Archeologia e Calcolatori
35.1, 2024, 269-284
doi 10.19282/ac.35.1.2024.18

LEAST-COST PATH ANALYSIS FOR THE RECONSTRUCTION OF THE COMMUNICATION NETWORKS BETWEEN THASIAN AMPHORAE WORKSHOPS AND OTHER SITES IN THE 4TH-3RD CENTURY BC

1. Introduction

This contribution illustrates the application of the Least-Cost Path (LCP) analysis to reconstruct the potential roads, pathways and maritime routes connecting the amphorae production sites with the other sites in the *chora* of Thasos and with the port of Thasos. The archaeological investigations in the ancient city of Thasos began in the 1930s by the École Française d'Athènes. From the 1970s, the entire territory was explored through surveys allowing the identification of about 350 sites dating to the Archaic until the Imperial period (Grandjean, Salviat 2000, 39; Brunet 2004, 80). The island of Thasos is located in the northern Aegean and has always been at the centre of commercial and cultural networks between inland Greece and Anatolia. Since its foundation by Parians settlers in around 680 BC, Thasos urban centre (*asty*) has been located at the island's northernmost point facing the maritime commercial route from Athens to the Black Sea (Fig. 1). The control of this route brought commercial advantages to Thasos since it allowed to export the Thasian wine, one of the greatest sources of wellness and self-sufficiency for the city together with minerals, marble and agricultural products, all over the eastern Aegean and the Black Sea (Brunet 1996, 54-57; 2008, 90; 2019, 53; Foxhall 2007, 57). The entire island is considered the territory (*chora*) of Thasos which is made up of scattered and isolated farms, clustered settlements, rural sanctuaries and craft production sites (Brunet 2019, 48).

The Thasian wine was exported overseas and circulated locally in amphorae with a unique shape immediately identifiable with the island. They have vertical handles and a button-shaped foot; the body was wide in the 5th century and became slimmer between the 4th and 3rd century BC (Garlan 1988, 12). Thasian amphorae regularly bear one or two stamps on their handles most likely to control the wine or ceramic production somehow. However, evidence from the workshops shows that a large quantity of them actually remained unstamped (Garlan 1999, 2007). The stamps have been the main focus of the archaeological research of the amphorae production sites because the stamps with the annual magistrate's name are important for the reconstruction of the chronology of the amphorae production. The stamping system can be divided into two main chronological groups: 1) the older stamping system used between ca. 430 and ca. 330 BC, where the two

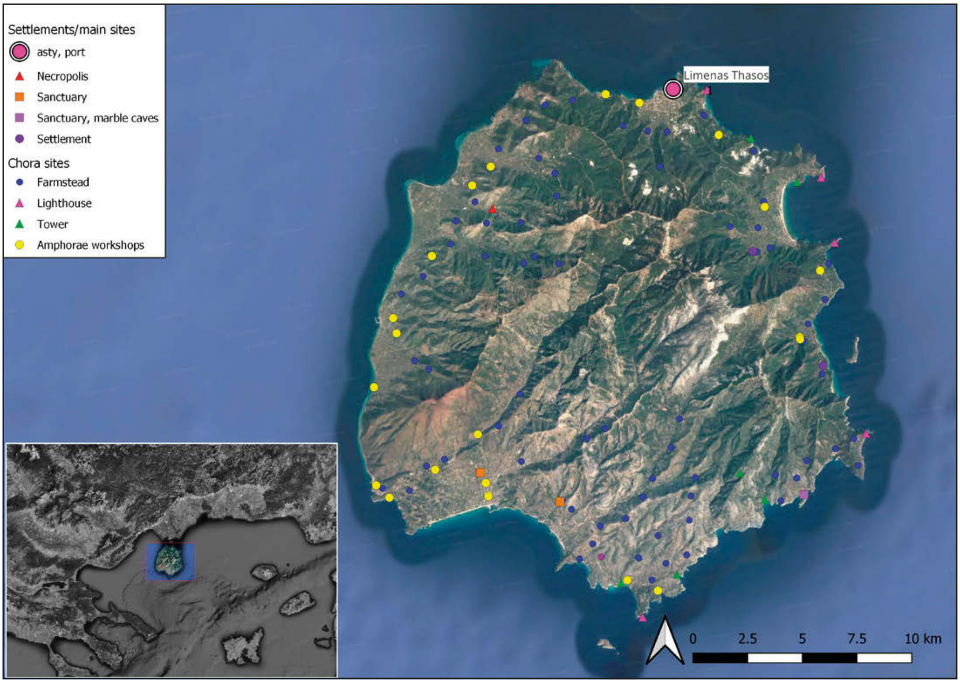

Fig. 1 – Location of the island of Thasos in the northern Aegean and sites distribution in the 4th-3rd centuries BC (elab. by the Author).

stamps indicated the name of the eponymous magistrate and the name of the 'manufacturer', as traditionally interpreted (Garlan 1999); 2) the later stamping system in use from ca. 330 to the 2nd century BC and it had only the name of the eponymous magistrate in combination with a symbol, that probably indicated the 'producer' (Garlan 1988, 18).

The surveys of the École Française d'Athènes allowed the identification of about 20 workshops producing wine amphorae, tiles and plain wares spread throughout the island along the coastlines (Brunet 2004; Garlan 2004, 312; Tomei 2022, 243) (Fig. 2). Eight workshops (Fig. 2, white dots) had been explored with archaeological excavations (Vamvouri Ammoudia, Kounophia, Kalonero, Koukos, Limenaria and Chioni), the others are known only by the surface collection of materials. Amid the 4th-3rd century BC workshops, only Vamvouri Ammoudia and Kounophia have remains of kilns. Vamvouri Ammoudia is located at the island's southern end, very close to the beach.

The excavations (1979-1980) revealed the firing area with three kilns: two small, U-shaped kilns 1.5 m and 0.9 long respectively and a large kiln with an oval-shaped combustion chamber (2×2.8 m) dug into the bedrock

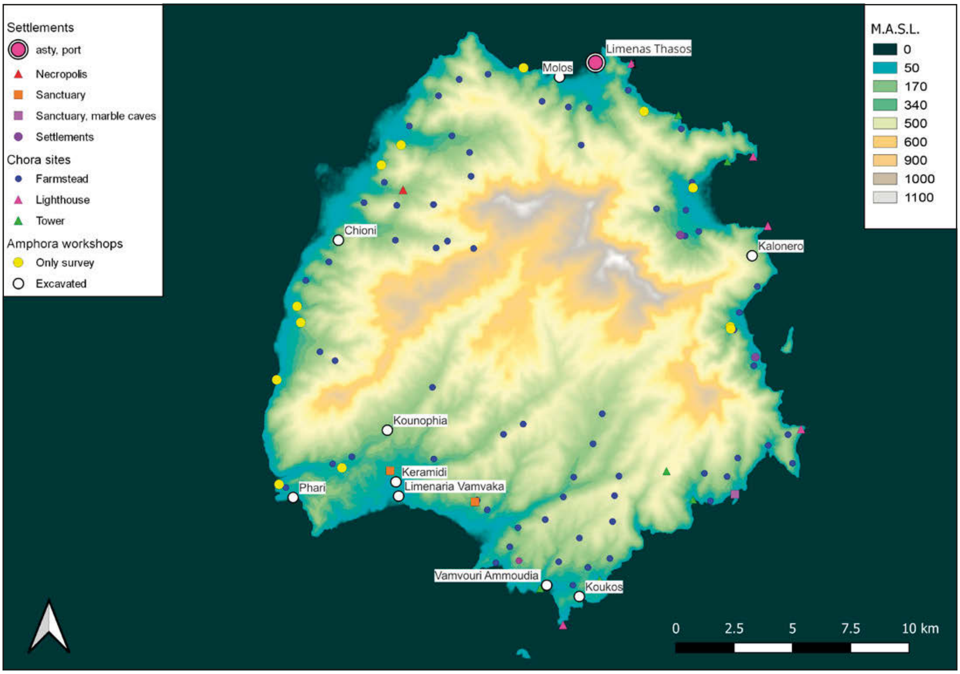

Fig. 2 – Distribution map of the amphorae workshops in the *chora* of Thasos (elab. by the Author).

and a stoking channel opened to the southwest (Garlan 1986, 205-207). The combustion chamber is surrounded by a square enclosure with thick walls made of stones and pebbles held together with clay, probably to insulate the kiln during the firing (Garlan 1986, 207). The ceramic materials found in the soundings include a great number of plain table ware, amphorae and tiles fragments, which were the main output of the kilns. Several amphorae and tiles were stamped with the later stamping system, dating the activity of the workshop from ca. 320 to 250 BC (Garlan 1986, 213-217).

Kounophia is situated in the southwestern part of the island on the hill slopes at an altitude of ca. 90 m asl. The fieldwork (1984) unveiled two phases of occupation: 1) a ceramic workshop, active from the beginning of the 3rd to the first quarter of the 2nd century BC; 2) a small rural necropolis with three tombs inside the abandoned kiln, probably connected to a Roman settlement nearby (Brunet 1986, 811). The kiln had a pear-shaped combustion chamber (diameter: 2.8 m) and like at Vamvouri Ammoudia, it was surrounded by a square enclosure of walls made of limestone blocks. The ceramic deposits included amphorae and tiles with ca. 700 stamps dating between ca. 290 and 170 BC, and plain wares including fragments of *pithoi* (Brunet 1986, 811).

The workshops without preserved remains of kilns (Kalonero, Koukos, Limenaria, Keramidi, Chioni, Molos) show large deposits of ceramic fragments, including kiln wasters and furniture, mainly amphorae sherds, tiles and plain wares, suggesting that they were not specialised only in the production of wine amphorae but produced also pottery for domestic use. For example, Kalonero is located on the eastern coast and the ceramic material recovered includes a significant number of plain ware fragments and some small black gloss ware fragments, although most of the sherds belong to wine amphorae. Amongst them, ca. 30 stamps belong to the older system and a further 30 handles bear the later system stamps, thus the activity of the workshop is placed within ca. 370 and 305 BC (Garlan 1986, 225). Koukos, in the southern end of the island near Vamvouri Ammoudia, has remains of a possible porch with walls made of limestone blocks and tiles and a big deposit of ceramic fragments which includes plain wares, *pythoi*, pyramidal and disk loom weights, kiln furniture, firing wasters and amphorae.

The stamps belong to the later system and date the site between ca. 340 and ca. 265 BC. However, the majority of the amphorae fragments were not stamped, with a proportion of 1 stamped to 3 unstamped (Garlan 1979, 225-229). The workshop of Koukos was active almost contemporaneously with Vamvouri Ammoudia and 14 names of eponymous magistrates found within the stamps at Koukos are also present at Vamvouri Ammoudia but associated with different symbols (Garlan 1979, 251). It is possible, therefore, that the two workshops produced wine amphorae for different landowners or middlemen at the same time (Tomei 2022, 254). The other workshops (Limenaria: Bechtsi, Theodoroudi 2017; Keramidi: Garlan 1985; Chioni: Garlan, Karadima-Matsa 1996; Molos: Garlan 2004) were also active between the beginning of the 4th to the 2nd century BC, according to the chronology of the stamps.

The position of the workshops along the coastline was strategic to ease the movement of the ceramic outputs in a predominantly mountainous territory towards the port of Thasos, from where most likely the stamped amphorae were shipped overseas. Indeed, a milestone dated to the mid-5th century BC found at the rural sanctuary of Aliki (Salviat, Servais 1964; Sintès 2008, 641), on the southern coast of the island, is important evidence of the existence of an ancient road connecting the city with the rest of the *chora*.

Its hypothetical coastal itinerary has been reconstructed by Bonias *et al.* (1990) and Sintès (2008) based on the inscription, the archaeological remains and the Ottoman pathways or *kalderimia*. The presence of roads and pathways was important for the ceramic workshops for connecting them with the marketplaces and for moving the raw materials (clay, temper, fuel) from the source places. Likewise, the maritime routes along the coasts might have been used for transporting large quantities of ceramic materials, especially the amphorae, from the production sites to the main port, as the lighthouses along the eastern and southern coasts and the numerous mooring installations suggest (Brunet 2019, 48). Therefore, access to roads, pathways and the seaside were key factors in the settlement choice of the Thasian ceramic workshops, besides the proximity to raw material sources and potential marketplaces (Tomei 2022, 282).

2. The Least-Cost Path to trace the terrestrial roads

2.1 *Methodology*

The LCA assumes, at a general level, that «humans will tend to economize many aspects of their behaviour, encompassing everything from speech to movement» (Surface-Evans, White 2012, 2). This concept has been applied by archaeologists and social scientists to study human behaviour, including movement in the landscape. Indeed, humans prefer to travel and socially and physically interact with more accessible landscapes, where movement requires less effort (Surface-Evans, White 2012, 2).

The application of the Least-Cost Analysis (LCA) using GIS software to archaeological case studies has constantly increased in the last decade as a tool to address a wide range of research questions (Herzog 2014, 223). Indeed, the approach allows archaeologists to investigate past connections and networks between peoples and places that have social, political, and economic significance (Surface-Evans, White 2012, 2). The book edited by White, Surface-Evans (2012) collects a wide variety of applications of GIS LCA analyses to different archaeological research questions (White, Surface-Evans 2012). The most common applications of the LCA are the Least-Cost Site Catchment, the LCP and the Cost Surface analyses. The Least-Cost Site Catchment investigates the accessibility of resources in the area around a site (Pecere 2006; Herzog 2014, 223).

The LCP determines the minimal-cost route between two locations (Connolly, Lake 2006, 252-255; Herzog 2020, 333) and it is based on two cost models: the isotropic cost, that does not consider the direction of movement between the raster's cells, and the anisotropic costs, that, on the contrary, takes into account the direction (Herzog 2014, 227). LCP is frequently used to reconstruct old routes connecting sites within the landscape, but also to investigate the spatial pattern of distribution of sites in a certain area or to model water or terrestrial transport (Herzog 2014, 228). Archaeologists most commonly use the slope as the cost raster to calculate the LCP, which is an anisotropic model because the effort of travelling between the cells depends on the slope's direction (Herzog 2014, 227). The most popular slope-based cost functions are the default Esri ArcGIS's[1] Slope, which measures topographic slope in percentage or degrees, and the Tobler hiking function, which provides a time estimate of the movement in the land (Herzog 2014, 233).

However, slope is not the only cost factor that influences the effort of movement: land use and the presence of rivers, creeks or lakes may be obstacles for people walking or travelling with wheeled vehicles or pack animals, so they should be taken into consideration in modelling human movement in the land (Herzog 2014, 235). Lastly, the Cost Surface Analysis models the travel time and energy consumption of an individual to move on the land through the analysis of grids simulating the geomorphology of the landscape and the presence of natural/artificial obstacles (Wheatley, Gillings 2002, 147-163; Pecere 2006, 185). As an example of archaeological application, Pecere (2006) models a surface based on travel costs and agricultural potential to study the settlement dynamics between the Iron Age and the Archaic period in Daunia (southern Italy).

For this research, the LCP has been used to model the possible paths connecting the ceramic workshops with the farmsteads spread in the territory and the port of Thasos. The analysis has been performed with the software ArcGIS 10. The ArcGIS Least-Cost Path tool uses two rasters: 1) the cost surface, which is a weighted raster that represents the ease of movement between the cells of the raster, and it may include topographic (slope and relief), natural (e.g., rivers) and anthropic (land-use) information (Newhard *et al.* 2008; Seaman, Thomas 2020); 2) the cost back-link raster, which defines «the direction or identifies the next neighbouring cell along the least accumulative cost path from a cell to reach its least-cost source» (Esri ArcGIS Pro 2023[2]).

The processing workflow is represented by a diagram (Fig. 3). The primary dataset required for the processing is the Digital Elevation Model (DEM) of the island, which has been downloaded from the European Environment Agency (EEA) Copernicus Land Monitoring Service Database[3] and has a spatial resolution of 25 m. From the DEM, the Slope is calculated, which is a raster representing the steepness of the land's surface expressed in degrees (Newhard *et al.* 2008, 93). Since it is not known the land use in the 4th-3rd century BC island of Thasos, only the reliefs, slopes and rivers as topographic and environmental constraints are considered (Newhard *et al.* 2008, 93).

The vector layer representing the rivers has been rasterised before

[1] The softwares preferred by archaeologists for the LCA are the Esri ArcGIS Spatial Analyst package which includes the Cost Distance and Path Distance as anisotropic cost models and the Cost Path to generate the LCP, and the open source GRASS r.walk which estimates walking time (Herzog 2014, 226).

[2] https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources; https://support.esri.com/en-us/gis-dictionary.

[3] https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1/view.

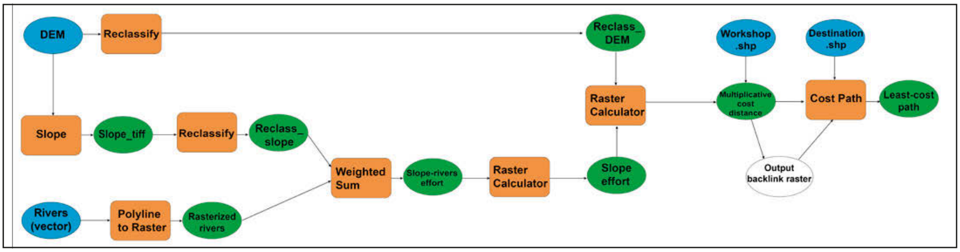

Fig. 3 – Diagram showing the workflow to calculate the Least-Cost Path in ArcGIS 10 (elab. by the Author).

applying the weighted sum with the Slope raster to get the 'slope river effort' surface, which reflects more accurately the areas with more expenditure cost to walk up and down (Newhard *et al.* 2008, 92). In order to perform the weighted sum and calculate the slope effort, it is necessary to reclassify the elevation model and the Slope because ArcGIS only considers positive values as valid for the processes. The slope effort surface is calculated with the Raster Calculator using the formula *tan(slope)/tan(1)* (Newhard *et al.* 2008, 94). Then, the slope effort is multiplied by the DEM, resulting in a cost surface (Multiplicative Cost Distance) that emphasises the slope information in high slope regions and elevation information in low relief areas (Newhard *et al.* 2008, 95). The Multiplicative Cost Distance has been used as the input cost raster to generate the Cost Distance, which calculates «the least cumulative cost from each cell to specified source locations over a cost raster» (Esri GIS Dictionary 2023). The Cost Distance generated also the Cost Back-Link raster. The Cost Distance and the Cost Back-Link are the basis on which the LCP is calculated. The source and destination points used to generate the Cost Distance and the LCP are vector features, in this case, points: the workshops as places of departure; the port of Thasos and the farmsteads as destinations.

2.2 *Results*

The results of the LCP analysis are shown in Fig. 4. The reconstructed paths follow the less steep zones, such as the coastal plains on the southern and eastern coasts, the lower slopes of the mountains on the western side of the island, and the river valleys. The hypothetical itinerary of the road (Fig. 5) known from the Aliki milestone, as already mentioned, on the information provided by the inscription, the remains of ancient routes and the Ottoman pathways (Bonias *et al.* 1990; Sintès 2008). The inscription indicates the distance in *orgyai*[4] between the city of Thasos and the sanctuary of Aliki,

[4] One *orgya* corresponds to ca. 1782 m (Sintès 2008, 647).

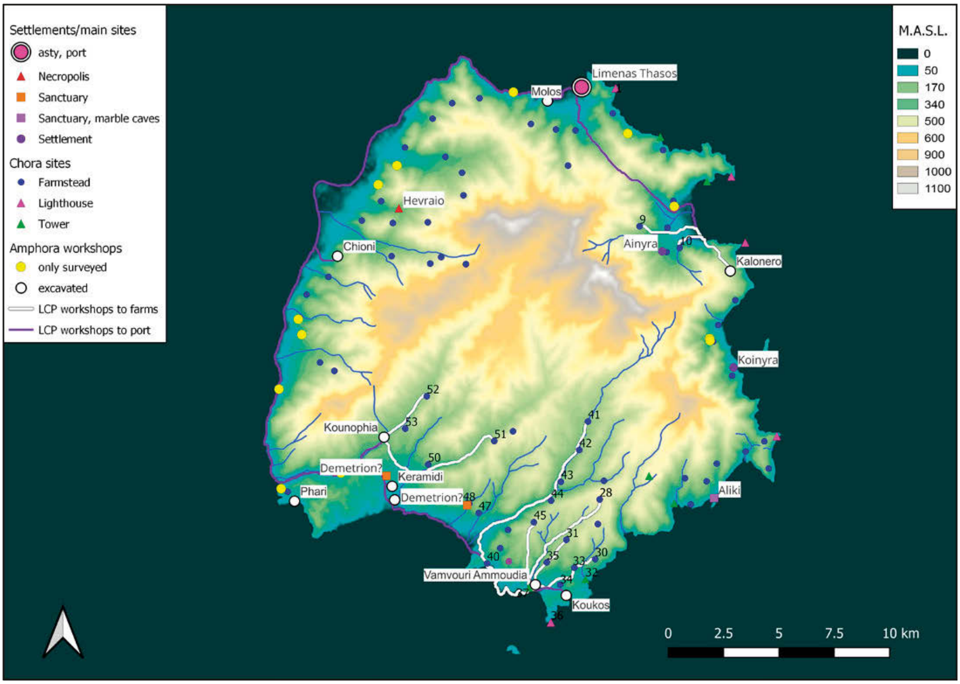

Fig. 4 – The resulting LCPs connecting the amphorae workshops with the port of Thasos (purple lines) and with the farmsteads (white lines) (elab. by the Author).

passing through the village of Koinyra on the eastern side of the island, which is about 20 km S of Thasos city. Then it mentions the distance between Aliki and the Diasion (sanctuary of Zeus) located at Demetrion, which was somewhere in the southern end of the island. After the sanctuary, the road follows the coast (Bonias *et al.* 1990, 76; Sintès 2008, 641). Therefore, it was a circular road following the coastal plains along the south-eastern, southern and western sides of Thasos; whereas, between the *asty* and Ainyra and Koinyra, it probably crossed the lower slopes of the mountains because on this side of the island the shores are very narrow and steep (Sintès 2008, 649).

The LCPs connecting the amphorae workshops with the city of Thasos have the same layout of the coastal road and it is particularly evident between Kalonero and Thasos and, on the southern coast, between Koukos and Phari (Fig. 4, purple line). The LCP, on the one hand, confirms the coastal itinerary of the road, and, on the other one, that the coastal road itself was the easiest way to travel between the amphorae workshops and Thasos port, where the wine amphorae were loaded into the ships and shipped overseas. Following the lower slopes of the mountains and the coastal plains, carts dragged by

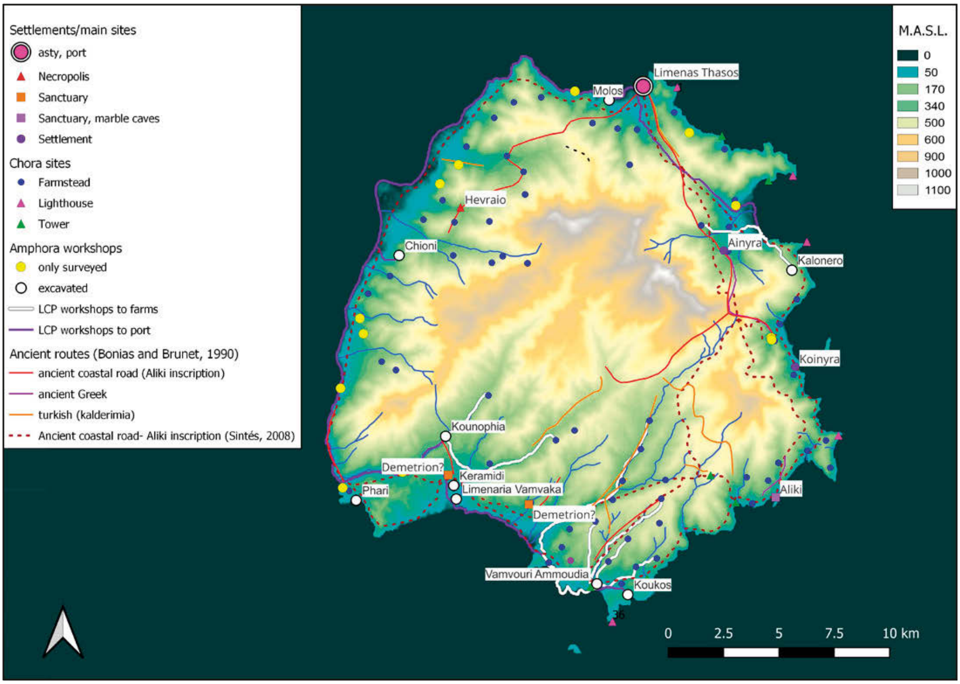

Fig. 5 – The resulting LCPs connecting the amphorae workshops with the farmsteads and the port of Thasos compared with the coastal road as reconstructed by Sintés (2008) and Bonias *et al.* (1990), and the Ottoman rural pathways (elab. by the Author).

donkeys or mules could safely transport the ceramic products with a low risk of breakages during the transportation.

Remains of ancient roads and the Ottoman rural pathways or *kalderimia* – which may have followed ancient pathways – crisscrossing the island (Fig. 4, orange lines) have been understood as evidence of an ancient network of pathways connecting the settlements and isolated farmsteads spread in the interior part of the island (Bonias *et al.* 1990, 76-78). Again, the LCPs calculated between the pottery workshops and some farmsteads (Figs. 3, 4, white lines) confirm the presence of such a network, which was important for the transportation of raw materials, products, and knowledge. In addition, the LCPs follow the same itinerary as the *kalderimia*, confirming that these modern rural pathways may have retraced ancient routes. The LCPs, as well as the Ottoman pathways, run along the creeks, the valleys and the lower slopes where the movement of wheeled wagons and pack animals was easier. For example, the LCP connecting Vamvouri Ammoudia with the farmsteads 41-44 traces a *kalderimi* and follows a stream valley (Fig. 6). Interestingly,

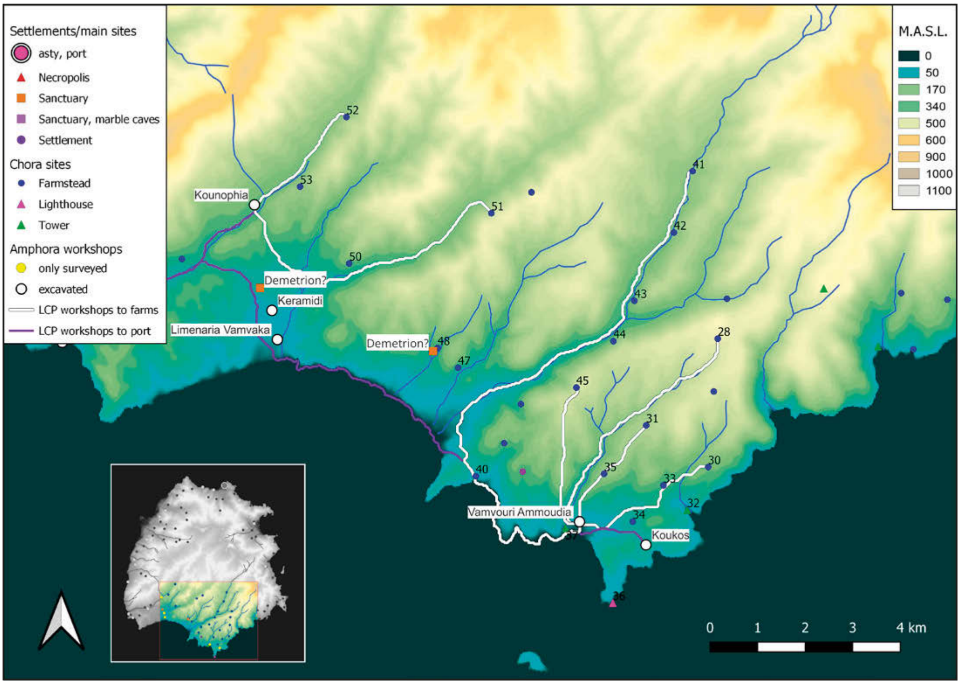

Fig. 6 – The LCPs (white lines) linking the southern workshops Kounophia, Vamvouri Ammoudia, and Koukos with the farmsteads scattered in the countryside (elab. by the Author).

the alignment of the farmsteads 41 to 44 indicates that along the stream there was an ancient route connecting the rural sites, or that the creek itself was used as a communication way perhaps when dry during the summer. Similarly, the LCP between Kounophia and the farmsteads 52 and 53 follows a stream and the lower slopes of the mountains (Fig. 6).

3. The Least-Cost Path to reconstruct maritime coastal routes

3.1 *Methodology*

As shown in Fig. 1, the majority of the amphorae workshops in Thasos are located on or close to the shoreline where ships could easily moor, and load those amphorae destined for overseas trade from the port of Thasos. Even though coastal navigation can be as dangerous as sailing on the open sea because the coastal topography can exacerbate the dangers caused by adverse conditions, Thasos is an island offering shelter against the prevailing winds (Morton 2001, 116-117, 146). Sailing around the island should normally be safe all year round, although Hesiod advises avoiding sailing from the end of October/beginning of

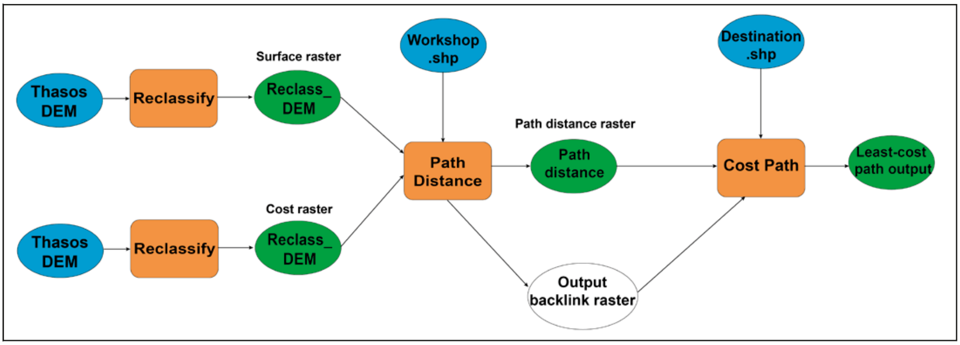

Fig. 7 – Diagram showing the workflow to model the sea routes using the Least-Cost Path analysis based on the Path Distance raster (elab. by the Author).

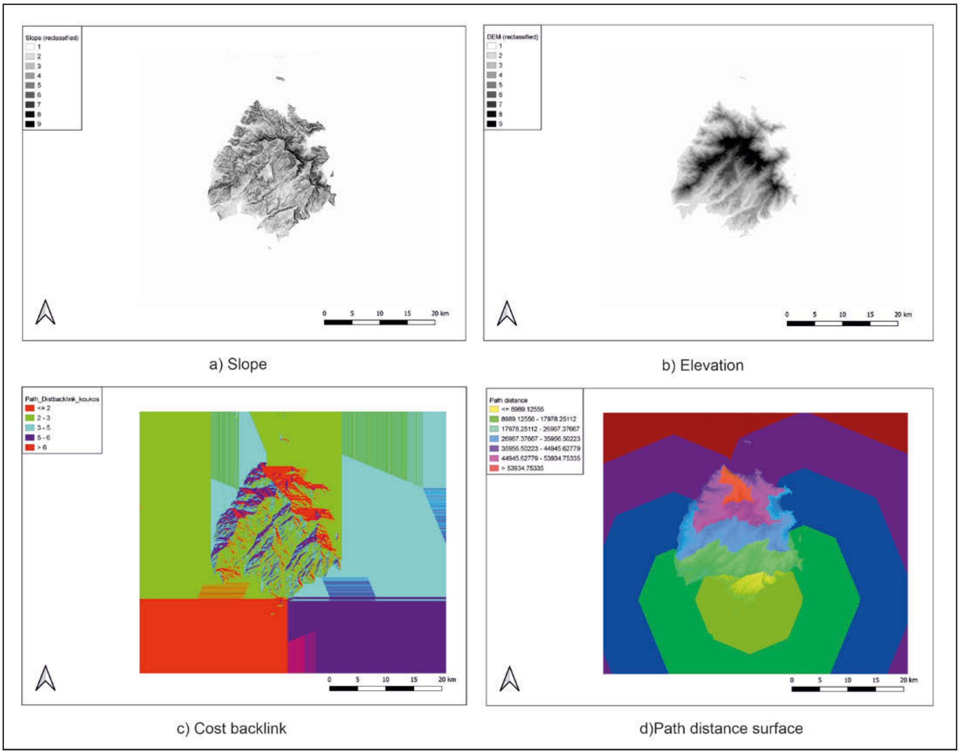

Fig. 8 – Main steps in the modelling of the cost surface and sea routes of Thasos (elab. by the Author).

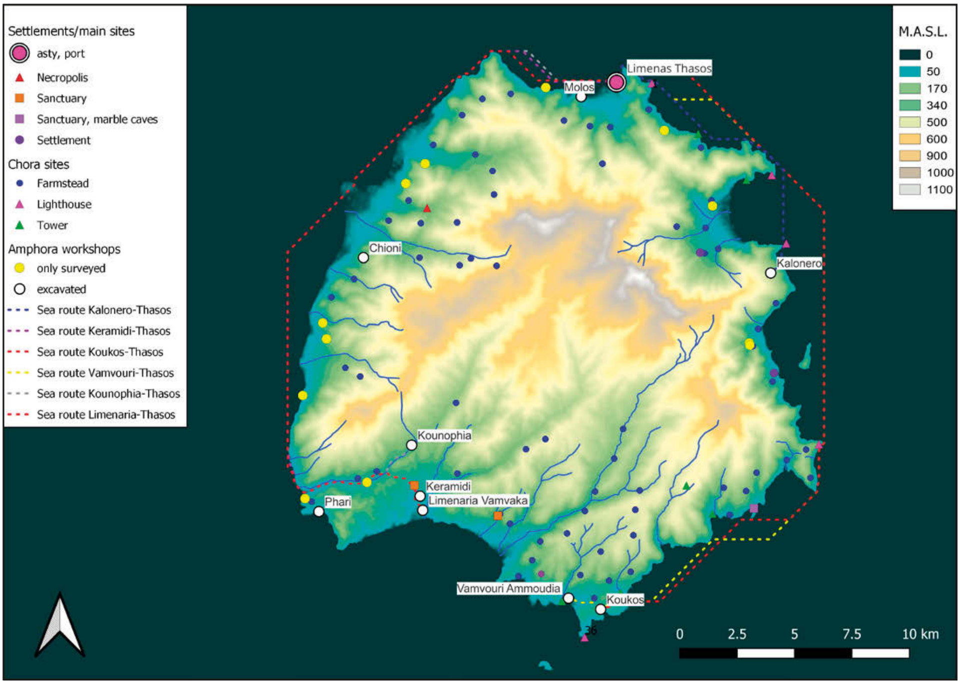

Fig. 9 – An hypothesis of the coastal maritime routes connecting the amphorae workshops with the port of Thasos as resulting by LCPs modelling (elab. by the Author).

November until summer as the winds are stronger (Hes. *ED*, 620-630). When sailing is possible under favourable weather conditions, travel distances should be short, since the circumnavigation of the entire island is 80 km.

Shipping by sea large quantities of amphorae from the workshops to the port is likely to have caused less damage to the products and been more efficient than carrying them on donkeys' shoulders or by carts across difficult and abrupt terrains. The model workflow (Fig. 7) used to reconstruct the sea routes along the coasts of Thasos is largely similar to the one described in section 2.1. However, instead of Cost Distance, the Path Distance is used to generate the cost surface necessary to calculate the LCP as indicated in Alberti's (2017) modelling of ancient sailing (Fig. 8). The Path Distance is similar to the Cost Distance since they both determine the minimum accumulative travel cost from a source to each cell location on a raster. Nonetheless, Path Distance calculates the accumulative cost over a cost surface while compensating for the actual surface distance that must be travelled and for the horizontal and vertical factors influencing the total cost of moving from one location to another (Alberti 2017, 3; Esri ArcGIS Pro 2023).

However, since wind direction and speed data (Alberti 2017, 4-5) were not easily available for this research, the sea routes are calculated as LCPs based on the Path Distance using the elevation as a vertical factor and the slope as a horizontal factor. In this way, the Path Distance is a helpful heuristic device to model and explore possible transport routes on the sea along the coasts of the island (Fig. 9).

3.2 *Results*

The LCPs show that navigation from the southern workshops, like Vamvouri Ammoudia and Koukos, was easier along the East coast, where the numerous remains of ancient lighthouses may suggest that it was a popular (although dangerous, as the coastline was high and jagged) route in antiquity (Brunet 2019, 48). From the workshops in the southwestern side, like Limenaria, Keramidi and Kounophia, the western route along the coast was preferable (Fig. 9). The comparison of the distance and cost values, calculated by GIS, between the terrestrial and maritime routes suggests that the maritime ways were more efficient because they saved on the effort to travel from the amphorae workshops to the port of Thasos (Tab. 1). However, choosing between terrestrial and maritime transport was not straightforward. Which way was more beneficial, depended on seasonality, load capacity and speed.

Workshop	Maritime routes		Land routes	
	Km	CostPath Value	Km	CostPath Value
Kalonero	14	16543	12	66517
Koukos	36	36639	48	67316
Vamvouri Ammoudia	37	38181	46	64452
Kounophia	34	35393	35	51156

Tab. 1 – GIS calculated comparison of the distance and the CostPath value between the land and the maritime routes from the workshops to Thasos.

4. Discussions and conclusions

The LCP analysis proves to be a valid approach to reconstruct the communication networks in the Thasian countryside during the 4th and 3rd centuries BC. In particular, it proves that the location of the amphorae workshops favoured the smooth connection with the other sites, especially the scattered farmsteads and the city of Thasos, and the easy transport of the ceramic products either through land travel or coastal navigation. Indeed, their location maximised access to the main coastal road – whose existence is known based on the Aliki inscription – which allowed the movement of people and goods with less effort because, according to the LCP analysis, it runs along the areas of lower slope, such as the coastal plains and the valleys. The coastal road appears to be particularly helpful for the workshops located on the southern and western coasts of the island where the coastal plains are larger and ceramic products can safely travel on carts or donkeys' shoulders.

The workshops were also connected with scattered farmsteads by a network of smaller pathways, whose routes have been reconstructed either from visible archaeological remains, such as the Ottoman *kalderimia* or through LCP analysis. Therefore, travelling between workshops and farmsteads was possible by using pack animals and carts that supplied them with pottery, tiles and amphorae to be filled with wine. The road and the pathways also contributed to making more manageable the transport of raw materials for pottery making, like clay, temper and fuel, from the sources in the proximity of the workshops (Tomei 2022, 261-265).

Besides the land routes, LCP demonstrates that the location of most workshops on the shoreline, where the boats could easily moor and load the amphorae, favoured their transportation via coastal navigation. Indeed, the LCPs show that sailing from the workshops on the southern and eastern coasts was more efficient and save on travel costs in terms of distance and effort. This is particularly true in the eastern side of the island where the shores are more abrupt and the coastal plains are shorter, thus land travelling would be difficult and wine amphorae at risk of breakage. However, sailing cannot be practised all year round, so land travelling remained a valid option also for the eastern workshops.

Lastly, the LCP analysis confirms the layout of the coastal road that Bonias *et al.* (1990) and Sintès (2008) reconstructed basing on the epigraphical evidence of the milestone found in Aliki. Similarly, some of the LCPs connecting the workshops with sites located in the interior of the island follow the layout of the modern and Ottoman rural pathways, suggesting that they could have been used also in antiquity.

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ABSTRACT

This article explores the application of Least-Cost Path analysis to reconstruct potential transportation routes connecting amphorae production sites on the island of Thasos in northern Aegean. Characterized by wine production as a significant source of wealth during the Classical period, approximately 20 amphorae workshops-identified with surveys- date back to the 4th and 3rd century BC. By utilizing LCP analysis, the study demonstrates the strategic placement of these workshops and reveals their connectivity to the countryside and the port of Thasos. The proximity of the workshops to the main coastal road and maritime routes facilitated the efficient transportation of amphorae to the port. Furthermore, a network of rural pathways played a crucial role in linking the workshops with scattered farmsteads, ensuring a seamless supply chain for ceramic products. This research sheds light on the importance of spatial analysis in retracing ancient communication networks combined with historical and archaeological sources.