NATIONAL TECHNICAL UNIVERSITY OF ATHENS
School of Rural, Surveying and Geoinformatics Engineering
Department of Infrastructure and Rural Development

GIS-Assisted Optimal Design of Maritime Transport Systems

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

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NATIONAL TECHNICAL UNIVERSITY OF ATHENS

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Βέλτιστος Σχεδιασμός Συστημάτων Θαλάσσιων Μεταφορών με Χρήση Μεθόδων GIS

ΓΙΑ ΤΗΝ ΑΠΟΚΤΗΣΗ ΔΙΔΑΚΤΟΡΙΚΟΥ ΔΙΠΛΩΜΑΤΟΣ

ΞΕΝΟΦΩΝ ΟΡΦΕΑΣ ΚΑΡΟΥΝΤΖΟΣ

ΣΥΓΚΟΙΝΩΝΙΟΛΟΓΟΣ ΜΗΧΑΝΙΚΟΣ, M.Sc.

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ΤΡΙΜΕΛΗΣ ΣΥΜΒΟΥΛΕΥΤΙΚΗ ΕΠΙΤΡΟΠΗ

1. Κεπαπτσόγλου Κωνσταντίνος, Αν. Καθηγητής ΕΜΠ
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O.K.

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ABSTRACT

The adverse environmental impacts of fossil fuels in the shipping industry call for a shift towards more sustainable maritime transport models and overall decarbonization. In order to address this issue, environmental impacts associated with the operation of maritime networks must be considered in their design and planning processes, while also aiming to address several inequalities, such as accessibility, cohesion, and connectivity of every component of the network. As maritime networks show high complexities and intricate topological characteristics, advances in spatial data analytics and the use of geospatial methods call for the development of a new spatial decision support system (SDSS) to assist in network design. In this context, the scope of this dissertation is to develop a versatile and easily adaptable Geographical Information Systems based (GIS-based) methodological framework based on spatial data sccience models and techniques for evaluating, planning, and restructuring existing maritime networks, exploiting recent technological advances in fully electric zero-emission ferries. Specific objectives of the dissertation include: a) the development of a comprehensive methodological framework for emissions monitoring and environmental evaluation of a maritime network, along with the identification of areas of high CO_2 emissions for the implementation of emissions mitigation strategies, b) the development of a methodological framework for the redesign of existing networks, integrating the establishment of zero-emission routes in the design process of maritime networks, c) the development of efficiency indices for network ports in combination with a Slacks Based Measure Data Envelopment Analysis (SBM-DEA) model for the evaluation of ports and areas where targeted interventions for improvement are needed. The proposed framework is applied in the Greek Coastal Shipping Network, with emissions mitigation performance of the newly proposed network compared with conventional slow steaming strategies. Lastly, the newly proposed network is compared to the existing one, considering environmental, accessibility, and social cohesion aspects.

Keywords: Maritime Transport, Zero-Emission Maritime Networks, Electric Maritime Transport, Spatial Data Analytics, Geographical Information Systems (GIS), Spatial Decision Support System (SDSS)

ΠΕΡΙΛΗΨΗ

Οι δυσμενείς περιβαλλοντικές επιπτώσεις των ορυκτών καυσίμων στη ναυτιλία απαιτούν τη στροφή προς πιο βιώσιμα μοντέλα θαλάσσιων μεταφορών για απανθρακοποίηση. Ως προς αυτό, οι περιβαλλοντικές επιπτώσεις από τη λειτουργία ναυτιλιακών δικτύων πρέπει να λαμβάνονται υπόψη στις διαδικασίες σχεδιασμού τους, ενώ παράλληλα απαραίτητη είναι η αντιμετώπιση διαφόρων ανισοτήτων, όπως η προσβασιμότητα, η συνοχή και η συνδεσιμότητα κάθε στοιχείου του δικτύου. Καθώς τα ναυτιλιακά δίκτυα παρουσιάζουν υψηλή πολυπλοκότητα και περίπλοκα τοπολογικά χαρακτηριστικά, η ανάπτυξη ενός νέου χωρικά σχετιζόμενου συστήματος υποστήριξης αποφάσεων (SDSS) για την υποβοήθηση του σχεδιασμού των δικτύων είναι απαραίτητη, βάσει των εξελίξεων στην ανάλυση χωρικών δεδομένων και η χρήση γεωχωρικών μεθόδων. Το αντικείμενο της παρούσας διατριβής είναι η ανάπτυξη ενός ευέλικτου και εύκολα προσαρμόσιμου μεθοδολογικού πλαισίου βασισμένου σε Συστήματα Γεωγραφικών Πληροφοριών (ΣΓΠ), μοντέλα και τεχνικές ανάλυσης χωρικών δεδομένων για την αξιολόγηση, το σχεδιασμό και την αναδιάρθρωση υφιστάμενων ναυτιλιακών δικτύων, αξιοποιώντας τις πρόσφατες τεχνολογικές εξελίξεις στα πλήρως ηλεκτρικά πλοία μηδενικών εκπομπών. Οι ειδικοί στόχοι της διατριβής περιλαμβάνουν: α) την ανάπτυξη ενός ολοκληρωμένου μεθοδολογικού πλαισίου για την παρακολούθηση των εκπομπών και την περιβαλλοντική αξιολόγηση ενός ναυτιλιακού δικτύου, καθώς και τον εντοπισμό περιοχών υψηλών εκπομπών αερίων CO_2 για την εφαρμογή στοχευμένων παρεμβάσεων, β) την ανάπτυξη ενός μεθοδολογικού πλαισίου για τον επανασχεδιασμό των υφιστάμενων δικτύων, ενσωματώνοντας διαδρομές μηδενικών ρύπων, γ) την ανάπτυξη νέων δεικτών αποδοτικότητας για τους λιμένες του δικτύου σε συνδυασμό με ένα μοντέλο Περιβάλλουσας Ανάλυσης Δεδομένων λαμβάνοντας υπόψη περιθώρια χαλάρωσης (SBM-DEA) για την αξιολόγηση των λιμένων προς στοχευμένες παρεμβάσεις για βελτίωση. Το προτεινόμενο μεθοδολογικό πλαίσιο εφαρμόζεται στο ελληνικό ακτοπλοϊκό δίκτυο, συγκρίνοντας τα περιβαλλοντικά του οφέλη με συμβατικές στρατηγικές μείωσης ταχύτητας, ενώ επίσης συγκρίνεται με το υφιστάμενο δίκτυο, λαμβάνοντας υπόψη περιβαλλοντικούς παράγοντες, την προσβασιμότητα και κοινωνικής συνοχή του δικτύου.

Λέξεις κλειδιά: Θαλάσσιες μεταφορές, Ναυτιλιακά Δίκτυα Μηδενικών Ρύπων, Θαλάσσιες Μεταφορές υπό Ηλεκτροκίνηση, Ανάλυση Χωρικών Δεδομένων, Γεωγραφικά Συστήματα Πληροφοριών (GIS), Σύστημα Υποστήριξης Χωρικών Αποφάσεων (SDSS)

ΕΚΤΕΤΑΜΕΝΗ ΠΕΡΙΛΗΨΗ

Αντικείμενο έρευνας

Οι δυσμενείς επιπτώσεις των ορυκτών καυσίμων στο περιβάλλον και τη δημόσια υγεία απαιτούν στοχευμένες δράσεις και την προσαρμογή των σύγχρονων μεταφορών στα περιβαλλοντικά πρότυπα βιωσιμότητας. Υπό αυτό το πρίσμα, η ναυτιλία επίσης στοχεύει στην επίτευξη συγκεκριμένων περιβαλλοντικών στόχων, όπως αυτοί έχουν οριστεί από τον Διεθνή Ναυτιλιακό Οργανισμό (International Maritime Organization – IMO). Έτσι, η βιωσιμότητα των ναυτιλιακών δραστηριοτήτων κερδίζει όλο και περισσότερο το ενδιαφέρον, με τον τομέα της ναυτιλίας να εστιάζει στις προσπάθειες απαλλαγής από εκπομπές αερίων του θερμοκηπίου. Καθ' όλη τη διάρκεια των ετών, οι ερευνητές έχουν εξετάσει διάφορες λύσεις με στόχο την απανθρακοποίηση του ναυτιλιακού τομέα για την βελτίωση του περιβαλλοντικού αποτυπώματος των θαλάσσιων δικτύων, με τα εναλλακτικά καύσιμα να αποτελούν μια εκ των πλέον πολυσυζητημένων λύσεων προς την επίτευξη των περιβαλλοντικών στόχων του IMO. Ωστόσο, άλλες στρατηγικές έχουν επίσης εφαρμοστεί με επιτυχία, κυρίως σε εμπορευματικές μεταφορές, όπως η μείωση της ταχύτητας των πλοίων, επιτυγχάνοντας τόσο οικονομικά, όσο και περιβαλλοντικά οφέλη. Ακόμη, τα τελευταία χρόνια, όπως σε όλους τους τομείς μεταφορών έτσι και στην ναυτιλία, οι ερευνητές εστιάζουν το ενδιαφέρον τους και στο αντικείμενο της ηλεκτροκίνησης, με συγκεκριμένες περιπτώσεις εφαρμογής ηλεκτρικών πλοίων να παρουσιάζουν μεγάλο ενδιαφέρον, κυρίως σε πολυνησιακά κράτη όπως οι Σκανδιναβικές χώρες. Ωστόσο, η ομαλή μετάβαση της ναυτιλίας στην ηλεκτροκίνηση δεν μπορεί να γίνει μη λαμβάνοντας υπόψιν συγκεκριμένους τεχνολογικούς παράγοντες, όπως οι υπάρχουσες τεχνολογίες και οι συνολικές δυνατότητες των αμιγώς ηλεκτρικών πλοίων, κυρίως σε ζητήματα του λειτουργικού τους εύρους. Ιδιαίτερη σημασία δίνεται στο γεγονός πως η εφαρμογή ηλεκτροκίνητων πλοίων, τουλάχιστον κατά τον χρόνο συγγραφής της παρούσας διατριβής, γίνεται αποκλειστικά σε δρομολόγια μικρού μήκους, εντός οριοθετημένων υδάτινων συστημάτων, καθώς και σε πολυνησιακά συμπλέγματα με συνδέσεις μικρών αποστάσεων μεταξύ των λιμένων. Σύμφωνα με τα παραπάνω, καθίσταται σαφές πως η εφαρμογή ηλεκτροκίνητων πλοίων, έως σήμερα, δύναται να γίνει στην πλειοψηφία της σε ναυτιλιακά δίκτυα μικρών αποστάσεων, καθώς και σε περιπτώσεις όπου η πολυπλοκότητα του δικτύου επιτρέπει την εισαγωγή δρομολογίων αμιγώς ηλεκτρικών πλοίων. Λόγω του ότι η πολυπλοκότητα του δικτύου αποτελεί μια παράμετρο που απαιτεί την εξέταση των ιδιόμορφων χαρακτηριστικών του σε χωρικό επίπεδο, η ανάλυση και ο σχεδιασμός των δικτύων αυτών, με σκοπό την αξιοποίηση των σχετικών τεχνολογιών, πρέπει να γίνεται σύμφωνα με την υλοποίηση ενός χωρικά συσχετιζόμενου συστήματος υποστήριξης αποφάσεων ή Συστήματος Υποστήριξης Χωρικών Αποφάσεων (Spatial Decision Support System – SDSS).

Ενώ υπάρχουν αρκετές μελέτες που ενσωματώνουν την ανάλυση χωρικών δεδομένων και εφαρμογές βασισμένες στα Γεωγραφικά Συστήματα Πληροφοριών – ΓΣΠ (Geographic Information Systems – GIS) για την αξιολόγηση διαφόρων πτυχών των θαλάσσιων μεταφορών, όπως οι εκπομπές ή η συνολική ασφάλεια, δεν έχουν υπάρξει σχεδόν καθόλου μελέτες που να χρησιμοποιούν μεθόδους ανάλυσης χωρικών δεδομένων στις διαδικασίες σχεδιασμού ενός δικτύου θαλάσσιων μεταφορών. Ειδικά όταν εξετάζεται η συμπερίληψη πλήρως ηλεκτρικών οχηματαγωγών πλοίων σε ένα ναυτιλιακό δίκτυο για τον σχεδιασμό δρομολογίων μηδενικών εκπομπών, έως τον χρόνο συγγραφής της παρούσας διατριβής, αυτή είναι η μόνη μελέτη που εξετάζει τον σχεδιασμό περιβαλλοντικά βιώσιμων ναυτιλιακών δικτύων μέσω της χρήσης μοντέλων βασισμένων σε ΓΣΠ και μεθόδων ανάλυσης χωρικών δεδομένων.

Σε αυτό το πλαίσιο, το αντικείμενο της παρούσας διατριβής είναι η διερεύνηση και εφαρμογή μεθόδων χωρικής ανάλυσης για τον σχεδιασμό ναυτιλιακών δικτύων στο πλαίσιο της μετάβασής τους στην ηλεκτροκίνηση. Ειδικοί στόχοι της διδακτορικής διατριβής αποτελούν:

- η ανάπτυξη ενός ολοκληρωμένου μεθοδολογικού πλαισίου για την παρακολούθηση των εκπομπών και την περιβαλλοντική αξιολόγηση ενός ναυτιλιακού δικτύου, καθώς και τον εντοπισμό περιοχών με υψηλές συγκεντρώσεις εκπεμπόμενων αερίων θερμοκηπίου για την εφαρμογή στοχευμένων παρεμβάσεων,

- η ανάπτυξη ενός μεθοδολογικού πλαισίου για τον επανασχεδιασμό των υφιστάμενων δικτύων, ενσωματώνοντας διαδρομές μηδενικών ρύπων με αμιγώς ηλεκτροκίνητα πλοία,
- η ανάπτυξη νέων δεικτών αποδοτικότητας για τους λιμένες του δικτύου σε συνδυασμό με ένα μοντέλο Περιβάλλουσας Ανάλυσης Δεδομένων λαμβάνοντας υπόψη περιθώρια χαλάρωσης (SBM-DEA) για την αξιολόγηση των λιμένων με σκοπό την διενέργεια μελλοντικών στοχευμένων παρεμβάσεων για περαιτέρω βελτίωση.

Μεθοδολογικό Πλαίσιο

Κύριος στόχος της παρούσας διατριβής είναι η ανάπτυξη ενός ολοκληρωμένου συστήματος υποστήριξης χωρικών αποφάσεων για τον σχεδιασμό δικτύων θαλάσσιων μεταφορών με την εισαγωγή διαδρομών μηδενικών εκπομπών, με προσανατολισμό στην ενεργειακή αποδοτικότητα και τη βιωσιμότητα μέσω της εκμετάλλευσης της ηλεκτροκίνησης. Η επιτυχής και ομαλή ενσωμάτωση αμιγώς ηλεκτροκίνητων πλοίων σε ένα ναυτιλιακό δίκτυο πρέπει απαραίτητα να λαμβάνει υπόψιν τις ιδιαιτερότητες, τους περιορισμούς και τις ενεργειακές απαιτήσεις αυτών των πλοίων, ενώ από πλευράς δικτύου είναι απαραίτητο να εξετάζονται οι ιδιομορφίες και η πολυπλοκότητά του. Σύμφωνα με αυτά, το πρόβλημα του σχεδιασμού αυτών των δικτύων εξετάζεται στην παρούσα διατριβή ως ένα χωρικά πολύπλοκο πρόβλημα με συγκεκριμένους στόχους, σημαντικότερος εκ των οποίων είναι η μείωση του περιβαλλοντικού αποτυπώματος του υπό εξέταση δικτύου. Επιπροσθέτως, επιμέρους στόχοι της διατριβής είναι η διατήρηση ή βελτίωση του παρεχόμενου επιπέδου υπηρεσιών προς τους επιβάτες, με την διατήρηση ή βελτίωση των χρόνων διαδρομής από την ενδοχώρα προς τους νησιωτικούς προορισμούς του δικτύου, ενώ επίσης απαραίτητη προϋπόθεση είναι η επίτευξη καλύτερης συνδεσιμότητας μεταξύ όλων των λιμένων του δικτύου επιτυγχάνοντας περισσότερες συνδέσεις μεταξύ των λιμένων του δικτύου, με στόχο την βελτίωση της προσβασιμότητας και της κοινωνικής συνοχής.

Αρχικά, στην παρούσα διατριβή εφαρμόζονται μέθοδοι και μοντέλα χωρικής ανάλυσης για τον εντοπισμό περιοχών με υψηλές συγκεντρώσεις εκπομπών CO_2. Οι περιοχές που εξετάστηκαν παρουσιάζουν υψηλές συγκεντρώσεις κυρίως λόγω χαμηλής ενεργειακής αποδοτικότητας των πλοίων, καθώς και λόγω δημιουργίας υψηλής κίνησης μη αποδοτικών πλοίων σε συγκεκριμένες περιοχές του δικτύου όπως προκύπτει από τον συνολικό σχεδιασμό των δρομολογίων, με αποτέλεσμα την περιβαλλοντική επιβάρυνσή τους. Μέσω της χρήσης διαφόρων μεθόδων, όπως αυτές που εφαρμόστηκαν στην παρούσα μελέτη, είναι δυνατόν να εντοπιστούν περιοχές με υψηλές συγκεντρώσεις εκπομπών CO_2, με τον εντοπισμό αυτό να αποτελεί κομβικό σημείο για τη στοχευμένη και αποτελεσματική εφαρμογή διαφόρων στρατηγικών μείωσης εκπομπών αερίων θερμοκηπίου, όπως η μείωση της ταχύτητας στα πλοία (slow steaming). Τα αρχικά ευρήματα δείχνουν ότι η παρούσα στρατηγική έχει δυνατότητες και παράγει ενθαρρυντικά αποτελέσματα, ωστόσο η χρήση της ως μοναδικού μέτρου για τη μείωση των εκπομπών CO_2 μπορεί να μειώσει το ποσοστό εκπομπών μόνο σταδιακά, ιδίως όταν εφαρμόζεται αποκλειστικά σε αυτές τις συγκεκριμένες περιοχές υψηλών συγκεντρώσεων. Ενώ υπάρχει η δυνατότητα να μειωθεί η ταχύτητα του στόλου σε ολόκληρο το δίκτυο για καλύτερα αποτελέσματα όσον αφορά τις εκπομπές αερίων του θερμοκηπίου, τα αποτελέσματα δείχνουν ότι δεν μπορεί να θεωρηθεί βιώσιμη επιλογή, λόγω των μεγαλύτερων καθυστερήσεων στους χρόνους ταξιδιού των επιβατών. Κατά συνέπεια, μια τέτοια πιο «επιθετική» στρατηγική θα απαιτούσε από τους επιβάτες να ανεχθούν σημαντικά αυξημένες χρονικές καθυστερήσεις, γεγονός που, στο πλαίσιο της εγχώριας επιβατηγού ναυτιλίας, αποτελεί μη ρεαλιστική επιλογή, καθώς δημιουργεί διάφορα ζητήματα προσβασιμότητας. Μέσω της εφαρμογής και των δύο στρατηγικών στοχευμένα σε συγκεκριμένες περιοχές υψηλών εκπομπών CO_2 που παρουσιάζονται στην παρούσα διατριβή, καθίσταται προφανές ότι το ελληνικό ακτοπλοϊκό δίκτυο απαιτεί ουσιαστικές βελτιώσεις όσον αφορά το περιβαλλοντικό αποτύπωμα και την αποδοτικότητα του στόλου του, καθώς αξίζει να σημειωθεί πως ο στόλος είναι γερασμένος και περιλαμβάνει περιβαλλοντικά μη αποδοτικά πλοία, με ορισμένα από αυτά να βρίσκονται σε λειτουργία για περισσότερα από 25 χρόνια.

Έτσι, στην παρούσα διατριβή εξετάζεται κατά πόσο είναι εφικτή η εισαγωγή ηλεκτροκίνητων πλοίων μηδενικών ρύπων σε συγκεκριμένες περιοχές του δικτύου. Καθώς αντιμετωπίζεται ένα πρόβλημα με σημαντικές χωρικές ιδιομορφίες που συνδέονται με περιβαλλοντικές πτυχές, χρησιμοποιήθηκαν μέθοδοι χωρικής ανάλυσης, όπως το πολυμεταβλητά μοντέλα Τοπικών Δεικτών Χωρικής Αυτοσυσχέτισης (Local Indicators of Spatial Association – LISA) για τα προκαταρκτικά αποτελέσματα. Τα θετικά αποτελέσματα από το εν λόγω μοντέλο αναδεικνύουν τις δυνατότητες για τη μετάβαση του ελληνικού ακτοπλοϊκού δικτύου προς την ηλεκτροκίνηση και, ως εκ τούτου, τον μετριασμό των εκπομπών. Επιπλέον, αξιολογούνται οι υφιστάμενες υποδομές για τις Ανανεώσιμες Πηγές Ενέργειας (ΑΠΕ) και οι δυνατότητες του δικτύου για μελλοντική ενεργειακή εκμετάλλευση. Στόχος είναι να αξιολογηθεί κατά πόσον οι περιοχές που εντοπίστηκαν θα μπορούσαν να αξιοποιήσουν τις εγκαταστάσεις ΑΠΕ για την κάλυψη των ενεργειακών τους αναγκών, σε σχέση με τους διαθέσιμους πόρους στις υπό εξέταση περιοχές. Η μεθοδολογία που προτείνεται στο πλαίσιο της παρούσας έρευνας δείχνει ότι μπορούν να επιτευχθούν εξαιρετικά ακριβή αποτελέσματα λαμβάνοντας υπόψη τόσο τα χωρικά όσο και τα μη χωρικά χαρακτηριστικά τέτοιων χωρικά περίπλοκων δικτύων, με θετικά αποτελέσματα ως προς τις ενεργειακές δυνατότητες του δικτύου σχετικά με την εκμετάλλευση ΑΠΕ. Επιπλέον, το μεθοδολογικό πλαίσιο επιδιώκει να προσφέρει ένα εύκολα προσαρμόσιμο μοντέλο που μπορεί να εφαρμοστεί σε άλλα σενάρια με διαφορετικές παραμέτρους, ανάλογα την κάθε περίπτωση του δικτύου που εξετάζεται. Τα ευρήματα της έρευνας παρουσιάζουν δυνατότητες σε διάφορους τομείς, συμπεριλαμβανομένης της εφαρμογής υπό-δικτύων μηδενικών εκπομπών ρύπων μέσω της εισαγωγής πορθμείων (hubs) , από όπου δύνανται να λειτουργούν ηλεκτροκίνητα πλοία τα οποία θα εξυπηρετούν τις αναγνωρισμένες διαδρομές που προκύπτουν από την εφαρμογή του σχετικού μεθοδολογικού πλαισίου. Περισσότεροι από ένας λιμένες αναδείχθηκαν ως βιώσιμοι κόμβοι, ενώ οι δυνατότητες των εντοπισμένων περιοχών για αξιοποίηση των ΑΠΕ είναι επίσης υποσχόμενες. Εκτός από τα παραπάνω προκαταρκτικά αποτελέσματα, η δημιουργία βέλτιστων διαδρομών μεταξύ των εντοπισμένων λιμένων κόμβων και λιμένων που θα εξυπηρετούνται από ηλεκτροκίνητα πλοία είναι μεγάλης σημασίας για την μετέπειτα συνολική αναδιάρθρωση του δικτύου.

Κατόπιν των θετικών αποτελεσμάτων που προέκυψαν κατά την προκαταρκτική ανάλυση σκοπιμότητας, ως προς το εάν είναι εφικτή η εισαγωγή υπό-δικτύων μηδενικών ρύπων στο υπό εξέταση ναυτιλιακό δίκτυο, εξετάζεται η συνολική αναδιάρθρωση του δικτύου. Το προτεινόμενο μεθοδολογικό πλαίσιο παρέχει μια ολιστική και ευέλικτη προσέγγιση για την υποστήριξη των διαδικασιών λήψης αποφάσεων κατά το σχεδιασμό ενός δικτύου που ενσωματώνει διαδρομές μηδενικών εκπομπών. Η συνολική προσέγγιση του δικτύου είναι απλοϊκή και προσαρμόζεται εύκολα σε οποιοδήποτε δεδομένο δίκτυο υψηλής πολυπλοκότητας και χωρικής ιδιομορφιών. Μια σύνοψη του προτεινόμενου μεθοδολογικού πλαισίου, το οποίο ακολουθεί την προσέγγιση "cluster first-route second" για τον εντοπισμό των σχετικών ιεραρχιών των λιμένων στο σύνολο του δικτύου και την αναγνώριση συγκεκριμένων συστάδων (clusters), με κύρια σημεία ως εξής:

1. Εντοπισμός των αρχικών υπό-δικτύων μηδενικών εκπομπών μέσω της χρήσης της διμεταβλητού μοντέλου LISA, όπως περιγράφεται αναλυτικά στο κεφάλαιο 4 της διατριβής.
2. Προσδιορισμός ιεραρχιών λιμένων με βάση την επιβατική κίνηση και την ύπαρξη μεγαλύτερων λιμένων σε κοντινή απόσταση για την ανάθεση μικρότερης χωρητικότητας ηλεκτροκίνητων πλοίων για μελλοντικές διαδρομές μηδενικών ρύπων. Σε αυτό το πλαίσιο, λιγότερο «δημοφιλή» νησιά με χαμηλότερη ζήτηση επιβατών παρουσιάζουν υψηλότερες πιθανότητες να γίνουν προορισμοί που θα εξυπηρετούνται εξ ολοκλήρου μέσω ηλεκτροκίνητων πλοίων. Η λογική πίσω από αυτή την προσέγγιση είναι αρκετά απλή και μπορεί να συνοψιστεί στο γεγονός ότι, εάν ένας λιμένας είναι αναποτελεσματικός όσον αφορά τις επιθυμητές εκροές του (που είναι η συνολική εξυπηρέτηση επιβατών και η αξιοποίηση της χωρητικότητας των πλοίων που εκτελούν τις σχετικές διαδρομές), πρέπει να πετύχει υψηλότερη βαθμολογία στους περιβαλλοντικούς του στόχους μειώνοντας το αποτύπωμά του, προκειμένου να εξισορροπήσει την αναποτελεσματικότητα της ροής επιβατών του. Έτσι, τέτοια λιμάνια επιλέγονται ως αρχικοί υποψήφιοι για να συνδεθούν αποκλειστικά με άλλα νησιά μέσω δρομολογίων μηδενικών εκπομπών και ηλεκτρικών πλοίων.
3. Φιλτράρισμα της υπάρχουσας βάσης δεδομένων. Μετά την ολοκλήρωση των βημάτων 1 & 2, το σύνολο των υπό εξέταση δεδομένων αρχίζει να μειώνεται στη συνέχεια σε μέγεθος, ενώ επαναλαμβάνονται τα παραπάνω βήματα μέχρι το απαραίτητο επίπεδο που επιθυμείται από του υπεύθυνους λήψης αποφάσεων. Αξίζει να σημειωθεί ότι

διαφορετικά δίκτυα έχουν διαφορετικές ανάγκες μείωσης του περιβαλλοντικού τους αποτυπώματος και, ως αποτέλεσμα, η συνολική "ευαισθησία", η οποία δείχνει το επίπεδο μείωσης των εκπομπών CO_2 που πρέπει να επιτευχθεί, ενδέχεται να διαφέρει μεταξύ των διαφόρων δικτύων, ενώ διάφοροι άλλοι παράγοντες μπορούν επίσης να επηρεάσουν τη συνολική διαδικασία λήψης αποφάσεων. Στην περίπτωσή μας, κατά τη στιγμή της συγγραφής του παρόντος, οι τεχνολογίες ηλεκτρικών πλοίων είναι ακόμη αρκετά νέες με συγκεκριμένα όρια στις λειτουργικές ταχύτητες των πλοίων, επομένως μόνο τα λιγότερο δημοφιλή νησιά θα ληφθούν υπόψη στη διαδικασία του σχεδιασμού του δικτύου, έτσι ώστε να επηρεαστούν λιγότεροι επιβάτες από τις αλλαγές στους χρόνους ταξιδιού και τις μεταφορές μεταξύ πλοίων στους λιμένες διαμεταφοράς (hubs).

4. Ομαδοποίηση με βάση την πυκνότητα στα υπόλοιπα λιμάνια του συνόλου δεδομένων. Στην περίπτωση της παρούσας διατριβής, επιλέχθηκε μια μέθοδος αυτορρυθμιζόμενης ομαδοποίησης (HDBSCAN). Όπως περιγράφεται στην συνέχεια, με την HDBSCAN χρησιμοποιούνται μεταβαλλόμενες αποστάσεις για τον διαχωρισμό συστάδων διαφορετικής πυκνότητας από τον αραιότερο θόρυβο, καθιστώντας την HDBSCAN την πλέον βασιζόμενη στα δεδομένα μέθοδο συσταδοποίησης, απαιτώντας έτσι τη μικρότερη παρέμβαση από τον χρήστη, καθώς απαιτεί μόνο τα ελάχιστα χαρακτηριστικά ανά συστάδα. Στην παρούσα διατριβή, οι ελάχιστοι λιμένες ανά συστάδα που εξετάστηκαν ήταν 2. Επιπλέον, οι λιμένες που χαρακτηρίζονται ως "θόρυβος" μετά από τη μέθοδο συσταδοποίησης (δηλαδή οι λιμένες που δεν ανήκουν σε συγκεκριμένη συστάδα) πρέπει να αντιστοιχίζονται σε μια άλλη, η οποία σε αυτή την περίπτωση επιλέγεται ως η συστάδα με τον λιμένα που βρίσκεται πλησιέστερα σε αυτές.
5. Το βήμα 4 οδηγεί σε διαφορετικές συστάδες στο δίκτυο, με διαφορετικές διαδρομές που πρέπει να αντιστοιχηθούν σε κεντρικούς λιμένες διαμεταφοράς (hubs) για τις ανάγκες εξυπηρέτησής τους. Σύμφωνα με αυτό, προτείνονται οι βέλτιστες συνδέσεις για κάθε λιμένα κάθε συστάδας μεταξύ τους και με την ηπειρωτική χώρα.

6. Για την παροχή καλύτερης συνδεσιμότητας μεταξύ κάθε συστάδας του δικτύου, λαμβάνεται υπόψη ένας ακόμη περιορισμός, ο οποίος είναι ότι κάθε συστάδα πρέπει να συνδέεται με κάθε άλλη συστάδα, με τουλάχιστον ένα λιμάνι της συστάδας Α να παρέχει σύνδεση με ένα άλλο (τουλάχιστον) λιμάνι της συστάδας Β. Ο σχετικός περιορισμός λαμβάνεται υπόψιν τόσο για λόγους επίτευξης καλύτερης συνδεσιμότητας, όσο και για λόγους τήρησης του παρόντος νομοθετικού πλαισίου, όπως ισχύει στην περίπτωση του ελληνικού ακτοπλοϊκού δικτύου. Σε αυτή την περίπτωση, η εγγύτητα είναι ο πρώτος και σημαντικότερος παράγοντας που πρέπει να ληφθεί υπόψη, καθώς στόχος είναι η παροχή διασυνδέσεων μεταξύ των συστάδων με βάση τις συντομότερες δυνατές συνδέσεις μεταξύ τους, με τις επόμενες συνδέσεις να σχεδιάζονται για αμιγώς ηλεκτρικά οχηματαγωγά πλοία, όπου είναι δυνατόν.

Η εφαρμογή του παρόντος μεθοδολογικού πλαισίου οδηγεί στην συνολική αναδιάρθρωση του ελληνικού ακτοπλοϊκού δικτύου, με αρκετούς λιμένες πλέον να συνδέονται αποκλειστικά με αμιγώς ηλεκτροκίνητα πλοίων μηδενικών ρύπων. Το προτεινόμενο πλαίσιο εστιάζει κατά βάση στη δημιουργία και την επακόλουθη αξιολόγηση των διαδρομών μηδενικών εκπομπών στα λιμάνια του δικτύου, τα οποία προκύπτει πως βελτιώνουν σημαντικά τη συνολική αποδοτικότητα των λιμένων, ιδίως όσον αφορά την περιβαλλοντική αποδοτικότητα. Ειδικότερα, ακόμα και σε περιπτώσεις όπου η αποδοτικότητα ως προς την συνολική συνδεσιμότητα των λιμένων μπορεί να μειώνεται, λόγω της αποκλειστικής σύνδεσης με αμιγώς ηλεκτροκίνητα πλοία μηδενικών ρύπων, τα αποτελέσματα αποδεικνύουν πως επιτυγχάνεται σημαντική βελτίωση ως προς την συνολική αποδοτικότητα των λιμένων μέσω της αναδιάρθρωσης του δικτύου. Επιπλέον, τα αποτελέσματα της παρούσας διατριβής τονίζουν ιδιαίτερα την ανάγκη για την ενίσχυση της αποδοτικότητας των λιμένων ως προς την εξυπηρετούμενη επιβατική κίνηση, μέσω της βέλτιστης αξιοποίησης της χωρητικότητας του στόλου, στοχεύοντας στην εξυπηρέτηση όσο το δυνατόν μεγαλύτερου αριθμού επιβατών ανά δρομολόγιο σε κάθε λιμάνι. Ως συνέπεια, λαμβάνοντας υπόψιν την αυξημένη περιβαλλοντική αποδοτικότητα λόγω της μείωσης των εκπομπών CO_2 σε σχέση με τον όγκο των μεταφορών, καθώς και την αύξηση της αποδοτικότητας ως προς την εξυπηρετούμενη επιβατική κίνηση, καθίσταται επίσης εφικτή η μείωση του περιβαλλοντικού αποτυπώματος ανά επιβάτη και διανυθείσα απόσταση.

Από την εφαρμογή του σχετικού μεθοδολογικού πλαισίου καθίσταται σαφές πως υπάρχουν σημαντικές δυνατότητες για τη βελτίωση όχι μόνο της περιβαλλοντικής αποδοτικότητας όλων των λιμανιών που εξετάζονται στην παρούσα διατριβή, αλλά και της συνολικής τους αποδοτικότητας, λαμβάνοντας υπόψιν παράγοντες επιβατικής κίνησης, ενεργειακής βιωσιμότητας και συνδεσιμότητάς τους. Ωστόσο, ενώ η αύξηση της συνολικής αποδοτικότητας των λιμένων χρησιμοποιώντας τους προτεινόμενους δείκτες που παρουσιάζονται στην παρούσα διατριβή είναι ενθαρρυντική, είναι απαραίτητο να συγκριθούν οι προτεινόμενοι δείκτες σε συνδυασμό με τη σχετική αποδοτικότητα των λιμανιών μεταξύ τους, μέσω της χρήσης του αναπτυγμένου μοντέλου SBM-DEA. Ωστόσο, ιδιαίτερη προσοχή δίνεται στην ερμηνεία των αποτελεσμάτων λόγω του γεγονότος πως με την παρούσα μέθοδο, μικρότερα λιμάνια χαμηλότερης ζήτησης προκύπτουν να βρίσκονται σε μειονεκτική θέση όταν συγκρίνονται με μεγαλύτερα λιμάνια υψηλότερης ζήτησης και αυξημένων δυνατοτήτων. Συνεπώς, κατά την εφαρμογή του προτεινόμενου μεθοδολογικού πλαισίου, τα αποτελέσματα από το μοντέλο SBM-DEA κρίνεται απαραίτητο να αναλυθούν και να εξεταστούν σε συνδυασμό με τους προτεινόμενους δείκτες αποδοτικότητας, ώστε να δίνεται μια πιο ολοκληρωμένη εικόνα της απόδοσης των υπό εξέταση λιμένων.

Τα αποτελέσματα και από τις δύο τις προτεινόμενες μεθόδους επιβεβαιώνουν τη σημασία της συνολικής συνδεσιμότητας των λιμένων, ιδίως για τα νησιά με πολλαπλές συνδέσεις και διαδρομές. Η αρχική υπόθεση, σχετικά με το ότι η ελαχιστοποίηση των εκπομπών CO_2 είναι ουσιαστική για τη συνολική αποδοτικότητα των λιμανιών επιβεβαιώνεται, ενώ ειδικά στα δίκτυα επιβατών, η βελτίωση τόσο της συνολικής συνδεσιμότητας όσο και η δημιουργία δικτύων μηδενικών εκπομπών μπορεί να αυξήσει τη συνολική αποδοτικότητα των λιμένων. Ωστόσο, είναι σημαντικό να σημειωθεί ότι, ενώ το μοντέλο SBM-DEA θα ωφελούσε κυρίως τα μεγάλα λιμάνια με υψηλότερη ζήτηση που είναι καλύτερα σε θέση να συνδυάσουν και αυτά τα δύο στοιχεία, τα αποτελέσματα έδειξαν επίσης σημαντικές βελτιώσεις στα μικρότερα λιμάνια χαμηλότερης ζήτησης κατά την σύνδεσή τους με δρομολόγια μηδενικών ρύπων, καθώς του μοντέλου υλοποιείται με τέτοιον τρόπο ώστε να είναι κυρίως βασισμένο στην περιβαλλοντική αποδοτικότητα. Ωστόσο, όπως προαναφέρθηκε, τέτοια μοντέλα και τα αντίστοιχα αποτελέσματά τους πρέπει πάντα να ερμηνεύονται με προσοχή, καθώς είναι γενικά πιο χρήσιμα σε περιπτώσεις όπου οι δυναμικές των λιμανιών δεν εμφανίζουν σημαντικές διακυμάνσεις, όπως σε αυτές που υφίστανται στο ελληνικό ακτοπλοϊκό δίκτυο. Συνεπώς, ένα κύριο μειονέκτημα του μοντέλου SBM-DEA είναι ο σχετικός του χαρακτήρας, καθώς μετρά την αποδοτικότητα σε σχέση με μια σειρά από Μονάδες Λήψης Αποφάσεων (DMUs). Κατά συνέπεια, η ύπαρξη των μεγαλύτερων λιμανιών υψηλής ζήτησης τα οποία χαρακτηρίζονται από άριστη συνδεσιμότητα, αποδοτικότητα εξυπηρετούμενης επιβατικής κίνησης και διαδρομές μηδενικών εκπομπών που λειτουργούν από/προς αυτά θα οδηγούσε σε σημαντικές αυξήσεις της αποδοτικότητας, μειώνοντας επομένως την αποδοτικότητα των λιμανιών χαμηλότερης ζήτησης, τα οποία μπορεί κατά συνέπεια να παρουσιάζονται λιγότερο αποδοτικά. Ωστόσο, αυτή η σχετική μείωση δεν θα υποδείκνυε απαραίτητα έλλειψη προόδου στις βιώσιμες λειτουργίες τους, επιβεβαιώνοντας έτσι την ανάγκη για μια πιο ολιστική και ισορροπημένη ερμηνεία των αποτελεσμάτων συνδυαστικά τόσο μέσω των προτεινόμενων δεικτών αποδοτικότητας όσο και του μοντέλου SBM-DEA.

Όσον αφορά τη συνολική αναδιάρθρωση του δικτύου και το νέο προτεινόμενο σχέδιό του με βάση ορισμένα κριτήρια και προσεγγίσεις, τα αποτελέσματα παρουσιάζουν θετικά στοιχεία, από οικονομική και περιβαλλοντική άποψη, καθώς και για την αύξηση της συνολικής προσβασιμότητας και συνοχής. Πιο συγκεκριμένα, το προτεινόμενο δίκτυο παρουσιάζει μεγάλες αυξήσεις όσον αφορά την εξοικονόμηση καυσίμων από τη συνολική κατανάλωση, κατόπιν της εισαγωγής δρομολογίων μηδενικών ρύπων, οι οποίες με τη σειρά τους οδηγούν σε περιορισμούς του περιβαλλοντικού αποτυπώματος του δικτύου μέσω της μείωσης των εκπομπών CO_2 από τις λειτουργίες των πλοίων. Επιπλέον, ένα από τα πιο κρίσιμα σημεία της διατριβής παραμένει το γεγονός ότι τα αποτελέσματα σε ότι αφορά την συνολική προσβασιμότητα δείχνουν σημαντικές βελτιώσεις στο δίκτυο, με τους χρόνους ταξιδιού των επιβατών να μειώνονται, ειδικά σε νησιά όπου η συνδεσιμότητα ήταν αρκετά περιορισμένη στο υφιστάμενο δίκτυο.

Ως αποτέλεσμα, το προτεινόμενο δίκτυο προσφέρει ένα πιο ομοιόμορφα κατανεμημένο επίπεδο εξυπηρέτησης για τους επιβάτες, με βελτιωμένους χρόνους ταξιδιού στις περισσότερες περιπτώσεις, ενώ παράλληλα επιτυγχάνει να είναι πιο περιβαλλοντικά και οικονομικά βιώσιμο, ειδικά σε σύγκριση με τα αποτελέσματα της εφαρμογής άλλων πιο συμβατικών στρατηγικών. Καθίσταται σαφές από τα αποτελέσματα της διατριβής ότι είναι ζωτικής σημασίας να χρησιμοποιηθούν μέτρα τόσο απόλυτης όσο και σχετικής απόδοσης για την πιο σωστή μέτρηση και αξιολόγηση της απόδοσης των λιμένων και των δυνατοτήτων αναδιάρθρωσης του δικτύου, μέσω της χρήσης ενός μεθοδολογικού πλαισίου υποβοηθούμενου από συστήματα GIS για τον σχεδιασμό αποτελεσματικών δικτύων θαλάσσιων μεταφορών. Αξίζει να σημειωθεί ωστόσο πως απαιτείται περισσότερη έρευνα για την περαιτέρω βελτίωση αυτών των μοντέλων και δεικτών απόδοσης και την επεξεργασία μεθόδων για την υποστήριξη μικρότερων λιμένων χαμηλότερης ζήτησης στη μετάβαση προς τη βιωσιμότητα, σε δίκτυα όπου η συνολική τους απόδοση μπορεί αρχικά να φαίνεται μειονεκτική όσον αφορά τις σχετικές αποδόσεις των λιμένων.

Συμπεράσματα και Συνεισφορά Έρευνας

Κύριοι στόχοι της διδακτορικής διατριβής, όπως προαναφέρθηκαν, αποτέλεσαν:

- Η συστηματική βιβλιογραφική ανασκόπηση σχετικά με τις κύριες χρήσεις των γεωχωρικών τεχνολογιών, δεδομένων και μεθόδων σε ναυτιλιακά δίκτυα, μαζί με τον εντοπισμό περιοχών μελέτης όπου αυτά χρησιμοποιούνται ανεπαρκώς.
- Η ανάπτυξη ενός μεθοδολογικού πλαισίου βασισμένου σε GIS για την παρακολούθηση των εκπομπών σε περιοχές ναυτιλιακών δικτύων για την παροχή πληροφοριών με στόχο τις στοχευμένες παρεμβάσεις απανθρακοποίησης.
- Η ανάπτυξη ενός ολιστικού και προσαρμόσιμου μεθοδολογικού πλαισίου βασισμένο σε τεχνολογίες GIS για το σχεδιασμό ενός δικτύου θαλάσσιων μεταφορών υπό το πρίσμα της ένταξης διαδρομών μηδενικών εκπομπών.
- Η ανάπτυξη σχετικών μετρήσεων μέσω δεικτών αποδοτικότητας για την αξιολόγηση και παρακολούθηση της δυναμικής του δικτύου, με στόχο συνεχείς και στοχευμένες βελτιώσεις με την αξιολόγηση των αποτελεσμάτων τους.

Οι ερευνητικές δραστηριότητες της διατριβής περιλαμβάνουν την ανάπτυξη μοντέλων βασισμένων σε τεχνολογίες GIS καθώς και συμπληρωματικών αλγορίθμων προκειμένου να επιτευχθούν οι στόχοι που έχουν τεθεί, όπως προαναφέρθηκαν. Αυτά τα μοντέλα και οι αλγόριθμοι παρουσιάζονται εκτενώς στην παρούσα διατριβή, με την εφαρμογή τους να εξετάζεται στην περίπτωση του ελληνικού ακτοπλοϊκού δικτύου και συγκεκριμένα δίνοντας ιδιαίτερη έμφαση σε δύο διακριτές, ιδιαίτερα απαιτητικές και χωροταξικά πολύπλοκες περιοχές του Αιγαίου. Τα αποτελέσματα έδειξαν αρχικά την ευελιξία των μοντέλων που αναπτύχθηκαν, με τις αντίστοιχες ροές εργασίας τους να προσαρμόζονται εύκολα σε άλλα ναυτιλιακά δίκτυα, ενώ επιτυγχάνονται επίσης σημαντικά κέρδη σε διάφορες επιχειρησιακές πτυχές που εξετάζονται.

Συνολικά, η παρούσα διατριβή δίνει τη μέγιστη δυνατή έμφαση στη σημασία της ανάλυσης χωρικών δεδομένων, η οποία μπορεί εύκολα να εφαρμοστεί για τον σχεδιασμό των θαλάσσιων μεταφορών και τον προγραμματισμό μεταφορών γενικότερα, προκειμένου να βοηθηθούν οι σχετικοί φορείς και οι υπεύθυνοι χάραξης πολιτικής στη λήψη αποφάσεων. Κατά συνέπεια, η παρούσα διατριβή αποτελεί ένα προκαταρκτικό αλλά καινοτόμο βήμα προς τον σχεδιασμό δικτύων θαλάσσιων μεταφορών υπό ηλεκτροκίνηση με βάση τις τρέχουσες τεχνολογικές εξελίξεις και την εκμετάλλευση τεχνολογιών GIS. Ενώ απαιτείται περισσότερη έρευνα για την προσαρμογή των διαδικασιών σχεδιασμού με περισσότερες μεταβλητές και εκτιμήσεις, η διατριβή τονίζει ότι η χρήση των διαθέσιμων και κατάλληλων δεδομένων μπορεί να διευκολύνει σημαντικά όλες τις διαδικασίες στο σχεδιασμό των μεταφορών, ειδικά εάν αυτό ήταν δυνατό σε έναν τόσο περίπλοκο τομέα όπως ο ναυτιλιακός μεταφορά. Τέλος, το υλοποιημένο εξ ολοκλήρου σε περιβάλλον GIS μεθοδολογικό πλαίσιο σχεδιασμού, καθώς και η χρήση τεχνολογιών χωρικής ανάλυσης, αναδεικνύουν την ανάγκη της εκμετάλλευσης των τεχνολογιών αυτών στην διαδικασία σχεδιασμού και λήψης αποφάσεων, αποδεικνύοντας πως η εφαρμογή τους είναι εφικτή ακόμα και στον αρκετά ιδιόμορφο τομέα της ναυτιλίας σε ένα ναυτιλιακό δίκτυο μεγάλης πολυπλοκότητας.

Προτάσεις για μελλοντική έρευνα

Η χρήση πληθώρας δεδομένων στις θαλάσσιες μεταφορές δημιουργεί νέες δυνατότητες στον αποτελεσματικό σχεδιασμό συστημάτων θαλάσσιων μεταφορών. Οι εξελίξεις στην τεχνολογία όσον αφορά την αποθήκευση ενέργειας και τις ανανεώσιμες πηγές ενέργειας, η ανάλυση δεδομένων σε συνδυασμό με γεωχωρικές μεθοδολογίες και η διαθεσιμότητά τους μπορούν να χρησιμοποιηθούν για να προτείνουν νέες εναλλακτικές προς τη μείωση των ανισοτήτων προσβασιμότητας των δικτύων, περιορίζοντας ταυτόχρονα το περιβαλλοντικό τους αποτύπωμα. Ωστόσο, η βιβλιογραφική ανασκόπηση αποκάλυψε σημαντικά κενά στην υπάρχουσα βιβλιογραφία, λαμβάνοντας υπόψη τον σχεδιασμό θαλάσσιων δικτύων υπό την εισαγωγή ηλεκτροκίνησης για τη δημιουργία δρομολογίων μηδενικών εκπομπών, μέσω της χρήσης ολοκληρωμένων διαδικασιών σχεδιασμού λαμβάνοντας υπόψη διάφορες χωρικές πτυχές, όπως τα ιδιόμορφα τοπολογικά χαρακτηριστικά διαφορετικών δικτύων. Σε αυτό το πλαίσιο, η διατριβή παρέχει ένα ευέλικτο σύστημα υποστήριξης χωρικών αποφάσεων (SDSS) που εστιάζει κυρίως στον σχεδιασμό του δικτύου θαλάσσιων μεταφορών με στόχο την αύξηση της περιβαλλοντικής απόδοσης του δικτύου, την αύξηση της προσβασιμότητας και την βελτίωση της κοινωνικής συνοχής, καθώς και την βελτίωση της συνολικής αξιοποίησης του διαθέσιμου στόλου και της χωρητικότητάς του, με αποτέλεσμα την συνολική βελτίωση της απόδοσης των λιμένων, καθώς και του δικτύου ως σύνολο.

Η ανάπτυξη εργαλείων και συστημάτων υποστήριξης αποφάσεων για τη βοήθεια του σχεδιασμού θαλάσσιων δικτύων εξελίσσεται συνεχώς, προάγοντας τις βιώσιμες μεταφορές και γενικά τις προσπάθειες απανθρακοποίησης στη ναυτιλία. Καθώς η τεχνολογία προχωρά, τόσο οι διαθέσιμες τεχνολογίες που θα χρησιμοποιηθούν στην ηλεκτροκίνηση των πλοίων θα αναπτύσσονται, δημιουργώντας έτσι τη δυνατότητα για μελλοντικές μελέτες για την προώθηση του βιώσιμου σχεδιασμού δικτύων με τη συμπερίληψη διαδρομών μηδενικών εκπομπών. Η παρούσα διατριβή παρείχε ένα ολοκληρωμένο, εύκολα προσαρμόσιμο μεθοδολογικό πλαίσιο προς αυτή την κατεύθυνση, εστιάζοντας στον σχεδιασμό υποδικτύων μηδενικών ρύπων σε ένα μεγαλύτερο δίκτυο, αξιοποιώντας τα διαθέσιμα χωρικά δεδομένα για τον προσδιορισμό των δυναμικών του δικτύου, των περιοχών που χρειάζονται άμεσες και στοχευμένες παρεμβάσεις και παρέχουν σημεία αναφοράς για συνεχή παρακολούθηση, αξιολόγηση και βελτίωση οποιουδήποτε δεδομένου δικτύου. Καθώς προτάθηκαν κατάλληλες στρατηγικές για τον περιορισμό του περιβαλλοντικού αποτυπώματος του δικτύου και τη βελτίωση της προσβασιμότητας σε ολόκληρο το δίκτυο, υπάρχουν ακόμη αρκετές πτυχές που πρέπει να αντιμετωπιστούν.

Όσον αφορά το σχεδιασμό του δικτύου υπό ηλεκτροκίνηση, είναι απαραίτητο για μελλοντική έρευνα να αξιολογηθούν οι παράγοντες ασφάλειας από τη λειτουργία τους. Αρχικά, είναι απαραίτητες εκτενείς δοκιμές ηλεκτρικών οχηματαγωγών σε συνθήκες όπως αυτές του ελληνικού ακτοπλοϊκού δικτύου ή οποιουδήποτε εξεταζόμενου δικτύου όπου προτείνεται η χρήση τους για την προσαρμογή και την αξιοπιστία των αναφερόμενων αποτελεσμάτων λαμβάνοντας υπόψη την κατανάλωση ενέργειας. Καθώς οι περιορισμοί εμβέλειας θα μπορούσαν ενδεχομένως να αλλάξουν σημαντικά από τη λειτουργία τέτοιων οχηματαγωγών σε αντίξοες καιρικές συνθήκες, είναι σημαντικό να αξιολογηθεί αυτή η πτυχή και να συμπεριληφθεί στη διαδικασία σχεδιασμού του υπό ανάλυση ναυτιλιακού δικτύου. Για παράδειγμα, στην περίπτωση αυτής της διατριβής, υποτίθεται ότι τα ηλεκτρικά πλοία που εξετάζονται λειτουργούν υπό τις καιρικές συνθήκες στις οποίες λειτούργησαν στις δοκιμές του έργου τους, κάτι που δεν συμβαίνει πάντα, ειδικά σε αντίξοες καιρικές συνθήκες σε θαλασσοταραχές στο Αιγαίο. Καθώς η κατανάλωση ενέργειας ποικίλλει σημαντικά ανάλογα με τις συνθήκες λειτουργίας, απαιτείται ενδελεχής προσομοίωση για την ακριβή εκτίμηση των ενεργειακών απαιτήσεων διαδρομής, εκτός από εκτεταμένες δοκιμές. Ως αποτέλεσμα, οι αξιολογήσεις των καιρικών συνθηκών είναι απαραίτητες για να εκτιμηθεί εάν τα ηλεκτρικά οχηματαγωγά μπορούν πραγματικά να λειτουργήσουν στις προτεινόμενες περιοχές και προτείνεται ιδιαίτερα να ενσωματωθούν στη διαδικασία σχεδιασμού. Επιπλέον, σε περιπτώσεις όπου μόνο ορισμένες περιοχές εμφανίζουν αντίξοες καιρικές συνθήκες, απαιτείται έρευνα για τη βέλτιστη δρομολόγηση υπό καιρικές συνθήκες για να αξιολογηθούν οι αυξήσεις στην κατανάλωση ενέργειας και η επιχειρησιακή σκοπιμότητα συνολικά.

Επιπλέον, στην παρούσα διατριβή χρησιμοποιήθηκε σταθερή ζήτηση ταξιδιού ανά λιμάνι για την αξιολόγηση των λιμενικών ιεραρχιών και των εφικτών περιοχών λειτουργίας ηλεκτρικών πλοίων. Σε περίπτωση που ήταν διαθέσιμοι σχετικοί πίνακες προέλευσης-προορισμού (OD tables), τα αποτελέσματα θα μπορούσαν να διαφέρουν σημαντικά από αυτά που προκύπτουν σε αυτή τη διατριβή, αποκαλύπτοντας ένα από τα πιο σημαντικά ζητήματα που αντιμετωπίστηκαν, καθώς η διαθεσιμότητα δεδομένων ήταν αρχικά σημαντικό εμπόδιο για τους σκοπούς της μελέτης, απαιτώντας εκτεταμένη συλλογή τους, καθαρισμό, επεξεργασία και γενικά τη δημιουργία χωρικών βάσεων δεδομένων σε περιβάλλον GIS οι οποίες θα πρέπει να είναι πάντα διαθέσιμες στους υπεύθυνους χάραξης πολιτικής για την καλύτερη λήψη αποφάσεων. Επιπλέον, πρέπει επίσης να ληφθεί υπόψη ο προγραμματισμός δρομολογίων, ώστε να διασφαλίζεται η βέλτιστη λειτουργία του δικτύου, ειδικά υπό εποχιακές παραμέτρους. Λαμβάνοντας υπόψη ότι το δίκτυο ποικίλλει σε μεγάλο βαθμό ως προς τη ζήτηση επιβατών και τις υπηρεσίες που προσφέρονται κατά τη διάρκεια διαφορετικών περιόδων του έτους, μελλοντικές μελέτες θα πρέπει να περιλαμβάνουν εποχιακές παραμέτρους στις διαδικασίες σχεδιασμού οποιουδήποτε ναυτιλιακού δικτύου.

Από μεθοδολογική άποψη, απαιτήσεις που σχετίζονται με τις προτεινόμενες παραμέτρους σχεδιασμού δικτύου, όπως τα επιθυμητά κριτήρια, μπορούν εύκολα να ενσωματωθούν στη διαδικασία σχεδιασμού. Σε αυτή την περίπτωση, η συλλογή δεδομένων και οι συνομιλίες με ενδιαφερόμενα μέρη, φορείς χάραξης πολιτικής και άλλες σχετικές ομάδες είναι απαραίτητες για να υπάρξει κατανόηση και να οδηγήσουν σε ιεραρχικές αξιολογήσεις διαφορετικών κριτηρίων που ενσωματώνονται στη διαδικασία σχεδιασμού, μέσω διαφόρων μεθόδων, όπως AHP, FAHP κ.λπ. Εφόσον τα κριτήρια αυτά και η αντίστοιχη σημασία τους αξιολογηθούν, οι προτεινόμενοι σχεδιασμοί δικτύων θα μπορούσαν επίσης να προσφέρουν διαφορετικές λύσεις που σχετίζονται με την άποψη κάθε ομάδας με διαφορετικούς στόχους, όπως λύσεις προσανατολισμένες στον επιβάτη ή τις ναυτιλιακές εταιρείες σε κάθε δίκτυο. Η ευελιξία του προτεινόμενου μεθοδολογικού πλαισίου γίνεται εμφανής από την ικανότητά του να εκμεταλλεύεται πολλαπλές πηγές δεδομένων για την καλύτερη αξιολόγηση της απόδοσης του δικτύου και των στοιχείων του, παρουσιάζοντας έτσι περισσότερες πληροφορίες σχετικά με τη λειτουργία του. Μέσω της χρήσης τέτοιων δεδομένων, μπορούν να προκύψουν πρόσθετες μετρήσεις απόδοσης και αποδοτικότητας, οι οποίες με τη σειρά τους μπορούν να χρησιμοποιηθούν σε μελλοντικές διαδικασίες επανασχεδιασμού και προβλήματα βελτιστοποίησης για περαιτέρω βελτίωση των λειτουργιών του δικτύου.

Επιπλέον, αν και οι παραδοσιακές μεθοδολογίες ομαδοποίησης είναι σχετικά απλές όσον αφορά την εφαρμογή τους, σε ορισμένες περιπτώσεις αυτές βασίζονται σε αυθαίρετα όρια και τιμές παραμέτρων κάτω από κάποιο τύπο πληροφοριών με βάση τα υπάρχοντα δεδομένα ή τις προτιμήσεις του χρήστη. Ενώ η χρήση της HDBSCAN εξακολουθεί να είναι η πιο βασισμένη σε δεδομένα μέθοδος ομαδοποίησης, εξακολουθεί να απαιτεί συγκεκριμένη εισαγωγή από τον χρήστη (π.χ. τον ελάχιστο αριθμό λιμένων ανά ομάδα). Για την αντιμετώπιση τέτοιων ζητημάτων, οι μέθοδοι ομαδοποίησης που βασίζονται σε μοντέλα, όπως οι αλγόριθμοι μηχανικής μάθησης, μπορούν ακόμα να εφαρμοστούν για τον περιορισμό της υποκειμενικότητας, ως ένα βήμα προς την εξαγωγή αποτελεσματικότερων συμπερασμάτων.

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ABBREVIATIONS

AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AIS	Automatic Identification System
AMF	Air Mass Factor
Bi-LISA	Bivariate Local Indicators of Spatial Association
CO_2	Carbon dioxide
DBSCAN	Density Based Scanning Algorithm with Noise
DEA	Data Envelopment Analysis
DINF	D-Infinity
DMU	Decision-Making unit
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
ELSTAT	Hellenic Statistical Authority
EMSA	European Maritime Safety Agency
ESDA	Exploratory Spatial Data Analysis
ESS	Energy Storage Systems
EU	European Union
EU MRV	European Union Monitoring, Reporting and Verification
FAHP	Fuzzy Analytical Hierarchy Process
GA	Genetic Algorithm
GIS	Geographic Information Systems
GCSN	Greek Coastal Shipping Network
GHG	Greenhouse Gas

GRT	Gross Register Tonnage
GT	Gross Tonnage
HDBSCAN	Hierarchical Density-Based Spatial Clustering of Applications with Noise
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
KPI	Key Performance Indicator
LISA	Local Indicators of Spatial Association
LoS	Level of Service
LP	Linear Programming
LSMGO	Low-Sulfur Marine Gasoil
MCDM	Multi-Criteria Decision-Making
MEPC	Marine Environment Protection Committee
MFD	Multiple Flow Direction
MGIS	Marine GIS
MILP	Mixed-Integer Linear Programming
NECA	NO_x Emission Control Areas
NO_2	Nitrous Dioxide
NO_x	Nitrous Oxide
NPV	Net Present Value
NSR	Northern Sea Route
OMI	Ozone Monitoring Instrument
OPTICS	Ordering Points To Identify the Clustering Structure
PM	Particulate Matter
RES	Renewable Energy Sources

RoPax	Roll-on/Roll-off Passenger (Ship)
RoRo	Roll-on/Roll-off (Ship)
SBM-DEA	Slacks-Based Measure Data Envelopment Analysis
SCP	Spatially Complex Problem
SCR	Selective Catalytic Reduction
SDSS	Spatial Decision Support System
SECA	Sulfur Emission Control Area
SO_2	Sulfur Dioxide
SoC	State of Charge
SO_x	Sulfur Oxide
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSP	Traveling Salesman Problem
VRS	Variable Returns to Scale

1 INTRODUCTION

In the modern world, the escalation of population growth, the evolution of technology, and the expansion of the global economy are instigating a rapid consumption of non-renewable resources, leading to detrimental impacts on the environment. Nevertheless, a shift is becoming evident in various societal sectors, with an increasing emphasis on sustainability rather than just profit. Among these sectors, the maritime shipping industry presents an interesting case study. With its importance in the global economy, maritime shipping holds a pivotal role, offering a cost-effective and efficient way to transport goods on a global scale. It is this industry that keeps the wheels of commerce turning, transporting the vast majority of goods that form the backbone of the global trade network.

However, with the boon of global trade comes a bane. The environmental impact of maritime transport, inherently linked to the growing demand for goods, is seeing a consistent upswing. Therefore, addressing this issue, this research seeks to explore how Geographic Information Systems (GIS) can be harnessed to optimize maritime transport systems. The aim is to demonstrate that it is indeed possible for a sector like shipping to operate profitably while lessening its environmental impact. The focus here is to reconcile the notions of 'profitable' and 'sustainable' within the shipping industry, thereby contributing to a healthier planet and a sustainable future.

Waterborne transport has been an important branch in the history of the world for centuries and the evolution of civilizations. The concept of the transport of people and goods is based on movement between significant geographical distances and today's societies are increasingly dependent on it. From simple movement to the provision of goods and services. transport systems support a wide range of productive activities every day activities of our lives. Among the modes of transport, maritime transport has dominated and is not unfairly characterized as the backbone of global trade or the driving force of globalization since more than 90% of world trade is carried by sea. Waterborne transport covers the totality of all transport operations through waterways and those that are carried out with a fixed periodicity between ports are classified as maritime transport. Maritime transport is divided into international and domestic (within the territory); the former being known as sea transport and the latter as coastal transport.

Island transport, which is one of the fields of study, deals with the movement of people and goods that take place on islands and is clearly identical to the term coastal shipping. The physical characteristics of the island space are those that impose severe constraints on transport systems, in terms of the way they can be used, the extent of the transport service, the cost, capacity and reliability of the transport project. For islands, a good transport system provides the possibility of minimizing the physical 'disadvantage' of distance from the mainland and major economic centers, therefore improving overall accessibility and local economies.

1.1. Status Quo of the Greek Coastal Shipping Network

Planning of maritime services focuses on the efficient fleet utilization and the provision of an acceptable level of service, so that profitability is achieved. However, externalities of maritime operations, especially environmental impacts, are often overlooked by planners and operators. Greenhouse gas (GHG) emissions from transportation have doubled since 1970, while in comparison to other modes of transport, GHG emissions in the shipping industry are projected to rise by 50-250% until 2050, due to the sector's continuous expansion (Smith et al., 2014; Zisi et al., 2021). Heightened environmental concerns have prompted the International Maritime Organization (IMO), other marine institutions, and the research community to recommend various approaches for the gradual phasing out of fossil fuels in the shipping sector. Several studies have investigated the environmental footprint of maritime operations and proposed mitigation actions, such as the use of cleaner fuels and slow steaming (Crist, 2009; Eide et al., 2009; Franc & Sutto, 2014; Ju & Hargreaves, 2021; Rehmatulla et al., 2017; Xing et al., 2020; Zisi et al., 2021). Slow-steaming in particular is the reduction of a vessel’s operating speed, which apart from cutting operating costs, can considerably reduce emissions (Cariou, 2011; Degiuli et al., 2021; Pastra et al., 2021; Woo & Moon, 2014; Yin et al., 2014), especially for high-speed vessels (Psaraftis et al., 2009).

The Greek Coastal Shipping Network (GCSN) offers connection between Greek mainland ports and fifty-five inhabited Aegean islands (M. B. Lekakou & Remoundos, 2015), carrying about 12 million travelers and 2.5 million vehicles annually in 2019 (Hellenic Statistical Authority - EL.STAT, 2019). The GCSN consists of about 115 ports, 89 of which are exclusively connected by sea, with no active airline connections at the port’s island, and is operated by a total of 97 vessels (S.E.E.N., 2022). As Aegean islands are popular tourist destinations, the GCSN demand exhibits high seasonality: the summer peak period (June-September) accounts for about 45% of total annual demand for ferry transportation (Hellenic Statistical Authority - EL.STAT, 2019). Both conventional and high-speed catamaran ferries are operating in the GCSN, with the latter servicing routes mainly during the summer peak period.

The performance and operations of the GCSN have been widely investigated in the past (Goulielmos, 1998; Kapros & Panou, 2007; M. B. Lekakou, 2007; M. B. Lekakou & Vitsounis, 2011; Mitropoulos et al., 2022; Sambracos, 2001; Schinas, 2009), with the literature indicating the paramount importance of the GCSN to the economic growth and social cohesion of the Aegean islands with the mainland and between them, therefore retaining the country’s overall cohesion and accessibility to all areas at an adequate level of service. The latter practically translates to acceptable travel times, during both peak and off-peak seasons. Especially during summer peak periods, fast access to the Aegean islands is crucial for accommodating high tourist flows and providing supplies to tourist facilities, while it improves the islands’ attractiveness as tourist destinations and, as a result, their economic viability and growth. This is mostly achieved by increasing speeds of conventional ferries and by routing high-speed (catamaran) ferries, while also increasing the overall frequency of trips in high traffic periods in the summer. Although high speed ships provide an increased level of service and limit travel times as possible in order to meet passengers’ demands, they unavoidably worsen the GCSN environmental footprint, as greenhouse gas (GHG) emissions and pollutants increase, in an otherwise environmentally sensitive archipelago (Bigano & Sheehan, 2011; C. Iliopoulou et al., 2018).

Over the past years, the shipping industry in Greece has evolved into a sophisticated network, facilitating travel across a diverse range of routes: from the mainland to various islands, between different islands, and even from mainland to other mainland destinations. Consequently, this network has interconnected around 100 islands and 200 ports (M. B. Lekakou, 2007). Shipping companies utilize their fleets to cater to several domestic routes. These include areas like the Cyclades, Crete, the Dodecanese, the North Aegean, the Saronic Gulf, the Sporades, and the Ionian Sea. t's interesting to note that the industry exhibits oligopolistic traits (M. Lekakou et al., 2021). To illustrate, the shipping market comprises of twenty-three (23) companies in total, although only a mere eleven (11) of these firms operate the primary routes of the network. It is also worth noting that the Greek shipping market is still deeply interconnected with the fully liberalized Adriatic shipping market (Schinas, 2009).

In general, the sector's operations demonstrate a distinct pattern of strong seasonality, with a third of the annual traffic recorded during the summer. This pattern significantly impacts the financial results of the companies involved, as seasonality leads to an uneven focus of companies on particular routes, usually the more profitable ones, leading to a degree of deregulation in the market and network. In addition, during the first and fourth quarters of the year, passenger traffic is substantially reduced, as seen in many years (Hellenic Statistical Authority - EL.STAT, 2019), leading to shipping companies mostly relying in the summer periods to break even and be financially sustainable. Practically, this implies that goods transportation from the mainland to the island territories is facilitated via the ports of Attica. The underlying reason is the 'centripetal structure' of the current network, characterized by connections with the country's central port, Piraeus, and the lack of a decentralized 'radial network', or a 'Response System'. In English terminology, this would be referred to as a 'Hub & Spoke' network (M. Lekakou et al., 2021). Concerning the fleet, as of the preparation of the dissertation, collected data of 97 ships reveal an average age of just under 30 years (29.45 years). Notably, 6 ships (6.19%) are up to 10 years old, 7 (7.22%) are older than 10 years and up to 20 years old, 45 (46.39%) are older than 20 years and up to 30 years old, and lastly, 39 (40.21%) are over 30 years old.

Evidently, the fleet is perceived as subpar concerning age and environmental impact, necessitating compliance with new regulations by the International Maritime Organization (IMO) regarding ballast water and environmental footprint reduction. It's crucial to maintain high-quality transport services, independent of day-to-day challenges such as network structure, port infrastructures, and market dynamics (supply and demand). Over the next decade, there is a pressing need for fleet renewal as most of the fleet will reach the age of 40 years (XRTC Business Consultants, 2020) (XRTC Business Consultants, 2020). All companies highlight in their annual financial reports the impact of fluctuating fuel prices, as fuel represents the largest expense for these companies, accounting for 44% of total operating costs, prompting companies to hedge part of the risk associated with fuel price changes (XRTC Business Consultants, 2020). The modifications in IMO regulations also raise the possibility of increased ferry fares due to necessary alterations to ships, which could, in turn, eat into companies' profits. Of particular importance is the fact that the Greek market is deeply interconnected with the fully liberalized Adriatic market, which serves as an international connection (Schinas, 2009).

It is becoming clear through relevant studies that one of the main objectives of decision and policy makers, as well as shipping companies is to provide both sustainable and efficient maritime services. As environmental parameters are gaining the interest of researchers and the shipping industry overall, design and planning of maritime services is directed towards optimizing the operation of the utilized fleets, while also meeting transport demand and environmental goals. Considering maritime networks, there are always several issues to be addressed regarding the design and planning processes, which mainly include adjustments to the size and mix of the fleet, fleet development and management (assignment of specific vessels to the commercial fleet), vessel routing and scheduling (Christiansen et al., 2007). However, in the case of the GCSN, maritime transport is not just an added service but rather a necessity. As a result, environmental consequences from fleet operations are not always compensated with the adequate transport work.

In terms of the regulatory framework of the GCSN, the shipping market is a fully liberalized one. Specifically, prior to 2002, the maritime transport sector's policy framework was hallmarked by the centralization of decision-making within the Ministry of Maritime Affairs & Insular Policy and the Aegean. The Ministry's authorities included setting fare levels, determining service frequencies, prescribing the annual service period, and managing the vessel crews, all of which however eventually led to a deterioration in overall competitiveness. As a result, Law 2932/2001 (Government Gazette no. 145/A/27-6-2001), which adopted provisions from European Union Regulation 3577/1992 that called for abolishing cabotage rights, initiated a shift towards a more liberalized and competitive market. Cabotage rights, which essentially granted nations exclusive rights to transport passengers and goods between its ports, were thus abolished, facilitating free provision of transport services. This transition allowed any shipowner, complying with European Union standards, to freely operate ships on Greek routes. Additionally, the specific Law ratified the Stockholm Agreement (Directive 2003/25/EC), which gradually lowered the age limit from 35 to 30 years and provided for state-supported ferry services (intervention in instances where certain islands lacked sufficient service frequencies). This legislative move aimed to increase competitiveness in the shipping industry, while also ensuring the adequacy of connections, and enhance overall navigation safety. It is also worth noting that from 1998 to 2001, Greek shipowners updated their passenger ships based on a technological boom that allowed for larger, faster, and more capable vessels.

After 2002 and until the preparation of this dissertation, the Ministry of Maritime Affairs & Insular Policy implements a central planning system for the shipping industry that ensures connectivity between the islands and mainland Greece, as detailed in Ministerial Decision 2253.1-1/70759/20 (Government Gazette no. 4775/B/29-10-2020). As per Article 3 of the decision, there are three key points. First, island ports serving as prefecture capitals must have at least three weekly connections with mainland ports throughout the year via at least one main line. Secondly, that aren't prefecture capitals should maintain a connection with the capital of their respective prefecture at least three days a week throughout the year, either directly or via connecting service. Lastly, islands under the same administrative Region should be connected at least once a week, directly or through a connecting service, with the Region's headquarters.

The Ministry of Maritime Affairs & Insular Policy, acting as the authoritative body, initially establishes an Indicative General Shipping Network that outlines the minimum number of routes on which ships should operate. Subsequently, individual companies can submit applications for regular services on their desired routes. These applications are evaluated, and eventually, a network of regular services is formed. In case the formed network does not meet the minimum service requirements or if companies have not submitted necessary takeover applications, the Ministry offers the opportunity to sign contracts—serving as an additional incentive—for public service obligations ranging from one to twelve years. These contracts grant exclusive commercial exploitation rights to specific routes. Following this process, if routes remain that are still not serviced, they are designated as non-commercial or 'barren' lines. For these routes, the state offers funding in the form of lease payments (or more commonly subsidies) to ensure necessary services are provided. After identifying such "non-commercial" lines, a public government tender is initiated for them, which describes the required service frequency and the maximum rent for each route, which varies based on route distance, demand characteristics, and vessel type.

1.2. Status Quo of Ports of the Greek Coastal Shipping Network

In order to better understand the network's complexities and functioning, the identification and categorization of its ports consists an essential preliminary step. Through this, it is possible to examine overall network adequacy, and provide insights regarding the infrastructure and any potential issues that may arise during peak periods, such as the summer months. The term 'port' generally refers to a secure harbor that offers protection for incoming ships to conduct commercial operations.

Modern ports serve as vital connections between marine and land transportation systems, primarily catering to the hinterland and typically situated near urban centers. A modern port requires more than just infrastructural developments, as it also requires expensive superstructures and significant links to the hinterland as it is a component of the supply chain, offering integrated solutions for combined transport, with its primary role being to provide services that reduce not just the costs of the port services offered but also the overall cost of product transportation. As per the 8315.2/02/2007 Joint Ministerial Decision (Government Gazette no. 202/B/16-02-2007), titled "Classification of Ports", the country's ports vary in importance based on their impact on the international and national transportation network. After close examination of the existing legislation, it becomes clear that this is also highly connected to their distinct geostrategic position and differing development potentials within the context of maritime corridors of the trans-European and national transportation networks. Consequently, they are classified as:

- **Ports of International Interest**: Piraeus, Thessaloniki, Volos, Alexandroupoli, Elefsina, Igoumenitsa, Heraklion, Kavala, Corfu, Lavrio, Patras, Rafina, Mykonos, Mytilene, Rhodes, Souda-Chania
- **Ports of National Significance**: Argostoli, Zakynthos, Thira, Kalamata, Katakothos, Corinth, Kyllini, Kos, Lagos, Paros, Preveza, Rethymno, Vathi, Samos, Syros, Chalkida, and Chios
- **Ports of Major Interest**: Ag. Constantine of Fthiotida, Agios Nikolaos of Lassithi, Aegina, Aegio, Gythio, Thassos, Itea, Kymi, Lefkada, Messolonghi, Myrina of Lemnos, Naxos, Nafplio, Nea Moudania, Patmos, Samothrace, Poros, Kefalonia, Skiathos, Skopelos, Sitia, Spetses, Stylida, Tinos, and Hydra
- **Ports of Local Importance**: All other ports of the country

It is worth noting that responsible for the overall planning and development of the national ports policy is the General Secretariat for Ports, Port Policy and Maritime Investment, with its goal being to enhance the ports and port facilities with modern infrastructure.

To better assess the significance of the Greek ports and their contribution to the cohesion and functionality of the network, overall passenger demand in the GCSN must be considered. Transport service demand fluctuates according to shifts in the associated demand. High demand periods are referred to as peak periods, while low demand periods are characterized as off-peak or recession periods. The demand in the country is highly seasonal as mentioned above, peaking in July and August, and exhibits substantial spatial variability. This demand displays notable unevenness in both its qualitative and quantitative attributes, depending on the destination. Locations such as Crete, Syros, Tinos, Mykonos, Paros, Naxos, Ios, Thira (Santorini), Chios, and Mytilene often experience high demand and concurrently, high service frequency. Approximately 40% of the islands in the Aegean low-service zone commonly encounter increased issues in winter due to the cancellation of services caused by unfavorable weather conditions.

Considering the years prior to the COVID-19 pandemic and assessing the openly available data from the Hellenic Statistical Authority (Hellenic Statistical Authority - EL.STAT, 2019) and the Foundation for Economic & Industrial Research (IOBE, 2021), there aforementioned issues are becoming clear, as shown below.

Table 1. Percentage change in domestic and international passenger transport (compared to previous year). Author's processing.

Passengers	**2015 – 2016**	**2016 – 2017**	**2017 – 2018**	**2018-2019**
Domestic (embarked / disembarked)	-1.24%	6.74%	3.63%	1.65%
International (Total)	-14.07%	10.16%	5.96%	-0.81%
International (Disembarked)	-14.83%	11.09%	6.79%	-1.26%
International (Embarked)	-13.32%	9.21%	5.09%	-0.35%
TOTAL CHANGE (%)	**-1.82%**	**6.90%**	**3.74%**	**1.53%**

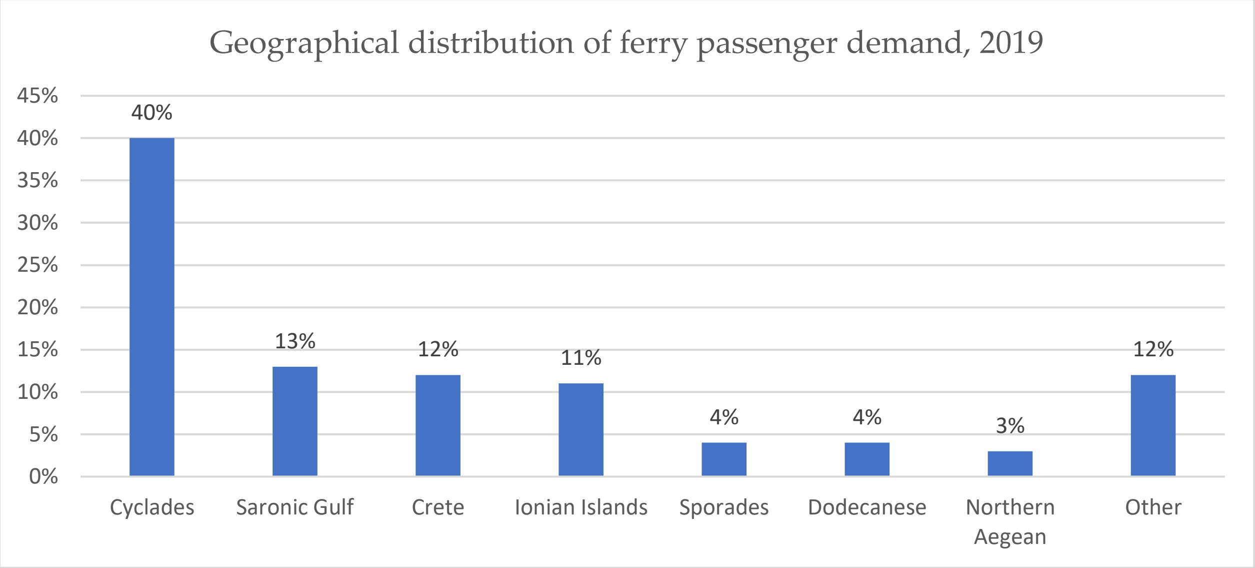


Figure 1. Geographical Distribution of Ferry Passenger Demand, 2019. (IOBE, 2021). Author's processing.

The above data show a steady increase in passenger demand for ferry traffic, considering passengers. While it is not in the scope of this study, it is worth noting that freight demand via ferry transport also showed an important increase from 2015 to 2019, at approximately 16% (Hellenic Statistical Authority - EL.STAT, 2019; IOBE, 2021). However, in terms of passenger spatial distribution, increasing passenger traffic is shown in the islands of Cyclades, with other islands showing lower demand. This will also become clear in next sections of the thesis, where an initial evaluation of passenger demand of the network's ports verifies this.

1.3. Issues of the Greek Coastal Shipping Network

Greece's unique geographic complexity includes a lengthy coastline totaling around 17,700 km, of which approximately 10,000 km belong to the islands. This is a distinctive characteristic not found in any other member of the European Union, apart from the Scandinavian countries with the case of the fjords. This multi-island nature necessitates comprehensive and high-quality transportation solutions, while also intensifying the understanding of social aspects of coastal shipping in order to maintain territorial continuity and to promote fair economic growth and accessibility on the islands. As a result, the connection of island regions in Greece to the mainland is crucially dependent on transportation conditions and methodologies (Panagiotopoulos & Kaliampakos, 2019). In order to facilitate social cohesion and territorial unity, coastal shipping acts as a 'bridge', creating marine highways suitable for economic and social development. However, the prospects for island-mainland connection vary, particularly in the Aegean region, where severe weather conditions often result in numerous route cancellations.

Several studies have highlighted the fact that the term "accessibility" is highly interrelated with island ferry transport (Karampela et al., 2014; Panagiotopoulos & Kaliampakos, 2019; Spilanis et al., 2012). In general, accessibility operates as a dual-function construct. The first function pertains to the actions or opportunities to be pursued, while the second concerns the expenditure of effort, time, or cost necessary to achieve these actions or opportunities. Adding complexity to the term accessibility is the concept of remoteness, which profoundly influences at least three primary facets of an island region. These include the local culture and society, the natural environment, and economic development.

In the study of Karampela et al. (2014), overall accessibility of 40 Greek islands was evaluated and described as a function of travel time form service hubs of the network. The evaluation was based on overall connections, travel times and frequency of connections on a weekly basis, separately for ferry services and air connections, if any were existent. The sum of offered transport services was then weighted based on passenger usage rates and visualized on isochrone maps. The study revealed several islands in the Aegean Sea which were highly underserviced and required immediate policy interventions regarding their connected shipping routes, especially during the winter months, where passenger travel deteriorates. As results showed a network which still required better coverage, due to several gaps in network structure, it becomes clear that the network's ability to reliably and effectively service the smaller, more remote islands from central hubs is in doubt. The study also showed that increasing local daily or frequent connections between smaller, less accessible islands to/from nearby larger ones could be the solution to creating a more cost-effective and efficient operating model in the Aegean. As a result, it is highlighted that smaller, more remote islands of the network are highly dependent on larger neighboring islands of higher demand, thus creating a spatially complex problem considering the design of the GCSN.

In addition to the ports of the GCSN, the network design approach itself also shows certain disadvantages. The operating model for Greece's maritime transport system is mostly linear and following the approach of the Traveling Salesman Problem (TSP), defined as a route that starts and ends at the same main hub (in most cases, Piraeus), making stops at intermediate ports depending on the route. This structure relies on large-capacity vessels, considering them a 'prerequisite' to meet the transport demand in the Aegean, especially during the summer months when passenger and vehicle traffic from mainland ports to the islands is at its highest.

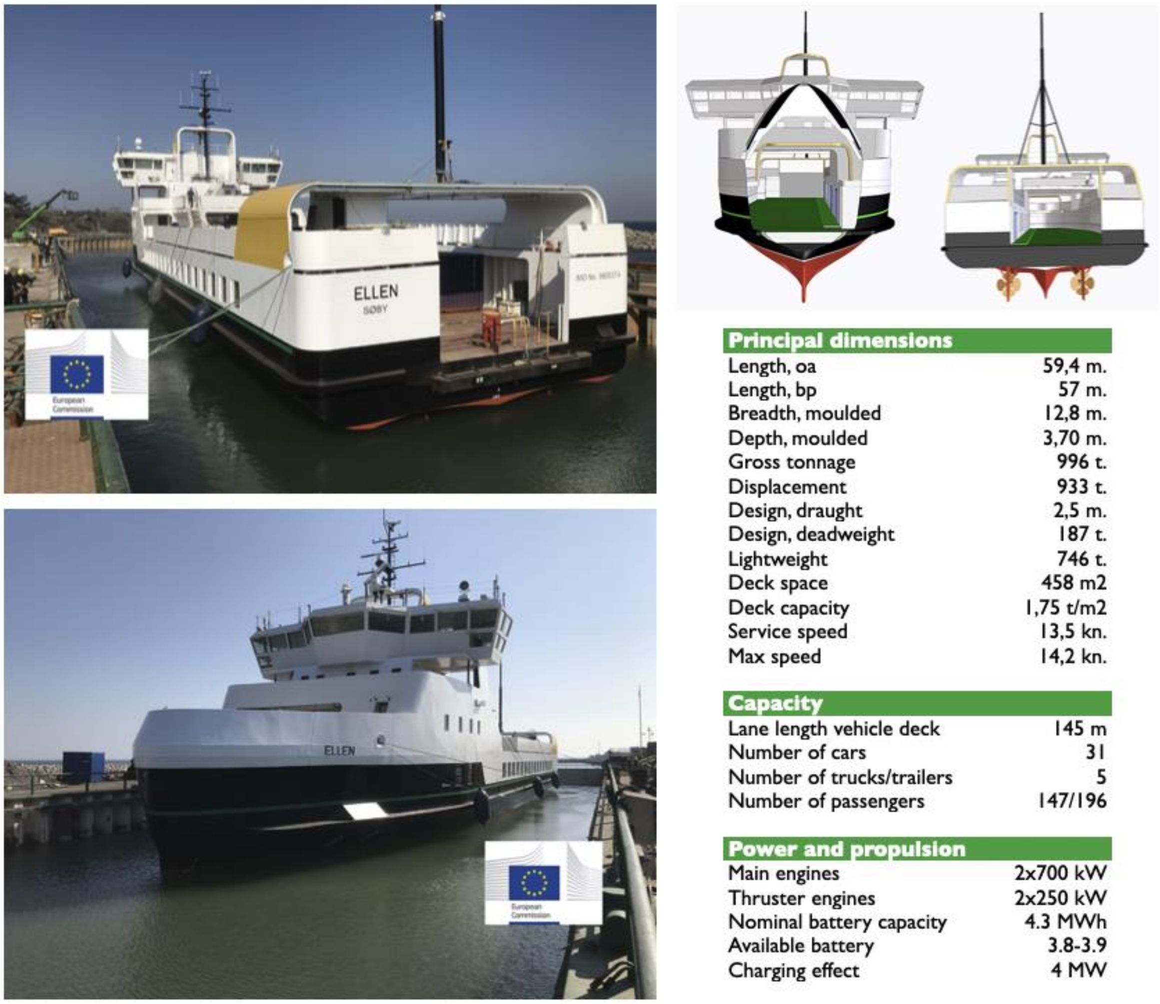
However, despite this structure, the efficiency of the operating model is less than ideal. The need to meet minimum routing requirements encourages ships to dock at many intermediate ports, leading to long operating hours, long distances, and excessive fuel consumption. This inevitably results in a sharp increase in operating costs, GHG emissions and a deteriorated Level of Service (LoS) for passengers, while also preventing the execution of more than one route per day. The quality of this model, and maritime transport in general in the Aegean Sea, is closely tied to port infrastructure. Much of the infrastructure at Aegean ports is currently deemed inadequate and outdated, lacking the application of new technologies. This deficiency significantly impacts the safety of ships, crews, and passengers, especially during adverse winter conditions. According to data provided by IOBE and existing port characteristics from MarineTraffic (IOBE, 2021; MarineTraffic, 2022) nine out of ten ports have problematic ramps, while almost half face depth issues, hindering the approach of modern coastal vessels.

Most of the ports are also unsuitable for cruise ship berthing, and the lack of passenger waiting areas and adequate parking spaces are significant concerns regarding port infrastructure. These issues are compounded by poor interconnectivity with other modes of transport, especially during the night. Lekakou (2021) argues in her study that the requirements set by the Ministry, as mentioned above, are not adequately justified as they are applied indiscriminately to all islands, regardless of their size, insularity level, and connection status. Gagatsi et al. (2014) also share this view, stating that these factors worsen the vulnerability of the existing operating model.

It is clear from the above studies and available data that the design and operation of the GCSN show several problems. As a result, while also considering decarbonization efforts in the maritime sector, it is necessary to provide a more modern approach to the design and planning process of maritime operations, in order to address all aforementioned issues, considering the environmental sustainability of islands and the GCSN as a whole. Especially in the case of the GCSN or other regional insular networks, complexities and topological characteristics should be considered in the design process of such networks, thus constituting spatially complex problems (SCPs).

1.4. Ferry Electrification and the E-ferry Project

One of the main points of this dissertation is to incorporate the introduction of zero-emission routes in the design and planning of a maritime network. For such purposes, the fully electric E-ferry “Ellen” is considered as a model electric ferry to be utilized for the introduction of zero-emission routes, with some of its main characteristics shown on the figure below. The E-ferry project is a novel initiative backed by the European H2020 program, dedicated to conceptualizing, constructing, and showcasing a completely electrically driven 'eco-friendly' ferry. This ferry operates without creating pollution or CO_2 emissions. The initiative seeks to facilitate environmentally-friendly, zero greenhouse gas emission, and air pollution-free waterborne transportation, specifically catering to island communities, coastal regions, and inland waterways in Europe and elsewhere.



Principal dimensions	
Length, oa	59,4 m.
Length, bp	57 m.
Breadth, moulded	12,8 m.
Depth, moulded	3,70 m.
Gross tonnage	996 t.
Displacement	933 t.
Design, draught	2,5 m.
Design, deadweight	187 t.
Lightweight	746 t.
Deck space	458 m2
Deck capacity	1,75 t/m2
Service speed	13,5 kn.
Max speed	14,2 kn.

Capacity	
Lane length vehicle deck	145 m
Number of cars	31
Number of trucks/trailers	5
Number of passengers	147/196

Power and propulsion	
Main engines	2x700 kW
Thruster engines	2x250 kW
Nominal battery capacity	4.3 MWh
Available battery	3.8-3.9
Charging effect	4 MW

Figure 2. The fully electric powered green ferry “E-ferry Ellen” and its main characteristics (Source: http://e-ferryproject.eu/. Accessed Jun. 22, 2022)

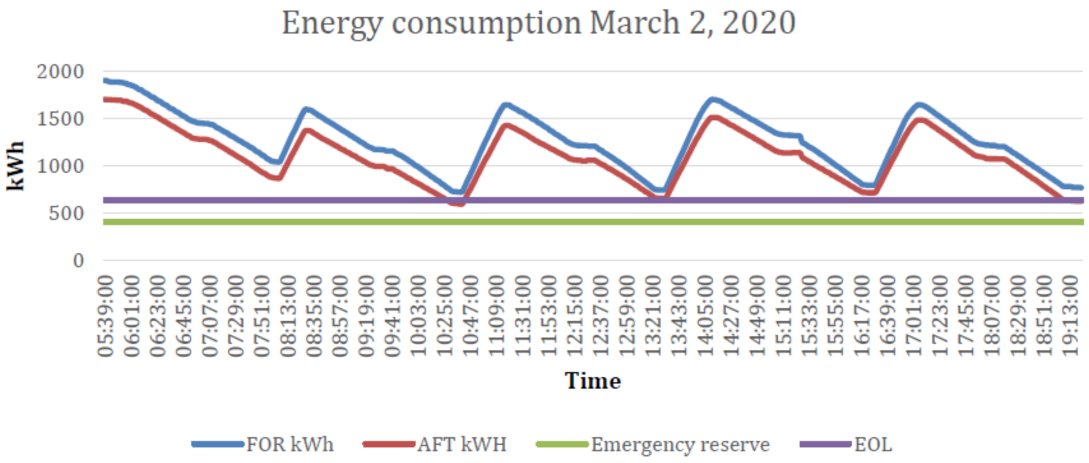
The goal of the E-ferry project is to employ an exceptionally energy-efficient design concept and demonstrate a fully electric, emission-free, medium-sized ferry capable of transporting passengers, cars, trucks, and cargo. Initially, the E-ferry was expected to operate over longer distances than any electrically propelled ferry has achieved before, which is over 5 nautical miles. While Ellen is considered a small sized passenger ferry, it is still one of the largest fully electric ships, at least at the time of preparation of this dissertation. Results of the project showed that it is capable of operating a route of 22 nautical miles (38 km), between Soeby-Fynshav and Soeby-Faaborg in Denmark, thanks to its large lithium battery of 4.3MWh, which is the largest battery built until this time for a passenger ferry. The ferry is intended for coastal and inter-island operation, with its main advantage being the fact that, in comparison to the best technological alternative (a newbuilt tier III diesel-electric), estimations show that it is much more environmentally friendly, especially if it is charged using renewable energy sources (RES) (European Maritime Safety Agency - EMSA, 2020). Based on the reports and findings of the project, estimations show high environmental savings of 2520 m. tonnes of CO_2, 14.3 m. tonnes of NO_x, 1.5 m. tonnes of SO_2, 1.8 m. tonnes of CO and half a m. tonne of particulate matter per year. On the same note, in comparison to an existing ferry of similar type, emissions could be limited by 4000 m. tonnes of CO_2, 70.8 m. tonnes of NO_x, 2.4 m. tonnes of SO_2, 3.1 m. tonnes of CO and 1.4 m. tonnes of particulate matter per year.

As reported by the E-ferry project, its main operational points are:

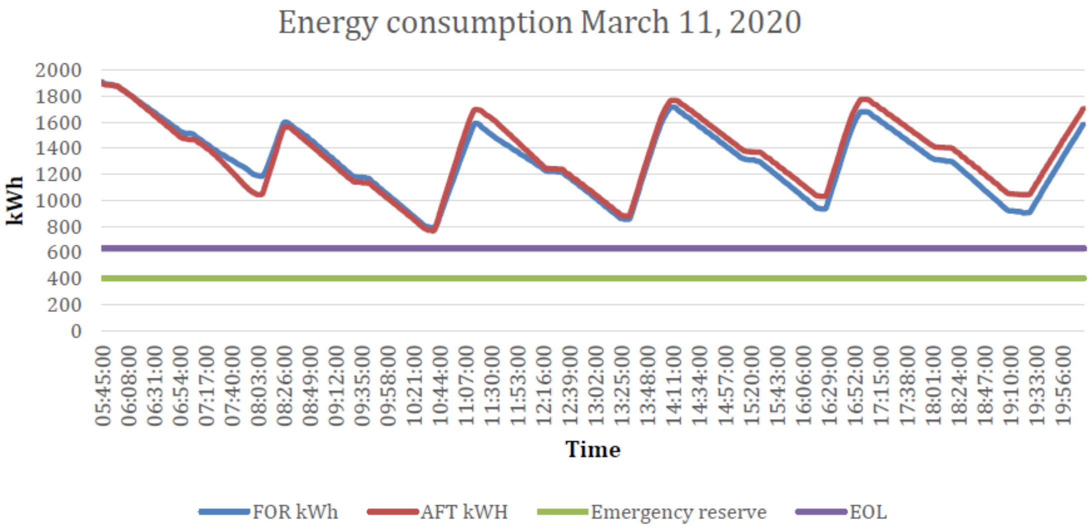
- High Speed (up to 14.5 knots).
- Improved charging (in only one point of the route).
- Improved sailing range between needed charging periods (2x13NM).
- Worldwide largest battery capacity for maritime use (3,5-4 MWh).
- The peak charging power of the E-ferry battery pack and its shore charging connection will be up to 4 MW.
- New lightweight materials being different kinds of carbon composites in addition to the more traditional aluminum light weight solutions for superstructure.
- Able to operate in ice conditions up to 15-20 cm.

- Reduced wave heights from wake significantly compared to existing ferries for even at higher speeds than these. This will be of comfort to people and wildlife living in the vicinity of the ferry routes.
- Meeting international requirements: E-ferry meets the latest and highest intact and damage stability criterion for ferries, being a two-compartment ship going well beyond the safety requirement for operation in coastal areas (category C and D normal trading areas for the typical island ferry).

As reported in the final information package of the E-ferry project (2020), the E-ferry showed even better range capabilities than the already expected ones, showing that it is capable of operating on distances much larger than the one where it is already in operation. Specifically, while weather conditions in the area of operation play a significant role in range capabilities, the E-ferry "Ellen" was characterized by stable battery consumption on variable speeds of 12 to 14 knots, with operational tests showing an average energy consumption of 73 kWh per nautical mile travelled. As a result, a 22 nautical mile trip would, under the conditions tested, consume about 1600kWh, which is much lower than its operational battery capacity, reported at 3.8MWh. Energy consumption patterns, as measured and reported in the final information package of the E-ferry project are shown below.



(a)



(b)

Figure 3. Energy consumption patterns for (a) March 2 and (b) March 11, 2020 (Source: http://e-ferryproject.eu/Portals/0/InfoPackage/eFerry_Information_Package.pdf. Accessed: 15 Jul 2023)

In addition to the operational capabilities of the E-ferry Ellen, charging infrastructure supporting the ferry's operation is also highly important. Initially, the charging effect was specified as 4 MW, supplied via 4 separate charging lines, each of 1 MW. This translates to about 66.6 kWh per minute, however not accounting for any losses that may occur during charging. The following figures show the charging infrastructure of the E-ferry Ellen and results of charged kWh per minute on four different charging breaks.

Figure 4. Port charging infrastructure for the E-ferry Ellen. (Source: http://e-ferryproject.eu/. Accessed Jul. 15, 2023)

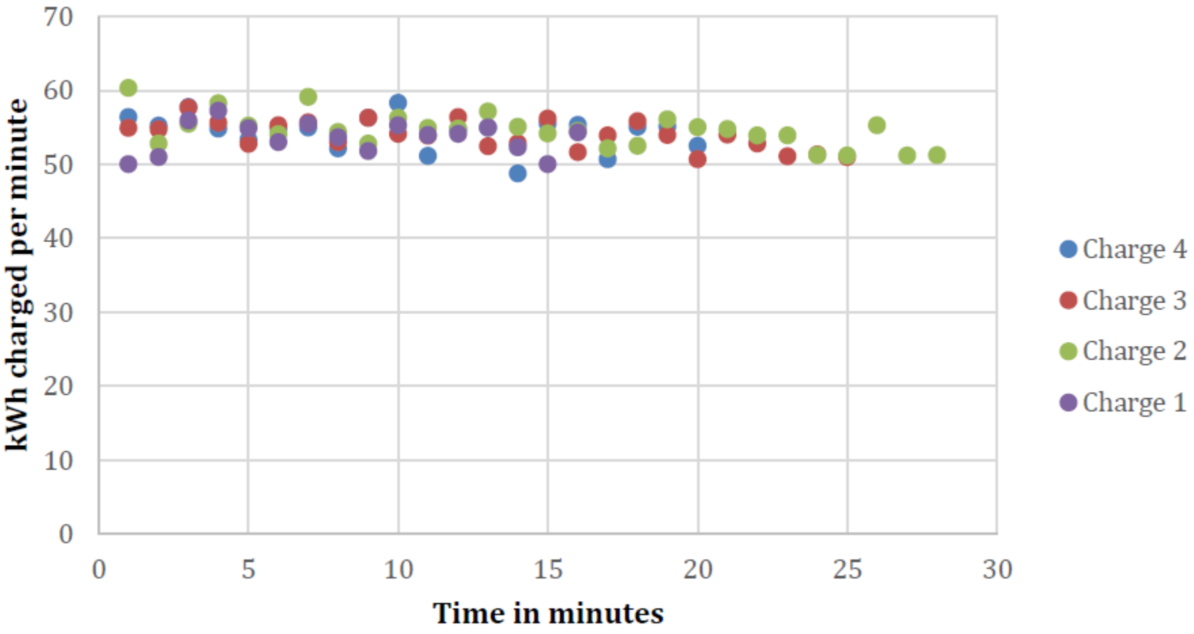


Figure 5. Charged kWh per minute on four charging breaks. (Source: http://e-ferryproject.eu/Portals/0/InfoPackage/eFerry_Information_Package.pdf. Accessed: 15 Jul 2023)

Data regarding energy charged per minute is obtained directly from the Power Management System aboard the ship, which however does not take into account any potential losses. As reported, energy efficiency from shore to battery (charging process) has been determined to be a factor of 0.92, translating to an 8% loss. Comparing the anticipated maximum charge per minute of 66.6 kWh to the highest achieved charge (60 kWh per minute), there's a discrepancy of approximately 9.9%, which is slightly more than the calculated loss, which however may translate to inaccuracies in the data input, as reported in the last information package of the project.

However, while initial tests show very promising results regarding charging speed, when tested during operation charging speed seems to drop even more. Specifically, it is reported that charging speed is highly related to State-of-Charge (SoC) levels, and is mostly effective below 80% SoC, which is 300kWh. This is better shown in the following figure, where there is a clear “flattening” of the charging lines when reaching above 3000kWh.

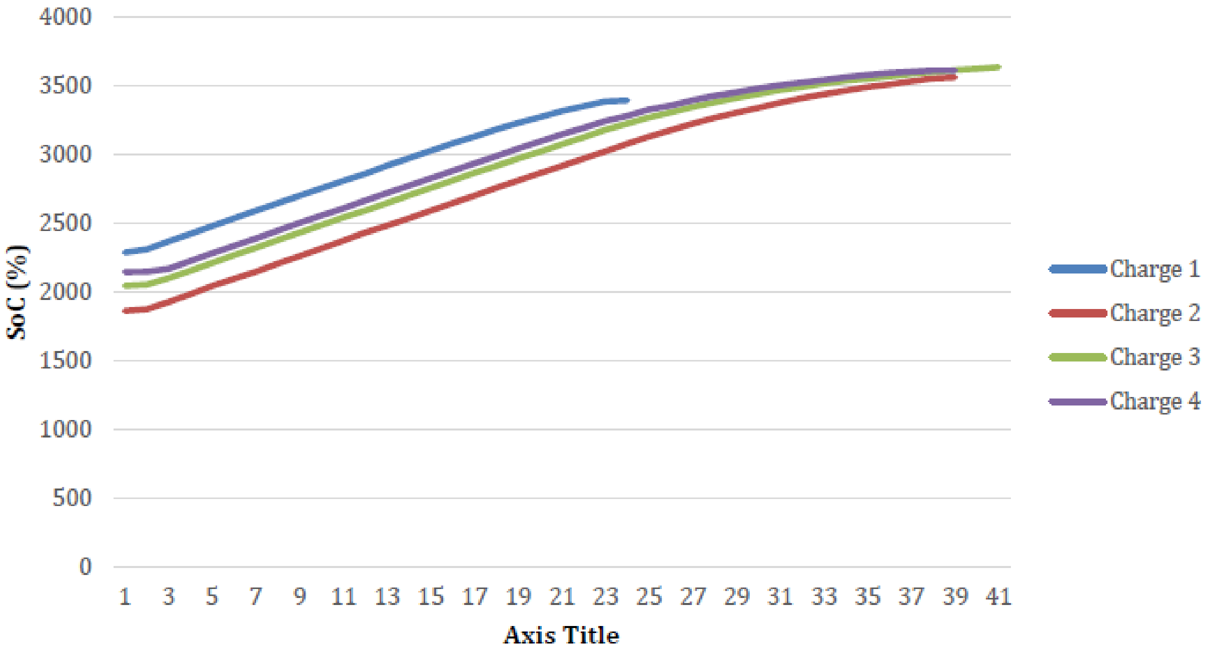


Figure 6. Charging break pattern in relation to operation schedule on Apr. 1, 2020 (Source: http://e-ferryproject.eu/Portals/0/InfoPackage/eFerry_Information_Package.pdf. Accessed: 15 Jul 2023)

Understandably, the higher the SoC of the E-ferry batteries before initiating charging, the faster the 80% level will be reached. Considering this along with the duration of continued charging beyond the 3000kWh levels and the resulted decreases in efficiency, the four charging intervals of an operational day for the E-ferry yield greatly differing efficiencies concerning the average quantity of kWh charged per minute, as shown on the following table.

Table 2. Efficiency of charging time with current E-ferry operation schedule (Source: http://e-ferryproject.eu/Portals/0/InfoPackage/eFerry_Information_Package.pdf. Accessed: 15 Jul 2023).

Charging break no.	SoC at charging start	Minutes charged	kWh charged	kWh per minute (average kWh/min)
1	60%	24	1105	46
2	49%	39	1696	43.5
3	54%	41	1589	38.8
4	56%	39	1463	37.5

Initial estimates of the project for energy losses or energy efficiency factors were set at 0.95 for the charging phase (grid to batteries) and 0.92 for power usage during operation (batteries to propeller), thus implying an estimated total loss from transformers to propellers of 0.87. Potential energy losses identified and evaluated result in higher energy losses from the grid to the batteries than initially projected, with almost a 3% deviation.

As the E-ferry Ellen will be utilized in this study as the basis for zero-emission route assignment, the aforementioned data are crucial for not only quantifying energy needs for the operation of the zero-emission fleet, but also to generate results regarding port times and total travel times to each port of the network. Considering the aforementioned test results of the E-ferry Ellen, there are specific characteristics that will be taken into consideration in the design and planning process while introducing such ferries. Most notably, a carrying capacity of 180 passengers is considered to evaluate whether such ferries can service specific islands of the network. In terms of energy consumption, an average energy consumption of 73kWh per nautical mile travelled is considered, while in terms of charging speed at ports, an average of 40kWh per minute of charging is assumed for the purposes of the study. Lastly, an average operating speed of 14 knots is used for travel time calculations in later chapters.

These assumptions are in line with the reported data of the latest E-ferry Information Package and will be considered on later stages of the dissertation, and included in all calculations made from this point forward. It is also worth noting that several other findings reported in the Information Package, such as operational and infrastructure related costs, economic, and societal evaluation results, while not in the scope of this dissertation, should be considered for any future study on zero-emission battery-powered ferries.

1.5. Research Scope and Objectives

In recent years, environmentally friendlier means of transport have shifted the attention of the research community towards alternative fuels and in some cases the electrification of certain transportation networks. In light of decarbonization efforts in the maritime industry, greener fuels and policies have increasingly gained popularity, while also bringing forth new opportunities and challenges in the design and planning processes of more sustainable maritime networks. Acknowledging that maritime networks can be highly complex, especially in regards to spatial and topological characteristics, the scope of this dissertation is to develop a methodological framework based on spatial data analytics and Geographical Information Systems (GIS) methods for planning efficient and sustainable maritime transport systems, considering decarbonization efforts and technological advances in the industry.

Reasonably, the successful integration of zero-emission battery-powered ships in maritime networks needs to consider several limitations, such as operational range constraints, energy supply and the necessary level of service (LoS) they offer to users. While there is an abundance of models for maritime network design, there have been very limited ones including the introduction of zero-emission routes, while close to none considering both their integration and spatial complexities of maritime networks as an interconnected aspect in the design and planning process. Therefore, operational constraints of such vessels and the need to simultaneously address network complexities dictate the need for introducing appropriate decision-making tools, and a framework which is specifically developed to support the design of sustainable and efficient maritime networks which include zero-emission routes.

To that end, the primary objective of this dissertation is the development of a comprehensive spatial decision support system (SDSS) for the design of zero-emission routes on maritime networks, oriented towards energy efficiency and sustainability, through the exploitation of battery-powered zero-emission ferries. In addition, technologies such as those described in the previous chapter can ensure fast energy transmission to fully electric-powered ferries, thus mitigating existing energy-related concerns and limitations, especially if energy supply can be achieved through renewable energy sources (RES). However, as charging can, for the time being, only be feasible during port calls, passenger travel times and overall network reliability is highly significant and challenging. As a result, policy-makers and operators are faced with even more challenging conditions to develop efficient decision-making strategies for the successful and reliable operation of such ferries in the effort of mitigating emissions and limiting the carbon footprint of their networks, while also focusing on providing passengers with adequate LoS, translated to acceptable travel times, overall accessibility, and network cohesion.

Especially in the case of Greece and its domestic maritime network in the Aegean, the Greek Coastal Shipping Network (GCSN), accessibility and cohesion issues, and fleet renewal needs have all been highlighted in numerous studies in the past (Gagatsi et al., 2014; Panagiotopoulos & Kaliampakos, 2019; Schinas, 2009; Spilanis et al., 2012). To address such issues and better evaluate where these are present, the dissertation initially aims to develop GIS-based databases to monitor and assess regions of the network where accessibility, cohesion, and environmental interventions are necessary. A comprehensive GIS-based framework exploring spatial patterns of overall port connectivity, passenger traffic demand and high emission areas is proposed, utilizing available data collected from several sources.

Overall, the dissertation aims to highlight the need for the inclusion of the spatial aspect of maritime networks, especially regional ones, in their design and planning process, as this brings up the necessity and challenge for new approaches, actions and strategies for the successful operation of more sustainable, efficient, and cohesive maritime networks. Consequently, the scope of this dissertation is to explore and develop spatial analytics-based methods for the assessment and monitoring of certain aspects of maritime networks, along with their design under zero-emission route considerations, thus highlighting the importance of spatial analytics and methods in an industry where these are highly under-utilized.

1.6. Research Methodology

The first step of this dissertation was to identify the research objective and the determination of suitable spatial-based methodological frameworks. Related problems of the research included evaluating the environmental footprint of the network, cohesion and accessibility issues of ports under study, and the overall data-driven spatial dynamics of the network considered. As spatial characteristics are considered highly important for the network under study, it is noted that the proposed methodological framework aims to address a spatially complex problem (SCP), that of the design of a cohesive, environmentally sustainable, and efficient maritime network.

As the problem defined has several aspects that need to be considered and proposes a novel methodology, both in terms of the methods used and the integration of zero-emission fully electric ferries, the state-of-the-art review focuses on two distinct aspects. First, as an initial evaluation of the network's structure and environmental footprint was necessary to compare initial and resulted states, the review initially addressed methodologies considering emissions monitoring through spatial analysis techniques and specific focus on the geographic extent of maritime GHG emissions, considering both global and international networks and more regional ones. Secondly, as a novel mitigation strategy is considered, that is the introduction of zero-emission routes, performance comparisons between the more novel approach proposed and conventional methods were more than necessary. Consequently, a review of existing slow steaming strategies is provided, in order to gain a more comprehensive view of one of the most commonly used strategies for fuel savings and emissions mitigation from maritime operations.

As slow steaming is addressed, as a more conventional strategy for emissions mitigation, electrification in the maritime industry is also addressed in the state-of-the-art review. As the introduction of zero-emission routes consists one of the main components of the dissertation, a clear gap is noted in the literature review regarding the incorporation of zero-emission routes considerations in the design and planning process of maritime network structures. As most studies still mostly focus on technical aspects of electrified maritime transport, economic evaluations, and charging infrastructure related issues, a clear lack of a comprehensive methodological framework for the establishment of such routes is shown. In addition to this, as the establishment of such routes is clearly connected with operational range constraints, at least up until this moment, network complexities and topologies need to be addressed. As a result, a review of spatial data analytics and the utilization of spatial methodologies also shows a lack of such methods in the design and planning process of maritime transport networks, or at the very least a clear under-utilization, as such methods and spatial data analytics overall are only being used in emissions monitoring and maritime safety studies.

As this study focuses on the integration of zero-emission routes to the design of maritime networks, energy supply of such routes is crucial. To that end, the study presents a concise review of how spatial analysis methods can also be used to address the issue of renewable energy source (RES) potential in certain areas of interest. As several studies have focused on multi-criteria site evaluation and selection for the establishment of RES facilities and related infrastructure, this dissertation also considers such preliminary evaluations to be pivotal in the design process. This approach considers the fact that if certain regions are not characterized by high potential in terms of RES infrastructure will in turn not be able to independently cover their energy supply needs and be self-sufficient and, as a result, will not be truly considered areas of zero-emissions in the future.

In addition to all related evaluations and overall assessment of the network's potential to transform some of its parts to zero-emission ones, quantitative evaluations are necessary to address network efficiency before and after the introduction of such routes and the restructuring of the network as a whole. On that note, a comprehensive review of studies focusing on the efficiency of maritime networks and ports is provided, showing that performance and efficiency evaluations have always been paramount in maritime transport. Key Performance Indicators (KPIs) have been one of the most common ways to measure the performance of maritime components, while more recently Data Envelopment Analysis (DEA) models have also supported such processes. As such methods have provided valuable insights on the performance evaluation of maritime components, a Slacks Based Measure Data Envelopment Analysis (SBM-DEA) model is also introduced in this dissertation to facilitate the performance assessment process of the ports of the network, in relation to network operations.

With this study focusing on the importance of spatial analysis methods and spatial data analytics overall in the maritime transport sector, the next step involved the development of a GIS-based methodological framework for the evaluation of the geographical aspects and relationships of each aforementioned aspect of the network and its components. After investigating such aspects and highlighting their importance in understanding network operations and port relations, the main goal of the study was to propose a comprehensive and easily adaptable methodology for the restructuring of the network, while taking into account its topological aspects and complexities, areas where targeted interventions are necessary, and the country's legislative framework.

The first part of the dissertation was to assess the environmental footprint of the network and the areas where CO_2 emissions show high clustering. To do this, after the creation of the relative databases and their incorporation to GIS environments, different spatial autocorrelation models were utilized to assess whether emissions show specific spatial patterns and, therefore are distributed in specific ways and areas. As the workflow suggests, in case global spatial autocorrelations models result in specific spatial patterns, Local Indicators of Spatial Association (LISAs) are utilized to assess where exactly such specific patterns exist. More specifically, global models are the answer to "if" there is specific spatial distribution, or spatial patterns, while local models answer to "where" such patterns are found. As the network's routes are operated by different kinds of ships with different characteristics, especially in terms of fuel consumption, and therefore emissions generated, an analysis of areas where ship traffic is high would not be enough, due to the fact that certain ships are more polluting than others. This approach offers a more suitable way to not only address where areas of higher CO_2 concentrations exist, but also show whether there are direct connections of such areas with certain less energy efficient ships of the fleet.

In order to assess whether the environmental footprint of the network can be limited, while operating with the existing fleet, slow steaming scenarios are introduced in the study based on existing studies for fast and large RoPax vessels. These scenarios are introduced for two reasons. First, to evaluate whether slow steaming alone could limit the environmental footprint of the network, and secondly, to provide a benchmark for its comparison in terms of emissions mitigated with the more modern approach of the introduction of zero-emission routes. For the introduction of zero-emission routes, a more novel approach utilizing LISAs is considered, that of the Bivariate LISAs. The Bi-LISA approach is part of the multivariate LISAs domain, where in contrast to their univariate counterpart, additional variables are considered to assess spatial relationships. For the introduction of zero-emission ferries and the identification of zero-emission routes, there are two important variables to consider. The first variable considers port passenger traffic, due to the fact that battery-powered electric ferries have a maximum passenger capacity and, therefore, cannot service ports of higher passenger demand. The second, considers a port's geographic location and relation to other ports, by considering the number of ports that can be possibly reached from said port accounting for the operational range constraints of a battery-powered electric ferry. Consequently, in case results show specific areas where there are both ports of high variables under study and ports of low traffic but high number of ports reached by battery-powered electric ferries, a sub-network can be introduced in such areas.

However, one of the main drawbacks of this method is the need for clusters to exist, which in turn may result in some low-demand ports in close proximity to higher-demand ones to not be considered as ports to be serviced by battery-powered electric ferries. In order to rectify this, an additional evaluation of remaining ports of the dataset is considered, which accounts for the aforementioned variables by assessing whether there are remaining ports of low passenger demand in proximity to others which can be reached by the operating range of an electric ferry. To successfully address this, a GIS-based model is developed which generates all possible routes within electric ferry range from each port of the study, considering obstacle routing, thus accounting for the topological characteristics of the network. As a result, in addition to the preliminary Bi-LISA results, all islands and ports that can be serviced through electric ferries are found.

The next step is the overall restructuring of the network, which follows a cluster-first route-second approach. As the dataset of ports under study is reduced to only the ports that cannot be serviced by electric ferries, routes between such ports need to be designed. In order to provide the best possible service for such ports, density-based clustering through Density Based Scanning Algorithm with Noise (DBSCAN) methods is utilized to identify clusters between the remaining islands based on distance constraints. The approach incorporates the main points of the existing legislative framework, regarding minimum connections between clusters, main regions of study, and the mainland, while also focusing on establishing the zero-emission routes, independently to the design of the main routes for each cluster generated. While this results in islands serviced by zero-emission routes to be highly dependent on ports of the cluster to which they belong, the proposed routes aim to provide better level of service through acceptable travel times, connectivity, and also limit the environmental footprint of such ports, leading to truly zero-emission islands.

Lastly, efficiency indices are created for each port of the study, focusing on connectivity, environmental and passenger traffic aspects. To provide better insights on whether the proposed approach for the restructuring of the network can potentially achieve better environmental efficiency, while also retaining or improving the provided level of service, results from the created indices are compared, additionally to new travel times for each port connection with the mainland. These results are also supported by the development of an SBM-DEA model to assess overall port efficiency based on the aforementioned aspects of each port, in relation to network operations. The goal of the proposed methodological framework was to propose a novel approach and the necessary tools and methods to policy-makers and operators, through the development of a spatial decision support system (SDSS) to be integrated in the design and planning process, in order to facilitate the creation of a more environmentally sustainable and connected network, thus improving overall accessibility and cohesion, while limiting environmental externalities.

The dissertation outline, as described above, is shown in the following figure.

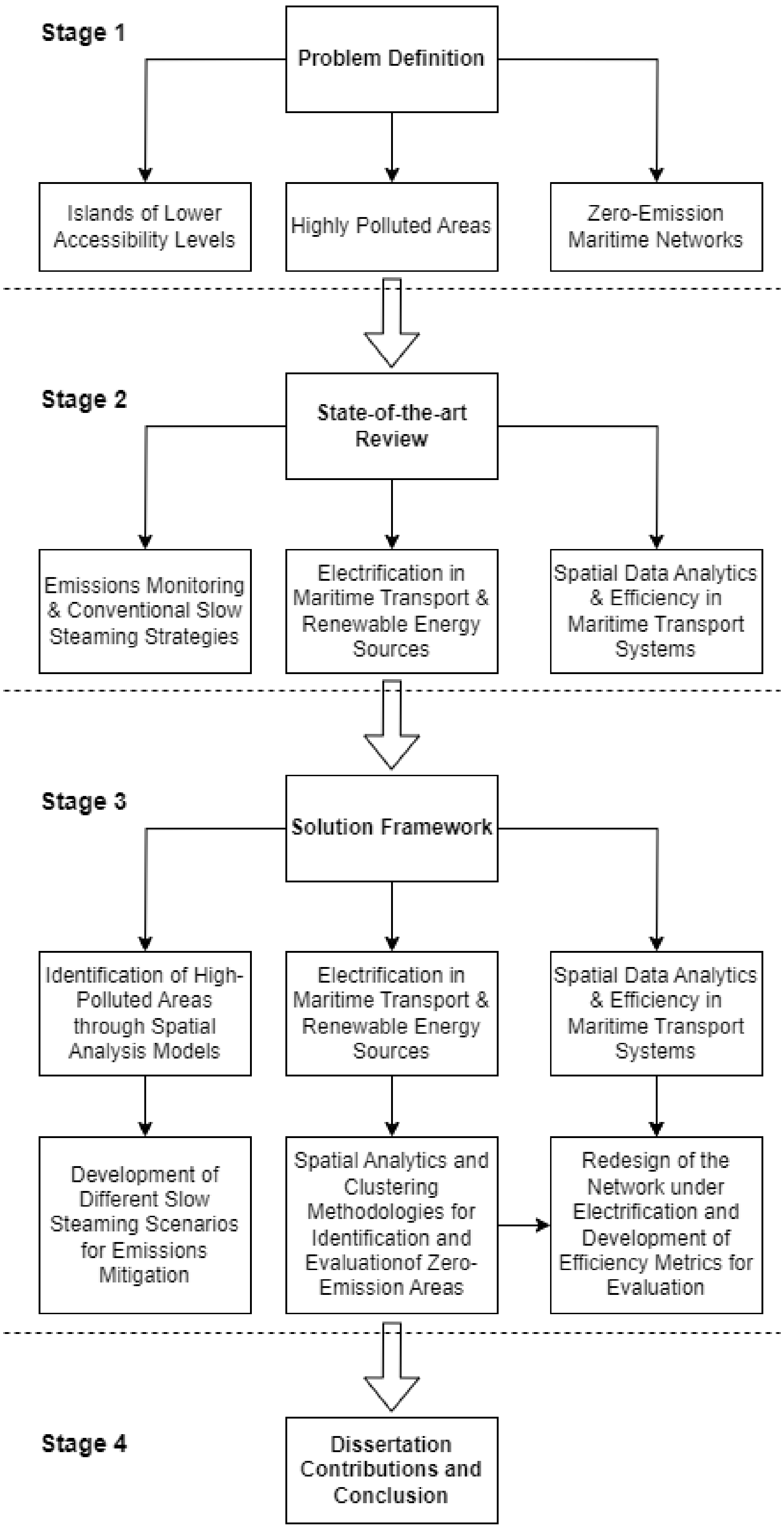


Figure 7. Dissertation Outline

1.7. Structure of the Dissertation

The dissertation main text is structured as follows:

1) The second chapter provides a comprehensive state of the art review, including all aspects addressed in the dissertation as follows:
    i. A review of studies on emissions monitoring through spatial analysis techniques
    ii. A review of studies on conventional slow steaming strategies
    iii. A review of studies on electrification in maritime transport
    iv. A review of studies on the utilization of spatial data analytics in maritime transport
    v. A review of studies on the identification of potential areas for the establishment of renewable energy source (RES) facilities for energy supply
    vi. A review of studies on the efficiency and performance evaluation in maritime transport systems
2) The third chapter provides a methodological framework for emissions monitoring and implementation of slow steaming strategies under different scenarios, through the utilization of collected data and their integration to GIS environments; the models, strategies implementation and generated results are presented.
3) The fourth chapter focuses on the establishment of zero-emission sub-networks through Bi-Variate LISA applications; methodology and results for two regions considered are presented.
4) The fifth chapter provides the methodological framework for the restructuring of the network under spatial considerations, and the development of efficiency indices for the network's ports, supplemented by results from the development of an SBM-DEA model; methodology, and results are presented before and after the restructuring of the network.
5) The sixth chapter summarizes conclusions of the dissertation and paths for future research.

Finally, a list of related publications to the current dissertation is provided at the end of the text.

2. STATE OF THE ART REVIEW

2.1. Maritime Transport Emissions

Over the past several years, a variety of strategies have been employed within the shipping sector to adhere to the stringent environmental regulations imposed by the International Maritime Organization (IMO). These methods, inclusive of slow-steaming, route optimization, and hull fouling management, reflect an industry-wide attempt to diminish the environmental footprint associated with maritime transport. Nevertheless, it's important to note that these strategies have only resulted in a relatively modest decrease in emissions, approximating 10-15% as reported by Ammar (2018) and Cullinane and Cullinane (2013).

The IMO continues to pledge its commitment to reducing Greenhouse Gas (GHG) emissions, in accordance with the preliminary actions instigated during the 72nd Marine Environment Protection Committee (MEPC 72). This commitment is projected to culminate in a gradual limitation on the usage of fossil marine fuels by the year 2050, as anticipated by Raucci et al. (2017). The issue of air pollution stemming from maritime transport has been subject to increasing scholarly interest over the past few years, with researchers such as Aksoyoglu et al. (2016), Russo et al. (2018), and Zhu et al. (2022) making notable contributions in the field. Additionally, the relevance of spatial data analytics-based emission inventories has also been recognized as instrumental in efficiently overseeing the externalities arising from maritime transport (Johansson et al., 2017; Okada, 2019; Topic et al., 2021). While there are several studies assessing emission inventories and monitoring of shipping environmental externalities, there is a specific research gap regarding coastal shipping.

Considering emission studies integrating spatial analysis methods, the importance of spatial data analytics becomes clear. However, it is crucial to note a scarcity of studies in the existing literature that focus explicitly on the emissions resulting from domestic shipping and the incorporation of spatial data analysis, with only a handful of recent studies, most notably those of Buber et al. (2020) and Toz et al. (2021) providing an in-depth examination of this particular area. Emission inventory studies have deployed a variety of techniques for estimating emissions. These approaches generally fall into one of two categories: bottom-up or top-down methodologies. The utility of both these approaches has been explored and demonstrated in several studies.

For instance, the study of Aksoyoglu et al. (2016) offers a critical examination of the impact of marine transport emissions, particularly sulfur, on air pollution levels. Despite recent regulatory changes, emissions, especially outside the designated sulfur emission control areas (SECAs) and from other non-regulated components, have been on an upward trend over the past two decades. To address this, the researchers utilized a comprehensive air quality model to analyze the impact of shipping emissions on ozone and PM2.5 components as well as the deposition of nitrogen and sulfur compounds in Europe for the year 2006. Key findings include significant increases in particulate sulfate in the Mediterranean, the English Channel, and the North Sea, and increases in particulate nitrate in areas with high land-based NH_3 emissions like the Benelux region. Furthermore, the study found that not only do ship emissions affect atmospheric concentrations of pollutants, but they also significantly increase the depositions of nitrogen and sulfur compounds along shipping routes. The results obtained suggest that future emission developments from ships and land-based NH_3 will play a pivotal role in European air quality. The study highlighted the need for better regulation of maritime emissions and argues that despite increased sulfur regulation in recent years, the effects in Europe are currently limited, as the standards mostly apply to new vessels and there are no established NO_x Emission Control Areas (NECAs). The authors stressed that unless emission controls for existing vessels are strengthened and NECAs established, marine-derived nitrogen oxide emissions in European waters could match those from land-based sources by 2020. In addition, predicted increases in maritime emissions could offset the benefits gained from reductions in land-based emissions, posing significant challenges for future air quality management in Europe. The researchers suggest that for future air quality management, emphasis should be placed on improving emission inventories, especially for ammonia, a key precursor for secondary inorganic aerosol formation. They also note that a significant reduction in marine NO_x emissions could affect ozone formation and secondary inorganic aerosol formation due to changes in chemical regimes, providing valuable insight for future air quality regulations.

The study of Goldberg et al. (2019) provided an in-depth examination of the NO_x emissions inventory in Seoul, South Korea, utilizing a regional Ozone Monitoring Instrument (OMI) NO_2 product that had been adapted from the standard NASA product. Initial steps involved the development of a regional OMI NO_2 product. This was accomplished by recalculating the air mass factors with a high-resolution gridded (4 km × 4 km) Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) model simulation, which demonstrated improved proficiency in capturing NO2 profile shapes in urban settings. The model was then further refined by the application of a spatial averaging kernel. This modification allowed for consideration of subpixel variability, which is critical in areas of high spatial complexity. These two key modifications, recalculating the air mass factors and applying the spatial averaging kernel, resulted in OMI NO_2 values in the regional product that were substantially higher than those originally observed, particularly in urban and industrial areas. Additionally, the study implemented the top-down approach using both the standard and regional NASA OMI NO_2 products to determine NOx emissions in the Seoul metropolitan area during the KORUS-AQ field campaign. The resulting data revealed significant underestimations in NO_x emissions when compared to the bottom-up inventory. To complement the findings, the research team also compared the NO_2 and NO_x values simulated by WRF-Chem to observations acquired by aircraft. This revealed a model underestimate. A doubling of NO_x emissions in the WRF-Chem model for the Seoul metropolitan area resulted in a better alignment with KORUS-AQ aircraft observations and the recalculated OMI NO_2 tropospheric columns. This suggested that changes in model resolution had a more substantial effect on the Air Mass Factor (AMF) calculation than alterations to the South Korean emissions inventory. Conclusions emphasized that the results were specific to the Seoul metropolitan area, taking into account the complex geographical features of the region. The study demonstrated a solid methodological framework for improving the understanding of NO_x emissions and atmospheric NO_2 columns in specific urban regions, while also being adaptable and easily applied to other world regions using other satellite datasets to produce high-quality, region-specific, top-down NO_x emissions estimates.

The research of Czermański et al. (2021) provides an in-depth examination of container shipping emissions, their reduction, and their overall impact on the environment. Container shipping, being the most significant emission producer within the maritime shipping industry, has necessitated various measures to curtail its emission levels, as highlighted in the researchers' comprehensive study. Their study utilizes an energy consumption approach to estimate container ship emissions, including sulfur oxide (SO_x), nitrous oxide (NO_x), particulate matter (PM), and carbon dioxide (CO_2), based on 2018 datasets on container shipping and average vessel speed records. Importantly, their approach estimates ongoing emission reductions continuously, effectively filling data gaps, as the most recent global container shipping emissions records were from 2015. Their findings present container shipping as one of the top-ranked emission activities, emphasizing the magnitude of air emissions generated. They point to a promising reduction potential in principle pollutants and air emissions after 2020 in conjunction with global cap requisites. According to their research, the anticipated reduction in SO_x may reach an impressive 85%, while PM could potentially see a 33% reduction. Once the Tier III limit is fully implemented post-2021, NO_x reduction could reach around 80%. However, they predict a paradoxical swell in CO_2 emissions due to a transition to low-sulfur marine gasoil (LSMGO) fuel and increased energy demand from scrubbers and Selective Catalytic Reduction (SCR). The research acknowledges the probable impact of future IMO regulations related to the Energy Efficiency Design Index (EEDI), which may stimulate development of innovative and cost-effective propulsion systems. They highlight various energy-related solutions to improve efficiency, such as alternative propulsion via liquefied hydrogen fuels or electricity, new ship propulsion technology in response to the EEDI's increasing energy efficiency standards, and innovative design and modification features for both new and existing ships. They also advocate for a detailed consideration of ship speed in emission estimates as emission levels are highest at sea. In addition, the authors argue that the demand for container shipping is likely to increase in the long term, thus necessitating the industry's commitment to emission reduction. The energy consumption approach they present offers a way to estimate current emission levels and potential reduction areas accurately, filling in the data gaps left by the absence of updated records from international organizations. They emphasize the approach's value in aiding the early-stage detection and continuous monitoring of environmental impacts. The authors conclude that the container shipping industry's commitment to reducing its ecological footprint is not just crucial for achieving sustainable development goals, but is also needed to ensure its future operation license.

Froemelt et al. (2021) developed a detailed, spatially-resolved modelling framework that supports policymakers in deriving effective environmental interventions by providing quantitative information on local consumption patterns, production systems, and policy scenario outcomes. The model merged the strengths of top-down and bottom-up approaches and was tested through two case studies, combining a highly detailed bottom-up model for Switzerland, focusing on individual households, with a top-down macro-economic approach through a newly developed Swiss sub-national, multi-region input-output model. The first case study computed production-based greenhouse gas emissions and consumption-based carbon footprints for all Swiss cantons. The study found that rural cantons have higher production-based emissions per gross domestic product than more urban cantons due to different economic structures. Conversely, city cantons have the highest consumption carbon footprints per inhabitant due to high per-capita gross capital formation. The second case study assumed a lifestyle change for an individual household, including a complete physical retrofit of the home. The regional environmental and economic consequences along the supply chains were evaluated, highlighting the usefulness of the modelling framework for informing policymakers about the expected benefits and potential downsides of specific interventions. Notably, the second case study underscored the importance of considering rebound effects. These are situations where improvements in resource efficiency led to increased resource consumption due to behavioral or other systemic responses, with their newly developed modelling framework being able to quantify the variability of environmental impacts in a particular area and allowing for highly detailed policy scenario computations. Furthermore, their study assisted in the identification of where and at which scale impacts may occur, thus indicating which issues can be controlled within a particular jurisdiction, thus assisting in involving important stakeholders, whether along supply chains or at different governmental levels.

A recent study by Doundoulakis & Papaefthimiou (2022) employed reported real data for actual fuel consumption from the EMSA/MRV-THETIS database to evaluate the validity of their estimated results. In their study, they set out to perform a comparative analysis between estimated and actual fuel consumption and CO2 emissions. A few years ago, reports detailing actual fuel consumption were collected from ship owners to determine expenses on each trip. While these reports were not publicly available, nowadays due to the requirements of EU MRV regulation, ship owners report data including fuel consumption and CO2 emissions, leading to the availability of the EMSA/MRV-THETIS database. In their study, they followed the bottom-up methodology presented in a recent publication where the fuel-energy consumption and air emissions of ships were calculated, with their produced results compared to reported emissions data from the EMSA/MRV-THETIS database (MRV). This comparison revealed a small difference in the results (about 6–12%), proving the reliability of the bottom-up methodology for this geographic area and ships in study. Their paper concluded by highlighting the significance of the EMSA/MRV-THETIS database in providing actual fuel consumption and CO_2 emissions data from ships, which is crucial for researchers involved in the calculation of air emissions in shipping. The study followed the bottom-up methodology to calculate the fuel consumption and CO_2

emissions of ships for the year 2020 and compared the results to reported emissions data from the database. The difference in total fuel consumption was about 6.14–12.07%, and the difference for total CO_2 emissions was about 5.66–11.85%.

While in this dissertation the aforementioned data are also utilized to provide insight regarding emission monitoring in Greece, it's important to underline that these data serve a distinct purpose; to provide a benchmark on two instances. First, to evaluate the initial results of slow-steaming strategies and whether these could be sufficient in themselves to restrain the environmental footprint of the network. Secondly, on providing a benchmark on the overall efficiency evaluation of ports and routes of the network, which will be thoroughly described on later chapters. Therefore, the intention of the study through the utilization of such data was not to contrast estimated and reported actual data, but to provide a methodological framework for assessing the environmental viability of slow-steaming and other emission mitigation strategies.

2.1. Conventional Slow Steaming Strategies

Over the past several years, the maritime sector has been increasingly recognizing the potential of slow steaming as an effective greenhouse gas (GHG) mitigation strategy. While the deployment of this particular GHG reduction tactic has been extensively scrutinized within the realm of liner shipping, particularly in the context of containerships (Cariou, 2011; Woo & Moon, 2014), it is continuing to garner attention as a potential long-term solution to achieve the decarbonization of the shipping sector.

The effectiveness of the slow steaming approach, when implemented by shipping companies, is inherently tied to the volatility of bunker prices. This connection stems from the fact that slow steaming is primarily a strategy to minimize fuel consumption, which in turn can result in substantial cost savings. In this regard, Cariou (2011) has highlighted the potential for the strategy to be sustainable in the long term, provided that bunker prices persist within a break-even threshold of $350-$400. In the context of this study, it's important to note that the bunker prices for most conventional fuels still employed in the shipping sector remain above the aforementioned break-even price point. This observation is grounded in data reported by World Bunker Prices (Ship & Bunker, 2023).

Recent research continues to recognize slow steaming as a potentially viable GHG mitigation strategy in the maritime sector, despite the fact that the bulk of existing literature remains primarily concentrated on the process of decarbonization from liner shipping, particularly from containerships. For instance, in the study of Gospić et al. (2022), two major decarbonization strategies were considered, including slow steaming and gasification, in the context of a container ship route between Shanghai and Hamburg, by utilizing computational fluid dynamics and potential flow theory to calculate resistance, propulsion characteristics, and added resistance in various sea conditions to determine fuel consumption and CO_2 emissions. Pelić et al. (2023) also investigated the effects of slow steaming, although highlighting that its efficiency highly depends on the ship's design speed, size, and travel conditions of the examined area. Although noting that applying slow steaming to large, medium, and high-speed ships can significantly cut fuel costs and environmental impact without requiring substantial additional investment, it is also underlined that market conditions, as well as the customers' and passengers' willingness to accept longer travel times need to be considered.

In addition to slow steaming, numerous studies have also assessed the impact of various other potential decarbonization strategies. Some of these strategies include exploring advancements in power systems (Pan et al., 2021), alternative fuels, and policy-related measures (Balcombe et al., 2019), all of which could contribute to more efficient reductions in CO_2 emissions. This cumulative body of research suggests a multi-faceted approach towards mitigating GHG emissions, recognizing the potential of slow steaming while also exploring other promising avenues to achieve more sustainable maritime transport.

As made clear by the abundance of relative studies, slow steaming continues to be a significant point of interest in the literature, as a potential strategy for reducing CO_2 emissions within the shipping sector. Concurrently, there's an escalating interest to broaden its application beyond just containerships, and to evaluate its effectiveness on more localized or regional scales, as opposed to just the global level typical of containership trade. While the body of literature is abundant in the analysis of slow steaming strategies as they pertain to liner shipping and containerships, other types of shipping have also been subject to similar scrutiny. Specifically, the adoption and compliance of RoRo and RoPax shipping companies with respect to slow steaming measures have been studied (Raza et al., 2019). Additionally, a number of studies have zeroed in on the overall impact of slow steaming at a more regional level, such as in the Mediterranean (Degiuli et al., 2021).

However, an apparent limitation emerges when considering the literature concerning the evaluation of slow steaming strategies in the context of domestic shipping and fast ships. In fact, only a few studies have delved into this particular aspect, with the works of Psaraftis and Kontovas (Psaraftis et al., 2009; Psaraftis & Kontovas, 2009) being the most notable. In their study, Psaraftis et al. (2009) highlighted that while high-speed vessels yield higher emissions per tonne-km, reducing their speed could have significant implications for the shipping industry, such as the need for more ships and increased cargo inventory costs. Therefore, while speed reduction appears a straightforward method for decreasing emissions, its side-effects can lead to non-trivial costs, potentially making it less cost-effective. The study also emphasizes that speed reduction's effectiveness strongly depends on the possibility of reducing port time, highlighting the critical role ports play within the intermodal supply chain. As a result, addressing shipping emissions involves a multi-faceted approach that goes beyond operational changes on the ship, incorporating broader logistical considerations and an overall efficient supply chain management. The research of Psaraftis and Kontovas (2009) also provided an in-depth analysis of CO_2 emissions from the world's commercial fleet, utilizing data from the 2007 Lloyds-Fairplay world ship database. Different ship types such as bulk carriers, crude oil tankers, container vessels, and others were considered, and emissions were estimated both in terms of grams of CO_2 per tonne-km and total CO_2 produced annually, with the study providing a comprehensive emissions inventory which is crucial for researchers and policymakers in implementing relevant environmental regulations. However, the authors recognized that the study's findings are influenced by the quality and availability of data used, with more precise results requiring additional data, including worldwide ship movements and exact bunker consumption figures for the global fleet. In addition, the authors highlight the need for understanding regarding the relative impacts of different ship types and sizes on CO_2 emissions, which is valuable for prioritizing measures to reduce greenhouse gas emissions in shipping, as addressing GHG emissions from shipping is a complex task with substantial differences in opinions on how to proceed, indicating the need for collaborative approaches.

While the literature regarding the environmental impact of the maritime industry is extensive, domestic passenger shipping and the environmental externalities it generates has not been as thoroughly examined as other areas of maritime transport. Recognizing this research gap, parts of this dissertation intend to address this unexplored domain in the existing literature. To that end, one of the main goals of the study is to provide a robust methodological framework designed for the evaluation of CO_2 emissions and their spatial distribution. This will further involve assessing the implications of implementing conventional slow steaming strategies under various scenarios to assess the efficiency of CO_2 emissions reduction through such methods. By doing so, the goal is to extend the literature on the specific topic, contributing valuable insights into the potential of slow steaming within the context of domestic passenger shipping, while also comparing such strategies with the implementation of more aggressive strategies, such as restructuring the network with the introduction of zero-emission ships.

2.3. Electrification in Maritime Transport

In the current landscape of maritime transportation, strategies such as slow-steaming, route optimization, and hull fouling management have been implemented widely within the shipping sector as a means to comply with the International Maritime Organization's (IMO) environmental footprint regulations. Nevertheless, the tangible impact of these strategies has been relatively limited, with an overall reduction in emissions capped around a modest 10-15% (Ammar, 2018; Cullinane & Cullinane, 2013). One of the main reasons for this subdued impact is that these strategies predominantly focus on optimizing engine efficiency. This approach often overlooks the potential of green technologies and the utilization of renewable energy sources, which could significantly enhance the sector's environmental footprint (Koumentakos, 2019). The IMO has shown its ambition for future sustainability by outlining its intent to phase out fossil marine fuels by 2050 (Raucci et al., 2017). This commitment reflects the initial actions taken during the 72nd Marine Environment Protection Committee (MEPC 72) and is anticipated to undergo review in mid-2023 to develop a revised and more ambitious greenhouse gas (GHG) strategy (MEPC 80).

The concept of ferry electrification has emerged as a leading candidate in the pursuit of sustainable maritime transportation. It has gained significant traction in recent years, particularly as a strategy to mitigate the environmental footprint of the maritime sector. Several pioneering cases have already seen the operation of both hybrid-electric and fully electric ferries, with Scandinavian countries trailblazing the implementation of policies that encourage the transition to electric fleets (Sæther & Moe, 2021; Tarkowski, 2021). However, the road to ferry electrification is not without obstacles. As reported by Koumentakos (2019), challenges related to performance and cost efficiency can hinder the successful implementation of this initiative, often confining the transition to electric ferries to shorter sea maritime routes. In this light, numerous studies have investigated various aspects of ferry electrification, including technology, costs, and environmental impact.

Bellone et al. (2019) investigated the development of public transportation in the region of Vastra Gotaland in Western Sweden, which has recently seen a significant increase in public transport usage. This trend is expected to continue, leading to a predicted doubling of public transportation journeys by 2025. In response, capacity is projected to increase by 70% and travel times are expected to decrease by 20-25%. Alongside these developments, efforts are being made to transition to more environmentally friendly means of transportation through the use of alternative fuels, electrification, and increased automation. Their research strategy involved a thorough literature review and case study with Styrsöbolaget, a shipping company. The goal was to identify barriers and problems the company faced during the transition to battery operation and automation. Major issues highlighted included the current state of battery technology, charging infrastructure, and automation-related challenges such as autonomous docking, fleet trajectory optimization, and monitoring using new Artificial Intelligence (AI) technologies. The authors concluded that public transport worldwide is projected to significantly increase in volume. The study revealed that two ferries in Gothenburg are prepared for battery operation but have not yet converted due to technical, logistical, operational, and business challenges, with one potential solution being the use of induction coupling between ferries and quays for battery recharging. However, the technicalities of this fast connector still require further exploration, with the authors emphasizing the need for future research to focus on developing simulations to evaluate and optimize technological solutions to overcome the existing challenges. They suggested that employing AI techniques could enable route optimization, thereby minimizing energy consumption while adhering to given timetables, while also arguing that their research could provide valuable insights for the development of regulatory measures to address the current gap in regulations.

Reddy et al. (2019) delved into the relevance of autonomous passenger ferries as a sustainable solution to escalating congestion and pollution in urban areas, noting that approximately 40% of the global population resides near a coast, with urban centers typically located near the sea or along rivers. This is particularly evident in Norway, where a significant percentage of the population lives in coastal areas abundant with waterways like canals and fjords. As building bridges over these water channels can prove to be expensive and may obstruct marine traffic, urban ferries extend beyond mere tourist attractions and form an essential component of the city's multimodal transportation system while having a crucial role in mitigating road traffic and congestion. The study highlights that autonomous operation of passenger ferries, especially in light of technological advancements enabling higher levels of autonomy and emission-free energy systems, can offer a promising solution to zero-emission ferry transport, while autonomous passenger ferries could also address congestion issues. In addition, the benefits of autonomous ships extend beyond environmental advantages, as they can also reduce operational costs by up to 30%, enhance safety and reliability, optimize fuel usage, and provide increased opportunities for waterborne cargo transportation. However, numerous this study also notes that challenges need addressing for autonomous ferries to become viable sustainable transportation solutions. These include ensuring easy access for passengers, developing sensor fusion for situational awareness, interacting with manned ferries for collision avoidance, and optimizing emission and maintenance free energy systems operation.

Vicenzutti et al. (2020) examined the impact of electrification on a double-ended ferry, highlighting the increasing sensitivity towards environmental protection and emission reduction in maritime shipping. Due to stricter regulations on pollutants, adopting alternative onboard propulsion and energy generation systems is becoming a necessity with electrification presenting a promising solution to reduce pollution, providing flexibility in strategies employed for the onboard system. Moreover, combining a hybrid-electric system with the use of green fuel can potentially enhance emission reduction. Despite being the most environment-sustainable transport means for cargo and passengers globally, maritime shipping is grappling with reducing ships' pollutant emissions, as particular emphasis is on emission reduction within harbor and coastal areas, where vessels operate far from their optimal working points, leading to increased pollution. The shipping industry is forced to adopt “greener” solutions for new vessels or refit the propulsion systems of existing ones to enhance sustainability and decrease environmental impact, with three strategies currently being technically feasible; using ecological fuel, installing onboard exhaust gas treatment equipment, or resorting to the vessel’s electrification. The study presented a redesign and analysis of a ferry, utilizing a methodology considering various aspects of ship design and utilizing statistical analysis of existing ships and routes to define a mean operating profile for the ship being designed. Using proprietary algorithms, it was possible to analyze results achievable by different vessel configurations, although some elements, such as CO2 emissions related to the electrical energy supplied by the shore to the ship, have not been evaluated, as these depend on port electricity contracts and the potential presence of renewable energy sources in the port. Such issues also exist in the automotive sector, where the real impact of electric cars can't be assessed without analyzing the specific energy mix of the electricity grid to which the recharge stations are connected. The goal of the research was to analyze and propose solutions for green maritime transportation in the Adriatic area, emphasizing on integrated approaches, including ships, ports power systems, specific routes, and passenger/goods flows, in order to facilitate the decision-making processes considering tailor-made solutions to specific needs of each route.

Anwar et al. (2020) conducted a comprehensive review of vessel electrification in both industrial and academic contexts with the goal of developing knowledge and guidelines for the green transformation of vessels and ferries. Their study compared various pure electric and hybrid vessels based on performance attributes such as battery capacity, passenger and cargo capacities, and the size of the vessel. A distribution of vessels according to different countries and manufacturers was also provided, while the research further delved into the exploration of technical, operational, and legislative challenges associated with this transformation. The authors highlighted the maritime industry's significant role in the global transport of commodities, acknowledging its consequential impact on climate change, particularly near coastal areas. In the study, the European maritime economy, with its substantial ferry operations, was identified as a critical area for green transformation, with the authors highlighting that many ferries operating in Europe have not been updated in the last twenty years, thus contributing significantly to carbon emissions. The study also underlined the growing trend towards the electrification of ships through a hybridization process, which integrates various energy storage systems (ESS) and renewable energy sources (RES). Additionally, several challenges inhibiting the successful implementation of ferry electrification were discussed. Technical challenges included the long voyage distance of fully electric ferries and the need for battery charging during short port stays, necessitating specialized electrical infrastructure, while legislative challenges centered on energy regulations, such as taxes and ferry construction guidelines, are noted as not supportive enough to catalyze a shift towards green energy. Moreover, the study highlights that ferry crews require appropriate training to familiarize themselves with the new system's technical, operational, and safety issues. The authors also presented a knowledge development and implementation guide for ferry electrification, with their findings showing that Norway and Denmark are leading in ship electrification, and that two-thirds of electrified ships currently operate in hybrid mode, while the remainder are purely electric. They also revealed that the primary use of electric vessels is in transportation and tourism, although the most important issues considered in the study were the technical, operational, and legislative challenges for vessel electrification in the maritime sector, especially considering the need to protect the environment in port areas. Their study serves as an implementation guide for policymakers, academia, and other stakeholders to implement green energy in the maritime sector to reduce emissions and noise while improving performance and passenger satisfaction.

Kersey et al. (2022) undertook a comprehensive examination of the feasibility of the direct electrification of maritime vessels as a low-emission alternative to heavy fuel oil (HFO). International maritime shipping, primarily powered by HFO, has been recognized as a significant contributor to global CO_2, SO_2, and NO_x emissions. Despite this, the study also highlights that the electrification of maritime vessels has been largely underexplored, with the authors challenging outdated assumptions about battery cost, energy density values, and available onboard space. The study found that at battery prices of $100 per kWh, the electrification of intraregional trade routes of less than 1,500 km was economically viable with minimal impact on ship carrying capacity. Accounting for environmental costs extended this economical range to 5,000 km. The authors also projected that if battery prices fell to $50 per kWh, the economically viable range would nearly double. The study also presented a possible roadmap for the electrification of container ships within this decade, aiming to electrify over 40% of global container ship traffic, reduce CO_2 emissions by 14% for US-based vessels, and lessen the health impacts of air pollution on coastal communities, highlighting the urgency of identifying commercially viable zero-emission alternatives to HFO in the face of tightening regulations and the need to significantly curb the shipping sector's emissions to avert climate change. The authors highlighted ongoing pilot projects for battery-electric propulsion, suggesting it as a promising low-emissions alternative in the marine shipping sector, illustrating that battery-electric ships powered by renewable electricity offered a near-term pathway to reduce shipping emissions over intraregional and inland routes. The authors argued that future research should explore the overall economics of battery electrification, including opportunities for intermediate recharging en route and suggested that strategic adjustments to container shipping logistics, such as offshore recharging at major maritime chokepoints, could facilitate the electrification of long-distance transoceanic routes. Additionally, they pointed out that electrification provides several benefits over e-fuel alternatives, including global availability, cost-competitiveness, and potentially smaller capital cost, although concluding that while direct electrification is technically feasible and cost-effective, several challenges need to be addressed for commercial deployment. These include the high upfront costs due to existing battery prices and the need for large-scale, transmission-connected charging stations. The study also underscored the importance of policies such as financial incentives and regulations in supporting the transition to zero-emissions shipping.

A large part of the literature delves into the potential and feasibility of integrating electric vessels into maritime routes. Notable studies like those by Jeong et al. (2020) and Perčić et al. (2020) provide comprehensive lifecycle assessment analyses of ferry fleet electrification. Concurrently, numerous other studies have examined case-specific evaluations of electric ferry implementation, focusing on scenarios such as short-sea maritime routes, inland waterway corridors, and tourist boat cruises. For instance, Bianucci et al. (2015) aimed to evaluate the effectiveness of using an electric/hybrid ferry for tourist transportation, specifically in the context of the La Spezia Gulf and the surrounding natural parks in Italy. The study focused on defining the 'optimal' configuration for a ferry in terms of engine power, energy storage, photovoltaic system sizes, and the degree of hybrid or pure electric usage, considering factors like operating and initial costs, pollution, noise, and comfort. Given the limitations of battery storage systems, the study underlined the need for a well-targeted hybrid/electric system designed for the specific routes and stages in the transport service around the area. In addition, the study highlighted that while a hybrid ferry offers numerous advantages over a conventional engine ferry, the high cost and reduced energy density capacity of available electric energy storage systems present significant limitations in operations.

Bianucci et al. (2015) aimed to evaluate the effectiveness of using an electric/hybrid ferry for tourist transportation, specifically in the context of the La Spezia Gulf and the surrounding natural parks in Italy. Given the limitations of battery storage systems, the study underlined the need for a well-targeted hybrid/electric system designed for the specific routes and stages in the transport service around the area. The study also found that while a hybrid ferry offers numerous advantages over a conventional engine ferry, the high cost and reduced energy density capacity of available electric energy storage systems present significant limitations. The study of Bigerna et al. (2019) investigated the impact of tourism on environmental degradation through the tourists' willingness to pay for the introduction of an electric boat fleet to reduce CO_2 emissions. As demographic factors and visit duration times affected the willingness of passengers to pay, simulation results indicated the need for both price premiums and subsidies for the successful deployment of electric boats. Therefore, the research emphasized the role of public and private authorities in facilitating a transition to sustainable tourism, including the implementation of educational strategies to promote a model of tourism grounded in sustainability. Palconit and Abundo (2019) also focused on the potential of transitioning to green maritime transportation in the Philippines, by identifying potential sites and vessels suitable for electric ferry operations, targeting a total of 9201 vessels feasible for retrofitting with electric systems. The authors showed that retrofitting a vessel within the specified GRT ranges of the study, traveling 2.13 hours per day minimum and consuming 16L of fossil fuels, can reduce CO_2 emissions by 15.65 tons per year, while if all identified vessels were converted to green energy, it could result in a 22.09% reduction in CO2 emissions from the transportation sector.

More recently, Savard et al. (2020) investigated the feasibility of electrifying ship navigation along the Northern Sea Route (NSR), made more accessible by the ice retreat from the North Pole due to global warming. Their feasibility analysis took into account tonnage constraints for navigating the NSR, the cost of energy production, and the potential location of several ports. While under current economic conditions, the solution proved not profitable, as technologies and economic conditions evolve, the prospect of full electrification became more promising, with a hybridization stage of ships engines being necessary, especially due to the current economic advantage of heavy fuel oil-powered vessels. Perčić et al. (2021) focused on exploring and evaluating alternative power system configurations to lessen the environmental impact of inland waterway ships, specifically within the Croatian inland waterway sector. The developed models assessed the lifetime emissions and associated costs of different power configurations for three distinct types of inland waterway vessels; cargo ships, passenger ships, and dredgers, while accounting for GHG emissions. Their study concluded that while the battery-powered ship configuration with photovoltaic cells was the most environmentally friendly, its life-cycle costs were quite high, except for the case of passenger ships where this option was feasible. The results highlighted the fact that current national policies could generally influence the choice of more cost-effective but environmentally damaging diesel engines. Wahnschafft & Wolter (2021) also focused on the rising demand for environmentally friendly alternatives to conventional diesel-powered tourist boats, particularly in European cities renowned as tourist destinations, such as Berlin. The authors noted that while the shift towards environmentally friendly waterborne transport has been slow due to various business, regulatory, and policy barriers, there is a growing market for zero-emission tourist cruises and vessels. In addition, the study showed that several tourists are willing to pay a premium for eco-innovative options like electric boats, thus underlining the need for more effective marketing strategies targeting specific tourist groups, coupled with supportive public policy and funding, which can ultimately facilitate the commercialization of electric mobility on water.

In addition to the exploration of electrification, the literature also examines associated challenges such as the needs and placement of charging infrastructure, as well as integrated route planning and charging infrastructure planning. Most notably, Zhang et al. (2017) presented a multi-period ship charging station location optimization model aimed at addressing the complex challenge of location determination for ship charging stations, with their model consisting of three stages. Initially, from the viewpoint of the external environment, all potential ship charging station sites are identified through feasibility analysis. In the second phase, the final sites are selected from the list of potential candidates, with ship charging demands guiding the decision-making process, while in the final phase, the optimal capacity for each selected ship charging station is determined. The process takes into account factors such as construction costs and the service capabilities of different grades of charging stations, applying optimization methods to reach the most cost-effective and functional solution. The authors concluded that the proposed model effectively solves the location optimization problem for ship charging stations, and it can be easily generalized to address other problems related to facility allocation based on user demand.

Most recently, Khan et al. (2022) provided a comprehensive review of the latest technologies and future trends for electrifying marine vessels, focusing specifically on shore-to-ship charging, energy storage systems, and shore-side infrastructure. Through the provided literature review, the authors highlighted that the development of electric ferries and harbor charging stations using renewable energy sources is crucial, although there are still challenges like high costs, long charging times, and a lack of charging infrastructure at ports. In addition, two key methods for battery charging are discussed; wired and wireless connections. The choice of power system architecture for the charging system is vital to enhancing the efficiency and cost of the system, with the study concluding that the provision of cleaner energy for sea transportation from sustainable sources is a significant area for future research and development. Wang et al. (2022) also focused on optimizing the operations of electric ships, particularly regarding the location of charging stations, charging plans, route planning, ship scheduling, and deployment. In their study a mixed-integer linear programming (MILP) model was formulated with the aim of minimizing total costs, including charging, charging station construction, and ships' fixed costs, providing one of the first quantitative research studies to solve combinational operational problems for electric ships. Their results were promising, showing that the total cost of using electric ships is significantly less (only 42.8%) than using conventional ships, albeit requiring slightly more time to fulfill all transportation tasks. Sensitivity analyses also revealed the influence of various factors on the operations of electric ships, including battery capacity, charging speed, and volume capacity, verifying other relevant studies. While the authors acknowledged certain limitations, which include assumptions like constant sailing speed, linear energy consumption and travel distance relationship, and a constant electricity cost, the needs for large capacity batteries optimal volume capacity and service time limits are still highlighted to achieve cost and time efficiency.

It is apparent that the contemporary literature on ferry electrification comprises a wide array of studies, each emphasizing either technological advancements or specific application settings. In light of the growing decarbonization efforts within the shipping industry, the exploration of alternative fuels in short sea shipping has seen a surge of interest. However, further progress is essential to facilitate future technological solutions in this area (T. P. V. Zis et al., 2020). As it stands, the implementation of electrification within the shipping industry, viewed as a promising solution for reducing GHG emissions, is still limited to specific regions. The suitability for such a transition largely depends on factors such as topological characteristics and network energy demand. For instance, the Northern European countries (Tarkowski, 2021) stand out as examples of areas where electrification has been successfully adopted, given that their ferry routes are generally of shorter distances.

Taking into consideration the current state of electrified waterborne transport technologies, it is evident that range constraints necessitate the incorporation of spatial and locational aspects in the decision-making process for implementing electric ferry services. The understanding of the geographic specifics of each maritime route and the unique characteristics of individual networks will be instrumental in driving the adoption of electrification within the shipping industry.

2.4. Spatial Data Analytics in Maritime Transport Planning

A noticeable gap persists in the literature from a planning perspective considering network topology and complexity and their spatial characteristics overall. To the author's knowledge, no previous work has undertaken the task of identifying potential service areas within a ferry network that might be suitable for electrification, using spatial data analysis methods before this study (Karountzos et al., 2023). As mentioned before, only a select few studies have touched upon aspects like charging infrastructure placement or route planning for electric maritime services (Wang et al., 2022). In the wider transportation sector, the adoption of spatial analysis methods plays a crucial role in enhancing the efficiency and effectiveness of the design, planning, and operational decision-making processes. Several studies have already harnessed the power of spatial analytics to investigate operational inefficiencies within urban networks, with a special focus on transit route network design (Chioni et al., 2020; C. A. Iliopoulou et al., 2020). Thus, it is imperative that similar methods are applied to the maritime sector to achieve a more comprehensive understanding of the potential for ferry electrification.

The recent evolution of scientific literature has emphasized the vital role of spatial analysis techniques in conducting accurate assessments and close monitoring of emissions. These studies highlight the pressing need for the implementation of robust emissions mitigation strategies (Danylo et al., 2019; Uddin & Czajkowski, 2022). Within the context of the shipping industry, a burgeoning interest in spatial analytics has emerged, particularly in relation to emissions monitoring (Ding et al., 2018; Johansson et al., 2017; Russo et al., 2018; Topic et al., 2021). In parallel, numerous other studies have leveraged spatial analysis methodologies to evaluate the potential benefits of emissions mitigation strategies (Okada, 2019; Ülker et al., 2020a). Coastal shipping and ferry operations, by their very nature, predominantly take place between ports within the same country. This intrinsic feature often leads to short sea shipping being recognized as a highly viable alternative for reducing GHG emissions from road transport, particularly within the European context (Psaraftis & Zis, 2020). However, the scope of research in this area has been relatively constrained due to the limited presence of Ro-Ro and Ro-Pax ships within the global fleet. In contrast, most environmental studies have maintained a primary focus on liner shipping, especially containerships, given their more substantial contribution to GHG emissions (Psaraftis & Kontovas, 2009).

However, while spatial data analytics and GIS-based applications have played a critical role in emissions monitoring and inventories, their capabilities have been highly underused in other cases. Apart from emission monitoring studies and the aforementioned research of the author (Karountzos et al., 2023), GIS-based studies have been considered only in another research area; that of maritime safety. For instance, the study of Goralski and Gold (2007) proposed a new type of GIS-based decision-making support system for safe maritime navigation, considering multidimensional, unevenly distributed, and dynamic data.

A study which also highlighted the lack of GIS-based applications in maritime transport, compared to land transport, is that of Pantazis et al. (2018). Their study focused on the Coastal Transport Integrated System (Co.Tr.I.S.) research project, which was an EU and Greek government co-funded project aiming to develop an integrated and spatial information system for the optimal design of coastal transport lines. The study introduced a system which combined aspects from the fields of GIS, graph theory, operations research and optimization such as Genetic Algorithms (GAs) and game theory strategies like Nash Equilibrium. The research project aimed to enhance maritime network designs considering aspects such as distance, cost, time, and safety, by utilizing various spatial databases, maps, functions, modules, and interfaces to achieve the overall sustainability and "smartification" of the Greek islands. The authors concluded that, although challenges such as the full integration of statistical treatments and optimization modules need to be addressed while considering potential user perspectives, the GIS-based system could prove an innovative instrument that considers the economic, spatial, and social dimensions in the design process of coastal lines

More recently, Kao et al. (2021) presented an innovative GIS-based solution to enhance maritime safety aiming to prevent collisions between ships and offshore marine platform using an intelligent aid-to-navigation system, by utilizing Automatic Identification System (AIS) data. Their proposed system comprises three basic components; a fuzzy logic one that uses linguistic variables such as vessel size, relative speed, and approach distance to calculate the vessels' safe distance, a Marine GIS (MGIS) component that simulates alerts at varying levels of severity, and a warning indicator that signals the risk of collision. The main contribution of their study was the overall versatility of the system, allowing it to be potentially applied to other maritime structures such as offshore wind turbines and oil rigs, with the overall approach being a novel one regarding collision risks in increasingly congested maritime spaces.

Hu et al. (2023) have also utilized GIS data to develop an efficient and safe path planning system for autonomous maritime navigation. As traditional methods have focused mostly on shortest path routes, or have been unable to adapt to unexpected changes in the conditions of the maritime environment, the proposed system incorporated ship dynamics, optimizing fuel efficiency, and providing real-time route adjustments in case of unexpected obstacles, in order to tackle the aforementioned issues. The GIS-based system was validated through data-driven simulations, with results showing its effectiveness in providing safe, fuel-efficient, and dynamically adaptable navigation for autonomous ships, paving the way for future improvements, such as considering additional environmental factors and dynamic obstacle routing.

This section aims to clarify that there is an extended gap in the literature regarding the utilization of spatial data analytics and GIS-based frameworks in the design and planning process of maritime networks. Although the use of GIS has been critical in providing solutions on supplementary cases of maritime operations, there are still almost no studies, up until the preparation of this thesis, proposing a GIS-based framework for the design and planning of efficient maritime transport networks, while also considering port accessibility, operational environmental, and other factors. As a result, this dissertation aims to address this issue, through the conceptualization of a GIS-based framework that assesses several maritime network aspects, while considering its topological characteristics through spatial data analysis. The goal is to fill this specific gap in the literature, by providing a holistic approach for policymakers, researchers and stakeholders in the decision-making process for more efficient network planning and operations.

2.5. Renewable Energy Source Supply

Beyond the operational constraints imposed by technological progression, energy efficiency and supply present their own unique challenges when seeking to achieve zero-emission shipping. Within the context of the Greek Coastal Shipping Network (GCSN), the issues of energy supply and security are especially critical for the Aegean islands. This is particularly the case during summer periods when the islands experience an influx of tourists, thereby necessitating robust and well-planned energy supply strategies (C. Iliopoulou et al., 2018). For the optimal functioning of zero-emission systems, it is pivotal that the energy supply be predominantly derived from Renewable Energy Sources (RES). In doing so, we mitigate not only the operational emissions but also those arising from energy production. The interest in renewable energy has been consistently on the rise, notably so as the cost of various RES systems has been rapidly declining in recent years (Luderer et al., 2021).

The electrification of routes that connect islands, as well as catering to the islands' energy needs through the application of 100% RES energy systems, has been receiving increasing attention. While the environmental benefits of transitioning to fully zero-emission islands are substantial, there are numerous challenges that must be addressed (Pfeifer et al., 2020). Despite the complexity of criteria that need to be evaluated before determining an optimal site for the development of RES facilities, studies have consistently highlighted the benefits of leveraging spatial decision support systems and GIS software in facilitating the decision-making process. This is even more pertinent considering the increasing interest in offshore RES facilities.

For instance, Sourianos et al. (2017) considered the creation of a comprehensive methodology for optimal placement of offshore wind farms, implemented through a web-based Geographic Information System (GIS) software. As existing software for wind farm siting primarily considered wind power, cost, and potential energy production, these did not offer users the opportunity to evaluate various potential sites simultaneously. The researchers aimed to fill this void by proposing a software that factored in a more extensive array of considerations, including environmental, socio-economic, and spatial planning elements, thus allowing users to compare various candidate sites, while also acknowledging the promising wind potential in Greece, characterized by onshore wind speeds surpassing 8 m/sec. The cornerstone of this study was the development of a GIS-based software tool designed to execute the proposed methodology, incorporating the aforementioned holistic approach. The contributions of the study ultimately were the inclusion of public participation, its unrestricted geographical usage, and its GIS-based design that made its outputs compatible with all GIS software for further analysis in identifying suitable marine areas for offshore wind farm siting.

Vagiona and Kamilakis (2018) also investigated the creation and implementation of a comprehensive methodology for evaluating and prioritizing potential sites for offshore wind farm development at a regional level. This study also included technical, spatial, economic, social, and environmental aspects, with these criteria derived from both national legislative frameworks and international literature. The methodology employed Geographic Information Systems (GIS) and multi-criteria decision methods, specifically the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The outcomes of the study had the potential to support sustainable spatial development and policy-making for renewable energy resources, through the integration of GIS, AHP, and TOPSIS to determine the most suitable and efficient sites in the South Aegean Sea. It is worth noting that this study also contributed to the RES field through spatial data analysis, highlighting the importance of GIS software and methods, especially at regional levels. The research highlighted the importance of GIS-based decision support systems, especially in cases of insular countries, such as Greece, where the particularities of islands, such as remoteness, limited energy resources, vulnerability to external events, and heavy dependence on international trade agreements, pose unique challenges to sustainable energy growth.

The study by Taoufik and Fekri (2021) also conducted an extensive evaluation of offshore wind energy potential using an integrated methodology that combined Geographic Information System (GIS) and Fuzzy Analytic Hierarchy Process (FAHP), applied in Morocco. Their approach allowed for a comprehensive assessment of the most suitable locations for offshore wind farm development in Morocco, while also considering a range of environmental, socio-economic, and technical factors. This research also stands out due to its innovative application of GIS-based Multi-Criteria Decision-Making (MCDM) methodology, supplemented by Fuzzy Analytic Hierarchy Process (FAHP), for tackling complex site-selection challenges. The results provided valuable insights into the high economic potential of offshore wind energy exploitation in the case of Morocco, bolstering the country's ambition to become a green energy leader. Furthermore, one of the most important aspects of this and other relative studies is the fact that the methodology is highly adaptable for similar analyses in different regions, as is the case in most GIS-based methodological frameworks.

Considering several studies at the RES field, such as the aforementioned ones, it is shown that there is increasing potential for Greece and the GCSN to greatly benefit from such facilities. The opportunities regarding RES capabilities in the Aegean Sea are several, as it consists an area characterized by strong winds, thus offering a favorable environment for offshore wind farms. Furthermore, the extended periods of sunlight throughout the year augment the output of photovoltaic energy. In addition to the numerous inhabited islands, the region boasts uninhabited islets and other areas that could serve as potential sites for installing such facilities

In response to these considerations, an additional goal of this dissertation is to make a valuable contribution to the existing literature by also assessing the energy supply of electrified routes through renewable energy sources. Therefore, the dissertation aims to provide a holistic methodological framework for the evaluation of potential zero-emission maritime shipping networks, using the GCSN as a practical application setting, in order to also provide a foundation for future studies and policy-making in this critical area.

2.6. Efficiency of Maritime Transport Systems

Assessing the effectiveness of transport systems is a crucial in benchmarking any operational activity. It is through this assessment and efficiency measurement that one can manage, evaluate, and improve the system, and operational effectiveness can be measured through the use of Key Performance Indicators (KPIs). As stated by Hamel & Prahalad (1996), improvements are only possible and dependent on the capability to track performance. Meng & Minogue (2011) have also highlighted the fact that KPIs are important tools in performance measurement and monitoring, and that identifying the right KPIs is vital, but the process has inherent subjectivity, as each problem or situation demands its unique set of applicable and relevant KPIs. As a result, it is clear that it is not always a straightforward task to distill a complex operational scenario into a set of quantifiable metrics that accurately capture its performance.

In the shipping industry, where competition is high, the need for a consistent and universally accepted set of metrics, such as Key Performance Indicators (KPIs) has always been a necessity (Konsta & Plomaritou, 2012). Shipping KPIs are mostly centered around two fundamental aspects; internal improvement and external communication. As shipping includes a vast scope of operational aspects with the need for continuous adaptation and advancement in the ever-changing industry, the Shipping KPI standards were most recently revised and subsequently updated in 2020, with the BIMCO Shipping KPIs (2020). This updated standard remains an important reference point in the shipping industry for monitoring and evaluating operational performances.

Academic research in maritime transport and logistics often calls for custom KPIs to make performance comparisons before and after a specific intervention. Within economic evaluations, certain KPIs such as the Net Present Value (NPV) or payback period have emerged as universally applicable. These KPIs have been extensively employed in research related to shipping, such as in evaluating the economic implications of alternative fuel investments, wind propulsion, and port infrastructure (L. Jiang et al., 2014; Lindstad et al., 2017; T. Zis et al., 2014). As the focus shifted towards the global sulphur cap and the Initial Strategy of the International Maritime Organization (IMO), an increasing number of research works turned towards employing similar methodologies to assess economically the investments in alternative fuels (Gore et al., 2022), wind propulsion (Talluri et al., 2016), and port infrastructure (Innes & Monios, 2018). These are some of the examples showing the broad application of KPIs within the shipping industry, in order to evaluate several of its apsects.

In terms of environmental objectives, academic literature mostly focuses on KPIs that measure the absolute difference in emissions. In most cases, the implemented solutions result in either a reduction of absolute tons of CO_2, SO_x, or other emissions of interest, or the intensity level to which they are reduced. In shipping, earliest studies that focused on environmental externalities assessed the impacts of slow steaming, where the comparisons were usually made based on the volume of CO_2 mitigated per voyage over a defined time frame (Cariou, 2011). As the field advanced and additional data became accessible from shipping corporations that began to optimize sailing speed and route selection, it became evident that many of these decisions still showed some environmental trade-offs. For instance, installing a scrubber or utilizing low-sulphur fuel could augment the total CO_2 emissions (T. P. V. Zis et al., 2022), while slow steaming might instigate shifts towards land-based alternatives with unfavorable environmental repercussions (Holmgren et al., 2014). As a result, to carry out a precise comparison between operations before and after an intervention, it is essential to determine what is being measured. Considering environmental metrics, there are varying methodologies to accomplish this. Ideally, fuel consumption data would be obtained from ship operators, followed by the application of specific emission factors (often distinctive to the ship and engine) to compute the levels of pollutants. In some cases, ship operators may have live emission monitoring sensors installed, while in others, ship schedule information or Automatic Identification System (AIS) data is employed to gather information about sailing patterns, which, when combined with weather data, enable power prediction and consequent estimation of fuel consumption and associated emissions.

In cases of coastal shipping systems, where accessibility and overall connectivity of islands with the mainland and between them are paramount in retaining their economic viability, island port performance is highly important. While there is an abundance of research studies focusing on container port performance and efficiency, there are almost no studies focusing on the overall performance and efficiency of passenger ports in a shipping network. However, to a certain point, this is justified due to the fact that shipping networks that focus mainly on passengers exist only on few insular countries, such as Norway or the Philippines. Apart from performance measurement with the help of KPIs, there are several studies utilizing real world data through Data Envelopment Analysis (DEA) models. While the literature focuses mostly on container shipping, there are plenty of studies to be considered for coastal shipping networks, due to the similarities with container shipping and generally liner shipping networks.

Regarding DEA models, Chang (2013) analyzed the environmental and economic efficiency of Korean ports by developing a Slacks-Based Measure Data Envelopment Analysis (SBM-DEA) model considering exclusively port based operations, while also being one of the first studies to consider CO_2 emissions as undesirable outputs. Jiang et al. (2015) also introduced a comprehensive framework for quantifying port connectivity from a global shipping network perspective, considering the impact on transport networks when a port lacks transshipment services. Their study presented two models measuring connectivity in terms of transportation time and capacity, with meaningful insights from an analysis of major Asia Pacific ports. Na et al. (2017) applied an inseparable input–output slack–based measure model to determine the environmental efficiencies of eight container ports in China from 2005–2014. Despite regional variances, they found that pure technical environmental efficiency is generally low across ports, with input inefficiency and CO_2 emissions being significant factors, consequently suggesting policy implications for improved port management, reduced emissions, and increased efficiency, with potential to enhance both environmental and operational performance. Castellano et al. (2020) applied a multi-step strategy with original composite indicators to assess the environmental management of 24 Italian ports in 2016, utilizing DEA methods to balance economic efficiency against environmental costs and commitments. Their findings highlighted the importance of a comprehensive framework that integrates environmental and economic performance, revealing that ports implementing proactive green policies tend to achieve more optimal efficiency, thus encouraging further analyses on environmental efficiency and green policy strategies. Tovar and Wall (2022) have also explored the correlation between maritime connectivity and port efficiency, using a unique dataset of 16 Spanish ports from 2006–2016, finding strong positive relationships between the two, with modest connectivity improvements yielding significant output increases. To enhance port connectivity, and consequently efficiency, their study suggested policy measures including digitalization, network integration, and sustainable modernization, with the ongoing Spanish initiatives for innovative and environmentally friendly ports demonstrating the expected impact of these measures. Djordjević et al. (2023) utilizes a novel two-stage non-radial Data Envelopment Analysis (DEA) model to assess the environmental efficiency of Dublin Port, considering landward and seaward operations, factoring in engineering and policy measures to minimize CO_2 emissions. Their findings suggested that the number of terminals and capital expenditures significantly impact environmental efficiency, and even minor adjustments to key indicators can improve the port's efficiency.

While the aforementioned studies have undoubtedly contributed valuable insights into the complexities of port efficiency, there remains a notable research gap in comprehensive, multi-dimensional port efficiency evaluation. To date, investigations have typically focused on specific sectors or operational components within individual ports. These studies have yielded important findings related to factors such as CO2 emissions, connectivity, economic and environmental impacts, and capital expenditures. However, they stop short of exploring port efficiency in the broader context of an interconnected, dynamic shipping network, considering the interplay of all operational factors and their collective impact on overall network efficiency.

Consequently, a holistic analysis that considers overall port efficiency for each port, whilst accounting for the comprehensive network operations, remains unexplored. It is vital to extend our understanding to account for other aspects such as environmental externalities, passenger efficiency, and connectivity efficiency, all while considering network complexities and spatial characteristics. Moreover, there is a clear void in recognizing and measuring each port's unique contribution towards achieving sustainable, zero-emission networks, as electrification is gaining interest among researchers. These comprehensive factors and variables, when considered together, promise a more nuanced, actionable understanding of port efficiency in its entirety. As a result, the need for such a broad, network-centric evaluation is particularly pressing in terms of the decarbonization of maritime networks. With the growing need to achieve a more sustainable future, it is crucial to optimize efficiency at every level of a maritime transport network, from individual port operations to larger interconnecting systems. The research gap that this dissertation aims to fill is, therefore, an integrated and comprehensive analysis of port efficiency within the larger context of overall network operations, passenger and connectivity efficiency, environmental considerations, and each port's role in establishing zero-emission networks. By pursuing this direction, the goal is to expand our understanding of port efficiency beyond isolated components and into a broader, more interconnected perspective.

2.7. State of the Art Conclusions and Remarks

The comprehensive state of the art review of the literature in the previous chapters has laid the foundation for the development of the current dissertation by highlighting the importance and complexities of maritime transport systems, while also emphasizing in coastal shipping, and the need for improving its overall efficiency. Regarding the global maritime sector, it is underlined that the sector plays a pivotal role in global trade and economy and while containerization and the emergence of large ships have reshaped the industry's landscape, they've also played a role in port congestion issues and brought about various environmental challenges. As environmental issues are increasingly attracting the interest of researchers, policymakers and stakeholders, in accordance to the environmental regulations imposed by the International Maritime Organization (IMO), emissions monitoring has become critical in measuring and assessing environmental externalities from maritime transport. Up until this point, there are several studies exploiting spatial data analytics, in addition to bottom-up and top-down approaches for the estimation of emissions on several cases. However, while there have been several gains from the utilization of spatial data analytics on emissions monitoring in the maritime sector, their use has been quite limited as they are mostly seen on containership and other liner shipping studies. As a result, there is a clear gap in the literature regarding emissions monitoring studies which consider domestic (or coastal) shipping. On that note, this dissertation aims to fill this specific gap, by providing a data-driven GIS-based emissions monitoring system and methodological framework to identify areas where GHG concentrations are showing high clustering, consequently aiming to provide a versatile and easily applicable GIS-based approach for policymakers and stakeholders for more targeted interventions in areas where these are highly necessary.

In order to address the issue of environmental externalities from the shipping industry, one of the most commonly applied strategy is that of ship slow steaming. Slow steaming, which is the process of deliberately reducing the speed of cargo ships to cut down fuel consumption and carbon emissions, has been widely utilized as an effective GHG mitigation strategy, especially in liner shipping and is continuing to gather the attention of researchers and practitioners as a long-term solution towards shipping decarbonization. However, the economic sustainability of slow steaming largely depends on bunker prices, thus creating the need for exploring additional strategies to be applied, such as alternative fuels and advancements in power systems. As slow steaming has also been studied on several levels of application, either global or more local ones, the dissertation aims to address the issue on a more regional scale; that of domestic shipping, considering the Greek Coastal Shipping Network as the area of study. It is made clear in the literature that domestic shipping has not attracted the interest of researchers as much as other fields, due to the implications created from slow steaming, which would require interventions such as fleet renewals and increased cargo and passenger costs, making slow steaming non feasible or less cost effective in many cases. In addition to this, the implementation of slow steaming in passenger shipping would also create more issues, as providing acceptable passenger travel times is one of the main goals of any passenger transport system. In order to better assess the effectiveness of slow steaming as a GHG mitigation strategy in coastal shipping, while also comparing it to more aggressive strategies, the dissertation aims to address this issue and evaluate the proposed strategies' effectiveness in mitigating GHG emissions, while also providing an acceptable level of service in the network, which is translated in acceptable travel times.

One of the alternative GHG mitigation strategies explored in this study is the electrification of parts of maritime networks. The concept of ferry electrification has been gaining the interest of researchers in the last years, with most studies focusing on its technical, environmental and operational aspects for less than a decade. Electrification is considered an effective approach to diminish the environmental impact associated with the maritime sector, with numerous studies focusing on both hybrid-electric and entirely electric ferry operations, with Scandinavian nations leading the charge through policies that favor the shift towards electric fleets. Although the shift seems promising, issues pertaining to performance and cost-effectiveness may undermine this transition, restricting the use of electric ferries primarily to short-sea routes, therefore creating the need for recent research efforts focusing on different aspects of ferry electrification while accounting for technological aspects, financial considerations, and environmental repercussions. Regulatory measures, safety and reliability considerations, and increased costs are the main issues that need addressing, as these are the ones that in most instances hinder the transition, not only to fully-electric vessels, but to hybrid ones as well. However, one of the main issues in fully electric ferry transportation is that of operational range constrains, with most fully electric ferries being limited to certain operational cutoff distances travelled before needing a full charge. As a result, the current constraints of electric maritime technologies highlight the importance of considering geographic specifics and individual network characteristics in the decision-making process for electric ferry implementation, with a spatial complexity-based understanding of each maritime network being crucial to facilitate the wider adoption of electrification in the shipping industry. With this consideration, the current thesis aims to incorporate such range constraint factors in the design and planning process of zero-emission routes within maritime networks, through the proposed GIS-based methodological framework.

While there have been several studies incorporating spatial data analytics and GIS-based applications for the evaluation of different aspects of maritime transport, such as emissions or overall safety, there have been close to no studies utilizing spatial data analysis methods in the design and planning processes of maritime networks. Especially when considering the inclusion of fully electric ferries in a maritime network for the design of zero-emission routes, this is the only study which has addressed the issue through the use of GIS-based models and spatial data analysis methods (Karountzos et al., 2023). It is evident that there is a certain gap in the literature concerning the use of spatial data analytics in this area, as GIS-based applications are mostly being used as supplementary tools in the case of maritime operations. Although their use seems rather optional in cases where large-scale maritime networks are considered, the under-utilization of such systems on more regional and domestic networks means that spatial complexities and topologies of the examined networks are almost always ignored. This study aims to fill this specific gap in the literature, by proposing a methodological framework where topological factors and network spatial complexities are considered. Specifically, the framework could provide valuable insights in cases of insular countries, such as Greece, the Philippines and most

Scandinavian nations, especially when the integration of range constrained fleets, such as fully electric ferries, is included in the design and planning process of each network.

For the inclusion of fully electric ferries and the introduction of true zero-emission routes and sub-networks on any network, energy supply is also critical for the needs of such systems. While technological advancements and energy efficiency play significant roles in achieving zero-emission shipping, especially in the Greek Coastal Shipping Network (GCSN), sustainable energy supplies are critical. As a result, Renewable Energy Sources (RES) play a vital part in reducing emissions, with a growing focus in the literature on electrification and fully green islands. However, identifying optimal RES locations is highly complex, with tools like GIS software being critical the decision-making process. Studies have proposed methodologies for optimal site selection for offshore wind farms, considering various factors including environmental, socio-economic, and spatial planning elements, with several studies also focusing on offshore RES site selection in the Aegean Sea. Through the study of past researches, it is found that RES facilities offer significant potential for the GCSN, with strong winds and extended periods of sunlight enhancing the output of offshore wind farms and photovoltaic energy, respectively. This work aims to add to the existing literature by also assessing the energy supply of electrified routes through RES by evaluating existing infrastructure and the potential of islands and offshore areas to fully cover their energy needs, thus providing an additional analysis step in the overall methodological framework for future zero-emission maritime shipping networks.

In addition to the design and planning processes of maritime transport networks, the measurement, monitoring, and evaluation of the transport system’s efficiency is crucial in assessing and improving operations. In maritime transport, Key Performance Indicators (KPIs) have been widely utilized for this, despite the subjectivity involved in their selection and application. In the competitive shipping industry, a universal set of KPIs is essential, as most notably addressed by the Shipping KPI project, initiated in 2008 and updated in 2020, which established international standards for measuring and reporting performance in the industry, focusing on internal improvement and external communication. In academic research, specific KPIs are used to compare transport system performance before and after interventions, with economic evaluations commonly utilizing KPIs such as the Net Present Value (NPV) of projects or the payback period, as seen in shipping research focused on emissions control and alternative fuel investments. In addition to this, environmental KPIs typically measure the difference in emissions or the intensity level of emissions, with precise comparisons of operations before and after an intervention creating the need for careful determination of what is measured and how. In such cases, data is gathered from ship operators or Automatic Identification System (AIS) data to estimate fuel consumption and related emissions.

Port performance in coastal shipping systems has also been essential for maintaining economic viability and sustainability. While there is extensive research on container port performance, there is limited research on passenger ports within shipping networks. Several studies have used Data Envelopment Analysis (DEA) models to evaluate port efficiency using real-world data, taking into account factors like CO_2 emissions, connectivity, economic and environmental impacts, and capital expenditures. However, these studies have primarily focused on individual ports rather than the broader context of their operations in a shipping network as a whole. The existing research gap lies in the comprehensive, multi-dimensional evaluation of port efficiency within larger shipping networks, considering various operational factors and their collective impact on overall network efficiency. As a result, it is vital to extend understanding to other aspects such as environmental externalities, passenger efficiency, connectivity efficiency, and each port's contribution towards sustainable, zero-emission networks. Consequently, this dissertation aims to fill this gap by conducting an integrated analysis of port efficiency within the broader context of overall network operations, aiming to provide a more holistic understanding of port efficiency in its entirety, as the final step in evaluating the efficiency of the maritime network under examination, before and after the completion of targeted interventions in its design and planning.

Considering all the above conclusions and remarks, this dissertation advances maritime transport studies by addressing gaps in maritime emissions monitoring, exploring the effectiveness of slow steaming, and examining the potential of electric ferry integration in domestic shipping networks, using the Greek Coastal Shipping Network as a case study. As emissions monitoring has primarily focused on global shipping, and not domestic coastal shipping, this work aims to rectify this using a GIS-based approach for targeted interventions. The feasibility of slow steaming, a long-standing strategy for reducing fuel consumption and emissions, is also explored for regional coastal shipping, compared to alternative strategies, such as network electrification which is also considered, additionally noting that geographic, economic, and technological constraints have limited its adoption to date. The study employs spatial data analysis and GIS-modeling to understand these constraints better, suggesting the potential for fully electric ferries, particularly on insular routes, supported by renewable energy sources, with their role emphasized as a critical element in achieving truly zero-emission maritime networks, with the dissertation assessing energy supply potentials, especially in the Aegean Sea. Lastly, the work proposes a comprehensive evaluation of port efficiency within larger shipping networks, encompassing environmental, passenger, and connectivity aspects. The intended outcome is a comprehensive understanding of maritime network efficiency, enabling more effective future interventions and policy-related strategies for the design, planning and efficiency improvement of maritime transport networks.

3. EMISSIONS MONITORING AND SLOW STEAMING STRATEGIES

On the basis of existing research studies, the goal of this dissertation is to provide a holistic GIS-based approach for the design and planning of efficient maritime transport systems. In order to do so, the goal of this dissertation is to provide a holistic GIS-based approach for the evaluation of existing maritime networks based on several factors, while also assessing their potential for electrification through the introduction of zero-emission maritime routes. The model presented in this dissertation is a versatile one, which can easily be applied to any given network, while also facilitating changes in given parameters for the identification of zero-emission routes, with advancements in battery technologies and range constraints.

The methodological framework proposed in this thesis can be broken down in five stages, which are as follows:

1. **Status Quo and Existing Operations of Maritime Network**
    i. Data Collection
    ii. Data setting, cleaning and editing
    iii. Creation of GIS Databases for ships, routes and ports of the network
2. **Identification of areas with high CO_2 emissions, and application and evaluation of conventional slow steaming strategies at different levels**
    i. Identification of areas showing high clustering of CO_2 emissions via different spatial autocorrelation statistical models
    ii. Implementation of slow steaming strategies on different speed reduction levels and different areas for the evaluation of CO_2 mitigation under several scenarios
3. **Creation of Efficiency Indices for performance analysis**
    i. Initial evaluation of existing ports of the network through multivariate spatial analysis for the identification of under-serviced areas

- ii. Performance analysis of ports of the network via Slacks Based Measure Data Envelopment Analysis (SBM-DEA) model and Multivariate Local Indicators of Spatial Association (LISAs)

4. **Network Restructuring**

   - i. Generation of feasible zero-emission routes via GIS-based obstacle routing model
   - ii. Identification of port clusters where fully electric ferries can operate for the introduction of zero-emission routes via Bi-variate LISA model
   - iii. Exclusion of resulted ports to be serviced by fully electric ferries from the dataset and repetition of (ii) until all ports result in statistically non-significant areas
   - iv. Limiting of dataset until only main ports remain that cannot be serviced by fully electric zero-emission routes
   - v. Generation of new conventional routes to service remaining ports, through GIS-based cluster-first route-second approach through the application of Density Based Clustering methods and connectivity criteria

5. **Efficiency Evaluation of the Restructured Network**

   - i. Comparison of the Environmental Efficiency Index results of the restructured network with the ones of the base (existing) network
   - ii. Calculation of minimum necessary port calls per port to retain overall island accessibility
   - iii. Evaluation of overall Efficiency Index per port after the introduction of zero-emission routes
   - iv. Comparison of emissions mitigation by the introduction of zero-emission routes with conventional slow-steaming strategies

The overall workflow of the research, as mentioned above, can be thoroughly revised through the flowchart in the following figure, showing each step considered for the study.

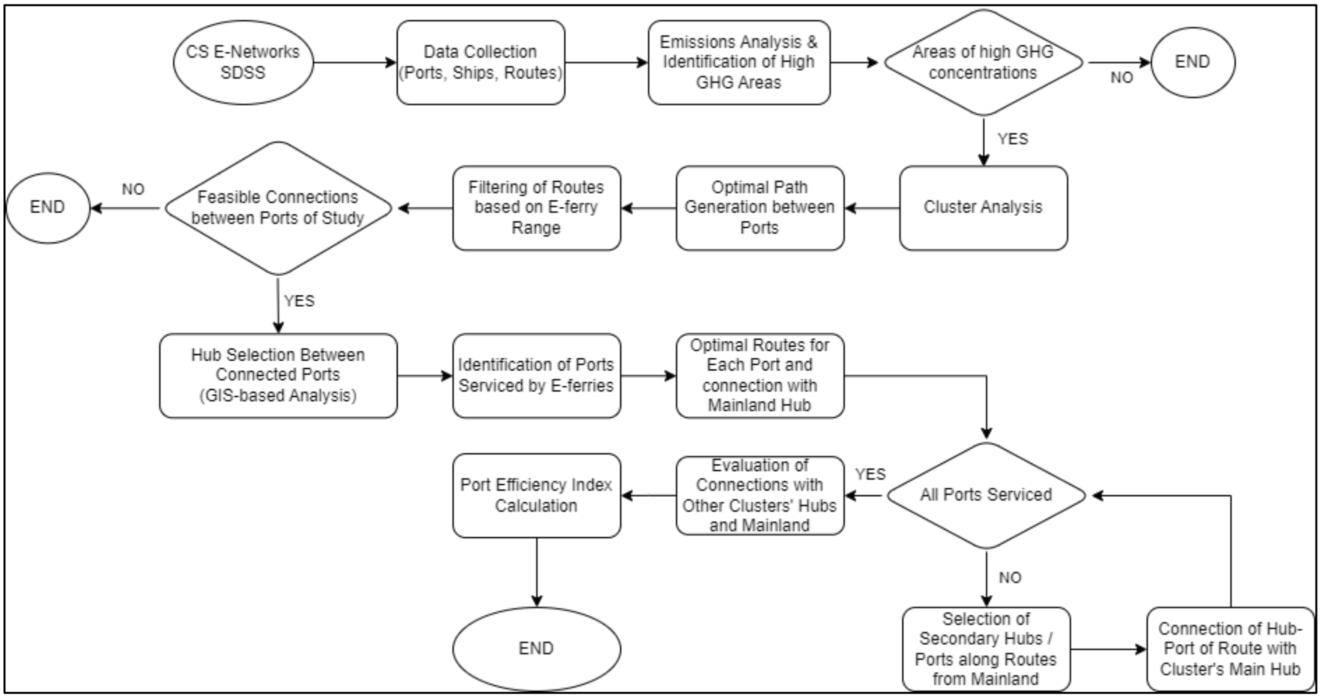


Figure 8. Methodology flowchart of the PhD research

In the next sections of the chapter, each step of the methodological framework will be thoroughly described and discussed. The main advantages of the presented methodological framework are its versatility and applicability, as it can be easily modified for any given dataset and other networks of variable scales. However, one of the main limitations of the framework is the fact that it is highly data-driven and requires extensive data collection and maintenance to provide insightful outputs for more targeted interventions.

3.1. **Data Collection**

In order to implement the methodology proposed in the dissertation, data collection from various sources is crucial. These sources include various tourist and travel website, such as Ferryhopper, websites of companies operating in the ferry sector, such as Blue Star Ferries, websites providing AIS data for ships, such as MarineTraffic and Marinus Directory, and openly available data provided by the Hellenic Statistical Authority (EL.STAT.).

The data collected is organized and coded as variables or directly digitized in a GIS environment, based on their characteristics and type. To ensure the data's accurate usage in problem analysis, it needs to be displayed in the right format. As a result, comprehensive databases are formed consisting of initial tables and geospatial data that include point, linear, and polygon type data. Specifically, the data collected consist of:

- Mainland and insular areas of the study, along with their respective ports
- Demographic and statistical data (population, embarked/disembarked passengers per port etc.)
- Total number of ferry routes and their characteristics (ports of call, trip duration and frequency, port distances etc.)
- Total number of ships operating in the network and their characteristics (length, width, speed, carrying capacity, etc.)

The entirety of relevant processes, such as recording, editing, digitization, visualization, and finally the analysis of data was conducted with available software, such as MS Excel, QGIS, ArcGIS and GeoDa. For the development of appropriate models for additional analysis through the utilization of the relevant data, Python 3.8 was used.

The results from the analysis of each distinct route and frequencies, regarding port calls and distinct routes connecting each port are shown on the following table. While not all ports will be utilized in this dissertation, due to data availability of other factors (most notably passenger demand data), available data should still be shown as part of the study.

Table 3. Port Connectivity Results including Port Calls and Distinct Connecting Routes (2020 data)

Port	Port Calls (3-month period)	Distinct Routes	Port	Port Calls (3-month period)	Distinct Routes
Aegina	494	1	Kythnos	520	5
Agathonisi	130	2	Lavrio	1482	6
Agia Marina	104	2	Leipsoi	260	7
Agios Efstratios	104	2	Lemnos	156	4
Aigiali	182	2	Leros	208	7
Amorgos	260	4	Marmari (Evoia)	624	1
Anaphi	104	3	Mesta	52	2
Andros	884	4	Milos	728	8
Ano Koufonisi	260	2	Mykonos	2080	20
Antikythira	156	5	Mytilene	234	5
Antiparos	6370	2	Naxos	1690	19
Arkoi	78	2	Neapoli	182	2
Astypalaia	182	3	Nisyros	182	5

Chalki	182	4	Oinousses	78	2
Chios	234	5	Paros	1898	16
Delos	0	0	Patmos	312	10
Diafani	52	2	Piraeus	3588	42
Donousa	78	1	Pounta (Paros)	5642	1
Evdilos	52	1	Psara	52	1
Folegandros	286	4	Pythagoreio (Samos)	130	3
Fournoi	130	4	Rafina	2054	11
Gytheio	52	2	Rethymno	52	1
Heraklion (Crete)	832	8	Rhodes	598	17
Ikaria	208	6	Riva	26	1
Ios	832	11	Samos	130	4
Iraklia	234	3	Santorini	1456	21
Kalymnos	338	10	Schinousa	234	3
Karlovasi (Samos)	78	3	Serifos	442	3
Karpathos	130	3	Sifnos	702	7
Karvonisi (Crete)	130	5	Sigri (Mytilene)	26	1
Kasos	156	4	Sikinos	104	3
Kastelorizo	104	3	Siteia	130	3
Kavala	182	5	Souda (Chania)	364	1
Kea	988	3	Symi	156	5
Kimolos	104	3	Syros	650	12
Kos	520	15	Tilos	104	3
Kythira	312	7	Tinos	1352	10

Considering population data and passenger demand for the ports of the study, these are shown on the following table. It is worth noting that passenger data (embarked and disembarked passenger data) were not available for all the above island ports, thus the dataset only includes these that had available associated data.

Table 4. Statistical Data of Ports of the Study Considering Island Population and Passenger Demand

Port	**Population**	**Average embarked (2015 – 2019)**	**Average Disembarked (2015-2019)**
Agathonisi	185	3288	3283
Agios Efstratios	270	6557	6472
Aigiali	1947	77817	78353
Amorgos	1947	77817	78353
Anaphi	271	12287	12301
Andros	9128	265046	267919
Ano Koufonisi	412	59040	59922
Arkoi	43	2011	2012
Astypalaia	1270	20101	20871
Chalki	702	9250	9297
Diafani	6709	17053	17094

Donousa	176	15151	15279
Evdilos	8431	78317	78479
Folegandros	787	45594	45765
Fournoi	1199	16037	16213
Ikaria	8431	78317	78479
Ios	2084	135009	135441
Iraklia	150	11707	11763
Kalymnos	15863	177106	173361
Karlovasi (Samos)	33335	120948	105703
Karpathos	6709	17053	17094
Kasos	1070	5831	5883
Kea	2472	138850	139013
Kimolos	899	42109	41640
Kos	33388	289857	283351
Kythnos	1436	80389	80432
Leipsoi	784	14626	14642
Leros	7915	65768	63576
Milos	4966	165882	166794
Mykonos	14165	697742	699463
Naxos	18340	462921	466971
Nisyros	982	22895	23438
Oinousses	796	17804	17903
Paros	13694	822161	824102
Patmos	3429	73081	73084
Pythagoreio (Samos)	33335	120948	105703
Rhodes	152538	310009	309928
Samos	33335	120948	105703
Santorini	17430	848548	860170
Schinousa	225	16632	16824
Serifos	1378	69014	68960
Sifnos	2543	118021	118519
Sikinos	270	9753	9781
Symi	3068	192072	191659
Syros	21473	318664	319591
Tilos	829	21406	20485
Tinos	8699	456056	453512

Considering the ships operating in the GCSN, collected data regarding their characteristics are shown on the following table.

Table 5. Characteristics of ships operating in the Greek Coastal Shipping Network

Name	Year Built	Length	Width	DWT	GRT	Max Speed (knots)	Mean Speed (Knots)	Pax Capacity (Summer)	Pax Capacity (Winter)
Flyingcat 4	1999	55.10	12.80	100	886	29.7	28.5	438	
Marmari Express	1985	96.40	16.60	911	1863	16.6	15	789	

Ionis	1977	96.30	17.40	880	2440	16.8	15.5	800	
Makedon	1972	90.10	15.40	457	1711	14.6	13.9	725	
Panorama	1987	101.30	17.50	1240	3426	14.1	13.8	700	
Evia Star	1980	87.40	17.00	940	1413	14.9	14.3	580	
Festos Palace	2002	214.00	32.00	6700	36894	22.2	21.2	2184	1865
Knossos Palace	2001	214.00	32.00	6700	36825	21.9	21.5	2184	1865
Kriti I	1979	191.80	29.40	5398	27239	20	18.9	1500	1500
Blue Horizon	1987	187.10	27.00	6005	27230	20	19	1488	1488
Elyros	1998	192.00	27.00	5186	33635	19	18.5	1874	1874
Blue Galaxy	1992	192.00	27.00	6911	29992	21	20.3	1740	1740
Kriti II	1979	191.80	29.40	5339	27239	21.1	20.4	1500	1500
Nissos Rodos	1987	192.50	27.28	6148	29731	20.4	19.9	2210	2210
Kydon Palace	2001	214.00	26.40	7237	37482	23.7	22.4	2500	2448
Mykonos Palace	2000	214.00	26.40	7440	37551	23.8	23.1	2500	2500
Olympus	1970	141.70	23.50	3260	12338	13.9	11.8	1000	
Talos	1971	124.20	19.20	2838	7171	15.6	14.6	12	12
Nearchos	1968	87.00	16.00	750	4163	14.2	13	12	12
Pelagitis	1978	151.00	20.00	8661	5363	13.2	12.6	12	12
Blue Carrier 1	2000	142.40	23.00	4650	13073	16.6	15.5	12	12
Delos Express	1992	40.15	6.90	28	246	17.5	14.9	309	
Orca	1997	43.35	11.32		263	12.1	11.7	-	
Mykonos Riviera	2016	32.00	6.00			17.4	16.7	-	
Mykonos Jewel	2015	28.00	7.00		114	21.3	13.6	-	
Ilias T	2012	22.48	5.74		73	19.5	19.1	123	
Olympios Zeus	1999	59.00	14.60		488	11.1	10.3	354	243
Dodekanisos Pride	2005	40.10	11.46	51	499	31.5	30.3	280	
Dodekanisos Express	2000	40.00	11.00	40	528	28.1	27.7	337	
Rodon	1992	34.00	9.00	77	308	22.8	21	297	
Hsc Cat	1990	74.00	26.00	209	3012	29	26.2	700	
Blue Star 2	2000	176.10	26.20	5075	29858	11.7	9.2	1854	1854
Blue Star Myconos	2005	141.00	21.00	2651	8129	25.1	24.7	1915	1915
Blue Star Patmos	2012	145.90	23.20	2637	18664	21.8	18.5	2000	2000
Blue Star 1	2000	176.00	26.00	4500	29858	20.2	19	1890	1890
Ariadne	1996	195.95	27.00	6174	30882	23.3	22.2	2045	2045
Nissos Samos	1988	192.91	29.40	7622	30694	19.7	19.1	2202	2202
Champion Jet 1	1997	86.27	26.00	350	5007	40.8	26.3	1000	
Naxos Jet	1992	73.60	26.00	197	1903	26.7	25.5	700	
Seajet 2	1998	42.00	10.00	50	500	34.8	33.6	386	
Superjet	1995	42.00	10.30	50	493	37.9	30.5	394	
Tera Jet	1999	145.81	22.00	1200	11374	27.8	26.8	2000	
Power Jet	1996	82.30	23.00	344	5335	25.6	23.1	800	
Champion Jet 2	1996	86.62	26.00	340	5005	35.4	34.4	1000	
Worldchampion Jet	2000	86.60	24.00	1530	6402	46.2	30.9	1310	

Paros Jet	1996	105.00	18.00	1139	3560	36.2	23.7	850	
Andros Jet	1997	59.90	17.80	184	2695	29.3	19.9	600	
Mega Jet	1995	78.33	26.00	250	3989	29.8	21.1	845	
Aquablue	1975	137.00	22.03	2250	12891	17.6	17	1300	
Aqua Jewel	2002	96.00	16.60	461	3040	24.2	15.3	661	
Rapidlink Jet/Caldera Vista/ Master Jet	1991	74.00	26.00	660	3003	28.4	25.6	700	
Blue Star Naxos	2002	124.00	18.90	1896	10438	21.3	21	1474	1474
Blue Star Delos	2011	145.00	22.00	2767	18498	25.7	24.8	2400	2400
Blue Star Paros	2002	124.20	18.90	1896	10438	21.8	20.8	1474	1474
Diagoras	1990	142.00	23.00	3348	15362	19	18.1	1462	1462
Blue Star Chios	2007	141.00	21.00	1960	13955	26.2	25.9	1782	1782
Highspeed 4	2000	92.60	24.00	470	6274	38.6	29.6	1010	
Hellenic Highspeed	1997	100.30	17.10	340	4662	24.9	23.5	727	
Flyingcat 3	1998	47.45	11.80	40	614	33.8	33.2	342	
Hsc Superspeed	2002	54.50	15.08	269	853	35.1	25.9	400	
Supercat	2000	45.36	12.00	75	662	30.7	28.4	400	
Superrunner	1998	100.00	17.10	340	4724	14.5	13.7	809	
Superferry II	1974	121.70	19.20	1029	4986	19.5	19.3	1630	
Superferry	1995	121.00	20.00	1258	10047	18.3	17.3	1760	
Superexpress	1998	91.00	26.00	366	5832	36.7	25.9	1070	
Fast Ferry Andros	1989	115.00	21.00	2131	4682	21.1	19.2	1200	
Ekaterini P	1990	116.50	18.00	1300	3948	15.5	12.4	1127	
Theologos P	2000	118.10	21.00	3227	4935	18.7	18.4	1154	
Thunder	1998	86.60	24.00	400	5992	8.8	8.1	1068	
Adamantios Korais	1987	100.10	17.20	977	8324	17.4	16.4	800	
Dionisios Solomos	1990	121.50	21.00	2373	4530	16.8	16.6	1050	
Speedrunner 3	1999	100.30	17.10	340	4697	31.5	30.3	800	
Santorini Palace	2005	85.00	21.20	470	4927	34.3	33.4	1160	1160
Prevelis	1980	142.50	23.50	3300	15354	17.2	16.8	927	927
Artemis	1997	89.70	14.00	325	1612	14.8	14.5	512	512
Panagia Skiadeni	1986	83.70	13.50	679	3234	16	15.1	700	
Maistros Santorini	2015	25.00	6.00			18.7	17	200	
Kapetan Christos	1970	96.80	15.80	1088	3633	14.5	13.8	12	12
Iosif K	1979	133.00	21.60	5300	9464	14.1	13.3	92	92
Ag.Antonios	1977	71.8	15.18	148	592	11.5	10.9	320	
Kyriarchos IV	2017	26.00	6.00			23.4	22.7	130	
Express Skopelitis	1986	44.90	8.00	142	438	12.5	12.1	340	
Melina II	1980	72.50	13.60	162	649	10.3	9.9		
Nisos Kalymnos	1970	61.80	10.00	302	755	12.9	12.2	500	
Zefyros	2017	25.00	7.00		121	17.1	15.1	85	
Patmos Star	1991	35.20	7.60	42	230	11.9	11.3		

Joy Star	1993	40.10	6.90	49	245	14.7	14.3	287	
Stavros	2000	84.00	14.40	913	3764	15.3	14.8	700	
Sebeco	2018	32.00	7.00		140	19.9	19.1	80	
Daskalogiannis	1993	60.00	15.70	391	649	10.1	9.4	1200	
Armenistis	1972	106.50	16.00	2500	4529	13.1	12.1	20	20
Psara Glory	1980	58.00	13.60	337	717	10.9	10.4	600	
Oinoussai III	1997	42.70	8.40	80	365	10.5	10.1	300	
Aeolis	1968	40.00	9.00	41	242	8.8	8	12	
Porfyrousa	1997	75.46	14.00	1650	1239	12.8	11.2	453	
Agios Nektarios	1999	75.25	14.40	227	1871	12.9	11.7	600	
Sifnos Jet	1999	52.40	13.00	120	906	33.5	33.3	366	

As this dissertation utilizes data from the EU-MRV system, not all of the above ships report data as it is not mandatory for them. As a result, the following table shows average operational speed and fuel consumption, based on reported data available, as well as CO_2 emissions based on consumption of Heavy Fuel Oil (HFO) for several ships of the dataset.

Table 6. Ship operational and environmental characteristics based on reported EU-MRV data

Vessel	**Avg. Speed (knots)**	**Avg. F.C. (kg/nm)**	**Avg. CO_2 emissions (kg/nm)**
AQUA JEWEL	17.41	71.17	221.62338
ARIADNE	19.59	182.9567	569.72706
BLUE GALAXY	17.51	198.9467	619.51992
BLUE HORIZON	17.21	172.4533	537.01968
BLUE STAR 2	21.35	258.3733	804.57456
BLUE STAR CHIOS	21.45	187.02	582.38028
BLUE STAR DELOS	22.03	237.16	738.51624
BLUE STAR MYKONOS	22.40	199.7633	622.06302
BLUE STAR NAXOS	19.56	127.4833	396.9831
BLUE STAR PAROS	20.09	135.29	421.29306
BLUE STAR PATMOS	20.32	209.1067	651.15816
CHAMPION JET 2	28.97	142.475	443.66715
ELYROS	19.75	200.1633	623.30862
FAST FERRIES ANDROS	18.09	60.67	188.92638
FESTOS PALACE	20.34	270.23	841.49622
KRITI I	18.38	177.05	551.3337
KYDON PALACE	21.49	265.52	826.82928
NISSOS RODOS	18.67	171.0533	532.66008
NISSOS SAMOS	18.08	157.84	491.51376
PREVELIS	14.34	95.84667	298.46652
SUPEREXPRESS	23.96	146.2	455.2668
SUPERFERRY II	17.84	139.97	435.86658
THEOLOGOS P.	18.09	58.735	182.90079

As these are the only ships of the network reporting data to the EU-MRV system, these are the ones that will be utilized in next chapters for the calculations of route emissions and the subsequent identification of areas with high CO_2 emissions.

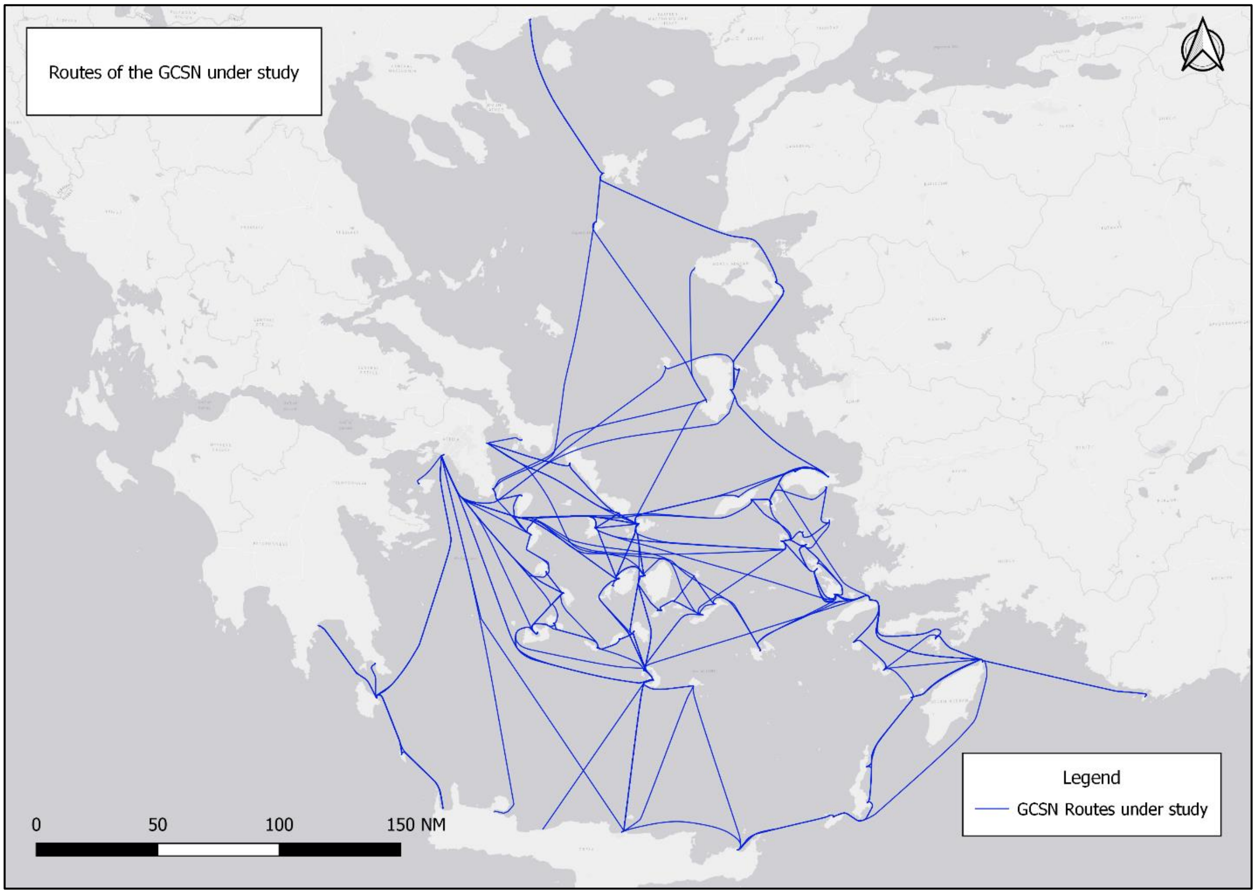
3.2. Identification of Areas with High CO_2 Emissions

The research method used in this stage of the study focuses on finding areas with high CO_2 concentrations and applying conventional slow steaming in these regions, based on the results of the different spatial analysis models. To put this method into practice, we consider the case of the Greek Coastal Shipping Network (GCSN), which is the Greek domestic shipping network in the Aegean Sea. In this context, slow steaming is introduced as a way to reduce the environmental impact of the GCSN, focusing on mitigating CO_2 emissions, without applying any other strategy such as the renewing of the fleet. In order to address the issue, spatial analysis tools are used in a GIS-based environment for the identification of such high CO_2 emissions areas. To evaluate the effectiveness of the proposed strategy, several different scenarios are created and compared, which consist of different levels of speed reduction and different areas of implementation.

3.1.1. Data and Assumptions

While the GCSN structure leaves little room for changes, due to policies applied by the Greek state, decreased flexibility from operators and accessibility needs (Karampela et al., 2014; Katarelos & Koufodontis, 2011), slow-steaming of the fleet could be considered as a transitional solution, at least until new, more environmentally friendly or even zero-emission ship technologies are introduced to the network, through the fleet’s much needed renewal. However, it is acknowledged in this study that reducing the fleet’s speed on the whole network is not always a viable solution, due to the deterioration of the provided level of service, as travel delays will become highly noticeable. As such, slow steaming should be implemented in most sensitive areas of the Aegean Sea, to improve the GCSN environmental footprint, without compromising the quality of provided services. In this context, the study attempts to identify areas of the Aegean Sea, where high GHG emissions are encountered and exploit them for assessing the potential of implementing different slow-steaming strategies for improving the environmental footprint of the GCSN. For that purpose, spatial analysis techniques are applied in a GIS environment.

Reported maritime CO_2 emissions from the European Union Monitoring, Reporting and Verification system (EU-MRV) (European Maritime Safety Agency, 2019) are used for the purposes of this study. Although maritime CO_2 emissions can be estimated through mathematical models (Deniz et al., 2010a; Jing et al., 2021; D.-P. Song & Xu, 2012a; S.-K. Song & Shon, 2014a; Tarelko & Rudzki, 2020a; Ülker et al., 2020b; Uyanık et al., 2020a), in accordance to the EU Regulation 2015/757, reported CO_2 emissions should be used so as to avoid statistical variances of model based estimations. However, one of the major drawbacks of EU-MRV data is the fact that, based on EU Regulation 2015/757, CO_2 emission reports only apply to vesesls with above 5000 gross tonnage. In the case of this study, not all vessels operating in the Aegean sea are above 5000 GT in size, and their respective operators and shipping companies are not obliged to report either CO_2 emissions or fuel consumption. In such a case and for the purposes of this study, when a route is operated by a vessel of not-reported CO_2 emissions, this route is assumed to be operated by a vessel of the same type, similar capacity and engine characteristics, for which such data exists. All available emission data are then added to a GIS database and incorporated to their respective main routes of the GCSN as linear spatial features, as shown on the following map (Fig. 1). Both ship and route data are analyzed up until 2019, as after that year there were several disruptions and changes on the GCSN due to the COVID-19 pandemic and, therefore, 2019 routes are used as the base scenario of the GCSN under normal operations.



Map 1. Existing routes of the Greek Coastal Shipping Network (Data collection from shipping companies and ferry planning services as of 2019)

Through the use of the actual reported EU-MRV data, which concern fuel consumption, time at sea and CO2 emissions, it is possible to calculate a ship's average operating speed on an annual basis, thus taking into consideration a vessel's actual speed, rather than its max or design speed, resulting in better accuracy of the output results. This is also important as updated fuel consumption and CO2 emissions can be estimated in cases where slow-steaming is proposed. Nevertheless, even though speed reduction on all routes of the GCSN would be an option, it would also cause scheduling and travel time issues. As a result, through the use of GIS software and spatial analysis methods, it is crucial to identify routes where there are high concentrations of CO2 emissions. For the calculation of CO2 emissions, the average fuel consumption of each ship per nautical mile travelled is utilized, with an emission factor of 3.114, considering Heavy Fuel Oil used by the ships of the study, which is in conjunction with reported CO2 data from the THETIS EU-MRV database. As a result, CO2 emissions for each trip and per distance are calculated as follows:

$$CO_2 = FC * F_{CO_2} \tag{1}$$

where:

CO_2 the CO_2 emissions in metric tonnes, FC the ship's fuel consumption and F_{CO_2} the CO_2 emission factor for heavy fuel oil, which equals 3.114.

Aspects such as route planning, trip frequency, and the broader scope of ship traffic play a significant role in total emissions. However, it's crucial to note that the Greek fleet is an ageing one, with older ships being typically less energy-efficient. For example, within the routes inspected for this study, 18 of the 23 ships analyzed have reported emissions of more than 400kg of CO_2 per each nautical mile travelled. The fleet's overall average CO_2 emissions per nautical mile stand at 523.35kg of CO_2. In terms of data regarding the routes collected in this research, on average, around 180 metric tonnes of CO_2 emissions are produced per trip, which ultimately translates to a total of 13936.82 metric tonnes of CO_2 from the Aegean fleet on a single trip basis. The fleet's general inefficiency, in terms of environmental performance, is visually depicted in Figures 9 and 10, which display ship CO_2 emissions per distance traveled (kg/nautical mile) and total CO_2 emissions produced per round trip on each route, respectively.

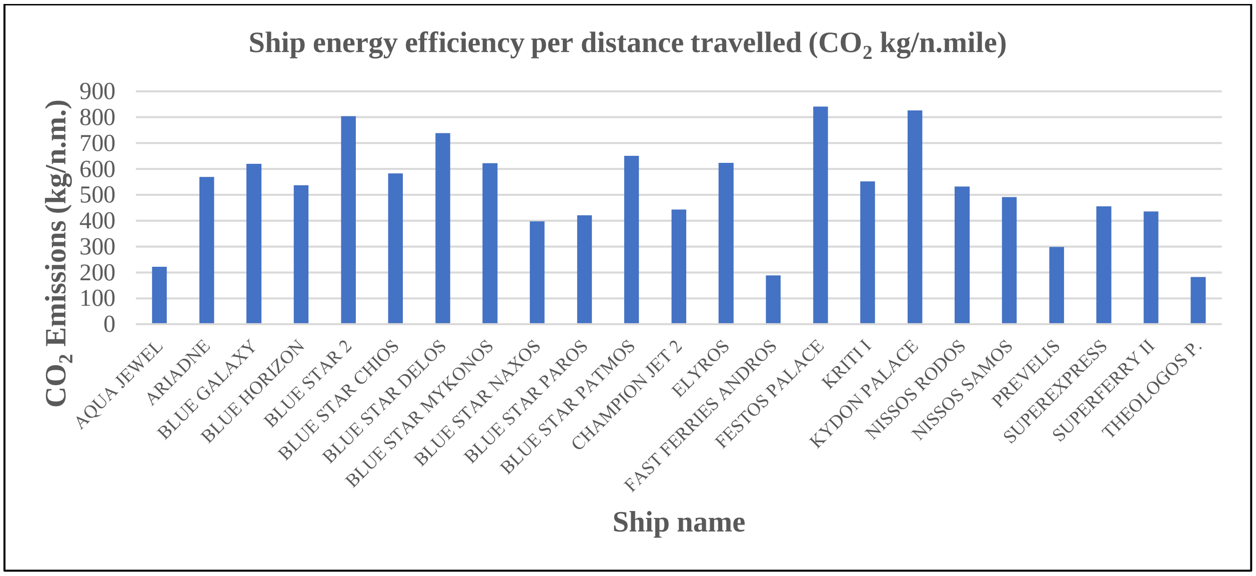


Figure 9. Ship energy efficiency per distance travelled, depicted as kg of CO_2 emitted per nautical mile

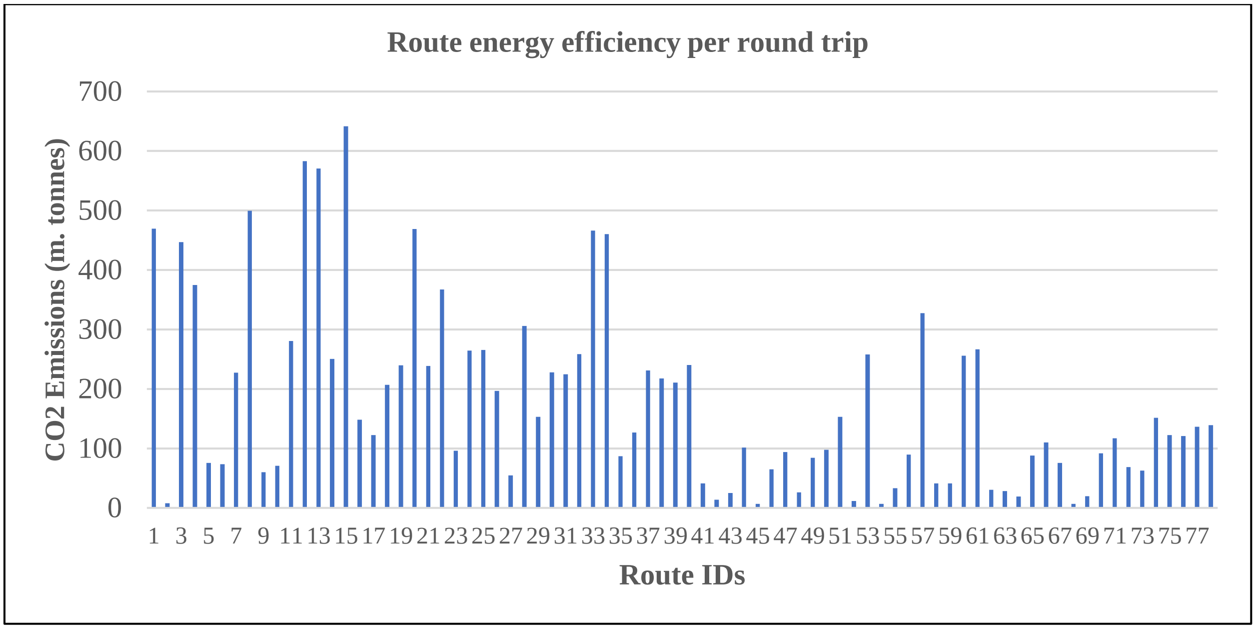


Figure 10. Route energy efficiency per trip, depicted as CO_2 emissions (m. tonnes) generated per round trip on each route of the study

While it is clear that there are several routes which cover larger distances, especially those originating from the mainland and leading to the Dodecanese islands, the majority of vessels utilized on the routes of the Aegean largely contribute to total CO_2 emissions. In addition to the fleet's energy and environmental inefficiency, ship traffic also plays a crucial role in creating areas where CO_2 emissions are showing high concentrations and creating clusters, thus leading to certain areas of the Aegean requiring extensive attention and more targeted interventions for their overall decontamination, at least considering air quality levels. This dissertation aims to assess whether such areas exist in the Aegean, in order to propose certain GHG mitigation strategies for the environmental efficiency of the GCSN, while also evaluating the results of their implementation by utilizing a GIS-based decision support system.

3.1.2. Spatial Analysis and GIS Framework

The use of GIS has become popular in the last decades, in cases where it is highly important to analyze and visualize the spatial characteristics of certain data. Several studies have assessed the impact of certain techniques for mapping data clusters, such as hot spot analyses (Grubesic & Murray, 2001; Prasannakumar et al., 2011; Said et al., 2017), how different techniques of mapping clusters work (Jana & Sar, 2016; Sánchez-Martín et al., 2019), while such methods are also widely utilized in the transportation literature (C. Iliopoulou, Milioti, et al., 2018), especially in the analysis of traffic accidents and other risk related data sets (Aghajani et al., 2017; Colak et al., 2018; Prasannakumar et al., 2011; Truong & Somenahalli, 2011).

This study assesses whether there is a certain pattern of CO_2 emissions in the Aegean Sea, based on the current structure of the GCSN, by utilizing two widely applied methods of analyzing patterns and mapping statistically significant clusters. Those two spatial autocorrelation regression methods consist of Moran's I Spatial Autocorrelation, followed by Cluster and Outlier Analysis (Anselin Local Moran's I) and of High/Low Clustering (Getis-Ord General G), followed by a Hot Spot Analysis (Getis-Ord Gi*), thus ultimately utilizing Local Indicators of Spatial Association (LISA) in both methods (Anselin, 2010). Regarding Moran's I statistic for spatial autocorrelation, it is given as:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{2}$$

where z_i is the deviation of an attribute for feature i from its mean $(x_i - \bar{x})$, $w_{i,j}$ is the spatial weight between features i and j, n is equal to the total number of features and S_0 is the aggregate of all spatial weights, given by:

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \tag{3}$$

while the z_I score for the statistic is computed as:

$$z_I = \frac{I - E[I]}{\sqrt{V[I]}} \tag{4}$$

where $E[I] = -1/(n-1)$ and $V[I] = E[I^2] - E[I]^2$.

On the other hand, the second method, determines the Getis-Ord local statistic, which is calculated as:

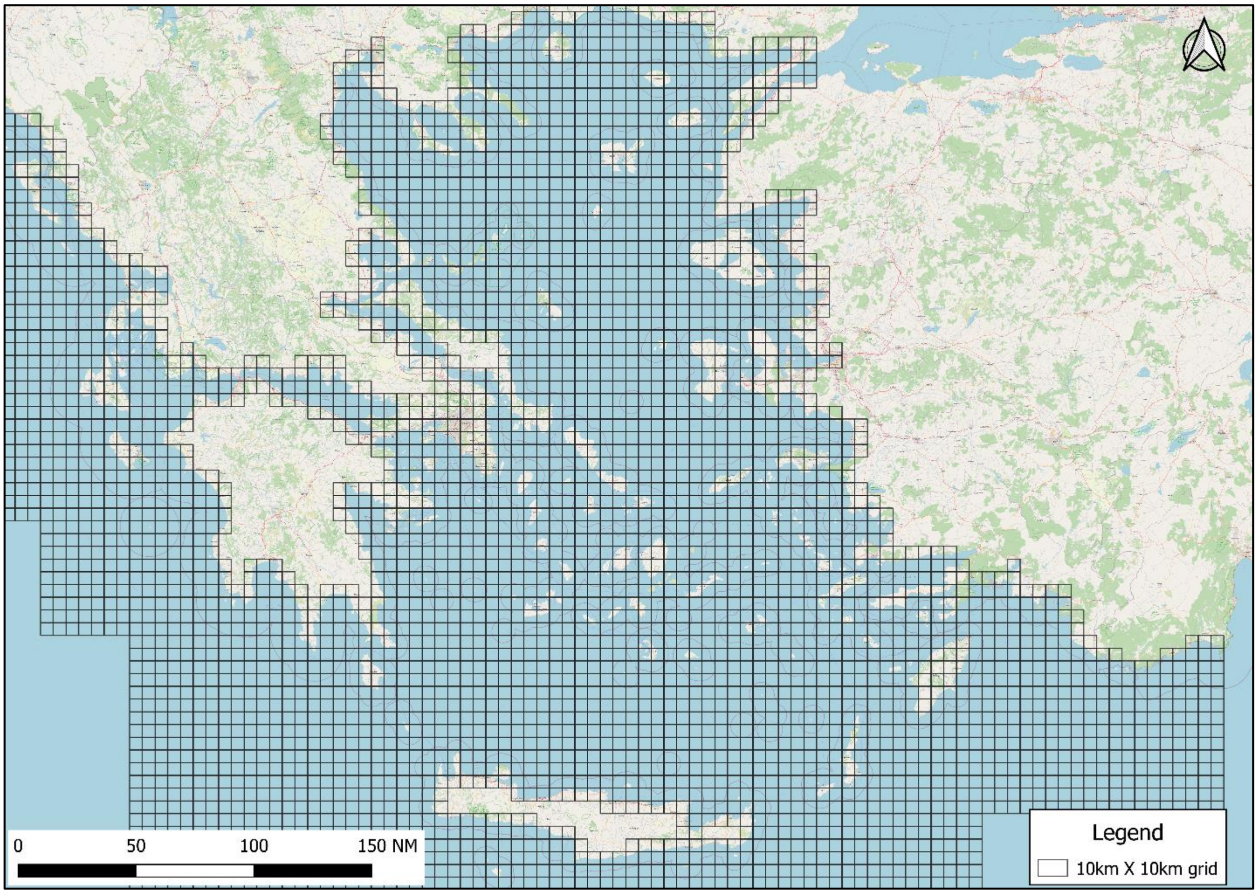
$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{5}$$

where x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{6}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \tag{7}$$

The G_i^* statistic is already a z-score so no further calculation for a z-index is required. On both instances, (2), (5) are used to calculate Moran's I and hot spot analysis indices respectively, while (3), (4), (6) and (7) describe each variable used on both processes to spatially assess the statistical significance of examined features. Spatial autocorrelation models like the two used in this study are crucial in identifying problematic areas where high concentrations of CO_2 emissions are observed. To better identify areas which show higher concentrations, or simply high CO_2 emissions areas, the whole region of study of the GCSN, which is the Aegean Sea, is divided in a 10km x 10 km grid, covering all routes of the study, as shown on Figure 4. Each route analyzed is then divided into distinct parts contained on each 10x10 quadrant, which will then be analyzed as a spatial feature regarding CO_2 emissions. In order to calculate CO_2 emissions on each polygon, the sum of parts of all routes crossing each is calculated based on fuel consumption and CO_2 emissions data for each ship operating each route. Both methods of spatial correlation are used to identify spatial features creating high concentration clusters, with CO_2 emissions as the main variable.



Map 2. Grid division of the study area on 10km X 10km quadrants

As part of this dissertation concentrates on slow steaming for improving CO_2 emissions from ships operating on said routes, a possible decrease of operating speed ranging from 5% to 20% is considered. A 20% or larger decrease could prove non feasible, due to the fact that it is necessary for the overall quality of service to remain on acceptable levels, which is translated to acceptable travel times for passengers. However, the only feasible way to maintain travel times and, thus, the same level of service for passengers and their trips, is to reduce port stop times as much as possible, if there are no alterations to network structure. In the case of passenger shipping, especially regarding the GCSN, this would be highly challenging, as port service times between stops amount for just a portion of the time that a passenger ship spends at sea, specifically only for boarding and disembarkation of cars and passengers, which in most cases could be between 5 to 25 minutes, depending mostly on each port's infrastructure and passenger flows. As a result, a reduction of port stop times could be explored, but would be possible only in cases of higher delays at port stops. Nevertheless, for the purposes of this dissertation, the maximum decrease in speed that will be explored will be at 20%, for the whole network and on selected areas of high CO_2 concentrations. The methodology used to both implement and evaluate the proposed slow steaming strategies under different scenarios are thoroughly described on the following section.

3.3. Slow Steaming Strategies

For the aforementioned solution, new fuel consumptions and CO_2 emissions are estimated based on the methodological framework presented by Psaraftis, Kontovas & Kakalis (Psaraftis et al., 2009), which is applied on high-speed ships, such as RoPax ferries, which are the types of ships servicing the routes of the GCSN. The methodological framework for estimating differences in fuel consumption at sea for slow steaming per trip is given on Eq. (8). It is worth noting that in this case, port fuel consumption is not taken into consideration, mainly for two reasons. First, given the overall structure of the network, it is assumed that port times are low, considering that the methodology is applied to a domestic passenger shipping network. Moreover, port fuel consumption is not added to the fuel consumption estimation in this study as added fuel consumption, as the average fuel consumption from the EU-MRV is used, which is the result of reported actual data of fuel consumption of a ship through different calculating and monitoring methods, thus taking into consideration both fuel consumption at sea and at ports. In addition, differences in CO_2 emissions are calculated on Eq. (9).

$$\Delta(F.C.) = \frac{L}{24 \cdot V_0} F_0 (a^2 - 1) \tag{8}$$

$$\Delta(CO_2\ emissions) = F_{CO_2} \cdot \left[\frac{L}{24 \cdot V_0} F_0 (a^2 - 1)\right] \tag{9}$$

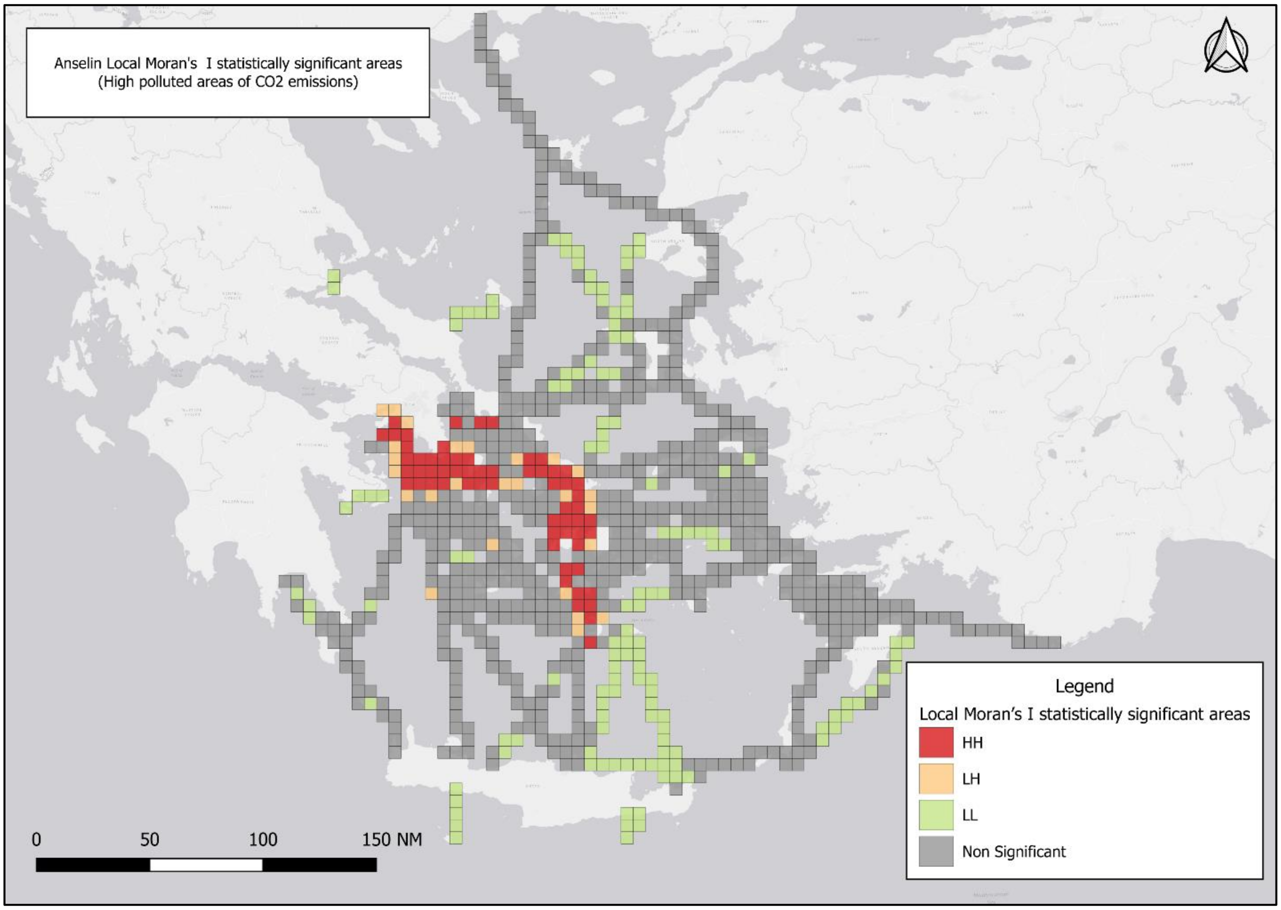
In the above equations, $\Delta(F.C.)$ shows the difference in fuel consumption, L the total distance travelled, V_0 the current average speed of the ship, F_0 the ship's reported average fuel consumption, $\Delta(CO_2\ emissions)$ denotes the difference in CO_2 emissions, F_{CO_2} is the emission factor used for CO_2 emissions and a is the speed reduction factor used for the purposes of the study, equaling between 0.80 and 0.95, for speed reductions between 20% and 5% respectively. In this study, the emission factor for heavy fuel oil will be used for the calculation of emissions, equaling 3.114, which is in accordance to the reported data of EMSA\THETIS-MRV (European Maritime Safety Agency, 2019) for most of the ships operating on the GCSN.

Based on the identification of areas with increased GHG emissions, two slow-steaming scenarios (strategies) for the reduction of CO_2 emissions are assessed. In the first scenario (Full Implementation

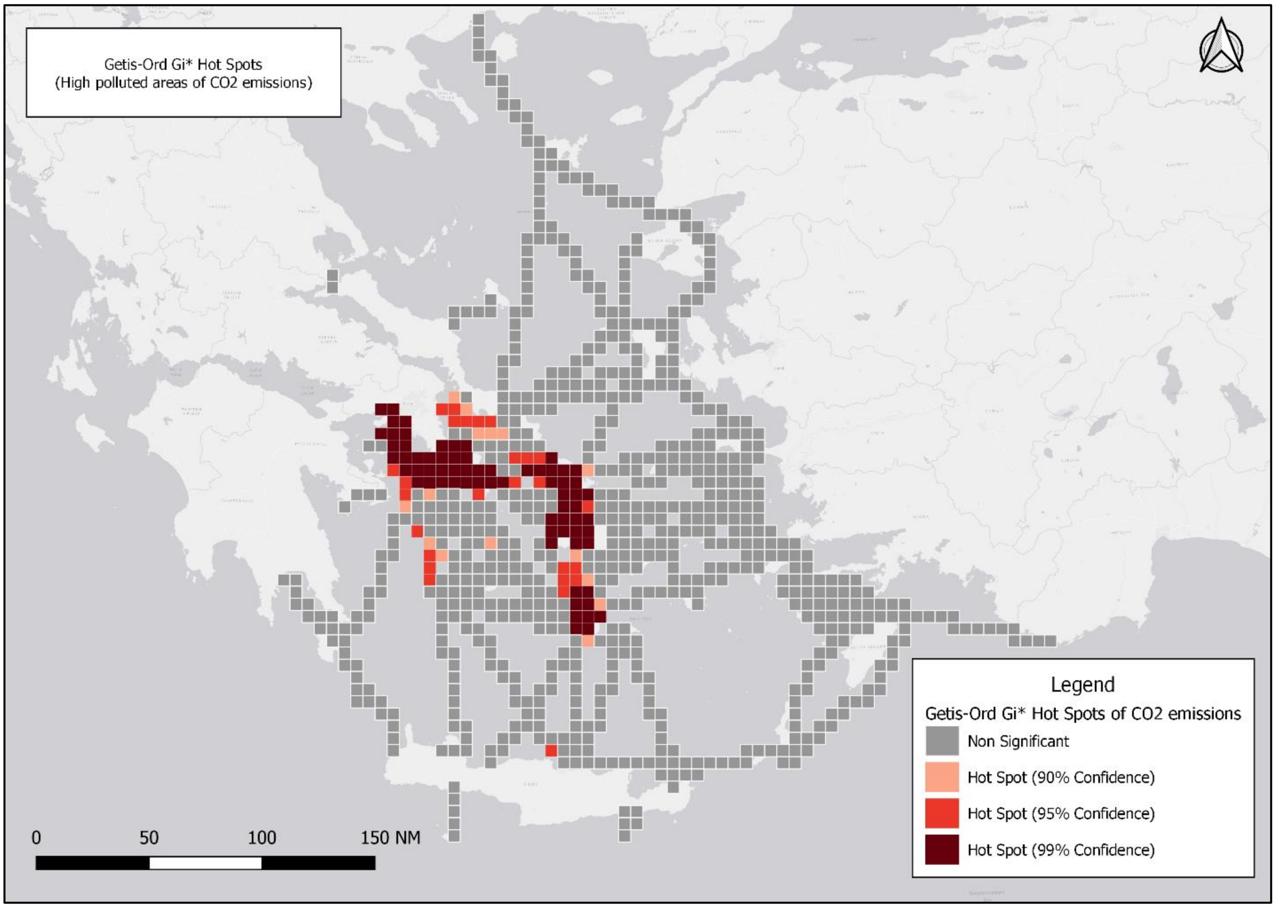
Scenario) slow steaming is applied on the whole GCSN. The second scenario assumes that slow steaming is implemented only on areas where high clusters of CO_2 emissions appear, simulating a scenario as if Emission Control Areas (ECAs) were to be implemented (ECA scenarios). For the ECA scenarios, all necessary data are calculated on the route parts which are included inside the boundaries of such areas, with fuel reduction being calculated for each part considering all four possible scenarios of 5%, 10%, 15% and 20% speed reduction. In both scenarios, fuel consumption and CO_2 emissions reductions are calculated on a three-month period, while time delays because of speed reduction are calculated on a single trip basis, which consists of all port calls between the port of origin and the island destinations of the specific route.

3.4. Results of High CO_2 Areas in the Study Area

Determining which areas will be utilized as ECAs for the purposes of this study is the first step for the implementation of slow steaming scenarios. As such, by utilizing the two different methods mentioned above for identifying areas of higher concentrated CO_2 emissions, corresponding maps of the results are generated. The first one presented in Figure 5 shows areas of high concentration of CO_2 emissions, whilst neighboring areas also show high values of CO_2 emissions, by performing a Cluster and Outlier Analysis (Anselin Local Moran's I), and by calculating Local Moran's I statistics of spatial association. Results of this analysis are best given by a code representing the cluster type for each statistically significant feature, such as "HH", denoting High-High areas, as mentioned above. Other statistically significant areas are shown as "LH" and "LL", denoting Low-High areas, which are areas of low CO2 emissions with neighboring areas of higher concentrations and Low-Low areas, which are areas of low CO2 emissions with neighboring ones of also low CO2 emissions. The outputs of "LH" are, to an extent, justified as they are shown near areas of the "HH" category, thus denoting areas where ship traffic and therefore emissions are low, with neighboring areas being the ones of high CO_2 concentrations The second map, which is shown on Figure 4, shows results of the Getis-Ord Gi* statistic, which is a hotspot analysis. Results of the statistic are more straightforward, as the higher the value of the statistic, the more statistically significant a feature, consisting of a hot spot having high values of CO2 emissions, with also neighboring features of high values of CO2 emissions. For statistically significant positive z-scores, the larger the z-score is, the more intense the clustering of high values (hot spot) while for statistically significant negative z-scores, the smaller the z-score is, the more intense the clustering of low values (cold spot). The following maps show areas where there are areas of high-clustering, with Map 3 showing Local Moran's I clusters and outliers, while Map 4 shows hot spots, categorized based on their statistical significance, with the scales denoting areas of 90%, 95% and 99% statistical significance respectively.



Map 3. Anselin Local Moran's I statistically significant areas of interest denoting areas of high CO_2 emissions



Map 4. Getis-Ord Gi* Hot Spots of statistically significant areas of interest denoting areas of high CO_2 emissions

Results from both methods do not show significant variations, considering High-High areas and Hot Spots of 99% Confidence levels. In the case of the calculations of Anselin Local Moran's I statistic, 61 areas were identified as High-High clusters. In the case of the Getis-Ord Gi* statistic, 69 areas were identified with a z-score higher than 3, denoting areas of high CO_2 emissions concentrations with a 99% statistical confidence, while an overall of 110 areas were identified with a Gi* statistic score where high clustering statistical confidence is at least 90%. For the purpose of this study, as the ECAs scenarios are implemented to provide more flexibility regarding less travel time delays, the more lenient case of slow steaming on the 61 areas of the first map is adopted as the first scenario (Level 1 Scenario). For the second slow steaming scenario, considered as an intermediate solution (Level 2 Scenario), all high cluster areas of the Getis-Ord hotspot analysis are considered as ECAs, which also denote areas of high CO_2 emissions. It is worth noting that all statistically significant areas (hotspots of more than 90% statistical confidence) of the Getis-Ord Gi* hotspot analysis are considered for the intermediate scenario, as statistically significant areas of at least 99% were almost similar to the Level 1 Scenario outputs of the Local Moran's I areas.

3.5. Results of Slow Steaming Strategies

To better evaluate the benefits of slow steaming, the same reductions will be implemented to both scenarios, which consist of reductions of 5%, 10%, 15% and 20%. In addition, a more radical scenario for slow steaming is implemented, which considers the full implementation of slow steaming on the whole GCSN. While this is a scenario that is not as viable in reality, as travel times will be highly increased, thus deteriorating the offered Level of Service (LoS) for passengers, it is implemented for comparison, in order to provide a benchmark to better evaluate the effectiveness of the two different strategies implemented on Level 1 and 2 scenarios.

The implementation of all different strategies aims to cover the potential of the GCSN for both economic and environmental benefits in fuel consumption and CO2 emissions reductions respectively. Although it would be possible to reduce a ship's speed more than 20% on smaller areas and, therefore, shorter route parts, the maximum speed reduction cutoff point of 20% is applied on all approaches, as a larger reduction would lead to less realistic outputs. Results of the different slow steaming scenarios are shown on Tables 1 to 3, showing the total fuel consumption reduction in metric tonnes, CO2 emissions reduction, the total time lost on the GCSN and passenger travel delays on a trip basis, as a result of slower speeds. Additionally, to better compare the different strategies, two more outputs are introduced, showing the overall efficiency of each strategy, by providing metrics on both fuel consumption and CO2 emissions reductions, relative to the total time lost on the GCSN from each slow steaming scenario. These metrics aim to provide insight on how effectively each strategy reduces emissions, while also aiming to reduce travel times as less as possible. As a result, the higher both these metrics are, the better the scenario implemented, although bearing in mind that both these metrics should be considered along with the absolute passenger delays. For instance, both these metrics show their highest values on the full implementation scenario of slow steaming, on all routes of the GCSN. While this may show that the rate of CO2 emissions mitigation to passenger delays is better, absolute travel time delay results show a highly deteriorated LoS for the GCSN. Consequently, all generated outputs must be considered before the evaluation of each scenario.

Table 7. Environmental and travel time impacts of Level 1 Scenario (Slow Steaming on Moran's I High - High Areas) for a 3-month period

Speed Reduction	5%	10%	15%	20%
Fuel Consumption Reduction (m. tonnes)	-760.952	-1482.881	-2165.787	-2809.670
CO_2 Emissions Reduction (m. tonnes)	-2369.606	-4617.693	-6744.262	-8749.313
Total time lost on GCSN (hours)	10.270	21.681	34.434	48.782
Fuel saved per hour lost (m. tonnes / extra hour)	74.095	68.396	62.896	57.596
CO_2 emissions mitigated per hour lost (m. tonnes CO_2 / extra hour)	230.73	212.98	195.86	179.36
Average time lost on trip (minutes)	9.48	20.01	31.79	45.03
Maximum time lost on trip (minutes)	19.89	41.99	66.70	94.49

Table 8. Environmental and travel time impacts of Level 2 Scenario (Slow Steaming on Getis-Ord High Clusters areas) for a 3-month period

Speed Reduction	5%	10%	15%	20%
Fuel Consumption Reduction (m. tonnes)	-1149.185	-2239.437	-3270.757	-4243.144
CO_2 Emissions Reduction (m. tonnes)	-3578.562	-6973.608	-10185.137	-13213.151
Total time lost on GCSN (hours)	13.198	27.861	44.251	62.688
Fuel saved per hour lost (m. tonnes / extra hour)	87.076	80.377	73.914	67.686
CO_2 emissions mitigated per hour lost (m. tonnes CO_2 / extra hour)	271.15	250.30	230.17	210.78
Average time lost on trip (minutes)	11.48	24.23	38.48	54.51
Maximum time lost on trip (minutes)	24.92	52.60	83.54	118.35

Table 9. Environmental and travel time impacts of Level 3 Scenario (Full Implementation of Slow Steaming on the GCSN) for a 3-month period

Speed Reduction	**5%**	**10%**	**15%**	**20%**
Fuel Consumption Reduction (m. tonnes)	-5790.12	-11283.32	-16479.58	-21378.92
CO_2 Emissions Reduction (m. tonnes)	-18030.44	-35136.25	-51317.41	-66573.94
Total time lost on GCSN (hours)	36.26	76.55	121.57	172.23
Fuel saved per hour lost (m. tonnes / extra hour)	159.69	147.40	135.55	124.13
CO_2 emissions mitigated per hour lost (m. tonnes CO_2 / extra hour)	497.27	459.01	422.11	386.54
Average time lost on single trip (minutes)	27.194	57.410	91.181	129.173
Maximum time lost on single trip (minutes)	103.454	218.402	346.874	491.405

While results on all scenarios are promising regarding fuel consumption and, therefore, the reduction of CO_2 emissions, it is important to take into consideration the total passenger time delays per trip on all approaches. Although both the Level 1 and Level 2 Scenarios do not have significant impacts on time delays, especially considering less affecting speed reduction strategies, both fuel and CO_2 emissions reductions are significantly less than those of the full GCSN approach. In order to reduce fuel consumption and CO_2 emissions on Level 1 and 2 Scenarios, it would be necessary to implement higher speed reductions, which as shown above would in fact impact passenger times by increasing time delays on a per trip basis. From the evaluation of the above results, an efficient strategy that could potentially reduce CO_2 emissions, while also aiming to provide acceptable travel times would be a 10% speed reduction on the Level 2 Scenario of the Getis-Ord Hot Spot ECAs. In this case, more CO_2 emissions are reduced than the 15% speed reduction of the Level 1 Scenario, while travel times are not affected as much, showing that targeted and concise selections on areas of slow steaming could lead to the much-needed mitigation of CO_2 emissions, while still maintaining an acceptable LoS, through less passenger time delays.

It is becoming clear from the above results that stricter policy measures are necessary for CO_2 emissions to be reduced. Although slow steaming can still generate promising results and be implemented as a transitional measure for mitigating CO_2 emissions, there are several additional strategies existing in the literature that could be implemented along with slow steaming for increased environmental benefits. There are also several economic benefits to be gained from slow steaming strategies. Results show that by achieving certain environmental goals through speed reduction on high-speed passenger ferries, operating costs can also be limited through fuel consumption reductions, albeit on a slower rate on some cases. Regarding environmental, economic and level of service-related impacts of slow steaming, there are several options that could provide the much necessary reductions on CO_2 emissions, while also providing acceptable passenger travel times on a given network such as the GCSN.

3.6. Conclusions and Discussion

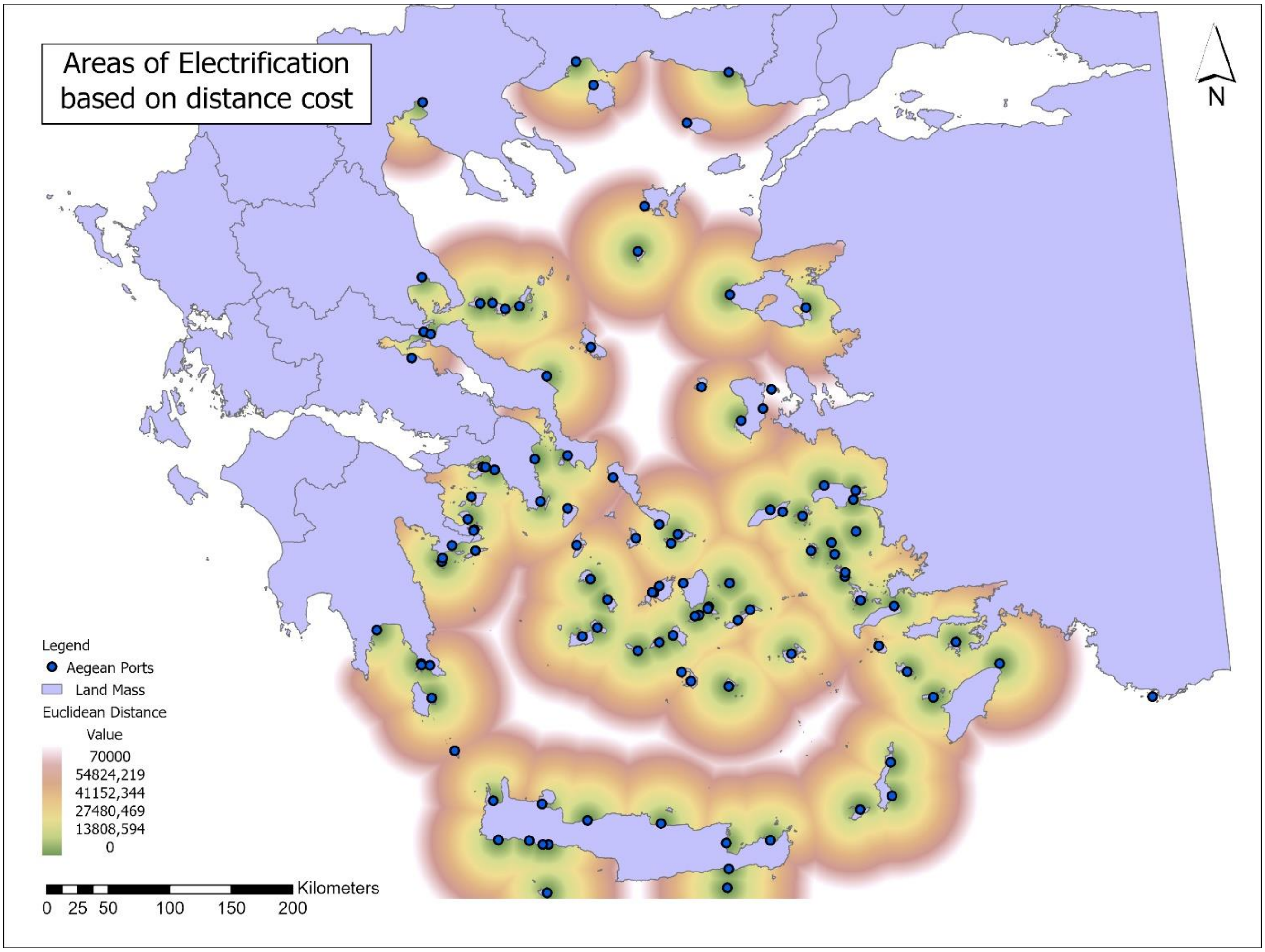
The primary objective of this chapter was to elucidate a methodological framework designed for identifying areas suffering from high CO_2 emissions as a result of domestic shipping operations. The GIS-based framework developed for determining areas with a high concentration of CO_2 emissions provides a preliminary evaluation to aid in decision-making, with its goal being to enhance the environmental footprint of the GCSN, with particular attention to areas where the reduction of CO_2 emissions is critical, while maintaining the necessary acceptable level of service.

Through the use of various methods, like those applied in this study, it is possible to identify locations with high CO_2 emission concentrations and existing clusters, with such identification being pivotal for the targeted and efficient implementation of diverse slow steaming strategies. The initial findings indicate that slow steaming has potential and produces encouraging results. However, using this single measure to reduce CO_2 emissions can only lower the emission rate gradually, especially when applied solely to those specific areas. While there is a possibility to decrease the speed of the fleet across the entire network for better GHG emission results, results show that it cannot be considered as a feasible option, due to higher travel time delays. As a result, such an aggressive strategy would necessitate passengers to tolerate significantly increased time delays which, in the context of domestic passenger shipping, is an unrealistic option, as it gives rise to several accessibility issues. Through the employment of both ECA strategies presented in this study, it becomes apparent that the GCSN requires substantial enhancements regarding its environmental footprint and the efficiency of its fleet, as it is worth noting again that the fleet is aging and includes environmentally inefficient ships, with some in operation for more than 25 years.

It is becoming clear that the selective application of slow steaming in certain areas could yield numerous positive environmental and economic effects. However, the decision-making process could benefit from considering additional variables. The aim would be to overhaul the entire network and optimize operations to achieve superior environmental efficiency, with several options that could enhance the decision-making process, such as adopting strategies including "smart-steaming" for the ships operating the network. This approach would prioritize operations that use the vessel's design speed as the optimal operational one, leading to a noticeable reduction in the fleet's environmental footprint. Another alternative is to investigate the potential impact of seasonal slow-steaming, which would lead to variations in the network structure during periods of lower demand. This approach would permit a higher level of flexibility regarding passenger times, enabling the implementation of more aggressive slow-steaming strategies on periods of lower passenger demand, thus being less impactful and potentially mitigate GHG emissions during months when passenger traffic is at its annual lowest. However, as shown from the above results, an overall restructuring of the network is considered necessary to supplement the efforts of GHG mitigation, with the inclusion and development of novel alternative routes and the integration of zero-emission ones to generate even more promising results, while also continuing to implement effective emission monitoring throughout the network. Additionally, an overhaul of the fleet with environmentally efficient ships, at least on areas where this is feasible and highly necessary, is more than necessary and essential for the GCSN, with the introduction of new ship types that utilize alternative fuels being paramount for operations on high-traffic routes, which are a significant contributor to the resulted areas of high CO_2 emissions shown on the above maps.

4. GIS-BASED ESTABLISHMENT OF ZERO-EMISSION MARITIME ROUTES

Spatial analysis is widely applied for identifying patterns and assessing trends in space and location-related problems. It can be defined as "*a collection of techniques to describe and visualize spatial distributions, identify atypical spatial locations or spatial outliers, discover spatial association patterns, clusters or hot spots, and suggest spatial regimes or other forms of spatial heterogeneity*" 2(Anselin, 1998). Spatial analysis methods have been used in shipping for analyzing vessel collision data in hotspots (Rong et al., 2021), NO_2 emissions in the Red Sea (Alahmadi et al., 2019), port traffic forecasting (Zhang et al., 2019), and the identification of possible collision paths in ship routes (Zhao et al., 2019). In a similar context, a methodological framework based on spatial analysis is developed for the identification of areas serviced by the GCSN where there is potential for the electrification of ferry routes with the support of existing and future RES facilities. The objective is to establish suitable locations for island hub-ports of the GCSN and then determine which nearby ports could be efficiently serviced by electric ships operating between said hub-ports and smaller islands with lower service requirements, relying on renewable energy, thus resulting in both zero-emission islands and their connecting ferry lines. An initial assessment of possible electrification areas, if it were to simply be based on range constraints and no other factors, is shown on the following map, in order to provide insights on the potential of the Aegean Sea for electrification. Danger areas, based on operational constraints are shown above the cutoff distance of about 55km, or 30 nautical miles.



Map 5. Preliminary analysis of potential areas of electrification in the Aegean based on range capabilities of electric ferries

The methodology proposed in this study is based on Exploratory Spatial Data Analysis (ESDA) (Anselin et al., 2010). ESDA is based on the collection and analysis of data on distances between objects and/or events (Fischer et al., 2019), which allows the investigation of spatial correlations with variables related to socio-economic, environmental, and network characteristics. For that purpose, the concept of "spatial autocorrelation" is exploited, which describes the presence of systematic spatial variation in a variable among different locations, meaning that locations that are close together have attributes of similar values (Getis, 2008). Spatial autocorrelation models have the advantage of deriving useful information by detecting deviations from global patterns of spatial association in a given geographic space as well as underlying hot spots for certain variables (Griffith, 2005). ESDA methods are increasingly gaining interest among professionals and academics, constituting the need for continuous improvements on existing software nd the development of newly introduced ones (Percival et al., 2022) to meet the research community's needs. As a result, ESDA methods are also considered in this study for the development of the methodological framework.

4.1. **Bivariate Local Indicators of Spatial Association**

A bivariate Local Indicator of Spatial Association (Bi-LISA) is developed for the purpose of identifying potential areas where spatial autocorrelation exists (Anselin, 2010) when taking into consideration two distinct variables and their spatial relationship. The Bi-LISA is derived from a bivariate local Moran's I model (based on Moran metrics). Moran's I statistics are applied in this study for measuring spatial autocorrelation, which is the presence of patterns in geographic data that are not due to chance; these statistics can be calculated at either the global or local level (Getis, 2010). Considering global Moran's I statistics in practice, a feature is considered of high value if it has a similar value to the mean one and of low value if it has a dissimilar value compared to the mean (Anselin, 2010). For a global spatial autocorrelation statistic, this takes on the general form, as seen on (10), while a generic form for a local indicator of spatial association is seen on (11).

$$\sum_i \sum_j w_{ij} f(x_i, x_j) \tag{10}$$

$$\sum_j w_{ij} f(x_i, x_j) \tag{11}$$

where:

$f(x_i, x_j)$ a measure of attribute similarity between a pair of observations x_i and x_j and

w_{ij} an indicator for geographical or locational similarity, in the form of spatial weights.

On the other hand, a Local Moran's I statistic measures spatial autocorrelation at the neighborhood level. In this case, the statistic is calculated by comparing the value of a feature to the values of its neighbors, and if its value is similar to the values of its neighbors, then the feature is considered of high value, whereas if the value is dissimilar to the values of its neighbors, then the examined feature is considered of low value (Anselin, 2010). The main difference in both statistics is evidently the level at which they are applied, with the global Moran's I statistic focusing on spatial datasets as a whole, thus being utilized when the main focus is to determine whether features show certain spatial patterns (such as clusters or outliers) by measuring overall spatial correlation in a dataset. As for local Moran's I statistics, they are used in cases where there is proof of spatial autocorrelation in order to determine where exactly certain patterns appear, as these measure spatial autocorrelation at the neighborhood (local) level, thus being highly useful when examining sub-regions of a larger area (Guo et al., 2013). Consequently, in most cases, the calculation of a global Moran's I statistic precedes the calculation of a local Moran's I statistic and, therefore, determines whether the latter is necessary.

The use of LISAs has been discussed in various studies (Bivand & Wong, 2018; Boots, 2002, 2003; Fotheringham, 1997). In most cases, LISAs are used to measure the spatial autocorrelation of a single variable in a dataset at the neighborhood level. In recent years, though, LISAs that account for more than one variable are gaining popularity (Bivand & Wong, 2018; Eckardt & Mateu, 2021; Oxoli et al., 2020), with their use being facilitated with the help of GIS software (Anselin et al., 2010). Bivariate LISAs are the most common ones regarding cases of more than one variable, as they take into account two distinct variables and measure their spatial autocorrelation in a dataset. They are considered an extension of the univariate LISAs while having certain advantages over them, mainly due to the fact that they can identify spatial patterns that may not be apparent when analyzing each variable separately. As a result, when analyzing two distinct variables where not only their respective importance to the dataset should be considered but also the spatial relationships between them, the use of bivariate LISAs is necessary.

The approach of the bivariate Local Moran's I model closely follows that of its global counterpart (Anselin et al., 2002) and can be defined as shown on (12) for the calculation of its statistics and determination of statistically significant areas:

$$I_{kl} = z_k^i \sum_{j=1}^{n} w_{ij} z_l^j \tag{12}$$

where:

$$z_k^i = \left[x_k^i - \overline{x_k}\right]/\sigma_k \tag{13}$$

$$z_l^j = \left[x_l^j - \overline{x_l}\right]/\sigma_l \tag{14}$$

and x_k^i the value of variable k at location I, x_l^j is the value of variable l at locator j, $\overline{x_k}$ and $\overline{x_l}$ the mean values of the variables k and l respectively, σ_k and σ_l the variance of X for variables k and l respectively and w_{ij} the elements of the spatial weights matrix (Anselin et al., 2002).

Spatial weights are key factors in most spatial models where the representation of spatial structure and typology is necessary (Getis, 2009; Getis & Aldstadt, 2004; X. Zhang & Yu, 2018), as they provide the way to create spatially explicit variables, such as spatially lagged variables and spatially smoothed rates. In essence, weights express the neighbor structure, which denotes the spatial relationships between the observations, as a $n \times n$ matrix W in which the elements w_{ij} of the matrix are the spatial weights. Such a matrix can then be used in order to encode a variety of spatial relationships, including contiguity, distance, and network connectivity (Anselin, 2022), so that spatial dependence is easily incorporated into statistical models, such as LISA statistics.

There are two basic strategies for creating the weight's values in order to quantify the relationships among features in a dataset; binary and variable weighting. In the case of this study, a binary strategy is applied for the spatial weights w_{ij}, with a value of 1 when i and j are neighbors and zero otherwise. By convention, the self-neighbor relation is excluded, so that the diagonal elements of W where *i*=*j* are zero. Row-standardization is applied, meaning that given weights w_{ij} are divided by the row sum as shown on (15).

$$w_{ij(s)} = {w_{ij}}\Big/{\sum_j w_{ij}} \tag{15}$$

With row-standardized weights applied, each row sum of the weights equals 1, while the sum of all weights S_0, as shown on (16), will equal n, which is the total number of observations.

$$S_0 = \sum_i \sum_j w_{ij} \tag{16}$$

In this study, spatial weights emphasize in contiguity with a queen's criterion, which leads to all eight neighbors of each cell in all directions equaling 1, while others will equal 0. In the proposed framework, a limitation is applied to the neighborhood distance set, which is given by the operating range of the electric ship, resulting in a maximum neighborhood distance threshold equal to the maximum operating range of the electric ship considered. Consequently, i and j are neighbors ($w_{ij} = 1$) when:

$$d_{ij} \leq \delta, \tag{17}$$

where:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{18}$$

with d_{ij} being the Euclidean distance for two points i and j with coordinates (x_i, y_i) and (x_j, y_j) respectively, while δ denotes the preset critical distance cutoff. After that combination, the final spatial weights matrix can be derived. In this study, the two variables selected for the spatial analysis are the total passenger flow of each island/port and each port's proximity to other ports in the study with respect to the given operating range of an electric ship.

For the purposes of the study, two popular and complex island groups in the Aegean are taken into consideration for the implementation of the Bi-LISA model. The first group consists of the islands of the Cyclades, and the second comprises islands from the Dodecanese and Eastern Aegean regions, as these islands show the highest passenger demand, especially in peak summer periods, while also being highly complex regarding topological characteristics. As this study focuses on the feasibility of introducing zero-emission electric ships to certain routes of the GCSN, topology is highly important as such ships can only operate over short sea distances. For this purpose, proximity between islands is considered the most important topological characteristic for the determination of island hub-ports, and therefore, it is used as the first variable of the proposed framework.

For the framework to generate reasonable results, proximity as a variable should be quantified for each port of the study. As such, features of the variable are designed for each potential hub port to show the number of islands that can be reached within a given operating range of an electric vessel. Those other ports that are within that operating range are identified using a proximity analysis method by determining the number of ports in a range of 16.5 nautical miles, which is the maximum operating range of an e-ferry (Gagatsi et al., 2016), reduced by 25% in favor of operational safety. As a result, as more ports are reached from a potential hub-port by an electric ferry, it is more likely for the examined port to be determined as a hub-port from which zero-emissions routes to other island-spokes can be introduced.

Overall passenger demand is also a variable considered for the selection of hub ports, with total embarking and disembarking passengers calculated for each port to describe that variable. The proposed framework takes into consideration the fact that for zero-emission routes to be applied, certain islands serviced by electric ferries will be reached with an added time delay due to the transfer of passengers from larger ships to smaller electric ferries. To compensate for that time loss and the fact that electric ferries have limited capacity capabilities compared to larger vessels, it is proposed that more popular islands, in terms of total passenger demand, are more suitable to be selected as hub ports. This assumption is made for two reasons: first, as more popular islands operate as hub ports and less popular ones as spoke-islands to be serviced by electric ferries, fewer passengers will be affected by time delays from passenger transfer at hub ports. In addition, as less popular islands will be operated by electric ferries, there is less chance for the electric ferries to reach their maximum capacity of passengers due to reduced passenger demand for such islands. With the proposed framework, while passengers to less popular spoke-ports will have to endure increased total travel times due to transfers, their overall environmental footprint will be reduced as part of their route will be electrified, with certain island destinations being serviced by zero-emissions routes.

For a better visualization of the results of the proposed framework, Moran's scatterplots are generated. An effective interpretation of a Moran scatterplot centers on the extent to which the linear regression line reflects the overall pattern of association between W_y and y (Anselin, 2019). The purpose is to find observations that do not follow the overall trend and thus tend to exhibit, to some extent or completely, local instability or non-stationarity. Therefore, with the help of a Moran scatterplot, it is possible to identify clusters of positive and/or negative associations, outliers, leverage points, and spatial regimes (Anselin, 2019; Anselin et al., 2007).

4.2. Evaluation of Renewable Energy Sources Capabilities

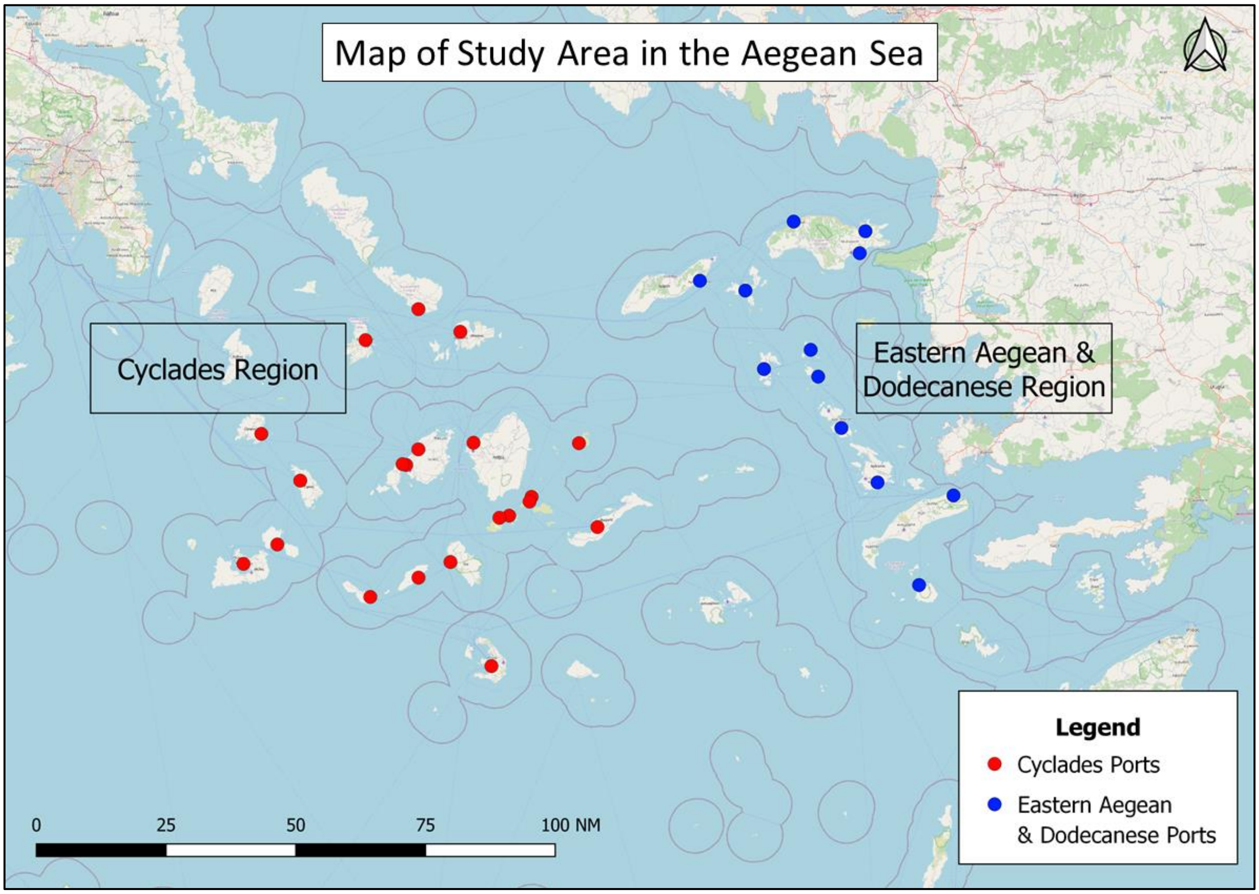
Numerous studies have applied spatial data analysis methods for the assessment of renewable energy sources' (RES) potential in different areas. Most of them have utilized GIS-based spatial decision support systems and multi-criteria analyses for the siting of renewable energy source facilities by combining several criteria with spatial variables, such as different stakeholder interests (Hanssen et al., 2018), land use, and geological constraints, in addition to economic benefits (Van Haaren & Fthenakis, 2011). While multi-criteria site evaluation studies have generally focused on onshore renewable energy source facilities, recent studies have also investigated offshore RES sites for efficient energy supply and decarbonization (Doorga et al., 2022; Vanegas-Cantarero et al., 2022). To this extent, an additional step proposed in this methodology is the evaluation of existing and future RES capabilities for the resulting areas under study to better assess the potential of the facilities supporting electricity-based shipping for zero-emission operations. To do this, open data for renewable energy source facilities were collected by the Greek Regulatory Authority for Energy for the resulted areas, consisting of existing wind and solar farms, either already in operation or under construction, to better assess the existing RES infrastructure. In addition, in order to evaluate the potential for future RES infrastructures, wind and solar data were collected from the World Bank Group's Global Wind Atlas and Global Solar Atlas, respectively. In order to gain better insights on the combined data for existing facilities and potential RES capabilities for the islands under study, fuzzy membership functions are applied to existing data and fuzzy overlays for their combination to provide a better understanding of whether the resulted areas can support the electrification of shipping routes by existing or future RES infrastructures.

4.3. Evaluation of Emissions Mitigation Strategy

Determining potential areas of electrification will yield zero-emission networks, thus resulting in certain routes of the network under study being replaced by electric battery-powered ferries. This replacement will lead to operational emissions nullification with the introduction of e-ferries. In order to provide better insight on the environmental benefits of the proposed methodology, it is necessary to determine the amount of GHG emissions saved because of electrification. To do so, an emissions analysis is conducted for 80 routes of the GCSN, servicing the islands under study, by utilizing reported maritime CO_2 emissions data from the THETIS EU-MRV platform for the European Union Monitoring, Reporting, and Verification system (European Maritime Safety Agency, 2019). As mentioned above, there are several studies which focused on the estimation of maritime CO_2 emissions through mathematical models (Deniz et al., 2010b; D.-P. Song & Xu, 2012b; S.-K. Song & Shon, 2014b; Tarelko & Rudzki, 2020b; Uyanık et al., 2020b), reported CO_2 emissions are used in this dissertation to avoid statistical variances of model-based estimations, resulting in more accurate results through measured data that are in accordance with the EU Regulation 2015/757. However, one of the major drawbacks of EU-MRV data is the fact that, based on EU Regulation 2015/757, CO2 emission reports only apply to vessels of over 5000 gross tonnage. In the case of this study, not all vessels operating in the Aegean Sea are above 5000 GT in size, and their respective operators and shipping companies are not obligated to report either CO_2 emissions or fuel consumption. In such a case and for the purposes of this study, when a route is operated by a ship that has not reported its CO_2 emissions, this route is assumed to be operated by an existing ship of the same type, similar capacity and engine characteristics, for which such data exists. All available emissions data are then added to a GIS database and incorporated into the respective main routes of the GCSN.

4.4. Results for Zero-Emission Sub-Networks

The methodology is applied to the GCSN routes to and from islands belonging to two Aegean Sea insular groups: the first group is that of the Cyclades Island chain, and the second island group comprises some islands from both the Dodecanese and the Eastern Aegean Island chains, as shown in Map 5. As the Aegean Sea is the focus of this study, these specific island groups (Cyclades and Dodecanese – Eastern Aegean) were selected due to the fact that they are separately treated in the GCSN. In total, 20 islands with 21 ports are selected from the first group and 12 islands with 15 ports from the second group, as shown in Table 10. Passenger demand data are derived from the Hellenic Statistical Authority (ELSTAT) (2022): for each island, passenger traffic (passengers embarking and disembarking) is presented on a yearly basis, from 2015 to 2019. For the purposes of the study, average passenger demand is the first variable of the Bivariate Local Moran's I model, with the second one being the number of ports in proximity that each port can service if it operates as a hub port. As mentioned, the distance used for the proximity analysis is 16.5 nautical miles, which is, as mentioned earlier, the maximum E-Ferry operating range, reduced by 25%, considering operational safety. Even though data on passenger flow between islands is not available as it is proprietary, in this case, where the GCSN mainly connects the Aegean islands to the mainland, demand for each island is considered sufficient for characterizing the importance of each island in the network. In addition, in this particular case, island grouping is straightforward due to the established practice in the GCSN (Cyclades and Eastern Aegean – Dodecanese). In other cases, such as this one, density-based clustering methods such as DBSCAN can be used as a first step to determine island groups. In this case, we applied DBSCAN with a search distance of 26.4 nautical miles and a minimum of 6 features (ports) per cluster and obtained the below grouping, as shown on Map 6.



Map 6. Case Study Areas: Ports of Cyclades (Red) and Eastern Aegean / Dodecanese Ports (Blue)

Table 10. Passenger Demand between 2015-2019 and Number of Ports in Proximity of Zero-Emission Ferries

	Island/Port Name	**Passenger Demand**						**Ports in proximity**
		2015	***2016***	***2017***	***2018***	***2019***	***Average***	
Cyclades	Aegiale (Amorgos)	17724	39848	46410	58209	62990	45036	2
	Antiparos	472177	511785	571365	652786	706252	582873	2
	Donousa	14024	27947	29900	40401	41483	30751	2
	Folegandros	79687	80797	94156	102663	102664	91993	1
	Ios	232362	245641	273055	312564	285136	269752	3

	Iraklia	20643	21174	23707	26117	26255	23580	4
	Katapola (Amorgos)	99038	91781	116972	127139	121057	111197	2
	Kimolos	70168	77937	84200	91592	93998	83579	2
	Koufonisia	99276	104893	122506	131912	131658	118049	5
	Mikonos	1186113	1194356	1410377	1571585	1667767	1406040	1
	Milos	257976	281333	336936	370876	423553	334135	1
	Naxos	764323	818549	947567	1035563	1087021	930605	5
	Paros	1409129	1438079	1648866	1832274	1958868	1657444	2
	Schoinousa	28511	31934	34919	36663	36738	33753	4
	Serifos	116553	120350	136810	152785	162859	137872	1
	Sifnos	195884	211494	159235	264729	272068	220682	2
	Sikinos	15760	17298	99403	23722	21975	35631	2
	Syros	522479	603145	631078	695731	731071	636701	1
	Thira	1457004	1387560	1789519	1984999	2117940	1747405	1
	Thirasia	23065	25596	27319	29241	25270	26099	1
	Tinos	757105	850208	941746	1000951	1001551	910312	2
Dodecanese & Eastern Aegean Islands	Agathonísi	802	7604	8394	7154	9025	6596	3
	Agios Kirykos (Ikaria)	59242	79021	66741	47085	32273	56872	2

	Arki	357	4184	5461	4524	6317	4168	4
	Evdilos (Ikaria)	84987	79647	106408	123494	114695	101846	2
	Fournoi	30651	36429	39792	35683	18764	32264	3
	Kalimnos	355964	320150	332428	357701	384620	350173	3
	Kardamaina (Kos)	8124	13548	6673	5294	6041	7936	3
	Karlovasi (Samos)	88862	87331	129788	115750	91638	102674	2
	Kos	600854	537061	528495	579027	591362	567360	2
	Leipsoi	17642	28879	33082	29768	36257	29125	4
	Leros	89653	126321	129908	134507	151987	126475	3
	Nisiros	53651	55444	44482	40045	42020	47128	1
	Patmos	107850	155444	166622	149471	166287	149135	3
	Pythagoreio (Samos)	11123	32044	35616	30185	34074	28608	3
	Vathy (Samos)	153604	86487	71738	85261	69377	93294	2

Spatial analysis results are shown in Map 6 and Figure 10, with the help of GeoDa software. Regarding the software used, it is worth noting that even though there is substantial mapping functionality in GeoDa, it is not a cartographic software by default. Its main objective is to use the maps as part of a framework of dynamic graphics, to interact with the data as part of the exploration process, especially for results of statistical modelling and spatial relationships. As a result, in generated results in maps and figures from said software, some standard cartographic features, such as a directional arrow, or a scale bar may be omitted, which although do not affect the results, their study, and overall comprehension.

Map 6 presents the results of the existing spatial autocorrelation of the examined ports with Bi-LISA outputs regarding statistically significant clusters, categorized into five distinct classes. Clustering results are based on the combination of the value pairs with respect to the normalized value of the variable (z-score) and the normalized value of the sum of the values of the neighbors weighted by the corresponding weights. These five categories are:

i. High – High: spatial entities with high values of both variables under study,

ii. Low – Low: spatial entities with low values of both variables under study,

iii. Low – High: spatial entities of low value for the first variable and high value for the second variable under study,

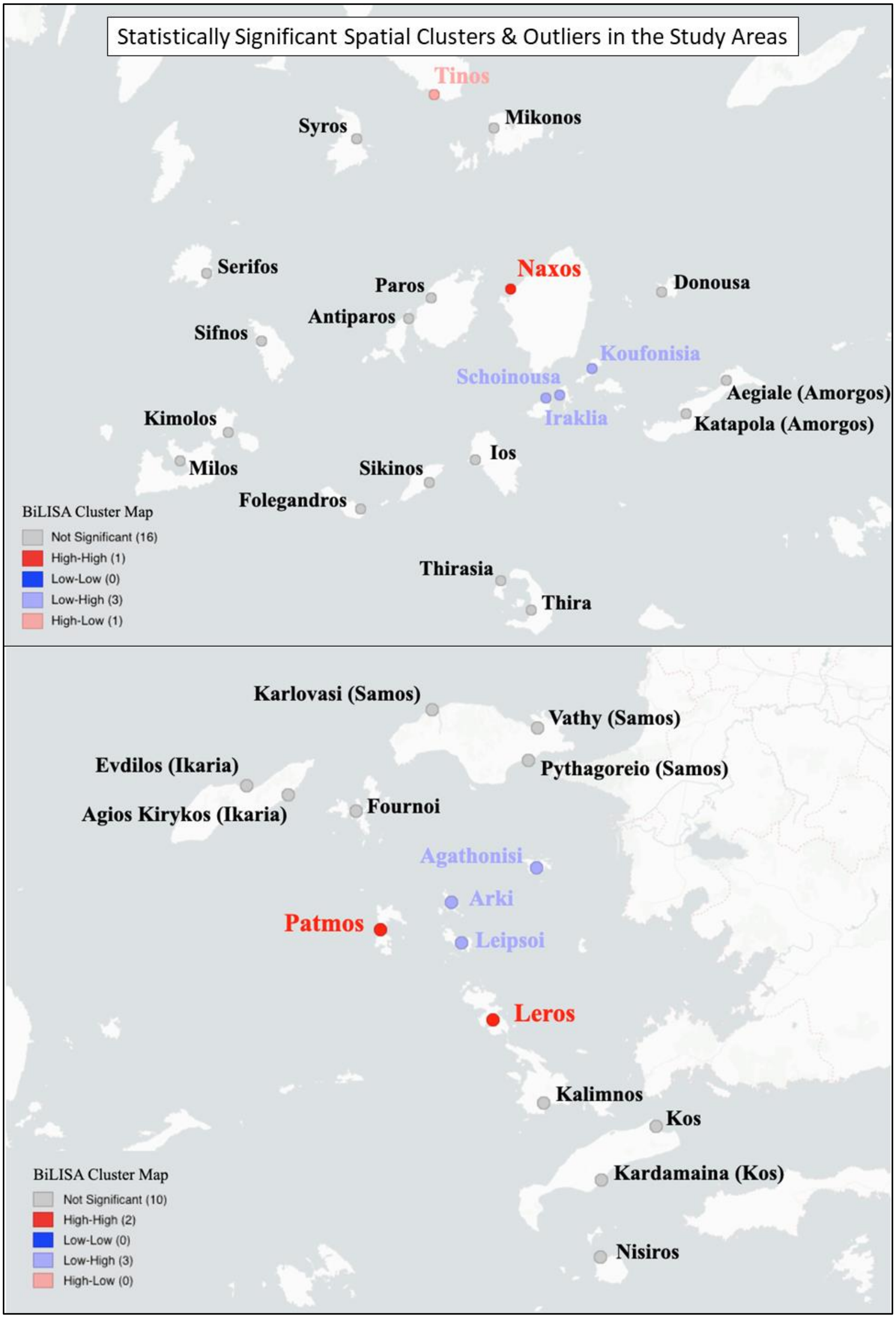
iv. High – Low: spatial entities of high value for the first variable and low value for the second variable under study,

v. Statistically non-significant areas

Taking into consideration the above categories, it becomes clear which categories present the optimal solutions for hub ports and for spoke ports. Cases denoted as High-High are considered the optimal candidates to operate as hub-ports, as they show high passenger flows while also showing a high number of spoke-ports in proximity. In addition, such features show high clustering and positive spatial autocorrelation with neighboring islands regarding both variables, meaning that they can service as many passengers as possible while also being able to service nearby islands with the use of electric ferries. On the other hand, features shown as Low-High show low clustering of the value of the first variable, which in this case is passenger flow, but high values regarding the second value, which is the proximity to neighboring ports. As a result, while such ports are less popular regarding passenger flows, they are more spatially clustered, making them ideal candidates to operate as spoke ports of a zero-emission sub-network and, therefore, be serviced by electric ferries. To better understand why these two categories are highly important in this study, Moran's scatterplots are exploited; Figure 3 shows off-diagonal quadrants of Moran's scatterplots for the two insular groups.

Regarding the Cyclades group, Naxos exhibits positive spatial autocorrelation and is classified as a High-High entity, as it shows high yearly passenger traffic flows, as do the neighboring islands of Mykonos and Paros. However, the difference in this case is made by the second variable, which shows the number of ports in proximity of an electric ship's operating range, with Naxos being able to service up to 5 different islands with electric ferries. On the other hand, the island of Tinos has a fairly high demand, and its major advantage is the opportunity to serve the neighboring islands of Syros and Mykonos as it is located in the middle of the distance between them. Nevertheless, it is classified as a High-Low entity compared to its neighboring islands (Syros and Mykonos), as these islands can in turn only service Tinos, and all three islands can only service a maximum of two ports with the use of electric ferries. The opposite happens in the case of Koufonisia, Iraklia, and Schoinousa (Low-High entities), which all have a high number of ports they can service in between them, thus showing high spatial clustering, but moderate to low demand while also neighboring with ports of higher values of the examined variables, as is for instance the port of Naxos.

As for the Dodecanese and Eastern Aegean Island group, Leros and Patmos are two islands ranked 3rd and 4th in terms of passenger flows among the other islands of the group studied. Due to their position and high centrality, they are identified as High-High entities. Islands of Low-High classification show demand that is more than 35 times less than Patmos, but even so, spatial proximity cannot be neglected, with these islands showing positive spatial clustering. It is clear that the islands classified as High-High entities (i.e., Naxos, Leros, Patmos) have the highest probability of eventually becoming hub-ports from which zero-emission routes will originate. As a result, a new sub-network can be introduced in the Cyclades between the hub port of Naxos and the spoke ports of Antiparos, Iraklia, Koufonisia, Paros and Schoinousa. As for the Dodecanese and Eastern Aegean group, sub-networks can be introduced between the hub port of Patmos and the spoke ports of Arki, Fournoi and Leipsoi. The aforementioned sub-networks are shown in Map 7, with the analysis results of the study variables shown in Figure 11.



Map 7. Cluster Maps of Potential Hubs (High-High features) & Spoke Ports (Low-High features)

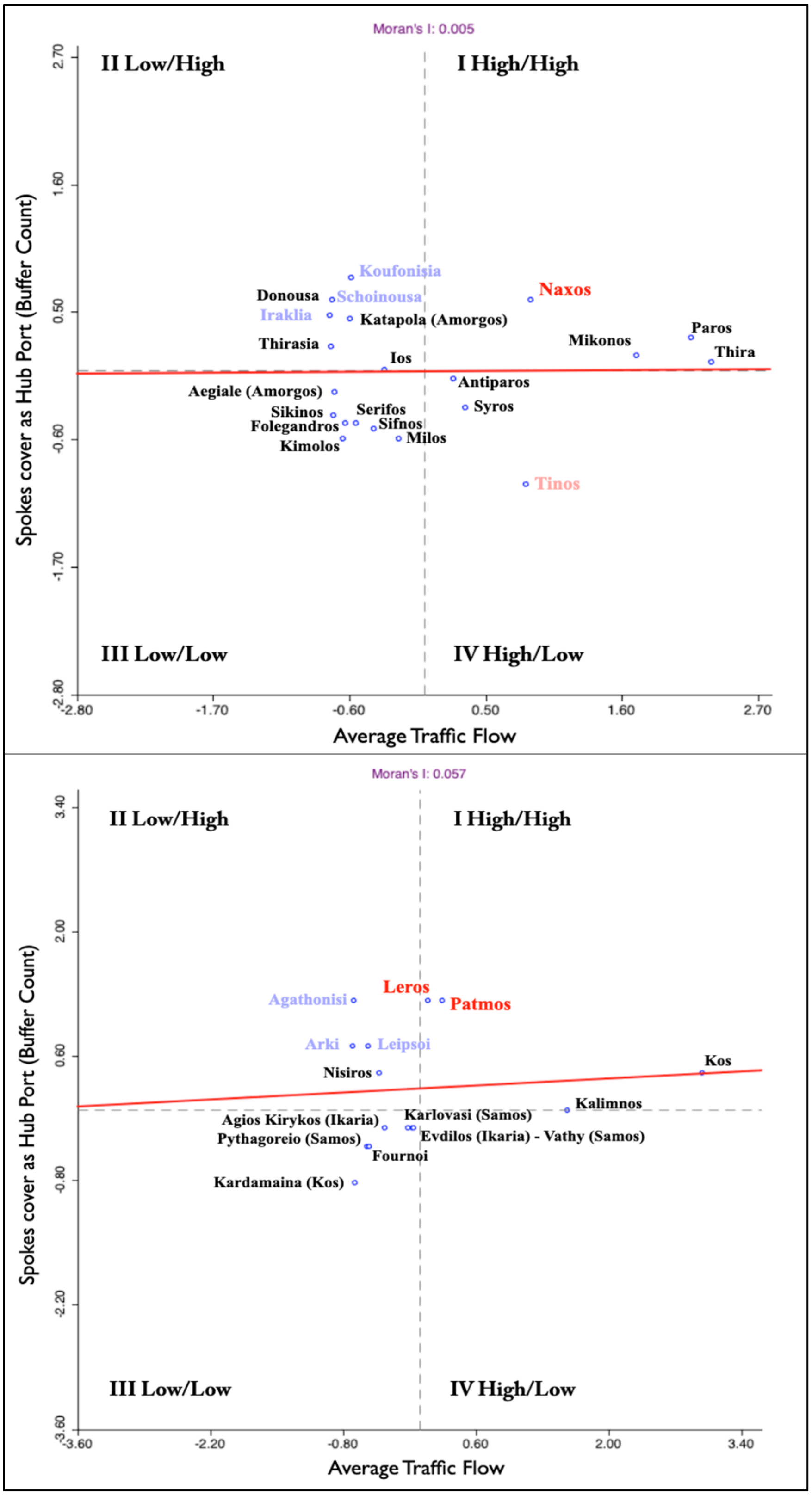


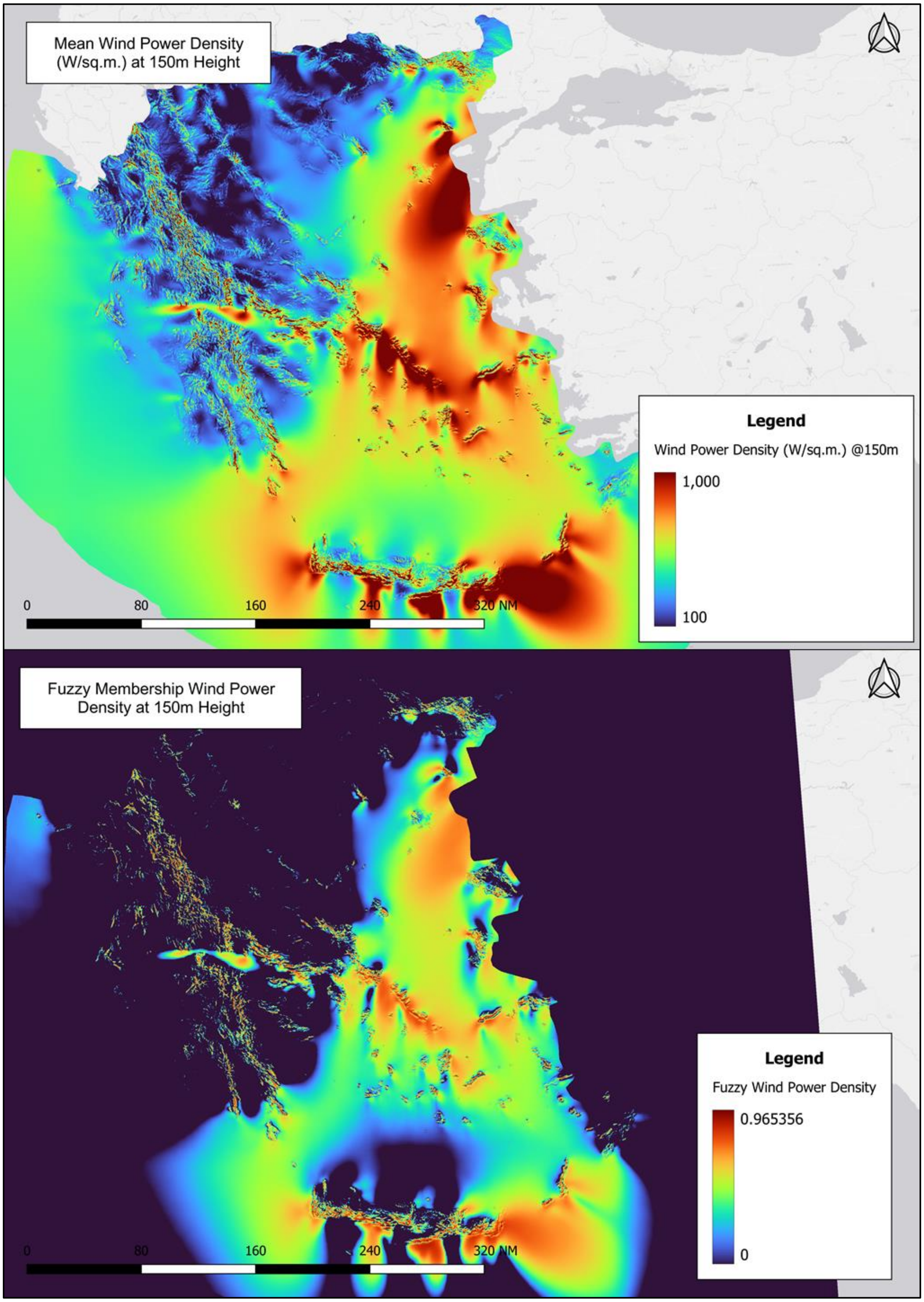
Figure 11. Bivariate Moran's scatterplots of statistically significant clusters and outliers, considering proximity and passenger demand variables

An evaluation of Moran's scatterplots facilitates the selection of both hub ports and spoke ports. Those ports that can operate as hubs can ideally be found in the top right quadrant of the scatterplot, as this is the area where High-High features are located. The top right quadrant shows features that have high values of both variables and, as a result, shows ports that are located in ideal positions to reach as many other ports as possible while also showing high passenger flows. As a result, as the quadrant shows more popular ports with higher passenger demand, larger ships can service the island, transferring both passengers traveling to the hub port and those seeking transfer to nearby islands, thus affecting fewer passengers in terms of travel delays. With the selection of hub ports, the second task for the determination of a zero-emission sub-network is the identification of its spoke ports. Those can be located on the top left quadrant of the Moran's scatterplot, as this shows ports of low passenger demand but with high spatial clustering between them, which are ideal to be serviced by smaller electric ferries due to low demands in passenger traffic and smaller operational distances. Consequently, ports denoted as Low-High are considered the best ones to operate as spoke ports.

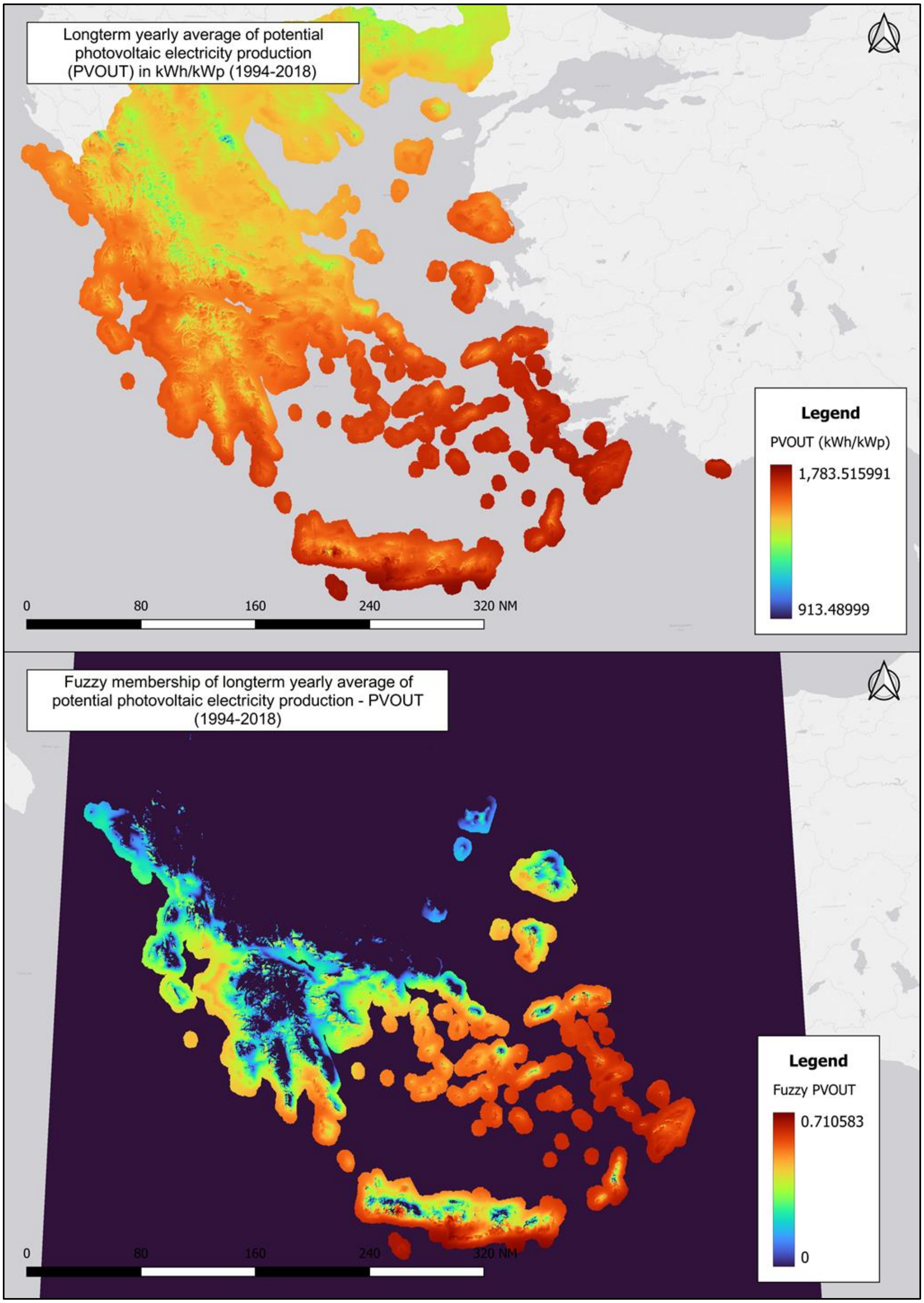
The above results show that in both island groups, a new zero-emission sub-network can be introduced. For the Cyclades group, a new sub-network can be introduced, with Naxos operating as a hub-port and Koufonisia, Schoinousa and Iraklia serviced by electric ferries as spoke-ports. For the Dodecanese/Eastern Aegean group, Patmos is considered the best possible port to operate as a hub port, with Agathonisi, Arki and Leipsoi operating as spoke ports serviced by electric ferries. In the case of the second group, while Leros can also operate as a single hub port or in conjunction with Patmos, if only one was chosen, it would be Patmos, as it shows higher passenger demand. Overall, spatial autocorrelation is found between two key variables that are essential for the design and operation of the GCSN. Ports chosen to operate as hubs must be located in strategic positions while also being able to service as many ports in close proximity as possible with electric ferries. As spatial relationships are evaluated, the above results are considered spatially optimal solutions.

4.5. Results of Renewable Energy Source Potential Evaluation

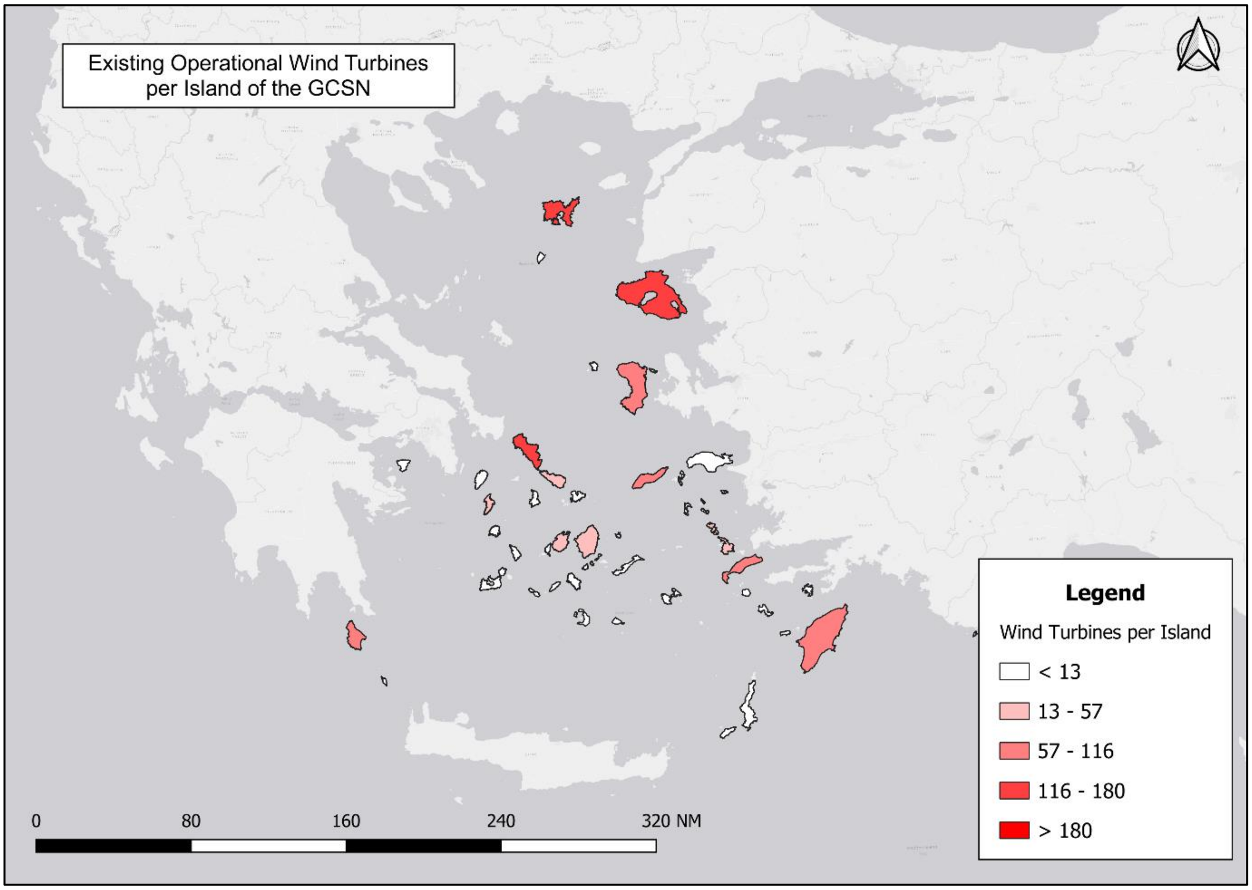
An additional evaluation of the resulted ports and areas under electrification, considering their RES infrastructure and capabilities, is necessary to assess whether there is potential in supporting the zero-emission routes through renewable sources, thus leading to zero-emission islands and their respective connections. In order to assess the potential for RES facilities, mainly wind farms and photovoltaic parks, data from the World Bank Group’s Global Wind Atlas and Global Solar Atlas were used, as shown in Maps 8 and 9. Considering wind power density data, these are selected on a 150-meter height, as there are several locations both in the Aegean islands and uninhabited islets that meet such a criterion and could potentially be selected for future wind farm installations. For the assessment of existing infrastructure, RES open data were acquired from the Regulatory Authority for Energy, consisting of already operational and under construction wind turbines in islands. Considering photovoltaic parks, there are no reported state-owned existing or under construction parks in the Greek islands supporting the electric grid, except private ones for household needs. As a result, only existing operational wind turbines are shown in Map 10. For a better comparative analysis of the data under study, fuzzy membership functions were applied to wind data, solar data, and existing RES infrastructure, which in this case only consisted of existing wind turbines on islands. The fuzzy membership functions were applied so that all data would then be transformed into a 0–1 scale in order for their final combination to be an output raster after conducting a fuzzy overlay on all three raster datasets. More specifically, considering solar and wind data, which consisted of photovoltaic electricity output and wind power density, an MS Large membership function was used, which calculates membership based on the mean and standard deviation of the input data, where large values have high membership, with a value of 1 for the mean multiplier and 2 for the standard deviation multiplier. However, in order to transform existing wind farm infrastructure data to a 0–1 scale, a linear membership function was used, as absolute values (existing wind turbines per island) were considered. In the case of a linear membership function, a membership value of 0 is assigned as the minimum value and a membership value of 1 as the maximum.



Map 8. Potential wind resources for wind farm facilities at areas under study. Initial data accessed from World Bank Group's Global Wind Atlas (https://globalwindatlas.info/en)

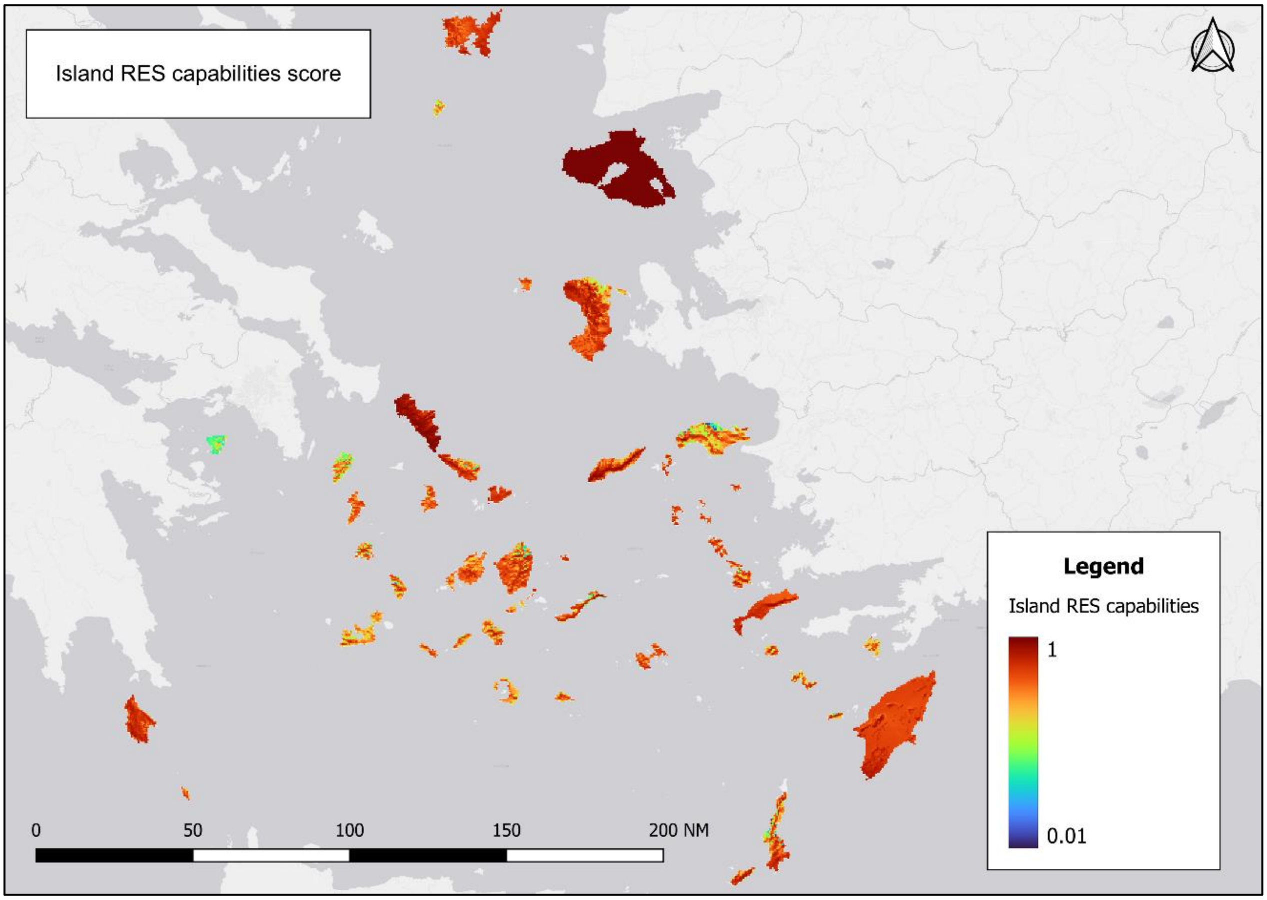


Map 9. Potential photovoltaic electricity production at areas under study. Initial data accessed from World Bank Group's Global Solar Atlas (https://globalsolaratlas.info) and SOLARGIS (https://solargis.com/)



Map 10. Existing operational wind turbines per islands on the islands under study. Initial data accessed from the Greek Regulatory Authority for Energy (https://www.rae.gr/)

After evaluating all available data, it is clear that the existing RES infrastructure in the Aegean Islands is still limited. However, there is a lot of potential regarding renewable resources for future investments, especially in the case of wind farm installations overall, in the Aegean, and in the resulted areas, which could prove vital for the future establishment of zero-emission ferry networks and, consequently, zero-emission islands. After combining all available fuzzy membership scaled data, a final raster is generated through the use of a fuzzy overlay increasive function with an aggregate (sum) overlay type, thus considering, for the purposes of this study and in this case, that a combination of existing infrastructure and potential resource data is more important than each standalone dataset. The aggregate RES capabilities score for all islands under study is shown in Map 11, while the RES existing infrastructure and the overall potential RES capabilities score for the resulted islands are shown in Table 11.



Map 11. Overall island potential for RES facilities, as a combination of existing infrastructure and available resources for future investments

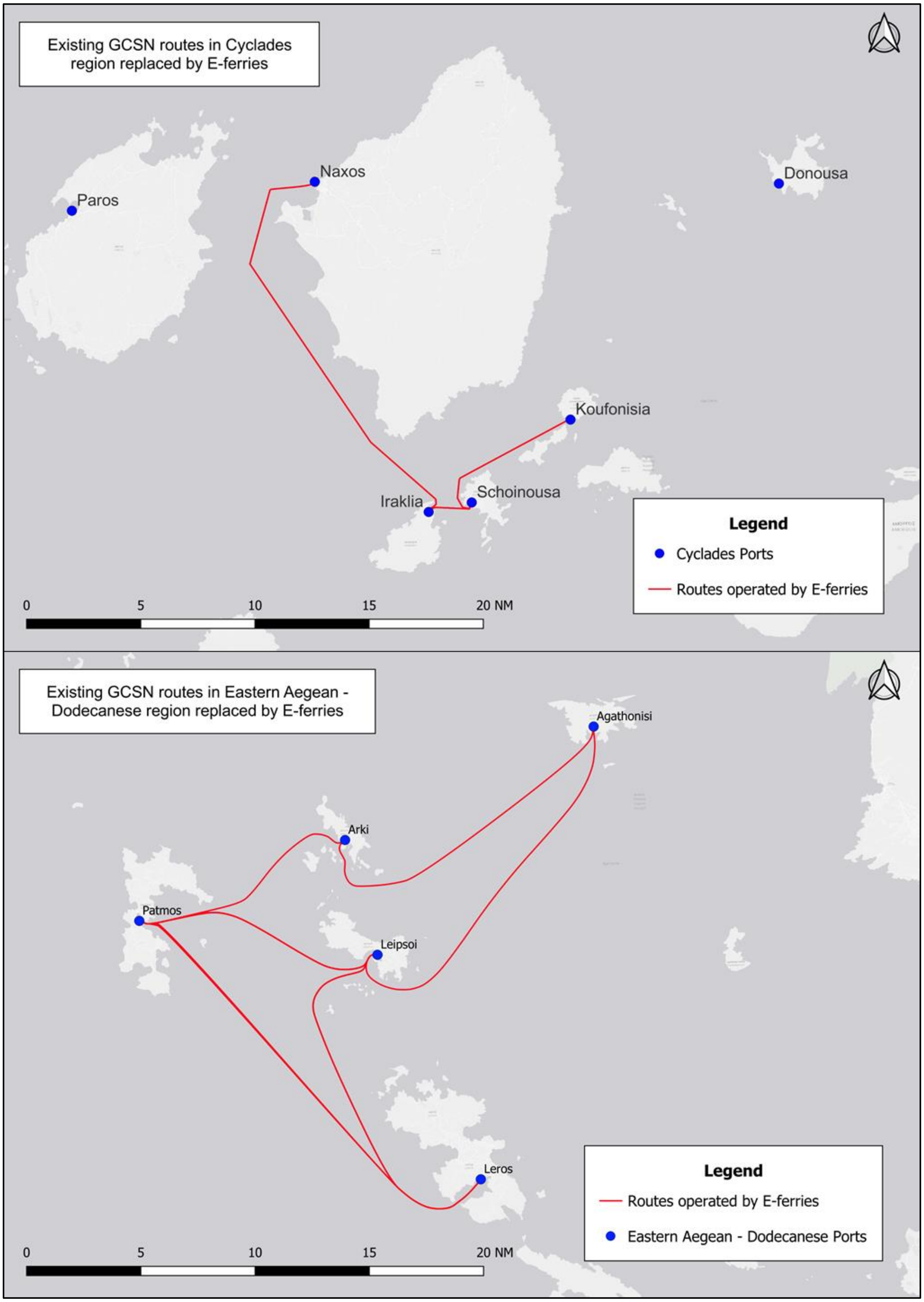
Table 11. RES capabilities and existing RES infrastructure on islands under study

Region	Island	Potential RES capabilities score	Existing RES infrastructure (Wind Turbines)
Cyclades	Naxos	0.82	57
	Schoinousa	0.67	0
	Iraklia	0.72	0
	Koufonisia	0.84	0
Eastern Aegean - Dodecanese	Patmos	0.84	2
	Agathonisi	0.85	0
	Arki	0.81	0
	Leipsoi	0.81	1
	Leros	0.84	29

4.6. Results of Emission Mitigation by Zero-Emission Routes

After determining the potential electrification areas for ferry transport and their RES capabilities, it is also important to evaluate the overall environmental benefits of the proposed methodology. The methodological framework proposed results in certain areas of a given network to operate as zero-emission areas, and therefore, certain routes servicing islands of lower demand being fully operated by e-ferries. As a result, ships operating such routes from a certain hub to the aforementioned islands will, in turn, be replaced by battery-powered ferries, which will lead to operational emissions nullification on the given routes. In order to better determine the environmental benefits of GHG emissions mitigation through this method, reported maritime CO_2 emissions data from the European Union Monitoring, Reporting, and Verification system, or EU-MRV (European Maritime Safety Agency, 2019) are utilized, with the mean operational fuel consumption of the ships operating on such routes used for the calculations of both fuel savings and CO_2 emissions reduction. For the calculation of CO_2 emissions, the emission factor for HFO (heavy fuel oil) is used, as it is the most widely used type of fuel for commercial ships such as the ones operating in the Aegean. Regarding route frequencies, summer period data were collected for round trips, with the trips' frequencies consisting of 3rd quarter 3-month period data (July to September). The routes that can potentially be replaced by battery-powered ferries with zero emissions for the Cyclades and Eastern Aegean-Dodecanese regions are shown in Map 11. Results for the Cyclades region regarding ship characteristics operating the replaced routes, fuel, and CO_2 reductions are shown in Tables 12 and 13, while results for the Eastern Aegean-Dodecanese region are shown in Tables 14 and 15. It is worth noting that in Tables 6 and 8, ships with an asterisk replaced the existing operating ones for the purposes of the study, as data were not available for the ones actually operating on the route under study due to them being less than 5000 GT and therefore having no obligation to report fuel consumption and CO_2 data to the EU-MRV system. More specifically, the ships used for the calculations were selected in such a way that their capacity capabilities (passengers and cars) and engine characteristics were roughly the same as the ones they replaced. In regard to the available data, "Aqua Jewel" replaced "Express Skopelitis" for the Cyclades routes, while "Champion Jet 2" replaced "Dodekanisos Express" and "Dodekanisos Pride" for the Eastern Aegean-Dodecanese routes. Between the two regions, the Eastern Aegean-Dodecanese region shows more promise, considering a 3-month period with more frequent routes, with 4183.52 metric tons of CO_2 mitigated and

1343.46 metric tons of fuel reduced. A much smaller reduction is shown in the Cyclades region, with only 611.69 metric tons of fuel reduced and an additional 1904.79 metric tons of CO_2 mitigated, although this is expected as the proposed routes to be replaced are fewer and the ports operating in the proposed system are in a more compact region, considering distances between ports.



Map 12. Existing GCSN routes to be replaced by battery powered zero-emission ferries in regions under study

Table 12. Route parts IDs and ship characteristics for each route replaced for Cyclades

ID	Route	Route Code	Nautical Miles	Operating Vessel for Calculations (2019)	Ship Mean Fuel Consumption (kg/n.mile)
1	Naxos - Iraklia	D-62	19.36	AQUA JEWEL*	71.17
2	Schoinousa - Koufonisia	D-62	7.49	AQUA JEWEL*	71.17
3	Iraklia - Scoinousa	D-62	2.22	AQUA JEWEL*	71.17
4	Iraklia - Naxos	D-64	19.36	AQUA JEWEL*	71.17
5	Koufonisia - Schinousa	D-64	7.49	AQUA JEWEL*	71.17
6	Iraklia - Scoinousa	D-64	2.22	AQUA JEWEL*	71.17
7	Schoinousa -Iraklia	D-17	2.22	BLUE STAR NAXOS	127.48
8	Naxos - Iraklia	D-17	19.36	BLUE STAR NAXOS	127.48
9	Schoinousa - Koufonisia	D-17	7.49	BLUE STAR NAXOS	127.48

Table 13. Fuel Reduction and CO2 emissions reduction for each route part in the Cyclades

ID	Fuel Consumption (kg per trip)	CO_2 Emissions (kg per trip)	Trips in 3-month period (13 weeks)	Fuel Reduction (tonnes / 3m)	CO_2 reduction (tonnes / 3m)
1	1377.64	4289.96	78	-107.46	-334.62
2	532.92	1659.52	78	-41.57	-129.44
3	157.93	491.78	78	-12.32	-38.36
4	1377.64	4289.96	78	-107.46	-334.62
5	532.92	1659.52	78	-41.57	-129.44
6	157.93	491.78	78	-12.32	-38.36
7	282.89	880.91	78	-22.07	-68.71
8	2467.69	7684.40	78	-192.48	-599.38
9	954.60	2972.61	78	-74.46	-231.86

Table 14. Route parts IDs and ship characteristics for each route replaced for Eastern Aegean – Dodecanese

ID	Route	Route Code	Nautical Miles	Operating Vessel for Calculations (2019)	Ship Mean Fuel Consumption (kg/n.mile)
1	Patmos - Leipsoi	D-1	11.59	BLUE STAR CHIOS	187.02
2	Arki - Agathonisi	D-76	15.489	CHAMPION JET2*	142.48
3	Leipsoi - Agathonisi	D-77	17.908	CHAMPION JET2*	142.48
4	Leipsoi - Leros	D-73	16.448	CHAMPION JET2*	142.48
5	Leipsoi - Patmos	D-73	11.59	CHAMPION JET2*	142.48
6	Leipsoi - Patmos	D-78	11.59	CHAMPION JET2*	142.48
7	Leros - Leipsoi	D-76	16.448	CHAMPION JET2*	142.48
8	Leros - Leipsoi	D-78	16.448	CHAMPION JET2*	142.48
9	Patmos - Arki	D-76	9.707	CHAMPION JET2*	142.48
10	Patmos - Leipsoi	D-72	11.59	CHAMPION JET2*	142.48
11	Patmos - Leipsoi	D-76	11.59	CHAMPION JET2*	142.48
12	Patmos - Leipsoi - Leros	D-20	28.038	BLUE STAR CHIOS	187.02
13	Patmos - Leros	D-33	21.011	BLUE STAR 2	258.37

14	Patmos - Leros	D-34	21.011	BLUE STAR 2	258.37
15	Patmos - Leros	D-8	21.011	BLUE STAR 2	258.37

Table 15. Fuel Reduction and CO_2 emissions reduction for each route part in the Eastern Aegean – Dodecanese

ID	Fuel Consumption (kg per trip)	CO2 Emissions (kg per trip)	Trips in 3-month period (13 weeks)	Fuel Reduction (tonnes / 3m)	CO_2 reduction (tonnes / 3m)
1	2167.56	6749.79	26	-56.36	-175.49
2	2206.80	6871.96	26	-57.38	-178.67
3	2551.44	7945.19	52	-132.67	-413.15
4	2343.43	7297.44	52	-121.86	-379.47
5	1651.29	5142.10	52	-85.87	-267.39
6	1651.29	5142.10	26	-42.93	-133.69
7	2343.43	7297.44	26	-60.93	-189.73
8	2343.43	7297.44	26	-60.93	-189.73
9	1383.00	4306.68	26	-35.96	-111.97
10	1651.29	5142.10	52	-85.87	-267.39
11	1651.29	5142.10	26	-42.93	-133.69
12	5243.67	16328.78	26	-136.34	-424.55
13	5428.68	16904.92	26	-141.15	-439.53
14	5428.68	16904.92	26	-141.15	-439.53
15	5428.68	16904.92	26	-141.15	-439.53

Considering the above results, there are clear benefits to be gained from the shift to battery-powered zero-emission ferries where this is feasible. While the methodology applied provided promising results, it is still important for future studies to include more variables in the framework. For instance, the operation of newer types of ships and the restructuring of the network will require extensive analyses of the optimal weather routing of such ships to limit power loss while also considering environmental factors. In addition, port infrastructure should also be considered a distinct variable for the evaluation of potential hub ports for the GCSN. Last, although potential areas for the introduction of sub-networks with electric ferries and hubs were determined, it is highly important for future studies to consider optimal routing for such sub-networks while also assessing the effects on passenger travel times.

4.7. Conclusions and Discussion

The Greek Coastal Shipping Network (GCSN) is a complex system, incorporating a multitude of variables that require consideration for its potential restructuring and enhancement. The goal of this dissertation presented in this section is to establish a framework that facilitates the assessment of various ports within insular groups, pinpointing those that hold promise as potential hubs for the establishment of zero-emission sub-networks. Given the intricacies of the GCSN and the accessibility challenges faced by many islands, the proposed methodology is intended to streamline the decision-support process, ultimately aiming in restructuring the network by prioritizing overall emission reduction.

As a problem with significant spatial implications tied to environmental aspects is addressed, multivariate Local Indicators of Spatial Association (LISA) model were utilized for preliminary results. The promising results from this model highlight the potential for the transition of the GCSN towards electrification, and therefore, emission mitigation. Furthermore, the existing infrastructure for Renewable Energy Sources (RES) and the potential capabilities on the islands are evaluated. The aim of this section is to assess whether the identified areas could leverage RES facilities to meet their energy requirements, relative to the resources available in the areas under investigation. The methodology proposed within this research indicates that highly accurate results can be achieved by considering both spatial and non-spatial characteristics of such spatially intricate networks. Additionally, this method seeks to offer an easily adaptable framework that can be applied to other scenarios with differing parameters. The research findings show potential in several areas, including the implementation of zero-emission networks through the introduction of battery-powered ferries servicing the identified routes. More than one port emerged as a viable hub, while capabilities of the identified areas for RES utilization also showed promise. In addition to the above preliminary results, the creation of optimal routes between the identified hub and spoke ports is of paramount importance. This, therefore, is also a priority of the dissertation and future studies should also consider this, especially on coastal shipping electrification, where the spatial characteristics of such complex networks should consist the central aspect of such researches.

5. NETWORK DESIGN AND EFFICIENCY ASSESSMENT

As mentioned on previous chapters, maritime transport is vital for global trade but also generates significant greenhouse gas emissions. This section of the dissertation introduces a new Efficiency Index for the Greek Coastal Shipping Network (GCSN), incorporating port connectivity and environmental impacts, in addition to the network's spatial characteristics and topology. The Index calculates port scores, with additional emphasis on zero-emission operations. The Index is applied both to the existing and a restructured network, which is generated considering environmental and other factors of sustainable operations. The index uses a GIS-based framework for spatial visualization, identifying key nodes, links, and investment areas to improve connectivity and reduce emissions. The Efficiency Index is targeted at stakeholders, providing a comprehensive measure of port connectivity and contributions towards maritime decarbonization. This chapter aims to highlight the importance of spatial characteristics in developing an Efficiency Index that considers environmental and economic factors and overall port accessibility, supporting strategic decisions for sustainable, zero-emission shipping networks.

5.1. Data Collection and Assumptions

In order to measure overall efficiency and, in return, construct the efficiency indices for the network's ports, data collection is necessary. Collected data for the ports and the overall network included overall passenger demand per port in embarked and disembarked passengers, the number of routes servicing each port, the frequency of each route on a weekly basis, the associated CO_2 emissions per port, generated by the aforementioned routes and total ship calls per route and port and, finally the feasible and actual zero-emission connections for each port. Regarding passenger demand, as only embarked and disembarked passenger data were available through the repositories of the Hellenic Statistical Authority (ELSTAT), these were collected on a pre COVID-19 period, from 2015 to 2019, as they show the network in its normal operations. Available data were collected on a yearly basis, while differences between embarked and disembarked passengers from each port did not show significant variations. As a result, mean data for the 5-year period from 2015 to 2019 were calculated and the maximum of disembarked and embarked passengers per port was chosen to reflect the passenger demand of each port. Sources regarding the routes of the GCSN and their frequencies were collected from various sources, such as Greek travel providers and their websites, shipping companies operating in the ferry sector, available AIS data repositories (e.g., MarineTraffic, Marinus Directory etc.) and the Hellenic Statistical Authority. In addition, ship data were collected for each route serviced, while CO2 emission data were made available through the EMSA \ THETIS-MRV system, where CO2 emissions from ships are reported according to the EU Regulation 2015/757, in addition to other data such as fuel consumptions, time at sea and other data of technical and operational efficiency. Through the use of these data, it is possible to calculate the actual operational speeds of the ships under study, while also associating CO2 emissions to each route of the study. An issue that came up during the data analysis process was that not all ships are obligated to report CO2 data to the EMSA \ THETIS-MRV system, with only ships over 5000GT needing to monitor and record related data. As a result, certain routes exist in this study which were operated by ships that were not reporting CO2 data. In order to overcome this issue, an assumption is made that these routes are operated by similar ships, in terms of offered capacity, engine characteristics and other available data, such as ship age, in order to replicate the network's operations on these routes as better as possible. Figure 1 shows the routes of the study for which relative data were collected to the extent of the GCSN.

5.2. Port Efficiency Indices

As most data were initially associated with each route, the next step was to associate each relative data to each port serviced by each route. As a result, each port was associated with each route and its relative data, thus creating a new dataset on a GIS environment which consisted of the available route information for each port, such as which routes call on each port, their respective yearly port calls per route, and total CO_2 emissions associated with each port from each route. The latter is calculated through an assumption made for each port on each route, where it is assumed that each port on a distinct route "shares" the total CO_2 emissions of a route's trip on equal amounts as the rest ports of the route, as if having the same importance and transport work generated CO_2 emissions as the rest. While essentially this is not exactly true, especially when considering more remote and more high-demand ports, this assumption is becoming less biased due to the fact that the relative environmental efficiency index of the study for each port is calculated in relation to passengers travelled to each port of the route. As a result, CO_2 emissions were calculated for each route and for each port that each route calls to.

Through the available data, each distinct index incorporated to the proposed port Efficiency Index is calculated as follows:

$$\text{Emissions Efficiency: EEf} = \frac{\text{CO}_2\text{ emissions from port ship calls}}{\text{Total yearly passenger demand}} \tag{19}$$

$$\text{Passenger Efficiency: PaxEf} = \frac{\text{Total yearly passenger demand}}{\text{Total ship calls on each port}} \tag{20}$$

$$\text{Connectivity Efficiency: CEf} = \frac{\text{Total ship calls on each port}}{\text{Total routes calling on port}} \tag{21}$$

$$\text{Zero} - \text{Emission Routes Efficiency: ZREf} = \frac{\text{Actual Zero}-\text{Emission Port Connections}}{\text{Feasible Zero}-\text{Emission Port Connections}} \tag{22}$$

Overall port efficiency for each port j is then calculated as shown on Eq. 23, after normalizing the aforementioned sub-indices, in order to generate reasonable results on the overall port efficiency index on a relative scale. It is also worth noting that emissions efficiency *EEf* is normalized inversely, as lower values of *EEf* are better (less CO_2 emissions per passenger on each port).

$$\mathrm{PE_j} = \frac{\sum_{i=1}^{n} w_i(\mathrm{Ef_i})}{\sum_{i=1}^{n} w_i} \tag{23}$$

where Ef_i is the normalized efficiency index for each sub-index *i* and w_i is the weight assigned to each sub-index *i*.

While weight assignment is possible and, in most cases, necessary, for the purposes of this dissertation it is considered that all sub-indices have equal weights, thus considering that they are of equal importance to the study. However, it is worth noting that for the Efficiency Index to generate reasonable calculations, all ports must have at least one feasible connection from/to them that can be serviced by zero-emission ferries. As zero-emission battery powered electric ferry technologies are capable of achieving safe operations on specific distance ranges, there are ports of the GCSN that were excluded from the study as no feasible zero-emission connection existed between them and other ports.

When considering the spatial characteristics of the efficiency indices created, in terms of ports analyzed, the network's ports do not show specific patterns on most cases. However, considering port connectivity efficiency, there is clearly a specific area where connectivity efficiency shows low clustering, when implementing both global and local Moran’s I statistics to assess spatial autocorrelation. While all other examined indices show a random distribution regarding spatial patterns, connectivity efficiency of ports of the study area shows a specific spatial pattern, which is low clustering on almost all ports of the Dodecanese/Eastern Aegean region, as shown on the following figure. It is worth noting that the model excludes results of over 0.05 significance level, with a randomization of 99999 permutations. This finding indicates that the specific region seriously lacks in terms of overall connectivity and accessibility on an overall basis, thus creating the need for targeted interventions to improve its cohesion with other regions and overall accessibility through offered routes.

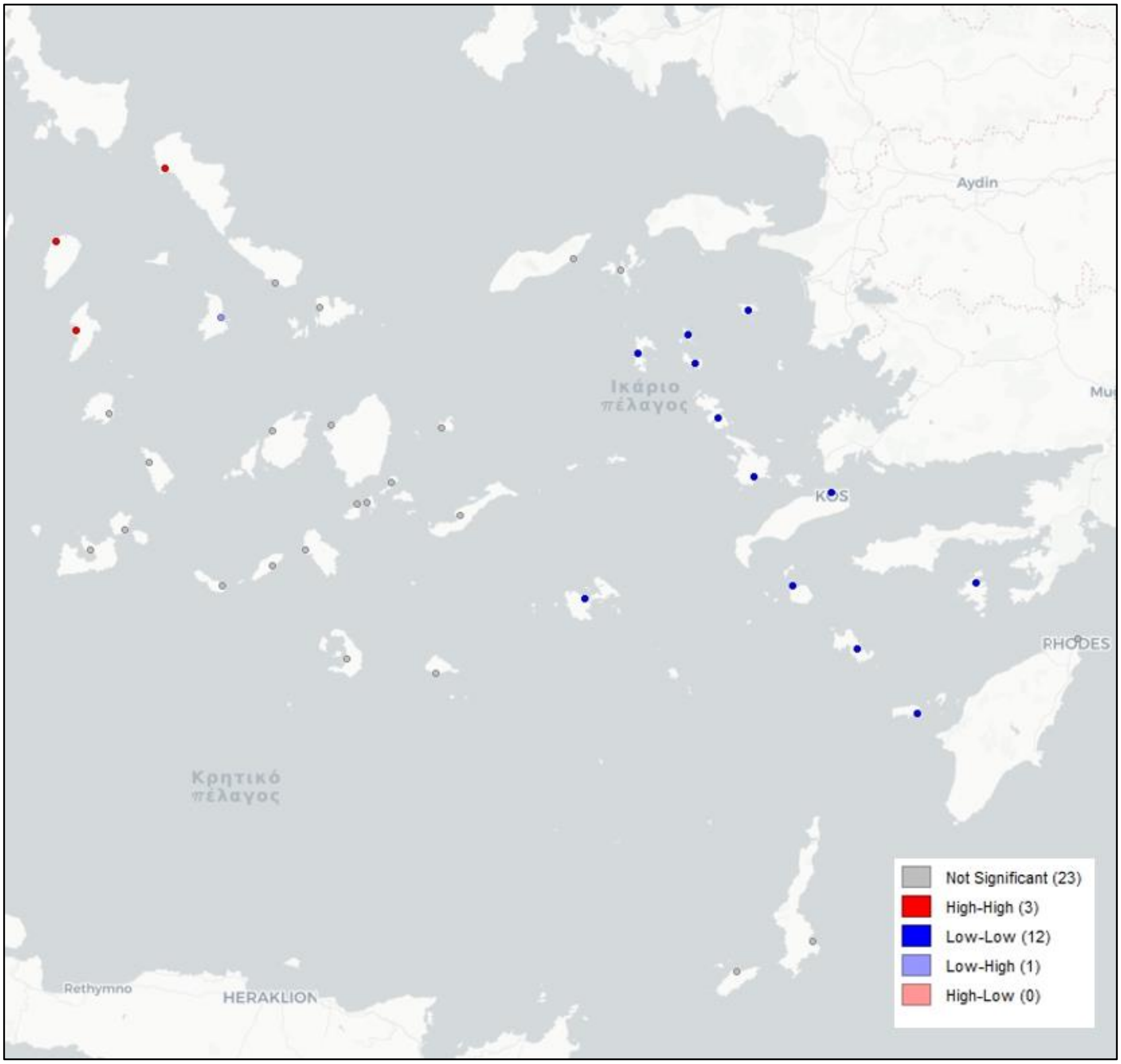


Figure 12. Connectivity efficiency spatial patterns in the study area (Local Moran's I)

As made clear by the above result, spatial data analytics are also utilized in this study, not only to assess environmentally compromised areas, but also to assess social inequalities in the network, by identifying ports with cohesion and accessibility issues. Such ports are showing low clustering in terms of their connectivity index, denoting an overall low level of service in terms of overall connectivity, both in terms of offered routes and trip frequencies. This can, to an extent, be understood due to the remoteness of such ports, which in order to be reached by the mainland require several hours in travel times, especially in cases of routes where stops are made to regions closer to the mainland, such as ports of the Cyclades. It is made clear that necessary and targeted interventions are needed to improve both the offered Level of Service (LoS) in terms of passenger travel times, as well as overall offered connectivity, in order to increase the accessibility levels of the islands in the Region.

5.3. Restructuring of the network

The next step of the study is restructuring the network based on the initial results of the Efficiency Index and several requirements in order to establish additional zero-emission routes, as per those described in the preliminary results of Chapter 4. Specifically, islands of lower demand are identified and evaluated based on whether they create clusters of low-demand ports with other ports of the study, while also having a high-demand port in proximity, so that the high-demand port can operate as a transshipment hub for E-ferry operations to and from the low-demand ports, as in the previous chapter. While on such island clusters the establishment of a zero-emission sub-network is possible, an additional step is considered where other low-demand islands which do not constitute a cluster are evaluated again on the basis of the existence of a feasible zero-emission route between them and a high-demand port in proximity.

The process for evaluating ports to be selected for service by zero-emission routes closely follows the logic of a cluster-first route-second approach and the overall restructuring of the network is based on this. As zero-emission routes are established on several ports, the initial dataset begins to decrease in size, as routes to/from only higher demand ports need to be planned. To resolve this issue, groups of the remaining ports need to be identified to be connected through conventional routes with the mainland. For this, a Self-adjusting clustering method was used (HDBSCAN). With Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN), varying distances are used to separate clusters of varying densities from sparser noise, making HDBSCAN the most data-driven of the clustering methods requiring the least user input, as it only requires the minimum features per cluster (Campello et al., 2013). In this study, the minimum ports per cluster considered are 2. In addition, ports characterized as "Noise" after this clustering method (i.e., ports not belonging to a specific cluster) must be assigned to a certain cluster, which in this case is selected as the cluster with a port closest to them. The above steps result to the generation of optimal routing solutions considering barrier data (i.e., land mass in this study) for each cluster. In order to provide better connectivity between each cluster of the network, another constraint is considered, which is that each cluster must connect to each other cluster with at least one port of cluster A providing a connection with another (at least one) port of cluster B. In this case, proximity is the first and most important factor to be considered, as the goal is to provide cluster interconnections based on the shortest possible connections between them, with subsequent connections planned for electric ferries, where possible.

In regards to routing around specific barriers or obstacles, there have been several studies addressing the issue of creating paths around obstacles. The algorithms known as Bug 1 and Bug 2 were formulated by Lumelsky & Stepanov (1987). With Bug 1, the route initiates along an original straight line connecting the starting point and destination. When it encounters an obstacle, the path circumnavigates the obstacle's periphery and continues from the point closest to the target. On the other hand, Bug 2 retains the original line, referred to as the m-line, and only departs from an obstacle's periphery when the m-line is intersected again. Bug 2's approach is considered a greedy strategy, which shows immediate advantages when dealing with simple obstacles. However, in the context of more complex obstacles, the careful methodology of Bug 1 often results in better performance (Choset et al., 2005). Figures 12 and 13 illustrate the way Bug 1 and Bug 2 work, respectively, while tackling randomly shaped obstacles.

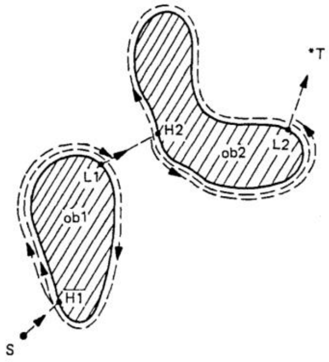


Figure 13. Automaton's path (dotted lines), Algorithm Bug1 (ob1, ob2, obstacles; H1, H2, hit points; L1, L2, leave points). (Lumelsky & Stepanov, 1987)

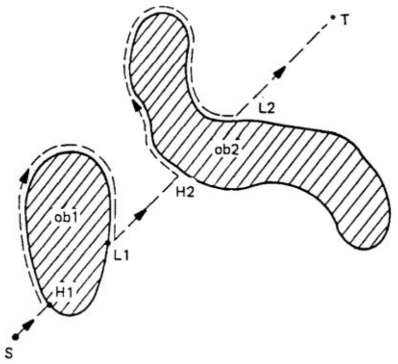


Figure 14. Automaton's path (dotted line) under Algorithm Bug2. (Lumelsky & Stepanov, 1987)

The Tangent Bug Algorithm is a globally convergent navigation technique for two degrees of freedom mobile robots. It is a range-sensor-based algorithm formulated by Kamon et al. (1996, 1998). Employing a 360-degree orientation resolution with no limits, the Tangent Bug Algorithm is an enhancement over the Bug 2 algorithm. It excels in establishing an optimal path, which is usually the shortest. However, its requirement for an infinite range to function effectively may result in substantial computational demands.

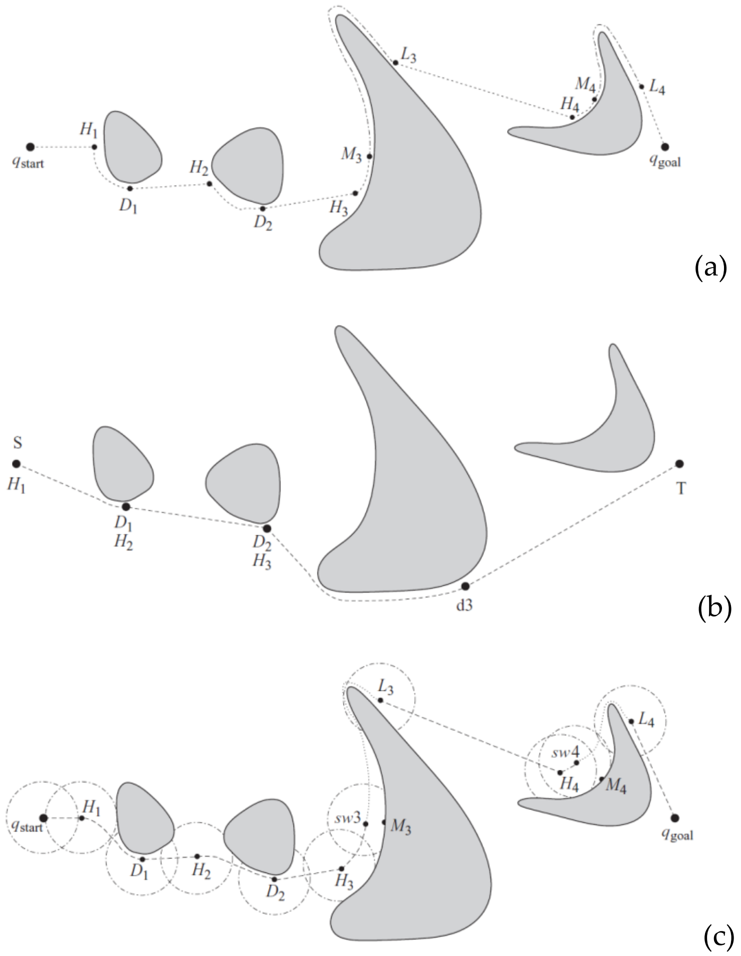


Figure 15. Implementation of the Tangent Bug Algorithm with: (a) zero sensor range, (b) finite sensor range, (c) infinite sensor range.

Khatib proposed an approach known as the Artificial Potential Field method (Khatib, 1985). This method navigates a robot as if it were a particle moving through a gradient vector field. The gradients in this context are seen as forces acting upon a robot particle, which is assumed to be positively charged. These forces pull the robot towards the goal, which is regarded as a negatively charged entity. Conversely, obstacles are assigned a positive charge, creating a repelling force that directs the robot away from potential impediments. By synthesizing these repulsive and attractive forces, the robot is efficiently guided from its initial point to the desired destination, while it successfully evades any obstacles in its path.

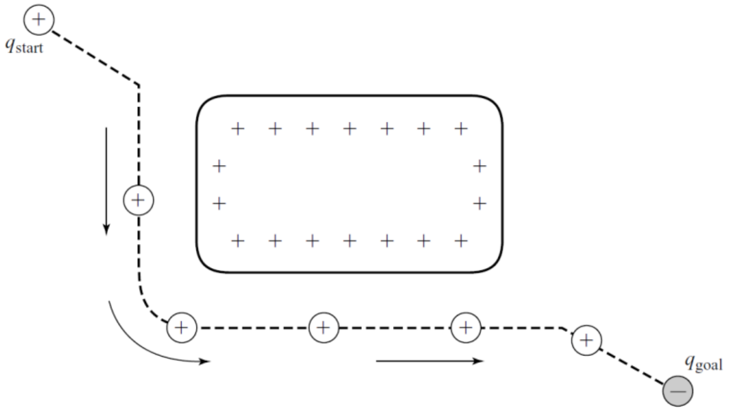
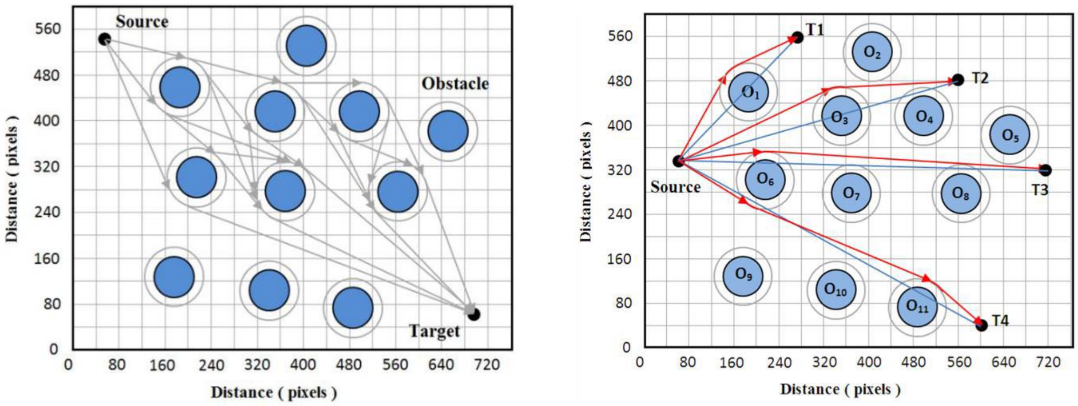


Figure 16. Example of Potential Field method. (Choset et al., 2005)

Several other studies have also used combined methods to address the issue. For instance, Rashid et al. employed a tangent visibility graph and then the Dijkstra method among possible paths (Rashid et al., 2013), with their approach shown on the below figure.



(a) (b)

Figure 17. Examples of using the tangent visibility graph algorithm (a) Trajectories from source to target (b) Shortest paths for different target locations. (Rashid et al., 2013)

Contemporary, sophisticated tools employ an array of strategies to determine the optimal path around obstacles or on cost-weighted terrains. Methods such as accumulated cost surface and slope line (Douglas, 1994) serve as the foundation for these tools in commercial Geographic Information System

(GIS) software. Initially, a distance accumulation raster is established, which incorporates restricted regions as barriers. This results in a back direction raster that delineates the direction necessary to exit a cell and revert to the origin point. The output's directional values are expressed within a compass range spanning 0 to 360 degrees. The choice of analysis cell size is crucial as it specifies the level of precision desired. These generated raster maps form the basis for computing the optimal line.

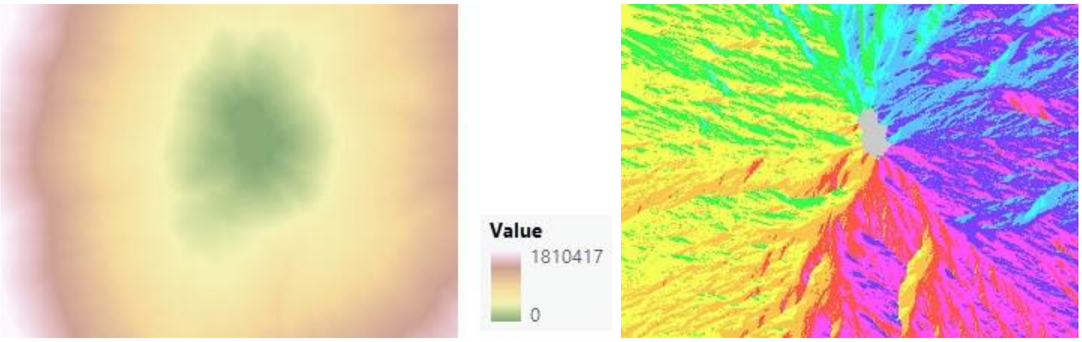
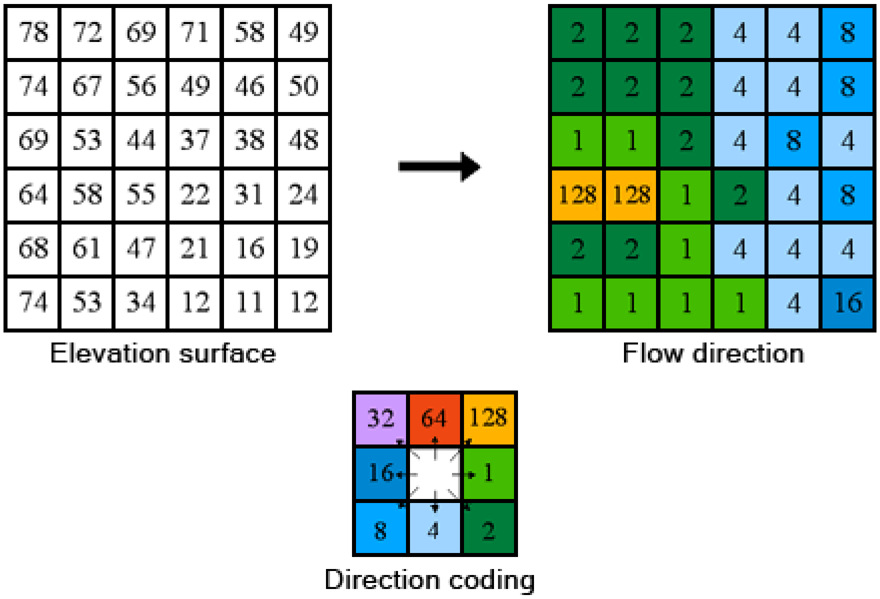


Figure 18. Rasters created to obtain optimal paths in ArcGIS Pro: (a) output distance accumulation raster (b) output back direction raster. (ESRI, 2023)

The processing of these calculations employs a D8 flow direction algorithm (ESRI, 2023), harnessing methods such as D8 (Jenson & Domingue, 1988), Multiple Flow Direction (MFD) (Qin et al., 2007), or D-Infinity (DINF) (Tarboton, 1997). The Multiple Flow Direction (MFD) algorithm, by Qin et al. (2007), shares the flow originating from a cell among its downslope neighbors. To calculate the fraction of flow directed to each downslope neighbor, an adaptive method is utilized, which takes into account local terrain conditions and generates a flow-partition exponent. Meanwhile, the D-Infinity (DINF) flow algorithm (Tarboton, 1997) ascertains the direction of flow by finding the steepest downward slope from among eight triangular facets crafted within a 3x3 cell window, centered on the cell of interest. The ensuing flow direction is depicted as a floating-point raster. This indicates a specific angle in degrees, which moves in a counterclockwise direction from 0 (symbolizing due east) to 360 (also standing for due east). Lastly, the D8 method (Jenson & Domingue, 1988) presumes that there are 8 valid output directions from each cell. It then identifies the direction of flow grounded on the steepest descent.



78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

Elevation surface

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

Flow direction

32	64	128
16		1
8	4	2

Direction coding

Figure 19. Coding of the direction of flow. (ESRI, 2023)

Considering the above methodology, the overall logic behind the restructuring of the network is based on two basic criteria. First, complex networks, such as maritime ones, show different relations between different ports and in many cases form clusters, when considering spatial characteristics and other factors impacting network operations. When considering any maritime network, there are several cases where underlying relations and spatially related clusters are becoming clear through network theory approaches, spatial data analysis methods and transport operations optimization considerations. Considering freight or passenger shipping networks, there is also an additional factor that should always be considered on the planning of operations and that is capacity utilization. Logistics operators are always striving to increase the capacity utilization of their means of transport, which in the shipping sector translates in the maximization of freight volume, while minimizing or even retaining given operating costs for a route on acceptable levels. However, in passenger shipping this is not always the case due to overall accessibility being a highly significant factor in operations. Specifically, as connectivity for islands on a given network is necessary, available routes and route frequencies are paramount in connecting remote areas and islands between them. However, the highly needed accessibility creates an important environmental issue, which of course is the negative impact of emissions to the environment. In addition, when weighted results for the efficiency of transport work are considered, such as CO_2 emissions per passenger and distance travelled, inefficiencies in ship capacity utilization become much clearer. Considering the GCSN, in order to avoid overall transshipment, passenger and freight transfers to different smaller vessels, it is quite common for larger vessels to travel to smaller, less popular islands as part of their routes to neighboring ports. However, capacity utilization on these ship trip legs is dropping considerably, related to other trip legs on port calls of more popular destinations.

In order to address this complex issue, a hub-spoke approach is implemented, along with a cluster-first route-second approach, as described above. However, redesigning a complex network can, in many cases, become highly data intensive. In addition to this, in the case of passenger networks many factors are in play and several sides to be considered. For instance, the optimal solution for stakeholders and operators may not be the optimal for passengers and vice-versa, especially when policy makers and the state set different standards on social and environmental issues, such as the overall offered level of service to passengers, island accessibility, impacts from ship emissions etc. Therefore, the focus of this study is to integrate all of these parameters to the design and planning process of the network, thus aiming to provide the best possible solution for all players, while also aiming to limit negative environmental externalities. To this goal, and considering this to be a spatially significant problem, a spatial decision support system (SDSS) is developed to facilitate the network design process and pose as a significant alternative to policymakers and operators who wish to address all aforementioned issues, while considering network complexity and topological factors in the decision-making process. The approach of the network is a simplistic one and easily adaptable to any given network of high complexity and spatial variance.

The first step is to identify which islands will be serviced through zero-emission routes. In addition to the preliminary results of chapter 4, where certain island groups have been already identified to create zero-emission sub-networks, there are certain cases of low-demand standalone islands which, due to the fact that they are in proximity to higher-demand ports but do not create clusters with additional low-demand islands, are not shown on the initial results as candidates to be serviced by zero-emission routes. After identifying low-demand ports, it is necessary to identify whether such ports are in proximity with a high-demand port in E-ferry range, either with direct connection or indirect one, considering that indirect connections are between a high-demand port and other lower-demand ports. As this is a spatially-dependent problem that requires the visualization of results to identify such areas, a GIS-based model is developed to visualize all feasible connections in electric ferry range for all islands. The model developed is shown in Figure 18, with an example of all resulting routes for the Cyclades Region shown on Figure 19, while filtered routes in E-ferry range are shown in Figure 20.

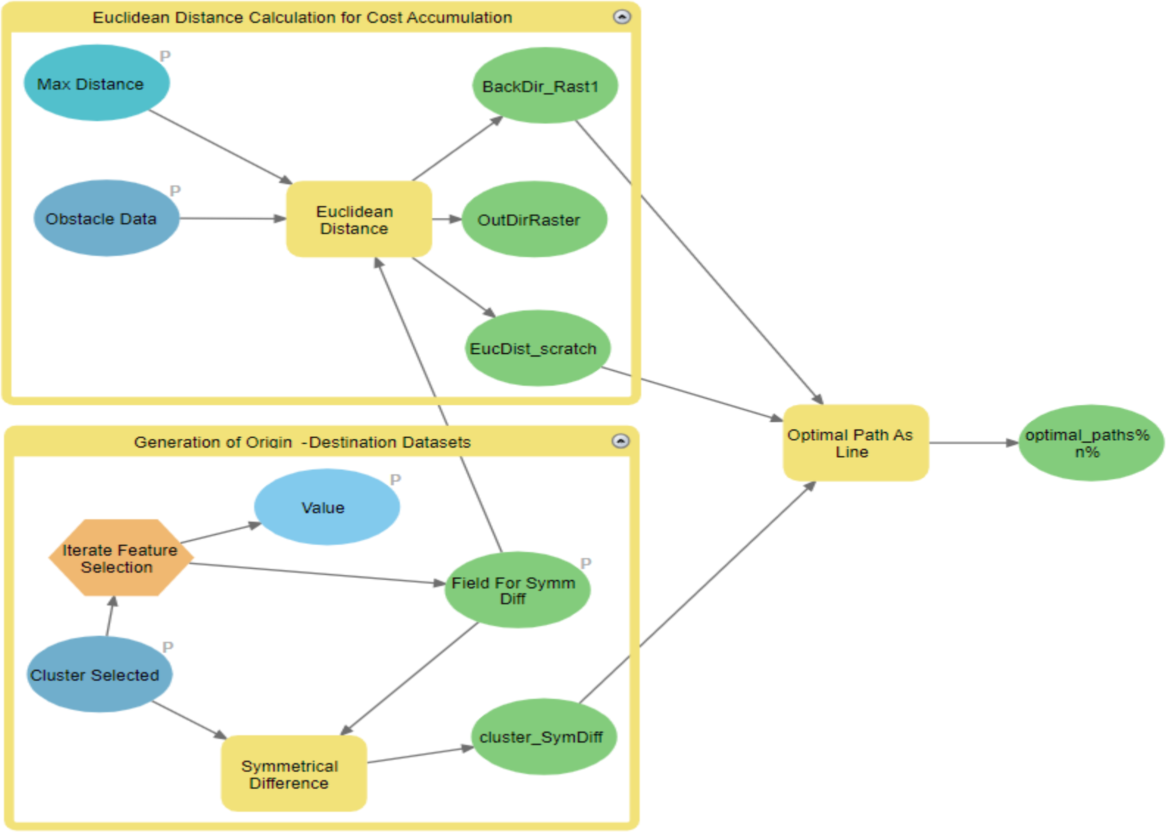


Figure 20. GIS-based model for the identification of optimal paths via obstacle-based routing

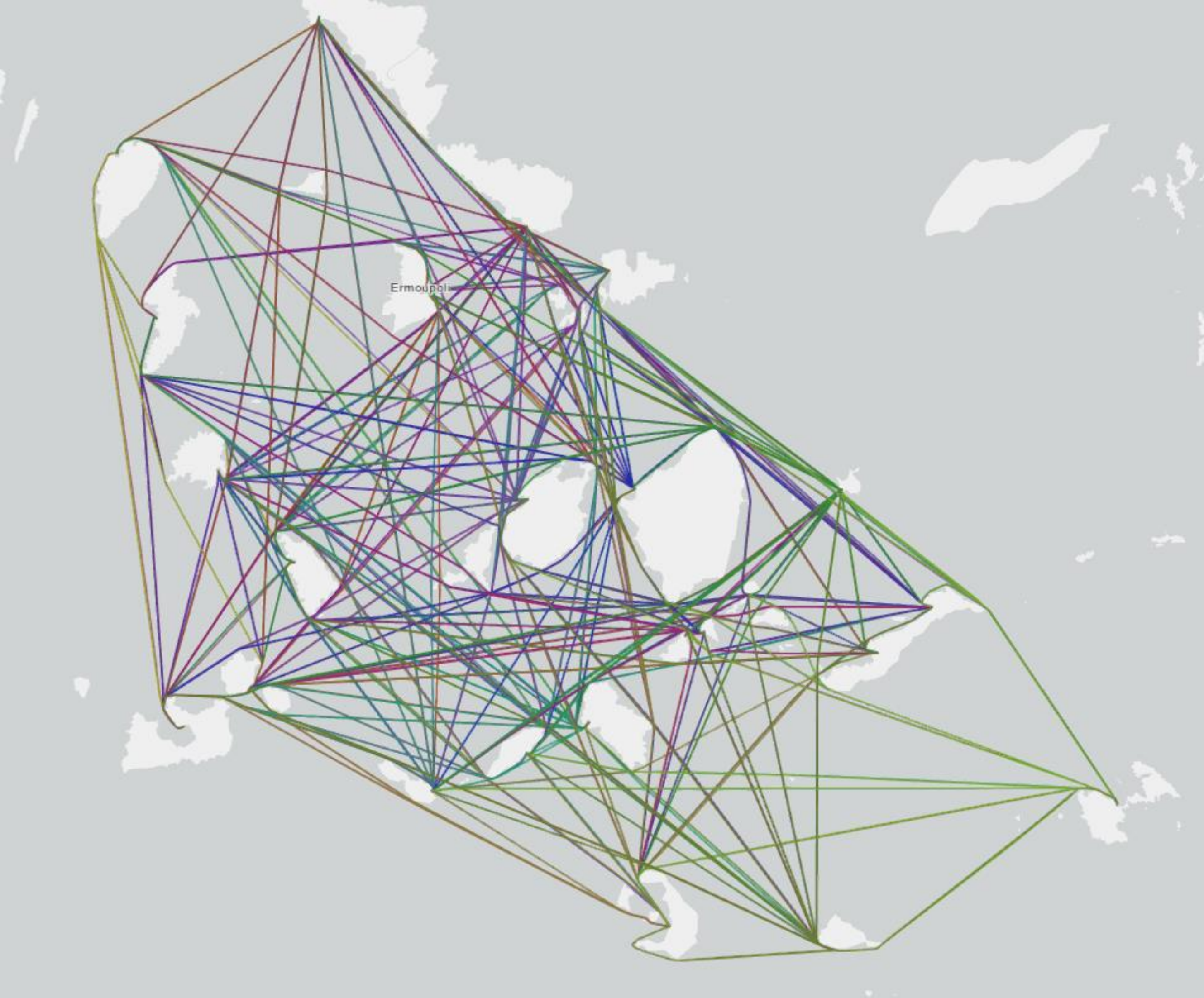


Figure 21. Example of all routes generated for the Cyclades Region, based on the model, with no cutoff distance set

The above example shows generated routes for the Cyclades Region, in case no specific cutoff distance is set in the model. In this case, the model iterates until it generates all possible connections between all features (ports) of the dataset. However, if a cutoff distance is set, as is the case in fully electric ferries such as the E-ferry, generated routes are then created based on the set distance, as shown in the figure below, showing only the feasible connections via E-ferry, with a maximum operating range of 30 nautical miles.

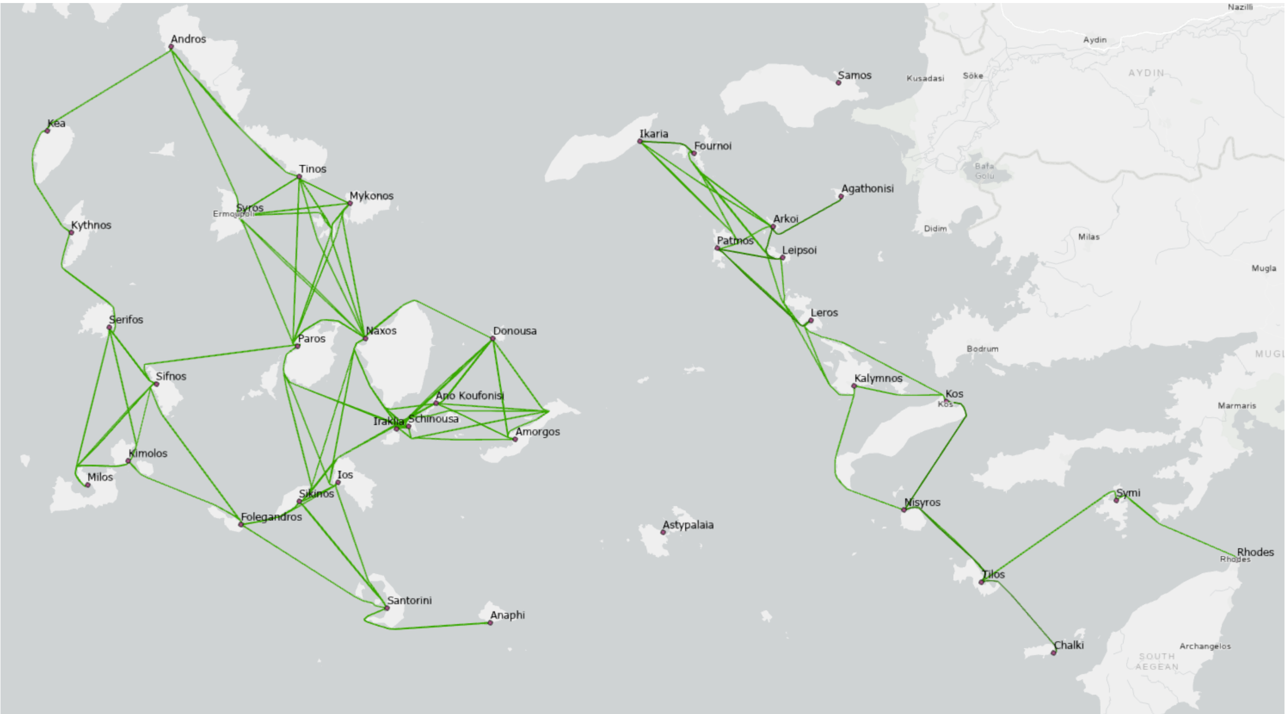


Figure 22. Filtered routes in E-ferry Range resulted from GIS-based model (cutoff distance set at 30 n. miles)

The next step is to identify which of the islands connected via feasible E-ferry routes are low-demand ports, which have high demand ports in proximity. Assuming at least one daily trip with E-ferry to and from such islands, with a maximum capacity of 180 passengers, low-demand ports are considered those showing weekly demand of at most 1260 passengers. In addition, high-demand ports are considered, for the purposes of this study, those which exceed a weekly demand of 2000 passengers. Based on the above results regarding feasible connections and weekly demand data, results for the Cyclades and Dodecanese/Eastern Aegean Regions are shown on Tables 12 and 13.

Table 16. Weekly Demand and Feasible Connections with High-Demand Ports in E-ferry Range for the Ports of Cyclades

Port Name	Weekly Demand	High Demand Ports in E-ferry Range	Port Name	Weekly Demand	High Demand Ports in E-ferry Range
Aigiali	1502	0	Kythnos	1622	1

Amorgos	1502	0	Milos	3213	1
Anaphi	**235**	**1**	Mykonos	13520	4
Andros	5120	3	Naxos	8948	5
Ano Koufonisi	**1135**	**2**	Paros	15937	6
Astypalaia	405	0	Santorini	16802	1
Donousa	**296**	**1**	**Schinousa**	**325**	**3**
Folegandros	**885**	**3**	Serifos	1326	2
Ios	2594	3	Sifnos	2122	2
Iraklia	**227**	**3**	**Sikinos**	**343**	**4**
Kea	2650	1	Syros	6122	5
Kimolos	**804**	**2**	Tinos	8753	5

Table 17. Weekly Demand and Feasible Connections with High-Demand Ports in E-ferry Range for the Ports of Dodecanese / Eastern Aegean

Port Name	**Weekly Demand**	**High Demand Ports in E-ferry Range**	**Port Name**	**Weekly Demand**	**High Demand Ports in E-ferry Range**
Agathonisi	**63**	**1**	**Leipsoi**	**280**	**2**
Arkoi	**40**	**1**	**Leros**	**1216**	**2**
Chalki	179	0	**Nisyros**	**453**	**2**
Evdilos	1526	**1**	Patmos	1434	**0**

Fournoi	**310**	**2**	Pythagoreio (Samos)	2159	**2**
Ikaria	1526	**1**	Rhodes	5949	**1**
Kalymnos	3367	**1**	Samos	2159	**2**
Karlovasi (Samos)	2159	**2**	Symi	3690	**1**
Kos	5455	**1**	**Tilos**	**403**	**1**

As shown on the above tables, there are several islands that can be serviced by zero-emission ferries. For the Cyclades Region, these are Anaphi, Ano Koufonisi, Donousa, Folegandros, Iraklia, Kimolos, Schinousa, and Sikinos. For the Dodecanese/Eastern Aegean Region, these are Agathonisi, Arkoi, Fournoi, Leipsoi, Leros, Nisyros, and Tilos. Specifically, the new designations for each port of the study are better shown on the following tables. Green colors denote ports serviced exclusively be electric ferries and zero-emission routes, blue color denotes hub-ports servicing more than one islands with zero-emission routes and orange color denotes ports of liner conventional routes.

Table 18. Cyclades ports categorization in the proposed new network

Port Name	Daily Demand	Weekly Demand	Low Demand Ports in E-ferry Range	High Demand Ports in E-ferry Range
Santorini	2400	16802	2	1
Paros	2277	15937	3	6
Mykonos	1931	13520	0	4
Naxos	1278	8948	**4**	5
Tinos	1250	8753	0	5
Syros	875	6122	0	5
Andros	731	5120	0	3
Milos	459	3213	1	1
Kea	379	2650	0	1
Ios	371	2594	**3**	3

Sifnos	303	2122	1	2
Kythnos	232	1622	0	1
Amorgos	215	1502	3	0
Serifos	189	1326	1	2
Astypalaia	58	405	0	0
Ano Koufonisi	162	1135	4	2
Folegandros	126	885	2	3
Kimolos	115	804	0	2
Sikinos	49	343	2	4
Schinousa	46	325	3	3
Donousa	42	296	2	1
Anaphi	34	235	0	1
Iraklia	32	227	3	3

Table 19. Dodecanese ports categorization in the proposed new network

Port Name	Daily Demand	Weekly Demand	Low Demand Ports in E-ferry Range	High Demand Ports in E-ferry Range
Rhodes	850	5949	0	1
Kos	779	5455	1	1
Symi	527	3690	1	1
Kalymnos	481	3367	2	1
Samos	308	2159	0	2
Ikaria	218	1526	2	1
Patmos	205	1434	4	0
Leros	174	1216	3	2
Nisyros	65	453	1	2
Tilos	58	403	2	1
Fournoi	44	310	3	2
Leipsoi	40	280	3	2
Chalki	26	179	1	0
Agathonisi	9	63	3	1
Arkoi	6	40	3	1

As the above ports are now excluded from the dataset, the next step is to identify clusters between ports left in the dataset, which consist of ports that are necessarily connected via routes serviced by conventional vessels (i.e., not zero-emission ferries). In order to identify clusters withing specific regions of the study, density-based clustering is utilized. In essence, this method identifies clusters of point features in a dataset (in this case, ports) withing surrounding noise based on their spatial distribution. There are three different clustering methods; defined distance (DBSCAN), self-adjusting (HDBSCAN) and multi-scale (OPTICS). In this case, the self-adjusting option is selected, which finds clusters of points in close proximity while utilizing varying distances, allowing for clusters with varying densities based on cluster probability or stability. HDBSCAN is selected in order to account for spatial complexities of the network, thus acknowledging that features of the dataset are not always spatially distributed on a specific pattern, as it is the most data-driven of the clustering methods and requires the least user input. In addition, it is worth noting that the minimum features selected per cluster in this case are two.

As a result, the resulting clusters for each region are as follows:

- Cyclades
    - Kea & Kythnos (2)
    - Serifos, Sifnos & Milos (3)
    - Paros and Naxos (2)
    - Syros, Tinos & Mykonos (3)
    - Ios & Santorini (2)
- Dodecanese
    - Ikaria & Samos (2)
    - Patmos & Leros (2)
    - Kalymnos & Kos (2)
    - Symi & Rhodes (2)

The next step is to connect the above clusters with the mainland and between them, based on specific criteria. Regarding main routes, it is crucial for the restructuring of the network to take into account all necessary points of the regulatory framework as described in the relative Greek legislation. While this is a factor that could have been omitted in the design process, it is acknowledged that regulatory frameworks and relative legislation should always be considered in the design and planning processes of maritime networks, in order to provide reasonable and realistic results. The three main points considered from the Greek regulatory framework, as mentioned in chapter 1.1, are as follows:

- Island ports serving as prefecture capitals must have at least three weekly connections with mainland ports throughout the year via at least one main line.
- Islands that aren't prefecture capitals should maintain a connection with the capital of their respective prefecture at least three days a week throughout the year, either directly or via connecting service.
- Islands under the same administrative Region should be connected at least once a week, directly or through a connecting service, with the Region's headquarters.

From these main points, certain criteria are set for the design process of the new network, such as:

- Islands within a Region that form a cluster should have at least one main and direct connection with the mainland.
- Islands within a Region that form a cluster should have at least one connection with other clusters of the same Region, either directly or via connecting service.
- Distinct Regions under study should be connected at least with one main connection, so that all islands of each Region can connect with each other, either directly or via connecting services.

Based on these criteria, the goal is to create connections between all clusters of the two regions under study, and from the mainland to said clusters. In addition, the goal is to also create connections between the regions of the study. The resulted new, restructured network aims to provide better cohesion between regions of the study, with results showing the least necessary connections per port based on the offered connecting routes. The main goals of the new proposed network are the future limitations regarding the environmental footprint of the network, while providing more acceptable travel times from the mainland to the ports of the network, thus improving accessibility and unimpeded connectivity throughout the Greek insular territories.

5.4. Development of SBM-DEA Efficiency Model

As this dissertation also discusses overall port efficiency and a restructuring of the network with new routes, an input-oriented Slacks Based Measure Data Envelopment Analysis (SBM-DEA) model is used to compare the results of the index with a non-parametric method, which is highly utilized in operations research. In the developed model, an input-based model is considered with two outputs for each Decision-Making Unit (DMU), both being desirable and considering passengers per port and total ship calls, thus showing overall passenger demand and connectivity of a port. As input, in this case, total fuel consumption associated with the ship calls of each port is used as an input. It would also be feasible to consider associated CO_2 emissions per port as input to the model, as it is assumed and verified by EMSA \ THETIS – MRV data that all ships of the network use conventional HFO, therefore meaning that CO_2 emissions have a linear relationship with fuel consumption, based on the relative emission factor of 3.114 for HFO. Another SBM-DEA model is also used to better evaluate the overall efficiency of ships of the existing fleet to be assigned to the new routes, with input being the mean fuel consumption of each ship per nautical mile travelled, desirable output the total passenger capacity and the mean speed of each ship considered.

Considering ports serviced, input consists of the total fuel consumption associated with each port from all routes on a yearly basis, while outputs consist of total passengers serviced and the total ship calls per port. In both cases, the SBM-DEA model is based on the Banker, Charnes, and Cooper (BCC) DEA model (Banker et al., 1984) under variable returns to scale (VRS), as later extended to also handle undesirable outputs (Seiford & Zhu, 2002). The general mathematical formulation of the model used in this study is developed as follows:

$$\text{Minimize: } \alpha \tag{24}$$

s.t.

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \alpha x_{i0} \quad \forall i \in \{1, \dots, m\} \tag{25}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{r0} \quad \forall r \in \{1, \dots, s\} \tag{26}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{27}$$

$$\lambda_j, s_i^-, s_r^+ \geq 0 \quad \forall i, j, r \tag{28}$$

where:

j is the index denoting ports,

i is the index over inputs,

r is the index over outputs,

x_{ij} is the amount of input i for port j

y_{rj} is the amount of output r for port j

λ_j is the weight given to port j in the linear combination of ports that forms the virtual port against which the efficiency of the port in question is measured

s_i^- is the slack for input i

s_r^+ is the slack for output r

a is the ratio of total weighted inputs to total weighted outputs

x_{i0} and y_{r0} are the input i and output r of the port under consideration (port 0)

The first two sets of constraints in Eq. 25 and 26 represent the input and output constraints for the ports, taking into account the slacks. The convexity constraint in Eq. 27 enforces the VRS assumption, while the final constraint in Eq. 28 ensures that all lambdas and slacks are non-negative. As a result, the efficiency of each DMU, which in this case are ports of the study, would then be:

$$\text{Relative efficiency score of } DMU_j = {}^{1}\!/_{a} \qquad (29)$$

In the context of the given optimization problem and the model formulated, α represents the inverse of efficiency under the assumption of variable returns to scale. Thus, minimizing alpha is equivalent to maximizing efficiency. The actual efficiency in DEA models is generally calculated as the ratio of the weighted sum of outputs to the weighted sum of inputs. However, in the BCC model used here, the efficiency of a Decision-Making Unit (DMU) is calculated by solving the aforementioned optimization problem, based on the given constraints and, given α consists the result of the optimization, the efficiency of a particular DMU would be its reciprocal, as given on Eq. 29. To better understand the purpose of minimizing this parameter, a here is used as an adjustment factor for inputs, thus minimizing it forces the virtual input (composed inputs from all ports) to match as closely as possible to the actual input of the evaluated port in each case, hence pushing the efficiency to be as high as possible. As Eq. 29 may produce results which are out of the 0 to 1 scale, a normalization step which is common practice in DEA models is also considered, in order to scale the efficiency scores between 0 and 1.

The above linear programming (LP) problem is solved for each DMU. The input constraints ensure that a DMU cannot use more of an input than what it actually uses or what can be produced by a combination of other DMUs, while the output constraints ensure that a DMU produces at least as much output as it actually produces or what could be produced by a combination of other DMUs. The convexity constraint ensures that the efficiency score reflects a convex combination of DMUs, thus ensuring variable returns to scale.

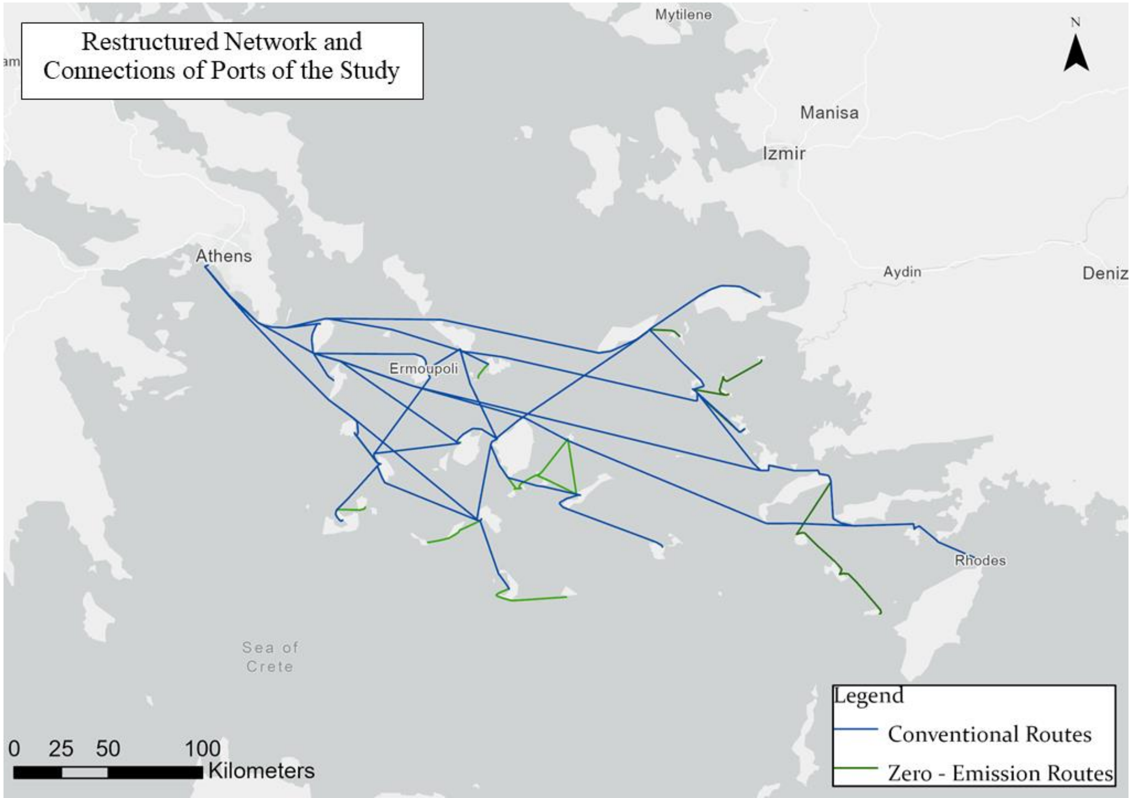
At this point, there are some important points to consider regarding the utilization of DEA models. First, the model assumes that all DMUs are operating under similar conditions and compares the performance of each DMU against a virtual DMU that represents the best practice in the data set. This is a fairly strong assumption, as not all ports show the same potential, characteristics and dynamics, so the interpretation of results should be done with care if there are known to be significant differences in the operating conditions of the DMUs. Secondly, the BCC model is used as it takes into account variable returns to scale, thus calculating efficiency on the notion that an increase in inputs given do not necessarily result in proportional increases in outputs, as is the case in ships or ports of the study, where if more investments (i.e., fuel consumed to reach port *j*) where to occur, this would not necessarily mean more passengers serviced or more ship calls per port.

In addition, as this is a slacks-based measure model, slacks represent the amount by which inputs could be reduced without affecting outputs (input slacks) or the amount by which outputs could be increased without affecting inputs (output slacks). However, large slacks might indicate inefficiencies that aren't captured by the efficiency score alone. Also, as mentioned before, efficiency scores produced by such models are relative and highly depend on the set of DMUs analyzed, so adding or removing DMUs could change the scores. Another key point to consider is the fact that DEA is highly sensitive to the quality of data, with any measurement error affecting the results significantly, while outliers can also have a large impact on the results. It should be highlighted that DEA models can be highly useful in benchmarking and performance measurement, but their results should always be interpreted with caution, while considering the assumptions made and limitations of such models.

The efficiency results generated through the development of the SBM-DEA model can provide valuable insight on whether ports of the network operate efficiently, considering operational parameters. However, the model is also used to evaluate whether its results are in accordance to the ones generated by the proposed efficiency index and compare any issues that may arise. The next section shows the results of the study, considering certain ports of the Greek Coastal Shipping Network.

5.5. The Proposed New Network

In order to compare results between the two scenarios of the existing and restructured network, the overall restructuring of the network based on the aforementioned methodology is conducted. The new network structure is shown on Map 12.



Map 13. New routes between the ports of the study after the establishment of Zero – Emission Routes to low-demand islands

It is worth noting that in the case of the restructured network scenario, only the most environmentally efficient ships of the existing fleet are selected to operate the proposed new routes, in order to also increase the environmental efficiency of the proposed conventional routes. In order to do so, ships were evaluated based on their passenger and car capacity and mean fuel consumption per nautical mile travelled. Each ship was assigned to each proposed route by evaluating the passenger demand for each port of each route on a daily basis by utilizing aforementioned available data. As a result, a base passenger demand for each route was calculated on a daily basis to provide a benchmark for both the ship assigned and the number of trips on a daily basis for each ship, in order to calculate total fuel consumption and CO_2 emissions for each route. Results regarding the new routes are shown on Table 20. It is worth noting that predicted daily passenger demand derives from the available data considering passenger demand of each port of the study area.

Table 20. Proposed Conventional Routes of the Restructured Network

Route Stops	Daily Passenger Demand	Ship Operating the Route	Daily Round Trips	Total Daily Fuel Consumption (m. tonnes)
Piraeus - Serifos - Sifnos - Milos	974	BLUE STAR NAXOS	1	26.22
Piraeus - Kea - Kythnos	623	AQUA JEWEL	1	9.61
Piraeus - Paros - Naxos - Amorgos - Astypalaia	3845	NISSOS RODOS	2	122.82
Pireaus - Syros - Tinos - Mykonos	2814	SUPERFERRY II	2	55.08
Piraeus - Ios - Santorini	2833	BLUE STAR CHIOS	2	98.47
Sifnos - Paros - Naxos	3894	BLUE HORIZON	1	14.95
Santorini - Ios - Sifnos	3156	KRITI I	2	41.39

Santorini - Ios - Naxos - Tinos	3744	ARIADNE	1	27.86
Sifnos - Syros - Tinos	1197	BLUE GALAXY	1	18.01
Piraeus - Kalymnos - Kos	1280	BLUE STAR PAROS	1	52.16
Piraeus - Patmos - Leros	389	ELYROS	1	70.63
Piraues - Symi - Rhodes	1376	BLUE STAR NAXOS	1	62.66
Piraeus - Ikaria - Samos	552	BLUE STAR MYKONOS	1	69.92
Samos - Ikaria - Patmos - Kalymnos - Kos - Symi - Rhodes	1025	BLUE STAR PATMOS	1	72.82
Naxos - Ikaria - Patmos - Kalymnos - Kos - Symi - Rhodes	1421	NISSOS SAMOS	1	69.64

Regarding the proposed new conventional routes, the goal is to achieve as many connections as possible between port clusters, without creating unnecessary overlaps, or more commonly route redundancies. Only the last two routes are having an overlap on connecting ports, which is justified due to the increased complexity and larger distances in the Dodecanese, in contrast to the Cyclades. As a result, 2 interconnecting routes are selected for the Dodecanese (one originating from the Cyclades), in order to achieve better connectivity between the islands of this complex. In relation to this, as distances between the islands of the Cyclades are generally smaller, more smaller interconnecting routes are selected between each distinct cluster of the study, with these being identified by the routes originating from the mainland (Piraeus) to the ports of each distinct cluster/group. The daily trips needed to retain the overall level of connectivity for each port are shown on Table 21. As several neighboring ports can potentially be connected through zero-emission routes of smaller operating distances, the needed future daily trips show promising and feasible results.

Table 21. Necessary Daily Port Calls to Retain Connectivity Levels with New Routes

Port	Daily Port Calls	Port	Daily Port Calls	Port	Daily Port Calls
Agathonisi	2	Kalymnos	2	Patmos	2
Amorgos	2	Kea	8	Rhodes	2
Anaphi	1	Kimolos	1	Santorini	4
Ano Koufonisi	3	Kos	2	Schinousa	1
Arkoi	1	Kythnos	3	Serifos	4
Chalki	1	Leipsoi	1	Sifnos	7
Donousa	1	Leros	1	Sikinos	1
Folegandros	1	Milos	4	Symi	2
Fournoi	1	Mykonos	3	Syros	2
Ikaria	1	Naxos	6	Tilos	1
Ios	4	Nisyros	1	Tinos	8
Iraklia	1	Paros	6		

Before assessing overall efficiency changes, it is crucial to identify two key parameters. First, as island accessibility and overall cohesion improvements are one of the goals of the dissertation, the first thing is to determine whether the newly proposed, restructured network improves island reachability from the mainland. As a result, the times to reach each island of the study from the mainland are compared with those of the existing network. However, there are two main assumptions to be considered, in order to better interpret such comparisons. First, island reachability mainly depends on ship speed. While there were several ships considered in this dissertation which showed greater actual (reported) operational speeds, the newly proposed conventional routes utilize the ones with the best possible efficiency, considering carrying capacities, due to the fact that apart from servicing main liner ports they would have to service passengers destined for zero-emission islands, until the hub-port of transfer. Thus, larger ships are utilized which can cover said passenger demands, while also being as environmentally efficient as possible. In addition, zero-emission routes leading to zero-emission islands are assumed to be serviced by the E-ferry Ellen, for which a 14-knot mean speed is considered. As a result, on several cases, comparisons are made between reachability times which depict travel choices of slower ships with the average time to reach a port, derived by data collected by various aforementioned ferry services and websites (such as Ferryhopper), which in general also include choices of faster vessels, albeit at higher prices. Secondly, port times on each port call are considered to be equal to 20 minutes for each stop considering conventional ship port calls, and 20 minutes or less, depending on overall consumption, for lower demand ports serviced by the E-ferry Ellen, as disembarked and embarked passengers are considerably less. Comprehensive results for each conventional route from the mainland, and each zero-emission route from each of their respective hubs are given on the following tables. In order to evaluate feasibility and safety of zero-emission route connections, in terms of adequacy of energy used, calculations for the zero-emission routes are made based on the assumptions that the E-ferry Ellen consumes 80kWh per nautical mile travelled and charges at a rate of 40kWh per minute at port, as derived by the reports of the ship.

Table 22. Trip Duration of Conventional Routes and Time to Reach Each Port

Route	Time to Reach (Minutes)				Total Duration (Hours)
	Stop 1	Stop 2	Stop 3	Stop 4	
Piraeus - Serifos - Sifnos - Milos	210.67	267.07	356.65		5:55
Piraeus - Kea - Kythnos	142.70	229.63			3:49
Piraeus - Paros - Naxos - Amorgos - Astypalaia	292.40	360.15	491.83	637.03	10:35
Pireaus - Syros - Tinos - Mykonos	259.99	319.78	370.85		6:09
Piraeus - Ios - Santorini	306.72	388.24			6:27
Piraeus - Kalymnos - Kos	531.07	596.98			9:55
Piraeus - Patmos - Leros	475.40	556.49			9:14
Piraues - Symi - Rhodes	687.64	776.69			12:54
Piraeus - Ikaria - Samos	371.71	488.15			8:06

Table 23. Zero-Emission Route Characteristics – Dodecanese / Eastern Aegean Region

Designation	Port	Distance from previous (n.miles)	Sea Time (mins)	Aggregate Time to Reach from Hub (mins)	Remaining Energy for next leg (kWh)	Charging time at port (mins)
Hub	**Patmos**	0	0.00		3800	
Spoke 1	Leipsoi	11	47.14	47.14	3520	15
Spoke 2	Arkoi	14	60.00	122.14	3000	15
Spoke 3	Agathonisi	26	111.43	248.57	**920**	**72**
Liner	**Ikaria**	0	0.00	0.00	3800	
Spoke	Fournoi	10	42.86	42.86	**3000**	**20**
Liner - Hub	**Kos**	0		0.00	3800	
Spoke 1	Nisyros	23	98.57	98.57	2760	20
Spoke 2	Tilos	19.2	82.29	200.86	2024	20
Spoke 3	Chalki	18.1	77.57	298.43	**576**	**80.6**
Hub	**Patmos**	0			3800	
Spoke 2	Leros	21	90.00	90.00	**2120**	**42**

Table 24. Zero-Emission Route Characteristics – Cyclades Region

Designation	Port	Distance from previous (n.miles)	Sea Time (mins)	Aggregate Time to Reach from Hub (mins)	Remaining Energy for next leg (kWh)	Charging time at port (mins)
Hub	**Naxos**	0	0.00		3800	
Spoke 1	Iraklia	18	77.14	77.14	2760	10
Spoke 2	Schinousa	2.2	9.43	96.57	2984	10
Spoke 3	Ano Koufonisi	7.1	30.43	137.00	2816	10
Spoke 4	Donousa	14.1	60.43	207.43	**1688**	**52.8**
Liner	**Milos**	0	0.00	0.00	3800	
Spoke	Kimolos	13	55.71	55.71	**3000**	**26**
Liner - Hub	**Ios**	0		0.00	3800	
Spoke 1	Sikinos	7.1	30.43	30.43	3432	5
Spoke 2	Folegandros	11	47.14	82.57	**2752**	**31.2**
Liner Hub	**Mykonos**	0			3800	
Spoke	Delos	5.5	23.57	23.57	3360	**11**
Liner Hub	**Santorini**	0			3800	
Spoke	Anaphi	25	107.14	107.14	**1800**	**50**

In the case of charging times at ports, resulted calculations in bold show the total needed charging time to for the return trips, while remaining energy calculations in bold show the remaining energy when reaching the last port of call for each zero-emission route. As the above results show, only one route from Kos to Chalki retains the 20-minute charging break on each port, due to energy needs arising from longer distances and the remoteness of Chalki. In any case, all proposed routes are feasible, at least in calm weather conditions as those on which the E-ferry Ellen is already tested. However, as this only provides an initial benchmark based on the existing capabilities of the battery powered "Ellen", as technologies advance, the above resulted routes can potentially support operations of other more advanced and less range-constrained electric ferries, for which additional routes can also be proposed through the methodological framework presented in the dissertation. Regarding overall times to reach a port of the study from the mainland, results are shown on the following table, with comparisons to the average travel time offered by existing services.

Table 25. Time to Reach from Mainland on Newly Proposed and Existing Networks

Port	Time to Reach on Proposed Network (mins)	Hours to Reach (Proposed Network)	Avg. time to Reach on Existing Network (mins)	Change (Minutes)
Agathonisi	753.97	12:31	No Data	-
Amorgos	491.83	8:10	450	41.83
Anaphi	525.38	8:43	660	-134.62
Ano Koufonisi	527.15	8:45	480	47.15
Arkoi	627.54	10:25	0	-
Astypalaia	637.03	10:35	540	97.03
Chalki	925.41	15:22	1650	-724.59
Delos	424.43	7:03	No Data	-
Donousa	597.58	9:55	420	177.58
Folegandros	419.29	6:58	390	29.29
Fournoi	444.57	7:23	510	-65.43
Ikaria	371.71	6:10	450	-78.29
Ios	306.72	5:05	360	-53.28
Iraklia	467.29	7:46	420	47.29
Kalymnos	531.07	8:49	660	-128.93
Kea	142.70	2:22	60	82.70
Kimolos	442.37	7:21	360	82.37
Kos	596.98	9:55	570	26.98
Kythnos	229.63	3:49	120	109.63
Leipsoi	552.54	9:11	500	52.54
Leros	556.49	9:14	570	-13.51
Milos	356.65	5:55	350	6.65
Mykonos	370.85	6:09	270	100.85
Naxos	360.15	5:59	300	60.15
Nisyros	725.55	12:03	810	-84.45
Paros	292.40	4:51	250	42.40
Patmos	475.40	7:54	465	10.40
Rhodes	776.69	12:54	1020	-243.31
Samos	488.15	8:06	570	-81.85
Santorini	388.24	6:27	420	-31.76
Schinousa	486.72	8:05	450	36.72
Serifos	210.67	3:30	180	30.67
Sifnos	267.07	4:26	210	57.07
Sikinos	367.15	6:06	615	-247.85

Symi	687.64	11:25	930	-242.36
Syros	259.99	4:19	165	94.99
Tilos	827.84	13:45	870	-42.16
Tinos	319.78	5:18	217.5	102.28

As made clear from the above results, the introduction of zero-emission routes has highly benefited several ports studied, which are now showing greater reachability, compared to the existing network. In the case of ports in the Cyclades Region, there are small changes to the total time to reach the islands, mostly between 30 minutes and 1 hour, except the island of Donousa, where a much larger increase in travel time is shown, as it is the last island serviced on a zero-emission route with the most port calls (Naxos-Iraklia-Schinousa-Ano Koufonisi-Donousa), whilst considering the relatively slow speed of the E-ferry “Ellen”. However, regarding the Dodecanese/Eastern Aegean Region, overall accessibility on its islands shows great improvement, as travel times greatly decrease, thus benefiting an area where social inequalities in terms of accessibility and cohesion were identified. Specifically, islands of the network show an average decrease of about 172 minutes, just under 3 hours, with a total of 864.08 minutes less regarding total travel times, with the change being clear, especially in the island of Chalki. However, the main advantage of the proposed network in improving cohesion and overall accessibility is the fact that all islands of the Region are now connected with main or zero-emission routes, as Arkoi and Agathonisi were two islands with limited connections, both in routes and connection frequency, mostly from closest islands. On average, even if Chalki was to be excluded, which shows great improvement in terms of travel times, the rest islands on zero-emission routes seem to retain their level of accessibility and even improve it, with a total of about 102 minutes saved in total travel times, and about 9 minutes on average per island, even when limited by the slower speed and charging times of the E-ferry “Ellen”.

Considering the network in its entirety, travel times show the aforementioned trend. Specifically, a total difference of almost 14 hours less compared to the existing network is made to total travel times, with an average of almost 24 minutes less per island. While these results do not show high promise, it should be noted that, as mentioned before, the resulted travel times are being compared to the average existing travel times which, in most if not all cases, include offered transport services through high-speed routes, with ships greatly exceeding the ones of the ships of the study. As a result, increases shown in some ports, such us the clusters of Mykonos-Syros-Tinos and Paros-Naxos are a result of comparison with average travel times where, in every case of the aforementioned islands, there were more than one high-speed ferry service offered.

In terms of fuel consumption and CO_2 emissions, the newly proposed model also achieves much better results than the existing networks. For the purposes of direct comparisons, from the 80 routes of the network digitized in the initial geodatabase, only those which call on ports of the study are considered, in order to provide direct comparisons with the newly proposed network. As a result, 47 routes were selected, as these were the ones calling on ports being considered to create newly proposed connections. The final 47 routes of the existing network were found to consume 2660.80 m. tonnes of fuel per round trip. On the contrary, the newly proposed conventional routes of the restructured network, based on the above resulted data were found to be significantly less-consuming, with a daily consumption of 812.24 m. tonnes of fuel, which consists a 69.47% decrease in daily fuel consumption. Even in the case where conventional routes were to be tripled in frequency on the newly proposed network, they would then consume 2436.72 m. tonnes of fuel, which still constitutes an 8.42% decrease in daily fuel consumption. Based on the results provided above regarding daily fuel consumption on the newly proposed network, without increasing conventional routes, and providing all other necessary port calls via zero-emission routes, there are savings of 1848.56 m. tonnes of fuel and 5756.42 m. tonnes of CO_2.

In case these routes were to be servicing islands on a daily basis, fuel consumption on a weekly basis would be 5685.68 m. tonnes of fuel, while on a 3-month period (13 weeks) it would equal 73913.84 m. tonnes of fuel. These translate to 17705.21 and 230167.70 m. tonnes of CO_2 emissions, respectively. To provide a more comprehensive understanding of the great significance for redesigning the network, it is important to compare the extent to which the environmental impact of the network is limited, compared to conventional strategies, such as slow-steaming. Specifically, considering only the routes associated with the ports under study, comparative results of all strategies are shown on the following table.

Table 26. Environmental performance of different strategies (daily basis, round trips considered)

Environmental Strategy	**Selected Routes (m. tonnes fuel)**	**Whole Network (m. tonnes fuel)**	**Selected Routes (m. tonnes CO_2)**	**Whole Network (m. tonnes CO_2)**
	Fuel Reduction (m. tonnes)		**CO_2 emissions reduction (m. tonnes)**	

Slow Steaming (5% Reduction)	-243.062	-473.927	-756.896	-1475.81
Slow Steaming (10% Reduction)	-473.66	-923.551	-1474.98	-2875.94
Slow Steaming (15% Reduction)	-691.793	-1348.87	-2154.24	-4200.38
Slow Steaming (20% Reduction)	-897.461	-1749.89	-2794.69	-5449.15
Network Design with Zero-Emission Routes	**- 1848.56**		**- 5756.43**	

As shown on the above results, the establishment of zero-emission routes in specific parts of the network, where this is feasible, can significantly decrease conventional fuel consumption, while also limiting CO_2 emissions. Consequently, the design of the network with the integration of zero-emission routes is found beneficial in terms of network operations, both from economic and environmental aspects, while also without compromising on the offered level of service, by reducing ship speeds and therefore worsening travel times. In some cases, the overall benefits found from the newly proposed network show results similar to slow-steaming of the whole network at a 10% level, while results from the restructuring compared directly to routes associated with the ports of the study show almost as much fuel consumption and CO_2 emissions decreases as a 20% slow steaming strategy. However, slow steaming strategies were found to greatly compromise the offered Level of Service (LoS) of the network, while the newly proposed network is found to not only retain LoS through travel times as much as possible, but in some cases also improve overall accessibility and passenger travel times. Reasonably then, the proposed methodology implemented for the design of the newly proposed network, is found to be the most efficient and sustainable one, in terms of economic, environmental, and accessibility aspects.

In addition to the above results concerning network operations through newly designed routes, overall port efficiency is also evaluated. Results from the calculation of the sub-indices and overall port efficiency index are shown on Table 27 for the base scenario, which considers operations of the already existing network and on Table 28 for the restructured network scenario, with the establishment of zero-emission routes. It is worth noting that the Zero-Emission Routes Efficiency Index is not calculated on the base scenario, as no zero-emission connections exist, although it is considered in the overall port efficiency index, as feasible zero-emission connections exist for all ports of the study.

Table 27. Normalized Efficiency Indices for each port of the study (Base Scenario – Existing Network)

Port	Normalized Emissions Efficiency	Normalized Passenger Efficiency	Normalized Connectivity Efficiency	Overall Port Efficiency
Agathonisi	0.404	0.000	0.118	**0.131**
Amorgos	0.965	0.229	0.118	**0.328**
Anaphi	0.756	0.077	0.017	**0.212**
Ano Koufonisi	0.954	0.167	0.335	**0.364**
Arkoi	0.665	0.002	0.031	**0.174**
Chalki	0.335	0.021	0.053	**0.102**
Donousa	1.000	0.145	0.161	**0.326**
Folegandros	0.854	0.113	0.139	**0.277**
Fournoi	0.550	0.082	0.009	**0.160**
Ikaria	0.787	0.299	0.017	**0.276**
Ios	0.523	0.113	0.153	**0.197**
Iraklia	0.814	0.021	0.161	**0.249**
Kalymnos	0.783	0.413	0.014	**0.302**
Kea	0.858	0.095	1.000	**0.488**
Kimolos	0.973	0.315	0.017	**0.326**
Kos	0.575	0.441	0.017	**0.258**
Kythnos	0.837	0.120	0.248	**0.301**

Leipsoi	0.000	0.026	0.025	**0.013**
Leros	0.643	0.241	0.000	**0.221**
Milos	0.653	0.171	0.205	**0.257**
Mykonos	0.364	0.261	0.248	**0.218**
Naxos	0.428	0.208	0.198	**0.209**
Nisyros	0.443	0.089	0.022	**0.139**
Paros	0.599	0.344	0.297	**0.310**
Patmos	0.384	0.181	0.005	**0.143**
Rhodes	0.487	0.409	0.018	**0.229**
Santorini	0.602	0.491	0.132	**0.306**
Schinousa	0.874	0.040	0.161	**0.269**
Serifos	0.920	0.108	0.393	**0.355**
Sifnos	0.604	0.118	0.236	**0.240**
Sikinos	0.952	0.185	0.017	**0.288**
Symi	0.954	1.000	0.005	**0.490**
Syros	0.693	0.385	0.082	**0.290**
Tilos	0.816	0.150	0.017	**0.246**
Tinos	0.827	0.259	0.352	**0.359**

Table 28. Normalized Efficiency Indices for each port of the study (Restructured/New Network)

Port	Emissions Efficiency	Passenger Efficiency	Connectivity Efficiency	Zero-Emission Routes Efficiency	Overall Port Efficiency
Agathonisi	0.460	0.000	0.118	0.269	**0.404**
Amorgos	0.969	0.229	0.118	0.391	**0.347**

Anaphi	0.778	0.077	0.017	0.468	**0.523**
Ano Koufonisi	0.959	0.167	0.335	0.521	**0.532**
Arkoi	0.696	0.002	0.031	0.332	**0.408**
Chalki	0.398	0.021	0.053	0.368	**0.519**
Donousa	1.000	0.145	0.161	0.493	**0.493**
Folegandros	0.868	0.113	0.139	0.380	**0.413**
Fournoi	0.592	0.082	0.009	0.221	**0.323**
Ikaria	0.807	0.299	0.017	0.343	**0.392**
Ios	0.568	0.113	0.153	0.271	**0.310**
Iraklia	0.832	0.021	0.161	0.365	**0.407**
Kalymnos	0.803	0.413	0.014	0.370	**0.319**
Kea	0.871	0.095	1.000	0.617	**0.644**
Kimolos	0.976	0.315	0.017	0.389	**0.395**
Kos	0.615	0.441	0.017	0.518	**0.553**
Kythnos	0.852	0.120	0.248	0.430	**0.460**
Leipsoi	0.093	0.026	0.025	0.186	**0.413**
Leros	0.676	0.241	0.000	0.279	**0.360**
Milos	0.686	0.171	0.205	0.349	**0.420**
Mykonos	0.423	0.261	0.248	0.283	**0.424**
Naxos	0.482	0.208	0.198	0.336	**0.450**
Nisyros	0.495	0.089	0.022	0.318	**0.445**
Paros	0.636	0.344	0.297	0.369	**0.454**
Patmos	0.442	0.181	0.005	0.357	**0.247**

Rhodes	0.535	0.409	0.018	0.491	**0.547**
Santorini	0.639	0.491	0.132	0.378	**0.458**
Schinousa	0.886	0.040	0.161	0.327	**0.356**
Serifos	0.928	0.108	0.393	0.420	**0.421**
Sifnos	0.641	0.118	0.236	0.349	**0.401**
Sikinos	0.957	0.185	0.017	0.352	**0.363**
Symi	0.958	1.000	0.005	0.616	**0.530**
Syros	0.722	0.385	0.082	0.381	**0.440**
Tilos	0.834	0.150	0.017	0.500	**0.542**
Tinos	0.843	0.259	0.352	0.447	**0.474**

To better evaluate the above results, it is important to highlight the absolute increase in efficiency before and after the establishment of zero-emission routes. The absolute difference based on the proposed efficiency index shows an overall increase, especially in environmental efficiency for all ports. Essentially, if existing total port calls and passenger flows through them can be retained, the overall efficiency of the ports of the network increases on all ports, as shown on Figure 23. Results show that, even in cases where connectivity would decrease, there is still a lot of room for improvement through the restructuring of the network and the overall efficiency of the network. In addition, in many cases of ports of the network, passenger efficiency through better capacity utilization could be achieved, with more passengers travelling per each ship port call, thus also increasing environmental efficiency through total transport work, in terms of CO2 emissions generated per passenger per distance travelled. Results show that all ports of the study have several opportunities, not only in terms of environmental efficiency but overall efficiency considering passenger, environmental and connectivity efficiency.

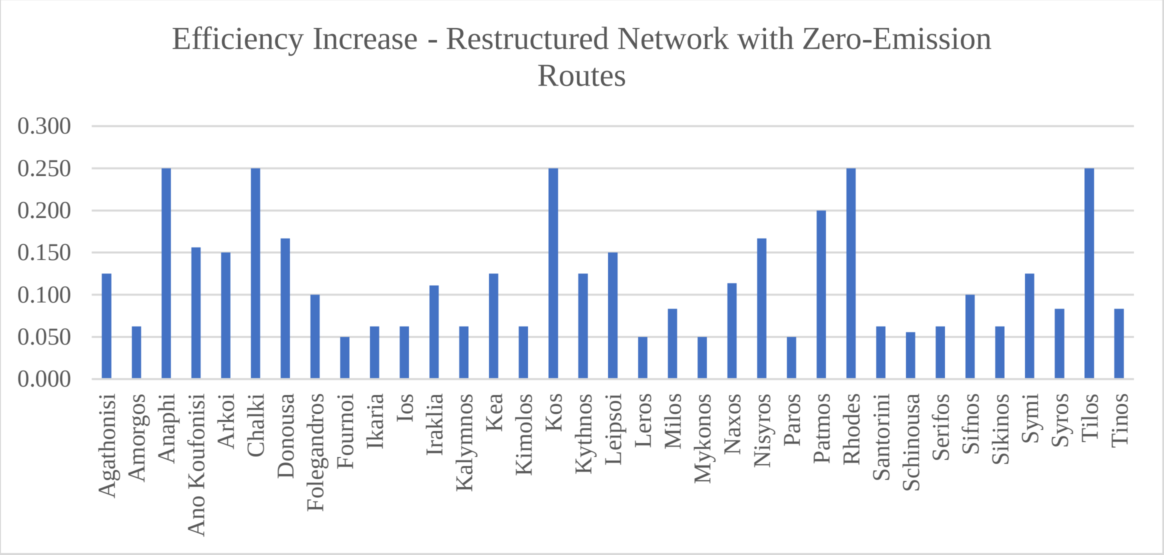


Figure 23. Absolute Efficiency Increase on Ports of the Study after the Establishment of Zero-Emission Routes

However, even though results show promise when considering the absolute changes in efficiency through the proposed index of the study, an additional evaluation is necessary, through the utilization of the input oriented SBM-DEA model developed. Through the utilization of the SBM-DEA model, relative efficiencies can be calculated to better assess the relations of the ports of the network between them, considering operational factors. It is worth keeping in mind though that relative efficiency can have negative impacts in measuring efficiency of smaller ports of lower demand, as they compare directly with the larger higher demand ports of the network. Consequently, results from the SBM-DEA model must be interpreted with caution and, in all cases, in relation with the results from the proposed efficiency index, in order to provide better insight on actual port performance not only relatively to larger ports but also in relation to previous operational conditions of the port on different network structures.

5.6. SBM-DEA Model Results

In the case of the SBM-DEA results, significance is shown to be given on overall connectivity, as efficiency on islands with more connections and routes is retained. However, the model also benefits the now environmentally sustainable ports of lower-demand islands, which in the proposed new network are serviced by zero-emission routes. Table 18 and figure 23 show the efficiency results. The

SBM-DEA model was formulated in Python 3.8 and results were generated using a desktop PC with a CPU of 3.8GHz and 32GB of RAM.

Table 29. SBM-DEA Model Results for Port Efficiency

PORT	EFFICIENCY UNDER EXISTING NETWORK	EFFICIENCY UNDER NEW NETWORK	ABSOLUTE CHANGE
AGATHONISI	0.473	1.000	0.527
AMORGOS	1.000	0.018	-0.982
ANAPHI	0.195	1.000	0.805
ANO KOUFONISI	0.990	1.000	0.010
ARKOI	0.359	1.000	0.641
CHALKI	0.259	1.000	0.741
DONOUSA	1.000	1.000	0.000
FOLEGANDROS	0.479	1.000	0.521
FOURNOI	0.127	1.000	0.873
IKARIA	0.197	0.004	-0.193
IOS	0.272	0.056	-0.216
IRAKLIA	1.000	1.000	0.000
KALYMNOS	0.312	0.025	-0.287
KEA	1.000	1.000	0.000
KIMOLOS	1.000	1.000	0.000
KOS	0.296	0.049	-0.247
KYTHNOS	0.583	0.360	-0.223
LEIPSOI	0.188	1.000	0.812
LEROS	0.113	0.005	-0.108
MILOS	0.331	0.447	0.116
MYKONOS	1.000	1.000	0.000
NAXOS	0.897	0.256	-0.640
NISYROS	0.125	1.000	0.875
PAROS	1.000	1.000	0.000
PATMOS	0.088	0.004	-0.084
RHODES	0.264	0.051	-0.213
SANTORINI	1.000	1.000	0.000
SCHINOUSA	1.000	1.000	0.000
SERIFOS	1.000	0.125	-0.875
SIFNOS	0.298	0.091	-0.207
SIKINOS	0.481	1.000	0.519
SYMI	1.000	0.027	-0.973
SYROS	0.448	0.301	-0.147
TILOS	0.158	1.000	0.842
TINOS	1.000	0.271	-0.729

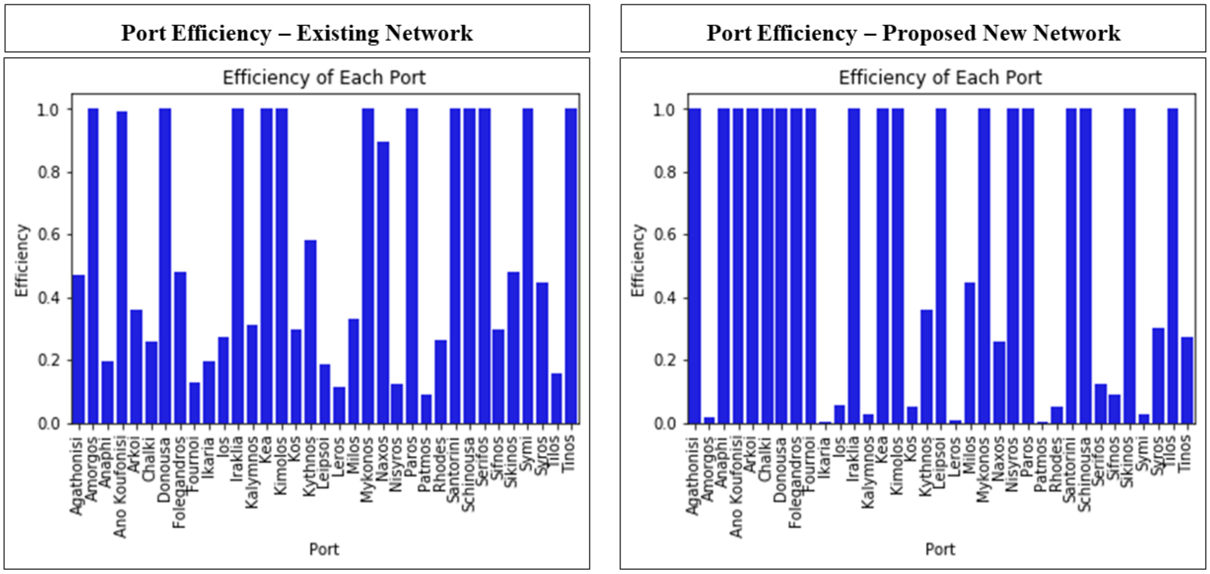
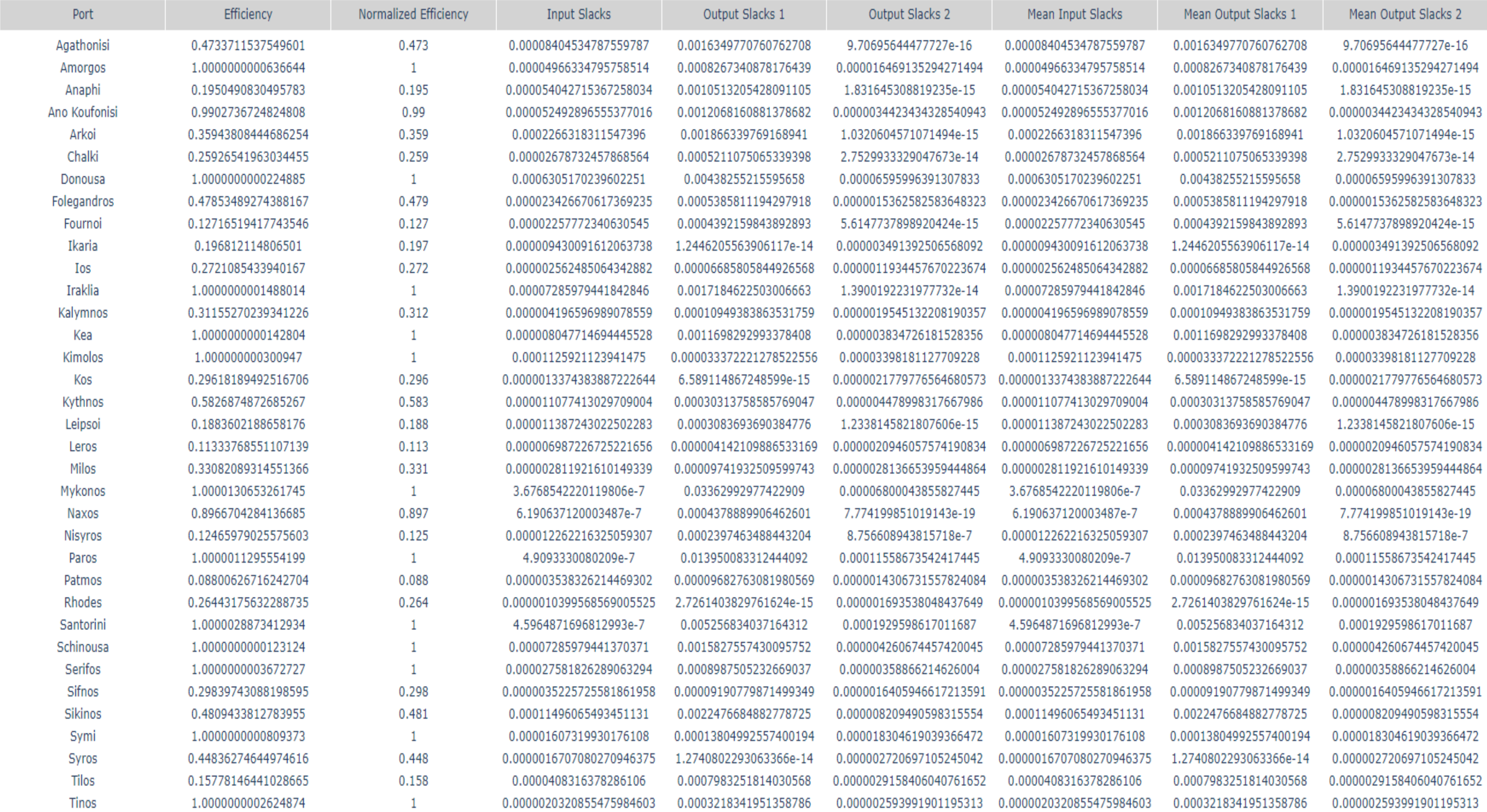


Figure 24. SBM-DEA Model Python Generated Plots for Port Efficiency

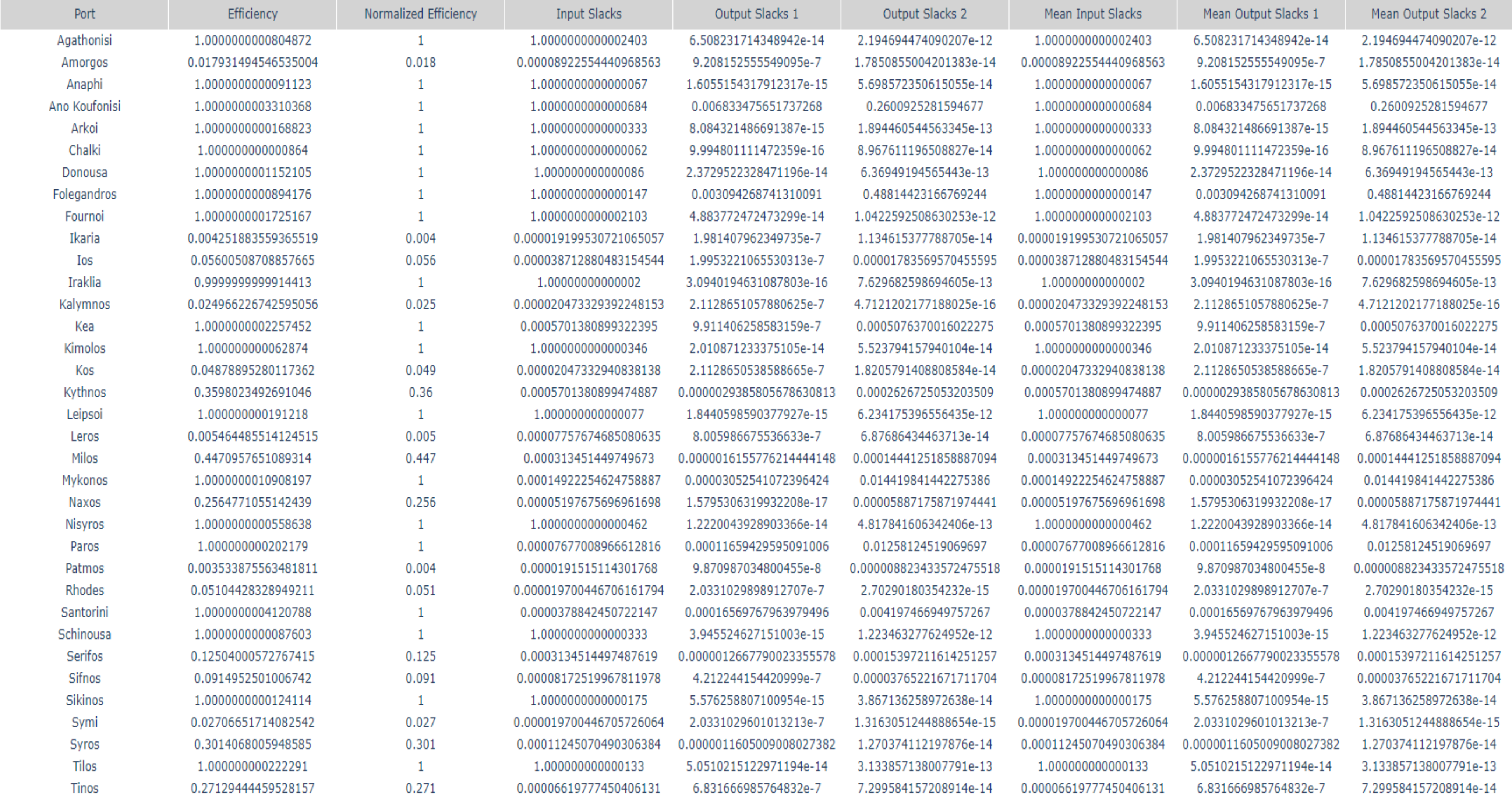
In addition to the above results, figures 24 and 25 show the full reports generated by the implementation of the SBM-DEA model.

Table 30. Detailed Results of the SBM-DEA Model – Existing Network



Port	Efficiency	Normalized Efficiency	Input Slacks	Output Slacks 1	Output Slacks 2	Mean Input Slacks	Mean Output Slacks 1	Mean Output Slacks 2
Agathonisi	0.4733711537549601	0.473	0.00008404534787559787	0.0016349770760762708	9.70695644477727e-16	0.00008404534787559787	0.0016349770760762708	9.70695644477727e-16
Amorgos	1.0000000000636644	1	0.00004966334795758514	0.0008267340878176439	0.000016469135294271494	0.00004966334795758514	0.0008267340878176439	0.000016469135294271494
Anaphi	0.1950490830495783	0.195	0.000054042715367258034	0.0010513205428091105	1.831645308819235e-15	0.000054042715367258034	0.0010513205428091105	1.831645308819235e-15
Ano Koufonisi	0.9902736724824808	0.99	0.000052492896555377016	0.0012068160881378682	0.0000034423434328540943	0.000052492896555377016	0.0012068160881378682	0.0000034423434328540943
Arkoi	0.35943808444686254	0.359	0.0002266318311547396	0.001866339769168941	1.0320604571071494e-15	0.0002266318311547396	0.001866339769168941	1.0320604571071494e-15
Chalki	0.25926541963034455	0.259	0.00002678732457868564	0.0005211075065339398	2.7529933329047673e-14	0.00002678732457868564	0.0005211075065339398	2.7529933329047673e-14
Donousa	1.0000000000224885	1	0.0006305170239602251	0.00438255215595658	0.00006595996391307833	0.0006305170239602251	0.00438255215595658	0.00006595996391307833
Folegandros	0.47853489274388167	0.479	0.000023426670617369235	0.0005385811194297918	0.0000015362582583648323	0.000023426670617369235	0.0005385811194297918	0.0000015362582583648323
Fournoi	0.12716519417743546	0.127	0.00002257772340630545	0.0004392159843892893	5.6147737898920424e-15	0.00002257772340630545	0.0004392159843892893	5.6147737898920424e-15
Ikaria	0.196812114806501	0.197	0.000009430091612063738	1.2446205563906117e-14	0.00003491392506568092	0.000009430091612063738	1.2446205563906117e-14	0.00003491392506568092
Ios	0.2721085433940167	0.272	0.000002562485064342882	0.00006685805844926568	0.0000011934457670223674	0.000002562485064342882	0.00006685805844926568	0.0000011934457670223674
Iraklia	1.0000000001488014	1	0.00007285979441842846	0.0017184622503006663	1.3900192231977732e-14	0.00007285979441842846	0.0017184622503006663	1.3900192231977732e-14
Kalymnos	0.31155270239341226	0.312	0.000004196596989078559	0.00010949383863531759	0.0000019545132208190357	0.000004196596989078559	0.00010949383863531759	0.0000019545132208190357
Kea	1.0000000000142804	1	0.00008047714694445528	0.0011698292993378408	0.00003834726181528356	0.00008047714694445528	0.0011698292993378408	0.00003834726181528356
Kimolos	1.000000000300947	1	0.0001125921123941475	0.000033372221278522556	0.00003398181127709228	0.0001125921123941475	0.000033372221278522556	0.00003398181127709228
Kos	0.29618189492516706	0.296	0.0000013374383887222644	6.589114867248599e-15	0.0000021779776564680573	0.0000013374383887222644	6.589114867248599e-15	0.0000021779776564680573
Kythnos	0.5826874872685267	0.583	0.000011077413029709004	0.00030313758585769047	0.000004478998317667986	0.000011077413029709004	0.00030313758585769047	0.000004478998317667986
Leipsoi	0.1883602188658176	0.188	0.000011387243022502283	0.0003083693690384776	1.2338145821807606e-15	0.000011387243022502283	0.0003083693690384776	1.2338145821807606e-15
Leros	0.11333768551107139	0.113	0.000006987226725221656	0.000004142109886533169	0.0000020946057574190834	0.000006987226725221656	0.000004142109886533169	0.0000020946057574190834
Milos	0.33082089314551366	0.331	0.000002811921610149339	0.00009741932509599743	0.0000028136653959444864	0.000002811921610149339	0.00009741932509599743	0.0000028136653959444864
Mykonos	1.0000130653261745	1	3.6768542220119806e-7	0.03362992977422909	0.00006800043855827445	3.6768542220119806e-7	0.03362992977422909	0.00006800043855827445
Naxos	0.8966704284136685	0.897	6.190637120003487e-7	0.0004378889906462601	7.774199851019143e-19	6.190637120003487e-7	0.0004378889906462601	7.774199851019143e-19
Nisyros	0.12465979025575603	0.125	0.000012262216325059307	0.0002397463488443204	8.756608943815718e-7	0.000012262216325059307	0.0002397463488443204	8.756608943815718e-7
Paros	1.0000011295554199	1	4.9093330080209e-7	0.013950083312444092	0.00011558673542417445	4.9093330080209e-7	0.013950083312444092	0.00011558673542417445
Patmos	0.08800626716242704	0.088	0.000003538326214469302	0.00009682763081980569	0.0000014306731557824084	0.000003538326214469302	0.00009682763081980569	0.0000014306731557824084
Rhodes	0.26443175632288735	0.264	0.0000010399568569005525	2.7261403829761624e-15	0.000001693538048437649	0.0000010399568569005525	2.7261403829761624e-15	0.000001693538048437649
Santorini	1.0000028873412934	1	4.5964871696812993e-7	0.005256834037164312	0.0001929598617011687	4.5964871696812993e-7	0.005256834037164312	0.0001929598617011687
Schinousa	1.0000000000123124	1	0.00007285979441370371	0.0015827557430095752	0.000004260674457420045	0.00007285979441370371	0.0015827557430095752	0.000004260674457420045
Serifos	1.0000000003672727	1	0.000027581826289063294	0.0008987505232669037	0.00000358866214626004	0.000027581826289063294	0.0008987505232669037	0.00000358866214626004
Sifnos	0.29839743088198595	0.298	0.0000035225725581861958	0.00009190779871499349	0.0000016405946617213591	0.0000035225725581861958	0.00009190779871499349	0.0000016405946617213591
Sikinos	0.4809433812783955	0.481	0.00011496065493451131	0.0022476684882778725	0.000008209490598315554	0.00011496065493451131	0.0022476684882778725	0.000008209490598315554
Symi	1.0000000000809373	1	0.0001607319930176108	0.00013804992557400194	0.000018304619039366472	0.0001607319930176108	0.00013804992557400194	0.000018304619039366472
Syros	0.44836274644974616	0.448	0.0000016707080270946375	1.2740802293063366e-14	0.000002720697105245042	0.0000016707080270946375	1.2740802293063366e-14	0.000002720697105245042
Tilos	0.15778146441028665	0.158	0.0000408316378286106	0.0007983251814030568	0.0000029158406040761652	0.0000408316378286106	0.0007983251814030568	0.0000029158406040761652
Tinos	1.0000000002624874	1	0.0000020320855475984603	0.0003218341951358786	0.000002593991901195313	0.0000020320855475984603	0.0003218341951358786	0.000002593991901195313

Table 31. Detailed Results of the SBM-DEA Model – New Proposed Network



Port	Efficiency	Normalized Efficiency	Input Slacks	Output Slacks 1	Output Slacks 2	Mean Input Slacks	Mean Output Slacks 1	Mean Output Slacks 2
Agathonisi	1.0000000000804872	1	1.0000000000002403	6.508231714348942e-14	2.194694474090207e-12	1.0000000000002403	6.508231714348942e-14	2.194694474090207e-12
Amorgos	0.017931494546535004	0.018	0.000008922554440968563	9.208152555549095e-7	1.7850855004201383e-14	0.000008922554440968563	9.208152555549095e-7	1.7850855004201383e-14
Anaphi	1.0000000000091123	1	1.0000000000000067	1.6055154317912317e-15	5.698572350615055e-14	1.0000000000000067	1.6055154317912317e-15	5.698572350615055e-14
Ano Koufonisi	1.0000000003310368	1	1.0000000000000684	0.006833475651737268	0.2600925281594677	1.0000000000000684	0.006833475651737268	0.2600925281594677
Arkoi	1.0000000000168823	1	1.0000000000000333	8.084321486691387e-15	1.894460544563345e-13	1.0000000000000333	8.084321486691387e-15	1.894460544563345e-13
Chalki	1.000000000000864	1	1.0000000000000062	9.994801111472359e-16	8.967611196508827e-14	1.0000000000000062	9.994801111472359e-16	8.967611196508827e-14
Donousa	1.0000000001152105	1	1.000000000000086	2.3729522328471196e-14	6.36949194565443e-13	1.000000000000086	2.3729522328471196e-14	6.36949194565443e-13
Folegandros	1.0000000000894176	1	1.0000000000000147	0.003094268741310091	0.48814423166769244	1.0000000000000147	0.003094268741310091	0.48814423166769244
Fournoi	1.0000000001725167	1	1.0000000000002103	4.883772472473299e-14	1.0422592508630253e-12	1.0000000000002103	4.883772472473299e-14	1.0422592508630253e-12
Ikaria	0.004251883559365519	0.004	0.000019199530721065057	1.981407962349735e-7	1.134615377788705e-14	0.000019199530721065057	1.981407962349735e-7	1.134615377788705e-14
Ios	0.05600508708857665	0.056	0.000038712880483154544	1.9953221065530313e-7	0.00001783569570455595	0.000038712880483154544	1.9953221065530313e-7	0.00001783569570455595
Iraklia	0.9999999999914413	1	1.00000000000002	3.0940194631087803e-16	7.629682598694605e-13	1.00000000000002	3.0940194631087803e-16	7.629682598694605e-13
Kalymnos	0.024966226742595056	0.025	0.000020473329392248153	2.1128651057880625e-7	4.7121202177188025e-16	0.000020473329392248153	2.1128651057880625e-7	4.7121202177188025e-16
Kea	1.0000000002257452	1	0.0005701380899322395	9.911406258583159e-7	0.0005076370016022275	0.0005701380899322395	9.911406258583159e-7	0.0005076370016022275
Kimolos	1.000000000062874	1	1.0000000000000346	2.010871233375105e-14	5.523794157940104e-14	1.0000000000000346	2.010871233375105e-14	5.523794157940104e-14
Kos	0.04878895280117362	0.049	0.00002047332940838138	2.1128650538588665e-7	1.8205791408808584e-14	0.00002047332940838138	2.1128650538588665e-7	1.8205791408808584e-14
Kythnos	0.3598023492691046	0.36	0.0005701380899474887	0.0000029385805678630813	0.0002626725053203509	0.0005701380899474887	0.0000029385805678630813	0.0002626725053203509
Leipsoi	1.000000000191218	1	1.000000000000077	1.8440598590377927e-15	6.234175396556435e-12	1.000000000000077	1.8440598590377927e-15	6.234175396556435e-12
Leros	0.005464485514124515	0.005	0.00007757674685080635	8.005986675536633e-7	6.87686434463713e-14	0.00007757674685080635	8.005986675536633e-7	6.87686434463713e-14
Milos	0.4470957651089314	0.447	0.000313451449749673	0.0000016155776214444148	0.00014441251858887094	0.000313451449749673	0.0000016155776214444148	0.00014441251858887094
Mykonos	1.0000000010908197	1	0.00014922254624758887	0.00003052541072396424	0.014419841442275386	0.00014922254624758887	0.00003052541072396424	0.014419841442275386
Naxos	0.2564771055142439	0.256	0.00005197675696961698	1.5795306319932208e-17	0.00005887175871974441	0.00005197675696961698	1.5795306319932208e-17	0.00005887175871974441
Nisyros	1.0000000000558638	1	1.0000000000000462	1.2220043928903366e-14	4.817841606342406e-13	1.0000000000000462	1.2220043928903366e-14	4.817841606342406e-13
Paros	1.000000000202179	1	0.00007677008966612816	0.00011659429595091006	0.01258124519069697	0.00007677008966612816	0.00011659429595091006	0.01258124519069697
Patmos	0.003533875563481811	0.004	0.0000191515114301768	9.870987034800455e-8	0.0000008823433572475518	0.0000191515114301768	9.870987034800455e-8	0.0000008823433572475518
Rhodes	0.05104428328949211	0.051	0.000019700446706161794	2.0331029898912707e-7	2.70290180354232e-15	0.000019700446706161794	2.0331029898912707e-7	2.70290180354232e-15
Santorini	1.0000000004120788	1	0.0000378842450722147	0.00016569767963979496	0.004197466949757267	0.0000378842450722147	0.00016569767963979496	0.004197466949757267
Schinousa	1.0000000000087603	1	1.0000000000000333	3.945524627151003e-15	1.223463277624952e-12	1.0000000000000333	3.945524627151003e-15	1.223463277624952e-12
Serifos	0.12504000572767415	0.125	0.0003134514497487619	0.0000012667790023355578	0.00015397211614251257	0.0003134514497487619	0.0000012667790023355578	0.00015397211614251257
Sifnos	0.0914952501006742	0.091	0.00008172519967811978	4.212244154420999e-7	0.00003765221671711704	0.00008172519967811978	4.212244154420999e-7	0.00003765221671711704
Sikinos	1.0000000000124114	1	1.0000000000000175	5.576258807100954e-15	3.867136258972638e-14	1.0000000000000175	5.576258807100954e-15	3.867136258972638e-14
Symi	0.02706651714082542	0.027	0.000019700446705726064	2.0331029601013213e-7	1.3163051244888654e-15	0.000019700446705726064	2.0331029601013213e-7	1.3163051244888654e-15
Syros	0.3014068005948585	0.301	0.00011245070490306384	0.0000011605009008027382	1.270374112197876e-14	0.00011245070490306384	0.0000011605009008027382	1.270374112197876e-14
Tilos	1.000000000222291	1	1.000000000000133	5.0510215122971194e-14	3.133857138007791e-13	1.000000000000133	5.0510215122971194e-14	3.133857138007791e-13
Tinos	0.27129444459528157	0.271	0.00006619777450406131	6.831666985764832e-7	7.299584157208914e-14	0.00006619777450406131	6.831666985764832e-7	7.299584157208914e-14

The above results indicate the reason why DEA model results should always be interpreted with caution, although they still provide valuable insights. In general, absolute changes in port efficiency show an average of +0.033, with average port efficiency in the case of the existing network equaling 0.570 and 0.603 in the case of the proposed new network. However, port efficiency in the restructured network case majorly favors ports which are serviced by zero-emission routes, as shown on the above results, with the largest increases in efficiency being those of Nisyros at +0.875, Fournoi at +0.873, Tilos at +0.842, Leipsoi at +0.812 and Anaphi at +0.805. As DEA models deal with relative efficiencies, the increases in efficiency of the more environmentally friendly ports, which are associated with zero-emission routes, impact the efficiencies of other ports of the study, most notably hubs as these are now burdened with the association of most fuel-consumed based emissions. On that note though, there are still certain high-demand ports retaining their overall efficiency, such as Paros, Santorini and Mykonos, where overall efficiency does not drop, mainly due to connectivity factors and overall popularity in terms of passenger demand. In these cases, such ports are benefited by the use of the SBM-DEA model, as they also contribute to decarbonization through zero-emission routes operating from them to neighboring ports, while also maintaining good accessibility levels and overall connectivity through several routes and ship calls.

Still, the way the model was developed, results seem reasonable and even with the existing bias, the model was still able to achieve better mean efficiency, assuming passenger demand and connectivity per port would remain the same, even though this may not be the case. While passenger demand could vary, if connectivity services were to also improve and incorporated to the model, with more efficient fleet assignment, efficiency results would increase even more, especially on ports which would not seemingly operate as efficiently as ports serviced by zero-emission routes. In the case of the developed model, environmental footprint limitations were only considered to optimize port efficiency, while also retaining the same fleet but assigning the most efficient ships on resulted routes, as these are shown above on their assigned routes.

However, evaluating results from the SBM-DEA model developed and the efficiency metrics proposed in the dissertation, it is concluded that both should be used in combination with each other, so as to provide a more comprehensive understanding of port operations and their efficiency based on several factors. The goal of these indices, in combination with the SBM-DEA model proposed, is to provide the necessary tools to policymakers, stakeholders and operators for the measurement of overall efficiency and performance of ports, while considering network operation parameters, which is an important gap in the literature and has not been assessed thoroughly in studies until this time.

5.7. Conclusions and Discussion

The proposed framework described in this chapter provided a holistic and versatile approach to support the decision-making processes in designing a network integrating zero-emission routes. The overall approach of the network is a simplistic one and easily adaptable to any given network of high complexity and spatial variance. While each step was comprehensively described, a summary of the proposed framework, which follows a cluster-first route-second approach to identify port hierarchies on the given network's dataset, with its main points being:

1. Identification of initial zero-emission sub-networks through the use of Bivariate LISA statistics, as implemented in Chapter 4 of the dissertation.

2. Identification of port hierarchies based on passenger traffic and the existence of larger ports in proximity to assign feeder vessels for future electrified routes. On this context, less popular islands of lower passenger demand are assigned higher probabilities to become transshipment destinations. The logic behind this approach is quite simple and can be summed up to the fact that, if a port is inefficient in terms of its desirable outputs (which is total passenger demand and capacity utilization on offered routes), it must score higher on its environmental goals, in order to balance its passenger flow inefficiencies. Thus, such ports become initial candidates to be exclusively connected with other islands through zero emissions routes and electric ferries.

3. Filtering of the dataset. After completing steps 1 & 2, the dataset starts to decrease subsequently in size while repeating the above steps to the necessary level set by decision makers. It is worth noting that different networks have different decarbonization needs. As a result, the

overall “decarbonization sensitivity”, which shows the level of decarbonization to be achieved might differ between different networks and several other factors can also impact the overall decision-making process. In our case, as on the time of writing, electric ferry technologies are still quite new, thus only less popular islands will be considered in the decarbonization process, so that less passengers are impacted by changes in travel times and ferry transfers.

4. Density-based clustering on the remaining ports of the dataset. In the case of this dissertation, a Self-adjusting clustering method was chosen (HDBSCAN). As mentioned, with HDBSCAN, varying distances are used to separate clusters of varying densities from sparser noise, making HDBSCAN the most data-driven of the clustering methods requiring the least user input, as it only requires the minimum features per cluster. In this dissertation, the minimum ports per cluster considered were 2. In addition, ports characterized as “Noise” after this clustering method (i.e., ports not belonging to a specific cluster) must be assigned to a certain cluster, which in this case is selected as the cluster with a port closest to them.

5. Step 4 leads to different clusters on the network, with different routes needed to be assigned for their servicing needs. The optimal connections for each port of each cluster with each other and with the mainland are now proposed.

6. To provide better connectivity between each cluster of the network, another constraint is considered, which is that each cluster must connect to each other cluster with at least one port of cluster A providing a connection with another (at least) port of cluster B. In this case, proximity is the first and most important factor to be considered, as the goal is to provide cluster interconnections based on the shortest possible connections between them, with subsequent connections planned for electric ferries, where possible.

The proposed framework in this chapter fundamentally deals with the establishment and subsequent evaluation of zero-emission routes in ports of the network, which have been found to greatly enhance the overall efficiency of ports, particularly in terms of environmental efficiency. Notably, even where connectivity efficiency might see a decrease, results prove that significant improvements are achievable through effective network restructuring. Furthermore, these findings underscore the potential for enhancing passenger efficiency via better capacity utilization, leading to higher numbers of passengers per ship port call. As a consequence, this can potentially lead to increased environmental efficiency due to the reduction in CO_2 emissions relative to transport work, considering CO_2 emissions per passenger per distance travelled. It is clear that there is vast potential for improving not only the environmental efficiency of all ports involved in this study but also their overall efficiency, considering passenger, environmental, and connectivity aspects. While the increase in absolute efficiency using the proposed indices is promising, it is imperative to use the proposed metrics in combination with the relative efficiency of the ports in relation to one another, through the use of the developed SBM-DEA model. However, caution should be exercised in interpreting these results given the potential for smaller, lower-demand ports to be disadvantaged when compared to larger, higher-demand ports. Consequently, results from the SBM-DEA model ought to be analyzed along with the proposed efficiency indices to get a more holistic understanding of the ports' performance on different aspects.

Results from both the proposed metrics and the SBM-DEA model developed affirm the importance of connectivity, particularly for islands with multiple connections and routes. The model has verified the assumption that minimization of CO_2 is integral to the overall efficiency of ports, while especially in passenger networks, the improvement of both overall connectivity and the establishment of zero-emission networks can increase overall efficiency. Nonetheless, it is important to note that, while the SBM-DEA model would largely benefit larger, higher-demand ports that are better able to combine both these components, results also showed significant improvements in smaller zero-emission ports, as the focus of the model is mostly based on environmental efficiency. Still, such models and their respective results should always be interpreted with caution, as they are generally more useful in cases where port dynamics do not show significant variations, such as the ones in the GCSN. Therefore, a key drawback of the SBM-DEA model is its relative nature, as it measures efficiency relative to a set of Decision-Making Units (DMUs). Consequently, the consideration of larger, high-demand ports with excellent connectivity, passenger efficiency and zero-emissions routes operating from/to them would lead to significant increases in efficiency, subsequently decreasing the efficiency of lower-demand ports, which in turn may seem less efficient by comparison. However, this relative decrease still would not necessarily denote a lack of progress in sustainable operations, thus necessitating a balanced interpretation of the results through the implementation and interpretation of both the proposed efficiency indices and the SBM-DEA model.

Regarding the overall restructuring of the network and its newly proposed design based on certain criteria and approaches, results show great promise, in terms of economic, environmental, and accessibility aspects. More specifically, the proposed network shows great increases in fuel savings from overall consumption after the introduction of zero-emission routes, which in turn lead to limitations of the environmental footprint of the network through decreases in CO_2 emissions from ship operations. In addition, one of the most crucial aspects of the dissertation remains the fact that accessibility results show significant improvements in the network, with passenger travel times reduced, especially in islands where connectivity was shown to be quite low, such as the Dodecanese/Eastern Aegean Region. Smaller, less popular islands of the network could benefit from the newly proposed design of the network, as overall cohesion is improved, while social inequality issues in terms of island reachability are also adequately addressed. As a result, the proposed network offers a more evenly distributed level of service for passengers, with improved travel times in most cases, while also achieving to be more environmentally and economically sustainable, especially in comparison with the results of other more conventional strategies. In order to better assess such improvements, the combination of proposed indices and efficiency models can provide several metrics to measure and evaluate network and port performances, under various considerations.

In conclusion, the dissertation aims to highlight exactly this issue on efficiency analyses. It has become clear from the results of the study that it is crucial to employ both absolute and relative efficiency measures to properly measure and assess port performance and network restructuring potentials, through the utilization of a GIS-assisted framework for the design of efficient maritime transport systems. The proposed efficiency index in this study aims to be utilized in parallel with DEA models, in order to provide a more holistic approach for efficiency analysis studies, especially in cases where the design and planning of sustainable maritime operations is necessary on networks where ports show different dynamics. More research is required to further refine these models and efficiency indices and work out methods for supporting smaller, lower-demand ports in the transition towards sustainability in networks where their overall efficiency may initially seem disadvantageous in terms of relative port efficiencies.

6. CONCLUSIONS AND FUTURE RESEARCH

In this chapter, an overview of the dissertation’s objectives and work undertaken is discussed, with key points presented and conclusions drawn from the results of the application of the proposed methodological framework. In addition, future research suggestions are highlighted.

6.1. General Facts

Decarbonization in the maritime industry has been increasingly gaining the interest of researchers, stakeholders and policymakers for several years. Maritime transportation systems are expected to play a crucial role in the shift towards more sustainable shipping, especially considering technological advancements towards zero-emission systems. Especially in maritime transport networks which are characterized by an aspect of necessity, rather than commodity and goods trading, such as coastal passenger ones, decarbonization policies are not always easily implemented. In that context, the scope of this dissertation was to systematically analyze a highly complex maritime transport network and propose a GIS-based methodological framework for the design of a more efficient alternative, considering several operational aspects. More specifically, the dissertation investigated the design of a maritime transport system integrating zero-emission routes in its design and planning processes, while also highlighting the need for performance monitoring and efficiency evaluation on such networks, through the utilization of spatial data analytics. The objectives of the dissertation were:

- The systematic literature review on the main uses of geospatial technologies, data, and methods in maritime networks, along with the identification of areas of study where these are highly underutilized.
- The development of a GIS-based methodological framework for emissions monitoring in areas of maritime networks to provide insights for targeted decarbonization interventions.
- The development of a conceptual GIS-based framework for the design of a maritime transport network under zero-emission route considerations.

- The development of relative metrics through efficiency indices for the evaluation and monitoring of network dynamics, aiming towards constant and targeted improvements by the evaluation of their results.

Dissertation research activities included the development of GIS-based models and supplementary algorithms in order to achieve the objectives set, as mentioned above. These models and algorithms were presented and discussed, with their application being tested in the case of the Greek Coastal Shipping Network, and specifically in two distinct, highly demanding, and spatially complex regions of the Aegean. Results initially showed the versatility of the models developed, with their respective workflows being easily adaptable to other maritime networks, while also achieving significant gains on several operational aspects considered.

6.2. Conclusions and Contributions

The utilization of an abundance of data in maritime transport creates new potential in the efficient design of maritime transport systems. Advancements in technology in terms of energy storage and renewable energy sources, data analytics combined with geospatial based methodologies, and their availability can all be utilized to propose new paths towards diminishing accessibility inequalities of networks, while also limiting their environmental footprint. However, the state-of-the-art review revealed major gaps in the existing literature, considering the design of maritime networks under electrification for the establishment of zero-emission routes, through the use of comprehensive design processes considering several spatially related aspects, such as the intricate topologies of different networks. In this context, the dissertation provides a versatile spatial decision support system (SDSS) mainly focusing on maritime transport network design under zero-emission routes inclusion, while addressing social inequalities on ports of a network, by improving overall cohesion and island accessibility.

6.2.1. Emissions Monitoring and Decarbonization

First, in order to assess the need for decarbonization, initial evaluations of existing networks are necessary. In order to measure how well a network operates, in terms of environmental efficiency, initial data collection, creation of appropriate GIS databases, digitization and visualization of collected data are necessary processes. While statistical data evaluations are still necessary, the association of such data on specific routes and areas of the evaluated network is crucial in providing the necessary decision support tools to policymakers and stakeholders for more accurate environmental assessments, which not only provide insights on more polluting routes, but also areas where targeted interventions may be necessary.

The identification of areas with high concentrations of CO_2 emissions can be achieved through several methods and models. While several studies in the literature review have addressed the issue of emissions inventories and monitoring, studies which have addressed the issue as a spatial problem have mostly focused on quantification and visualization of emissions, rather than providing a more comprehensive framework for the identification of specific clusters, which reveal areas where interventions are highly necessary. The dissertation provided a step towards this direction, by proposing the implementation of spatial autocorrelation models for the more accurate analysis and identification of clusters of areas with high CO_2 emissions. More specifically, the dissertation contributed on:

- Identifying whether there are certain spatial patterns in areas of the network, either clusters or outliers based on the spatial autocorrelation model of Global Moran's I. The model is able to identify that there is a specific spatial pattern showing clustering of CO_2 emissions. In order to identify the kinds of clusters identified in the study area, Local Indicators of Spatial Association (LISAs) are utilized, such as the Local Moran's I statistic, which results in areas of high values of CO_2 emissions clusters.
- For the verification of results and identification of additional areas of clustering, spatial pattern analysis through the use of the Getis-Ord General G statistic of overall spatial association was utilized, confirming the existence of high valued hotspots in the study area. Additionally, hotspot analysis with the use of Getis-Ord Gi* statistic was utilized to identify high valued clusters in the study area under certain statistically significant confidence levels.

As the used spatial autocorrelation models provided varying results, leading to less areas of clusters in the first case of the Local Moran's I, compared to the implementation of the Getis-Ord Gi* statistic, with areas of 90% confidence level or more selected. The varying results were expected and necessary for the purposes of the study, which aimed to provide different levels of implementation for conventional slow-steaming strategies for decarbonization to be applied. The implementation of such strategies was considered necessary in the dissertation, as it would provide an initial benchmark for the purposes of comparison between such conventional strategies and the proposed introduction of zero-emission routes in the network design.

While the results of the implementation of such strategies on selected areas of the network, where this was most needed, yielded significant results, the offered level of service (LoS) was impacted. Specifically, while the implementation of slow steaming strategies on the identified areas with high CO_2 emissions of the network showed promising results, in terms of CO_2 reductions, the offered LoS was deteriorated, as translated in passenger travel times, with increasing delays in island accessibility times. As a result, conventional slow steaming strategies, while still highly useful until the time of writing of the dissertation on several other cases of maritime transport, are not always easily applied in cases of high accessibility requirements, such as coastal shipping passenger networks, where late arrivals are unwanted, and in some cases unacceptable. Even though such strategies could still be implemented, speed reductions would have to be much less than needed as to not deteriorate overall LoS, which would however lead to almost insignificant gains to fuel consumption and CO_2 emissions limitations.

6.2.2. Identification of Zero-Emission Sub-Networks

As each maritime transport network is unique and characterized by significant topological complexities and different dynamics, each network design problem can be considered a spatially significant problem. In addition to this, when integrating zero-emission routes in the design process, range constraint parameters of the assigned ships on such routes should always be taken into consideration. The proposed methodological framework takes into consideration both of these assumptions; first, that each maritime transport network is characterized by high complexity in terms of topological characteristics, and secondly, that operations of the network are highly dependent on available technologies and fleet capabilities. Especially in the case of zero-emission routes, as of the time of writing of the dissertation, battery powered electric ferries are characterized by smaller operating ranges, being capable of sailing distances of at most 30 nautical miles. In addition, carrying capacities of such zero-emission ferries, both in terms of passengers and cars, are still low, able to carry almost a tenth or less passengers than a fully operational RoPax ship.

These constraints create the need to assess areas where the implementation of such zero-emission ferries is feasible. Such areas would require island distances to be as low as possible, while also being characterized by low passenger demand per port, in addition to ideally being as close as possible to a larger port, in order for it to act as a hub and support the operations of the zero-emission sub-network. It is evident that this is a problem including several variables and assumptions such as:

- Port passenger demand.
- Distances between ports.
- Specifically low passenger demand ports in proximity with each other.
- The existence of a larger (higher demand) port in proximity to the lower passenger demand ports, in order to support hub operations.

In order to address the multivariate nature of the problem, while also considering topological factors, as described above, it is necessary to identify clusters of ports in the study which meet the above requirements. In order to do this, the dissertation proposes the implementation of Multivariate Local Indicators of Spatial Association models, for the identification of feasible zero-emission sub-network areas. By utilizing passenger demand data and the reachability capabilities of ports to others of the study with zero-emission electric ferries, the Bivariate Local Moran's I LISA is utilized. Through its use, initial results are generated, which include clusters of ports where zero-emission routes can be introduced, for the servicing of specific low demand islands from larger hub-ports of higher demand. Preliminary results identified two areas where zero-emission sub-networks can be introduced, one in each region considered for the purposes of the dissertation.

In addition to the resulted areas, an analysis of existing and potential renewable energy source (RES) capabilities of the resulted areas and islands was conducted. The analysis showed that most of the islands of the Aegean have significant potential, especially in terms of future RES infrastructure installations, which can in turn supply the zero-emission routes with clean energy, thus leading to energy self-sufficient islands and sub-networks. By electrifying only the routes of the described preliminary analysis, significant reductions were found considering fuel consumption and CO_2 emissions, therefore showing promising results in terms of emissions mitigation from the electrification of specific parts of the network, where of course this is feasible due to existing technologies. Until the time of writing of the dissertation, the aforementioned preliminary results and their analysis consist the only methodology proposed for the identification and evaluation of areas able to support zero-emission maritime connections.

As other studies have mostly focused on technical aspects of the operation of electric ships on such routes, the dissertation aims to fill this gap by proposing a comprehensive approach to include zero-emission routes in the design process of maritime networks, considering network operations and dynamics, by proposing a GIS-based methodology utilizing available spatial data, which are highly underutilized in the maritime transport sector.

6.2.3. Efficient Network Design under Electrification

As mentioned above, at the time of writing of this dissertation, maritime network design under electrification is highly limited in existing studies, while almost no studies focus on providing a comprehensive framework for the re-design of an existing network considering zero-emission routes. As most existing studies have focused on the operation of electric ferries under mostly technical concerns on specific routes, this study takes a step further by proposing a comprehensive approach for the restructuring of complex existing networks of variable dynamics and topological characteristics by focusing on the inclusion of zero-emission routes.

However, in order to evaluate how the newly proposed network operates, in comparison to the existing one, the dissertation provides certain metrics so as to measure overall efficiency of basic components of the network. In the case of this dissertation, and due to the fact that passenger networks may show social inequalities in terms of accessibility and island reachability, ports of the study area are considered as basic components of the network to be evaluated, considering environmental, connectivity and demand factors. Four distinct efficiency indices are proposed, which are:

- The emissions efficiency index, which equals CO_2 emissions generated from port ship calls per total yearly passenger demand
- The passenger efficiency index, which equals total yearly passenger demand per total ship calls on each port
- The connectivity efficiency index, which equals total ship calls on each port per the total number of routes calling on the port
- The zero-emission routes efficiency index, equaling the actual per maximum feasible zero-emission port connections per port

The above indices are used to measure overall port efficiency of each port, based on given equations in chapter 5.2. In addition to the aforementioned indices, an SBM-DEA input-based model was developed to evaluate port efficiency results, in combination with the proposed indices. By proposing the above indices, it is possible to provide better insights and understanding in terms of port efficiency, as generally results only from the DEA model would require caution in their interpretation. As a result, by utilizing the results both from the proposed indices and the DEA model, it is possible to ascertain efficiency changes in basic network components related to ports of a given network, while also eliminating the relativeness of results, as generated by DEA models.

After the development of the relative indices and the DEA model, a comprehensive methodological framework for the restructuring and design of the existing network is developed, which is based on a cluster-first route-second approach, integrating zero-emission routes in the network design process. The proposed framework takes into consideration spatial data, topological characteristics of the network, while also considering policy-related aspects, in accordance to the existing legislative framework for the Greek Coastal Shipping Networks. Through the identification of clusters of zero-emission ports, along with those of ports connected through conventional routes, zero-emission routes are generated first, with conventional routes generated on the next step. As a result, with several zero-emission routes existent in the newly proposed network, emissions mitigation shows highly promising results, with the environmental footprint of the newly proposed network being reduced to about a third on the routes connecting the analyzed ports. In addition to this, even with the slower travel times of electric ferries and transfer times on hub-ports of the zero-emission sub-networks, overall travel times remain at acceptable levels, while on several islands now serviced by zero-emission routes, travel times also show significant decreases.

Therefore, the approach proposed regarding maritime network design under electrification is not only capable of reducing the environmental footprint of the network, but also improve overall accessibility. Considering the case study of the dissertation, which is the Greek Coastal Shipping Network, social inequality issues are addressed as well, with the existing operations of the GCSN impacting several islands with low connectivity levels, cohesion with other islands and the mainland, as well as overall reachability with high travel times and, therefore, a deteriorated level of service. While legislative framework aspects were considered, it is worth noting that certain limitations are still existent. The proposed network did not aim to provide the optimal solution generated by an optimization model from a specific point of view, such as the operators' or passengers' sides only, or considering a specific aspect, such as emissions or cost minimization. However, the proposed framework considers all necessary aspects and available data to propose the design of a maritime network which addresses most issues related to environmental, economic, and accessibility aspects, therefore providing a more holistic data-driven approach based on realistic limitations and implications of several aspects.

In conclusion, the design process of the network has achieved the goals set by the dissertation in the beginning of this research. First, it has limited, as much as possible, social inequalities in the network, by proving better accessibility through reduced travel times on several less popular ports of the network. Secondly, it has provided the necessary workflow considerations to integrate self-sufficient zero-emission routes in the design process of any maritime network, through a versatile and easily applicable methodological framework. Thirdly, it has achieved significant results in emissions mitigation, showing that the design of maritime networks under electrification can greatly limit CO_2 emissions through the integration of zero-emission routes, compared to conventional emissions mitigation strategies. Last but not least, the dissertation achieved to highlight the fact that spatial data analytics and GIS-based methodologies should always be utilized to provide a more holistic understanding of network dynamics, to identify areas where improvements are necessary, and to continuously monitor several aspects of network performance and ports' efficiencies. Through the utilization of the proposed indices and the use of spatial data analysis methods, the dissertation has provided the necessary tools to monitor, evaluate, and improve any given network, provided that relative data are available.

Overall, the proposed research contributes to a general policy framework promoting sustainable and socially equitable maritime transportation, focusing on route electrification and data-driven design. Regarding network design, the proposed framework can be employed as a two-step design process by initially identifying feasible areas in the network for zero-emission routes, prior to the design of main routes. As maritime transport is one of the areas where spatial data analytics have been widely underutilized, especially in the design and planning processes of networks, the dissertation aims to provide an alternative approach in such processes, in order to facilitate policymakers, stakeholders and network operators in decision making, through the development of a comprehensive and versatile SDSS.

6.2.4. Future Research Suggestions

The development of tools and decision support systems to assist maritime network design is continuously evolving, promoting sustainable transport and generally the decarbonization efforts in shipping. As technology advances, so will the available technologies to be utilized in ferry electrification, thus creating the potential for future studies to promote sustainable network design with the inclusion of zero-emission routes. This dissertation provided a comprehensive, easily adaptable methodological framework towards this direction, focusing on the design of zero-emission sub-networks within larger maritime networks, exploiting available spatial data to identify network dynamics, areas in need of immediate and targeted interventions, and to provide benchmarks for continuous monitoring, evaluation, and improvement of any given network. As suitable strategies were proposed to limit the environmental footprint of the network and improve accessibility on the entirety of the network, there are still several aspects to be addressed.

With respect to network design integrating electric ferries, it is necessary for future research to assess safety factors from their operation. First and foremost, extensive testing of electric ferries in conditions as the ones of the GCSN, or any examined network where their use is proposed, are necessary for the adjustment and reliability of reported results considering energy consumption. As range constraints could potentially alter significantly from the operation of such ferries on adverse weather conditions, it is crucial to assess this aspect and include it in the design process of the under analysis maritime network. For instance, in the case of this dissertation, it is assumed that the electric ferries considered are operating under the weather conditions on which they operated on their project tests, which is not always the case, especially in adverse weather conditions on the rough seas of the Aegean. As energy consumption significantly varies with operational conditions, thorough simulation is required to accurately estimate route energy requirements, in addition to extensive testing. As a result, weather conditions evaluations are necessary to assess whether electric ferries can actually operate in the proposed areas, and they are highly suggested to be incorporated in the design process. Additionally, in cases where only certain areas show adverse weather conditions, optimal weather routing research is needed to assess increases in energy consumption and operational feasibility in general.

Furthermore, in this dissertation, fixed travel demand per port was utilized to assess port hierarchies and feasible areas of electric ferry operations. Under the presence of data regarding OD matrices, results could vary significantly from those generated in this dissertation, revealing one of the most important issues addressed, as data availability was initially a major hindrance for the purposes of the study, requiring extensive data collection, cleaning, editing and generally the creation of GIS databases which should always be available to policy-makers for better decision-making. In addition, scheduling must also be considered as well to ensure optimal operations of the network, especially under seasonality parameters. Considering that the network highly varies in passenger demand and services offered during different periods throughout the year, future studies should include seasonal-based parameters in the design processes of any maritime network.

From a methodological point of view, requirements related to proposed network design parameters, such as desired criteria can be easily incorporated in the design process. In this case, data collection and talks with stakeholders, policy-makers and other related groups are necessary to provide an understanding and lead to hierarchical assessments of different criteria incorporated in the design process, through various methods, such as AHP, FAHP etc. As such criteria and their respective importance are evaluated, proposed network designs could also offer different solutions related to the point of view of each target group, such as passenger or operator-oriented solutions. The versatility of the proposed methodological framework is underlined by its ability to exploit several sources of data in order to better evaluate the performance of the network and its components, thus revealing more information regarding its operation. Through the use of such data, additional performance and efficiency metrics can be derived, which can in turn be utilized in re-design processes and optimization problems to further improve network operations.

In addition, although traditional clustering methodologies are relatively simple in terms of implementation, in some cases these rely on arbitrary thresholds and parameter values under some type of contextual information or user preferences. While the use of HDBSCAN is still the most data-driven clustering method it still requires specific user input (e.g., the minimum number of features per cluster). To address such issues, model-based clustering methods, such as machine learning algorithms, can still be applied to limit subjectivity, as a step towards data-driven inference.

Overall, this research highlighted the importance of spatial data analytics, which can be readily applied for maritime transport planning, and transport planning in general, in order to assist maritime operators and policymakers in decision-making. Consequently, this work constitutes a preliminary but novel step towards planning maritime transport networks under electrification based on current technological advances. While more research is required to adjust the design and planning processes with more variables and considerations, the dissertation highlights that the utilization of available and suitable data can highly facilitate all processes in transport planning, especially if this was possible on a sector as complex as maritime transport.

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JOURNAL & CONFERENCE PAPERS RELEVANT TO THE THESIS SCOPE

1. **Karountzos, O.,** Kepaptsoglou, K. & Schinas, O. (2024) A GIS-Assisted Framework for Maritime Network Design Under Electrification and Port Efficiency Evaluation (TRBAM-24-00424). Transportation Research Board Annual Meeting 2024, Jan. 7-11, Washington DC, USA
2. **Karountzos, O.**, Kagkelis, G. & Kepaptsoglou, K. (2023). A Decision Support GIS Framework for Establishing Zero-Emission Maritime Networks: The Case of the Greek Coastal Shipping Network. Journal of Geovisualization and Spatial Analysis, 7, 16. https://doi.org/10.1007/s41651-023-00145-1
3. **Karountzos, O.**, Kepaptsoglou, K. & Schinas, O. Identifying Spatial Inequalities and High CO2 Concentration Areas in the Greek Maritime Transportation System. International Conference ITS2023: Intelligent Systems and Consciousness Society. Nov. 2-3, Patras, Greece, 2023
4. **Karountzos, O.**, Kepaptsoglou, K. & Schinas, O. (2023). Developing an Integrated Efficiency Index for Coastal Shipping Networks Incorporating Connectivity, Spatial Analysis and Decarbonization Factors. 11th International Congress on Transportation Research. Sep. 20-22, Heraklion, Crete, Greece
5. **Karountzos, O.**, Kagkelis, G., Iliopoulou, C. Kepaptsoglou, K. (2023). Mapping High GHG Emissions Areas in the Aegean Sea: A GIS Framework for Determining Critical Areas for Emission Reduction Strategies (TRBAM-23-00182). Transportation Research Board Annual Meeting 2023, Jan. 8-12, Washington DC, USA
6. Kagkelis, G., **Karountzos, O.** & Kepaptsoglou, K. (2023). Exploring the Possibility for Zero-Emissions Sub-Networks in the Greek Coastal Shipping Network: A GIS Framework for the Evaluation of Potential Areas for Electrification (TRBAM-23-00441). Transportation Research Board Annual Meeting 2023, Jan. 8-12, Washington DC, USA
7. Iliopoulou, C., **Karountzos, O.**, Kopsidas, A., Kepaptsoglou, K. (2021). Hybrid MOPSO- RO model for designing reliable electric public transportation networks. Euro 2021, Athens, Greece.

8. Iliopoulou, C., Kopsidas, A., **Karountzos, O.**, Kepaptsoglou, K. (2021). Reliable electric public transportation network design considering charging waiting times. Presentation at ICTR 2021, Rhodes, Greece

SCIENTIFIC WORK WITHIN THE WIDER RESEARCH FIELD

1. **Karountzos, O.**, Liazos, A., Kepaptsoglou, K. (2024). Spatial Decision Support System for the Assessment of High-Risk Areas and Contributing Factors in Road Traffic Accidents: Application to the Northern Road Axis of Crete, Greece (TRBAM-24-00337). Transportation Research Board Annual Meeting 2024, Jan. 7-11, Washington DC, USA
2. Makari, M., **Karountzos, O.**, Liazos, A., Kagkelis, G., Kepaptsoglou, K. (2023). Spatial Distribution of Road Traffic Accidents in Crete: Identifying Accident Hotspots and Contributing Factors for Effective Road Safety Management. 11th International Congress on Transportation Research. 20-22 Sep 2023, Heraklion, Crete, Greece
3. Tzouras, P., Delialis, P., **Karountzos, O.**, Kouretas, K., Gkatzelia, V., Tsigdinos, S., Kepaptsoglou, K. (2023). A dashboard to explore the spatiotemporal traffic flow variations in Athens, Greece. 11th International Congress on Transportation Research. 20-22 Sep 2023, Heraklion, Crete, Greece
4. **Karountzos, O.**, Photis, Υ.Ν. (2018) Quality of life and modern cities: A methodological framework for the analysis and evaluation of sustainability levels of neighborhoods, 11th International Conference of the Hellenic Geographical Society Proceedings. ISBN: 978-960-606-047-2, Govosti Publications. 12-15 April 2018, Lavrio Greece
5. **Karountzos, O.**, Photis, Υ.Ν. (2018) Walkability in modern cities: A methodological framework for the analysis and evaluation of sustainability levels of neighborhoods. 11th International Conference of the Hellenic Geographical Society Proceedings. ISBN: 978-960-606-047-2, Govosti Publications. 12-15 Apr 2018, Lavrio Greece
6. **Karountzos, O.**, Photis, Υ.Ν. (2017). Quality of life and modern cities: Methodological framework for determining and evaluating the levels of sustainability of 32 neighborhoods of the Prefecture of Attica in a GIS environment. 5th National Hellenic Rural and Surveying Engineering Conference. 14-15 October 2017, Athens

Curriculum Vitae

General Information

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Education

2019 -	Ph.D. Candidate, National Technical University of Athens (NTUA) Thesis: GIS-Assisted Optimal Design of Maritime Transport Systems
2019	M.Sc. in Shipping Management, University of Piraeus. GPA: 8.68/10
2017	Diploma in Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens (NTUA), GPA: 7.51/10

Scholarships and Achievements

2022	Thomaidio Award for Scientific Publications in Conference Proceedings
2022	Scholarship for the preparation of a doctoral thesis from the State Scholarship Foundation
2022	Scholarship for Teaching Assistance in the field of Transportation Engineering at the School of Rural, Surveying and Geoinformatics Engineering at NTUA
2018	Selected at COSMOTE Hackathon Final Phase (12 Best Greek Teams)
2017	2nd Best Undergraduate Thesis Award, 5th National Hellenic Rural and Surveying Engineering Conference

Teaching Assistance at the School of Rural Surveying & Geoinformatics Engineering, NTUA

2022 –	Transport Project Planning - Economics
2022	Planning – Study – Operation of Road Works
2022	Transportation Systems
2022	Rail Transit
2020 –	Road Construction II – Traffic Engineering
2020 –	Road Construction III – Design and Operation of Traffic Junctions

Research & Professional Activities

Period	**Role**	**Project**
2023	Researcher	InWalk – Incentives for Walking, NTUA
2023	Researcher	SIM4MTRAN – Development of micro-mobility systems, NTUA
2022	Researcher	Daily Update on Transport Issues from the Laboratory of Transportation Engineering of the School of Rural, Surveying and Geoinformatics Engineering of NTUA via ERT SA Radio, NTUA
2020 – 2022	Researcher	Zero Emission Public Transport: Design Models and Decision Support System (ZEPHYR), NTUA
2018 –	Freelance Engineer	Freelance Surveying, Geoinformatics and Transportation Engineer, Technical Office
2015	Intern	Rural and Surveying Engineer Internship, NTUA

Languages

Greek	Native Speaker
English	Excellent (Proficiency of University of Michigan)
French	Good (Delf B1 Diploma)

Technical Skills

Programming Languages	Python, Visual Basic, SQL, C++
Statistical Analysis Software	SPSS, R
Spatial Analysis – GIS Software	ArcGIS, QGIS, GeoDa
Other Software	Microsoft Office Suite, AutoCAD Civil 3D, nanoCAD Pro

Memberships

2023 –	Member of the Hellenic Institute of Transportation Engineers
2018 –	Member of the Hellenic Association of Rural and Surveying Engineers
2018 –	Member of the Technical Chamber of Greece