA sites. Hersonissos is with different font as it is dated in later periods. (Wallace, 2007, fig. 10, p. 259)

defense (Nowicki, 2000, p. 14-15). Notably, the longevity of some LM Settlements, extending into the Classical and Hellenistic periods, poses challenges in deciphering the urban structure of the EIA (Nowicki, 2000, p. 14-15).

The general area of focus is known as Minoas Pediada. Pediada has been a region of utmost importance for the island of Crete (Panagiotakis et al., 2013, p. 16). Settlement history in the region begins as early as the Neolithic. Two of the most important Minoan palaces, the one of Knossos and the one of Malia belong to this region, as well as the important city-states that dominated in the area from the Classical period and the ages that followed, such as Knossos, Lyttos, Lykastos, Arkades (Fig. 12). Moreover, in the region, one of the oldest communication systems has been identified by N. Panagiotakis, during the Pediada survey project, as well as the discovery of a large variety of archaeological sites (Panagiotakis et al., 2013).

The communication system utilized Soroi (Fig. 17), artificial hill-like beacon structures ("fryktories") for transmitting fire signals, established around the 2nd Millennium BCE. These pyramidal structures facilitated settlement connectivity, suggesting an early communication network, persisting alongside the entangled settlement pattern since the Bronze Age (Panagiotakis et al., 2013, p. 18). The Soroi, after their abandonment, maintained a role as landmarks which is testified even in the modern period (Panagiotakis et al., 2013, p. 19). This proves that communication between settlements in the region of Pediada seems to have been based on visibility ever since the Minoan period (Panagiotakis, 2004, p. 43). This focus on the visual properties must have affected transportation in the subsequent periods of the EIA in Crete.

The Pediada settlement pattern has been developing ever since the Prepalatial period (3100-1900 BCE) (Panagiotakis & Panagiotaki, 2011, p. 727), however, an important shift is observed during the LM-IIIC,

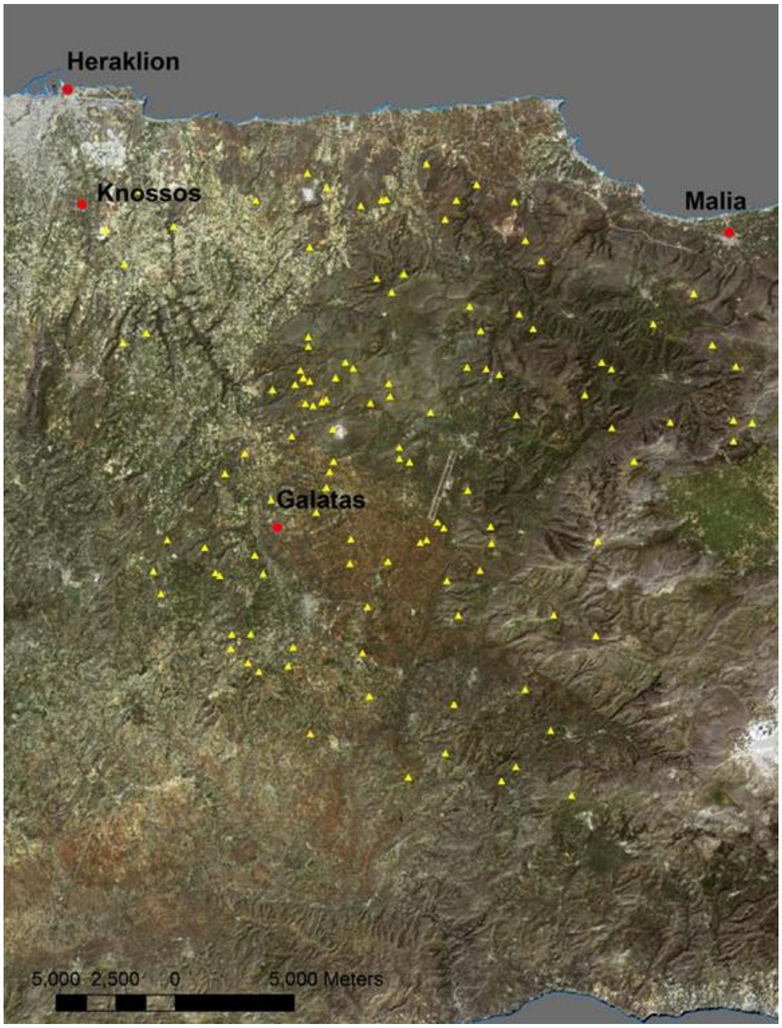


Figure 17 Distribution of Soroi in the Pediada region (Panagiotakis et al., 2013, fig. 2, p.16)

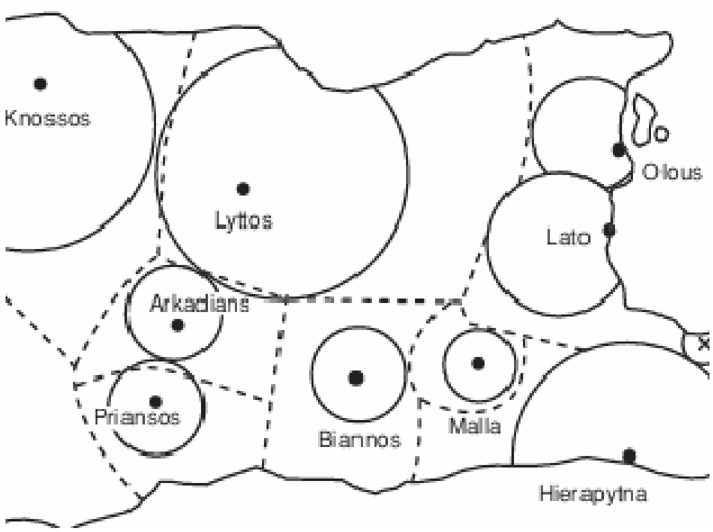


Figure 18 Expansion of Cretan cities in the Hellenistic period (Chaniotis, 2005, Map 3, p. 131)

as in most places of the island. During the LM-IIIC, the Minoan settlement of Kastelli declined. Around the same period, the hill of Smari, Profitis Ilias gets re-occupied, while the settlement of Lyktos starts to blossom. The acropolis of Smari, which dates to the Prepalatial period, was reused around 1200 B.C. Its total abandonment occurs somewhere between the 8th and 7th century B.C. (Kotsonas, 2022, p. 143) The acropolis was fortified during the LM period, but during the EIA, habitation was continued by a smaller community, possibly by a local clan/kin (Kotsonas, 2022, p. 143). This clan must have been allied with the city of Lyktos (Wallace, 2003a, p. 257). The final abandonment of the site must have been due to the urban nucleation with Lyktos as a center (Wallace, 2003a, p. 257).

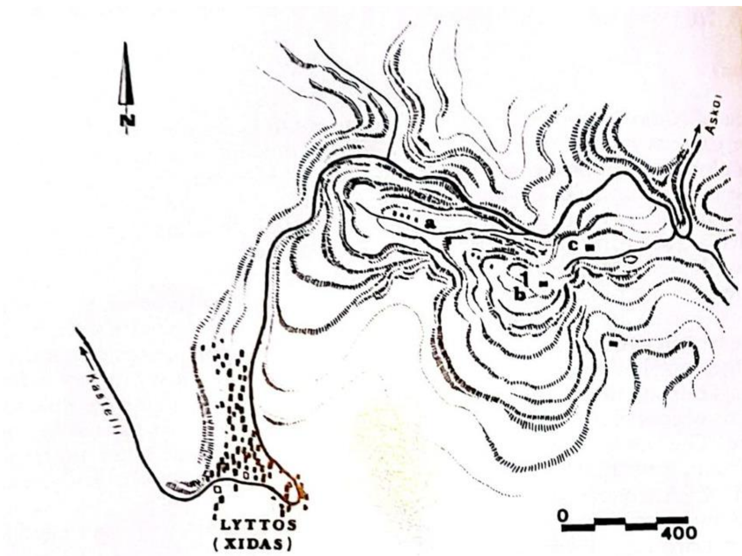


Figure 19 Plan of Lyttos. On the SE the modern village of Xidas. The acropolis is tagged as number 1. (Nowicki, 2000, fig. 102, p. 178)

Nestled in the heart of Central Crete, Lyttos or Lyktos (the former is the name of the city from the Classical period and afterward) lies on the north-western part of the Lasithi plateau. The city is extensively mentioned by ancient writers. Lyktos was a strong participant during the Cretan wars of the Hellenistic period, while it was also heavily connected with the city of Sparta (Chaniotis, 2005, p. 242; Perlman, 1992). The two cities had either developed an alliance or Lyktos was a Spartan colony, sharing customs and laws with the Laconian city-state (Kotsonas, 2019, p. 399; Perlman, 1992). From 221 to 220 B.C. the city of Lyttos was destroyed by the Knossians, during the "War of Lyttos", one of the most important wars in Cretan antiquity (Chaniotis, 2005, p. 9).

The site of Lyktos has been drawing the interest of archaeologists ever since the dawn of Cretan Archaeology in the 19th and 20th centuries, especially of one of the most prominent figures of the period, the Italian epigrapher Federico Halbherr (Kotsonas, 2019, p. 403). Honorio Belli, a naturalist and doctor, was the first to record the ancient landscape of Lyktos, during his trips to Crete ever since the end of the 16th century (Kotsonas, 2019, p. 404). Chatzi-Vallianou, the excavator of Smari, tried to interpret the site as the location of Minoan Lyttos, with the subsequent transfer of the settlement to the Xidas hill (Chatzi-Vallianou, 2016). However, excavations at Lyktos have managed to unearth material dating from the PG and the following periods (Kotsonas, 2022, p. 430). The city is mentioned in Linear B tablets under the name “ru-ki-to” (Τσικριτσής, 2024), but the formation of the city-state is prone to have happened in the PG period (Παναγιωτάκης, 2024)

Lyktos is located close to Xidas (Fig. 19), a village that belongs to the Minoa Pediada municipality. Around 1 km east of the village lies a hill between the road that connects Xidas with the village of Askoi. The hill forms a ridge which has on one side the chapel of Ag. Georgios and on the other the chapel of Timios Stavros (Nowicki, 2000, p. 177). The location of Lyktos can be defined as having strong strategic characteristics (Nowicki, 2000, p. 177). Considering the creation of the modern road structure and the landscape development happening in the last two centuries, the importance of the site could be better understood before the 19th century (Nowicki, 2000, p. 177). Nowicki (2000) describes the location of Lyktos as a “gentle” hill as it appears to the visitor. Spratt (1865) describes it as a site that had control of the Lasithi Plateau which lies on its east.

Lyktos falls under the jurisdiction of the Minoa Pediada prefecture, situated within the Minoa Pediada municipality, part of the Heraklion regional unit. The municipal boundaries stretch between Kastelli and Arkalochori in the west, with the natural boundary of the Lasithi Plateau to the east, extending southward to Keratokampos. The west border of Pediada is the mountain of Iouktas. The elevation of the area averages between 200 and 600 meters, with exceptions such as the Iouktas mountaintop, reaching approximately 800 meters (Nowicki, 2000). The area consists of the Omphalion Pedion, some central villages such as Kastelli and Arkalochori, as well as others such as Nipiditos and Astritsi (Panagiotakis, 2004, p. 40-43). Rivers and water bodies can be found in the boundaries of Pediada, but for this thesis, the focus is the northeast part of the area, where the Aposelemis River lies on the north of Lasithi.

It needs to be noted that Lyktos is located at an altitude of circa 630m above sea level. This has led scholars to reach the fact that Lyktos was a commanding center of the area, especially when considering the high visibility provided by the height of the site (Nowicki, 2000, p. 177). One can see the coast of Hersonissos and Mallia on the north, the Pediada plain on the east, while also being able to see Herakleion on the northeast, while the Asterousia mountains can also be seen on the south. On days with clear skies, the south and north borders of Crete as well as the important mountains of the central and eastern parts can be seen. The high visual properties of the site must have played a significant role in its urban and territorial development, considering that most sites lying around can be seen from the top of the Xidas hill (Nowicki, 2000, p. 177). The development of Lyttos might have played a crucial role in the transitional changes occurring in the northern Lasithi area during the PG (Nowicki, 2000, p. 177).

Lasithi Plateau is a plain that expands around 5 by 8 km. in size, while it lies at about 800 meters above sea level. It is a plain diachronically exploited by the communities that emerged around it, while its potential is not periodic. The ridges of Louloudaki, Afendaki, Sarakino, and Virgiomeno provide a natural barrier that separates the plain of Lasithi from the one on Pediada (Nowicki, 2000, p. 147). On the north of the Louloudaki ridge, the site of Gonies to Flechtron is located and it connects the Avdou-Gonies valley with the entrance to the Lasithian Plateau (Nowicki, 1995, p. 696-697; Nowicki, 2000, p. 148) The Ambelos pass is the natural pathway that connects Lasithi with the north coast. Karfi and Papoura settlements were nearby so they probably had control over this specific path (Wallace, 2007, p. 266). Based on Mavraki-Mpalanou et al. (2016), this pass must be the one that starts from Lyktos, passing from the settlements in the Aposelemis Valley, close to the modern village of Avdou, in the Avdou-Gonies Valley. From the north natural entrance to Lasithi, the acropolis of Lyktos can be seen, at a distance of around two hours of walking. Watrous and Blitzer mention a continuity of the Minoan Past in the Archaic Period. By the 6th century, Lasithi had already been inside the territorial control of Lyktos (Watrous & Blitzer, 1982).

The Northern Lasithi (Fig. 20) area is significant as it is an area that was subdued to the territorial control of Lyttos during the Classical Period, which must have started developing since the early stages of the city, during the Dark Age and PG period. The Lasithi plateau is located on the south of the Malia plain, from which it is separated through a series of hills, with the most important being the one of Selena, which is known for its high visibility properties, which were also exploited during the second world war (Nowicki, 2000, p. 148). To enter the plateau one must pass through the ridge created by the hills of Selena and Louloudaki. This route probably matches with the Ampelos pass. The Papoura mountain, which provided two routes one on the west and one on the east, was an important point for walkers. The foothills of the

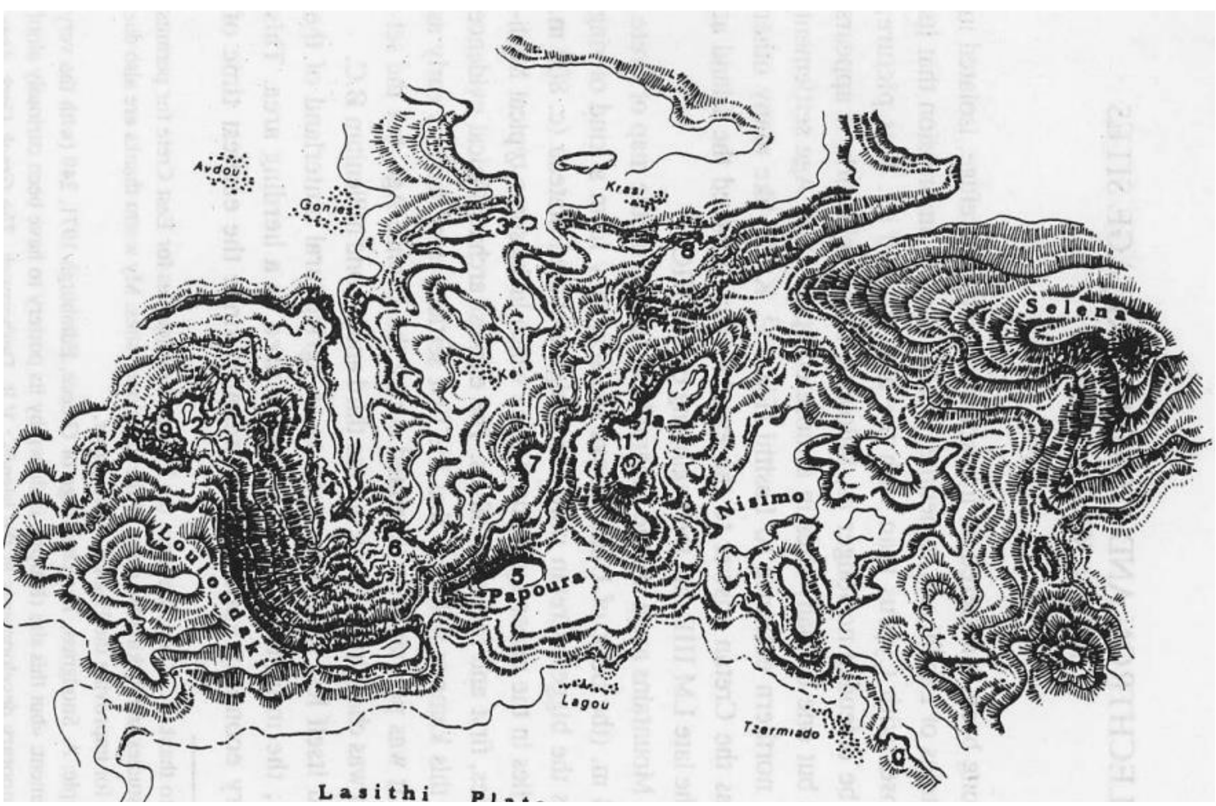


Figure 20 Plan of Northern Lasithi Area including Dark Age sites around Kera, modern villages and the Louloudaki and Selena hills (Nowicki, 1995, fig. 1, p. 694)

Plateau lying on its north part also provided a way to reach the areas of Hersonissos, Stalida and Mallia, by following the Aposelemis Valley (Nowicki, 2000, p. 148). It needs to be noted that all sites that exceed the height of 800m are used by shepherds, as noted by Nowicki (2000), This phenomenon can probably explain how these lands might have been exploited in the past periods.

The landscape is dotted with villages, both sizable and modest, while large expanses remain less suitable for settlement, primarily utilized by shepherds and farmers. As Nowicki astutely observes, traversing the terrain is facilitated along a north-south axis, aligning with the geographical contours of Crete (Nowicki, 2000, p. 22).

A variety of Dark Age sites can also be seen from Lyktos, such as Smari, Profitis Ilias, the Maza hill in Kalo Chorio, Gonies to Flechtron near the village of Gonies, and the Kera valley that contains a variety of sites of the same period (Nowicki, 2000, p. 177). The actual form of the EIA town has not yet been unearthed, considering the importance of the city from the Classical to the Roman period, which led to an evolved urban structure, where the previous stages cannot be distinguished easily. However, the recent excavation project and surveys in the area have managed to produce some strong evidence for the existence and the development of the city during the EIA (Kotsonas et al., 2021).

During the PG, Lyktos initially had control of the nearby Maza hill, lying on its north, in the area of Kalo Chorio (Nowicki, 2000, p. 175). Subsequently, it expanded its borders to the east by gaining control of the Avdou-Gonies valley. In the Archaic period, Lyktos continued to assert its dominance by extending control over the Lasithi Plateau (Nowicki, 2000; p. 177). The hill has control of the entrance of the Potamies Valley and has a view of the surrounding area with Knossos and the Dikti mountains on the west and the southeast (Nowicki, 2000, p. 175). Maza is an important location as it could have been a landmark for travelers moving from Central Crete to Lassithi, as it was in the route connecting the two regions, and also for those moving from Lyktos to Hersonissos. Maza provides quite some evidence for an occupation that evolved during the late stages of the Dark Age, during the PG and G periods (Nowicki, 2000, p. 175). A spring on the northeast of the hill (ca. 300m) has been an attraction for people and an important parameter for the nearby settlements that developed in the area (Nowicki, 2000, p. 176).

In recent decades, the Ephorate of Antiquities of Heraklion has excavated numerous new sites during the works for the creation of the Aposelemis river dam, primarily between Potamies and Avdou villages (Mavraki-Mpalanou, 2013, p. 4). These sites, located in the valley of Aposelemis (Fig. 21), connect the Pediada Plain to the Lasithi Plateau and the Dikte Mountains, with potential ties to coastal areas like Mallia (Christakis et al., 2015, p. 302). Some were previously identified by Panagiotakis in the Pediada Survey, highlighting the valley's significance as a natural route linking mountainous and coastal regions (Christakis et al., 2015, p. 302). These sites can be found parallel to the flow of the river, moving along the Potamies Valley, starting from the village of Avdou and moving to the northwest, to the village of Potamies and they are dated from the Minoan period until the Byzantine age (Mavraki-Mpalanou et. al., 2016). On the north of the valley, the Mochos ridge lies (Mavraki-Mpalanou et al., 2016, p. 4)

The Aposelemis River is part of the surrounding area of the North Part of Pediada, which is known as Lagkada. The river helps with transporting water gathered in the Lasithi Plateau. The water from Lasithi is important for irrigating the villages of the east part of Pediada. Water streams passing from the villages of Kastamonitsa, Aski, Karouzana, and Xerokamares are connected with the Aposelemis River and reach the delta of the river located on the north, on Kato Gouves, west of Hersonissos (Mavraki-Mpalanou et. al, 2016; p. 3-4).

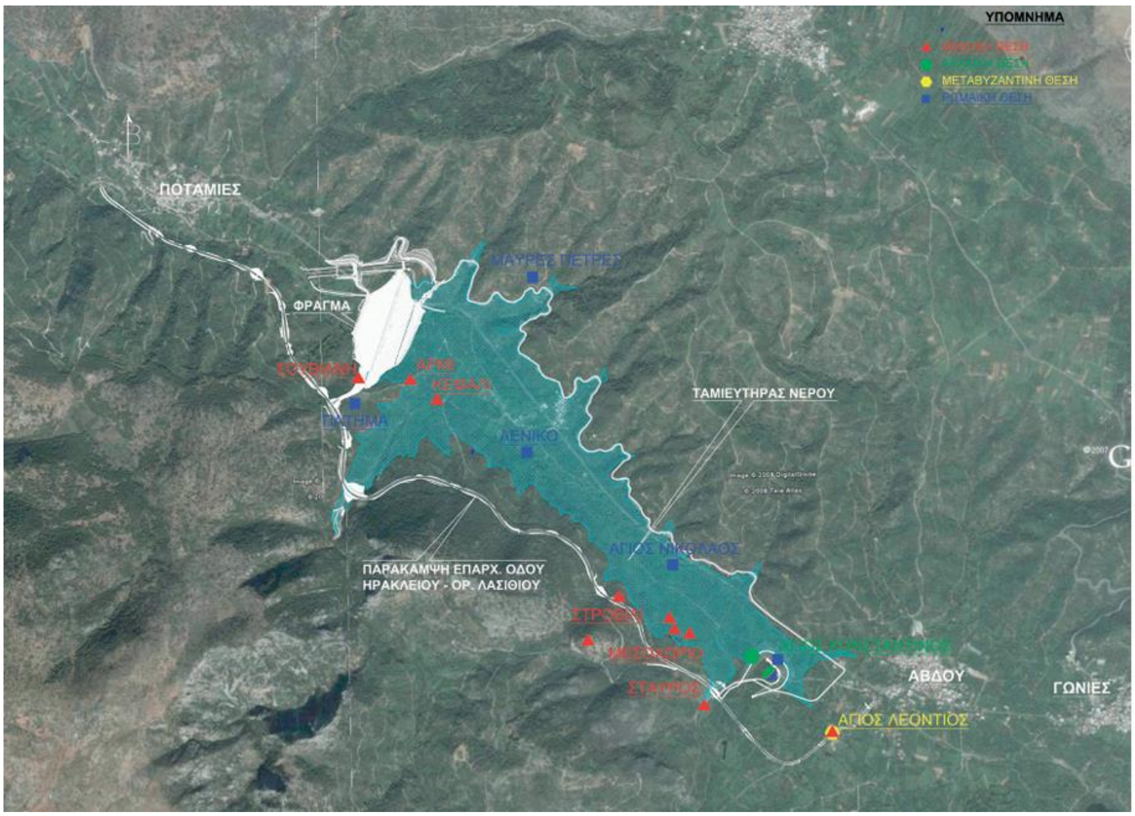


Figure 21 Area of the Aposelemis Dam from Avdou to Potamies. Red: Minoan Sites, Green: Archaic Sites, Blue: Roman Sites, Yellow: Late Byzantine Sites (Mavraki-Mpalanou et al., 2013, Map 1, p. 388)

During the Early Geometric, new sites started to appear, with a development of the areas of Avdou, Gonies, Krasi, Kera, Karfi, and Papoura (Mavraki-Mpalanou et. al, 2016, p. 12). These sites were at their peak in the early years after the Dark Age of Crete (Nowicki, 2000). A shift from the Minoan period can be observed, however, all these locations are close to the area of the Aposelemis Valley (Mavraki-Mpalanou et. al, 2016, p. 12). The exact motifs of this movement are not clear and are part of an important debate by scholars of Cretan Archaeology (Mavraki-Mpalanou et. al, 2016, p. 12).

The diachronic character of settlement in the area is easy to understand considering that the region was constantly occupied from the Minoan times until today with an established path network connecting the different settlements of the area. This network must have remained in use during the EIA period as well with the formation of new paths that were connecting the newly-founded sites (Mavraki-Mpalanou et al., 2016, p. 12-13).

The patterns of habitation in Central Crete during the PG mirror those of the LM-IIIC period. Older settlements exhibit continuous occupation, indicating a link between the EIA residents and their Bronze Age ancestors (Judson, 2018, p. 194). While the hypothesis of high nucleation in the area is frequently discussed, the connections between these settlements and their regional landscape have not been adequately explored (Judson, 2018, p. 195).

Krasi and Kera, situated between Louloudaki and Selena, are villages with a long history of occupation(Nowicki, 2000, p. 159-160). Kera shares similar characteristics with Krasi and is also home to ancient settlements, benefitting from its proximity to natural springs (Nowicki, 2000, p. 160-162). Karfi, one of the highest-in-elevation Dark Age settlements, lies between two hilltops and was a significant peak sanctuary during the Middle Minoan periods (Nowicki, 2000, p. 165-166). Kalderimia pathways connected Karfi with surrounding areas, facilitating communication and accessibility (Nowicki, 2000, p. 166). Papoura, another vital site from the Dark Age onward, also featured Kalderimia paths linking the Lasithi Plateau with Central Crete. It likely held strategic importance due to its control over routes connecting the

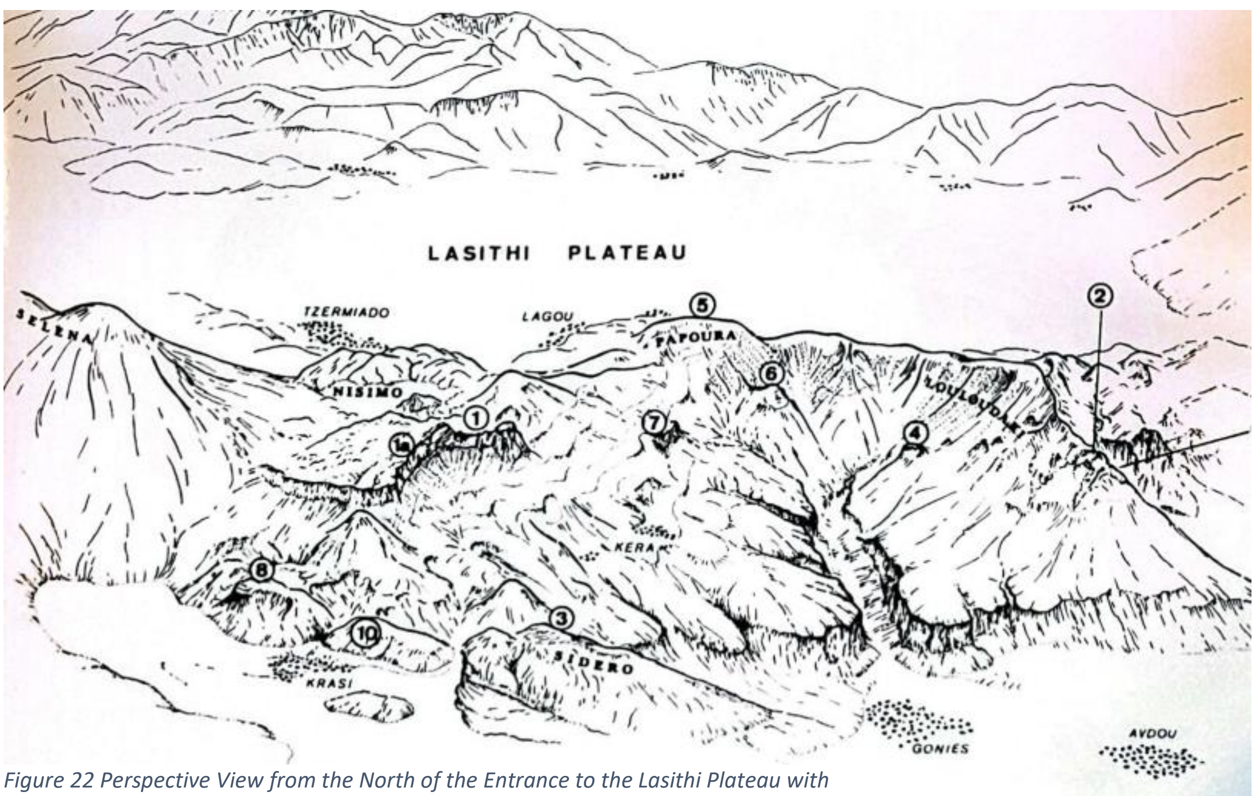


Figure 22 Perspective View from the North of the Entrance to the Lasithi Plateau with Dark Age Sites (Nowicki, 2000, fig. 89, p. 159)

Lasithian entrance with the Gonies-Avdou valley. Evidence suggests continuous occupation until Roman times, with a decline possibly in the 5th century B.C. as populations shifted to lower elevations. During the PG and G periods, Karfi inhabitants moved to Papoura (Pendlebury, 1939; Nowicki, 2000, p. 166; Watrous, 1982). Karfi, Gonies to Flecthron, and Papoura were sacred sites in the LM and PG periods (Mavraki-Mpalanou et al., 2016, p. 12)

All of these sites are located south of the Aposelemis Valley, forming a cluster between the valley and the Lasithian Plateau (Fig. 22, 23), so it would be safe to assume that they must have been under the territorial control of Lyttos. These areas were part of the Lyktian territory (Fig. 18) during the Hellenistic period (Chaniotis, 2005) so the connections between them are believed to originate during the period under study. Connectivity between these sites could have been established much before the PG period, with a stronger relation during the Archaic period, before reaching their final stage in the Hellenistic.

At last, Lyktos is heavily connected with Hersonissos, the port of the city that lay in the mountains, during the Classical era and onwards. With the urban expansion of the Lyktian territory, Hersonissos, during the Roman period, was known as the Coastal Lyttos (Mavraki-Mpalanou et. al, 2016). A large stone-paved road connecting Lyktos and Hersonissos must have existed during Roman times (Papadaki & Milidakis, 2023). The city is mostly known for its Roman period, however, its existence in previous periods can be testified from fragmentary finds. For the G and Archaic period of the city, the evidence is mostly limited to pottery sherds (Kotsonas, 2022, p. 143). The discovery of a Geometric wall is the only proof of a structure from the period (Kanta & Serpetsidaki, 2015, p. 66).

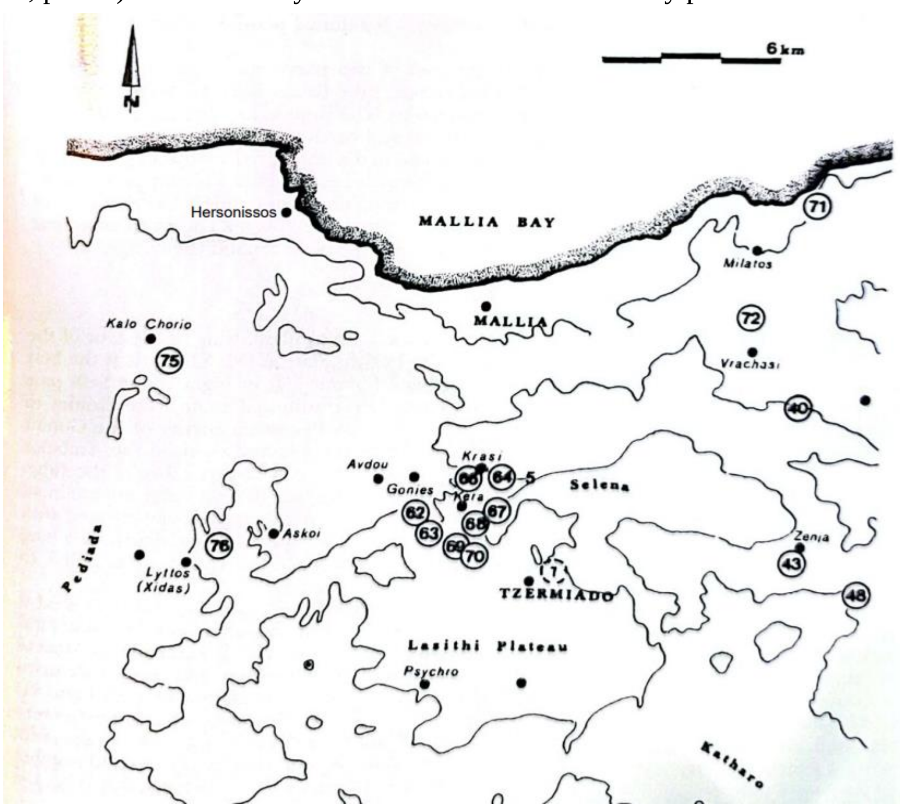


Figure 23 Map of Central Crete with LM-IIIC, Geometric, Archaic sites and modern villages (Nowicki, 2000, fig. 79, p. 147)

4.5 On the paths inside the study area

In the study by Mavraki-Mpalanou (2016), focusing on the streets and paths that were passing from the Aposelemis Valley, a variety of routes were identified. The study aimed to examine the communication network of the North Pediada area, and the results of the works for the Aposelemis dam that uncovered several archaeological sites (Mavraki-Mpalanou et al., 2016).

Along this street network that dates back to the Neopalatial period, a lot of Minoan remains have been found. Topographical features of the area and local toponyms were really useful for the identification of the network, and for the identification of regional landmarks used for traversing the landscape (Mavraki-Mpalanou et al., 2016, p. 4). The aforementioned study focuses, also, on the excavation material and the transportation infrastructure remains that were found close or within settlements. Moreover, remains of guardhouses that protected and controlled the passing routes were also discovered, however, their use was limited during the Middle Minoan period (Chrissoulaki, 1999). We do not have any evidence for the existence of these structures after the end of the Bronze Age (Chrissoulaki, 1999).

The existence of these sites and settlements during the EIA allows the formation of a hypothesis that, as in the previous Minoan network, these sites must have been used as landmarks for transportation. The control of Lyktos in the area is well-known during the Classical period and afterward (Chaniotis, 1999), but as Nowicki suggested, the communication between Lyktos and North Lasithi must have been established from the PG to the Archaic period (Nowicki, 2000, p. 177). Previous Minoan locations across the road could have remained as parts of the network, but their character must have shifted to simpler agricultural communities, instead of the settlements that pre-existed during the Minoan times. Another hypothesis, that is important for this thesis, is the fact that the higher elevations of the new settlements in the mountainous areas, lying above the Aposelemis Valley, must have played a role in movement in the landscape. The visual properties of these new settlements should also be considered, as well as their role in navigating in the terrain.

The street network of Aposelemis was the means for people to move from the coast to the inland. Mavraki-Mpalanou et al. (2016) suggest that people must have stayed in touch with the traditional roads of the Minoan period, with the addition of new paths to access the newly-formed sites of the post-Minoan era. The exact location of the path-network is not known, but local sources testify to the existence of different paths. After discussions with local shepherds, paths connecting different archaeological sites or leading to modern villages are known, with a path from ancient Lyttos moving to the modern village of Ano Karouzana as an example. Further validation of these paths is necessary besides their computational analysis.

Regarding their phenomenological aspect, it is important to note that most of the sites mentioned in the text are intervisible; they can see and be seen from other sites. These visual parameters likely played a significant role in ancient travelers moving from one site to another. For instance, when approaching the Acropolis of Lyktos, an individual could see the settlement atop the hill, based on the current landscape. Another example is the site of Karfi from where the whole area of the Aposelemis Valley can be seen. A traveler would also be able to see the mountain top from almost every place in the path network. The same fact can be applied to the case of the Smari Acropolis, with its prominent location.

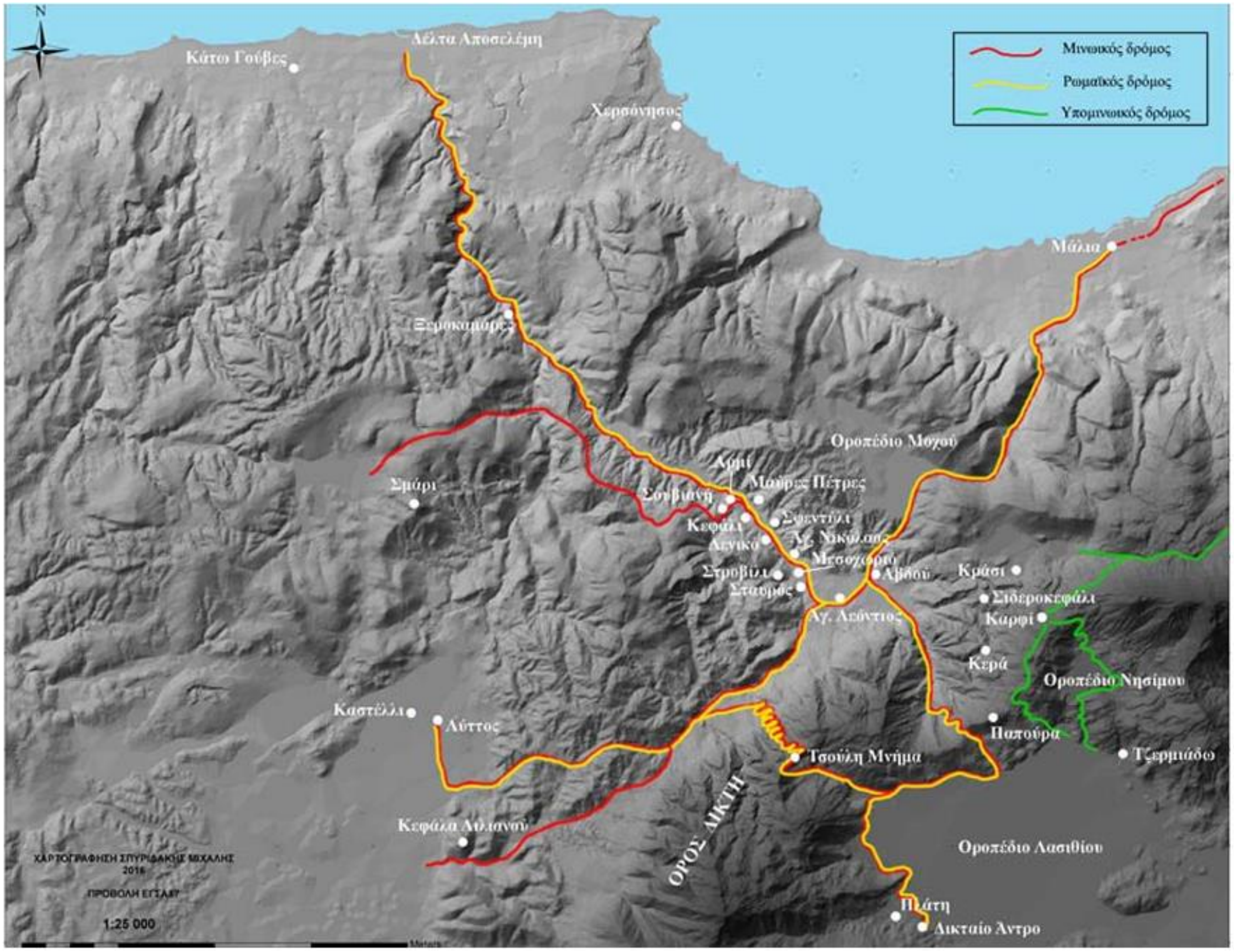


Figure 24 Hypothesized Path Network for the Pediada and Aposelemis Valley regions. Paths in red are Minoan, in yellow Roman and green Sub-Minoan (Mavraki-Mpalanou et al., 2016, Map, p. 2)

5. Methodology

5.1 Introduction

One of the objectives of this thesis is to delve into the movement and development of the path network in Central Crete during the EIA. Understanding ancient pathways is an important tool for studying social and economic networks and even cultural interactions of past communities. Besides the socio-political aspect, they can also expand our understanding of the human experience and peoples' relationship with their landscape.

However, the study of this particular subject is often researched using Geoinformatics software, such as ArcGIS and QGIS, and their established workflows and algorithms. Instead, this thesis seeks to employ a novel methodology by harnessing the potential of programming languages for two reasons; to explore their potential for exploring pathways in a study area and to test whether they can produce results that match those of the commonly-used available software.

Rather than solely generating results from a GIS and analyzing them, this project emphasizes understanding the underlying processes of the software. This approach aims to explore the capabilities of path-finding algorithms further. A pivotal aspect of this exploration will be the comparison between computed results obtained through coding-based Least Cost Paths (LCPs) produced by the use of the Python programming language and those generated by open-source GIS software, particularly QGIS. An important aspect is to support the notion of open science, which is why I am comparing these two methods as they are open-source, unlike other available software.

The goal of this thesis is two-fold. First, the methodology employed is an experiment to explore the validity of Python and coding-based methods to study such issues, as well as explore their results compared to GIS systems. Python's potential will be assessed through its application in processing and handling DEM data, a critical parameter in geospatial studies, as well as in path creation. By adopting this methodology, traditional aspects of LCP analysis will be scrutinized from a computational standpoint, enabling a deeper understanding of the mechanisms employed by GIS software.

On the other hand, the results will be assessed based on the available archaeological and historical data regarding the socio-cultural network of the study area of North-Central Crete during a period of the island that is described by limited visibility regarding the archaeological record. The path network that will be produced will also be assessed through a phenomenological perspective, by analyzing relevant references from the literature, as well as my personal experience in the area to test the possibility of the existence of each produced path and also to try and replicate an individual's experience of the Cretan Landscape. Thus, the main issues discussed in the previous chapters will be used as tools to interpret the results produced by the computational aspect of this research.

By combining archaeological and phenomenological perspectives and adopting a computational approach, this research aims to provide comprehensive insights into ancient movement patterns while contributing to the discourse on computational applications in archaeology. Nonetheless, this thesis addresses archaeological inquiries regarding ancient landscapes, and human movement, but also serves as evidence of Python's utility in computational archaeology.

5.2 Overview

In this chapter, each step of the methodology will be discussed in detail. Initially, the equipment and data used will be presented. Next, the procedures and decisions involved in handling and managing the raw DEM data will be examined, encompassing the pre-processing phase and the selection and implementation of smoothing and interpolation techniques. Subsequently, the creation of the cost surfaces necessary for operating the LCP algorithm will be elucidated, alongside the steps for path generation. Additionally, a subsection will be included to describe the procedures conducted on the QGIS software. Furthermore, a disclaimer outlining the use of the AI-language model ChatGPT will be provided.

5.3 Hardware and Software

For the methodology of this thesis, the hardware utilized included a Dell G15 5515 laptop equipped with an AMD Ryzen 7 processor, 16 GB of RAM, and an NVIDIA GeForce RTX 3060 GPU. The software utilized for programming included the Spyder Integrated Development Environment (IDE), essential for conducting scientific data analysis and executing Python scripts. Various Python Packages were also used for the manipulation of the data, the creation of cost surfaces, and the generation of the paths and visualizations, such as NumPy, Pandas, Rasterio, GDAL, Matplotlib, SciPy, and scikit-image. QGIS version 3.26.2 "Buenos Aires" was employed to compare the Python methodology with GIS. Instead of using the QGIS Python API (Application Programming Interface) the use of a separate IDE was explored to inspect its potential. QGIS was also instrumental in the creation of maps, while AutoCAD 2022 was employed for further map editing. At last, Google Earth Pro was used to extract coordinates and calculate distances, and ChatGPT version 4.o, for helping with the coding aspects, and partly for image editing.

5.4 Data

The DEM data utilized in this thesis was accessed through the United States Geological Survey (USGS) portal. USGS offers a comprehensive range of geospatial datasets utilized by researchers for cartographic modeling and various other purposes. The DEM employed in this study was derived from data collected during the Shuttle Radar Topography Mission (SRTM). The project was conducted from the early

2000s to 2014 to compile global elevation data (Herzog & Yepez, 2016, p. 3). The SRTM 1 Arc-Second Global data, with a spatial resolution of approximately 30·30 meters, provides vertical accuracy of around 16 meters absolute and 10 meters relative, while it is accessed on a geographic projection set in the WGS84 coordinate system. This resolution defines the size of each grid cell or pixel within the dataset, with each cell representing a specific area on the ground. While this resolution provides a detailed representation of the terrain, it may also contain high-frequency variations or noise that could potentially affect the analysis. The DEM includes elevation data for the Central-East part of Crete (Fig. 25) and was downloaded in the available GeoTIFF format. Additionally, a small dataset containing sites within the boundaries of the Study Area was manually compiled. Coordinates for these sites were gathered from Google Earth Pro and subsequently converted to the desired projection. Further details regarding these sites can be found in the *Archaeological Background* chapter, specifically in the Study Area sub-section. The list of the sites was created according to archaeological and historical data of the area.

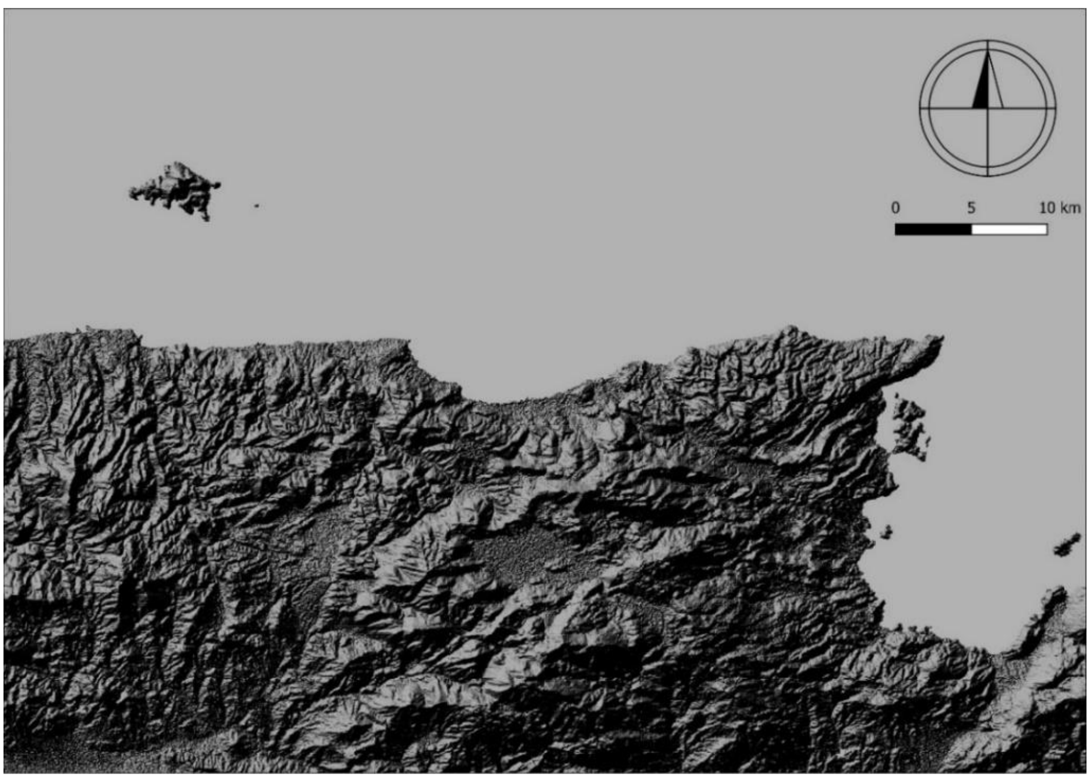


Figure 25 Hillshade of Raw SRTM DEM dataset for Central-East Crete

5.5 Python Workflow

In the following sub-sections, each step of the methodology will be discussed. Fig. 26 shows a diagram of each step that was taken. (See Appendix E for the Python Scripts)

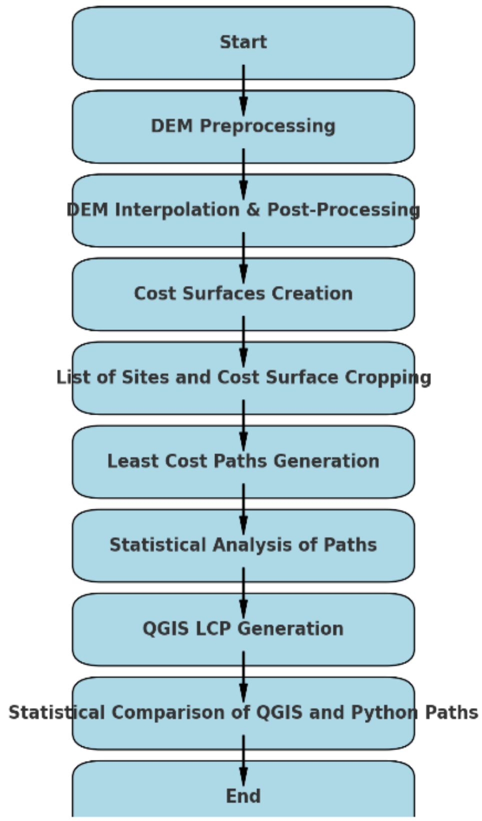


Figure 26 Workflow of the methodology

5.5.1 DEM Pre-processing

The initial step of this project involves manipulating and preprocessing the DEM data. This first step plays a crucial role in checking the data's quality and suitability for subsequent steps. It must be noted that the preprocessing of DEM data is often neglected in archaeological studies (Lewis, 2017, p. 72; Herzog & Yepez, 2016, p. 2; Herzog, 2022, p. 133). In this thesis, an experimentation of basic principles of preprocessing will be assessed.

First, the DEM is imported into the Spyder IDE. For the manipulation of the dataset, the Rasterio library (Gillies et al., 2013) was used for reading and manipulating the raster data. After importing the dataset, it is georeferenced to the Greek Projection System (EPSG: 2100) to achieve a more accurate spatial representation, instead of using the original projection, which is the WGS 84 World Projection. For the shift of the coordinates' projection, the GDAL (GDAL/OGR contributors, 2024) library was utilized. During this stage, the aim is also to check for negative values in the dataset, which are then changed to 0 by setting a minimum threshold limit. This helps avoid anomalies in the data. For example, basic statistics of the unprocessed DEM revealed a minimum elevation level of -29 meters, which is unrealistic for the area of focus and its mountainous morphology. While values of 0 are also unrealistic, they are easier to handle for the subsequent analysis, compared to the negative ones.

Negative elevation values in the DEM are a result of the data collection procedure and processing by the SRTM project. Such values can exist in areas below sea level or deep valleys; however, this is not the case for the area of focus. Transforming these values into 0 is crucial for creating the cost surfaces used in the subsequent LCP Analysis. Furthermore, Dijkstra's algorithm, which is used for LCP generation, requires only positive values to operate smoothly. While the value of 0 is not positive, it serves as an indicator for the algorithm to avoid such cells. Additionally, there are almost no negative values in the area where the path-finding algorithm is applied; however, this step was conducted to ensure that any potential negative values are addressed.

The 30-meter resolution of the dataset is quite adequate for geospatial analysis. Nonetheless, variations and alterations are apparent in the data. These alterations can be attributed to contemporary changes in the landscape, precipitated by the proliferation of human settlements and the construction of various infrastructural elements. The modernization of the terrain, characterized by the establishment of urban habitats, architectural edifices, and associated infrastructure, has induced substantial transformations in the natural topography. These anthropogenic interventions have engendered significant deviations from the original land morphology and its shape during the period under study.

To address this, a smoothing technique is applied to the dataset using Gaussian filtering, a common technique used in image processing (Li et al., 2021). This reduces noise and emphasizes broader trends or patterns in the data, improving data clarity while maintaining overall integrity. However, smoothing may lead to some level of resolution degradation, potentially resulting in the loss of fine-scale details present in the original dataset. The parameters of the smoothing operation, including the size of the smoothing kernel, are carefully selected to strike a balance between noise reduction and preserving important spatial features relevant to the study objectives. Hillshades (Fig. 25, 27) are generated to inspect the results of the preprocessing steps taken. For visualizations the Matplotlib package is used (Hunter, 2007)

Smoothing the DEM dataset provides the opportunity to make subsequent analysis computationally cheaper for different reasons. Smoothing is important for the reduction of the complexity of the data, making the application of various algorithms simpler, while it can also improve their performance. Also, with the reduction of noise, and sharp transitions in the data, a smoother dataset can facilitate more efficient computations, compared to raw and unprocessed data.

This procedure involves the utilization of a Gaussian filter with a sigma value of 3.0. In the context of Gaussian smoothing, the sigma value represents the standard deviation of the Gaussian distribution. It determines the extent of the smoothing effect applied to the data. A higher sigma value results in a more pronounced smoothing effect, while a lower sigma value preserves finer details in the dataset but may not effectively reduce noise. Adjusting the sigma value allows for fine-tuning the balance between noise reduction and preservation of important spatial features in the dataset. The selected value of 3.0 presents a balance for dealing with these issues and shows results that can be beneficial for the analysis. After this simple preprocessing of the data, the DEM is smoother, with negative values set to 0 and the maximum elevation around 2.100 meters, matching the actual highest elevation of this particular part of the island of Crete. The dataset is now better prepared for subsequent analysis and is easier to manipulate from a computational perspective.

The Root Mean Square Error (RMSE) was computed to check the quality of the processed data. RMSE shows the absolute fit of the created model to the data and lower values indicate that the model shows a good fitting. The Mean Absolute Error (MAE) was also calculated. This calculation focuses on the average difference between predicted and observed values. These metrics are often used to investigate and assess the results between models. In this case, they are particularly helpful for determining the quality of the smoothing technique.

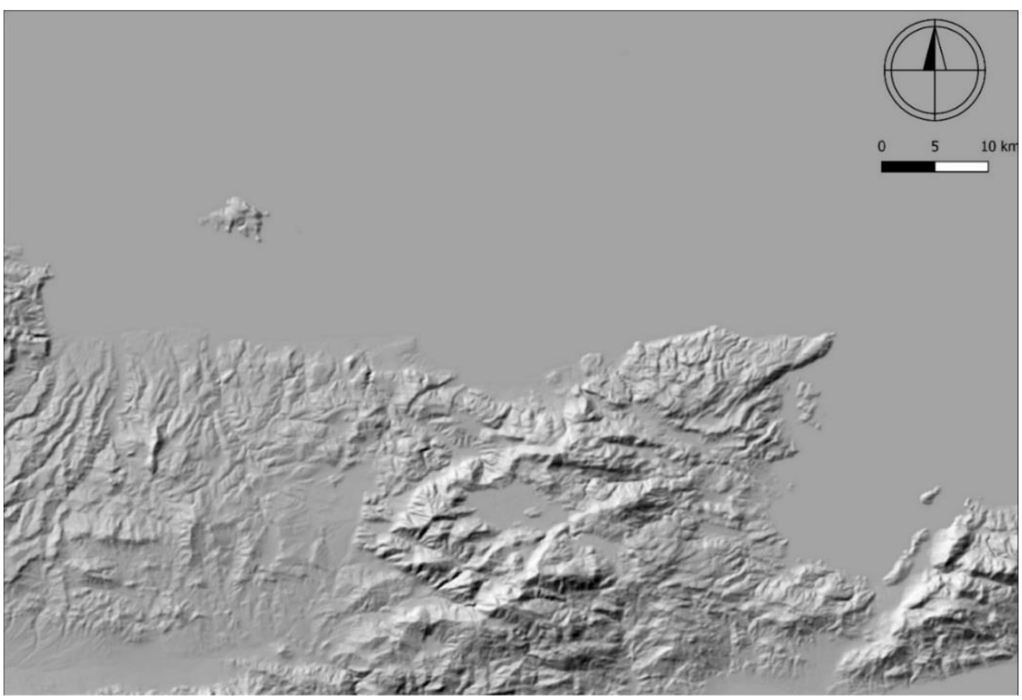


Figure 27 Hillshade of Smoothed DEM for the study area (Made in Python)

It needs to be noted that these pre-processing steps are merely an effort to try and make the landscape representation from the DEM data as realistic as possible. However, the achievement of this task is arduous and often impossible considering that the available DEMs are generated based on the modern landscape image (Herzog and Posluschny, 2011). The ancient landscape is hard to recreate due to the lack of complete archaeological datasets (Lambers and Saurbier, 2007).

5.5.2 DEM Interpolation & Post-Processing

1. Interpolation

In this phase, the focus shifts to the manipulation of the smoothed DEM dataset that was produced in the previous step. Although interpolation, a technique for computing missing values on a dataset (Conolly & Lake, 2006, p. 90), is not strictly necessary for the primary analysis of Least Cost Paths, it was an essential step for maintaining the correct georeferencing of the data during the preprocessing phase. While raster datasets are continuous by their nature, interpolation is important for ensuring data accuracy and alignment. After considering various interpolation methods, such as Inverse Distance Weighting (IDW) and Kriging, spline interpolation was chosen due to its ability to generate smoother surfaces and effectively connect irregularly spaced data points. Spline interpolation, accessed via the SciPy package (Virtanen et al., 2020), helps to ensure global smoothness across the data's surface while maintaining continuity between derivatives (Press et al., 1992).

Despite its advantages, spline interpolation is sensitive to outliers, which can introduce inaccuracies. Therefore, outlier management was conducted during preprocessing to mitigate this issue. Achieving a true representation of the ancient landscape is unattainable due to extensive alterations over time. The Bivariate Spline Interpolation technique was applied to create a smoother and more continuous surface from the raw DEM data. This method fits segmented polynomial functions between data points, ensuring better stability and avoiding irregularities (Press et al., 1992). The bivariate approach, suitable for two-dimensional datasets, fits different polynomials locally, aiding in understanding data variations across the DEM's space (Virtanen et al., 2020).

To perform the interpolation, x, and y coordinates were generated and shaped into a mesh using the "meshgrid" function from the NumPy Package (Harris et al. 2020). These arrays were then flattened and used as inputs for the interpolation function. Although interpolation is not directly needed for generating LCPs and considering that for geospatial analysis it is desired that the data are kept as intact as possible, its application was crucial for maintaining accurate georeferencing of the data. This step was vital to prevent misalignment and ensure the integrity of the geographic transformation of the data. By maintaining the correct georeferencing through interpolation, the DEM data was accurately prepared for subsequent analysis steps, particularly for generating the cost surfaces used in LCP creation. Thus, while not essential for the final analysis, the interpolation process was a necessary preparatory step to ensure the quality and accuracy of the geospatial data. For this reason, a smoothing factor of 0 was selected to retain data irregularities, preserving the dataset's variations and keeping it as close to its original form as possible.

2. Post-Processing

After the interpolation process, it was observed that negative values reappeared in the processed DEM, primarily along the coastline. These negative values were reset to 0 to avoid potential complications and to ensure they did not affect higher-elevation areas used in the analysis. The interpolated DEM was then saved in the GeoTIFF format for future reference and further analysis.

The quality of the preprocessing and processing steps for the DEM data was evaluated using simple statistical computations to assess changes in the data. In addition to the statistical analysis, the interpolated DEM was visualized for qualitative inspection during the post-smoothing and post-processing stages. The final results were saved and exported in TIFF format, allowing them to be imported into QGIS for detailed visual inspection.

5.5.3 Cost Surfaces

After the processing of the DEM data with the enhancement of their quality and their suitability for the subsequent steps of this thesis, a necessary step before proceeding to the generation of the LCPs, is the creation of the cost surfaces that will be used by the Pathfinding algorithm. Cost surfaces are the most crucial input for pathfinding applications. Cost surfaces can be created based on a variety of factors, which can either be natural or cultural. One of the most common factors used for the creation of cost surfaces is the slope of a terrain and its influence on movement. The use of a slope-based cost surface is apparent in this thesis.

For this reason, the initial step was to calculate the slope of the area and create a slope surface. The slope is generally calculated based on the simple formula of “Rise over Run”, while there also are other methods. “Rise over run” basically divides the difference in the elevation of two points by the horizontal distance between them. However, in geospatial applications and most importantly when studying movement, the cost of slope to an individual is crucial for understanding decision-making and path routes. The cost of the slope is calculated through the use of a variety of functions, each of which takes into consideration different parameters. In this research, Tobler’s Hiking function is the one that is employed, and more specifically a modified version of the original formula.

1. Tobler's Hiking Function

Initially, the cost was calculated based on Tobler's Hiking function in its original form. Before, a function based on Tobler's function was created to calculate slope and create a slope surface (Fig. 28, 30). This particular function is commonly encountered in archaeological studies relevant to understanding movement, and it has been established as a method yielding stable results. Tobler's function accounts for both the steepness and roughness of the terrain, as well as their impact on an individual's walking speed (The formula for calculating walking speed based on Tobler's function can be found in the *Methodological Background* chapter).

In Python, a function was created based on Tobler's formula. The formula's inputs include a z-factor, which is a constant indicating the effect of slope on walking speed by controlling the vertical component of the data and adjusting its scaling. A value of 1 is an initial standard, however, due to the nature of the elevation data, and after experimentation with different values, it was observed that a value of 4.0 (the selected one) or 5.0 is more suitable for visualization purposes, considering the case of the dataset used in the analysis. Besides the visual aspect, it benefits from balancing the exaggeration of slopes. The chosen values show a better fit for the dataset of my study area and allows a more accurate modelling of walking speed and slope impact. It needs to be noted that the adjustment of the z-factor on the one hand helps with fine-tuning the analysis but extreme values might have negative effects on the results.

The function calculates the gradient of the elevation data in both dimensions ("dx" and "dy": indicating grid cell size) using "np.gradient" for determining the slope. The computation of the gradient is useful for observing terrain steepness. Moreover, slope is calculated in radians that can be converted to degrees or percentages according to the needs of the analysis and the user. For the use of Tobler's function, degrees are the desired format. Error handling is also included to deal with invalid outputs. Overall, the main concept of this function is to assume that the input elevation data is correctly scaled while using the z-factor to refine the slope calculation.

```python
# Function to calculate slope using Tobler's hiking function
def calculate_slope_tobler(elevation_data, dx, dy, z_factor=1.0, output_format='degrees'):
    dz_dx, dz_dy = np.gradient(elevation_data, dx, dy)
    slope_rad = np.arctan(np.sqrt(dz_dx**2 + dz_dy**2) / (z_factor * 1.0))

    if output_format == 'degrees':
        slope = slope_rad * (180 / np.pi)
    elif output_format == 'radians':
        slope = slope_rad
    elif output_format == 'percent':
        slope = np.tan(slope_rad) * 100
    else:
        raise ValueError("Invalid output format. Choose 'degrees', 'radians', or 'percent'.")
```

Figure 28 The script of the calculation of slope based on Tobler's function

After calculating the slope, Tobler's hiking function is applied to compute the movement cost and generate a slope-based cost surface (Fig. 29). The function takes the slope angle as input and uses an exponential decay model to reflect how walking speed decreases with increasing slope. The slope is slightly adjusted and then passed through an exponential function, which sharply reduces the movement cost as the slope increases. This modified slope is multiplied by a scaling factor of 6 to determine the final cost surface. The resulting cost surface provides a measure of terrain difficulty, where lower values correspond to easier terrain and higher values indicate more challenging areas to traverse.

```
# Function to calculate cost using Tobler's hiking function
def calculate_cost_tobler(slope, z_factor=1.0):
    # Apply Tobler's hiking function: cost = 6 * exp(-3.5 * abs(slope + 0.05))
    cost_surface = 6 * np.exp(-3.5 * np.abs(slope + 0.05))
    return cost_surface
```

Figure 29 The script for the Tobler's Hiking Cost Function

1. *Modified Tobler's Hiking Function*

An important aspect of this thesis is the application of a relatively new approach in cost functions that modifies Tobler's Hiking Function by merging it with the MIDE (Método de Información de Excursiones: Excursion Information Method) method (Paris Roche, 2002). Both of these methods are included in the list of approaches that take into consideration the concept of anisotropy (Marquez-Perez et al., 2017). The method has also been applied by Lewis (2017).

In the related script, the objective was to generate a cost surface using the Modified Tobler's Hiking function by combining Tobler's principles with the MIDE method. This technique was developed on empirical data collected by hikers, involving trails in Spain and the time needed to traverse them (Marquez-Perez et al., 2017, p. 54). The MIDE method estimates the time required to travel a route by considering its length and slope. It calculates time delays based on projected length and elevation change, adding half the lesser delay to the greater one (Marquez-Perez et al., 2017, p. 58). The method adjusts maximum speed according to terrain type.

Adjustments to the Modified Tobler's Function include reducing the base walking speed from 6 km/h to 4.8 km/h, reflecting the slower pace typically achieved on challenging terrain (Marquez-Perez et al., 2017, p. 58). Secondly, shifting the curve's turning point from -2.7° to -2.454° fine-tunes the model to better replicate actual hiking behavior, as hikers maintain optimal speed on slightly less steep downhill slopes (Marquez-Perez et al., 2017, p. 58). Lastly, multiplying the impact of slope by a factor of 0.7 reduces the sensitivity of the model to slope changes, aligning it more closely with observed data where hikers can sustain higher speeds even on inclines (Marquez-Perez et al., 2017, p. 58). These modifications aim to balance the advantages of Tobler's function with the empirical precision of the MIDE method, resulting in a more realistic tool for estimating travel times on mountainous terrain and providing a more accurate model for hiking movement (Marquez-Perez et al., 2017, p. 58).

The Modified Tobler's Function Formula is:

$$Cost = max\ \_cost\_value - (4.8 \times e\ (-5.3 \times abs\ ((slope_{deg} \times 0.7) + 0.03))$$

$slope_{deg}$: $slope\ of\ the\ terrain\ in\ degrees$
e: $calculates\ the\ exponential\ factor$
abs: $calculates\ the\ absolute\ value\ to\ ensure\ that\ the\ slope\ value\ is\ positive$
$max\ cost$: $the\ maximum\ cost\ value\ of\ the\ surface$

2. Function to invert Cost Values

Initially, the slope is calculated using Tobler's hiking function, while the Modified Tobler's function is used to compute the cost surface. To aid in visualization, a function for inverting cost values has been implemented. This inversion addresses an unexpected issue where low values, representing high costs, can lead to counterintuitive results, such as areas that should be inexpensive appearing as high-cost zones (Fig. 31). To align the cost values with the expected outcomes, the inversion function subtracts the original cost surface values from the maximum value of the cost surface. This adjustment effectively flips the cost values, so that areas of low cost become high and vice versa, providing a more intuitive representation of the cost surface (Fig. 32). This script focuses on functions to better visualize the resulting cost surface. Basic statistics are computed to inspect the quality of the resulting cost surface and ensure its correctness.

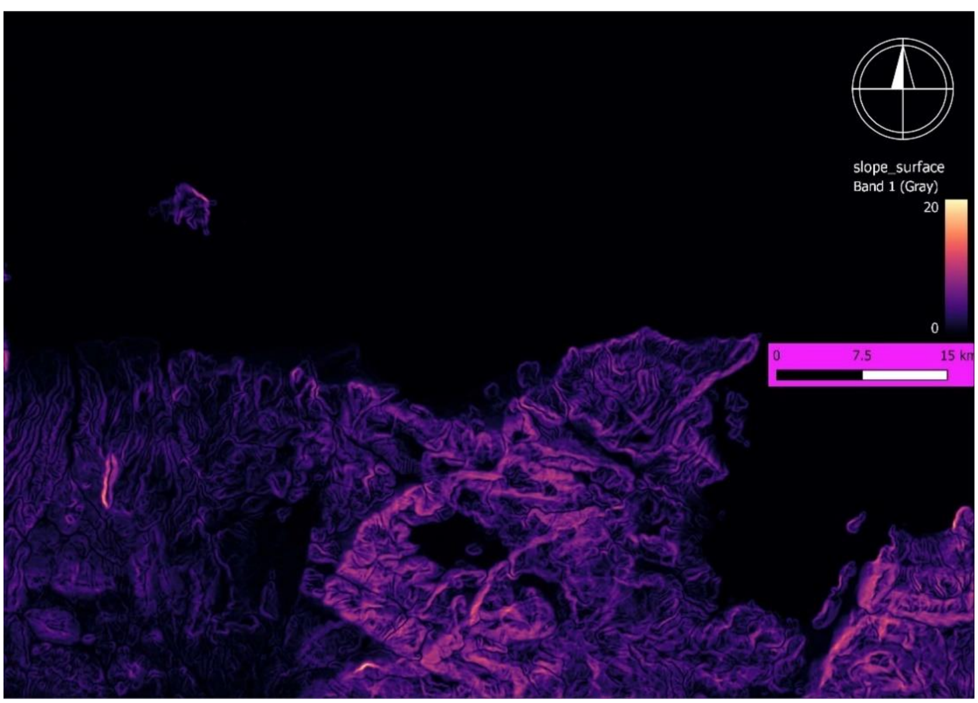


Figure 30 Slope Surface Based on Tobler's Hiking Function. Slope displayed in degrees

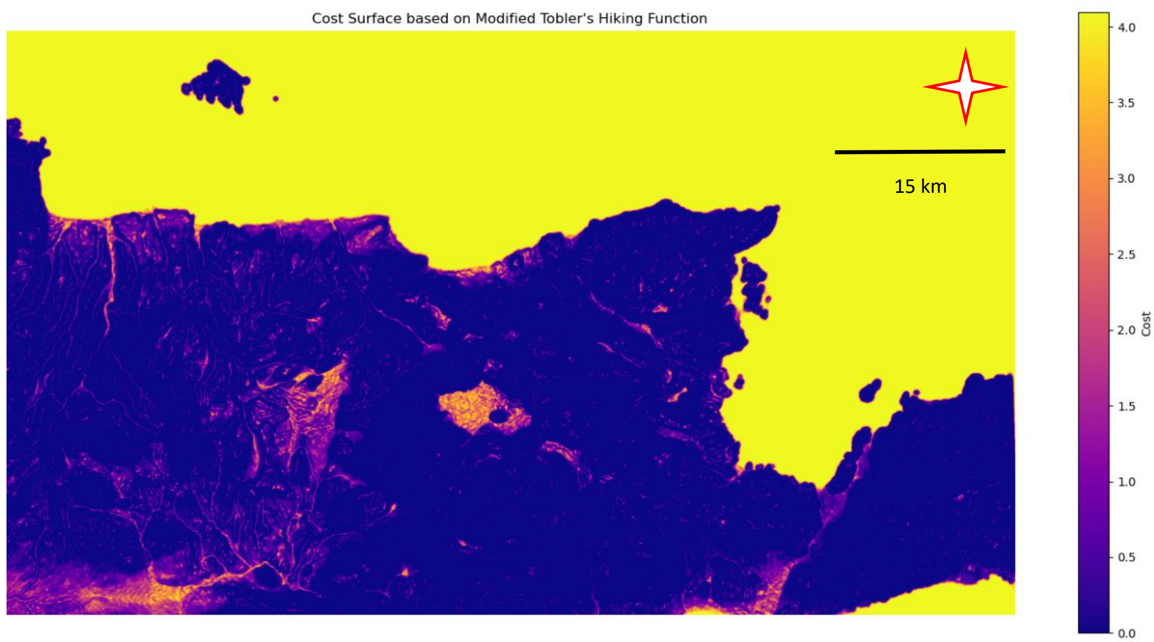


Figure 31 Incorrect Cost Surface with Low Costs as High Values and High Costs as Low Values

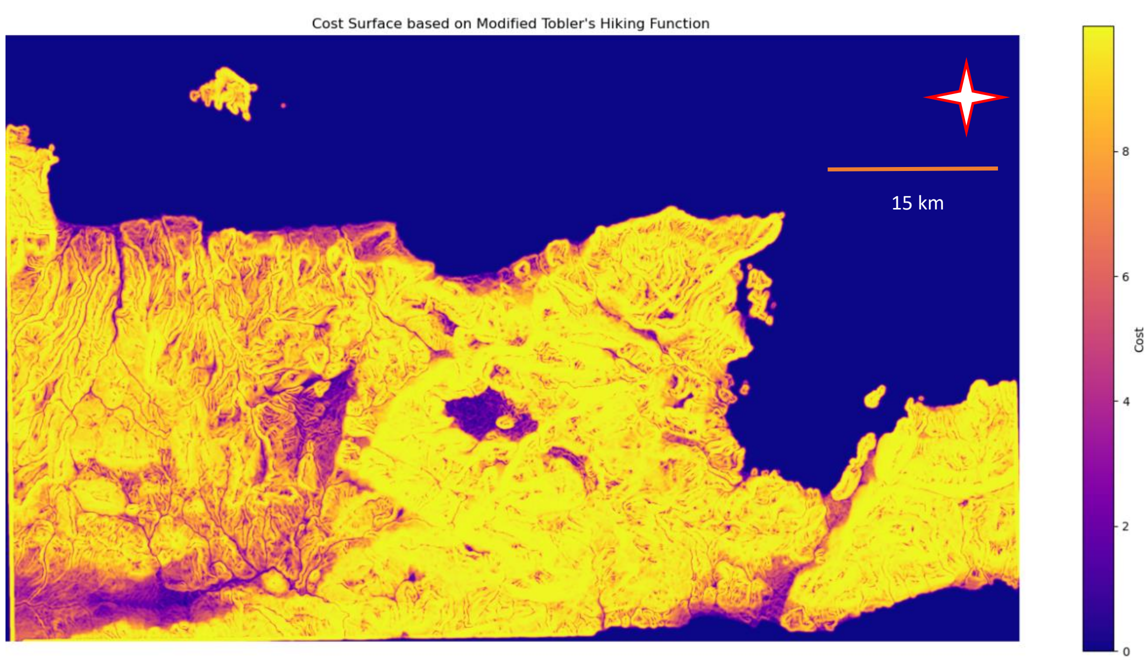


Figure 32 Inversed Cost Surface showing Cost Values correctly

3. Further modifications to the Modified Tobler's Hiking Function

Adjustments were made to the original formula to enhance visualization without affecting the relationship between slope and cost. These modifications were tailored to better represent the conditions of walking in Crete's mountainous and diverse terrain, as an effort for more accurate modeling of movement cost that would eventually generate more genuine least-cost paths (Fig. 33). For this purpose, different parts of the formula were edited.

First, the slope ($slope_{deg}$) value of the original formula is scaled by a factor of 0.5 to compress its range, ensuring an accurate computation that indicates its variations without extreme transitions. In the Cretan context, with the landscape that is described by rich variations from gentle inclines to steep climbs, applying this change provides a balance in the model, between sensitive slopes and realistic walking conditions. Secondly, the absolute value of the slope (abs) is applied so that all input values remain positive. This step maintains the validity of the computation and provides consistency for uphill and downhill slopes in the terrain. This is crucial for creating a cost surface that is logical considering real-world hiking experiences.

An important addition to the formula is the logarithmic compression (log). This function transforms the absolute slope values and smooths the cost surface by providing accuracy and representing the complexities of hiking on medium and steep slopes. The compression makes the model to show the gradual changes in the cost of walking that an individual would experience and giving a more realistic character to the model and the cost transitions. Its results are processed by an exponential function (exp) that inverts the compressing and defines better the relationship between walking costs and slope variations, by taking into consideration the reduced sensitivity of slope changes.

At last a scaling factor of 10.0 is multiplied by the result of the exponential function that benefits the visualization of the cost surface and scales it appropriately. This makes the range of cost values larger compared to the previous formula, but still on a practical level that is more fitting for the study area and the walking conditions of the specific region. The final form of the formula is the following:

$$Cost\ Surface\ =\ 10.0\ *\ exp(-3.5\ *\ log(1\ +\ abs(slope_{deg}\ *\ 0.5)))$$

These modifications were executed based on empirical experimentation with the original formula. The first goal was to create a cost surface that better reflects the conditions of the Cretan landscape, particularly in terms of slope and cost and to realistically model the walking experience of an individual traversing the landscape. Given the limited available data on other factors of walking it was essential to model the natural parameters as accurately as possible for the study of the LCPs. The second goal was to create a cost surface that is also visually enhanced. The logarithmic compression facilitates a more adequate representation of the gradual transitions in cost with slope, making the surface well suited for the application of the LCP algorithm (Fig. 34). The produced cost surfaces are exported into the GeoTIFF format, while also their projection is ensured to match the Greek Coordinate System (EPSG:2100) for consistency with the mapping standards used in my analysis.

5.5.4 List of Sites and Cost Surface Cropping

After handling the DEM data and creating the necessary cost surfaces, an important step was to identify the sites that will be used in the analysis. The sites that were selected are thoroughly explained in the *Archaeological Background* chapter. After choosing ten sites that are located in the area of focus, these were added into a csv dataset, based on coordinates that were accessed from Google Earth Pro.

With the use of GDAL, this list of coordinates was converted from the WGS84 Projection to the Greek system. After the conversion, the sites were visualized on top of the DEM and the Cost Surface. Moreover, the geospatial data were converted to limit the borders of the study area, to make the files lighter and easier to manipulate for the analysis and the implementation of the pathfinding algorithms.

The cropping of the area was based on the creation of a simple polygon, in Google Earth Pro, which was converted to the Greek projection (Fig. 35). The result is a much smaller area where all the sites chosen are included (Fig. 36). After this step, the conditions to proceed to the generation of the LCPs are matched. The cost surface was cropped to allow the algorithm to operate on a smaller dataset extent.

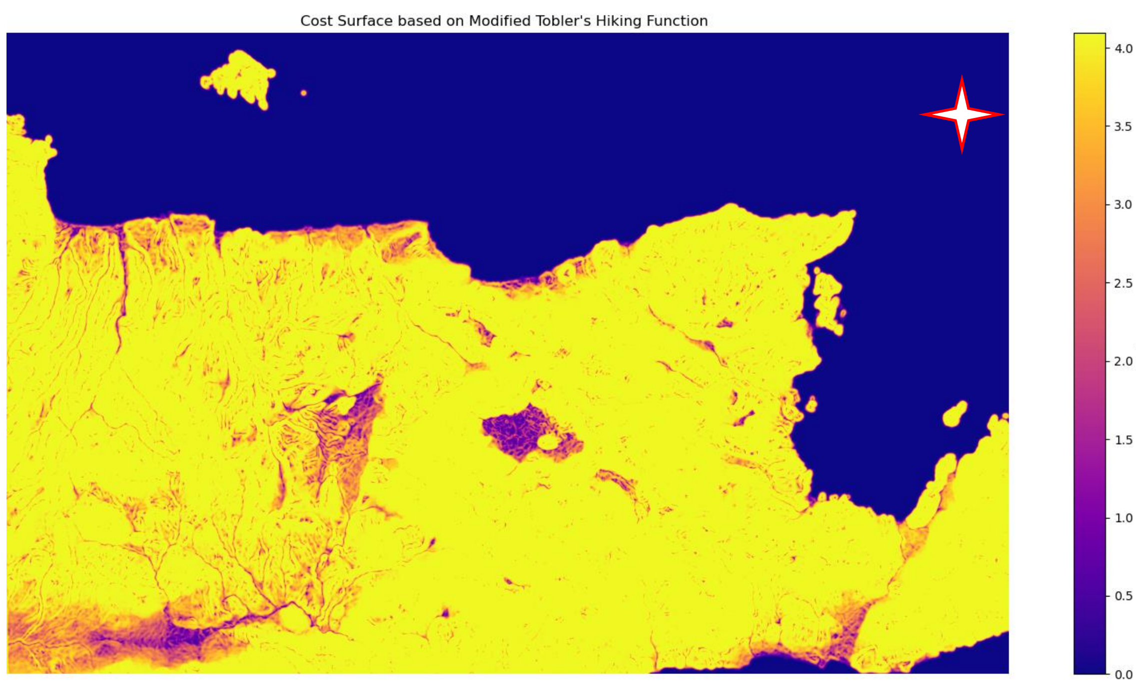


Figure 33 Cost Surface based on Modified Tobler's Hiking Function. Before the extra modifications

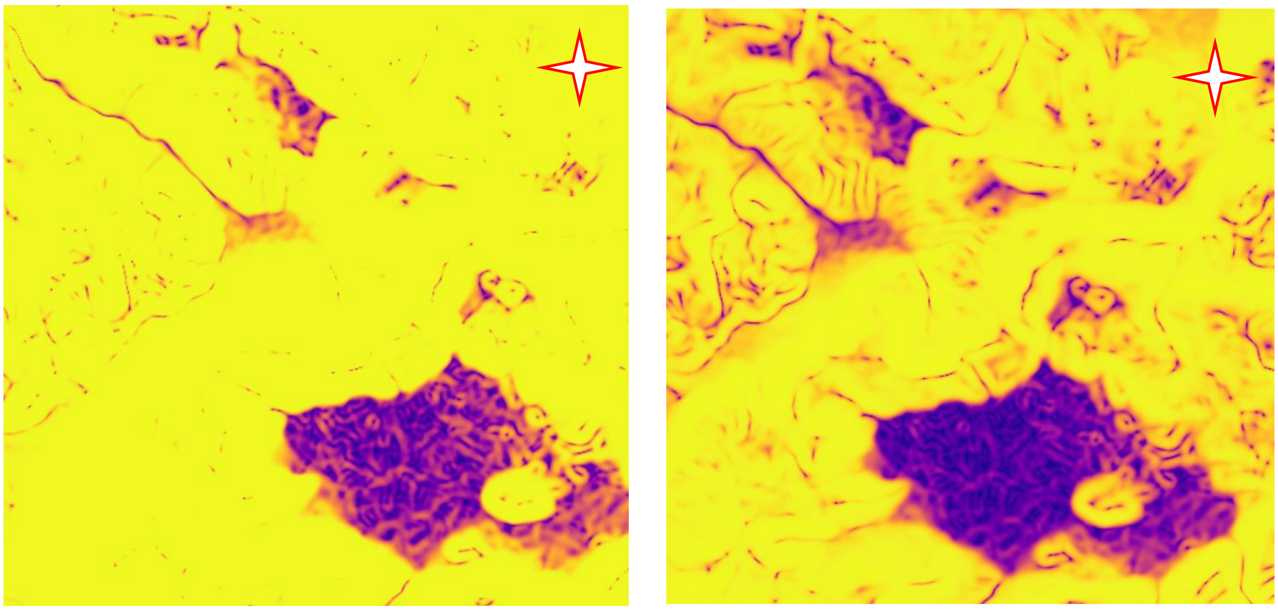


Figure 34 Details from the Cost Surface. The condition before (left) and after (right) the formula's modifications

Figure 35 Cost Surface Cropped on the Study Area

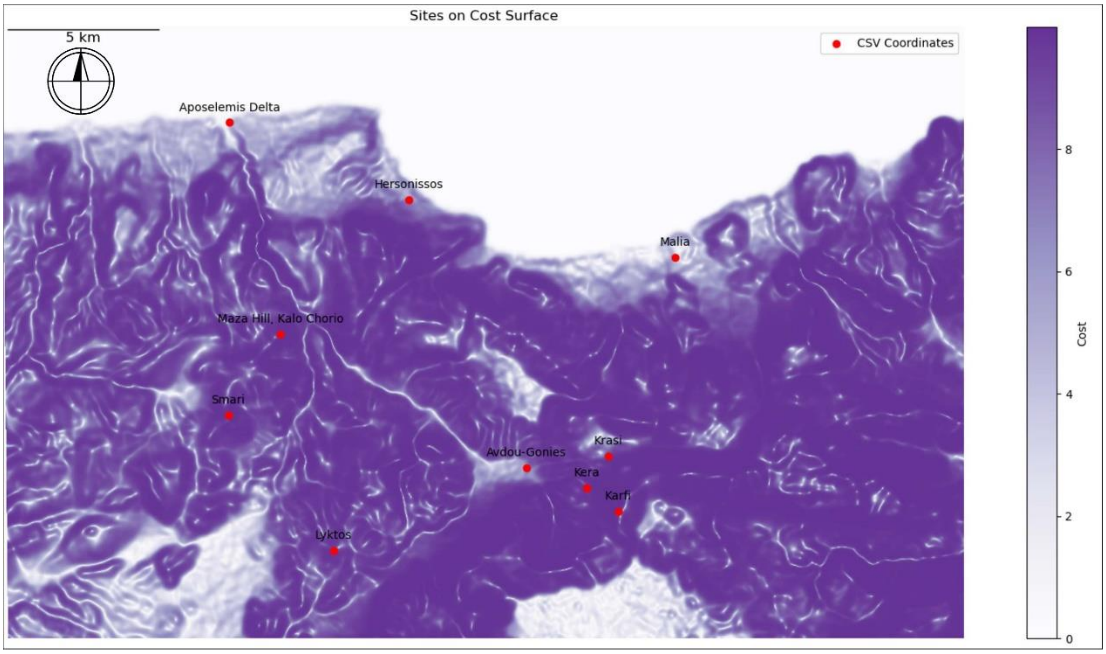


Figure 36 The main sites used in the analysis and some additional ones overlayed on the Cost Surface

5.5.5 Least Cost Paths

One of the main goals of this thesis is to examine the route network and connectivity between the sites of Lyttos and Hersonissos. As is already known these two major cities of Crete were heavily dependent on each other, especially during the Roman period. However, this project aims to explore when that relationship starts forming. It is generally hypothesized that these sites started developing during EIA period, while it is believed that Lyktos had control of the entire study area during the Hellenistic and Roman periods.

However based on older surveys it is also believed that the path network of the area had been developed ever since the Minoan period, and it remained the same for a long chronological period (Mavraki-Mpalanou et al., 2016). One of the main route arteries is believed to start from Lyktos, then moving to the Avdou-Gonies valley, on the northeast, where a vast majority of Minoan, EIA, Hellenistic and Roman sites have been located. The geomorphology and topography of the island of Crete pretty much define the terrain of the specific area. As the cost surfaces show, the path corridors can be observed with the naked eye.

Based on these ideas, the goal was to produce paths from Lyktos to Avdou-Gonies and from Avdou-Gonies to Hersonissos. At first, the CSV file that includes the coordinates and the Cost Surface based on the modified version of Tobler's Hiking Function is imported into Spyder. The files are firstly ensured that they are still projected in the correct coordinate system.

1. Functions created

At first, a function to extract the cost from the points that are selected was created. This function takes as inputs the selected points and transforms them from real-world locations into pixel coordinates in the raster dataset. The result is the cost of each point. The second function is a function to determine indices of the nearest cells in the raster from the given points. As the previous function, it takes the input points and converts them into pixel coordinates, which are then rounded to the nearest integers so as to identify and locate the nearest cells. This rounding identifies and locates the closest cells in the raster. Both functions are essential for handling and extracting information from raster data, to treat them based on the nature of the real world and they are often used in geospatial analysis. Additionally, the two coordinate conversion functions, which transform coordinates into the Greek coordinate system (EPSG:2100), are used to ensure that geographic transformations are correctly applied.

2. Paths

Before running the path-finding algorithm, the sites of the dataset and the ones that will be used as start- and end-points were visualized on top of the cost surface. For the generation of the paths, the algorithm that was used was accessed from the "scikit-image library", and more specifically from the "skimage.graph" module (Van der Walt et al., 2014). This module provides a variety of functions for graph-based operations and it is commonly used in image processing and computer vision operations. However, before running the algorithm it was deemed necessary to mask values of 0 appearing in the cost surface. Values of 0 were replaced with high-cost values. This masking operation is crucial to handle zero values in a proper manner, ensuring that the path-finding analysis does not misinterpret them. By replacing them with high values, the script prevents these areas from being selected by the path-finding algorithm and improves the quality of its results.

The "route_through_array" function efficiently finds paths through grid-like structures that represent a terrain or a surface. It takes parameters such as "cost" (2D array indicating traversal costs), "start" (starting point), and "end" (ending point). Additionally, it uses "fully_connected" to specify connectivity type with a choice of 4 (orthogonal) or 8 (orthogonal and diagonal) neighboring cells, and "geometric" for calculating distances (Euclidean or geometric). This function is invaluable for navigating grids, considering costs, connectivity, and distance to determine optimal path parameters, also a Boolean value, dictates whether the algorithm should compute distances between cells using the Euclidean (straight line distance) metric or a simpler geometric method. These parameters collectively enable the `route_through_array` function to efficiently determine the optimal path through the grid, taking into account various factors such as costs, connectivity, and distance calculation methods.

The function returns two main values: `indices` and `weight`. `indices` represents the row and column indices of the cells along the computed path. It provides the sequence of cells traversed from the start to the endpoint. Meanwhile, `weight` denotes the total cost or weight associated with the path, indicating the cumulative cost of traversing through the grid cells from start to end. These return values are crucial for analyzing and interpreting the computed paths, providing insights into optimal routes and associated costs within grid-based environments.

The function uses a modified version of Dijkstra's algorithm to compute a path. The cost surface is considered as a graph by the algorithm, in which each cell represents a node, and every neighboring one is considered as an edge. The algorithm starts from the start point and creates the path to reach the end point, based on the lowest cost values of the grid. The "fully_connected" parameter is a Boolean one. In this case, the parameter is set to "True", which considers 8 neighboring cells. At last, the "geometric" parameter is also set to true, so as to compute distances based on the Euclidean approach, that is more accurate, however more computationally expensive.

At first, single paths were computed, just to briefly explore the results of the algorithms. Multiple paths were also computed based on the same approach and by using the same function. By generating multiple paths variability is introduced in the cost surface. The original cost surface is imported with the inclusion of random noise and it helps to take into consideration uncertainty and environmental conditions of the terrain. To put it simpler, this variation creates 5 different cost surfaces to produce 5 different paths for each point-pair (The selection of the number of variations is defined by the user). Each altered cost surface shows a different scenario for movement, which can help understand decision-making based on possible terrain changes, the existence of obstacles, or other factors. The multiple paths allow the opportunity to explore how an individual might have changed their decisions based on different factors and show different possible routes. These paths, due to the introduction of variability are slightly different each time the algorithm is executed. Their variations can be observed both visually, as in the statistics they produce.

The same procedure was followed for each point-pair (Lyttos to Avdou-Gonies, Avdou-Gonies to Hersonissos). However, a new site was included to direct the algorithm's movement to pass from the hypothesized path network of the study area. Without its addition the algorithm would follow a path that does not match with reality and that will be discussed further in the *Results* chapter. The site is the site of Xerokamares, on the north of Lyktos and to the south of Hersonissos. The site is not connected to the EIA, but remains of the Aqueduct that was connecting the two cities have been found nearby. The nearby sites of Smari and Maza Hill are connected to the period of focus. The site is used due to the hypothesis that the path network of the area was created earlier than the period of study, in the Minoan Era. Xerokamares is located on the north-west of the village of Potamies, and it is located along the cross of the Aposelemis

River. By incorporating this site the path follows the route of the river, where on both sides of its flow sites from a variety of chronological periods have been found, as well as EIA ones (Mavraki-Mpalanou et al., 2016), further enhancing the hypothesis on the existence of the same path network for a long time. This will be discussed more extensively in the *Discussion* chapter. A path from Lyttos to Xerokamares was also computed to test the hypothesis that a route would possibly pass from there, considering the existence of the nearby sites. After producing the paths, they are all visualized on top of the cost surface. Moreover, they are exported and saved in JSON format so that they can be available for importing into a GIS.

5.5.6 Statistical Analysis of the Paths

After generating the Least Cost paths, both as single LCPs and the multiple alternative ones for each point-pair, the next step was to generate basic statistics. Regarding the single paths only the total length and the total cost of each path was calculated so that they can be compared with the same metrics of the QGIS paths. On the other side, on the multiple paths more metrics were computed to get a more exploratory view on the different paths that were created to compare their differences. The additional metrics include the elevation gain and loss of each path, their average slope in degrees, and their number of segments.

The total length was computed by summing up the Euclidean distances between consecutive points of a path. The straight line distance (Euclidean) between each adjacent point is calculated and summed up, considering the space of activity is 2-dimensional. The total length is the sum of these distances for each segment that a path consists of, providing a general measure for the horizontal distance that each path covers. The total cost is computed based on the cost surface. The 2D grid consists of cells, that each one represents the cost of crossing it. The cost values of the cells intersected by the path are summed to determine the total cost, providing insight into the relative difficulty of traversing each path.

Elevation gain and loss are metrics that represent the positive and negative changes in the elevation of each path. Gain is computed by summing up all positive transitions, while loss is the sum of the negative ones. Gain and Loss are calculated based on the DEM data. Then, the average slope for each path is calculated based on the “Rise over Run” formula. The slope of every segment is measured by the ratio of elevation change to horizontal distance, and then the values are averaged and converted into degrees, indicating the steepness of each path. At last, the number of segments (straight-line sections) comprising each path is provided to have a more detailed and granular view of the paths to inspect their complexity. These statistics are beneficial for a better inspection of each path’s characteristics and facilitate their comparison both between themselves, and those created by QGIS. Statistics were calculated by treating the paths as DataFrames, using the Pandas library (McKinney et al., 2010), and then exporting them into table format as CSV files.

5.6 QGIS Workflow

An important aspect to check the quality of the Computed LCPs is to compare the results of the script with the results that are generated by the LCP algorithm provided by QGIS. QGIS 3.26 “Buenos Aires” was the version of the software that was used for the creation of the paths. In Fig. 37 the workflow to execute the algorithm is shown. As is normal for creating LCPs, the algorithm demands as inputs a cost raster layer, the band of the cost raster, a starting point and an ending point. The cropped version of the Cost Surface that was based on the Modified Tobler’s Hiking Function was used, so as to direct the paths to move inside the borders of the study area, without following irregular directions for movement.

The algorithm relies on several key components: a Cost Raster Layer, which provides a numeric representation of traversal costs per spatial unit, ensuring absence of negative values, with NoData pixels denoting unreachable areas; The Cost Raster Band specifies the bad of the raster used for cost calculations; a Start-point Layer containing a singular origin from where the path begins; an End-point(s) Layer with destination point(s) indicating target location(s) for the determination of the path. By default, the algorithm computes paths to all provided destinations. However, an option to solely connect with the nearest endpoint can be enabled. Additionally, an optional feature to include Linear Referencing in PolylineM type outputs the least cost path with accumulated costs as linear referencing values, but it was not utilized in my analysis. The algorithm provided by QGIS makes use of a variant of Dijkstra’s algorithm designed for efficient shortest-path calculations on a weighted graph.

In comparison, the Python approach shows several distinct differences. The Cost surface data in Python is represented as a 2D array, demanding explicit manipulation, unlike the automatic handling provided by QGIS. Start and End Points in Python require more specification and their transformation into raster cells, while QGIS treats them as separate layers. Connectivity and distance metrics are customizable features in Python (Selection of Neighboring Cells) and not built in as in the GIS. Moreover, QGIS handles visualization and output management through its GUI (Graphical User Interface). The QGIS approach relies on its integrated tools, while Python provides flexibility.

The first path that was generated was the one passing from Lyktos to the Avdou-Gonies Valley. Next, an effort to generate the path from Avdou-Gonies to Hersonissos was made, however the path would take an alternate route, in comparison to the hypothesized path. As will be discussed in the *Results* chapter, this path made better sense than the one generated on Spyder. For this reason, as in the script, the site of Xerokamares was included to direct the algorithm. At last, a path from Xerokamares to Hersonissos was computed to reach the end-point.

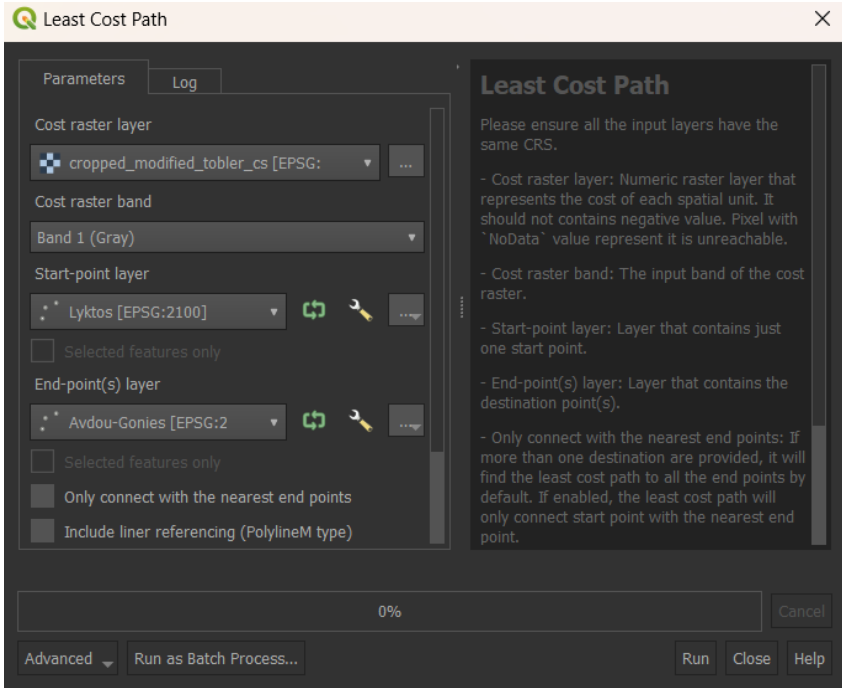


Figure 37 QGIS LCP User Interface

A notable point is that the input data used in the analysis were processed through Python. Although QGIS offers various tools for handling raw Digital Elevation Model (DEM) data and creating cost surfaces, this thesis aims to explore processing techniques and cost functions that are not readily accessible through the software. Consequently, QGIS was employed solely for the creation of the paths, while Python was used for the more specialized data processing and analysis tasks.

5.7 Statistical Analysis of QGIS and Python paths

After the creation of the paths from both QGIS and Python, it was deemed necessary to statistically compare them so as to have a better perspective on the quality of the results, besides visual inspection. The path lengths and costs were compared and the hypothesis on their similarities was tested through the use of of paired t-tests. This way it is better to explore the differences between the two approaches and evaluate the results of Python from a statistical perspective.

The hypothesis that is tested is the following:

$\underline{H(null): There\ is\ no\ significant\ difference\ in\ the\ lengths\ and\ costs\ of\ paths\ by\ the\ two\ methodologies}$

The selected technique for hypothesis testing was chosen due to its potential for conducting the desired comparison. The approach of paired t-test, also known as a dependent t-test is a statistical method that is used for comparing the mean values of related groups of data, as in this case the lengths and costs of the paths from the two approaches.

5.8 ChatGPT

The ChatGPT AI-Language Model was extensively utilized in the methodology of this thesis. It played a key role in assisting with coding tasks and, to a lesser extent, image editing, significantly contributing to the development of the research. Given the focus on studying geospatial issues from a programming perspective, the limited availability of relevant online documentation presented a notable challenge. ChatGPT's capabilities were instrumental in addressing these challenges. Both the free version and the 4.0 model were used, with the latter proving particularly valuable for more complex tasks such as code analysis and advanced image editing. Additionally, custom GPTs created by users, such as ScholarGPT and GEO+, provided essential support for specific academic needs. GEO+, for example, was especially useful for geospatial analysis tasks, demonstrating the relevance and adaptability of these specialized tools in academic research.

6. Results

6.1 Brief Overview of the Results

This chapter will present the results of the applied methodology. Initially, the outcomes of the data processing will be discussed through visual and statistical exploration, focusing primarily on the smoothing and interpolation techniques that were employed. Subsequently, the creation of the cost surface used in the analysis will be evaluated. Finally, the paths generated by Python and QGIS will be presented to assess the two methodologies. This chapter aims solely to cover the outputs of the machines; their interpretation and relevance to the broader research questions will be addressed in the *Discussion* Chapter.

6.2 Results of the Data Processing

A statistical evaluation between the original and smoothed DEMs was conducted to understand the results of the data processing steps. This evaluation aimed to explore the internal values and provide a more comprehensive perspective beyond visual inspection. Visually, the smoothing technique results in a slightly blurred version of the original dataset, indicating the effect of Gaussian filtering.

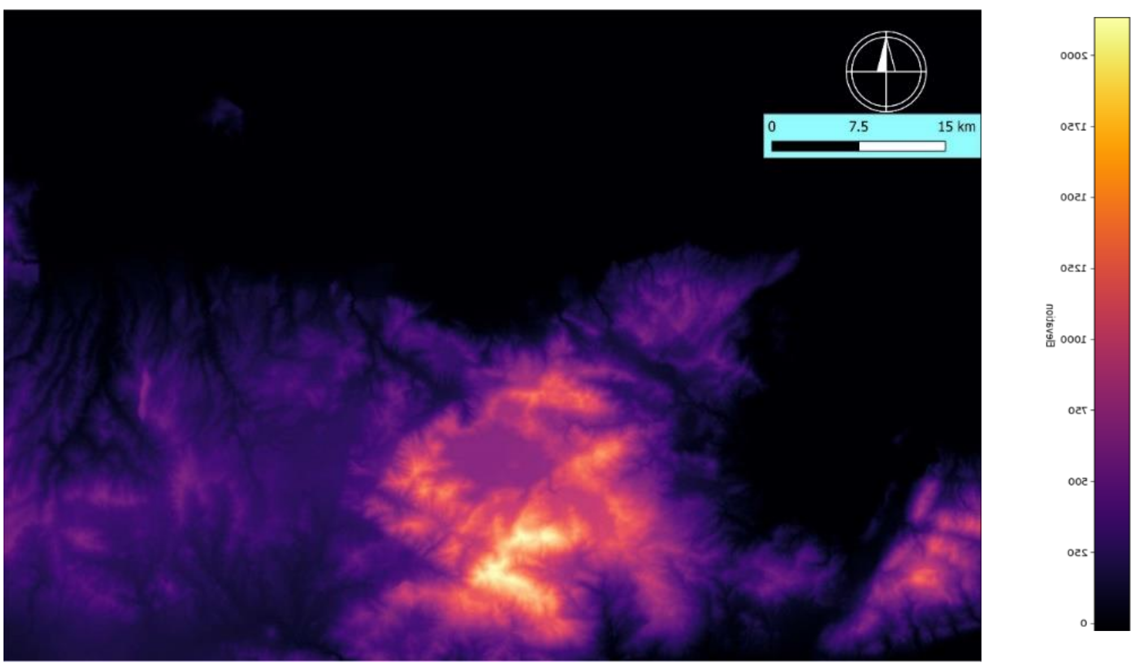


Figure 38 Raw DEM

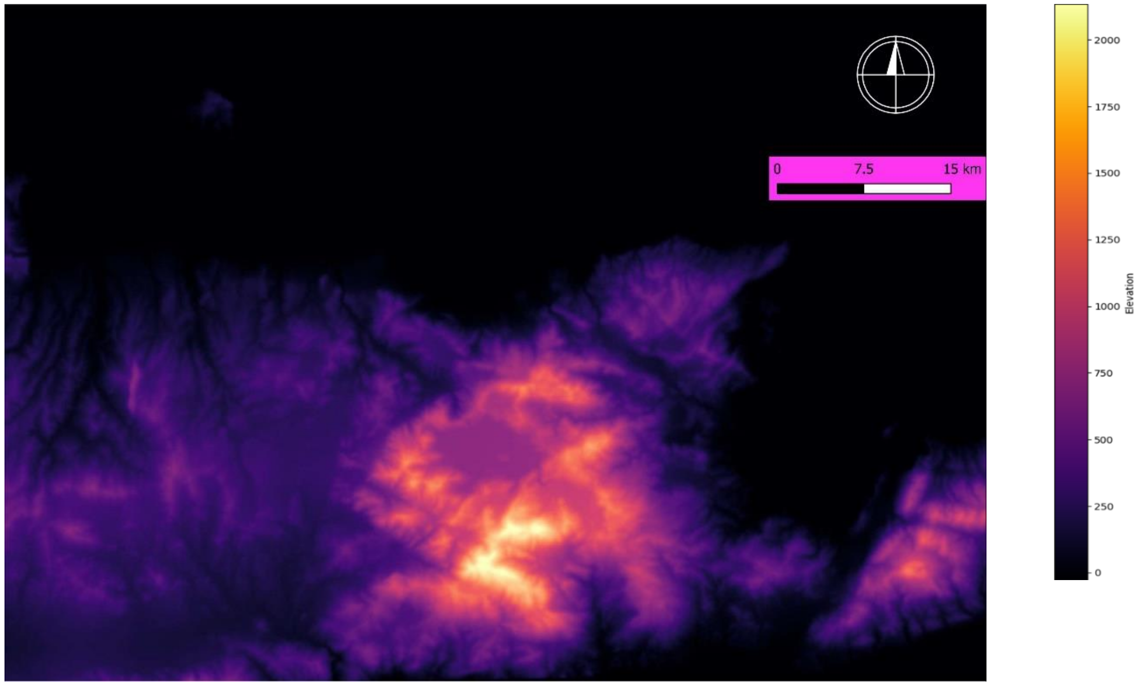


Figure 39 DEM Post-Smoothing

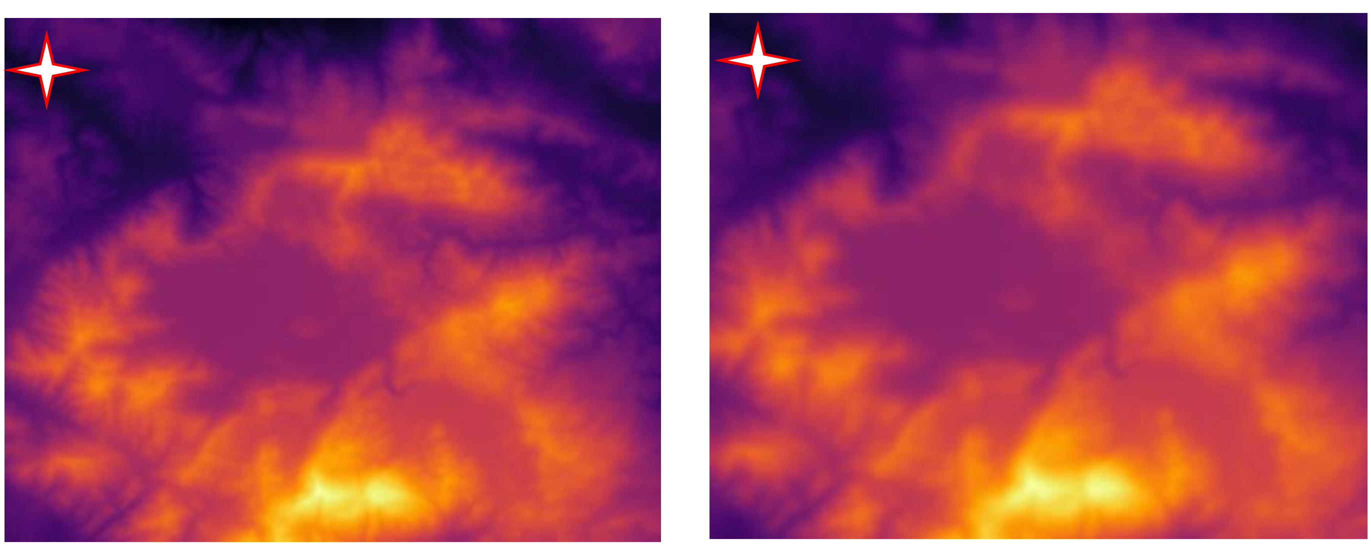


Figure 40 Details from the Original (Left) and Smoothed (Right) DEMs showing a part of the Study Area (Lasithi Plateau). In the smoothed one a blurred effect can be observed indicating the influence of the smoothing technique

The original and smoothed DEM present minor changes regarding their basic metrics (Fig. 38, 39, 40). The most important difference is on the minimum elevation that in the original DEM is at -29 m., but due to the function that changes negative values to 0, the smoothed DEM has a minimum value of 0. The maximum elevation shows a minor change of 35 m., with the raw DEM being at 2,135 m. and the smoothed at 2,100 m. The mean elevation is close to 125 m. for both cases, while the standard deviation is 274.2 m. for the raw DEM and 273.6 m. for the smoothed one. These metrics indicate that the effects of the smoothing technique were gentle and it managed to keep the dataset as intact as possible, maintaining the variability of the terrain.

Advanced metrics such as RMSE and MAE were also computed for the smoothed DEM which had an RMSE of 4.18 meters, demonstrating a moderate average deviation between the two datasets. The MAE, which measures the average magnitude of errors in a set of predictions, had a value of 1.59 meters between predicted elevations and those from the original dataset, further validating the effects of the smoothing and the gentle treatment of the data.

Regarding the interpolation, its role does not appear to enhance the quality of the dataset significantly. Its effects are minor compared to the smoothed DEM, indicating that the quality of the original SRTM DEM, with a simple smoothing effect, is adequate for conducting the Cost Surface creation and LCP analysis. Nevertheless, its removal negatively impacts subsequent steps in the coding process, as it affects the geographic alignment of the DEM data.

6.3 Cost Surface

In this study, a variety of cost surface models were created to explore which could provide the best approach for modeling the cost of walking on the Cretan landscape. The initial slope surface, created based on Tobler's function shows a broad range of terrain steepness with a mean slope of 2.24 degrees and a Standard Deviation of 2.63 degrees. This shows that the landscape is defined by gentle slopes and larger fluctuations. The cost surfaces were modeled based on this slope surface.

The simple Tobler's Hiking Function provides a cost surface with a maximum cost value of 5 and a standard deviation of 2.17, serving as a baseline but lacking the potential to manage the steepness of the terrain. On the other hand, the Modified Tobler's function produces an improved surface, compared to its original approach, by introducing parameters that are better for modeling real-world hiking behavior and conditions. The reduced maximum cost value (4.09) and standard deviation (1.77) offer a more detailed model regarding the difficulty of the terrain.

The further refinement of the Modified Tobler's Function with the extra adjustments presents a more suitable approach. The inclusion of the logarithmic compression and the scaling modulation produces a more accurate and visually appealing cost surface. With the increased maximum cost value (9.99) and the standard deviation (3.94), a more precise representation of the terrain's steepness and its gradual transitions is achieved. The lower mean cost compared to the Modified Tobler (Modified: 3.00, Extra-Modified: 2.37) suggests a better balance on high and low-cost areas of the surface, enhancing the quality of the model on representing the local parameters of the Study Area, and making it more suitable for the LCP analysis.

6.4 On the Python-Generated Paths

In general, the paths generated through Python follow the optimal routes based on the low-cost values of the cost surface. An important aspect of movement in the Cretan landscape is the limitations created by the island's topography. In the specific region of Minoas Pediada and the Aposelemis Valley, the mountainous terrain dictates the direction of movement. The rough outlines of the paths can be readily observed with the naked eye on both the DEM and the Cost Surfaces.

As mentioned in the *Methodology* chapter, besides the single paths (Fig. 41), multiple paths were also computed that are characterized by the introduction of variability in the cost surface. These multiple paths generally follow similar routes but they are slightly different each time the algorithm is executed. The difference is visually apparent (Fig. 42, Fig. 43), and also in their statistics. The resulting statistics are merely indicative samples, rather than fixed values. In the description of the paths, the ones that were generated by one run of the algorithm (Based on the paths from Fig. 43) are discussed to provide a general overview of the paths' characteristics. Most times the resulting paths are almost the same, but the possibility for the generation of outliers is evident, due to the variability that is applied to the cost surface. (See Appendix B for a larger Map of Single Paths and Appendix C for Multiple paths)

*** Python Single Paths are visualized with a title on the upper part of the image. The Purple Cost***

Surface is the same for both Python and QGIS

****Scales Included only on the Images displaying Paths for all Point-Pairs****

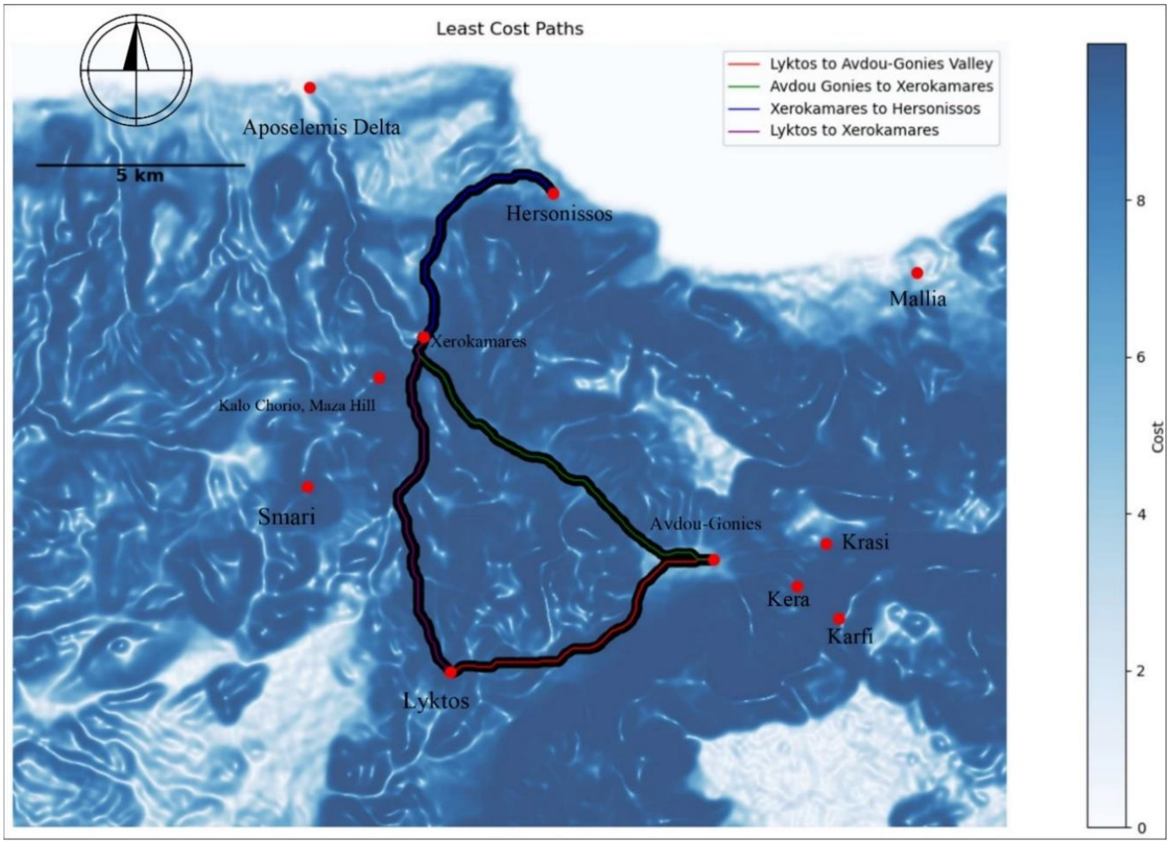


Figure 41 Single-Paths generated in Python

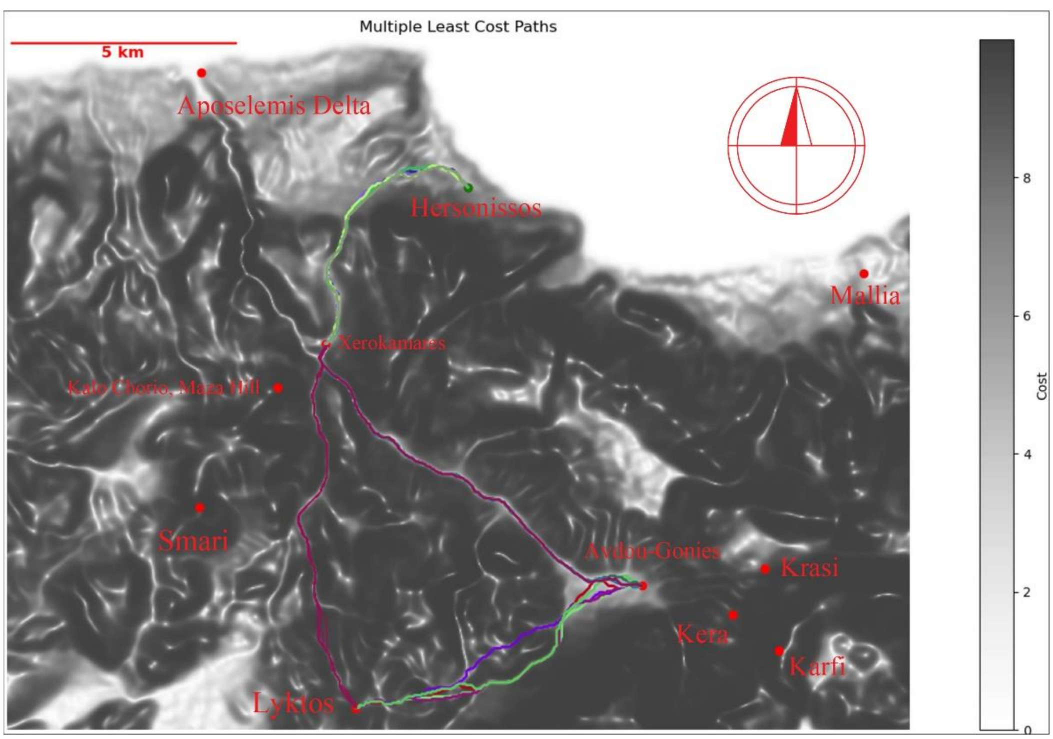


Figure 42 Multiple LCPs – Example 1

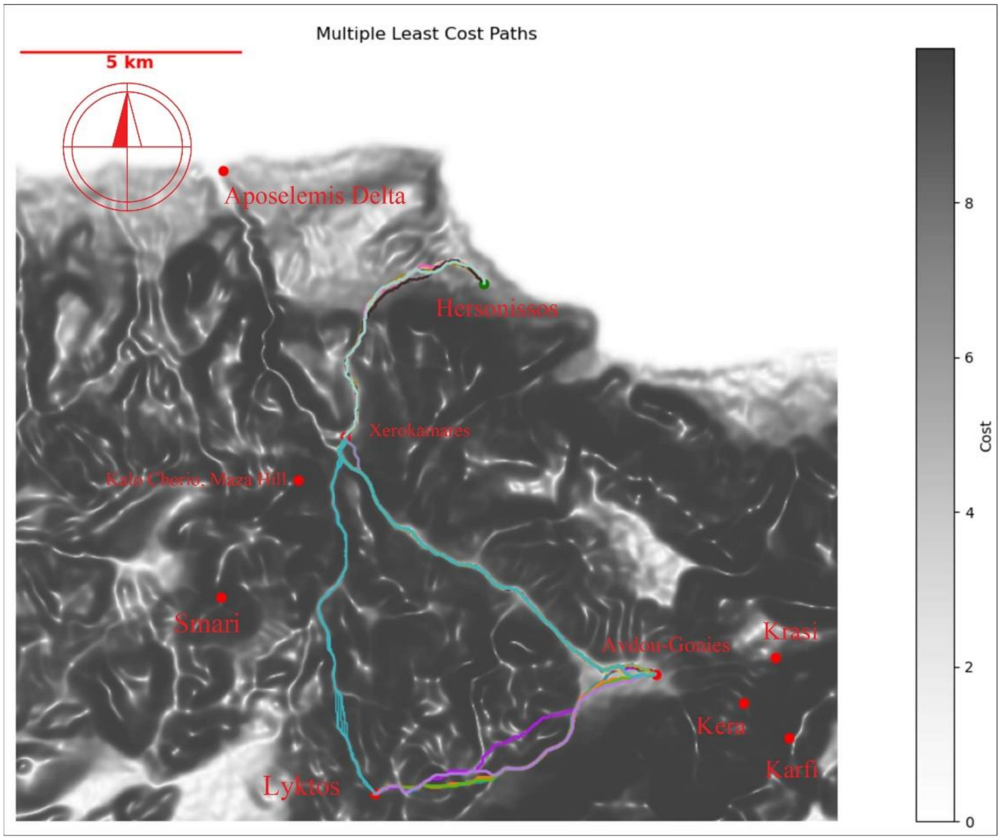


Figure 43 Multiple LCPs – Example 2

Table 1: Multiple-Path Statistics based on the paths from Example 2 (Indicative sample)

Path Label	Total Length (km)	Total Cost	Elevation Gain (km)	Elevation Loss (km)	Average Slope (degrees)	Number of Segments
Lyktos to Avdou-Gonies Valley - Path 1	7.88	1571.41	0.09	0.46	3.89	238
Lyktos to Avdou-Gonies Valley - Path 2	8.21	1574.31	0.05	0.42	3.43	251
Lyktos to Avdou-Gonies Valley - Path 3	7.92	1600.81	0.05	0.41	3.43	248
Lyktos to Avdou-Gonies Valley - Path 4	7.89	1592.75	0.05	0.41	3.47	246
Lyktos to Avdou-Gonies Valley - Path 5	8.0	1576.78	0.05	0.41	3.31	247
Avdou-Gonies Valley to Hersonissos - Path 1	15.21	1584.39	0.22	0.45	2.54	451
Avdou-Gonies Valley to Hersonissos - Path 2	14.92	1531.8	0.22	0.45	2.52	439
Avdou-Gonies Valley to Hersonissos - Path 3	15.45	1562.58	0.22	0.45	2.45	457
Avdou-Gonies Valley to Hersonissos - Path 4	14.76	1558.14	0.22	0.45	2.57	439
Avdou-Gonies Valley to Hersonissos - Path 5	14.7	1598.85	0.22	0.45	2.53	434
Avdou-Gonies Valley to Xerokamares - Path 1	10.25	1113.41	0.04	0.15	1.02	295
Avdou-Gonies Valley to Xerokamares - Path 2	10.03	1137.41	0.04	0.15	1.12	289
Avdou-Gonies Valley to Xerokamares - Path 3	10.29	1115.41	0.04	0.15	1.03	293
Avdou-Gonies Valley to Xerokamares - Path 4	10.26	1099.53	0.04	0.15	1.03	293
Avdou-Gonies Valley to Xerokamares - Path 5	10.37	1115.34	0.04	0.15	1.01	298
Xerokamares to Hersonissos - Path 1	6.77	1161.25	0.06	0.18	2.07	205
Xerokamares to Hersonissos - Path 2	6.78	1143.14	0.06	0.18	2.08	204
Xerokamares to Hersonissos - Path 3	6.83	1163.61	0.06	0.18	2.07	207
Xerokamares to Hersonissos - Path 4	6.6	1130.68	0.06	0.18	2.1	196
Xerokamares to Hersonissos - Path 5	6.85	1158.04	0.06	0.18	2.04	207
Lyktos to Xerokamares - Path 1	9.29	1820.44	0.04	0.52	3.53	287
Lyktos to Xerokamares - Path 2	9.26	1854.48	0.04	0.52	3.51	288
Lyktos to Xerokamares - Path 3	9.24	1848.51	0.04	0.52	3.55	287
Lyktos to Xerokamares - Path 4	9.2	1861.88	0.04	0.52	3.54	287
Lyktos to Xerokamares - Path 5	9.22	1855.25	0.05	0.52	3.56	287

6.5 On the QGIS-Generated Paths

In QGIS, only single paths were computed (Fig. 56) to facilitate a brief comparison with those generated by the Python approach, ensuring their validity. Generally, the single paths in QGIS closely align with those computed in Python, exhibiting minor or no deviations (Table 5). In terms of complexity, as can be observed from the segments comprising each path, the paths from Lyktos to Avdou-Gonies and from Avdou-Gonies to Xerokamares have one extra segment in QGIS. They also present a fragmentary difference in length as they are longer but only for a difference of some meters. Regarding their cost, they show a lower value of cost units compared to the Python approach. (see Appendix D for a larger map of the QGIS Paths)

Table 2: Single Path Statistics for Python Paths

Path Label	Total Length (km)	Elevation Gain (km)	Elevation Loss (km)	Average Slope (degrees)	Number of Segments
Lyktos to Avdou-Gonies Valley	7.82	0.05	0.42	3.59	246
Avdou Gonies to Xerokamares	10.06	0.04	0.15	1.06	288
Xerokamares to Hersonissos	6.6	0.06	0.18	2.15	200
Lyktos to Xerokamares	9.2	0.04	0.52	3.59	287
Avdou Gonies to Hersonissos	14.07	0.22	0.45	2.52	430

6.6 Overview of the Paths

1. *From Lyktos to Avdou-Gonies*

The first path is the one connecting the site of Lyktos with the valley of Avdou-Gonies (Fig. 44). There is not a specific site in the area but a medium point between the villages of Avdou and Gonies was selected, that serves as a point for the navigation of the algorithm. It needs to be noted that the site of Gonies To Flechtron is located on the southeast of the selected site point, and along with the other sites that are located nearby, they justify the selection of this specific waypoint. The path follows the route of least resistance based on the given cost surface. The single path has an approximate length of 7.82 km and a total cost of 1557.28 cost units. Elevation gain is at 0.05 km and loss at 0.42 km. The average slope is at 3.59° with 246 segments giving shape to the path (Table 3, 5). The QGIS path is at 7.86 km and has a Total Cost of 1562.77 cost units, with one extra segment (Table 5).

In the case of multiple paths, alternative routes can be observed (Fig. 45). Out of the 5 alternative paths, 4 of them seem to follow similar navigation routes with minor changes, however the 5th (blue) takes a northern route. The paths between this point pair shows more deviations compared to the other paths. The total length is approximately 8 km and Total Cost ranges from 1570 to 1600 cost units. Elevation Gain and Loss show similar values (Gain: 0.05 km/Loss: 0.41 km) with one outlier (Gain: 0.09km/Loss: 0.46 km). The same path also has a distinct value of 3.89° in Average Slope compared to the others that are close to 3.45°. The sum of segments ranges from 240 to 250 (Table 1).

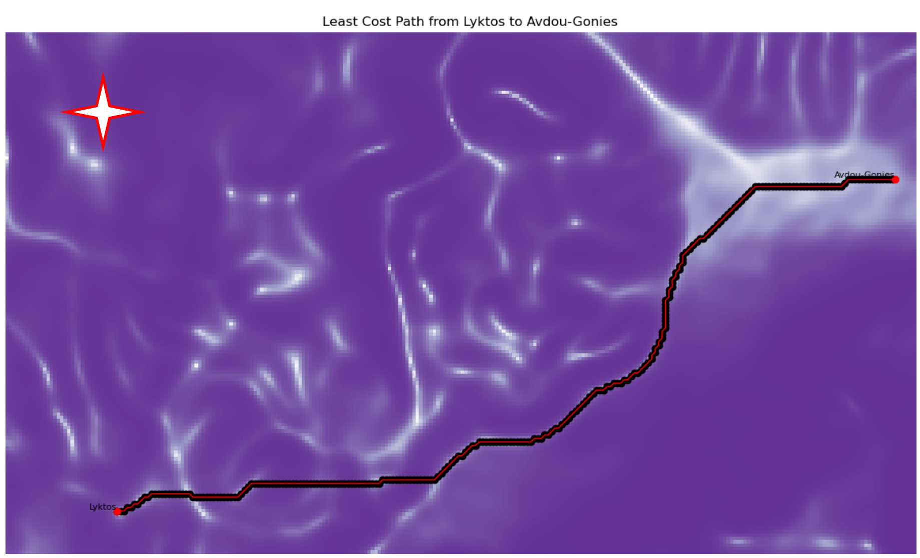


Figure 44 Single Path from Lyktos to Avdou-Gonies

Multiple Least Cost Paths between Lyktos and Avdou-Gonies Valley

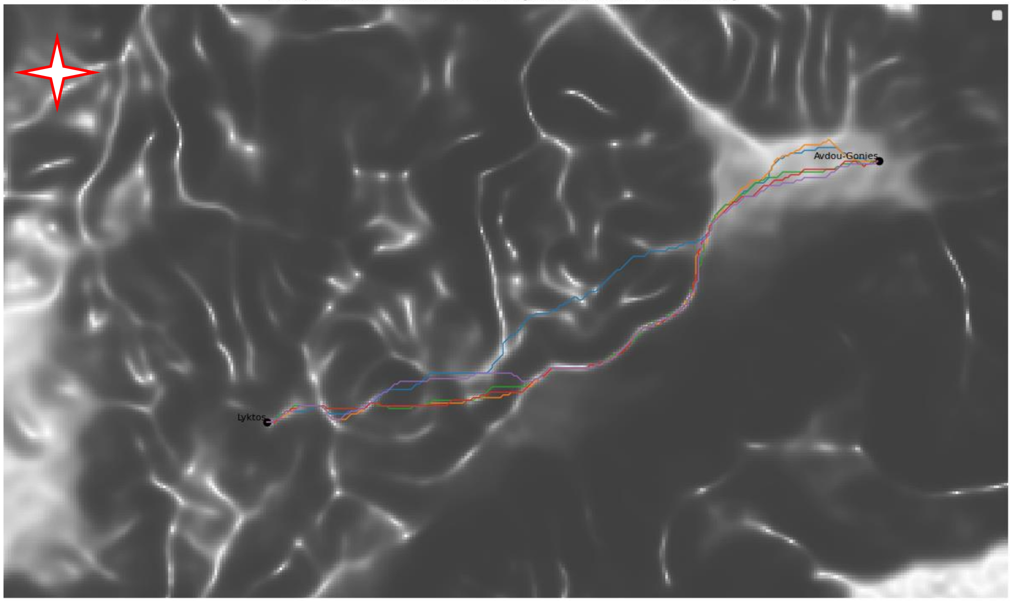


Figure 45 Multiple Paths from Lyktos to Avdou-Gonies

2. *From Avdou-Gonies to Xerokamares*

Regarding the path between the sites of Avdou-Gonies and Xerokamares, it can be observed that as in all paths, it follows the path of least effort, going from the areas of lower elevation (Fig. 46). The produced path travels parallel to the Aposelemis River. The single path has a total length of approximately 10.1 km and 1045.28 total cost. Elevation Gain and Loss are at 0.04 km and 0.15 km respectively. The average Slope is at 1.06° and the sum of segments is 288 (Table 3, 5). The QGIS path has the same length but a slightly higher cost, and as in the previous case, one extra segment (Table 5).

The multiple paths are more consistent (Fig. 47), with lengths ranging from 10 to 10.2 km with one close to 10.4 km (orange), costing around 1100 cost units, while Elevation Gain (0.04 km) and Loss (0.15) km are the same for all as in the single paths (Table 1). The average slope is at 1° with one exception being higher (at 1.12°) and the segments are mostly around 290 with one having 298.

Least Cost Path from Avdou Gonies to Xerokamares

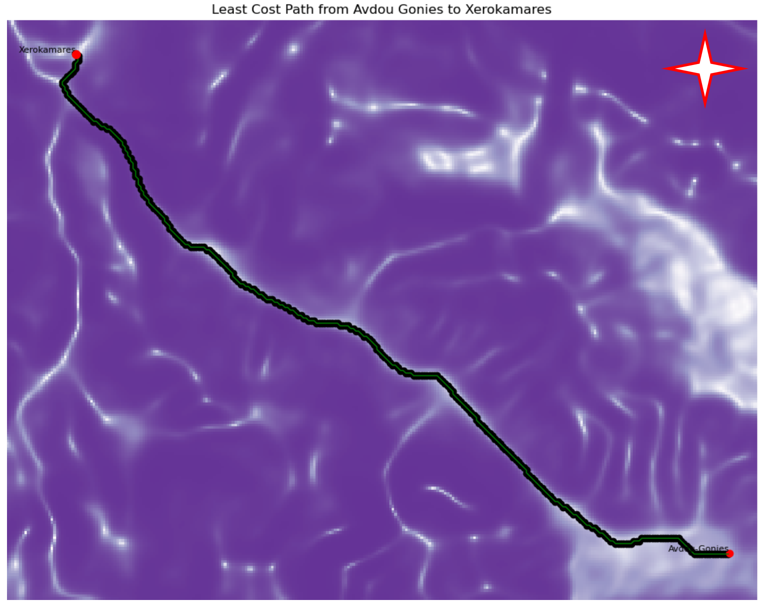


Figure 46 Single Path From Avdou-Gonies to Xerokamares

Multiple Least Cost Paths from Avdou-Gonies valley to Xerokamares

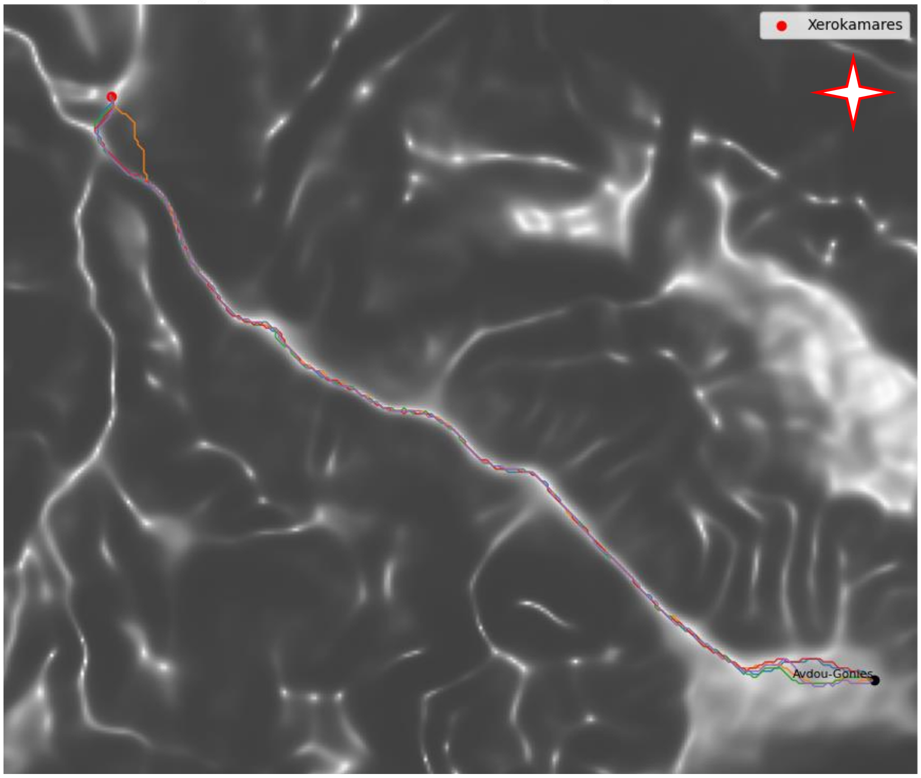


Figure 47 Multiple Paths from Avdou-Gonies to Xerokamares

3. From Xerokamares to Hersonissos

The path from Xerokamares to Hersonissos is the path that reaches the final waypoint of this study. The path manages to traverse the high-cost areas between the two waypoints by taking a semi-circular route to finally reach the coastal area of Hersonissos. The resulting paths are the shortest in length, with the single path (Fig. 48) being at 6.6 km and with a Total Cost of 1115 cost units. Elevation Gain is at 0.06 km and Loss at 0.18 km. The Average Slope is at 2.15° and the path consists of 200 segments (Table 3, 5). The exact same stats are evident for the QGIS path (Table 5).

The multiple paths (Fig. 49) show an average length of 6.7 km, while Elevation Gain and Loss at exactly the same level as the single paths. The average Slope is almost for every case close to 2.1°, while the number of segments has values ranging around 200. Total Cost has an average of 1150 cost units.

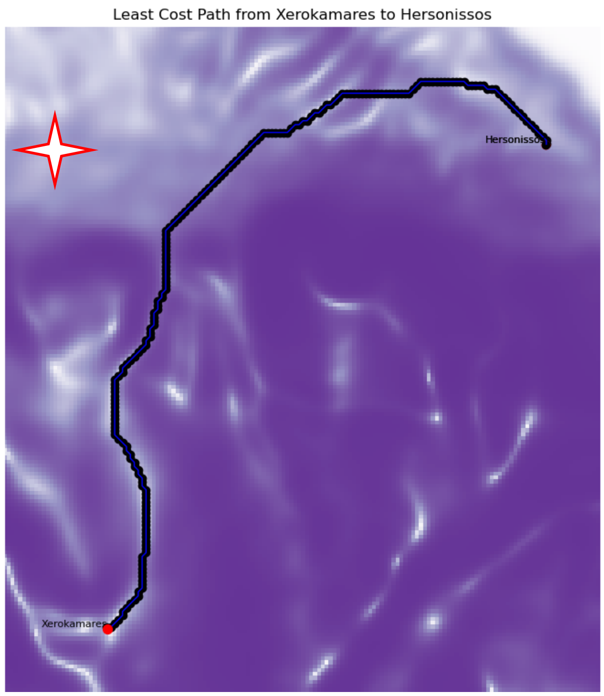


Figure 48 Single Path from Xerokamares to Hersonissos

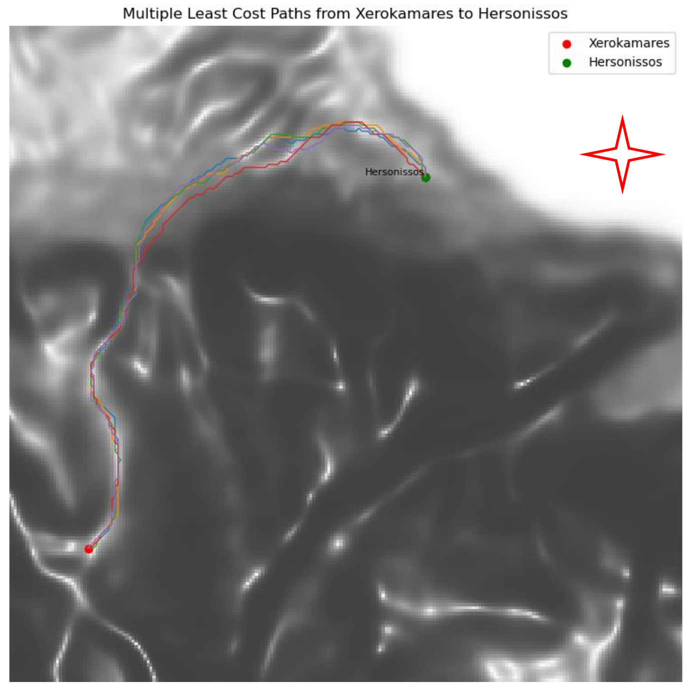


Figure 49 Multiple Paths from Xerokamares to Hersonissos

4. From Lyktos to Xerokamares

The path from Lyktos to Xerokamares serves as an alternate route to test the hypothesis of a path moving straight from Lyktos to Hersonissos, with a northern navigation. The path crosses through the hilly areas lying between the two sites and traces the low-elevation parts, passing close to the sites of Smari and Kalo Chorio lying on the west (Fig. 50). The single path has a length of 9.2 km and a Total Cost of 1798.35 cost units, making it the most expensive out of all paths. Elevation Gain is at 0.04 km and Loss at 0.52 km. The loss is also higher compared to the other paths. The average Slope is at 3.59° and the sum of segments is 287 (Table 3,5). The QGIS derivation has the same characteristics (Table 5).

The multiple paths (Fig. 51) are consistent with a total length ranging from 9.2 to 9.3 km. Elevation Gain, Loss, and number of segments are the same with the single paths. The

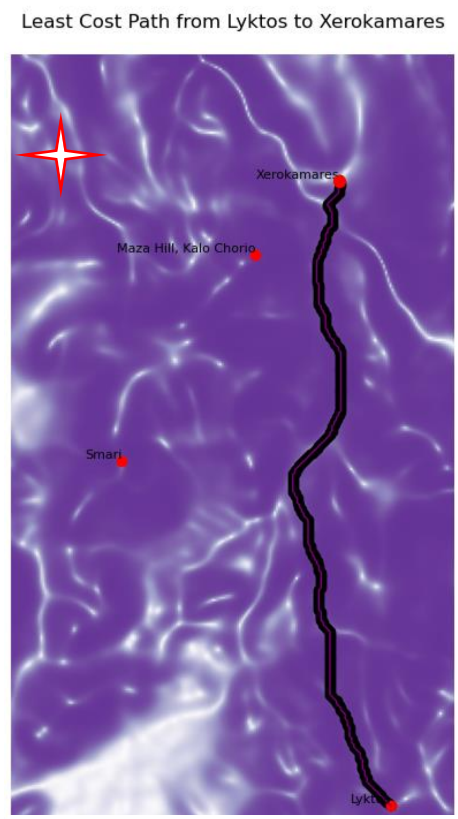


Figure 50 Single Path from Lyktos to Xerokamares

average Slope is around 3.5° to 3.55°. Total Cost has an average sum of 1850 cost units (Table 1). A notable result is the fact that in this case, the execution of the algorithm might produce a path (red) that significantly deviates from the others, taking a more circular route that moves further west (Fig. 52).

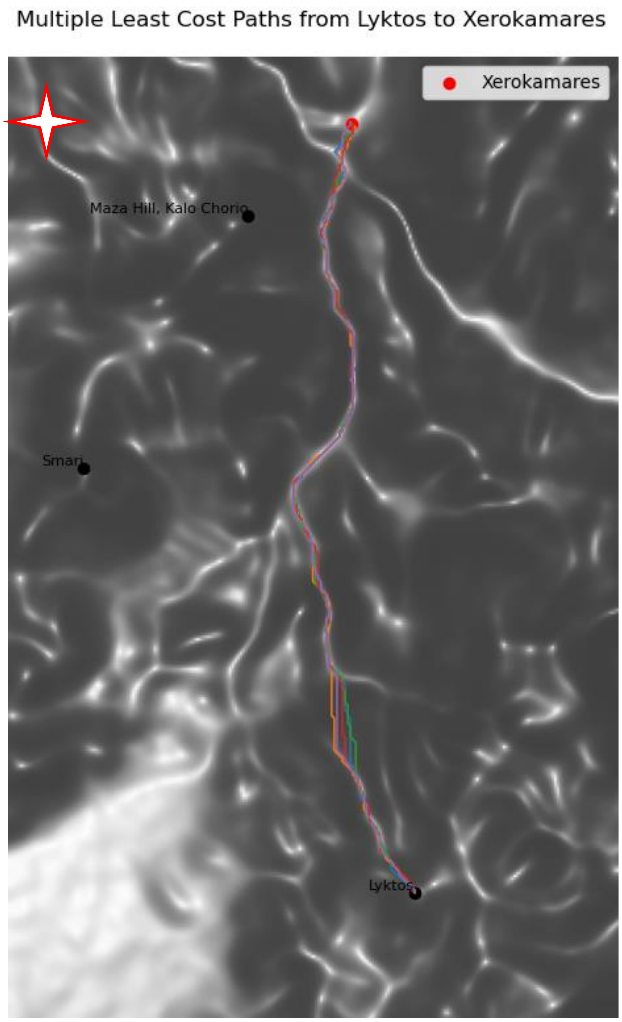


Figure 51 Multiple Paths from Lyktos to Xerokamares

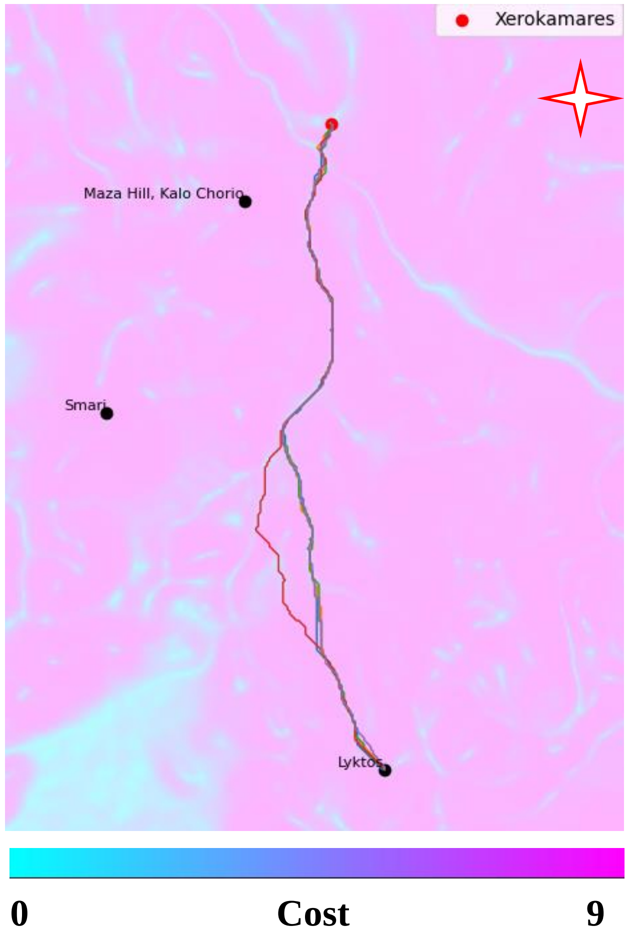


Figure 52 Example of Alternate Path produced by the Algorithm. Transparency of the Cost Surface has been modified for enhancing the visualization of the multiple paths

5. *From Avdou-Gonies to Hersonissos*

As discussed in the *Methodology* chapter, the initial planning was to create a path straight from Avdou-Gonies to Hersonissos. However, the output was problematic for both approaches. This path was not used for the statistical comparison between the two approaches, but it is a notable case indicating discrepancies in the manipulation of the cost surface data by the path-finding algorithm that was employed. The Python approach shows a route that follows the least cost route to reach the coast but before reaching Hersonissos it traverses through the sea, something that would not make sense in the practicality of the path (Fig. 54). The QGIS approach shows a more actual result, considering it does not go through the sea, but the length and cost of the path are huge (Fig. 55). Nevertheless, the outputs show a route that had a probability of existence considering the archaeological record but it will be evaluated in the *Discussion* chapter. The total length of the Python single path is at 14 km, with a total cost of 1467 cost units and consisting of 430 segments (Table 4). Elevation Gain is at 0.22 km and Loss at 0.45 km with an average slope of 2.52°. The QGIS path is much longer, at 22.2 km, consisting of 679 segments and a total cost of 6676.3 cost units (Table 4).

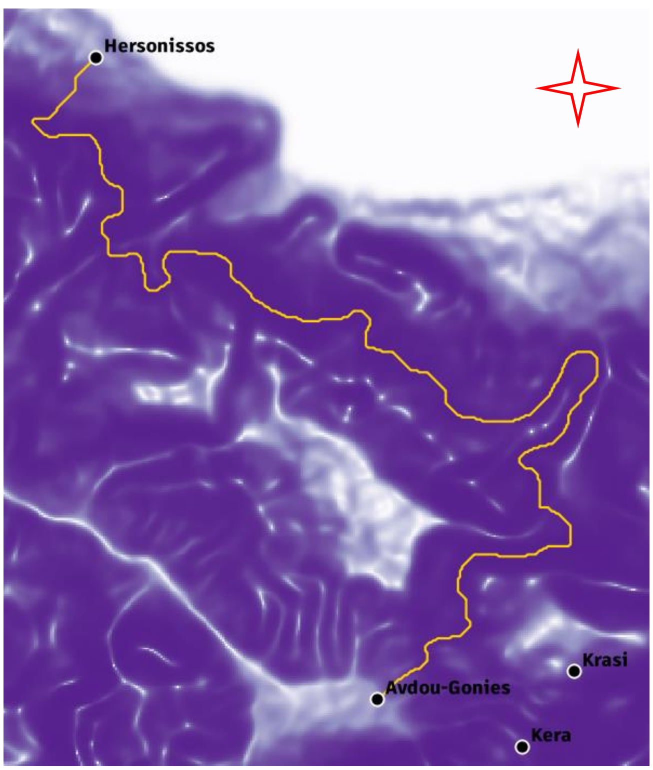


Figure 53 QGIS path from Avdou-Gonies to Hersonissos

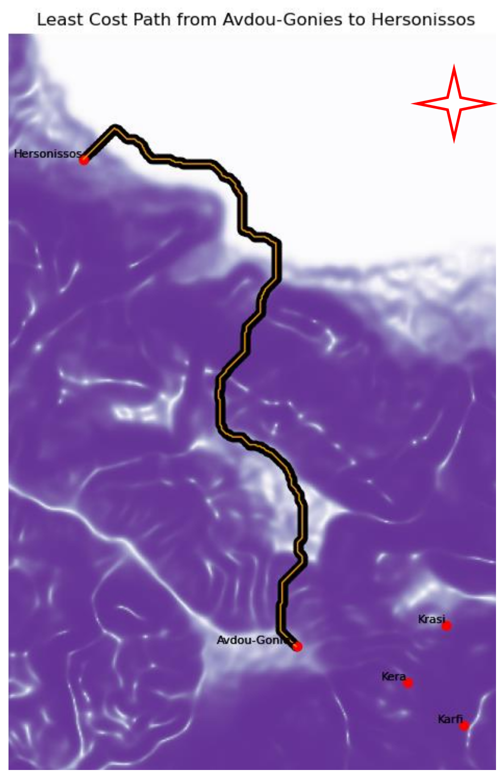


Figure 54 Python Single Path from Avdou-Gonies to Hersonissos

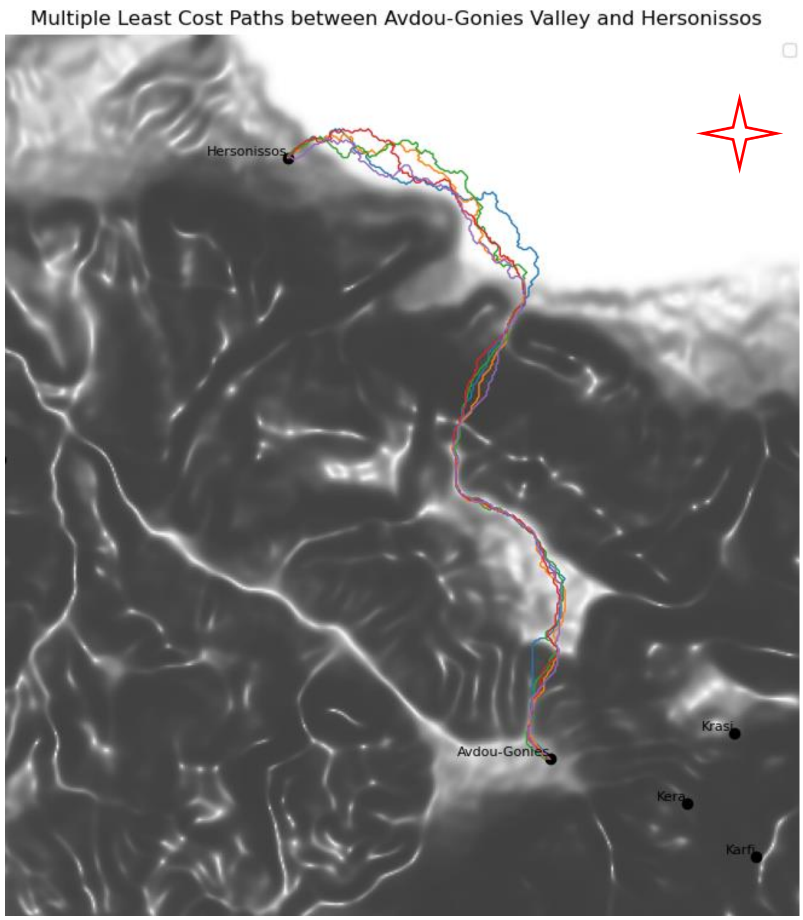


Figure 55 Multiple Paths from Avdou-Gonies to Hersonissos

The multiple paths (Fig. 55) have an average length of 15 km, while Elevation Gain and Loss have the same values as the Single Path's statistics. The average Slope has a mean value of 2.5°. Total Cost is between 1530 to 1600 cost units and the number of segments is approximately 240 (Table 1).

Table 3: Statistics for the paths from Avdou Gonies to Hersonissos for the two methodologies

Methodology	Path Label	Number of Segments	Length (km)	Cost
QGIS	Avdou to Hersonissos	679	22.19	6676.31
Python	Avdou to Hersonissos	430	14.07	1467.36

6.7 Statistical Comparison of the Python and QGIS Paths

The comparison of paths generated by QGIS and Python demonstrates minimal differences in both path lengths and costs. The lengths of the paths from Lyktos to Avdou, Avdou to Xerokamares, Xerokamares to Hersonissos, and Lyktos to Xerokamares are closely matched between the two methods. QGIS lengths are 7.86 km, 10.09 km, 6.60 km, and 9.19 km, respectively, while Python lengths are 7.82 km, 10.06 km, 6.60 km, and 9.20 km. Similarly, the costs associated with these paths also show minor differences. The QGIS costs are 1562.77, 1050.77, 1115.81, and 1798.35 cost units, compared to the Python costs of 1557.28, 1045.28, 1115.81, and 1798.35 cost units.

The statistical comparison of path lengths and costs generated by QGIS and Python using paired t-tests shows no significant differences between the two methods. For path lengths, the paired t-test resulted in a t-statistic of 1.20 with a p-value of 0.32. For path costs, the paired t-test resulted in a t-statistic of 1.73 with a p-value of 0.18. With a significance level (alpha value) of 0.05 applied to both hypotheses, the results suggest that the difference in path lengths and costs is not statistically significant.

Both sets of paths from the two methodologies follow similar overall routes with minor deviations. The slight differences are probably to be dependent to how each of the two algorithms handles the data provided by the cost surfaces. However, as a general observation, at some points, the QGIS paths seem to take sharper turns, while in contrary, the Python ones seem to be a bit smoother. Overall, from a visual inspection of the resulting paths, the differences between the two methodologies are very subtle. Their existence could be testified to small numerical discrepancies, however they are not significant enough to affect the visual results (Fig. 58, 59, 60, 61).

Table 4: Basic Statistics for Python and QGIS paths

Methodology	Path Label	Number of Segments	Length (km)	Cost
QGIS	Lyttos to Avdou-Gonies	247	7.86	1562.77
QGIS	Avdou-Gonies to Xerokamares	289	10.09	1050.77
QGIS	Xerokamares to Hersonissos	200	6.6	1115.81
QGIS	Lyttos to Xerokamares	287	9.19	1798.35
Python	Lyttos to Avdou-Gonies	246	7.82	1557.28
Python	Avdou-Gonies to Xerokamares	288	10.06	1045.28
Python	Xerokamares to Hersonissos	200	6.6	1115.81
Python	Lyttos to Xerokamares	287	9.2	1798.35

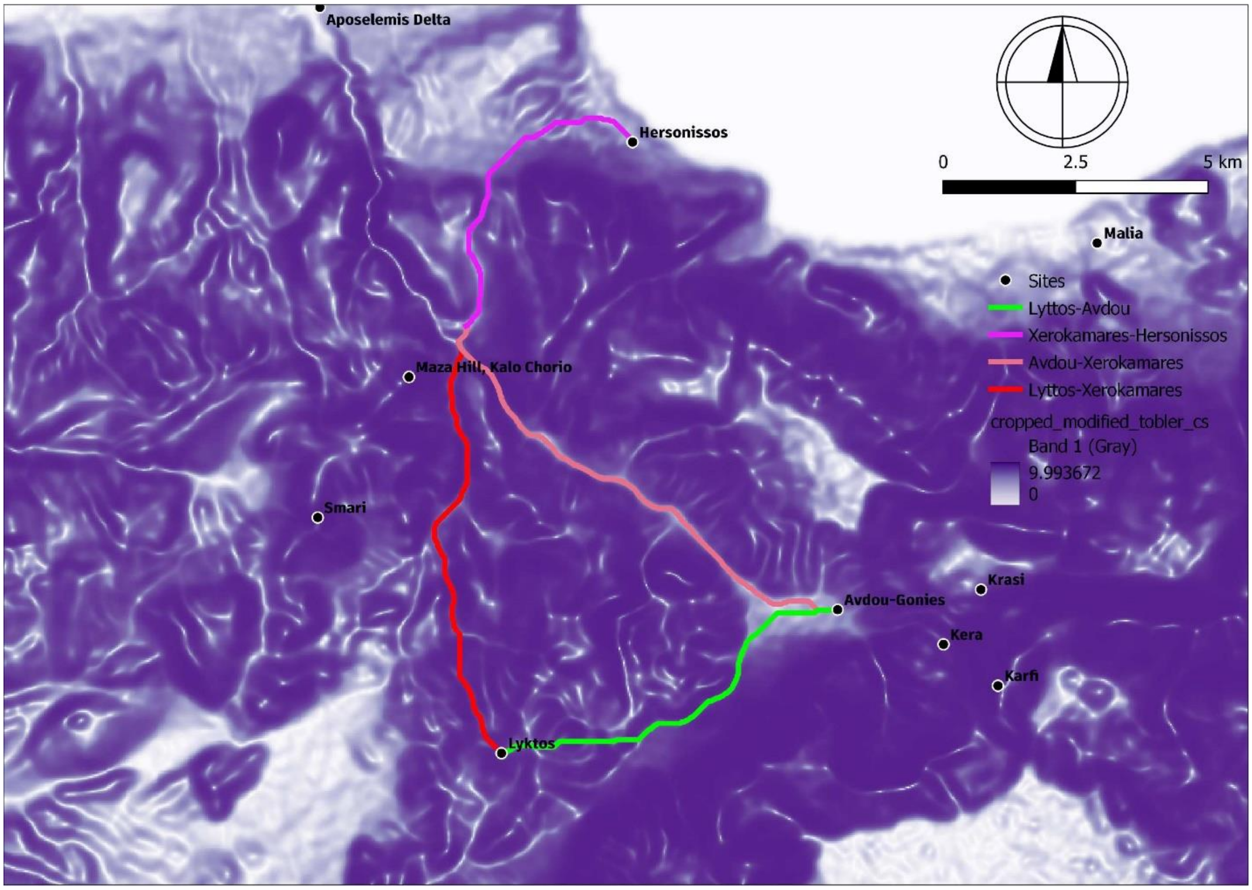


Figure 56 QGIS Paths

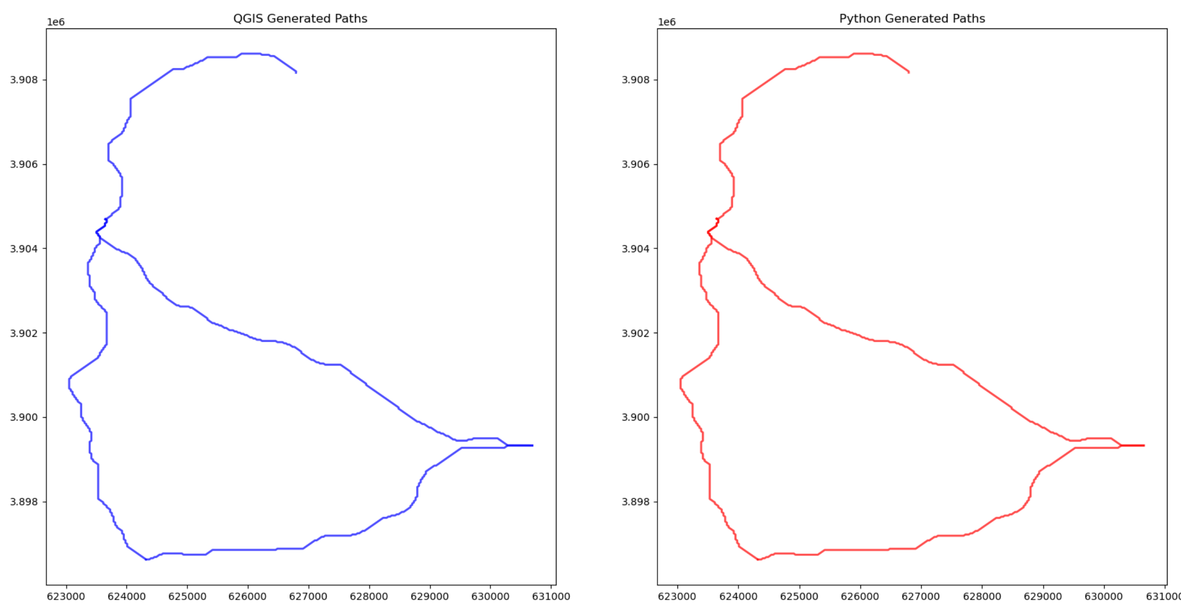


Figure 57 QGIS and Python Paths side by side

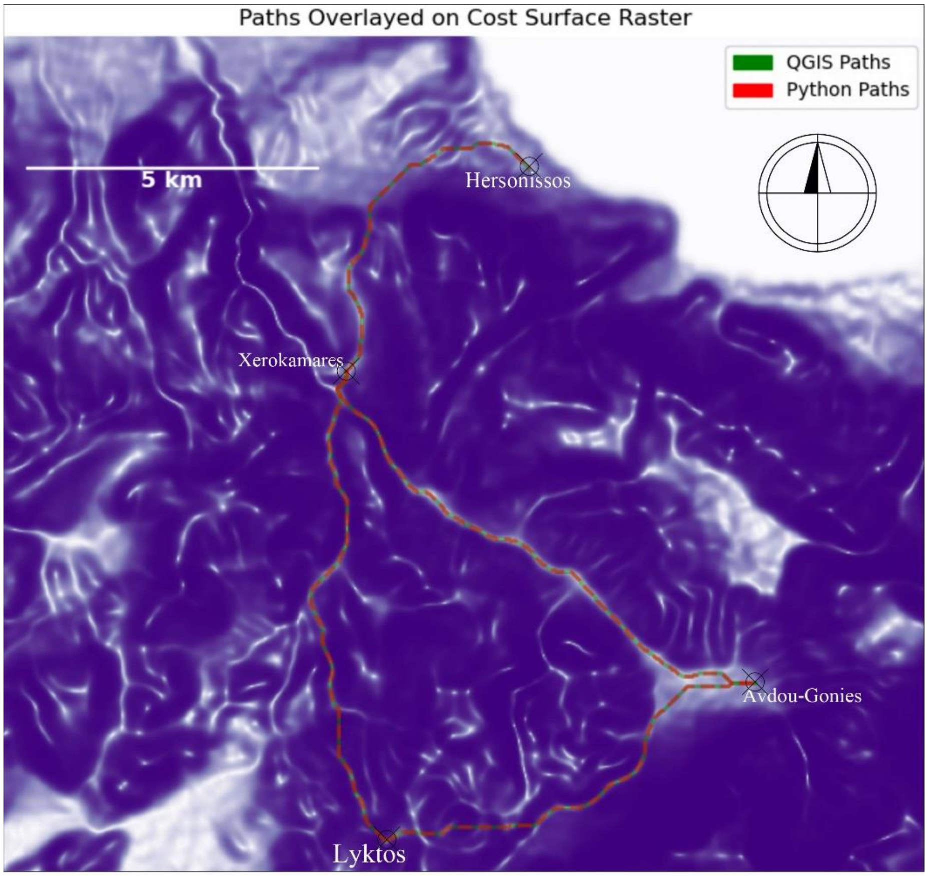


Figure 58 Python and QGIS Paths Overlayed on Cost Surface. QGIS: Green/Python: Dashed Red

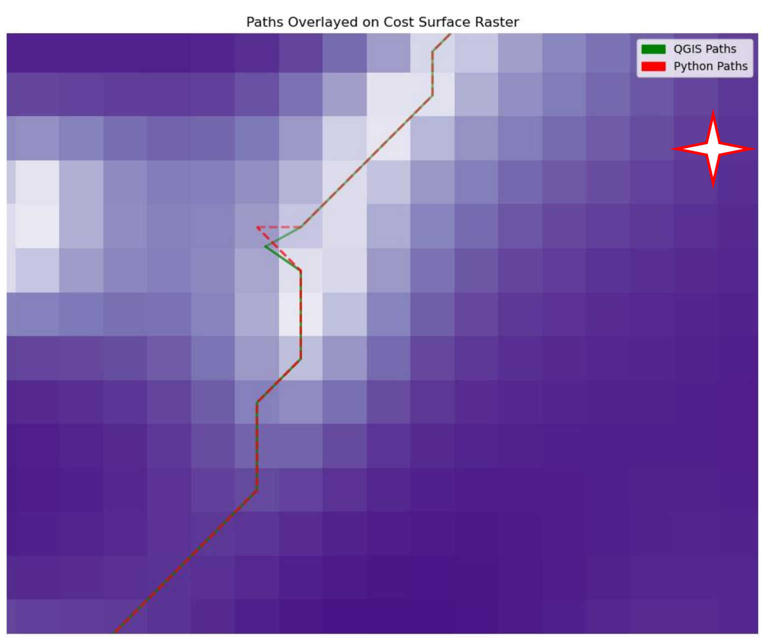


Figure 59 Minor Difference of QGIS-Python paths in the site of Xerokamares

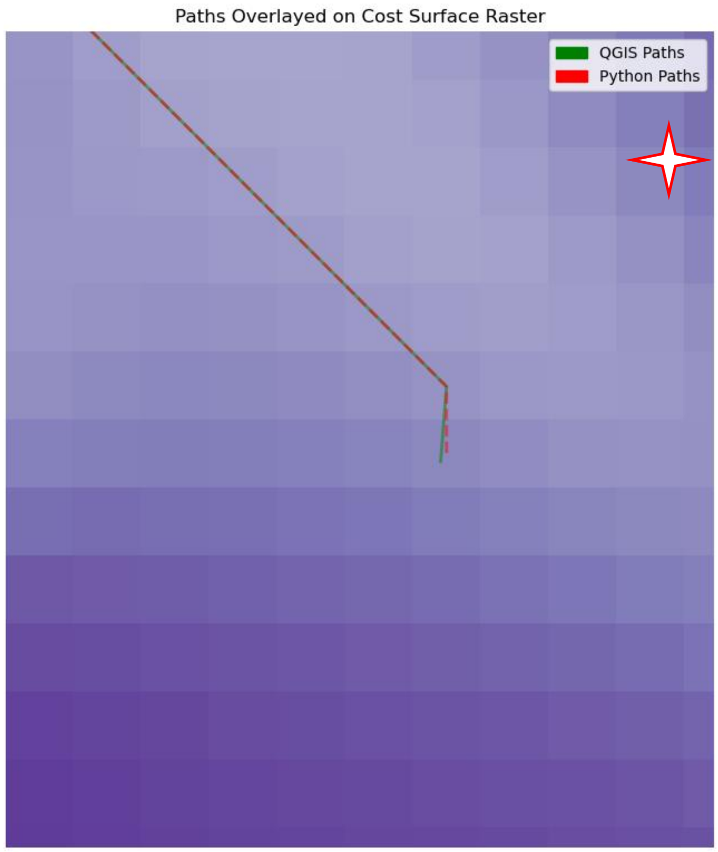


Figure 60 Minor Difference of QGIS-Python paths in the site of Hersonissos

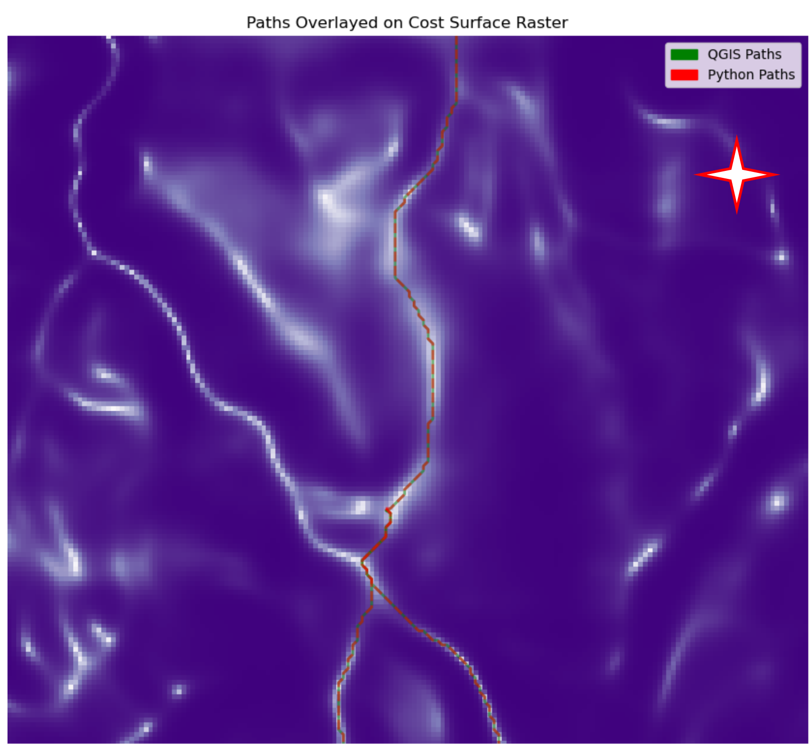


Figure 61 General Detail on the intersection of paths. From Avdou to Xerokamares, from Lyktos to Xerokamares and from Xerokamares to Hersonissos, validating the similar results of the QGIS and Python approaches

7. Discussion

7.1 Introduction

This chapter interprets the results of the applied methodology, focusing on the use of Python for manipulating elevation data, creating cost surfaces, and generating LCPs, with a comparison to the QGIS approach. Beyond methodological considerations, the Python-generated paths will be evaluated against the archaeological record to determine the method's effectiveness in studying human movement, particularly in understanding the path network of North-Central Crete. The objective is to identify any alignment with the archaeological record and previous studies and to draw conclusions about the phenomenological aspects of human movement in the area. As emphasized in the *Introduction* chapter, interpreting results is crucial in archaeological geospatial analysis, providing qualitative significance to quantitative outputs. This chapter will include a numerical interpretation of the results from the previous chapter, progressing to a qualitative analysis to explore the methodology's potential in addressing archaeological research questions and enhancing our understanding of past human experiences, by synthesizing the methodology with the theoretical and archaeological frameworks.

7.2 On the use of Python for Data Processing

Regarding the processing of the DEM data, Python proved to be a viable tool for handling issues of the dataset and preparing it so that it can be used in the subsequent LCP analysis. The application of the Gaussian Filtering for smoothing the DEM managed to make minor changes to the original dataset, which was essential for keeping it as intact as possible. The smoothed DEM is suitable for use with the impact of minor noise being reduced and without the addition of distortions that would have negative effects on the LCP analysis. Moreover, the variability of the terrain was not heavily affected, a necessary parameter for improving the quality of the LCP algorithm's results. By applying this smoothing, the data were prepared for the following steps of the analysis. The results from calculating the RMSE, and MAE metrics, besides providing a quantitative perspective on the processed dataset, provide evidence that the Gaussian Smoothing was effective as demonstrated by the low RMSE and MAE values for the smoothed dataset.

On the other hand, the interpolation process was a redundant step, regarding its effect on the quality of the dataset, but it was significant for the correct geographic projection of the DEM. Maintaining the integrity of the data is essential, thus the minor to 0 effects of the interpolation were proven efficient. Removing this step affected the coordinate projection of the dataset, leading to shifts that misaligned the DEM data and the list of sites used for the LCP analysis.

Overall, for the first step of the methodology Python manages to show positive results, proving its potential for manipulating geospatial data and preparing them for the subsequent geospatial analysis. The

Python approach opens space for experimentation with different techniques. The flexibility accessed through coding is significant. A primary goal was to assess issues of DEM management, considering that this subject is usually neglected in many studies (Lewis, 2017, p. 72; Lewis, 2021, p. 912; Herzog & Yepez, 2016, p. 2-3; Herzog, 2022, p. 133)

7.3 On the Modified Tobler's Hiking Cost Surface

The flexibility of Python can be observed in the Cost Surface creation process. Python's potential for creating custom cost functions through a more straightforward approach is significant compared to the use of the QGIS GUI tools, such as the Raster Calculator or the Graphical Modeler. This is observed in the application of the Modified Tobler's Hiking Cost Function. This cost function suggested by Marquez-Perez et al. (2017) is a great method for modeling walking costs in mountainous terrain as is the case of Crete. Through Python, a further modulation of the suggested formula was executed that was useful for achieving more accurate and precise modeling of the terrain's costs and for replicating actual hiking behavior.

Local characteristics of the study area were accurately represented in the resulting Cost Surface, compared to simpler approaches like the Simple Tobler's Cost Function. The modified cost function manages to introduce the concept of anisotropy, providing directional variability in the modeling of costs that is significant for exploring pathways matching real-life scenarios.

Based on the concept of affordances (Gibson, 1979) this function is useful for incorporating these ideas into the movement model. Gillings (2012) suggests avoiding the use of many Cost Surfaces. The resulting Cost Surface takes into consideration a few parameters that are important for creating a single cost surface that can be used for combining natural parameters with individual constraints to model landscape costs. The Modified Cost Function incorporates ideas based on Llobera's separation of constraints affecting human movement (Llobera, 2000). From landscape constraints, the topographical parameter explored is the slope and its effect on walking speed. Soil types and land cover could not be included due to the lack of relevant data. Datasets of water bodies were unavailable; therefore, the presence of rivers and springs will be evaluated during the interpretation of the paths, based on existing knowledge of their locations.

Regarding social/cultural constraints these will also be assessed based on the archaeological record as they could not be modeled. At last, on individual constraints, only speed was included but it was based on average human features. Modeling real-life variability in individual physicality was not achieved, as accounting for parameters such as sex and body types is a challenging task (Verhagen et al., 2019, p. 229).

Overall, the Modified Cost Function taking the time-based nature of Tobler's function, and the consideration of traveling time for a hiker carrying baggage based on the MIDE method, managed to provide a suitable Cost Surface as observed from the generated LCPs. As in Lewis's (2017) study, the cost function based on time parameters was also beneficial for the study area on Crete. After further refinement hiking costs are better modeled, providing a great match considering the actual topographic costs of the study area. Instead of creating a multifaceted complex cost surface a simple one based on slope and its effect on walking speed proved to be adequate according to Bevan's (2011) proposal.

7.4 Python vs QGIS

QGIS is an established methodology widely used among academics across various fields, including archaeology. Its capabilities for geospatial analysis are extensive, but this thesis focuses on LCP analysis. QGIS is known for its user-friendly interface and robust functionalities. LCP analysis can be easily executed through the software by simply setting the necessary input data. There are various approaches provided by different plugins in QGIS; the simplest one was used in this thesis to compare it with Python.

One limitation of QGIS is that its simplicity can be a drawback. It operates as a "black box": the user adds the necessary inputs and gets the results without fully understanding the underlying processes. Python, on the contrary, offers a solution to this problem.

Python provides significant potential for flexibility and straightforward control of the algorithms used for path-finding. Users can gain a deeper perspective on how the algorithms operate and enhance their potential by their potential for modulation. By understanding the computational processes involved in LCP analysis, researchers can adapt these methodologies to their research goals, leading to better use of the algorithms for specific problems and a clear understanding of how they work.

The Python approach might be more complex for traditional archaeologists compared to the ready-made tools provided by QGIS. However, it can help overcome the mere interpretation of results without understanding the underlying algorithms. This comprehension allows for more robust interpretations and potentially enhances archaeological insights.

As observed from the results of the applied methodology, the paths generated through both approaches are quite similar from both a visual and statistical perspective. The differences in the results are minor, as seen in the total lengths and costs of the paths. Hypothesis testing further validates this assumption. The use of paired t-tests signifies that there are no major differences, indicating that Python can provide results comparable to those produced by QGIS while offering greater customization flexibility, which is harder to achieve with geospatial software. The p-values produced by the tests were above the threshold of significance (0.05), a value (alpha value) that indicates that any differences between the two methods are most probably the results of random variation. The statistical robustness highlights the efficiency of the Python methodology for LCP analysis. The only issue appeared in the case of the path between Avdou-Gonies and Hersonissos, but the reasons for its failure are elaborated in the relevant sub-section (7.5.5)

Beyond the alignment of the paths and algorithmic operation, Python libraries such as Matplotlib provide further freedom in the visualization process, allowing users to visualize data in various ways that are helpful for analysis and interpretation. This is demonstrated by the various maps, hillshades, and the visualization of the paths displayed throughout the thesis.

7.5 On the paths

7.5.1 From Lyktos to Avdou-Gonies

The path from Lyktos to Avdou-Gonies reflects a gentle gradient, aligning with the overall terrain's characteristics. Its moderate slope, which is similar to the Lyktos to Xerokamares path, suggests reasonable movement and decision-making by the algorithm, which was successful in identifying an adequate path based on the hilly terrain of the area. The consistent results except a northern route, validate the algorithm's potential. The cost metric is higher than the other paths, due to the elevation levels of the area, and showing its effect and slope's impact on walking.

The route traverses the hill between Lyktos and Askoi and approaches the Lasithi Plateau, moving northwest of the Louloudaki hill, indicating a strategic route and enhancing its possibility. Its proximity to Louloudaki indicates a connection with the sites of the hill, like Gonies to Flechtron and the Phaneromeni Cave, enhancing its historical value. Travelers would encounter natural and artificial landmarks along the path, with the Karfi mountain, and the Lasithian entrance on their east, and the acropolis of Lyktos on its prominent position on the southwest. The path is enriched with visual cues. Locals discuss the existence of potential sites, however they need to be validated. The path shows connections with the modern road, with the exception that it does not pass through the Askoi village. Overall, the results present the success of the algorithm based on both the terrain data and the archaeological data of the area.

7.5.2 From Avdou-Gonies to Xerokamares

The path moving from Avdou-Gonies to Xerokamares might be the longest (ca. 10km) but it is the least costly one due to the low elevations along the Aposelemis River. The cost surface models the river's course as a low-cost area, naturally guiding the path, enhancing its possibility as a route for an individual. Despite the lack of hydrology-related data, the algorithm's decision is justified by the terrain's characteristics, while the river provides an accessible water source. The low average slope is another important parameter for the selection of this route.

Additionally, along the path, a traveler would be near the various sites that have been located in the area, providing a path that must have been used for a large chronological period, considering the constant occupation of the Aposelemis Valley. This path could also provide a sense of safety considering the various settlements of the area. The route's alignment with the Potamies valley, by avoiding the Mochos ridge on the north, signifies its practicality, while also offering resting places and resources. The algorithm shows consistent results with no deviations, while its combination with the archaeological data and the various natural features along it deems it as a realistic option, despite its length.

7.5.3 From Xerokamares to Hersonissos

The path from Xerokamares to Hersonissis is the shortest one, yet it has the highest elevation gain due to the hilly area separating the inner lands from the coastal area of Hersonissos. Despite this, the slope remains gentle indicating a route of accessibility. The algorithm is effective by strategically circumventing the Mirmigki Hill, to identify the path of least resistance. Consistency is observed among the multiple paths.

The inclusion of Hersonissos in the analysis is based on a hypothesis regarding its earliest occupation. The limited archaeological data suggest a minor human occupation during the EIA, through fragmentary finds and few structural elements. Despite this lack of data, Hersonissos could have belonged in this path network, considering its integration into the territory of Lyktos in later periods. The coastal reoccupation in the PG period is an important parameter, when such regions were again considered safe for occupation, compared to the full-of-threats period of the Late Minoan era (Nowicki, 2000, p. 17).

7.5.4 From Lyktos to Xerokamares

The path from Lyktos to Xerokamares was created to provide an alternate route that would directly connect to Hersonissos. It is the second longest path (ca. 9km) and it is the most cost-expensive, with an average slope of 3.6° similarly to the path moving from Lyktos to Avdou-Gonies. A major disadvantage of this path is that it does not pass from the site-cluster in the Aposelemis Valley area which limits the accessibility to sites for rest. Algorithmically, the path-finding process was effective. A notable path deviates from the others, following a western route of least cost, highlighting the introduction of variability in the cost surface for the creation of multiple paths.

The importance of the path lies to its proximity to key sites of the Dark Age, such as Smari and Maza Hill on its west. The inclusion of Xerokamares in the analysis is justified based on this proximity. A critical aspect of this path is its alignment with water streams from the villages of Kastamonitsa, Askoi, and Karouzana, which eventually connect with the Aposelemis River. The presence of a spring near Maza Hill, in its northwest, and the fact that the settlement of the hill had control both territorially and visually of the underlying Potamies valley, enhances the decision behind selecting Xerokamares as a waypoint. The spring of Maza, the water streams, and the Aposelemis River were attractive features for people in the past, leading to settlement development in the area (Nowicki, 2000, p. 176). The water abundance of the area along with the territorial safety of the Maza settlement that was connected with Lyktos could have provided factors for travelers selecting this path. The path can also be validated, considering the hypothesis for a Roman road that connects Lyktos with Hersonissos (Papadaki & Milidakis, 2023). However, the remains of this road are yet to be found.

7.5.5 From Avdou-Gonies to Hersonissos

An interesting case is the computed path from Avdou-Gonies to Hersonissos. Before deciding to include Xerokamares to the analysis, this was the initial desired path. However, both in Python and in QGIS the resulting path did not match the expectations, providing a problematic output. This path was not used for the statistical comparison between the two approaches, but it is a notable case indicating discrepancies in the manipulation of the cost surface data by the path-finding algorithm that was employed. In all other paths, the results are quite accurate and match real-world conditions.

The produced paths provide results with excessive path length and cost, while they are complex as can be observed through the number of segments consisting of them. The issues on this path probably stems from different factors relating to the Cost Surface and the algorithm's implementation. The adjustments to the original function might have smoothed out critical slope variations leading for the algorithm to favor more complex routes. The masking of zero-cost values could be another factor influencing this result. The selected algorithm from the "route_through_array" function could be another reason due to its nature of optimizing path accuracy. The algorithm's struggle to produce realistic paths highlights potential issues with the Cost Surface model that was used and the algorithm's sensitivity to the data. However, this issue was managed to be tackled through the archaeological data of the area, such as the site of Xerokamares which allowed the correct implementation of the algorithm resulting in accurate paths.

The QGIS path passes from high-cost areas and avoids low-cost ones showing major issues, but it manages to reach Hersonissos through a terrestrial route. The Python results are more accurate when moving through low-cost areas but the issue arises before the path reaches Hersonissos. Going around the Mochos Valley, it then reaches the coast and moves from inside the sea, a fact that does not make sense. However, the Python result seems more accurate, considering that in the existence of sea-related data, the algorithm would probably follow the coastline to reach its destination.

7.6 Evaluating the Path Network

The path network modeled in this thesis offers a detailed and realistic representation of movement within the study area. The high-elevation region of Lyktos is effectively connected with the sites in the Aposelemis Valley, extending to the coastal site of Hersonissos. The successful implementation of the path-finding algorithm has yielded paths that correspond well with the archaeological data, identifying optimal routes, that align with both Dijkstra's algorithm and the region's topography and geomorphology.

As discussed in the *Methodology* chapter, the rough outlines of the paths are reflected in the DEM and the produced Cost Surface, validating the impact of topography on movement orientation within the study area. The mountainous Cretan landscape with its steep slopes naturally directs movement through areas of lower traversal cost. The cost surface effectively depicts cost variations and the algorithm identifies paths of least resistance.

The generated path network closely aligns with the hypothesized streets and paths proposed by Mavraki-Mpalanou et al. (2016), particularly in the case of connecting Lyktos with the sites around the area of the Aposelemis Dam and extending northwest to the site of Xerokamares. However, Mavraki-Mpalanou et al. do not suggest a path leading to Hersonissos, focusing instead on the Minoan and Roman stages of the path network. A direct path from Lyktos to Xerokamares is not proposed either by Mavraki Mpalanou et al. but its existence seems plausible given the proximity of the path to the sites of Smari and Kalo Chorio

This extensive chronological coverage and the presence of sites from all periods of Cretan Antiquity provide evidence for the continuous use of the network during the EIA. It is important to note that guard houses found along these paths were used in the Middle Minoan period to provide safety on the roads and for travelers (Chrissoulaki, 1999). The presence of the Minoan Soroi, beacon structures that facilitated communication between sites in the Pediada region (Panagiotakis et al., 2013), further supports the early existence of this path network and its associated social network. In later periods, from the Classical to Roman times the region belonged to the territorial control of Lyktos (Chaniotis, 1999).

From a phenomenological perspective, the path network provides insights into how walkers experienced and perceived the landscape. Paths pass near older Minoan sites like Karfi and Smari, may have served as navigational markers. These visual parameters are also evident in Lyktos. Abandoned sites and Minoan structures along the paths likely served as socio-cultural markers supporting Llobera's (2000) ideas. According to Wallace (2003a), the sites of the LBA were integral to the social memory of the time. LM-IIIC sites were visible from the path network during the PG period and later.

Natural landscape markers, such as mountains and water sources like the Aposelemis River, would have been crucial for navigation in the Pediada region, as suggested by Murrieta-Flores (2010) and Verhagen et al. (2019). The continued use of the Minoan Soroi for navigation, even in modern times, underscores their importance even after their abandonment (Panagiotakis et al., 2013). The resulting path reflects the local knowledge of area's inhabitants and their relationship with the surrounding landscape and its pathways (Nowicki, 2002; Wallace, 2007, p. 252). This knowledge was significant for settlement development in the period under study (Wallace, 2007, p. 252).

Prent’s (2014) suggestion that Minoan ruins influenced the development of EIA society is relevant for understanding the path network of Pediada. The continued use of these paths likely resulted from evolving cognitive and social processes (Verhagen et al., 2019, p. 219). Territorial issues were still prominent even after the collapse of the Minoan palatial system, and safety concerns remained, suggesting that “authoritarian constraints” (Llobera, 2000) played a role in social development and the path network of the area (Nowicki, 2002, p. 169). Threats on the island extended beyond coastal dangers to include internal ones (Nowicki, 2002, p. 169).

Strategic locations were crucial for settlements (Wallace, 2003a, p. 257). The visibility of the path network sites like Lyktos, Karfi, and Smari, indicates a form of protection for the low-elevation settlements, that must have started developing in the EIA period. This validates that intervisibility was indeed an important factor for the settlements (Prent, 2014, p. 651) The transitional era likely impacted the maintenance of the path network which was crucial for trade, communication, and defense.

The development of settlements in the Aposelemis Valley area happened due to these issues and they played an important role as mediators between the mountainous sites and the coast. (Wallace, 2007, p. 263) The presence of sacred sites, such as the cave of Phaneromeni near Avdou, highlights the cultural significance of the social network and its paths, considering the sacred role of LBA sites that continued to be important until the Classical period (Chaniotis, 2009; (Cucuzza, 2013, p. 31). These factors collectively influenced the development and maintenance of the path network.

8. Conclusion

As a general remark, this thesis successfully achieved its primary objectives and adequately addressed the research questions that guided its development. By applying a multidisciplinary approach a comprehensive understanding and exploration of the methodological, theoretical and archaeological inquiries was obtained. The consideration of diverse issues offered a holistic view of the Early Iron Age path network in the selected study area in Crete.

The key methodological question concerning the potential of Python for geospatial analysis and particularly in studying and analyzing movement and path networks was addressed efficiently. Python demonstrated compelling capabilities for modeling movement within an archaeological context. The computational results produced were remarkably similar to those generated by QGIS, highlighting the programming language’s potential for archaeological geospatial applications. The methodology developed and applied in this research provides an alternative, computationally enhanced perspective on studying such issues. More importantly, it allows for a deeper understanding of the underlying processes that occur in the environment of a GIS, despite the coding-associated challenges.

The most significant contribution of this thesis is the in-depth exploration of the computational aspects of LCPs, which provided a clear understanding of the different methodological steps involved. One of the most common issues in geospatial studies, including the analysis of movement, is that GIS systems are often used primarily for their outputs, without thorough understanding of how they are produced (Herzog, 2010). This leads to oversimplified and mainly exploratory interpretations. By examining issues relating to the management of DEM data (Herzog & Yepez, 2015; Herzog, 2021), the creation of cost surfaces, path-finding algorithms, and statistical analysis (Herzog, 2014), this thesis developed a methodology that can be accessible to a wide audience. These aspects were thoroughly explored using Python, and the comparison with the open-source QGIS showed that the computational approach is robust, and demonstrated significant potential for archaeological applications.

Python’s flexibility and the opportunities it provides to the user for modulation and experimentation are the major advantages of this approach. While QGIS remains an established methodological tool, Python’s capacity for detail examination and customization can greatly enhance similar research, by also offering a view of the exact processes behind such methodologies.

Despite the strengths of the Python-based methodology, it is recognized that the computational results alone cannot answer questions related to the social aspects of the path network and how it was perceived by ancient people and communities. Movement analysis and GIS studies are often criticized for their deterministic nature (Van Leusen, 2000, p. 225; Gillings, 2012; Witcher, 1999; Gaffney and Van

Leusen, 1995), and this research tried to bridge the quantitative results with qualitative interpretations, by acknowledging such issues.

Drawing inspiration from phenomenological ideas relating to landscapes, like from the work of Tilley, Ingold, and Gibson, and by the introduction of these ideas into archaeology, as observed in the research by Llobera, Wheatley, and others (Wheatley & Gillings, 2000; Wheatley, 2004; Llobera, 1996), this thesis sought to interpret the results within a broader archaeological and anthropological context. While landscape parameters, such as slope and its effect on walking, were incorporated into the computational model, complex factors – such as the visual properties of the paths, their intervisibility with archaeological sites, and their proximity to sites and natural resources – were considered during the interpretative process. These insights were guided by the separation of movement constraints proposed by Llobera (2000) and the concept of affordances by Gibson (1979), adding depth to the interpretation of the paths (Van Leusen, 2000; Gillings, 2012).

From an archaeological perspective, the focus on this transitional period of the EIA Crete, after the collapse of the Minoan civilization and the end of the Bronze Age, was driven by the limited archaeological attention this period has received, despite the significant advances in recent decades. The study area covering the region of Minoas Pediada, North Lasithi, and the Aposelemis Valley, with its continuous and intense occupation since the earliest periods of Crete's history, was an ideal setting for applying the suggested methodology.

The application of this methodology revealed a socio-cultural network in Minoas Pediada during this transitional period, with the produced path network showing a high possibility of existence. The network closely resembles and validates the paths proposed during the Minoan period by the study of Mavraki-Mpalanou et al. (2016), and suggests possible alternate routes that may have connected various sites in the area. Notably, the modeled paths resemble the modern road system in the area, before the construction of the modern road system in Crete that happened during the second half of the 20th Century, validating the possibility of its continuous existence. Regarding the hypothesis on the earlier existence of Hersonissos, no significant conclusion could be drawn due to the limited archaeological knowledge of the site for the EIA, however, the possibility for the site to be occupied during this period is not neglected, and if it indeed was, then it would be part of the proposed path network.

While this thesis successfully met its objectives and explored various research questions, further research is needed to develop more robust interpretations. Methodologically, exploring alternate approaches, such as different input data, enhanced cost surfaces with additional parameters, and varying path-finding algorithms, could provide deeper insights into LCP methodologies. Alternate coding approaches could not be tested due to the advanced complexity and my limited knowledge of the field. Phenomenologically, employing techniques like Viewshed Analysis could offer a computational perspective on the visual properties of the landscape. This thesis was limited to literature-based findings and personal observations; future research could benefit from systematic data collection. Finally, to substantiate the LCP analysis results and the value of the interpretations for archaeological research, practical work, such as surveys and fieldwork is essential (Ejstrud, 2005). While computational approaches are adequate for testing hypotheses and forming theories, substantial evidence can only be obtained through direct, systematic archaeological research.

Abstract

This thesis investigates the application of computational methods in landscape archaeology, focusing on the Early Iron Age path network of Central Crete, particularly in the key sites of Lyktos, Hersonissos, and other secondary ones in the same area. It addresses key methodological and theoretical issues by employing the Python programming language for geospatial analysis and incorporating phenomenological perspectives to enhance understanding of ancient human-environment interactions.

Recent advancements in Landscape Archaeology have been significantly influenced by phenomenological approaches introduced by scholars like Tilley and Ingold, who influenced by the philosophers of phenomenology redefined the term “landscape” by emphasizing the embodied and experiential aspects of it. Based on their work, archaeologists like Llobera and Wheatley challenged the quantitative treatment of landscapes and further explored the dynamic relationship between humans and their environments, highlighting the importance of movement and perception in landscape archaeology.

Geographic Information Systems have been instrumental in landscape studies, but often reduce landscapes to static and quantitative data. This thesis critiques these limitations and proposes a novel methodological framework using Python for Least Cost Path analysis. This approach offers greater flexibility and insight into the computational processes behind geospatial analysis, addressing issues of conventional GIS tools by providing a detailed and customizable examination of movement patterns.

The main research questions are if Python-based LCP analysis can produce results comparable to those from traditional tools like QGIS and if this computational approach, enhanced by phenomenological perspectives can offer deeper insights into the social and path network of Early Iron Age Crete. The findings reveal that Python is a robust tool for geospatial analysis, producing results similar to QGIS while offering enhanced flexibility and detailed examination of computational processes. This methodology highlights the importance of understanding the underlying processes behind geospatial tools and demonstrates Python’s potential for archaeological research.

By integrating phenomenological ideas, this thesis interprets the computational results within a broader archaeological context. This approach considers different parameters of how ancient people might have perceived and navigated their surrounding landscape. The analysis uncovers a potential socio-cultural network in Central Crete, with modeled paths suggesting continuity with the earlier Minoan path network of the area and offering insights into connectivity and movement patterns of the Early Iron Age. Overall, this research shows that Python-based methods provide a valuable alternative methodology to traditional GIS and a nuanced understanding of ancient human-landscape interactions.

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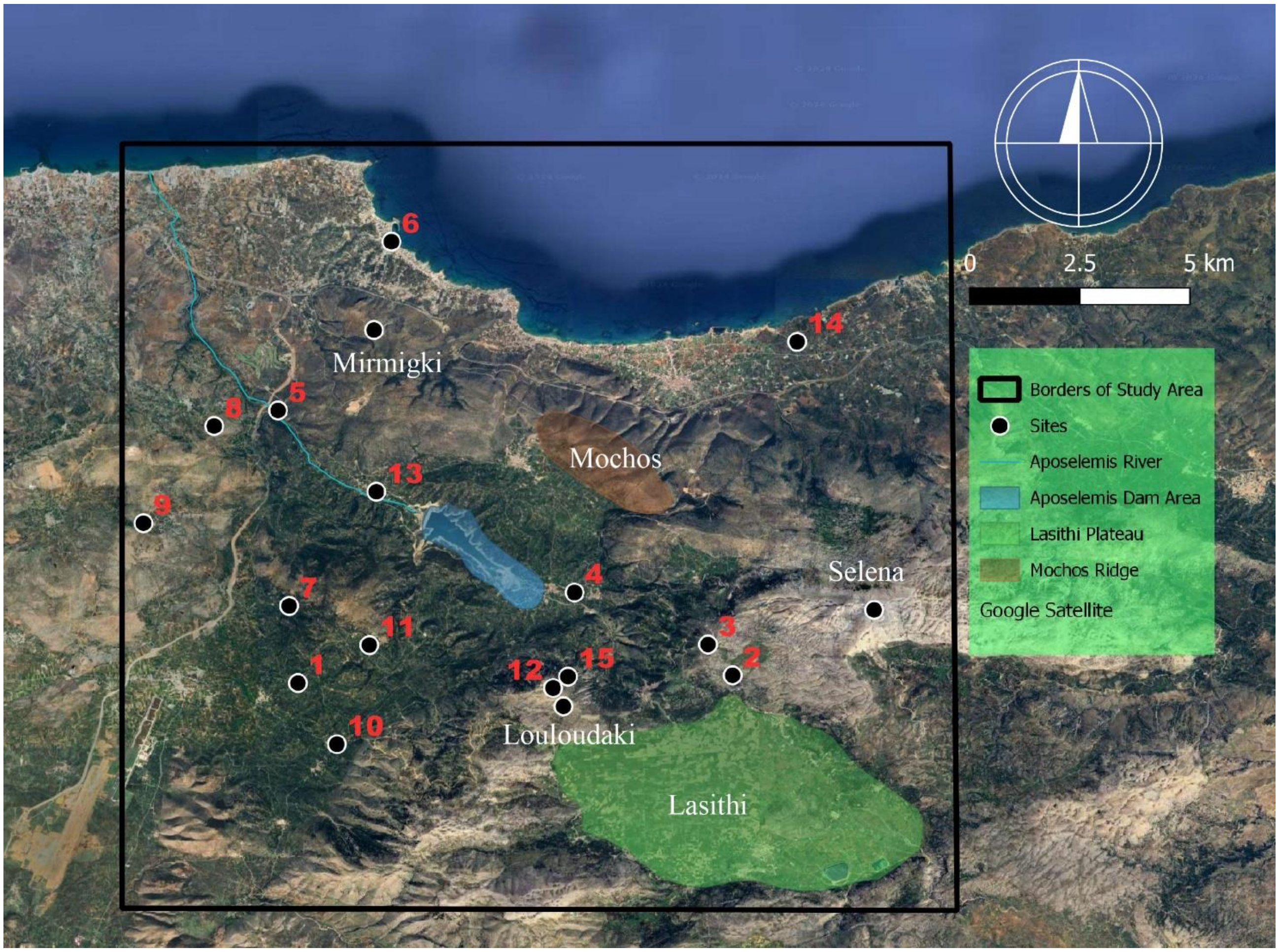
Appendix A

Map of the Study Area:

Sites are numbered. Names of Hills are displayed.



1: Lyktos 2: Papoura

3: Karfi 4: Avdou-Gonies

5: Xerokamares 6: Hersonissos

7: Karouzana 8: Maza Hill, Kalo Chorio

9: Smari 10: Kastamonitsa

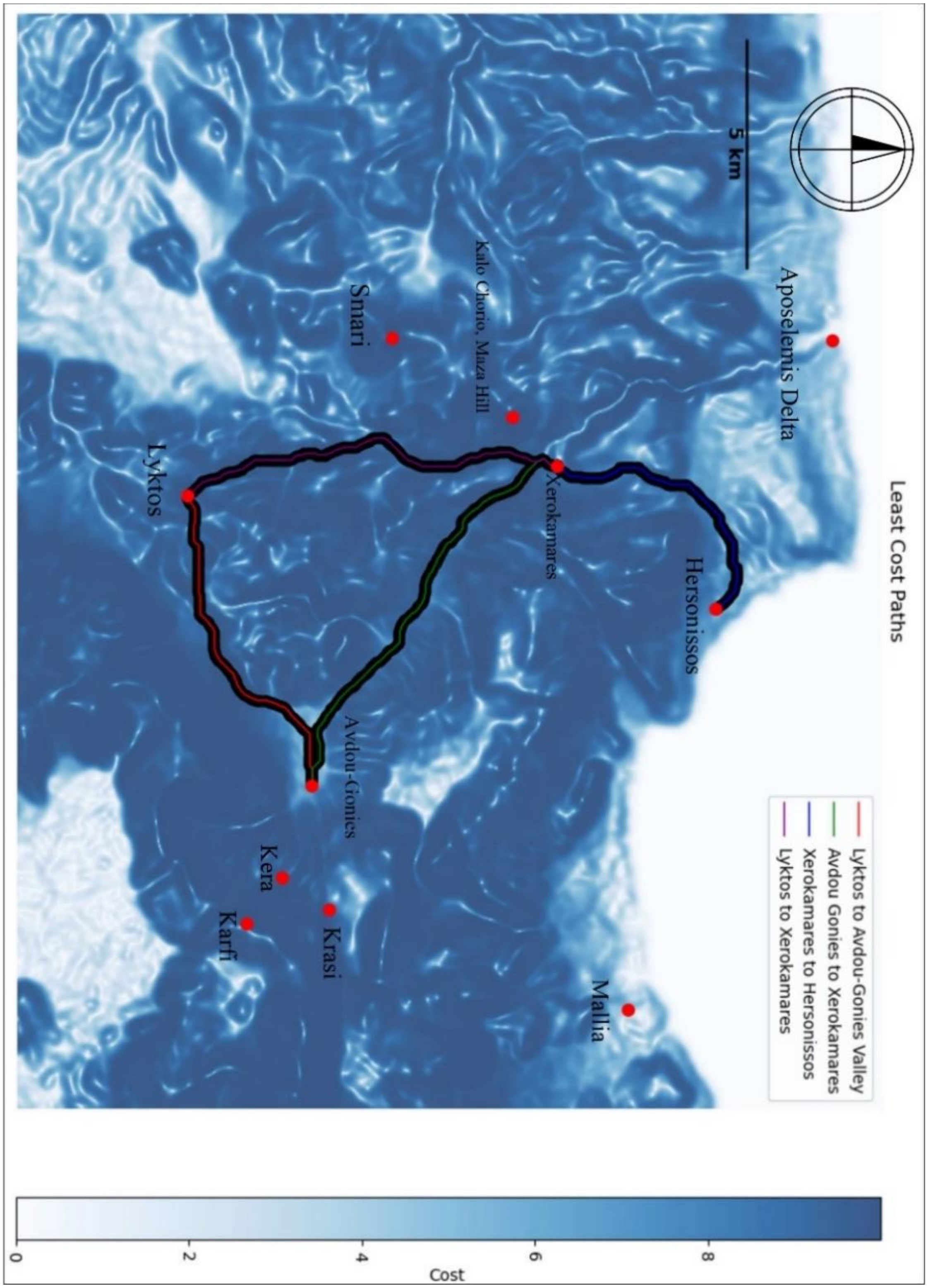
11: Askoi 12: Phaneromeni Cave

13: Potamies 14: Mallia

15: Gonies, To Flechthron

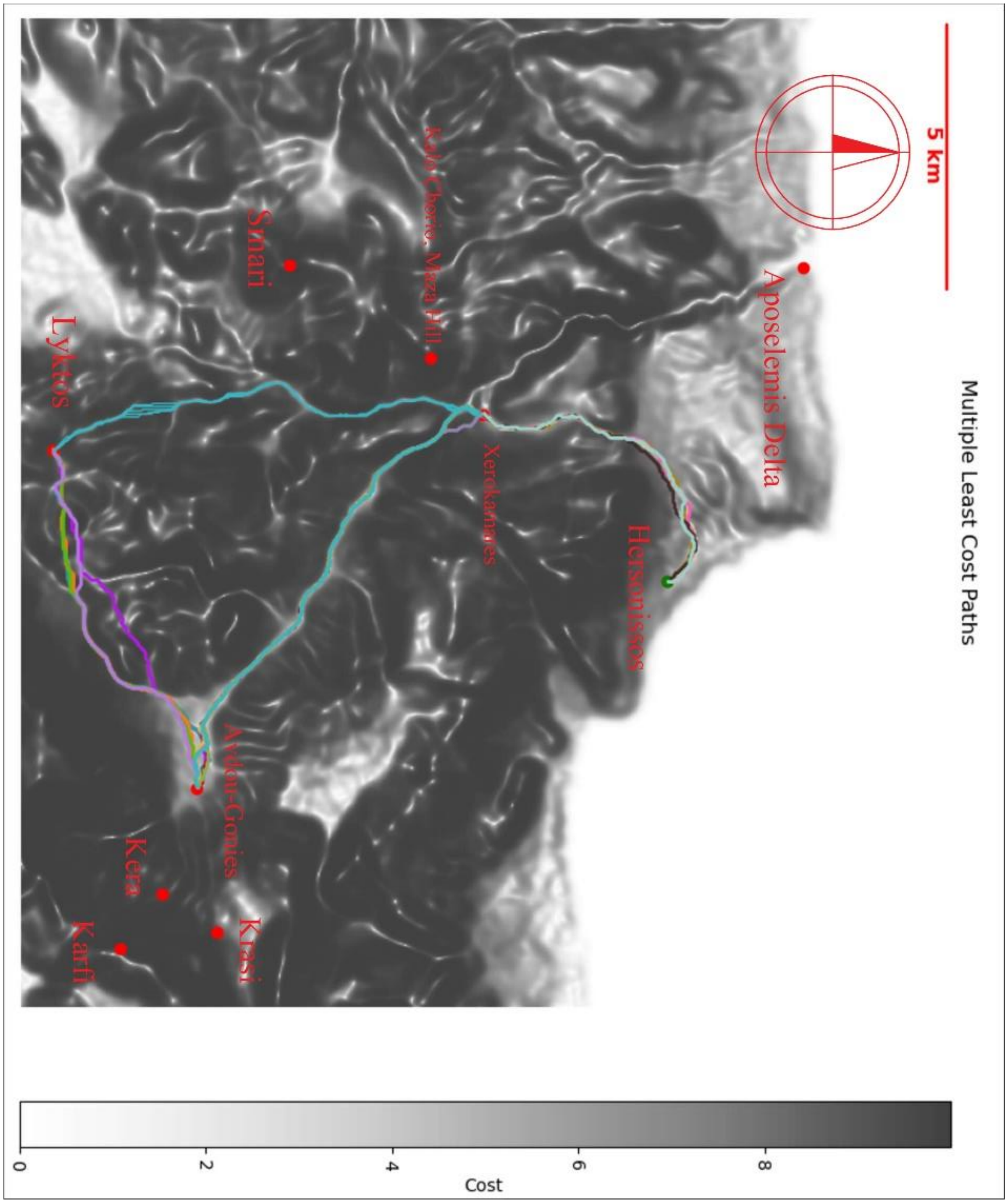
Appendix B

Least Cost Paths: Single Paths



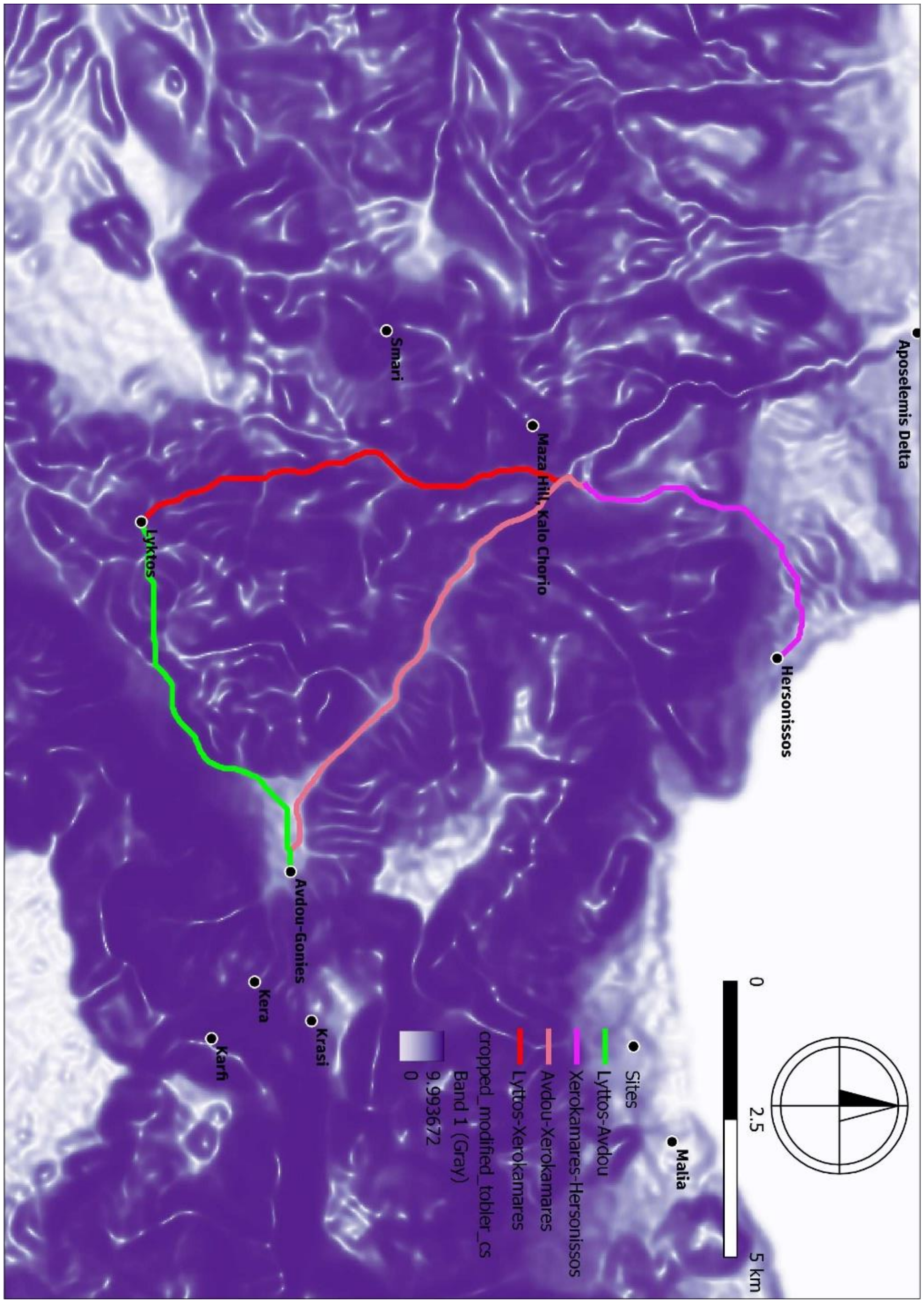
Appendix C

Least Cost Paths: Multiple Paths



Appendix D

Least Cost Paths: QGIS Paths



Appendix E

Instructions for running the Python Scripts:

Before executing the scripts, ensure that all the files, including the necessary data file (`Raw DEM: n35_e025_1arc_v3`), are located in the same directory.

Setup:

1. **Create an Independent Environment:**
   It is recommended to create an independent Python environment to install the required packages without conflicts. This will help in managing dependencies for the various tasks.
2. **Install Necessary Packages:**
   After creating the environment, install all the required packages. Depending on the package manager you prefer, you can install the required packages using either [pip] or [conda]

```
pip install [name of the package]
```

Or

```
conda install [name of the package]
```

3. **Running the Scripts:**

- The code is divided into multiple files, each corresponding to a specific task to avoid confusion.
- Execute the scripts in the order of their numbering to ensure that each task is completed sequentially and correctly.

A README.txt file will be included in the folder with more information for the scripts

Google Drive Link:
https://drive.google.com/drive/folders/1e9zHrA0jLWWbzrKtHL7HRSDfLQEYxDQp?usp=sharing

** For any issues with the Drive Link or the script, contact me on the following address:**

ted.andreopoulos@gmail.com