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Toward Cross-Scale, Multimodal Data Applications: An Exploratory Framework of Movement Model in "Sea-Channel-Island"

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Abstract

Geographic Information Systems (GIS) have been widely employed to model human activities, yet their application to prehistoric maritime migration—exemplified by the Austronesian expansion from coastal Asia to Pacific Islands—remains underdeveloped. This migration shaped a distinctive seascape, and analyzing it across the land-sea boundary is critical to understanding prehistoric cultural dissemination from terrestrial to maritime contexts. However, a dedicated methodology to resolve this spatial-temporal challenge is lacking. This paper proposes an integrated framework synthesizing multi-source terrestrial/marine, spatial/textual, natural/cultural, and historical/contemporary data. Three hierarchical models are formulated through GIS least-cost analysis. The maritime-scale model reconstructs movement corridors by calculating wind-driven pathways, with feasibility validated against shipwreck distributions. The channel-scale model identifies optimal visible and landfall islands across the critical strait. The island-scale model detects human landing sites and activity zones on islands. The research introduces a novel cross-scale trans-medium framework to analyze the dynamics of oceans, straits, and islands, substantiated by case studies and historical texts. This framework deciphers land-sea movement patterns shaped by human marine activities, revealing their spatial characteristics. Furthermore, it provides insights for archaeological investigations and enables systematic interpretation of cultural implications on a macro scale.

1. Introduction

The ocean preserves vital evidence of human civilizational exchange. Recent archaeological discoveries across Pingtan Island and its adjacent waters in southeastern China highlight its unique geo-historical significance. Excavations at the Keqiutou site unearthed Austronesian cultural artifacts, while the Haitan Strait has revealed the highest density of shipwreck assemblages documented along China's southeastern coast (Lv, 2015). These findings demonstrate that despite the challenge of wind stress, this corridor functioned as a critical pathway for cross-medium mobility from antiquity to modernity (Local Chronicles Compilation Committee in Pingtan County, Fujian Province, 2000). Systematic investigation of submerged and insular material culture continues to unveil profound legacies of humanity's maritime heritage.

1.1 Ancient Navigation: The Austronesians as a Case Study

The genesis and dissemination of the Austronesian language family exemplify early human transoceanic migration (Bellwood, 1991; Gray and Jordan, 2000; Gray et al., 2009; Jones and Matsuda, 2023). During the 16th century, Western travelers documented remarkable linguistic and phenotypic homogeneity among Pacific Island populations — observations that catalyzed the academic conceptualization of the Austronesian language family (Bellwood, 2017). Today, it represents the world's only major language family predominantly distributed across islands, encompassing 1,000–1,200 languages spoken by approximately 400 million people, ranging from Madagascar to Easter Island and Taiwan to New Zealand (Blust, 2022; Guo et al., 2023).

Genetic analyses of Lian Island skeletal remains (Ko et al., 2014) established that Austronesian-speaking populations migrated from southern China's Fujian coast ~ 6,000 BP. Subsequent genomic research (Yang et al., 2020) pushed this origin back to 8,400 BP in Fujian and adjacent regions. Pingtan Island—characterized by its distinctive climatic forcing and dense shipwreck clusters, along with Austronesian artifacts like those at the Keqiutou site, has been identified as the language family's migratory "anchor point" (Fan et al., 2024). Consequently, the trajectory of Austronesian expansion across the first post-mainland strait remains a priority focus in archaeological linguistics (Bellwood et al., 1995).

1.2 Modeling Movement in GIS

Navigational simulation advances understanding of marine ecosystems and human migratory behavior. David Lewis pioneered this approach in 1964 by reconstructing exceeding 1,400 kilometers of ancient voyages through natural navigation techniques (Lewis, 1972, 1966, 1964; Gatty, 1999).

Contemporary researchers leverage computational tools for such simulations. GIS platforms enable data storage, processing, integration, and visualization. The ArcGIS Toolbox quantifies sailing expedition costs (Alberti, 2018; Gustas and Supernant, 2019; Moutsiou and Agapiou, 2019; Fernández, 2021), while polygon-based models digitize ocean movement trajectories (Harpster and Chapman, 2019), and social network analysis maps maritime connectivity (Trapero Fernández and Aragón, 2022). Python-GIS integration simulates real-time movement within dynamic wind fields (Perttola, 2022), and cost surface models assess monsoon impacts on sail routing using empirical meteorological data (Gheorghiade and Spencer, 2024).

Current models, however, fail to reconcile the spatial question of Austronesian dispersal: extensive-scale diffusion across the Pacific (Figure 1) versus micro-scale activity clusters at locations like China's Pingtan Islands (Figure 2). This multi-scale discontinuity impedes digital reconstruction of trans-medium migration. Moreover, fragmented integration of archaeological and genetic geospatial data risks obscuring critical spatial patterns during ongoing excavations.

1.3 Research Purpose

This study pioneers a multi-scale navigational simulation framework to analyze early human migration patterns across the Haitan Strait. Utilizing ArcGIS Pro's Least-Cost Corridor (LCC) and Optimal Path (OP) algorithms, the framework spatially correlates simulation outputs with archaeological surveys, photogrammetric 3D models, and historical imagery. Research objectives include three sections. (1) Framework formalization and implementation. (2) Multi-scale simulation across three progressively nested spatial domains. Taiwan Strait (macro-scale), Haitan Strait (meso-scale), Cao Island (micro-scale) (Figure 1) to determine high-probability island discovery zones during maritime expansion, optimal landing islands, and archaeological site suitability. (3) Model validation through spatial congruence analysis between computational outputs and archaeological evidence. This integrated methodology advances understanding of early human maritime migration dynamics and settlement strategies.

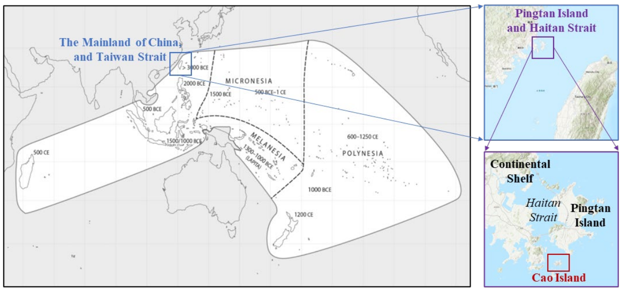

Figure 1. The comprehensive distribution of Austronesian languages (black block) (Bellwood, 2017), the Taiwan Strait serving as a conduit for dissemination from the mainland to the oceans (blue block), and Cao Island (red block) indicating the southern entrance of the Haitan Strait (purple block).

Figure 2. Haitan Strait and Cao Island.

2. Methodology

The exploratory framework integrates three multi-scale analytical models (Figure 3) designed to address spatial challenges across hierarchical dimensions.

Model 1 (Maritime Scale) simulates human navigation patterns using spatiotemporal wind field data (Safadi, 2016; Fernández, 2021; Gal et al., 2021; Gheorghiade and Spencer, 2024). This approach identifies high-navigability zones requiring prioritized investigation while excluding nonviable maritime sectors. These optimized marine corridors subsequently guide the identification of critical straits necessitating granular analysis.

Model 2 (Channel/Strait Scale) integrates bathymetric and terrestrial DEM data to quantify island accessibility within targeted straits. It assesses the probability of island encounter during waterway transit, and the accessibility likelihood of potential landing piers. The model identifies optimal islands for maritime landfall while demarcating targets requiring intensified investigation. This terrain-filtered priority directly informs microscale analysis.

Model 3 (Island Scale) reconstructs probable zones of historical human activity using centimeter-resolution Digital Surface Models (DSM) derived from drone oblique photography. The spatial accuracy of these reconstructions is archaeologically validated through systematic ground surveys and artifact distribution mapping.

The following sections detail the computational foundations of this framework.

2.1 Archaeological Survey

The archaeological survey integrates terrestrial and underwater investigations. (1) Terrestrial survey documents surface remains on islands (e.g., lighthouses, cottages, villages, wells, temples) using oblique photogrammetry via DJI Mavic 3E drones. High-resolution Digital Surface Models (DSM) were generated with Agisoft Metashape and DJI Terra software, providing foundational data for GIS spatial analysis. (2) Underwater survey examines shipwreck distribution relative to waterways. The prominence and height of an island substantially affect its visibility from the sea (Lewis, 1964), which is thus linked to the probability of landing on the island (Gatty, 1999).

2.2 GIS Spatial Analysis

GIS spatial analysis functions facilitate the quantitative examination of archeological data. In this exploratory framework, the following tools from ArcGIS Pro 3.4.2 were employed to derive corridors and paths: Cumulative Cost Distance (ESRI, 2025a), Least-cost Corridor (ESRI, 2025b), and Optimal Path as Line (ESRI, 2025c). The Viewshed tool (ESRI, 2025d) was employed to produce cumulative viewsheds based on linear features, depicting things that are more commonly seen during transit. It is essential to recognize that while the study's computer outcomes are depicted as "paths," the aim is to offer a visually navigable "directional" reference rather than suggesting that human dispersion adheres precisely to these linear trajectories (van Leusen, 2002; Wheatley and Gillings, 2002).

For ocean movement modeling, the surface raster uses a value of 1 to bypass null data limitations, while the cost raster incorporates wind speed. The horizontal grid utilizes wind direction data, and the coefficient acts linearly, indicating that as the angle between the forward direction and the wind direction increases, resistance correspondingly escalates. The resistance attains its peak value when the horizontal relative movement angle (HRMA) is -180° (i.e., when the forward motion is entirely opposed to the wind direction) (ESRI, 2025e).

For land movement, the surface raster and cost raster of the land movement model utilize the Digital Elevation Model (DEM). Vertical grids utilize slope data, with the vertical factor (VF)

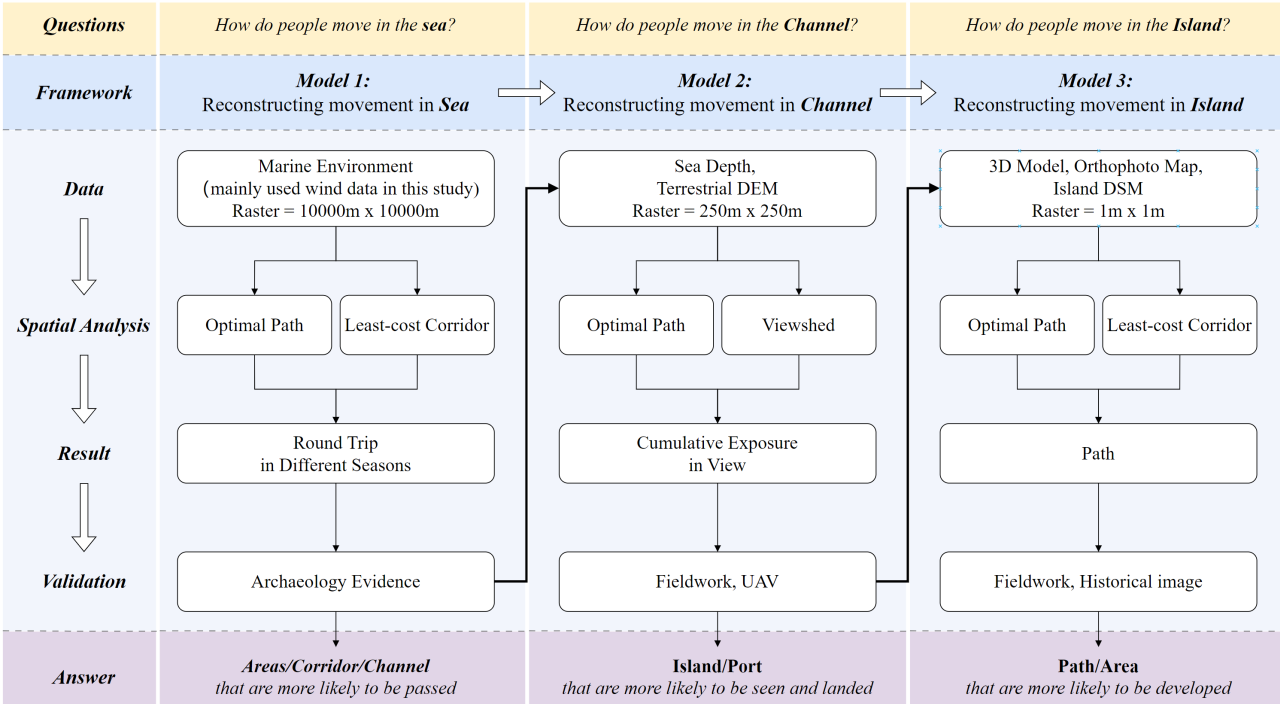

Figure 3. The system framework.

exhibiting a symmetrically inverse linear relationship (ESRI, 2025f), and the vertical relative moving angle (VRMA) constrained between -55° and 50° (He, 2008; Llobera, 2000). Horizontal grids utilize aspect data, with the horizontal factor (HF) represented as a linear function.

2.3 Historical Imagery as a Supplementary Verification

Historical imaging maps provide a pre-urbanization landscape (Zhang et al., 2024). This research employs declassified reconnaissance satellite imagery from the United States Geological Survey (U.S. Geological Survey), accessible at https://earthexplorer.usgs.gov/. It comprises CORONA KH-4 (August 23, 1965, medium resolution), and HEXAGON KH-9 (June 29, 1978, 2-4 feet accuracy). Google Earth temporal composites (2013–2024) track sequential landscape alterations, enabling verification of surface transformation patterns against model predictions.

3. Models and Results

This chapter presents the three models within the exploratory framework utilized to reconstruct human movement across various spatial scales.

3.1 Model 1: Reconstruction of Marine Movement

The dissemination from the southeastern Asian mainland coast to the islands is considered a defining feature of the Austronesian language family's continental origins (Ko et al., 2014; Bellwood, 2017; Yang et al., 2020). This model identifies five sites within the Taiwan Strait that feature typical Austronesian cultural artifacts: Tanshishan Site, Cao Island Site, Fengbitou Site, Fuguotun Site, and Fengbitou Site (Zhang, 1987; Blust, 2013; Bellwood, 2017), which function as the model's initial and terminal points. Marine environmental parameters are derived from the wind u and v vector data obtained from the Pacific Ocean Physical Data Archive Center (http://apdrc.soest.hawaii.edu/las86). The winter season in Southeast Asia, occurring from November to March, is predominantly impacted by northeasterly winds, whereas the summer season, from April to September, is chiefly affected by southwesterly winds (Fujian Pingtan County Local Chronicles Compilation Committee, 2000; Perttola, 2022). This model employs a grid resolution of 10,000m x 10,000m to prevent inaccuracies in interpolation resulting from discrepancies in precision and scale (Gillings et al., 2020; Gheorghiade and Spencer, 2024).

The Optimal Path tool in ArcGIS Pro was utilized to assess the transit networks among these five locations. The pathways demonstrate a notable degree of grouping overall (Figure 5a). The wind environment has influenced the establishment of a "south-north" and two "northwest-southeast" transportation networks. In contrast, the "southwest-northeast" network is virtually absent; for example, a significant "detour" exists between the Fuguotun Site and the Fengbitou Site. Paths were simulated from each site to numerous destinations on a case-by-case basis (Figures 5b-f). Figures 5d-f illustrate that summer trajectories predominantly orient northeast, but winter trajectories have a southwest tilt, possibly attributable to the dominant northeasterly winds in winter and southwesterly winds in summer.

The Least-cost Corridor tool in ArcGIS Pro was utilized to examine the easily traversable portions among these five sites (bigger color blocks represent more extensive passable areas), with the corridor threshold established at 25% for straightforward comparison. In the majority of instances (Figures 6b_1, c_1, e_1, f_1, g_1, h_1, i_1), the traversable regions during summer are more extensive. This is particularly apparent in the traversable areas between southern Pingtan and the Fengbitou Site (Figure 6e_1), between the Fuguotun Site and the Fengbitou Site (Figure 6g_1), and between the Fuguotun Site and the Fengbitou Site (Figure 6h_1). This scenario is probably associated with the subtropical monsoon zone of the Taiwan

Strait, characterized by a higher frequency of winter winds compared to summer winds, while the comparatively calm summer winds offer a broader area for movement. Nonetheless, exceptions exist. The traversable areas between the Fuguotun Site and the Tanshishan Site (Figure 6a2) and between the Cao Island Sites (Figure 6a2) demonstrate a "southerly drift," indicating that a portion of the easily navigable zone diverges from the land. This is primarily attributed to the northeasterly winds during winter. Moreover, it is posited that if humans situated in these anomalous regions are unable to return to the mainland or access the adjacent Penghu Islands, they may be perpetually propelled toward the Dongsha Islands by the northeasterly winds.

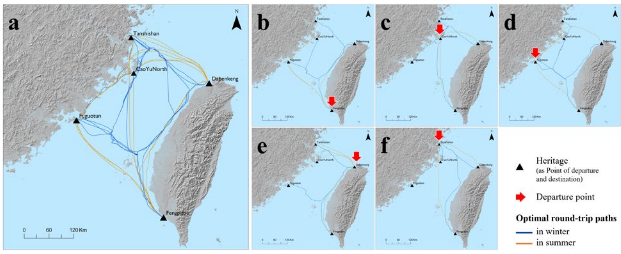

Figure 5. Analysis of the optimal paths between archaeological sites. (a) General trends. (b-f) Paths originating from each specific archaeological site, accordingly.

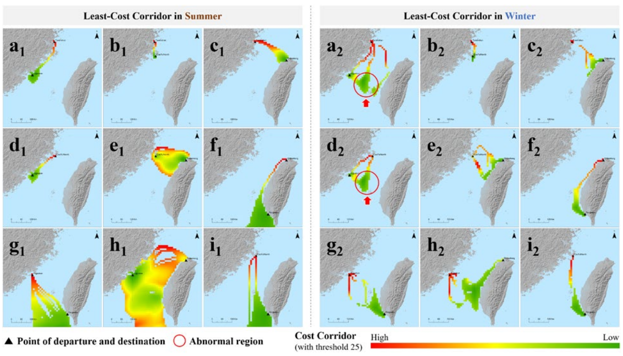

Figure 6. Analysis of the least-cost corridor between archaeological sites. Threshold cost percentage: 25%. (a_1-i_1) Corridors during the summer season. (a_2-i_2) Corridors in winter.

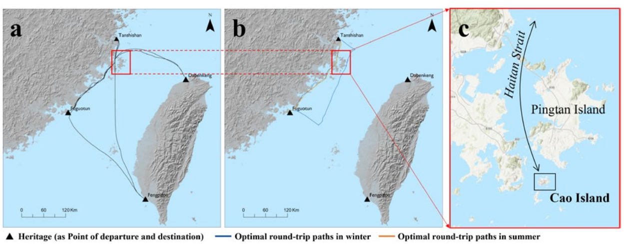

Figure 7. Key nodes and optimal paths. (a) Path through Haitan Strait. (b) The winter and summer round-trip itineraries between Fuguotun and Tanshishan. (c) Cao Island is a key southern corridor node.

Analysis of the winter and summer round-trip routes among the sites reveals that the maritime pathway from the Fuguotun Site to the Fengbitou Site adheres to a strategy of "initially navigating along the coast — transiting through the Haitan Strait — before traversing the Taiwan Strait." Both the outward and return routes employ the identical movement method (Figure 7a). During summer, the Haitan Strait is consistently selected for round-trip routes from the Tanshishan Site to the Fuguotun Site. Nonetheless, there exists a singular winter path that does not employ the Haitan Strait (Figure 7b). When the Haitan Strait is selected as the route, Cao Island, situated at the southern entrance of the waterway, serves as a crucial waypoint (Figure 7c). Underwater archaeological investigations indicate that the Haitan Strait has the highest concentration of shipwrecks along the Chinese coast (Lv, 2015). The Haitan Strait is an essential navigation zone when traversing the Taiwan Strait.

3.2 Model 2: Reconstruction of Channel Movement

The previous model's precision appropriately depicts movement patterns in the broad sea, yet it inadequately represents movements in confined waterways, leading to mistakes from insufficient precision (Figure 8a). This model employs nautical chart data at a scale of 1:50,000 to 1:750,000 (Figure 8b) and subsequently resamples it into a grid with a resolution of 250m x 250m. Maritime experience suggests that shallow regions frequently present an elevated danger of grounding (Safadi, 2016). Consequently, in this concept, deeper regions are regarded as more navigable zones. Two arbitrary sites are established outside the northern and southern entrances of the Haitan Strait to model the minimal movement corridors and ideal navigation routes from north to south (Figures 8c1-4).

The simulated trajectories closely align with the actual navigational routes at the northern and southern entrances, hence confirming the simulation's dependability. Additionally, "cumulative visibility" is computed based on four distinct trajectories to assess which regions are more prone to observation during navigation (Figure 9). The analysis indicates that Cao Island is the most significant region among the islands at the southern entrance of the Haitan Strait waterway. Field investigations reveal that when observing Cao Island from the north to the south at sea, its majestic peaks are shrouded in clouds, resulting in a visually striking impression (Figure 10a). Proceeding southward, Cao Island serves as the final notable tiny island before accessing the open sea via the Haitan Strait (Figure 10b).

Ancient textual records indicate that Cao Island held a key role in coastal defense, characterized by high winds and submerged reefs. Evidence suggests human settlement on the island before 1279, the year of the Southern Song Dynasty's collapse (Figure 11).

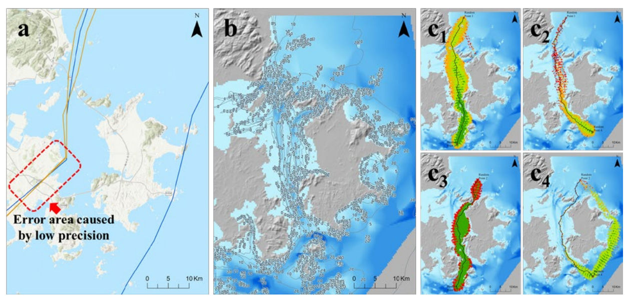

Figure 8. (a) Relatively low accuracy causes errors (red dashed box). (b) Create relatively high-accurate seabed elevations using contour lines from nautical maps at 1:50000-1:75000 scale. (c) Simulate north-to-south corridors and pathways from random places in the Haitan Strait.

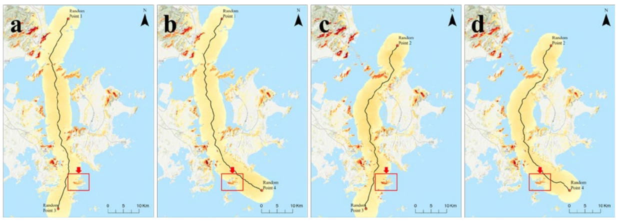

Figure 9. Cumulative visible area when crossing the Haitan Strait from north to south, with deep red areas suggesting frequent sightings. (a) Northwest to southwest, (b) northwest to southeast, (c) northeast to southwest, (d) northeast to southeast.

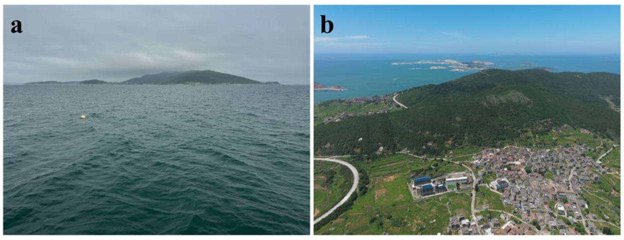

Figure 10. (a) Observing Cao Island while sailing in the north. (b) Gazing southward from the UAV, Cao is the final notable island before accessing the vast sea from the Haitan Strait.

Figure 11. (a) Dushi Fangyu Jiyao *讀史方輿紀*, essence of historical geography for reading. (b) Yue-Min Xunshi Jilve *粵閩巡視紀略*, record of Guangdong-Fujian inspection journey. (c) Wuxuan Ji *勿軒集*, a record of Xionghe's observations throughout the Song Dynasty.

3.3 Model 3: Reconstruction Movement on the Island

Data was collected at the island scale utilizing the DJI Mavic 3E drone for enhanced precision (Figure 12a). The Cao Island encompasses roughly 10 square kilometers, and researchers utilized a distributed mapping methodology to acquire oblique aerial pictures of the entire island. The data were further processed into 1:500 orthophotos (Figure 12b) and a DSM including a 1m x 1m grid resolution (Figure 12c).

In ArcGIS Pro, employing a 25% threshold for lowest-cost corridor and optimal path analysis revealed that, given identical mobility capabilities, the areas accessible after landing on the western portion of Cao Island (Figure 13b) are markedly nearer to the mountain summits, in conjunction with the existing residential zones (Figure 15). Comparing with historical aerial photos from 1978 (Figure 14b) suggests that this direction may have been one of the initial human habitation locations on Cao Island. Furthermore, a comparison of the simulated routes to the four docks on Cao Island (Figure 13) with Corona, Hexagon, and Landsat satellite imagery (Figure 14) revealed that from 1978 to 2013, numerous hiking paths on Cao Island were progressively abandoned, resulting in the retention of only the existing path ascending from the eastern side. It is conjectured that, on one hand, Cao Island experienced considerable modernization over the past 30 years, as evidenced by literature (Local Chronicles Compilation Committee in Pingtan County, Fujian Province, 2000). On the other hand, the existence of various early hiking paths suggests the presence of multiple ancient settlement sites at the mountain summits.

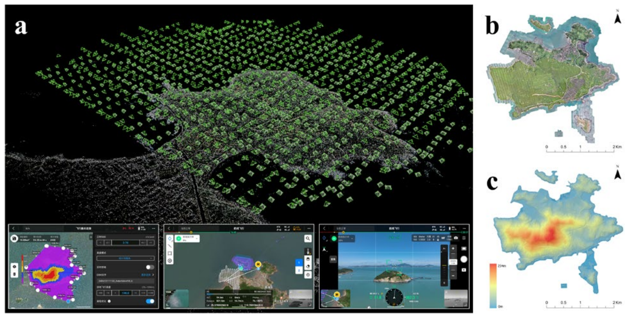

Figure 12. (a) RTK drones oblique photography. (b) Orthophotos. (c) Digital surface models.

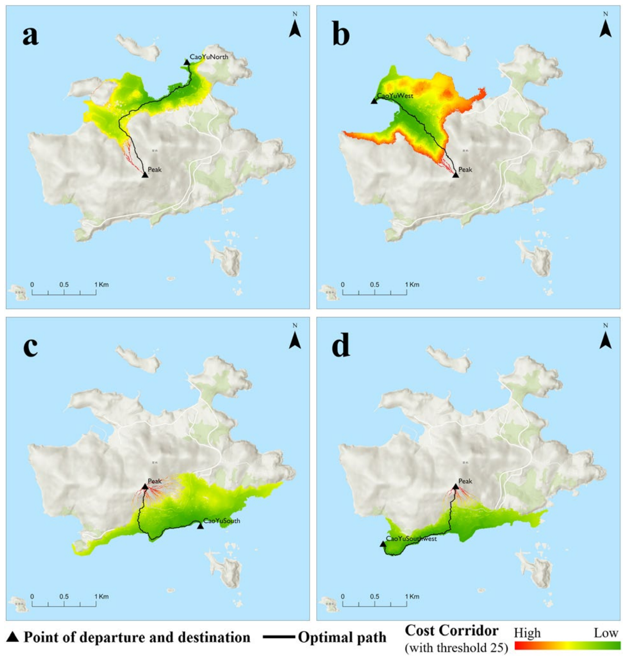

Figure 13. Ascents to mountain summits from various directions: from (a) north, (b) west, (c) south, and (d) southwest.

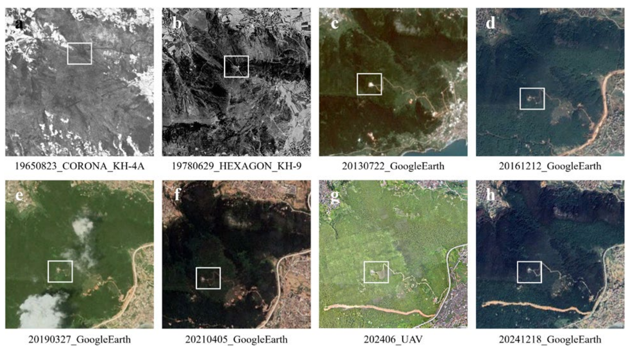

Figure 14. Comparison of climbing routes by period (white block indicates apex). (a-b) Keyhole series aerial photos (1965-1978) showing many hiking paths. (c-h) According to Google Earth and drone images (2013-2024), only one track remains.

Figure 15. Ancient buildings and docks in the west of the island.

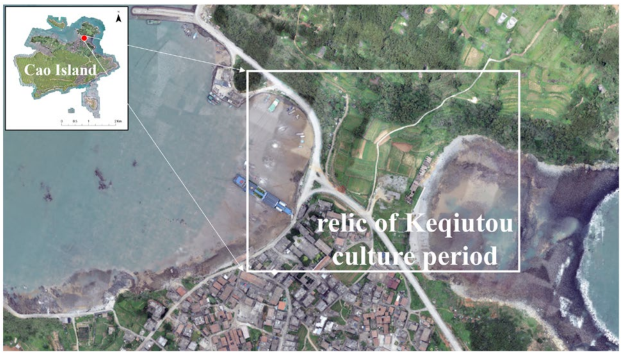

Figure 16. The area of the Keqiutou cultural relic was unraveled.

4. Discussion

4.1 Framework Efficacy

This methodological framework demonstrates initial success in addressing continuous spatial-scale variations, with conclusions substantiated by archaeological evidence. Currently in its foundational phase, the framework requires integration of additional behavioral factors (Gustas and Supernant, 2017; Kealy et al., 2018; Perttola, 2022; Gheorghiade and Spencer, 2024) to optimize functionality, which represents a key limitation for future refinement. Subsequent sections elaborate on these dimensions.

4.2 Framework Limitations

Model 1 is dominated by wind velocity and orientation. Simulation of marine motions requires a thorough study of wind, waves, and vessel conditions (Bellwood et al., 1995; Perttola, 2022), especially for Austronesian wind sail ships (Bellwood, 1979). Including extra parameters may help recreate authentic navigation conditions. This method will be considered in future framework updates.

In Model 2, the geography and tidal patterns of islands directly affect the choice of landing sites (Safadi, 2016). Despite the potential integration of erosion and deposition models, the reconstruction of past topography is problematic owing to a lack of credible data (Mehrer, 2005). Although the research employs contemporary nautical chart data to reconcile model validity with practicality, the examination of historical topographical alterations is a potential avenue for future development of the advanced framework.

In Model 3, this study utilizes historical photography and archaeological material to confirm the extent of human activity on the island, with quantitative analytic results predominantly corroborating archaeological findings. The validity of this alignment is insufficient. In the future, additional evaluations of on-site buildings, including docks, embankments, and subterranean burials, are essential to enhance the optimization of this model.

4.3 Extensible Framework's Future Goals

Current Applications: The framework has tackled inquiries about maritime archaeology. The research indicates that the Haitan Strait is likely one of the initial major routes for humans migrating from the southern coastal areas of Asia into the Taiwan Strait. Furthermore, Cao Island displays considerable visual prominence. The excavation of Keqiutou culture relics (Figure 16) by the Pingtan International Austronesian Research Institute (2019) further illustrates that Cao Island is not merely a significant juncture at the southern entrance of the Haitan Strait but also possesses considerable archaeological research and scholarly interest on a broader scale.

Prospective Utilizations: This framework aims to digitize and spatialize multidimensional information *spatial-non-spatial, cultural-natural, historical-present* to clarify maritime heritage significance. The comprehension of the ocean, its preservation, and the analysis of the human-ocean link are progressively significant subjects within the global academic community. Following UNESCO's proposal of *the Convention on the Protection of the Underwater Cultural Heritage* in 2001 (UNESCO, 2001), the initiation of the *Decade of Ocean plan* (UNESCO, 2021), the introduction of *the Actions* (UNESCO, 2024a), and the publication of a *White Paper* (UNESCO, 2024b), there has been an increasing focus on these matters. However, as of 2025, among the 50 ocean-related world heritage sites, only four are classified as mixed heritage sites, and none are cultural heritage sites (UNESCO, 2010, 1999, 1986, 2012, 2025). The comprehension of marine culture by humans remains considerably deficient. In light of this macro context, this study seeks to establish a framework that connects the humanities with marine environments to clarify the significance of marine cultural heritage.

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