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„The Jadeite Connection“
Modelling sea-routes in the Neolithic Aegean

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Mag. Sheba-Celina Schilk
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Betreuer/in:
Dr. Christian Neuwirth

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Contents

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1.1. Why model ancient seafaring?

Large water surfaces have long been seen as a border, limiting inhabitants to their islands and keeping mainlanders from getting to locations on the other side of the "big water". However, the Mediterranean is a great example of the contrary, a sphere of interaction between many different cultures from early on (e.g. Stampolidis 2003). Recent studies show that the importance of the Aegean Sea for communication and the spreading of the "Neolithic package" was crucial and has been underestimated in former scientific research on the topic (Horejs et.al. 2015). Especially the significance of seafaring knowledge and mental maps for early navigation on sea has been already highlighted by several scientific publications, e.g. Broodbank (2006, 210), who describes the taken routes as "(…) *risky, dangerous journeys, requiring greater skill at manoeuvring craft in different conditions and over a longer duration, predictive and navigational knowledge of currents and winds, and more extensive mental maps of land and seamarks*". Nevertheless, Horejs et.al. (2015, 293) stress, that "(…) *it is more than likely that mobile maritime scouting would have led to the discovery of the best obsidian source in the Aegean (Cherry 1981). Any initially even minor importance of seafaring knowledge would (or at least could) have been rapidly amplified via positive socio-cultural feedback.*" The impact along with it the importance of experience and knowledge on the movement of early seafarers within their maritime environment is, thus, something to be yet investigated – but which is the best method to do so?

It has been stated by Van der Leeuw (2004, 117-118), who summed up the advantages of modelling for archaeology, that "*archaeologists and historians have been called 'prophet[s] turned backwards', [as] they deal with a distant past about which they often know as little as about the future*." He defines four problems encountered in archaeology, two of which are of particular importance in this context: "*First, archaeologists cannot assume that their sense of the relationships between people and their artefacts is the same as that of people they study. Second, archaeology bases its interpretations on few and meagre clues about the past. Its theories are therefore generally underdetermined by observations; its data, moreover, are statistic. They reflect the results of dynamics between people and materials, landscapes, monuments, and so forth, but they do not reflect these dynamics themselves. The discipline therefore has difficulty linking cause and effect in the past.*" These problems also apply, of course, for the study of seafaring and its different drivers. In order to address these difficulties, mostly experimental archaeological investigations or sociological surveys are used, which generate of course interesting results. Nevertheless, they are often very time and money consuming, and the above mentioned possible discrepancy between modern, personal relationships to certain artefacts and the relationship of ancient cultures to the same objects, is of just as much importance when deducing ancient seafaring behaviour from modern fishing communities. Modelling can be a good solution, enabling the study of underlying processes and the impact of different factors within a system. It can be conductive to the explanation of observed phenomena and dynamics, like the spreading of knowledge, the exchange or trade of a product or material, the formation of social networks, or changes in a society. On the other hand, it can be used in order to predict developments. As stated by van der Leeuw (2004, 125) "*(…) dynamic models may also allow the archaeologist to some extent to experiment with different scenarios to explain particular sequences of cause and effect. One may, for example use (…) modelling to relate different environmental and social parameters (…). By running each scenario many times over, one may moreover assess the probability of certain outcomes given a particular set of initial conditions and one or more theories about the dynamics involved.*" Nevertheless it should be noted at this point, that the results gained with modelling cannot corroborate a suggested hypothesis, but can only support it. Also, it is highly dependent on the data input and the programmed processes.

Even though agent-based-modelling (ABM) is already a known method for studying different archaeological topics, including seafaring, the studies usually leave the human decision processes aside (cf. chapter 1.2.1., Path-reconstruction and Spatial Simulation in archaeology). The overarching aim of this Master Thesis is to contribute to the implementation of these factors by creating a basic ABM on the topic, testing the usability of GAMA software in general and the Belief-Desire-Intention structure (Taillandier et.al. 2016) in particular. In order to do so, the transport and exchange of jadeite axes in the Neolithic Aegean was used as a small scale case study, which can be enlarged in later steps. Seafaring is here seen as a method for exchange, influenced by environmental conditions and social relations – creating an interdependent system. The data used is based on the investigations of Lasse Sørensen, who studied the network and origins of the material over the past years (Sørensen 2017) and, who could determine two different sources of the used jadeite: the Alps and Syros (cf. chapter 1.2.2., Case Study). While the land routs used from the Alps towards the Aegean are known quite well already, the path taken on sea is still uncharted. This thesis wants to help to fill this gap by mapping the routes taken by the ships and producing a heat-map.

Research Question

Following Farrs (2006) approach of studying seafaring as a social action, the here presented work wants to try out the state of the art method of spatial simulation in order to develop a basic model of jadeite exchange during the Neolithic period of the region. As an overarching question it tests the usability of the Belief-Desire-Intention (BDI) structure in GAMA for working on archaeological topics. Additionally the study wants to contribute to answering the anthropological question of how human decision making, based on knowledge, emotions (in this first state “fear”) or character, influences ancient seafaring. Within this scope, two more focused questions are investigated: can the hypothesis of coastal-tramping-routes – thus the favouritism of early seafarers to stay close to coast and “jump” from coastal site to coastal site – being “common sense” and therefore the preferred method of seafaring be supported, or are there circumstances, under which open sea travelling is favoured? And second, can a possible route between the island of Syros and the sites with jadeite axes be seen.

1.2.1. Path-reconstruction and Spatial Simulation in archaeology

The reconstruction of networks in archaeology is a long ongoing topic and is usually based on *sourcing*, which means analysing the circuit of resources and objects and finding the source of used materials and their distribution – this can also be said for the Aegean region (e.g. Horejs et.al. 2015) studied in the here presented investigation. This method can give a lot of information on the participants of a network and looking at the distribution of working areas, half worked or finished products, data on the type of trading chain can be gained. Early exchange-networks in the Aegean region have been the topic of investigations under different aspects, often based on the exchange of Obsidian, as it has very specific characteristics facilitating the localisation of its origin (e.g. Knitter et al. 2012; Carter et al. 2013).

As recent approaches on modelling exchange networks Broodbank (2000), followed by Knappett et.al. (2008; 2011) should be mentioned, who developed the model of *imperfect optimisation*, connecting settlement seize, geographical distances and social factors. As mentioned by Tartaron (2013, 191), the model uses physical distances instead of quantitative data on travel time, though, causing certain inaccuracy.

Most GIS-based approaches base on the calculation of *least-cost-paths* (LCPs) which has made its way into archaeology already a long time ago (Gustas and Supernant 2017, 40; Doneus 2013, 318-335), even though the success of this method is highly dependent on the factors taken into account, as well as on the algorithm and program used (Gielt et.al. 2008; Herzog 2008; 2013a; 2013b; 2014). Case studies have been mainly focusing on terrestrial routs (e.g. Atkinson et al. 2005), however recently an increasing number of studies on seafaring uses this approach as a main concept mostly based on environmental conditions, visibility and means of transport – also used in other, not GIS-based ways of route reconstructions (e.g. Indruszewski and Barton 2008; Papageorgiou 2008; Callaghan and Scarre 2009; Cooper 2010; Leidwanger 2013; Newhard et.al. 2014; Bar-Yosef Mayer et al. 2015; Davies and Bickler 2015; Howit-Marshall and Runnels 2016; Safadi 2016).

As the planned study focuses on the reconstruction of sea-routes, one methodological focus has to lie on the reconstruction of wind and waves in order to reconstruct currents, hence the natural conditions of Neolithic seafaring. Numerous methodological studies have been conducted on this topic (e.g. Marghany, Ibrahim, and Van Genderen 2002; Cavaleri 2005; Asma, Sezer, and Ozdemir 2012; Chou et al. 2015; Safadi 2016; Siadatmousavi, Jose, and Miot da Silva 2016). Bar-Yosef Mayer et al. (2015) focus specifically on the reconstruction of sea-routes to and from the island of Cyprus, investigating especially the factor of winds for seafaring in this region.

For early seafaring coastal navigation and tramping are usually suggested (e.g. Morton 2001, 143), but open-sea routes existed and had their advantages (Morton 2001, 156–62). By the time of the Neolithic both the coastal and open water routes seem to have been already well established (Horejs et.al. 2015, 290).

The navigator's decision on which rout to take depended on a lot of factors, including not only natural conditions but also cultural aspects (e.g. allies/competitors, political circumstances, religious beliefs/centres, pirates). Recent attempts in archaeology focus on the implementation of socio-cultural aspects and interactions as new key factors (Robb and Farr 2005; Gustas and Supernant 2017), following studies of ancient texts and theoretical network theory (e.g. Farr 2006; Sindbæk 2007; Knappett et.al. 2008; Arnaud 2011; Tartaron 2013).

A problem of the often used Least-Cost-Path-reconstruction is the necessary assumption of an omniscient navigator, whose decisions are based only on rational, economical thinking (or *homo economicus*). Gained and passed knowledge on socio-cultural factors as well as decision-making can only be simulated by changing the cost values assigned in the cost-raster by the investigator.

A possible solution is the change to a different method: the usage of Agent-Based-Modelling (ABM), as its focus lies on the simulation of individuals (agents), who can adapt to situations and learn based on their interaction with each other and their complex environment (O'Sullivan and Perry 2013, 51). Only few attempts have been made (e.g. Crabtree 2016) using this method for the investigation of networks in archaeology – one of the most recent models being presented by Davies and Bickler (2015), who argue for a "*flexible voyaging simulation to model prehistoric seafaring. Combining freeware technologies in GIS, statistics, and agent-based-modelling (…)*" (2015, 215). However, they note that social factors, especially "*the influence of the navigator in voyaging choices*", remain an important aspect to include (2015, 221).

1.2.2. Case Study

a. The Aegean Neolithic Times – a brief overview

Chronologically the Neolithic period can be subdivided in an Early, Middle and Late period, which is followed by the Chalcolithic (ca. 6/5th-4th millennium B.C.) and the Bronze Age (ca. 4th -2nd millennium B.C.). In general it includes the absolute dates from the mid-8th millennium B.C. to the mid-6/5th millennium B.C., even though the exact dates vary depending on the geographical region under investigation.[1] The period is characterised by villages on hills (tells) as well as in lowlands, living of agriculture, herding and hunting as well as fishing (Alram-Stern 1996, 109, 186-188; 190; Horejs et.al. 2015, 297, 310-313). The connection between the different sites can be seen in the analysis of many different archaeological find categories – e.g. pottery, figurines or obsidian (Alram-Stern 1996, 116-175) – leading to the reconstruction of a (regional maritime) network, including e.g. the Cyclades, Crete, Dodecanese/east Aegean, Sporades, as well as Melos (as an obsidian source), and reaching at least as far as Kerame (Ikaria) in the eastern Aegean. It was well established already in Pre-Neolithic times, most likely as early as the Early-Holocene (Mesolithic period; Horejs et.al. 2015, 293). The importance of this maritime network for the spreading of the "Neolithic package" from the Middle East and Anatolia was discussed thoroughly by Horejs et.al. (2015).

b. Seafaring

Ecological factors

As stated by Papageorgiou (2008, 200) "*Although economic factors (fishing, acquisition of raw materials, exchange of goods, transportation and so on) were the principal incentive for the development of seafaring, its development per se was based on the one hand on the conditions created by the natural environment and primarily the sea, on the other on the technology that prehistoric people developed in order to deal effectively with the environmental conditions*" (cf. Technical factors).

Numerous studies have been conducted on the paleoclimatic conditions in the region under study over the past years, leading to the conclusion that the sea level rise dominating the previous time periods had been completed by middle Holocene period (about 5000BC) and the environmental conditions as well as the coastline at the beginning of the Late Neolithic were

[1] A large amount of publications can be found on the different chronological systems and their connection and congruence. Especially the chapters on chronology in Alram-Stern (1996, 83-105) as well as Reingruber et.al. (2017), Reingruber and Thissen (2009) and Thissen (2005) should be mentioned here.

very similar to the conditions nowadays[2] (Bintliff 1977; Rapp and Kraft 1978; McCoy 1980; Lamb 1982; Van Andel and Shackleton 1982; Lambeck 1996; Lambeck and Purcell 2004; Dalongeville and Fouache 2005 cited in: Papageorgiou 2008, 200-201; Morton 2001).

"*Since the geomorphology of the Aegean and the climatic conditions have not changed, it is assumed that the hydrodynamic conditions on the surface of the sea have remained the same. It is thus likely that the picture of sea circulation in the Aegean Sea in prehistory was similar to the present one*" (Papageorgiou 2008, 205; 1997, 427–429).

Two ecological factors are considered as crucial for early seafaring: currents (influencing mainly objects reaching a depth of about 1m) and winds (and the resulting waves).

The main counter-clockwise sea currents dominating the Aegean sea have been discussed thoroughly (e.g. Morton 2001, 38-46; Papageorgiou 2008, 204-209): the north-east Aegean sea current is "*created in the north-east Aegean region by the debouching of waters from the Black Sea (ancient Euxine Pontus) disperses throughout the entire Aegean Sea and determines sea circulation in it*" (Papageorgiou 2008, 204). This current facilitates the cruise from north to south following the west coast, enables a safe travel from east to west along the north coasts of the Aegean and even allows traveling the Cretan Sea towards Crete (Papageorgiou 2008, 205). A parallel north-north-east wind enforces this current almost the whole year long (Papageourgiou 2008, 205) and during the period between late spring and early autumn, it is additionally reinforced by the Etesian winds (Morton 2001, 48) blowing at medium strength. This, though, made travelling against the current nearly impossible or at least very difficult for bigger (sailing)boats. This fact makes the possibility of moving northwards from the centre of the Aegean Sea during the summer time using the north-east Aegean current very important (Papageorgiou 2008, 205-208). The other dominant current connects Crete with the Aegean Sea and the Black Sea flowing from the south to the north, on the one hand, and with the Adriatic via the straits of Kythera, uniting with the north-east Aegean current. Its northern course is generally weak, but the south winds blowing northwards can enforce it during the winter months (Papageorgiou 2008, 208). As summarised by Bar-Yosef Mayer (2015, 418), who relies on measurement data from the Royal Navy authority as well as several studies on the topic (McGrail 2001; Gerin et.al. 2009; Amitai et.al. 2010; Menna et.al. 2012; Poulain et.al. 2012), the currents for the area around Cyprus reach a speed of about 0,25 to 0,5 knots (about 20 – 25 cm/sec).

[2] At this point, it should be mentioned, though, that the coastline in the northern Turkish area of Çukuriçi Höyük changed drastically until now. The site (as later Ephesos) can be reconstructed to have been a coastal location in the period under study (Stock et.al. 2015).

A more crucial ecological factor for seafaring, whether traveling with a paddled or a sailing boat, is the wind, which has been studied a lot in the past decades and has been summarised thoroughly by Bar-Yosef Mayer (2015, 418-420) and Morton (2001, 48-61). Generally speaking, the weather conditions in the Mediterranean region are very constant during the summer with strong winds blowing from north to south (Morton 2001, 46). In the second half of the year the area is dominated by cloudy and stormy weather (Morton 2001, 47).

The above mentioned Etesian winds are hot, clear and steady and develop from the "*Azores anticyclone to the west and, more importantly, the Asiatic depression to the east*" (Morton 2001, 48). They can blow from anywhere between Northwest and Northeast. Their exact direction depends on the local topography as well as "*small fluctuations in atmospheric conditions*" (Morton 2001, 48). During the winter winds are less predictable and steady, both in their direction and duration (Morton 2001, 48). "*The most significant winds associated with the passage of depressions over Greece are the northerly Bora (and kindred winds) and the southerly Scirocco*" (Morton, 2001, 49). The former, a cold and very strong wind, goes from the North towards the Adriatic Sea. "*(…) similar winds, such as the modern Livas, and the ancient Boreas, Thraskias and Hellespontias, blow down through the river valleys in the mountains, across the coastal plains of Macedonia, Thrace and Thessaly, and onto the Aegean Sea*" (Morton 2001, 50). The Scirocco, in contrast, is a dusty and hot wind coming from the Sahara and blowing towards Europe reaching the area up to the northern coast of the Aegean region (Morton 2001, 51). Additionally, regular land and sea breezes develop especially during summer time, which change over the day and had to be known by a navigator. The daily cycle starts with the sea breeze in the late morning, which increases during the afternoon to die down at sundown. After several hours, the land breeze starts, which can reach up to 25km or more at sea, even though it is not as strong as the sea breeze, especially when it is cloudy. This wind continues until sunrise, when after another period with winds, a new cycle of breezes starts (Morton 2001, 51-53). Both types of breezes can be enforced by mountain and valley winds in areas, where the coast is submerged, indented and mountainous (Morton 2001, 53-56).

Bar-Yosef Mayer (2015, 420-423) shows for the summertime until October, a high percentage of favourable winds, reaching an average strength of 1-4, sometimes up to 6 Beaufort. Nevertheless, the resulting gathered wind-and-wave speeds used in this study show a very low resulting wave speed. Together with the general stable weather conditions, this leads to a preferred travel period between April and October. However, it is likely that winter season as well as night travelling was also practiced, though with more caution (Morton 2001, 255-266).

For orientation visibility is very important especially as there is no evidence of navigation aids for the time period and region under study. It is highly dependent on factors like haze, fog or dust (El-Fandy 1952; Dayan and Levy 2005 cited in: Bar-Yosef Mayer 2015, 420; Morton 2001, 61-66). It is usually assumed, that navigators tried to sail along visible coasts as much as possible – leading to the often suggested "coastal tramping"-strategy for early seafaring in the Mediterranean. Nevertheless, recent investigations (e.g. Horejs et.al. 2015; Morton 2001, 144-159) favour the usage of high seas as well as coastal routes already as early as the Pre-Pottery Neolithic (Horejs et.al. 2015, 289-290).

Aside of man-made harbours providing shelter for early seafarers, natural harbours evolved from marine erosion as well as other natural features played a crucial role in difficult situations and had to be found or known by the navigator. Morton (2015, 108-110) describes in his study not only the natural harbours of Emborio at Chios but also the "Calm Harbour" in the region of Torone (around Chalkidike) as well as Zea and Mounychia in the Piraeus with their "*oval shape and headlands stretching across the mouth from either side*" (Morton 2015, 109). All these harbours were very well known during the ancient Greek time and it can be assumed, that were also used already in earlier times.

One possible shelter during bad weather conditions was behind headlands (Morton 2015, 110-114). Here the Bay of Karystos, behind Geraistos, Sounion (the southeast extremity of Attica), Koressia at the northwest coast of Keos – serving as the main port of the island –, as well as the foreland of Palamidhi in the Gulf of Argos and the bay of Orikos should be mentioned.

Other sheltering natural features were river mouths (Morton 2015, 114-116) as well as protected locations behind islands (Morton 2015, 116-118). An example for the latter is "*the great rock of Monemvasia, off the east coast of the Parnon peninsula in the southeast Peloponnese*" and the high land of Euboia (Morton 2015, 117), but also the islands Cyprus and Crete or Kauda (near Crete) were used as a protection against very strong winds (Morton 2015, 118).

It should also be mentioned, that there were several harbourless coasts (Morton 2015, 137-142), especially extensive cliffs, which were likely avoided by early seafarers (Morton 2015, 142).

Technical factors

The success of a sea voyage can make or break with the vessel used – this applies as much on ancient seafaring as it does on modern. For the Neolithic and the Early Bronze Age several types of crafts could have been used, based on archaeological evidence and finds.

At this juncture, the earliest find of a boat dates to about 7700-7800 B.C. (9700-9800 BP).[3] This longboat was found at Pesse in the Netherlands (Johnstone 1980, 46-47 cited in: Bar-Yosef Mayer et.al. 2015, 415). Other longboats are known from Noyen-sur Sein in France, dating to 5960 +/- 100 B.C. (Mordant and Mordant 1992; Arnold 1999 cited in: Bar-Yosef Mayer et.al. 2015, 416;) and Lake Bracciano, Italy, dating to the sixth millennium B.C. (Calcagno 1998, 48 cited in: Bar-Yosef Mayer et.al. 2015). Ceramic models of vessels representing longboats (Lake Bracciano; Bar-Yosef Mayer et.al. 2015, 416) reed-bundle boats and sailing boats (Persian Gulf; Carter 2006 cited in: Bar-Yosef Mayer et.al. 2015, 416) can be dated to the Neolithic. Greek models probably representing "*dugouts, double dugouts, or paired logs*" (Marangou 1992, 40, 429/fig. 80g ; 1996; 2001; 2003, 14 cited in: Bar-Yosef Mayer 2015, 461-417) derive from Dispilio Lake, Kastoria and Tsangli in Thessaly. Additionally, representations of seagoing vessels of different sizes were discovered on Strofilas, Andros Island, Greece, and can be dated to the mid-fourth millennium B.C. (Liritzis 2010 cited in: Bar-Yosef Mayer et.al. 2015, 417). Archaeological evidence for seagoing crafts in the Mediterranean dates to the third millennium B.C. (Basch 1987, 55, 70, 80 cited in: Bar-Yosef Mayer 2015, 417).

The decision on which vessel type was used, highly depends on the amount of cargo transported on it. In can be assumed, that jadeite was transported in small amounts together with other products, including other exotic material (e.g. obsidian from Melos or Antiparos) and metal (in all states) as well as goods of daily use or even live stock. A study on the transportation of the latter to the island of Cyprus has been conducted by Vigne (2009, 816-817; Vigne et.al. 2014), leading to the conclusion that a double dugout with deck and sail was used in this case – a suggestion, that still remains unproven, though, due to lack of archaeological evidence (Bar-Yosef Mayer 2015, 417).

This concept is the base for most theories on early seafaring in the Aegean and Mediterranean (Broodbank and Strasser 1991 cited in: Bar-Yosef Mayer 2015), and will also be followed in the here presented work. It draws upon the assumption that dugouts are the earliest seagoing crafts used in the region (McGrail 1991, 90; Casson 1995, 8 cited in: Bar-Yosef Mayer 2015, 417) and calculations used by Broodbank and Strasser (1991), showing that the long and unstable vessel had to be stabilised if used for traveling on open sea for several hours, with a cargo of several hundred kg to two tons (Broodbank and Strasser 1991, 241 cited in: Bar-Yosef Mayer 2015, 417). Most likely this was done either by an out-rigger, or by a double canoe –

[3] As this Thesis concentrates on seafaring, evidence for river boats will not be incorporated into data on possible vessels used. Nevertheless it should be mentioned, that there is archaeological evidence for fishing boats used on the Nile, dating back to 9000 BP and burial-river boats from the 6th millennium BP (Hendrickx and Vermeersch 2000, 35; Ward 2006, cited in: Bar-Yosef Mayer 2015, 417).

both not known for the area and time period under investigation (Bar-Yosef Mayer 2015, 417). Dugouts were built, using "*various tools and techniques, such as scrapers, hammers, axes/adzes/chisels, and controlled fire, all of which were available (…) [already in the Neolithic]. Specifically,165 bifacial flint tools, mostly broad heavy axes, were found at the PPNC coastal site of Atlit Yam, and are more frequent there than in other Neolithic assemblages. The excavators propose that these axes may have been used for intensive woodworking, possibly for water craft.*" (McGrail 1998, 86; Galili et.al. 2004; Yerkes et al. 2014 cited in: Bar-Yosef Mayer 2015, 417).

At this point it is also worth mentioning the experiments of the ABORA - projects[4], conducted under the leadership of Dominique Görlitz (2007). In his publication he stresses the importance of reed boats for the development of vessels for several regions (2007, 15-19), and reviews the common interpretation of the two paddles, often shown in early depictures of vessels, as a sign for paddling boats. The latter critique is based on archaeo-experimental research, showing that bigger reed boats, once soaked with water cannot be moved only by manpower with two paddles, due to their weight (Görlitz 2007, 17). In recent years his experiments focus mainly on bigger reed sailing boats, comparable to Egyptian depictions, but formerly it also included dugouts and pirogues – usually with small sails (Fig. 1).

Fig. 1 – Pirogue experiment done by the Abora-Team (1994/95)
(©www.abora.eu; C. Lorenz/D.Görlitz)

[4] www.abora.eu; Görlitz 2007.

Even though there is evidence of the sail in the Mediterranean dating back as far as the 6000 – 5000 B.C. from Nubia in form of a rock carving (Qustul Incense Burner; Williams 1989, 96, fig. 4 cited in: Bar-Yosef Mayer 2015, 417) and woven flax exists already by 30.000 B.C. (Kvavadze et al. 2009 cited in: Bar-Yosef Mayer 2015, 417), the usage of sails for the Neolithic period cannot be proven up to this point. According to Bar-Yosef Mayer (Eshed et.al. 2004 cited in: Bar-Yosef Mayer 2015, 417) "*skeletal remains of humans discovered at the submerged costal site of Atlit Yam showed elbow abrasion and specific muscle markings which may have resulted from paddling*." This also supports the assumption of the usage of paddled boats for the time period under study (cf. Farr 2006, 90).

This means travel speed depended on the ecological circumstances and the manpower on the boat. The Papyrella, a reconstructed raft made of reed used to simulate Neolithic seafaring in the Aegean (Tzalas 1995 cited in: Bar-Yosef Mayer 2015, 418) reached an average speed of 1.65 knots (Tzalas 1995, 453) under favourable conditions, paddling with the wind and current with a crew of 6 men. Bar-Yosef Mayer suggests that a craft made of bundles can move at an average speed of less than 1 knot against a light or moderate breeze of 3-4 on the Beaufort scale, while reaching 1,5-2 knots traveling with the wind and that a dugout would be faster under favourable weather and current conditions.

Social factors

Usually, investigations focussing on early seafaring as well as on exchange network building or routs (on land or sea) are based mainly on environmental factors and the technological study of (water) crafts (Farr 2006, 91). Despite the significance of the two parameters the same importance should be attached to "*social organisation and knowledge*" (Farr 2006, 91) of seafaring, following Farrs approach of studying seafaring "*as a socio-technical process*" (Farr 2006, 91), where she states that "*when seafaring is viewed as a mode of travel, a way to cross space, to enable the transportation of people and ideas, in addition to artefacts and materials, and as a means of communicating and sharing knowledge across the landscape, it becomes not only a very social activity but our questions and answers become relevant to studies of Neolithic travel in general, whether it be by land or sea. One of the main themes to come out of this perspective of seafaring as social action, is that of knowledge.*" As a deduction, we can say that seafaring is the way people (humans) interact and react to the (environmental) circumstances they encounter while traveling at sea. This includes not only technical solutions but also the accumulation and passing of what Farr calls "*world*" – thus "*spatial and temporal awareness and an understanding of land and seascape and a perception of surroundings*" and "*local*" knowledge, referring to "*navigational lore, local weather and current conditions, location of resources and other social groups*" (Farr 2006, 92). As mentioned before while traveling at sea, it was inevitable to encounter situations with no coast (land) within the range of visibility do to distance as well as bad weather conditions (see also Bourdieu's theory of practical mastery (Gell 1985 cited in: Farr 2006, 92-93). A kind of "mental maps", consisting of the subjective memories of images or events of a journey (Farr 2006, 92-93), could have been passed from one navigator to another, transforming into a sort of common knowledge. Additionally, navigational knowledge had to be complemented with information on land- and seascape (including currents, winds and wave formation), lunar cycles, star courses and technical skills of navigation (speed, drift, and heading), as well as familiarity with fresh water sources, food and shelter, most likely resulting in confederations with other social groups (Farr 2006, 93). The here presented study implements and tests the importance of these social factors to the investigation of ancient seafaring and the modelling of sea routs in the Mediterranean.

1.2.3. Jadeite – an example of early exchange of exotic material

Starting already very early, “jade” (Eppler, 1999, 311-318 cited in: Schilk 2008, 62-64) and the other stones of this group were of great importance for a lot of cultures around the world. Nowadays, jade is defined as “*all green and opaque stones used and sold as gemstones*” (Schumann 2002, 170; Breisach and Rössler 2003, 82). The group can be divided in jadeite, chloromelanite, nephrite and jade-albite. The axes used as a database for this study were made of jadeite and nephrite, which is why they should be briefly described in the following chapter.

a. Gemmological description

Chemical and physical characteristics

	Jadeite	**Nephrite**
crystallisation	monoclinic	monoclinic
material	Natrium-Aluminium-Silicate	Calcium-Magnesium-Silicate
formula	Na_2O . AL_2O . $4SiO_2$	$Ca_2(Mg,Fe^{2+})5[OH I Si_4O_{11}]_2$
	$Na(Al,Fe^3)[Si2O6]$	2Cao . 5(Mg,Fe)O . 8SiO2 . H2O
Mohs	7	5,5-6,5
specific weight/ density	3,30 - 3,36 g/cm³	2,90 - 3,02 g/cm³
light refraction	1,654 - 1,667	1,614 - 1,641 and 1,600 - 1,627
birefringence	0,013	0,027
UV-light	depending on the colour: white or inert	inert
Chelsea-filter	green	green
polariscope	stays bright	stays bright
colour	white, rosé, purple, red, orange, yellow, blackish, green	white, rosé , red, orange, yellow, brown, purple, black, green, often with spots, veins or bands

Tab. 1: Jadeite and nephrite in comparison (based on Eppler 1999, 311-318; Schumann 2002, 172; Breisach and Rössler 2003, 82; Schilk 2008, 62-64).

Possibilities of confusion, imitations and synthetic products

As both of the stones belong to the same group, they can be confused with each other as well as with the other stones of the jade-group mentioned above. In addition, jadeite and nephrite show similarities to pseudophite, grossular and aventurine, prehnite, antigonite, williamsite, californite, smithsonite, agalmatolite, sassurite, amazon stone, bowenite, chrysoprase, connemara, pektolith, serpentine, verdite, emerald, emeraldite, and verd-antique. All of these stones are used more or less frequently as an imitation of jadeite and nephrite. Modern imitations include also glass, plastic or “triplets” (Eppler, 1999, 311-318 cited in: Schilk 2008, 62-64).[5]

The quality of the most valuable variety of Jade, the so-called Imperial Jade, an emerald green stone with a very high percentage of chromium from Myanmar is often also reached with colouring. This treatments can be recognised by a wide band at the absorption spectrum at around 6500 a narrower band at 6000, as well as a reddish reaction under the Chelsea-filter. Other treatments used with the Jade-group are bleaching, impregnation (green or purple stones are bleached with acid in order to remove brownish structures). This can cause breaks in the stones, which is why the treatments often are combined with resin treatment (Polymer). The latter treatments can be recognised by changes in the surface structure, as well yellowish fluorescence or visible fillings along the breaks. Most reliable for the determination of treatments are scientific investigation methods, including IR-spectroscopy, cathodic-luminescence or X-ray-photoelectron-spectroscopy (Eppler, 1999, 311-318 cited in: Schilk 2008, 62-64).

Modern Sources

The most important sources of jadeite (Eppler 1999, 312; Schumann 2002, 172) can be found in Asia, especially on the Upper Myanmar region, around Tawmaw, as well as in form of secondary sources along the Uru-river and as conglomerate in the region of Hwéka in Upper Burma. A well-known site in China lies in the province of Sinkiang, in the Kunlun Mountains. Other sources include Japan, Kazakhstan, Siberia, Canada and California, as well as Mexico.

Important nephrite sources (Eppler 1999, 318; Schumann 2002, 172;) are in New Zeeland, along the western coast of the southern island, in Western Sinkiang (China), but also in Russia around the Baikal Lake. Additionally, the stone can be found in Canada, Australia, Zimbabwe, Taiwan, Alaska, the USA, Mexico and Brazil. The sources in Upper Schlesia/ Poland do no longer exist.

Both stones were already used for ritual weapons, jewellery and statues for several thousands of years, and were of great importance and value especially in China and Middle-America (Mexico and Guatemala; Schilk 2008).

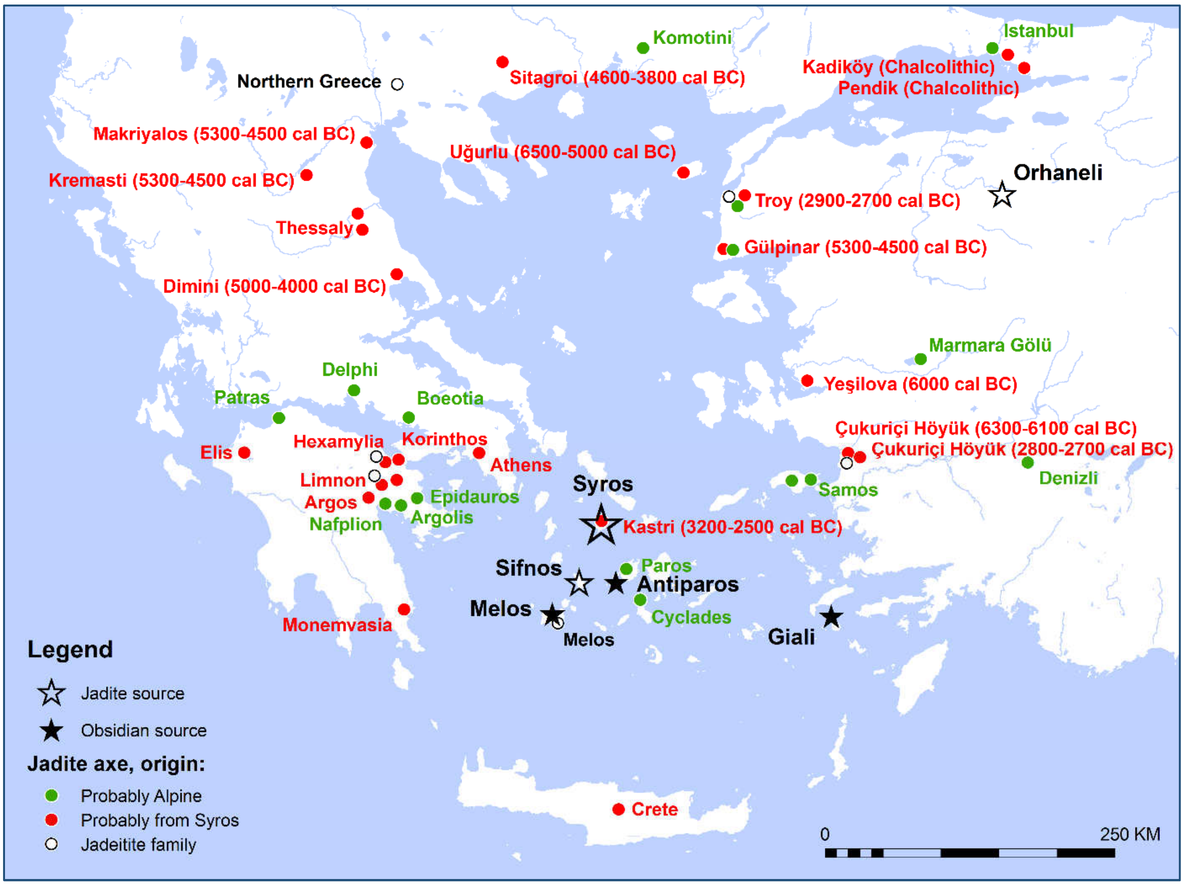
[5] Triplets are artificially combined stones (gems), made of on layer of a more valuable stone and two layers of either less valuable stones or synthetic material.

b. Jadeite in European Neolithic

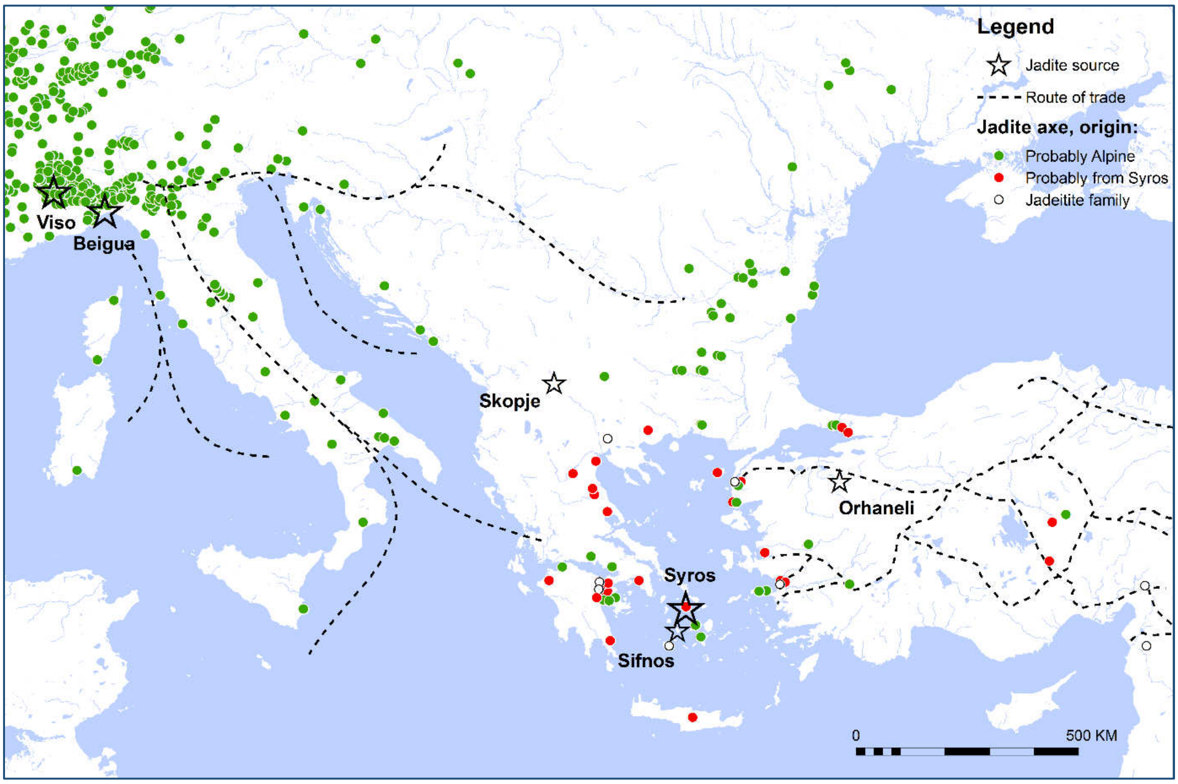
Fig. 2: Jadeite axe blade (Early Bronze Age, Çukuriçi Höyük), cited in: Sørensen et.al. 2017, 506, Fig. 10, 4 (Foto: N. Gail/ERC Prehistoric Anatolia)

In his work, Sørensen (et.al. 2017) collected a considerable amount of ritual nephrite/jadeite axes within the Aegean region dating from the Neolithic to the Early Broze Age. Jadeite axes have been found at a total of 23 sites dating from as early as 6300 – 6100 B.C. at Çukuriçi Höyük to 2900-2700 B.C. at the same site as well as at Troy (Sørensen et.al. 2017). The finds from sites at the South-West of Syros are stray-finds and therefore can’t be dated. In the model, they will still be used as “trading partners” within the network. Several closer and farther sources for the material are known for this period: jadeite could be found in the Alpine region of Italy (Monte Viso, Begigua), in the region of Skopje, in Orhaneli as well as the Greek islands of Sifnos and Syros (Map. 1 – Map. 2).

Exchange routes connected the Italian Alps with the rest of Italy, its coast and the Mediterranean as well as with the Western coast of Greece and the Black Sea. Land routes from the Eastern Aegean coast of Turkey towards the Middle East are very likely as well. Sites with axes of jadeite deriving from the island of Syros are well distributed around the whole Aegean coast, causing the conclusion, that the raw material was transported by sea, not only from the island to the closest location at the coast, but most likely directly to several or all of the sites. This doesn’t mean, though, that the route taken by the early seafarers is known in detail.



Map 1: sites of ritual axes (Sørensen 2017, with updates from October 2017)



Map 2: sites of axes, sources and trade routes (Sørensen 2017, with updates from October 2017)

A very thorough study on the Alpine sources of jadeite has recently been conducted by Pierre Petrequin et.al. (2012; 2017). Within this investigation he and his team also examined the jadeite sources at Syros located between Kambos and the bay of Lia (Petrequin et.al. 2017, 25). Even though the tools and production remains can prove the exploitation of the jades at Kambos, there are no signs of massive production and also the tools for final regularisation of the drafts done before polishing are missing (Petrequin et.al. 2017, 30). This leads to the conclusion, that Kambos was a minor manufacturing site of a modest and unstandardized production of jadeite axes using a "*selective collection of small blocks of secondary deposition*" (Petrequin et.al. 2017, 30) – namely the "*small blocks caused by erosion downstream of the primary deposits*" (Petrequin et.al. 2017, 30). The so far earliest radio carbon dates from Çukuriçi Höyük show an exploitation of the jadeite sources at Syros as early as the 6300 – 6100 B.C. (Final Neolithic, Anatolian Chronology; Sørensen et.al. 2017, 493, 506-508). This is much earlier than the usage of jadeite from Monte Viso in the Alps, starting during the mid-6th millennium B.C., from where the material also reached the Aegean – probably over a Balkan route (Sørensen et.al. 2017, 493-494). Within the frame of his investigations and fieldwork Petrequin and his team also showed, that Sifnos can be excluded as a source for the used jadeite (Petrequin et.al. 2017, 25; Sørensen et.al. 2017, 493).

Ethno-archaeological studies (Petrequin et.al. 1998; 1993; 2010; 2017) as well as the deposition practices show that the jadeite axes often functioned as exchange-goods between elites and were used as a sign of power, in myths and in rituals (Petrequin et.al. 2010, 192, 194, 196). Their importance and tradition was so important for the Alpine and the Aegean region, that the type of axes was also produced in local stone material as well as copper (Petrequin et.al. 2010, 196). Nevertheless, the blades made of jadeite from Syros all seem to be everyday working tools, due to their rough finishing touch (Sørensen et.al. 2017, 493). Based on the studies on Alpine jadeite axes done by Petrequin it can also be assumed for the Aegean region that the blades were exchanged as roughly polished blanks which were than adapted to local taste and criteria (Petriquin et.al. 2010, 194).

2. The model (ODD+D[6])

2.1. Purpose

The aim of this model is the investigation of seafaring in the Aegean Neolithic. Seafaring is seen in this context as a social action and a medium for people to connect and establish an early form of exchange network. Thus, a special interest lies on the importance of different influence factors for the navigators' decision making process and the interdependent system of the environment and exchange as a social system. This can contribute and complete the discussion of the importance of socio-cultural aspects in seafaring – as oppose to a purely environmentally based approach. The model is primarily designed for archaeologists studying early movement of people on sea, but also the transport of information and goods and can easily be adapted for testing the factors at different locations and time periods. Additionally it functions as a case study in order to bring forward the usage of Spatial Simulation as a method in archaeology. In the region under study, the sea-routes connecting the island of Syros and the local jadeite sources with the sites with blades made of the material (finished products) are not known by now. The model can contribute to this question by showing possible, most frequented routes and testing the influence of different factors for pathfinding decision making. It can also be used to test the theories on coastal tramping and open sea traveling in the Neolithic.

2.2. Entities, state variables and scales

The model includes three *entities*: the boat, the jadeite mine and the trading partners.[7]

Boats are defined by the state variables name, speed (2.8km/h), visibility (5km), energy level (33-100%, 2-6 people) and jadeite value (amount of jadeite an agent currently has). They also have a defined start and end travel time, as well as a home location and a target. They are controlled by the BDI (Belief-Desire-Intention) structure, using the social and emotions architecture and have additional variables for plan- and intention persistence. Boat agents use the *emotion* fear and have predefined *belief-variables* (location of the mine, location of the trading partners, possible shelter locations, if there is danger or not and if the boat has shelter), and *desire-variables* (find jadeite, trade jadeite, choose a trading partner to go to, go home, use jadeite himself and escape).

[6] ODD+D is a concept developed by Müller et.al. (2013) in order to include the description of human decision making progresses in ABMs. The author adapted the ODD+O structure in miner points as not all parts were necessary in this context, because several points are already discussed in separate chapters of this Master Thesis.

[7] The term "trading" should in this case be understood as exchange and is not used in the meaning of "trading" used for later time periods.

Trading partners also have a simple-BDI structure for future experiments, but don't use emotions or social links yet. They are characterised by the variable jadeite value. Based on the BDI-structure, all entities have a set of beliefs, intentions, rules and plans forming their *behaviour strategy* (see below).

Time is measured in two ways. Once in discrete steps 1 hour, for modelling the itinerary of a boat (e.g. when to take breaks or seek shelter for the night) and to connect the real time data (available as hourly measurement) to the agents actions and locations. Simulations will be run for 5139 hours (7 months), representing the time period between April and October. On the other hand time is modelled as in a dynamic way, simulating the sequence of different goals an individual wants to achieve and the actions it executes along the way.

The model is *spatially explicit*, using the *global environment* based on GIS data of the Aegean region and is defined by land and ocean. The ocean area is characterised by wave direction and speed at a location. Space is measured in km.

2.3. Process overview and scheduling

Each hour, the boat updates its speed according to the environmental conditions it finds in a grid cell. It also adds beliefs about all trading partner locations with an empty stock of jadeite in view distance and all mine locations in view distance. Trading partners up-date their jadeite value *each 24th step (day)*, simulating the daily use of the material. The *itinerary* the boat follows is also defined by hourly checks.

Initially, the boat has the desire to find a jadeite mine. In order to do so, it paddles on the ocean grid. If a new mine location is known, the boat agent develops a new desire of going to the mine and picking up jadeite. Once the corresponding value is above 0, the boat gets the desire of exchanging the jadeite. It chooses a trading partner, goes there and exchanges one package of jadeite with him, causing him to have a full stock. Then it checks its own material amount and if it still has jadeite, it looks for new trading partners. If it runs out of jadeite, it develops the desire of going to the mine to fill the stocks. The rules defining the used processes can be found more detailed in chapter 2.5.3. (Submodels).

2.4. Design concepts

Theoretical and Empirical Background. Detailed information on the theoretical and empirical background of the model can be found in chapter 1., Introduction (cf. especially 1.2.2., Case Study).

Emergence. Individual behaviour is based on the BDI-structure and is therefore emergent. Decisions and behaviour (resulting in a type of social system) depend on the personality and knowledge (of environment, others and themselves) of the individuals. Consequential, the routes frequented by the individuals emerge from the changing environment and social system. Nevertheless it should be noted that boats have an imposed itinerary, which they follow as a general outline, depending on their personality.

Individual Decision-Making. Decisions taken by the *boat*-agents according to their current desire in combination with their personality and emotions. Starting with the first desire to find jadeite and have it, a boat wants find trading partners for the material. For this, it will try to find the best (shortest and safest) route to the mine and from there to a trading partner according to environmental and social conditions. This leads to two different types of decisions: choices made to survive (resting/seeking shelter) and choices made to reach the defined objectives (exchange). Individuals adapt their behaviour according to their experiences and knowledge of the world and other individuals. A boats decision to take a certain route is based on its current "mental map" and current environmental conditions.

Individual Learning. The model uses belief-based learning on an individual level. Each agent has a database to store its knowledge (belief-base), serving as its memory. Here knowledge of a boats position, routes, environment and trading partners is stored and can be used in order to take decisions.

Individual Sensing. Individuals can see other agents (the mine and the trading partners) within a given visibility range. The environmental conditions of their current cell are assumed to be known (assuming the navigator has possibilities of seeing and measuring wave speed and direction).

Interaction. Boats interact directly with the trading partner they go to by trading with them. In a next step, the interaction will also include the decision of exchanging information.

Heterogeneity. Individual agents are not heterogeneous, as the only difference is defined by their state variables.

Stochasticity. The model uses stochasticity in order to represent the different personalities of boats, as they are not known and can vary.

Observation. The outcome of the data is observed from an omniscient perspective. Data on all the paths taken by the boats and their duration are collected until the end of each seafaring season enabling the creation of a heat map and the most frequented shelter points and trading partners. A distinct pattern of social connections and movement emerges.

2.5. Details

The model was created in GAMA (1.8). The source code can be made available upon request.

2.5.1. Initialisation. Each simulation starts with a specified number (1 by default) of boats and trading partners and a jadeite mine as a point location at Syros. The amount of trading partners derives from all known sites with a direct access to the sea, where jadeite axes were found (Sørensen et.al. 2017). The visibility range is defined to 5km by default. The personality and emotions of boats is set randomly and can also vary among simulations and the boat resting by default. The global environment is defined by a grid of ocean and land and the data on wind and wave speed and direction.

2.5.2. Input data & data processing.

The model uses GIS-point files to create the trading partners and the jadeite mine. The grid is created using a raster-file of the Aegean region and a file of slope for possible shelter locations, also generated in GIS. A sample file for speed and direction of wind and waves derives from netCDF-files. It was exported as a text file from ArcGIS and added as an attribute to the grid.
As basic models the BDI-Agents model (GAMA-Tutorial) was adapted for modelling the social relations and learning of the navigators and trading partners. It was combined with a model (Paddling for Obsidian) developed by the author during the UniGIS winter-school on Spatial Simulation in February 2018.

The Grid.

For the grid, the DEM of the Aegean was downloaded from the Copernicus-Database[8] and converted into a raster in order to represent ocean and land. For this the layer was projected into WGS84. The exemplary data on environmental conditions also derives from the Copernicus-Database[9]. It included an hourly time series of wind- and wave direction (in degrees) and speed (stokes drift velocity, in m/s). As big data tends to slow the program down a lot or even crash it, an example file of the wind-and-wave-direction from June, 15th at 1:00 pm was combined with the DEM-grid in GAMA. The wave-speed data turned out to be uncomplete, with a lot of missing measurement positions. The existing information showed, that the wave speed was always very low – staying within several centimetres / second.[10] As no area-wide data was available, the exemplary mean value of 0,048 m/s (or 2.88 m/h) was used for the speed – gained

[8] Copernicus Land Sercice (https://www.copernicus.eu/en/services/land), 07.03.2019.
[9] Copernicus Marine Service (https://www.copernicus.eu/en/services/marine), 07.03.2019.
[10] This is not surprising for open seas, as well described by Herbers and Janssen (2016, 1010).

by loading the file into NetCDF-Extractor, and reading out the VSDX values for the “origin”-conditions: 1, 93, 121 and the “shape”-conditions: 744, 1,1.[11]
Additionally, a slope raster of three categories (1/flat – 3/steep) was generated in order to represent the coast. This serves for the agent to find natural harbours in dangerous situations.

2.5.3. Submodels.
In the main part of the model is formed by rules, desires, beliefs and plans. Several submodels define the itinerary and the movement of the agents.

Energy level
The energy level of boats is updated every time step. The minimum and maximum level of 33% and 100% is based on the experiments of the papyrella (Tzalas 1995) and the following projects, where a maximum of 6 people could travel with a dugout. As working theory it was assumed, that at least 2 people were needed to move the boat. Paddling reduces the energy level by 5% per hour, resting resets it to the starting energy level.

Rules and Plans
The decision making process of the boat agent is defined by five *rules*:

- if the agent is afraid because there is a confirmed danger, it wants to escape;
- if the danger is not confirmed, but he is fearful, it also wants to escape;
- even if he is not afraid, but knows there is danger, it wants to escape;
- if the agent has jadeite, it wants to trade it;
- if the agent doesn’t have jadeite, it wants to find it.

In order to follow the desires (cf. 2.2., Entities, state variables and scales) the agent has at the given moment, it can use several *plans*:

Try to find jadeite. This plan is used at the beginning of the program, when the agent does not know any locations yet, so it has no target. It is connected to the intention of finding jadeite.

[11] The author is well aware of the fact that the exemplary data is not an actual representation of the changing conditions at sea, but decided to use one data set at the beginning status. More detailed environmental data should be entered during follow up research.

Get jadeite. Once the agent found the mine position, it remembers its location and paddles towards it. Once it is within a (given) action radius, it mines 5 units of the material and removes the intention of finding jadeite, which was still the ruling desire up to this point.

Find trading partners and exchange. Now that the boat agent gained jadeite, it develops the desire to trade it and wants to find settlements to do so, in case it has no trading partners, it has the option to go back home and start producing products with the material. If there are available trading partners it can remember, it will paddle towards the closest of them and exchange one package of jadeite with him, causing the trading partner to have full stock and thus be currently unavailable to trade to.

Seeking shelter. In case the agent should be looking for shelter according to its itinerary (see below), it will start by searching for the closest anchorage location and go there to rest, which will set its energy levels to maximum. It can also ignore the itinerary for a while, in case the agent is not afraid, and continue traveling for a bit, but if it is getting too late, it will be afraid and enter a second, faster plan to seek shelter. The agent will look for a coastal location with a higher base speed of 5km/h, at the same time losing more energy while moving.

Traveling itinerary

Initially the agent is set to be resting, until the starting time is reached and it starts traveling. At the end time for traveling the boat can either look for shelter – in case, it notices danger and is scared, or it can continue traveling. After four more hours, the boat checks if it is resting and in case it is still traveling, enters into fear mode, and looks for shelter. If the boat can't find a place for shelter and the energy level is less than 5, the boat dies, with a level above 5 it can take spend the night at open seas. If it can find shelter, it rests and regains its energy.

Movement along the grid

Movement without a defined target. When the agent does not know the location of the jadeite mine, it starts to move with the given speed and an angle of 50 degrees each step, using only cells defined as water. This movement lowers the energy lever by 5. In case the energy is less than 10, the agent takes a short break on water, gaining 10% of energy.

Movement with a defined target. Once, a target – the mine, a shelter location, a trading partner or the home location – is set, the agent starts move towards the target with a given basic speed of 2.8km/h using only cells defined as water. The used energy depends on the emotional state of the agent. Moving in a calm state lowers the energy by 5, in case the agent is afraid it paddles faster and the energy goes down by 8. Once the energy lever reaches a value less than 10, the agent has to take a break on water, gaining 10% of energy.

Movement algorithms

Two algorithms would define the influence of the environmental conditions on the boats speed and direction. While the equation for the speed adaption could be entered into the model, the change of heading caused by the wind and wave direction could not be implemented. This is caused by the missing concept of movement towards a specific target with a changeable heading value (cf. chapter 3., Discussion). As the two algorithms are connected to each other, implementing only one would not lead to the correct results, which is why the author decided to remove both of them from the code. In this case study, as mentioned above, the speed values of the surface conditions were quite low, thus the influence of it would not have changed a lot. Nevertheless the basic concept of the algorithms will be presented in the following as if they would have been implemented. The used data was oriented in the opposite direction of the agent's orientation (0 = west and 180 = east vs. 180 = west and 0 = east), the wind and wave orientation was rotated by 180 degrees within the equitation code for the angle α.

Update speed. Every step the agent calculates the speed by estimating the resulting force. Generally the following equation for acute-angled triangles is used, as this is closer to real-life situations than right-angled triangles (see also Fig. 3).

$$V_{b1} = \sqrt{V_b^2 + V_w - 2 \times V_b \times V_w \times \cos\alpha)}$$

Update direction. Every step the agent adapts its heading by estimating a new angle depending on the wind and wave direction it encounters. This can in general be done by using the following equation in order to calculate the new movement angle (α_x) in acute-angled triangles (see also Fig. 3).

$$\alpha_1 = \cos^{-1}\left(\frac{V_{b1}^2 - V_w^2 - V_{b2}^2}{-2 \times V_{b1} \times V_{b2}}\right)$$

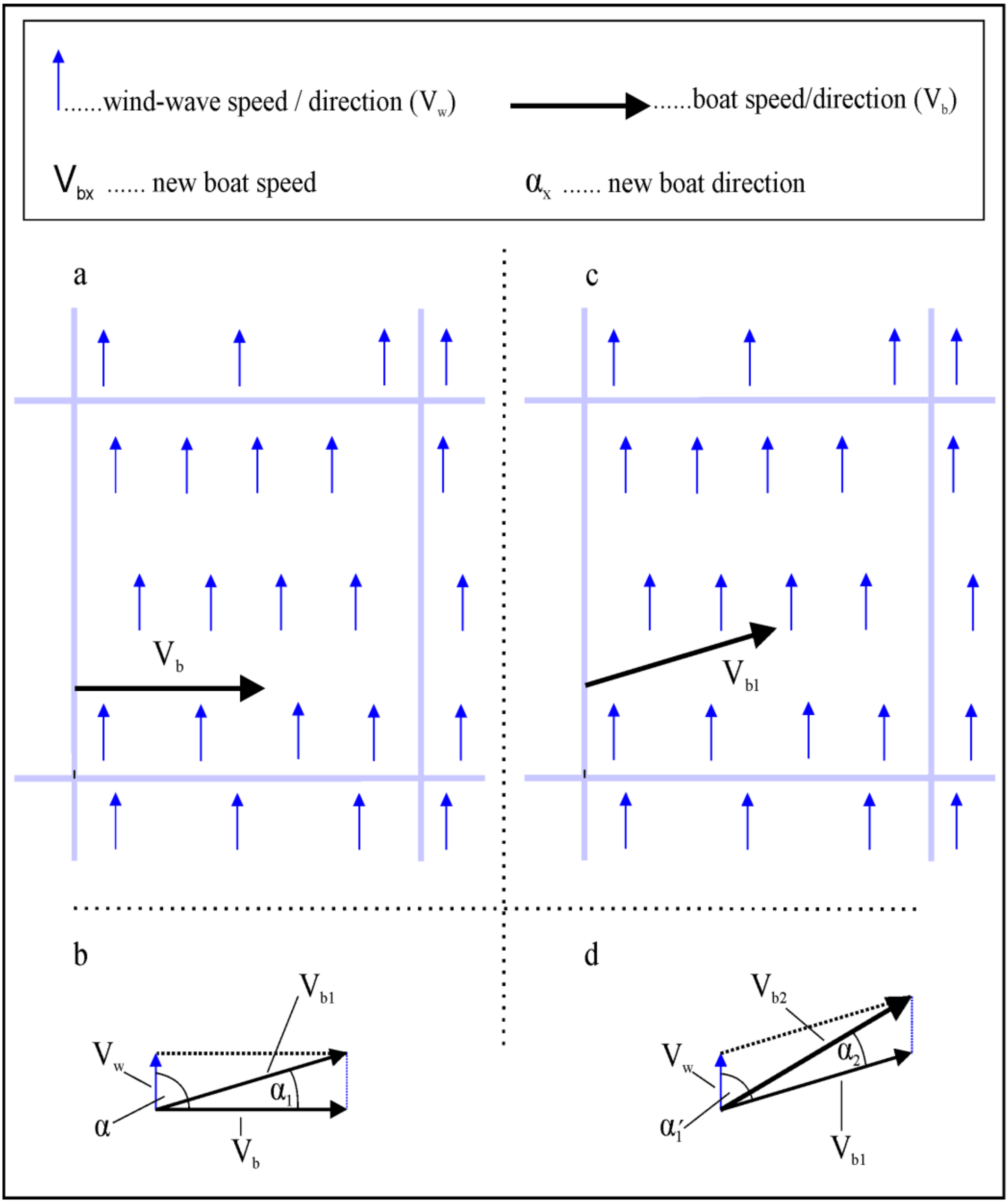
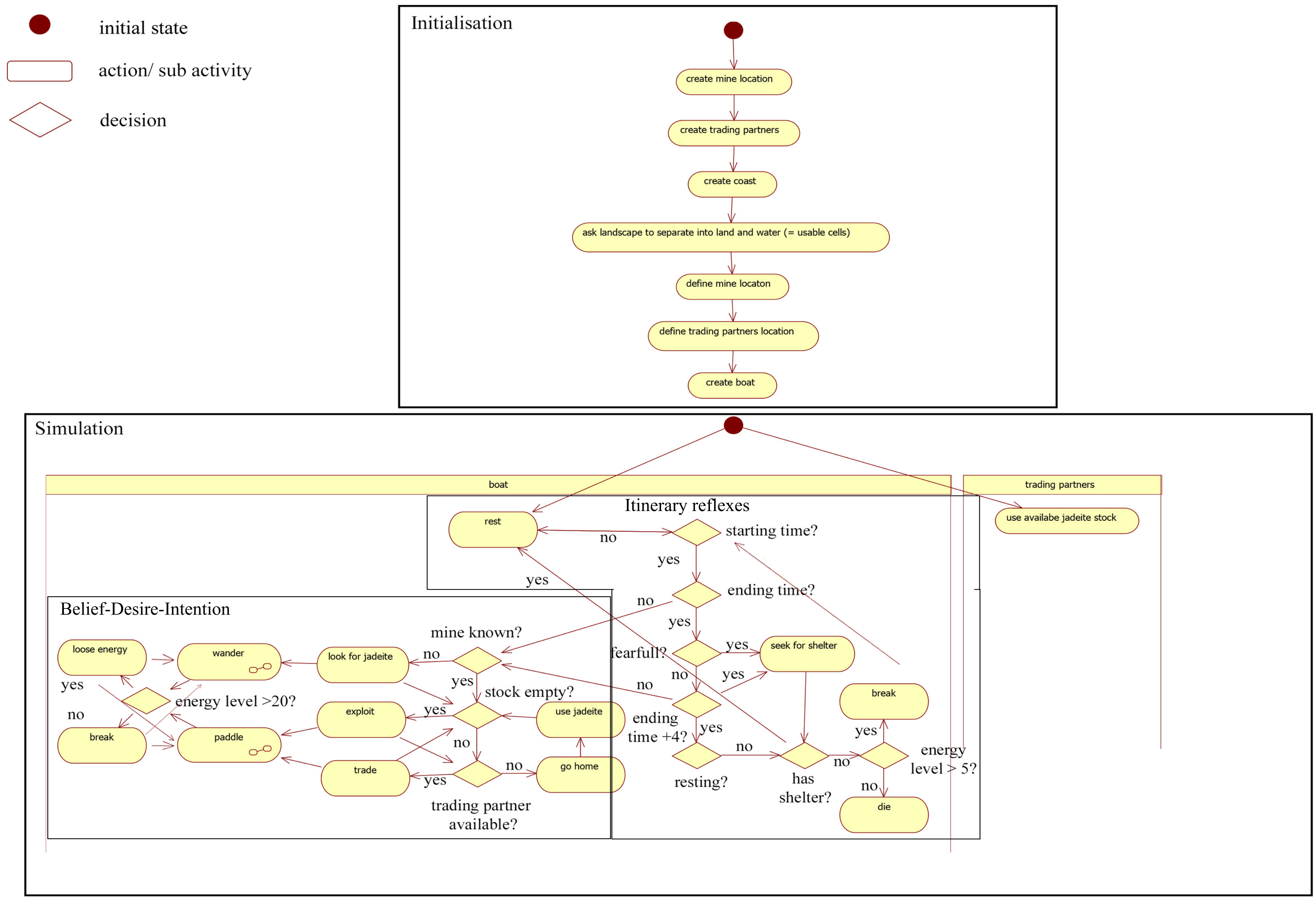


Fig. 3 - a-d: Influence of wind and wave (speed and direction) on the boat (speed and direction); b and d: trigonometric determination of the resulting speed (Vbx) and direction of travel (αx).

Using the jadeite (done by the trading partners)

The trading partner agents uses the jadeite exchanged with a boat by reducing the material's amount by 0.1 every day (24 hours).



UML Activity Diagramm

3. Experiments and study outcome

The model was tested in several steps at different states. At the beginning, only the social system without any real-live data was modelled (Fig. 4). Blue circles are possible shelter places, in this case allies – which were changed later into coastal locations, the boat searches for during the trip. Red dots are possible trading partners and the black triangle represents the mine, the boat tries to find at the beginning of the simulation.

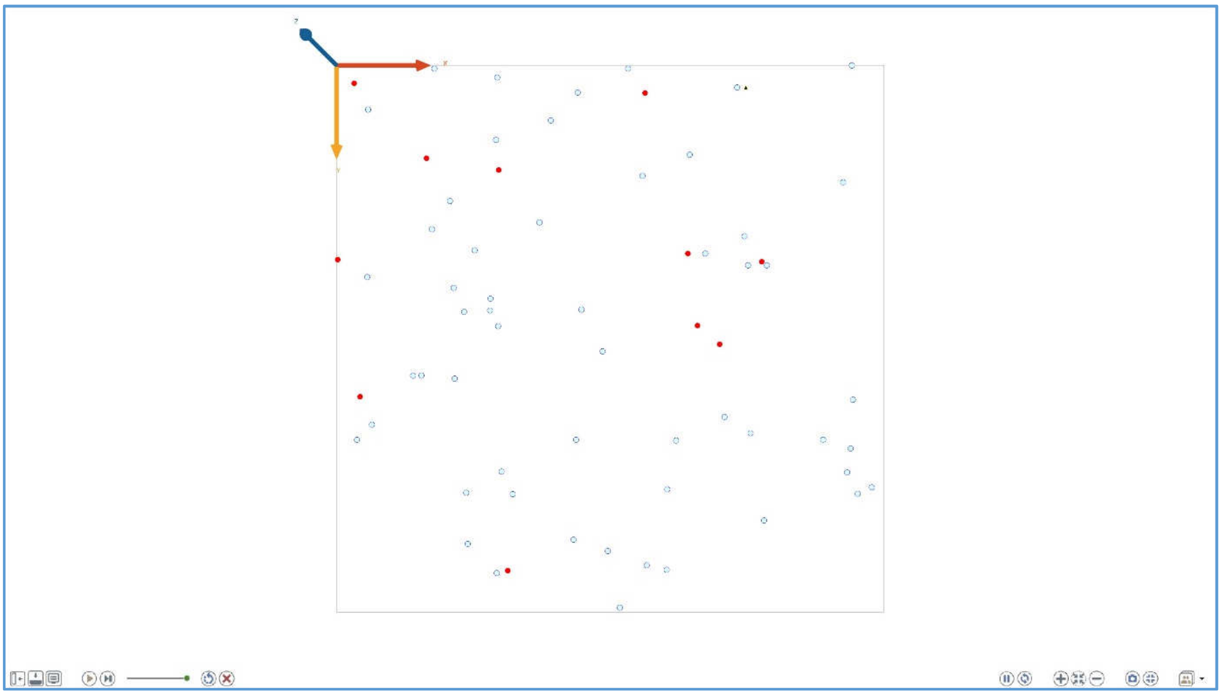


Fig. 4 – First simulations without environmental data: red dots = trading partners, blue circles = allies (shelter points), black triangle = mine location

Once, the general system worked, real-life data was added to the code, including a binary file of a part of the landscape,[12] a categorised file of the slopes of the area, where category 1 represented the flattest area – best to go ashore – and category 3 the steepest coastal line, where anchoring would be most difficult to impossible. The starting point was set around the middle of the landscape, as the most "neutral" position on the grid (Fig. 5).

According to the assumed travel period and the data on wind and wave direction and speed, the experiments were run from the beginning of April to the end of October – the year was set to the year of the environmental data (2016), as – not surprisingly – no B.C. dates could be set.

[12] The author is aware of the fact, that the Greek mainland is not completely represented, but as the used files where quite big already and used up a very big part of GAMAs space and the experiment is only conducted along the Aegean coast, the used area was considered sufficient for the first experiments with the data.

	visibility	action radius	probability of fear	duration	repetitions
experiment 1	200km	50m	0.5	April - October	20
experiment 2	200km	50m	0.0 - 1.0	April - October	5 each
experiment 3	20km	50m	0.5	April - October	20
experiment 4	50km	50m	0.5	April - October	20
experiment 5	all	50m	0.5	April - October	20
experiment 6	all	50m	0.5	10 years	1
experiment 7	all	50m	0.5	April - October	1000

Tab. 2 – Overview of the conducted experiments

Fig. 5 – Initial setting of the simulations with the starting point in the middle of the grid.

Already within the first runs of the experiment, some interesting outcomes could be gained. “Island hopping” usually explained with common sense, could be observed and is caused by the preference of spending the night on land – taking a break at sea is obviously more dangerous during a time small paddle-boats and not bigger sailing boats where used. Nevertheless, boats also travel over seas (at the fastes possible route) towards their targets.

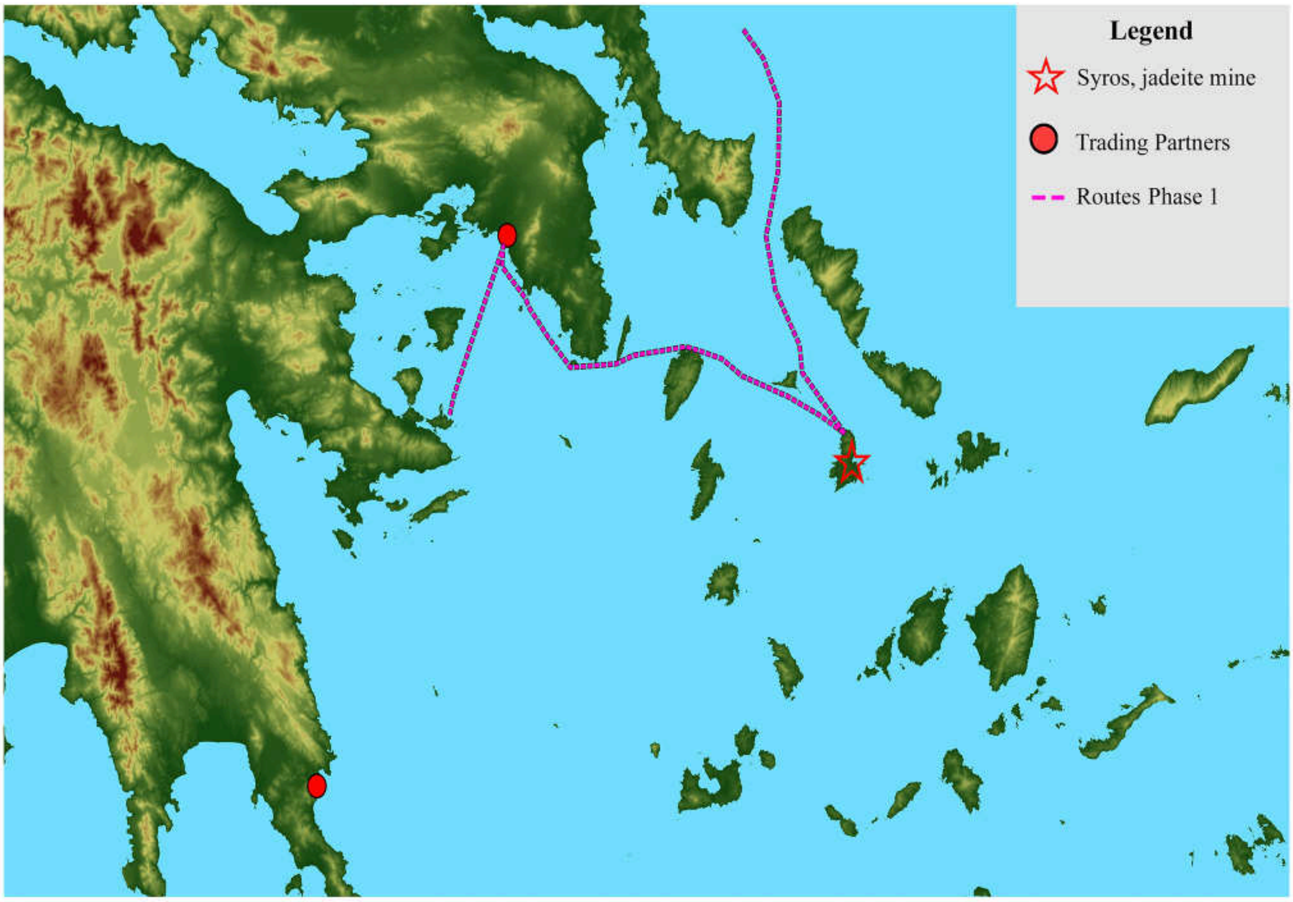


Fig. 6 - April, 7th

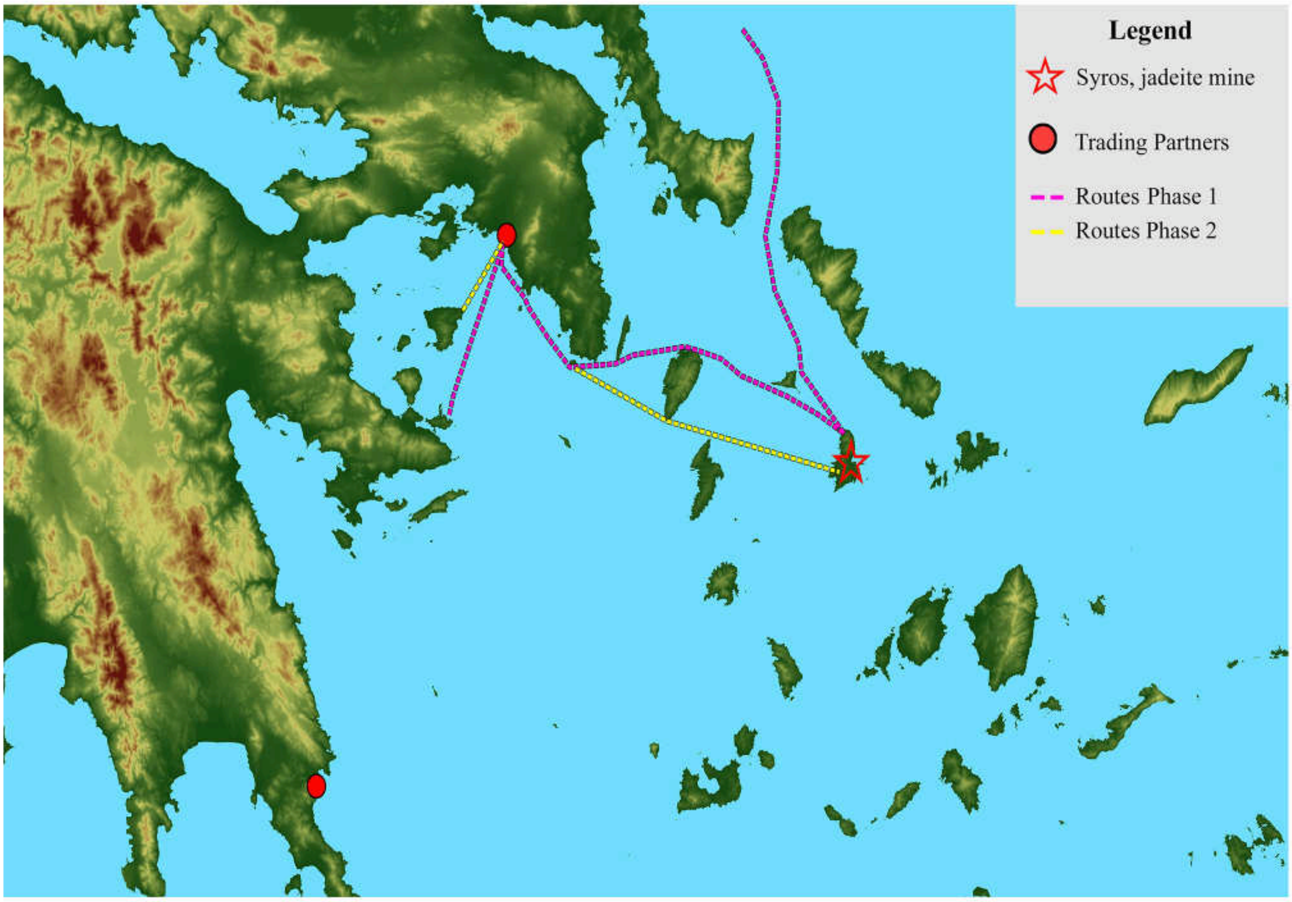


Fig. 7 - July, 24th

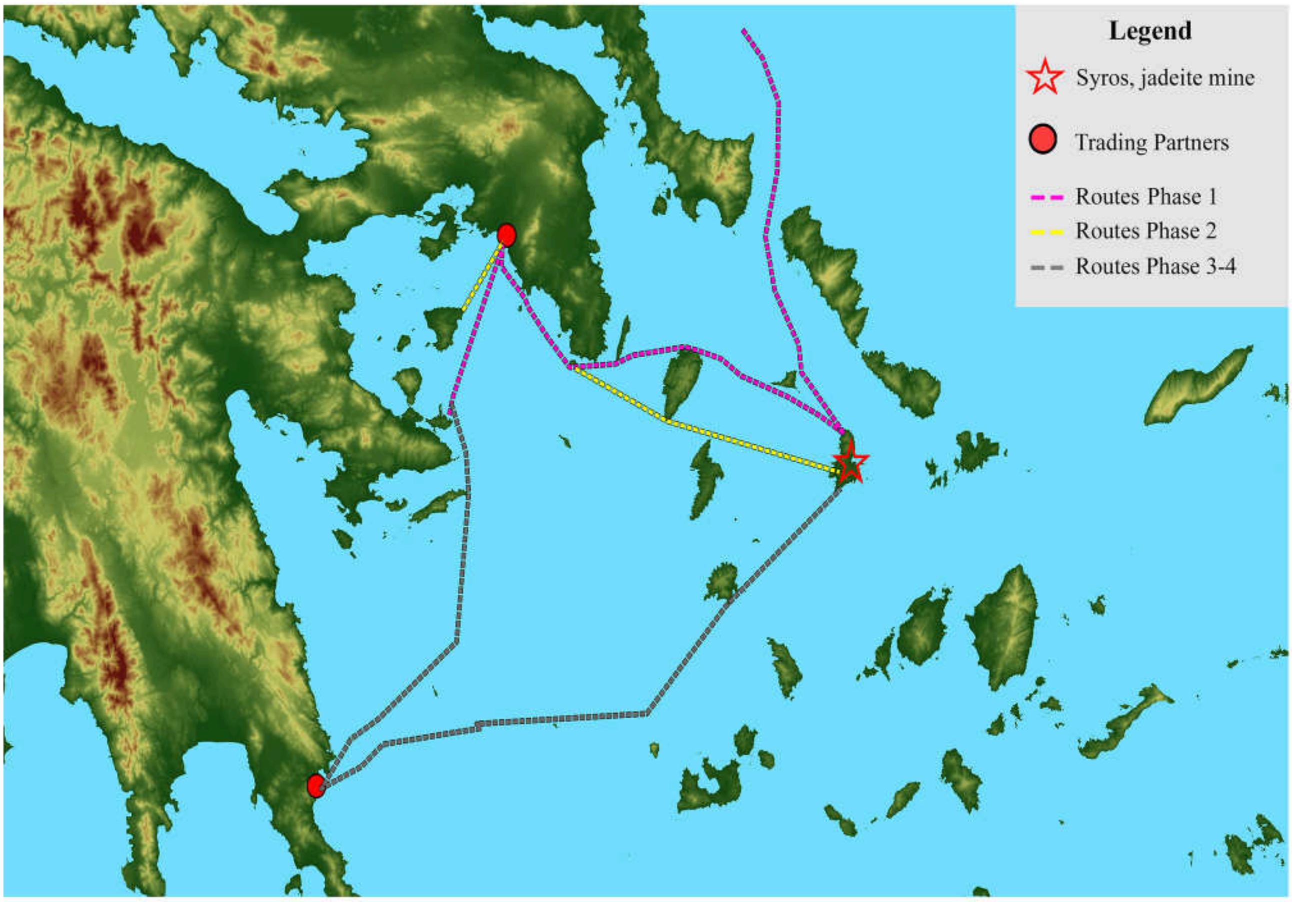


Fig. 8 - August, 5th - October 21st

Within the first month, the boat traveled between the mine, the closest trading partner, lying at the Greek coast (Fig. 6 and Fig. 7) and the coast but within the following months the navigator got to know one more location and included it into the travel route (Fig. 8).
In a next step, the visibility range was changed to a smaller distance of 20km (Fig. 9) – which is still quite far, as the real average view in a boat would be around 5km assuming a height of maximum 1.50m (5 feet).[13]

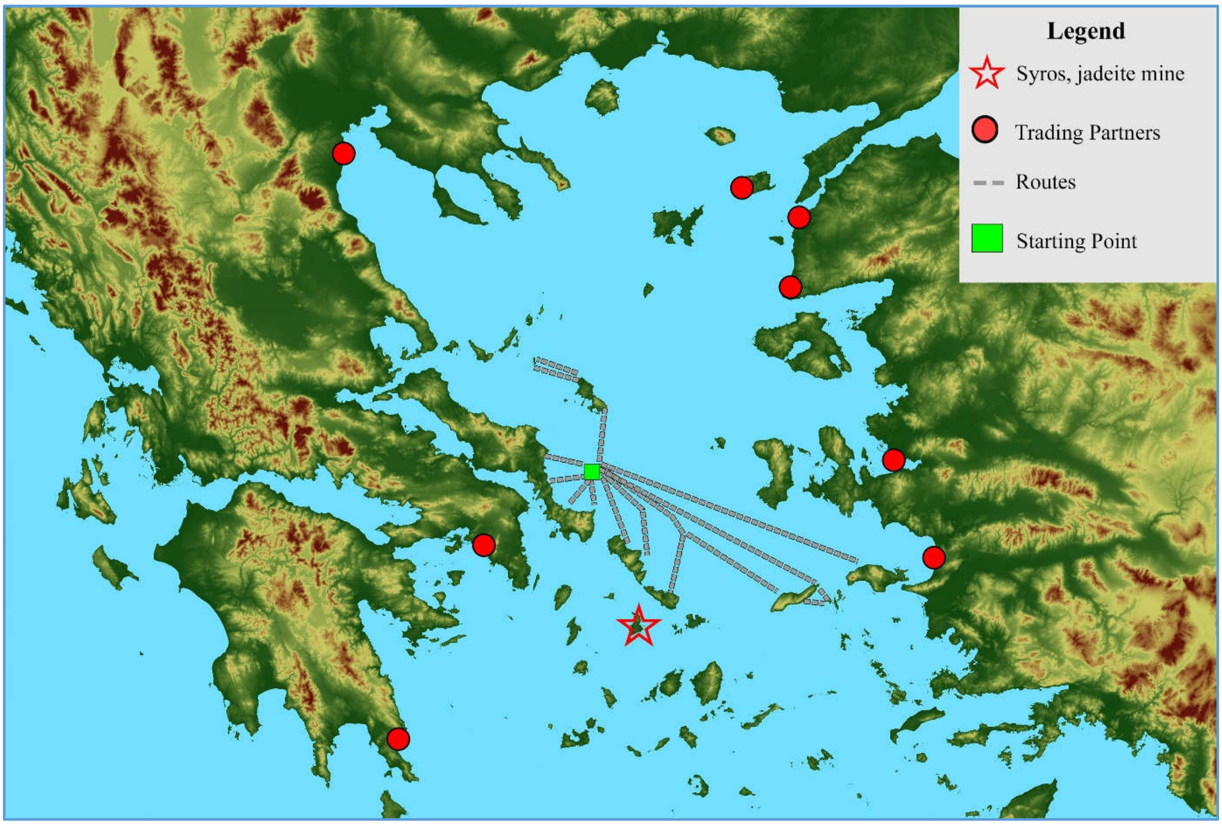


Fig. 9 – visibility = 20km, action radius = 50m

It was observable, how the agent started to wander without a target (breaks in the drawn path), and doesn't find the mine nor other trading partners. This experiment was run for the period from April to October with 20 repetitions, but the boat never reached the mine or the trading partners.
By increasing the visibility to 50km an interesting result could be gained, as the navigator decided to better go home and use the jadeite for producing his own products than trading it off to other partners (Fig. 10)

[13] Visible distance (in nm) = 1.17 x the square root of the height (in feet); km = nautical miles x 1.852;

Fig. 10 – visibility = 50km, action radius = 50m

As a last setting a situation of knowing all trading partners and the jadeite mine from the beginning was simulated. All experiments were repeated 20 times from April to October, the latter simulation conditions were also run 1 time for several years without stopping in October and one time as a Monte Carlo simulation, repeating it 1000 times. The latter allowed for mapping the most frequented anchorage locations (for shelter and exchange) as well as the most used routes (Map 3 and Map 4). The gained routes where transferred and reduced into a map in ArcGIS. In order to compare them with the monthly conditions a navigator would encounter, the wind- and wave data was included exemplarily for each month – always at the 15th at 1pm (Map 5-11).

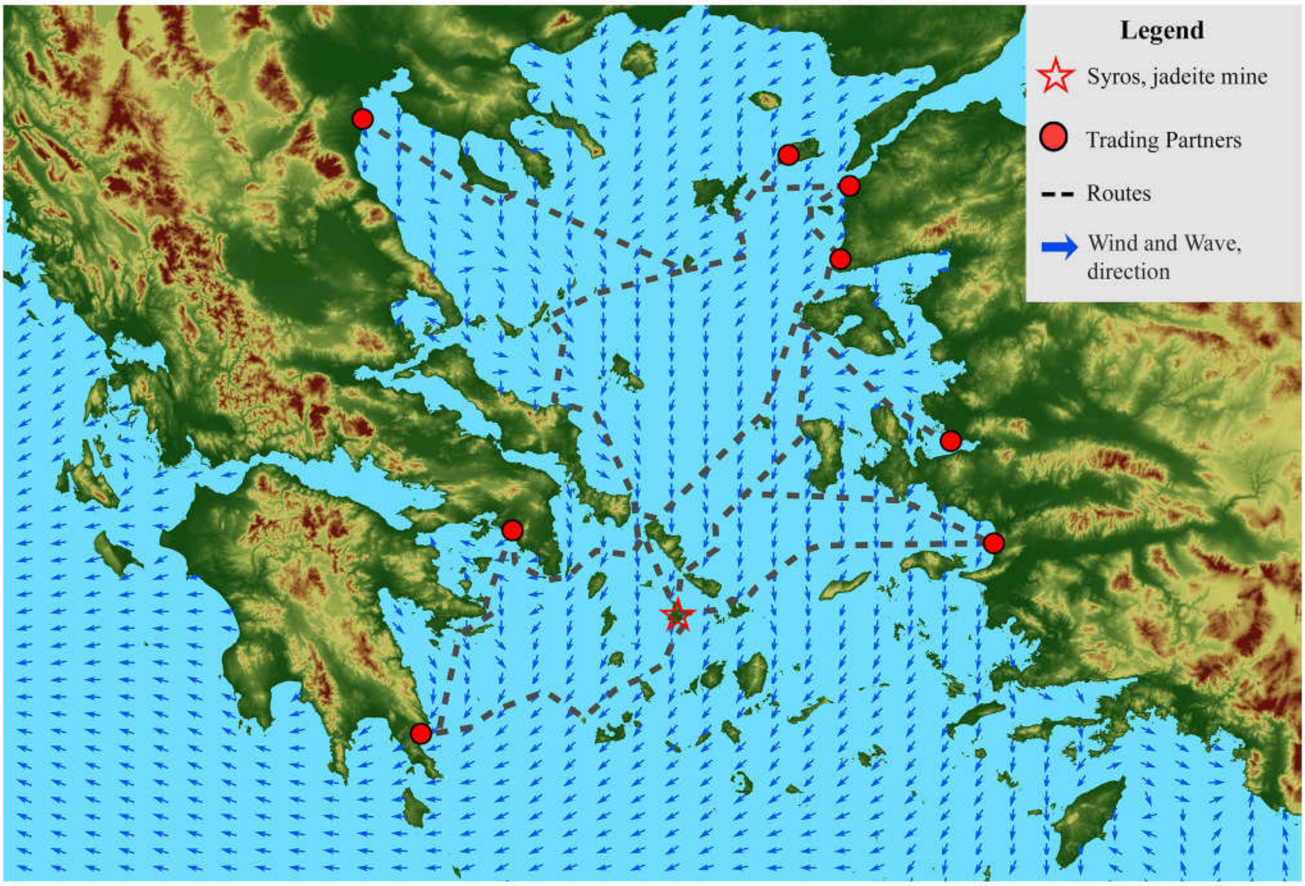
During all experiments it was observable that the knowledge of already taken routs and possible trading partners not only lowered the amount of wandering around (which of course was quite expected), but also diminished the interest of navigator in finding more settlements to trade with (cf. Map 3).

A special interest within the program functionality lay on the implementation of accessible coastlines, with a flat or almost flat slope. When looking at the output of the experiment, one can see, that in all cases, a suitable point could be found along the way and was used for shelter (Fig. 11).

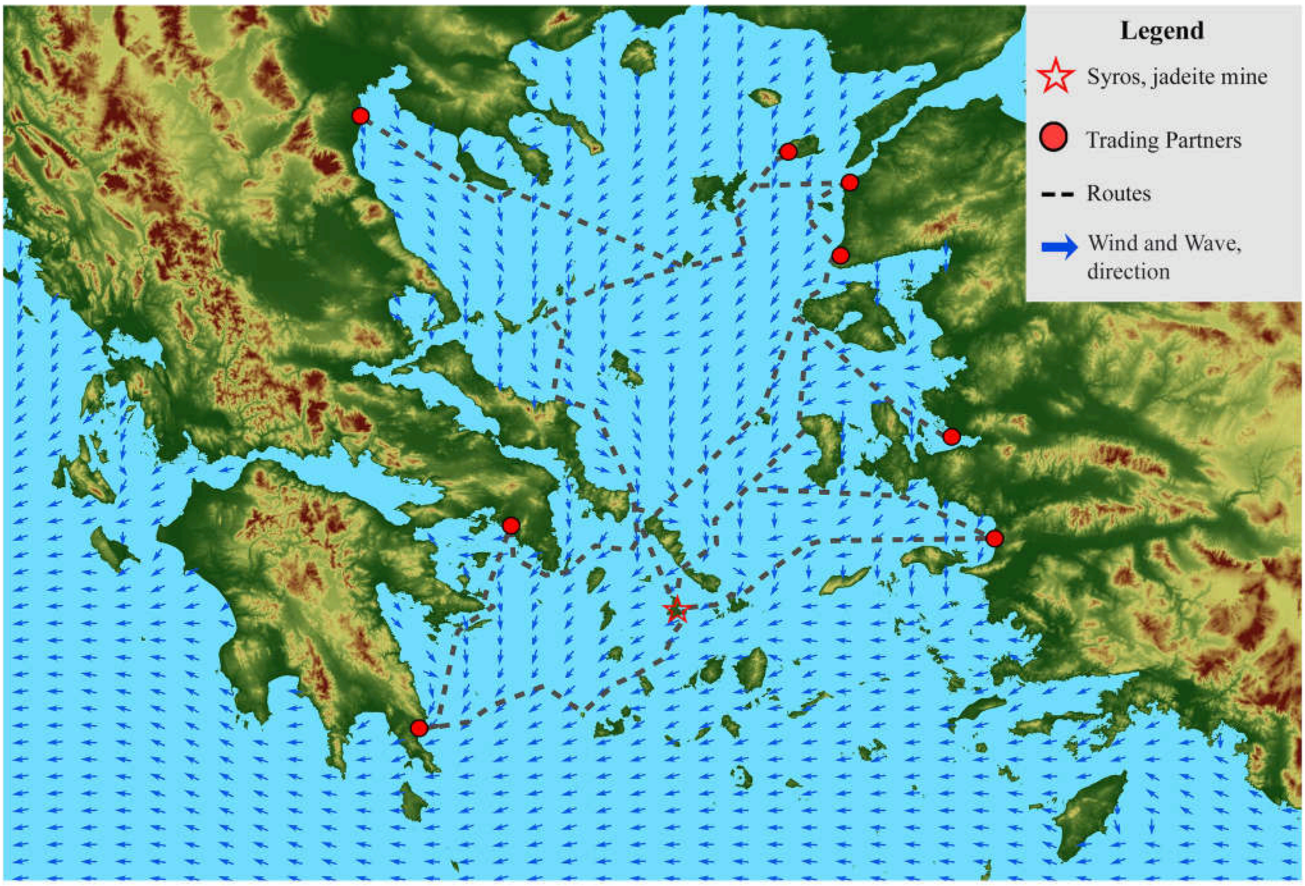
Map 3 - Most frequented anchorage locations (stars): highly frequented = bigger/darker, less frequented = lighter/smaller (red circles = trading partner locations, red star = mine)

Map 4 - Most frequented routes (lines): highly frequented = bigger/darker, less frequented = lighter/smaller (red circles = trading partner locations, red star = mine, purple stars = anchorage locations, see Map 3)

Map 5 - Time periode: April



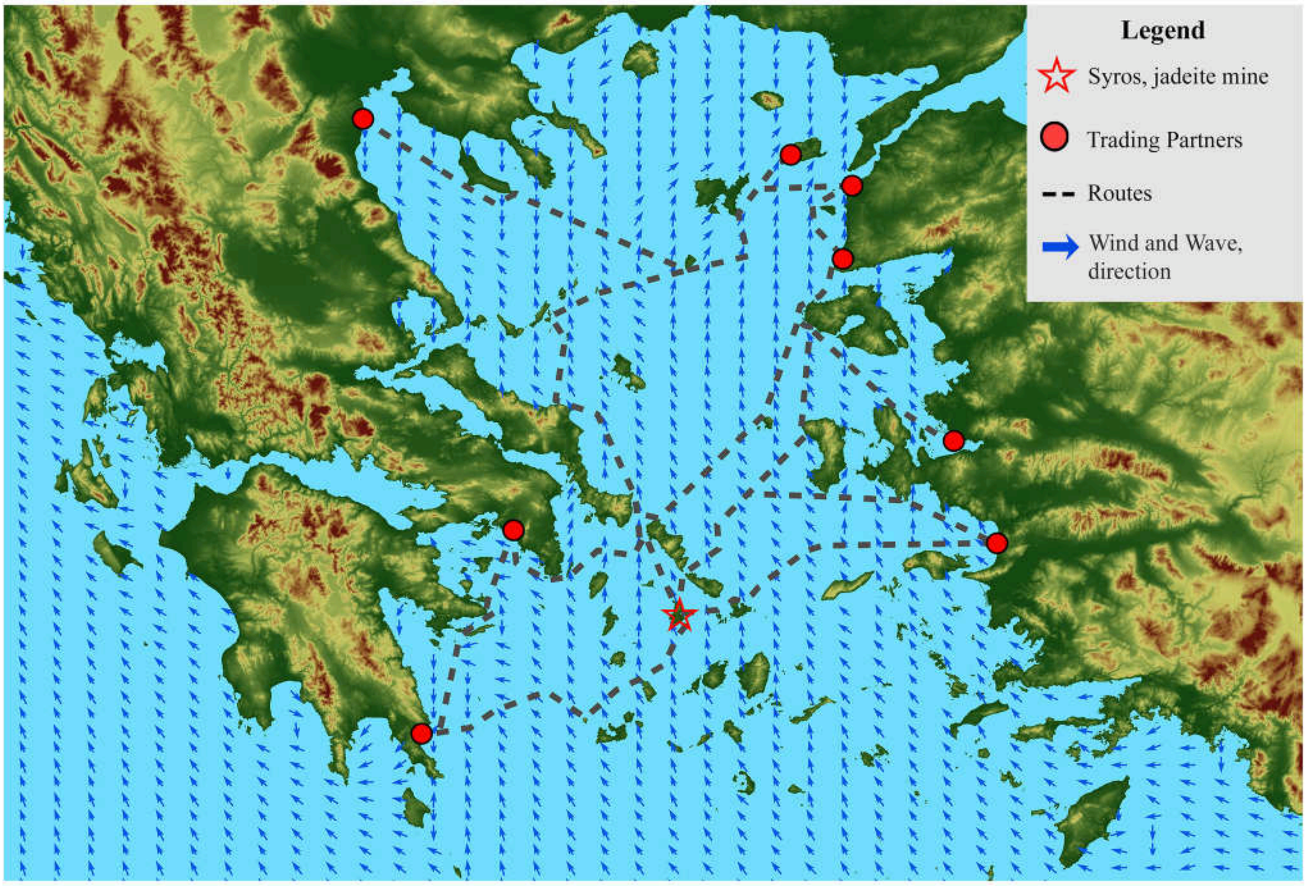
Map 6 - Time period: May



Map 7 - Time period: June

Map 8 - TIme period: July

Map 9 - Time period: August



Map 10 - Time period: September

Map 11 - Time period: October

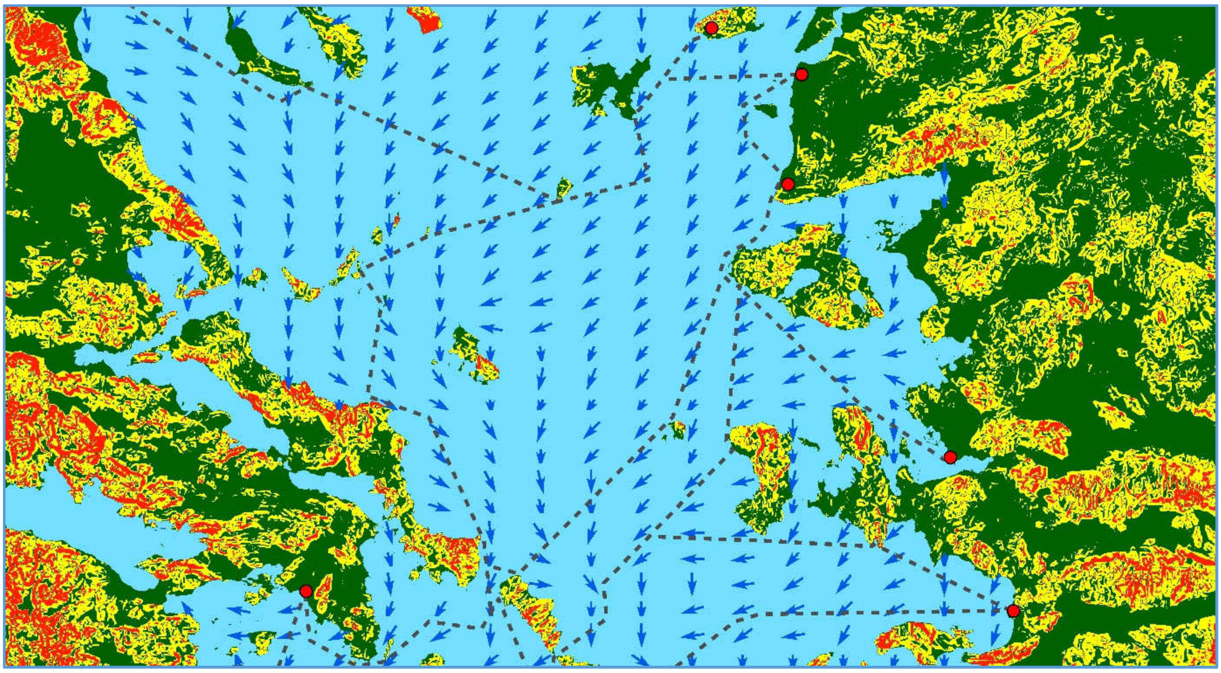


Fig. 11 – Routes and shelter points along the coast in comparison with the slope: green = flat, yellow = slightly steep, red = steep/not accessible.

It was especially interesting to see, that large areas of coast, which were quite suitable for going ashore, were not used by the navigator. From an archaeological point of view, these studies bear the potential to find out more about the location of possible unknown sights as well as the best or worst times to reach a settlement by sea. This of course would be even more so, the more factors – environmental as well as social – could be included into the model.

In order to test the influence of fear on the decision for coastal tramping and island hopping, the possibility of an agent of realising the possible danger of spending the night on open water and feeling fear was changed in steps of 0.1 within the possible range of 0.0 to 1.0 (0.5 being the default value). The simulation was repeated 5 times for each value. It was observable, that – as expected – the amount of stop overs on land declines proportionally and trading partners are reached faster the lower the possibility of fear. With a high amount of fear, the boat stayed very close to the coast. In several simulations, the agent stayed between the first exchange partner, the opposite coast and the mine, but in general the reached partners stayed the same throughout the simulations.

Discussion

Concerning the overarching question of this study – namely the usability of the BDI structure in GAMA for archaeological questions – it can be stated that BDI is highly suitable for the research questions treated here. The opportunities of simulating life-like decision processes and characters, enables detailed modelling of even complex social systems and behaviour. Even though at this point the full potential of character modelling, social norms and laws or knowledge exchange couldn't be tapped yet, it is already visible, that it bears a lot of possibilities for testing the importance of the "human factor" in movement (on sea or land). Changing the probability of the navigator feeling fear in the range of 0-1 showed, not unexpectedly, that the chosen routes tend to stay closer to the coast, the more fearful the agent is. The implementation of a more differentiated character – including e.g. openness, consciousness or agreeableness etc. – is expected to support this outcome even stronger.

This leads to the second part of the study, which wanted to gain insight into the archaeological question of navigation in the Neolithic and the importance of the human decision making process within it. Looking at the real life data on wind and wave speed and direction and using the mathematical algorithm presented in chapter 2 it is observable, that the influence of environmental conditions in the offshore zone under usual circumstances does not present a big obstacle while paddling towards a certain point. This does, of course, neither include stormy weather and other special circumstances nor the usage of sails, which would change the influence of wind drastically. Also one has to keep in mind that the used data only represents an example situation. Nevertheless, the experiments could show that the human experience and decision is a very important, if not more important factor in navigation. The realistic visibility of about 4 to 7km hinders finding unknown locations – like the jadeite mine or trading partners – severely (this shows evidently the influence of fog or other circumstances decreasing visibility). This causes the agent to tend to stay within a small area, in this study keeping it from finding the mine or other settlements. By increasing the visibility to an unrealistic point it was possible to imitate a known jadeite mine and to increase the chances of the agent establishing a (small) exchange network. But even with a very high visibility range, the locations in the northern region were never reached (with the exception of a situation, in which all trading partners were known from the beginning). This leads to the conclusion that early navigators had to have a very exploratory spirit or were forced by outer influences (e.g. climate changes, enemies or other) to move beyond the known regions. Another possibility would be a social system, in which information of other settlements, mines or possible exchange partners and their needs and exchanging goods is shared.

The third topic of this study, the common theory of island hopping and coastal tramping as the general way of traveling by boat, could also be observed in the here presented study. It is, though, caused by the (common sense) assumption navigators would avoid spending the night and taking breaks at open sea and not an emergent output.[14] Human shape and needs support the theory, at least for paddled boats. Main traveling routes and the used example data on wind- and wave direction can be seen in Map 5-Map 11 as well as on Map 4 and show, nevertheless, a mix of open-sea and coastal routes (if the navigator is not too fearful). This outcome should, though, be combined with natural conditions in order to be verified under “life-like” conditions. When looking at the map of most frequented anchorage locations, it is particularly striking that three of four exchanging partners along the Turkish coast, Troy, Yeşilova and Çukuriçi Höyük, are less frequented than the other locations. It would, though, be a misinterpretation to assume that this is a sign for them being less important or less included into the exchange network – material studies even show the opposite.[15] It points more likely towards the necessity of creating a more complex model of early exchange, by including more data and exchanging material, and a higher number of simulations under different situations (e.g. starting at the Turkish or Greek coastline). It should also be noted, that these where the last locations found by the agent.

When discussing the here presented model, and even though GAMA can be seen as a very helpful tool for archaeological questions in general, it cannot be avoided to mention a few problems and limitations the author encountered during the programming process, which are, of course, mainly contemplable for the specific case study treated here.

First of all, the geographical region of study was limited in size. Big files can generally be loaded into the program but can lead to a slow performance or even a crash.[16] This would not be a problem in a micro-regional study, but where questions on a macro-regional level, e.g. (trading or exchange) networks or migration, are the topic of interest, it could be limiting. It is especially unfortunate, that the Belief-Desire-Intention (BDI)-tutorial found in the GAMA documentation, which includes social norms, liking and other complex social factors, is still work in progress and was shortened for the version included into the latest GAMA software download.[17] One specific problem, which was encountered during this research, was the way, movement is programmed in GAMA. It includes two possibilities: either to move the agent

[14] For a possible future solution to this problem see chapter 4., Summary and Outlook.
[15] Data can e.g. be found in the numerous publications e.g. on small finds, lithic material or metal found at Çukuriçi Höyük.
[16] This problem is known and discussed by the GAMA support team in several fora, so it is very likely that it will be solved soon.
[17] GAMA 1.8; this is also a problem which is currently worked on and several updates have been made enlarging the tutorial again during the time span of this thesis.

towards a target using the shortest possible route, if required over a weighted grid – excluding the option of influencing the movement angle – or, to move it in a given direction and angle but without a fixed target. The first option does not really represent a life-like situation. The underlying algorithm for the movement seems to be very similar to least-cost-path-calculations in GIS, which, as stated in the introduction of this master's thesis, would postulate again a nearly omniscient navigator. The latter movement causes the agent to "jump" in the direction of the currents, thus drifting controlled only by the environmental conditions in its surroundings. This would remove the human factor from the experiment.

The reasons for this gap seems to be the difference between movement on land and on water: a person walking on land does not have to react the same way on wind or other (environmental) conditions as someone in or on water, as it is a different medium to move in, and found circumstances can even change ones route against ones will. When e.g. studying the movement of plankton or other drifting objects as well as fish in a river with a steady current direction, this would not cause a problem. But when it comes to the movement in water towards a target, a special solution has to be found. However, at this point of time, this type of movement does not yet exist in GAMA.[18] Nevertheless, GAMA has a high potential and definitely presents a good alternative to other modelling software like NetLogo, especially caused by its high flexibility and compatibility with data formats, as well as an easy to learn programming language and very clear user interface and graphics. At this place it should also be mentioned that GAMA has a very constructive, fast and helpful user support.[19] It can enlarge purely GIS-based studies, like least-cost-path-analyses or others, as well as research on human interaction with nature, e.g. the effects of settlements on the surrounding eco-system.

[18] A possible work around, which could not yet be checked for its applicability is described in chapter 4., Summary and Outlook.

[19] Special thanks of the author should be given to P. Taillandier who was a great support and was of great help during the coding process.

4. Summary and Outlook

The here presented work could show that the Belief-Desire-Intense (BDI) structure in GAMA has a very high potential for simulating human behaviour as it can depict a lot of different decision processes. This is a definite plus point of GAMA in comparison to other software. The opportunities of simulating the character of an agent to a very detailed point allows for studying even complex social systems and proved to be highly suitable for the question of the importance of the human factor on route decision making. That makes it a very suitable software for simulating archaeological theories and models and can contribute to answering a lot of different questions. Topics of investigation can include not only trade and movement, but also developments of settlements, colonies or the interaction of the human species and its environment. Nevertheless there are a few limitations to take into consideration when working with GAMA.

It could be shown that the theory of coastal tramping and island hopping can not only be explained by *common sense*, but also by the necessity of taking breaks on land, but that travelling the open seas was still an option, and necessity, in early seafaring. Nevertheless, this outcome is not yet completely emergent, as boats are programmed to take breaks after a certain point. One solution in order to change this could be to leave the decision of taking breaks on land completely to the navigator and his character and emotions and let the news of boats sinking during the night at sea (or also because of natural conditions) spread via social contacts. An agent could then decide based on knowledge and experience (of others).

It can be observed that the influence of human character and decision making in early times of seafaring is generally underestimated, as either knowledge of other settlements, necessity of movement or high exploratory spirit is needed for this kind of undertaking. Also the environmental conditions of paddled trips in the region under study seem to be of less influence as thought, but this is still a theoretical assumption waiting to be thoroughly tested.

Concerning the possible routes a paddled boat could have used to and from the jadeite mine at Syros, the experiments produced several maps of main possible paths as well as one of the most frequented anchorage points.

Several things could not be covered in this Master Thesis, as this would have gone beyond the scope of it, but could or even should be done in a following project. If the problem of implementing the influence of environmental data on the movement of an agent can be solved, the environmental conditions could be refined, by including a bigger set of wind and wave data and currents as well as simulating rain and storms. It would be very interesting and necessary to review the applicability of a work around option for the movement skill, suggested by P. Tailandier,[20] but as this is a rather complex way of moving the boat over the grid, developing and implementing the needed algorithms would unfortunately need more time than the frame of this Master's Thesis allows – hopefully future studies can fill these still existing gap.

On a social level, there are a few next steps that could add more detail and complexity to the here designed model. One would be adding sailing boats as this could change the influence of environmental conditions drastically. The boats could also be adapted by changing the general energy level, now a combination of man power, to a more detailed group of factors – e.g. water, food or rest. It would also be important to enlarge the complexity of the navigators' character, thus taping the full potential of BDI, by including openness and other factors, and to test the influence of these factors. This could even help to gain insight into the important psychological characteristics of early seafarers, even though this could only be seen as a mental exercise rather than a fact.

It is not very likely that jadeite was a main product in early (or later) exchange networks. Most probable it was one of many goods traded and has probably been picked up on the way of getting other materials (e.g. obsidian or metals), thus, enlarging the exchange network by adding more products and trading partners would contribute an even more significant results. Additionally it would be interesting to see, how communication and sympathy among trading partners as well as with the boats or among boats (e.g. the above mentioned news on deaths at sea), including social norms and laws, as well as allowing product orders, would change the outcome of the model – especially as this would move the focus of influence away from the visibility range more towards the social system.

The generated model does not, of course, reach the level of complexity needed for studying a complete social-ecological system of seafaring and, thus, does not claim to completeness, but it could contribute to visible proof of the importance of implementing human interaction into (sea-) routes, on one hand, and showing the possibilities and limits of the used software on the other.

[20] This suggestion was made in a personal correspondence via the GAMA forum, February 2019.

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