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Designing the freight transport network of Greece

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To my family

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Abstract

Considering the importance of freight transport in the economy and growth of Greece, this diploma thesis focuses on the design of a new freight transport network for the country. The key aspect of the thesis is to define the transport hubs across the country. Initially, we introduce suitable definitions, methods, and practice of freight transport networks. This includes a review of the existing mathematical models proposed and used for freight transport network design. Subsequently, in order to design the Greek freight transport network, we first set up the underlying full network (nodes and arcs) of both the mainland and island parts of Greece. In the second step, we estimate the freight transport demand and the related transport costs over the full network. Having derived the appropriate data, we apply the most appropriate mathematical model form the literature to the Greek case. The results provide the proposed location of the hubs for various configurations (1 to 8 hubs). The results also indicate considerable reductions in transportation costs as the number of hubs increases. Furthermore, we investigated changes in the transportation cost as a function of the inter-hub transportation discount factor α. Opportunities for further research include the application of a more suitable grouping analysis to define the network origins and destinations, as well as development of a model that will take into account the operational and investment costs related to hubs, as well as suitable capacity constraints. Finally, international transport could be taken into account by setting the gates of the country as nodes of the network and by considering the related flows in the o-d matrix.

Εκτεταμένη Περίληψη

Μια από τις πιο σημαντικές οντότητες του μεταφορικού δικτύου είναι αυτή των εμπορευματικών κόμβων. Ως εμπορευματικούς κόμβους εννοούμε εγκαταστάσεις στις οποίες συγκεντρώνονται οι ροές από πολλαπλές αφετηρίες και διοχετεύονται σε έναν ή πολλαπλούς προορισμούς, μειώνοντας έτσι δραματικά το πλήθος των συνδέσεων. Οι εμπορευματικοί κόμβοι μπορούν να χρησιμοποιηθούν αποκλειστικά και μόνο για μεταφόρτωση χωρίς να παρέχουν αποθήκευση, αλλά μπορούν να διαθέσουν και υπηρεσίες αποθήκευσης, διανομής, συσκευασίας (co-packing), ετικετοποίησης (labeling) και άλλες υπηρεσίες προστιθέμενης αξίας. Η εύρεση της κατάλληλης τοποθεσίας κόμβων στο δίκτυο έχει ιδιαίτερη σημασία στη μείωση του συνολικού κόστους μεταφοράς.

Η ανάπτυξη Πανελλαδικών δικτύων μεταφορών στην πράξη έχει επιτευχθεί μόνο από τις εταιρίες ταχυμεταφορών οι οποίες πραγματοποιούν διανομές περιορισμένου βάρους φορτίων (π.χ. μέχρι 30 kg). Τα Πανελλαδικά αυτά δίκτυα έχουν εμπορευματικούς κόμβους σε 5 - 7 μεγάλες πόλεις της Ελλάδας. Πρακτικές εφαρμογές δικτύων μεταφοράς φορτίων υψηλότερου βάρους περιορίζονται ανάμεσα στις τρεις μεγάλες πόλεις της Ελλάδας την Αθήνα, την Θεσσαλονίκη και την Πάτρα.

Η παρούσα διπλωματική εργασία επικεντρώθηκε στο σχεδιασμό εθνικού δικτύου εμπορευματικών μεταφορών και συγκεκριμένα στη χωροθέτηση των εμπορευματικών κόμβων στον ελλαδικό χώρο. Το πρόβλημα χωροθέτησης στο οποίο βασίστηκε ο σχεδιασμός είναι το p-hub median (Campbell, 1994b). Αποτελεί πρόβλημα εύρεσης της κατάλληλης τοποθεσίας εμπορευματικών κόμβων σε ένα δίκτυο λαμβάνοντας υπόψη τη ζήτηση και το κόστος μεταφοράς μεταξύ των κόμβων.

Για την εφαρμογή του προβλήματος, απαιτείται ο ορισμός του δικτύου, δηλαδή των κόμβων (ομάδες νομών) και των τόξων σύνδεσης των κόμβων αυτών. Δημιουργήσαμε αυτό το δίκτυο που περιλαμβάνει 27 κόμβους τόσο στην Ηπειρωτική όσο και στη Νησιωτική χώρα. Για τα τόξα χρησιμοποιήθηκε το δίκτυο αυτοκινητοδρόμων και αυτό των ακτοπλοϊκών συνδέσεων.

Σημαντική συνεισφορά της παρούσας διπλωματικής εργασίας είναι η εκτίμηση της ζήτησης εμπορευματικών μεταφορών και του κόστους μεταφοράς στο παραπάνω δίκτυο. Η εκτίμηση της ζήτησης βασίστηκε στην περαιτέρω επεξεργασία διαθέσιμων στοιχείων της ΕΛΣΤΑΤ. Τα παρεχόμενα δεδομένα αφορούσαν το βάρος (σε τόνους) μεταφερθέντων προϊόντων μεταξύ των 14 περιφερειών για το έτος 2016. Τα στοιχεία αυτά ανήχθησαν στις 27 ομάδες νομών του δικτύου με βάση ορισμένες παραδοχές. Η εκτίμηση του κόστους βασίστηκε στην εκτίμηση του χρόνου μεταφοράς μεταξύ των κόμβων του δικτύου.

Για τον τελευταίο εξετάστηκαν τρεις περιπτώσεις. Όσον αφορά τις συνδέσεις μεταξύ των κόμβων που βρίσκονται στην ηπειρωτική Ελλάδα, η εύρεση του χρόνου μεταφοράς έγινε με τη χρήση ενός απλού εργαλείου του Υπουργείου Μεταφορών και Υποδομών που παρείχε την απόσταση και μέσω κατάλληλης παραδοχής για την ταχύτητα έγινε η εύρεση του χρόνου μεταφοράς. Όσον αφορά τις συνδέσεις μεταξύ κόμβων που βρίσκονται ο ένας στην ηπειρωτική Ελλάδα και ο άλλος στη νησιωτική, αρχικά έγινε η εκτίμηση του λιμένα που συνδέει κάθε ηπειρωτικό με κάθε νησιωτικό κόμβο. Ο συνολικός χρόνος μεταφοράς προέκυψε από το άθροισμα του χρόνου οδικής μεταφοράς χρησιμοποιώντας (ηπειρωτικός κόμβος-λιμένας σύνδεσης), του χρόνου αναμονής στο λιμένα σύνδεσης και του χρόνου μεταφοράς χρησιμοποιώντας το θαλάσσιο δίκτυο (λιμένας σύνδεσης-νησιωτικός κόμβος). Τέλος όσον αφορά τις συνδέσεις μεταξύ νησιωτικών κόμβων, για εκείνους που εξυπηρετούνται από απευθείας δρομολόγια ο χρόνος μεταφοράς υπολογίστηκε με βάση τον χρόνο μεταφοράς του απευθείας ταξιδιού. Στην περίπτωση απουσίας απευθείας σύνδεσης, ο χρόνος μεταφοράς υπολογίστηκε από το άθροισμα του χρόνου της θαλάσσιας μεταφοράς από τον έναν κόμβο προς τον λιμένα εξυπηρέτησης, το χρόνο της οδικής μεταφοράς από το λιμάνι εξυπηρέτησης σε πιθανό άλλο λιμένα εξυπηρέτησης, τον χρόνο παραμονής στο λιμένα αυτό και το χρόνο της θαλάσσιας μεταφοράς από το δεύτερο λιμένα εξυπηρέτησης στον νησιωτικό κόμβο προορισμού.

Για την επίλυση του προβλήματος p-hub median χρησιμοποιήθηκε το περιβάλλον MatLab. Μετατράπηκε το παραμετροποιημένο μαθηματικό μοντέλο σε κατάλληλο κώδικα και χρησιμοποιήθηκε η συνάρτηση επίλυσης μικτού γραμμικού προγραμματισμού του MatLab. Το πρόβλημα επιλύθηκε για διαφορετικό αριθμό κόμβων (από 1 έως 8 κόμβους). Οι λύσεις παρείχαν τις τοποθεσίες ίδρυσης των εμπορευματικών κόμβων. Όπως αναμένονταν όσο αυξάνεται το πλήθος των κόμβων αυτών, τόσο μειώνεται το μεταφορικό κόστος (τόνοι-ώρες). Επιπλέον ανάλυση ανέδειξε τη σχέση του παράγοντα έκπτωσης α και του μεταφορικού κόστους.

Η εργασία αποτελεί το έναυσμα ενασχόλησης και έρευνας στον τομέα του σχεδιασμού εθνικού δικτύου εμπορευματικών μεταφορών στη χώρα μας. Μελλοντική έρευνα μπορεί να επικεντρωθεί στην εφαρμογή μιας πιο εξειδικευμένης μεθόδου ομαδοποίησης χρησιμοποιώντας 3 διαστάσεις τη γεωγραφική θέση, το ΑΕΠ και τον πληθυσμό καθώς και προηγμένη μέθοδο ομαδοποίησης (clustering) . Επιπρόσθετα, θα είχε σημαντικό ερευνητικό αλλά και πρακτικό ενδιαφέρον να ληφθούν υπόψη οι παράγοντες του κόστους εγκατάστασης και του λειτουργικού κόστους στην επιλογή των εμπορευματικών κόμβων. Επιπλέον, θα μπορούσαν να ληφθούν υπόψη και οι διεθνής μεταφορές στην λήψη αποφάσεων προσθέτοντας τις πύλες της χώρας ως κόμβους του δικτύου και χρησιμοποιώντας τις αντίστοιχες ροές στον πίνακα Προέλευσης-Προορισμού.

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Chapter 1 Introduction

Freight transport contributes decisively to the economic and social enhancement of a country (Γενίτσαρης, 2010). Its importance is evident from its significant contribution to the country's Gross Domestic Product, which is of the order of 6% (Γενίτσαρης, 2010). Freight transport is an activity that constantly evolves based on the development and changes in the market system globally.

Greece ranked 26th in Europe in this area, based on the related infrastructure, services offered and the responsibility to the environment (EUROSTAT, 2016). The dominant mode in our country is road transport 81.3% of all freight transport in terms of tons, followed by marine transport with an 18.5% share, rail transport 0.46% and air transport 0.02% (EEL and UAegean, 2014). The high share of road transport derives from the fact that distances between major cities in Greece are limited, and freight rail is not an ideal mode over such short distances. Regarding road transport and the modes used, the weight of transported goods during 2016 by private trucks was 304.7 million tones, while 105.7 million tones were transported by public usage trucks. (ΕΛΣΤΑΤ, 2018) The total number of private trucks in 2016 was 1.296.328 and of public usage trucks 36.495. (ΕΛΣΤΑΤ, 2017)

Despite the importance of road freight transport for Greece, the design of a national freight transport network has not received the appropriate attention. Only express delivery service companies have designed their own express transport networks. However, for larger loads (e.g. over 30 kg), there is no national freight transport network. The limited private networks that exist comprise line haul routes connecting Athens to Thessaloniki, and Athens to Patras. The rest of the country is served by small local transport companies, each serving one or more local areas.

This diploma thesis focuses on the design of a national freight transport network to be operated by land and sea transport modes. This topic fills a significant gap in current practice and related research. Specifically, the thesis identifies the locations of hub facilities throughout the country, that form the nodes of this national transport network.

The rest of the thesis is organized as follows: In Chapter 2 we review the related literature on freight transport networks, present the fundamental problems of hub location and select the most suitable model for our work. In Chapter 3 we develop the architecture of the freight transport network and estimate the parameters of the problem. In Chapter 4 The selected optimization model, fully parametrized, is solved as well as the results are presented. Finally, the conclusions of this thesis are summarized and proposals for future research are presented in Chapter 5.

Chapter 2 Background of freight transport network design

An increasing number of companies are realizing that supply chain can be used as a strategic weapon (Watson *et al.*, 2012). Taking this into account, they invest heavily into the improvement of their supply chains including into developing efficient sustainable supply chain networks, thus gaining an advantage over their competitors.

A physical supply chain consists of suppliers, plants, warehouses, distribution centers and retail outlets. All these entities are connected through the links of the supply chain network, the design of which is essential for successful operations.

> *"Supply chain network design (SCND) is the practice of locating and rationalizing the facilities within the supply chain, determining the capacity of these facilities, determining how to source demand through the network and selecting modes of transportation in a manner that provides the required level of customer service at the lowest cost."* (Spinnaker, 2001)

Thus, companies strive to determine the number and the location of their plants and/or warehouses and distribution centers in order to reach and serve their customers at the right time, with the right items and quantities, at the lowest possible cost. In addition to facility location, decisions to be made include the size/capacity of each facility, and supplier selection. The core issues in designing a supply chain network are cost, service level, and sustainability. System-wide costs include production and purchasing cost, inventory holding cost and transportation cost (Watson *et al.*, 2012). It is claimed that 80% of supply chain cost is predetermined by the design of the product and the supply chain network (Watson *et al.*, 2012). Thus, it is evident that a well-structured supply chain network provides significant advantage.

A critical part of the supply chain network concern its hubs that support the transfer of goods between the various entities of the chain. The hub concept is based on the principle of reducing the number of links between m origins and n destinations from mxn to $m + n$. In the hub concept (Figure 2.1), loads from several suppliers are transported to the origin hub, and they are reloaded to the line haul transportation service that connects the origin and the destination hubs. At the destination hub the loads are transferred to distribution vehicles to reach the end clients (last mile service). Note that the flows may be reversed from the hub at the bottom of the Figure to the hub at the top, or mixed.

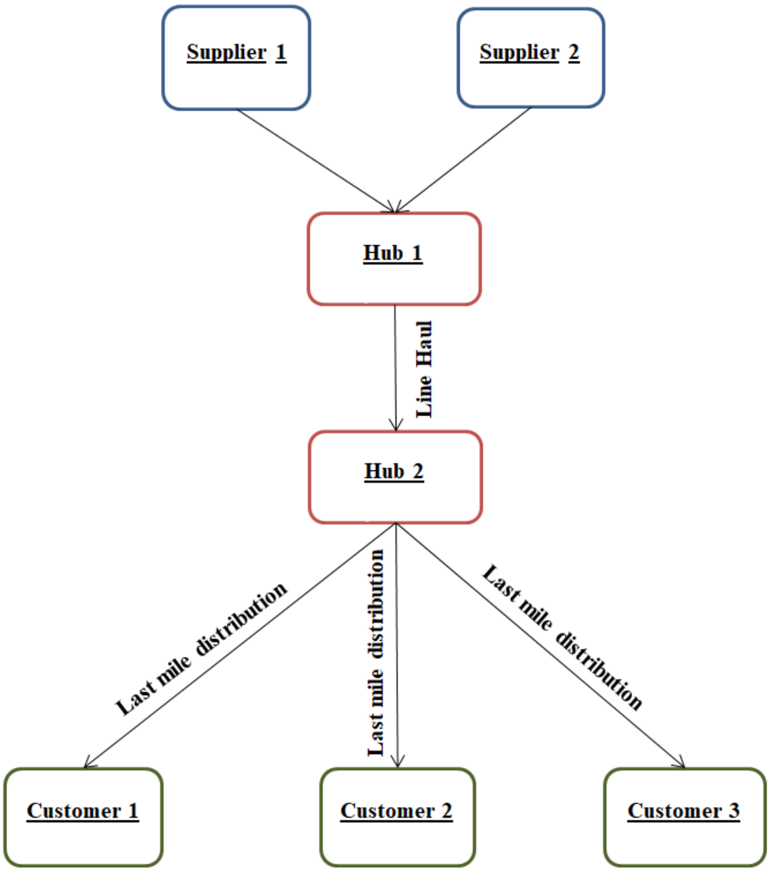

Figure 2.1 Hubs in supply chain

In national transport, hubs are trans-shipment facilities with very limited storage capacity, equipped with loading/unloading resources between the line haul and the last mile services. In international transport, hubs are called logistics platforms. They facilitate the transfer between different transport modes (e.g. truck-rail, ship-rail, truck-ship, etc.) and may include significant container or unit load storage facilities (e.g. container yards, or warehouses, respectively), as well as other facilities.

In logistics platforms, different kinds of services may be provided, including a) logistics services such as intermodal transport, distribution, warehousing and b) value added services such as assembly, co-packing, labeling and post manufacturing (Essadi *et al*, 2016; Botha, 2008). Additionally, Logistics Service Providers may share the hub assets between them, in the context of a collaborative framework of operation.

More formally, in the bibliography there are five (5) types of logistics hubs (dos Santos Vieira *et al*, 2016):

- Transport logistics hubs. Hubs without substantial storage facilities which are mainly used for trans-shipment. The may be used by multiple customers. Typical examples include facilities of transport and/or forwarding companies, seaports and airports. (Huber *et al.*, 2015)
- Distribution hubs/centers. They are the links between manufacturers and the final customers of the supply chain (dos Santos Vieira *et al*, 2016). Main activities include storage, delivery, packing, consolidation, and value adding services (Huber *et al.*, 2015). They can be used by large manufacturers or retailers, and by Third Party Logistics Providers (3PL). In this type we can identify urban hubs, mainly located outside metropolitan areas aiming to achieve better distribution and to ease traffic as well as parking requirements through consolidation/deconsolidation of shipments (dos Santos Vieira *et al*, 2016; Watson *et al.*, 2012).
- Industrial hubs. They manage flows of materials between different levels of manufacturing. They are distinguished into commodities industrial hubs and manufactured goods industrial hubs. For example, materials coming from one level of manufacturing (e.g. a factory) are stored in an industrial hub and from there they are transported to the next level of manufacturing (e.g. another factory). (Trappey *et al.*, 2011; dos Santos Vieira *et al*, 2016)
- Port hubs. Mostly used for international trade. For example, in a port hub containers may be unloaded from a large liner ship and transferred to short sea shipping vessels. Also, freight may be unloaded from ships and transferred to land transport modes (rail or truck).
- Reverse hubs. Are facilities that support all the activities related to the materials coming from reverse flows. Those activities may include the conservation, remanufacturing, recycling and redistribution of the materials. (dos Santos Vieira *et al*, 2016 ; Ellen McArthur Foundation, 2013).

Hubs are critical in a supply chain network, since they contribute significantly to cost reduction and improvement of responsiveness. (Qingguang & Jingxian, 2010) Also, in hubs various stakeholders may share infrastructure, facilities, equipment and information, thus achieving economies of scale, efficiencies, win-win collaboration and gaining considerable competitive advantages.

The current thesis focuses on transport logistic hubs (the first type in the above list), and in particular on the location of the hubs in a transportation network. The case studied is a national transport network that serves Greece, both the mainland and the islands.

2.1 Fundamental problems of freight transport network design

The decision on hub location is a strategic one and should consider both quantitative (e.g. performance indices) and qualitative (e.g. city/region's land attractiveness) criteria (Essadi *et al*, 2016). The idea behind the hub location problem is to identify the most appropriate hub locations to process freight flows along their route from the origin to the destination (O-D). The consolidation of flows that will occur in those hubs can reduce transportation cost by exploiting economies of scale and allowing the origin-destination pairs to be linked with considerably fewer links. In these problems, origin and destination are designated by i and j respectively. There are three types of O-D trips. Direct trips (not via hubs), trips through one hub and trips through two or more hubs. (Campbell, 1994b)

A small example to understand the concept behind the hub location problem is presented in Figure 2.2, which shows the transportation cost from two origins to the same destination using different path scenarios. The O-D pairs, could use (a) direct trip ,(b) one hub trip (Origin 1-h2-Destinaton, Origin 2-h2-Destination) and (c) two hub trips (Origin 1-h1-h2-Destination, Origin 2-h1-h2-Destination). The numbers on the arcs are the costs of transport between the O-D pairs. From this figure, it is evident that the consolidation of flows in the hubs reduces the transportation cost and links between the O-D pairs. Specifically, the cost of option (a) is 1020, the cost of option (b) is 820 and the cost of option (c) is 570.

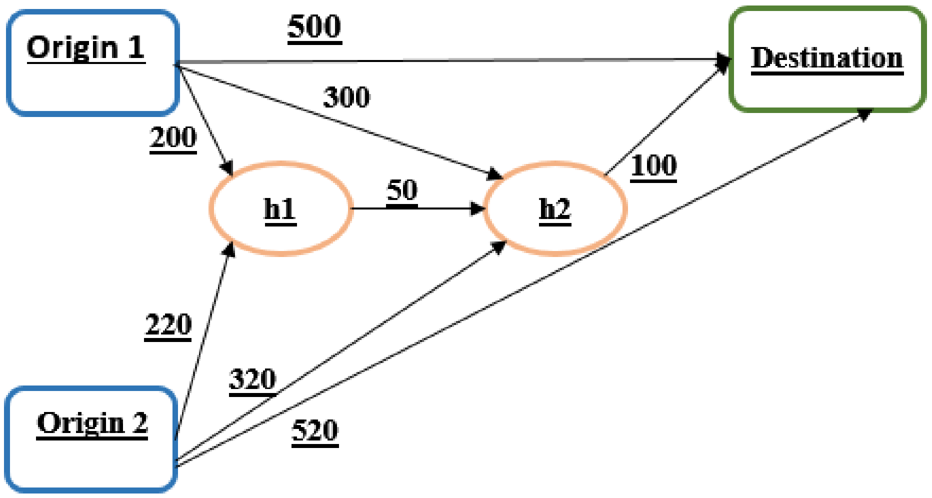

Figure 2.2 Hub location problem

The transportation hub location problem has been actively researched for over 25 years. The leading researchers of the hub location problem (Campbell 1994b; O' Kelly 1986) were inspired by the p-median problem which was introduced by Hakimi in 1965. Specifically (Campbell 1994b) proposed the four fundamental hub location problems: the p-hub median problem, the uncapacitated hub facility location problem, the p-hub center problem and the hub covering problem. In those problems a non-negative flow is associated with every O-D pair and an attribute such as distance, time or cost is associated with the movement (Campbell, 1994b).

2.1.1 The p-hub median problem

The p-hub median problem bears similarities to the p-median problem (Hakimi, 1965). In the former problem the location of p hubs must be identified given that the number (p) of the hubs is known, direct O-D flows are not permitted and the O-D pairs visit two hubs at most. The objective of the p-hub median problem is to minimize the total cost of transport (Campbell, 1994b, Farhani *et al.*, 2013).

In this problem i and j stand for the origins and destinations respectively and belong to a set $A \in \{1, \dots, n\}$, where n is the number of the demand locations (origin/destination). Also k, m are indices used for the potential hub locations, that belong to a set $B \in \{1, \dots, r\}$, where r is the number of the possible hub locations.

The problem is formulated as follows:

Minimize $$\sum_i \sum_j \sum_k \sum_m W_{ij} X_{ijkm} C_{ijkm} \quad (2.1)$$

Subject to,

$$\sum_k Y_k = p \quad (2.2)$$

$$Y_k \in \{0, 1\}, \forall k \quad (2.3)$$

$$0 \leq X_{ijkm} \leq 1, \forall i, j, k, m \quad (2.4)$$

$$\sum_k \sum_m X_{ijkm} = 1, \forall i, j \quad (2.5)$$

$$X_{ijkm} \leq Y_k, \forall i, j, k, m \quad (2.6)$$

$$X_{ijkm} \leq Y_m, \forall i, j, k, m \quad (2.7)$$

Where,

W_{ij} is the flow from i to j (e.g. demand).

c_{ij} is the standard cost per unit from i to j (e.g. distance, time).

C_{ijkm} is the cost per unit from i to j via hubs k and m in that order.

$$C_{ijkm} = c_{ik} + a\, c_{km} + c_{mj}$$

α is the hub-to-hub discount factor which ranges between 0 and 1. Factor α reduces the transportation cost due to the economies of scale achieved through consolidation of loads and improved truck loading. Thus, $a < 1$, .and the appropriate value should be set through relevant measurements and experience.

X_{ijkm} is the decision variable that represents the fraction of flow from i to j that is routed through k and m.

Y_k is a variable that takes the value of 1 if location k is a hub and the value of 0 otherwise.

The objective function minimizes the total transportation cost of O-D pairs. Equation 2.2 establishes exactly p hubs, the number p is given exogenously. Equations 2.3 confine Y_k to be zero or one. That is, each candidate location may include one of the p hubs or not. Equations 2.4 set the range of X_{ijkm} to be between zero and one. Equation 2.5 ensures that the entire flow will be directed from i to j through some hub pairs. Equation 2.6 – Equation 2.7ensure that all flows go through hubs; the demand from origin i to destination j cannot be allocated to a hub pair (k, m) unless k and m are selected as hub facilities.

This problem is of high complexity, since the number of decision variables X_{ijkm} can be very large with increasing number of nodes in the hub network (Farahani *et al*, 2013). Furthermore, the problem does not consider direct routes from origin i to destination j which may be advantageous.

2.1.2 The uncapacitated hub location problem

The objective of this problem is to minimize the transportation cost identically to the p-hub median problem. The main difference is that in this problem the number of hubs is not specified and a non-negative fixed cost is associated with each potential hub location (Campbell, 1994b; Farahani *et al.*, 2013) .

The problem is formulated as follows:

Minimize
$$\sum_i \sum_j \sum_k \sum_m W_{ij} X_{ijkm} C_{ijkm} + \sum_k F_k Y_k \qquad (2.8)$$

Subject to,

$$Y_k \in \{0, 1\} \, , \forall k \qquad (2.9)$$

$$0 \leq X_{ijkm} \leq 1, \forall\, i,j,k,m \tag{2.10}$$

$$\sum_{k}\sum_{m} X_{ijkm} = 1\,, \forall\, i,j \tag{2.11}$$

$$X_{ijkm} \leq Y_{k}\,, \forall i,j,k,m \tag{2.12}$$

$$X_{ijkm} \leq Y_{m}, \forall i,j,k,m \tag{2.13}$$

Where,

F_k is the fixed cost to establish a new facility at location k

The objective function (2.8) aims to minimize the cost of transport considering that the establishment of a hub is associated with a non-negative fixed cost. Moreover, constraints (2.9-2.13) are identical to constraints (2.3-2.7) of the p-hub median problem.

2.1.3 The p-hub center problem

This problem is similar to the p-hub median problem. The difference is the Mini-Max form of the objective function. Center problems are used for locating emergency service facilities. Additionally, this type of location problem is useful for perishable or time sensitive items, since it considers the worst case scenario of maximum travel times (Campbell, 1994b; Farahani *et al.*, 2013) .

In this problem cost C_{ijkm} refers to time, α is a time discount factor due to higher speed on the inter hub links. The location of the p hubs is found based on the fact that the maximum costs for any origin-destination pair need to minimized.

The problem is formulated as follows:

Minimize $$maximum_{i,j,k,m}\{X_{ijkm}C_{ijkm}\} \tag{2.14}$$

Subject to,

$$\sum_{k} Y_k = p \tag{2.15}$$

$$Y_k \quad \in \{0, 1\} \; \forall \; k \tag{2.16}$$

$$X_{ijkm} \; \in \{0,1\} \; \forall \; i, j, k, m \tag{2.17}$$

$$\sum_{k} \sum_{m} X_{ijkm} = 1 \, , \forall \; i, j \tag{2.18}$$

$$X_{ijkm} \; \leq Y_{k} \, , \forall i, j, k, m \tag{2.19}$$

$$X_{ijkm} \leq Y_m, \forall i, j, k, m \tag{2.20}$$

The formulation of this problem is almost identical to the p-hub median problem except for constraint (Equation 2.17) that restricts X_{ijkm} to be zero or one; this means that the entire flow of X_{ijkm} will go through hubs k and m. Also, the number of hubs is not prespecified.

2.1.4 Hub covering problem

In this problem a demand location can only be served by a hub that is close enough to it. For this purpose, the cost of transportation C_{ijkm} , the cost from i to j via hubs k and m , must be less or equal to a certain value γ. The latter is the maximum cost for covering links connecting the demand nodes. C_{ijkm} and γ are given as inputs in the problem.

$$C_{ijkm} \leq \gamma_{ij} \tag{2.21}$$

Through (Equation 2.21) a new variable V is defined. V_{ijkm} is 1 if hubs k and m serve the O-D pair (Equation 2.21), and 0 otherwise (Campbell,1994b; Farahani *et al.*, 2013) .

The problem is formulated as follows:

Minimize
$$\sum_{k} F_k Y_k \tag{2.22}$$

Subject to,

$$Y_k \quad \in \{0, 1\} \forall k \tag{2.23}$$

$$X_{ijkm} \leq Y_k, \forall i, j, k, m \quad (2.24$$

$$X_{ijkm} \leq Y_m, \forall i, j, k, m \tag{2.25}$$

$$\sum_{k} \sum_{m} V_{ijkm} X_{ijkm} \geq 1, \forall i, j \tag{2.26}$$

With constraints similar to the other problems, the objective function (Equation 2.22) aims to minimize the total cost of establishing a new hub facility. Equation 2.23 - Equation 2.25 are similar to Equation 2.3 and Equation 2.6-2.7 of the p-hub median problem. Equation 2.26 ensures that each demand pair is covered at least one time by a hub pair (Campbell, 1994b; Farahani *et al.*, 2013).

All aforementioned problems can be applied in real case scenarios, and they can cover many domains, such the airport industry, and land transportation systems (Farahani *et al.*, 2013) .

2.2 Applications of freight transport network design

For many years research has focused on passenger transportation design and modelling. Freight transport modelling is a recent development. The main motivation behind these recent trends includes development of policies for freight innovation in Europe and the US (Tavasszy, 2006).

Of particular interest is the design and development of a freight transport network, which may significantly affect economic growth, create wealth and jobs, and enhance trade and geographical accessibility (Kallas, 2011). The development of an efficient freight transport network will affect the logistics performance of an area, region or country (Essadi, 2016). Moreover, having a well-structured network (a) quicker response is attained, (b) costs are reduced, (c) environmental footprint is reduced and (d) traffic is streamlined (Tavasszy, 2006).

As a result, many models of freight transport were created in Europe, the US and globally. All these freight transport network models overviewed in Sections 2.2.1 and 2.2.2 are based on the 4 steps and the 5 layer process.

- The four step model comprises two sets of two steps each. The first set concerns the commodities generation and consumption, as well as the formation of the from-to flow matrices. The second set involves modal choices and the assignment of flows in the network. (McNally, 2007; Tavasszy 2012).
- The five layers process, estimates the choices in a framework of layers. Those are: Production and consumption, Trade (Sales and Sourcing), Logistics services, Transportation services, and Network and routing (Tavasszy, 2006). At the production and consumption layer, choices about facility location, trip generation and consumption patterns are made. At the layers of Trade and Logistics services, inventory location choices are made. At the last two layers, choices about mode and the route are made respectively.

2.2.1 International Applications of freight transport network design

As already mentioned in the introduction of this chapter there is a significant work conducted in freight transport modelling applications. In this section, we review characteristic examples of national freight model systems, such as the Swedish SAMGODS, the Norwegian NEMO, the Dutch SMILE, the SLAM which is part of the

European model SCENES, the British EUNET, the Los Angeles LAMTA and the Dutch Goodtrip (Huber *et al.*, 2015).

SAMGODS AND NEMO (Network Model for Freight Transport)

In 2001 Sweden and Norway recognized the need to strengthen their national freight transport systems. To do so they decided to consider logistics-related decisions, which till then were not taken into account in strategic transport models. With that trigger, a new freight model was created, called SAMGODS (de Jong, 2005).

SAMGODS is a Swedish national freight model which is used for national short and long term analysis and simulation of goods transport as well as for macroscopic scale analysis. It forecasts all possible supply chain scenarios and transport policies, considering developments in economy and trade (Huber *et al.*, 2015; de Jong, 2016).

This model is based on a several sub-models and its structure can be described as ADA model system (Aggregate-Disaggregate-Aggregate). The aggregation level consists of data representing production and consumption (PC) flows. The disaggregation level involves decisions that need to be made in order to select the shipment size and the mode choice (de Jong, 2016). The objective of the model is to minimize the total transportation cost.

The general idea of the model is to determinate the flows of transported goods between the production (P) and consumption (C) locations. Those flows may concern goods for final consumption or goods for intermediate consumption. The required data were given by the Commodity Flow Survey (CFS) which took place in 2001 and 2004/2005 (de Jong, 2016); in the survey results, the flows were all measured in tones and Swedish crowns (SEK) by commodity type.

Based on the PC input, the O-D matrix of flows is generated, in order to be used for network assignment. This is performed in three steps (de Jong, 2016).

1. The first step consists of disaggregating the data and allocating flows to firms at the P and C end.
2. The second step consists of modeling logistics decisions made by the firms such as location of the sender and the receiver, location of the ports, airports, railway

road and consolidation centers, use of consolidations and distribution centers, modes that are used, type of vehicle and shipment size (de Jong,2016).

3. The third step aggregates the shipment to O-D flows and routes of vehicles in order to be assigned to the network.

In the third step of the network assignment, the model determines which flows are covered by direct road transport, ports, airports, and railway terminals or via logistics hubs (Huber *et al.*, 2015). In this model, logistic hubs are defined as locations of transshipment and storage. To determinate the modes and vehicle types, the model uses three sub-programs. The first one, called BuildChain, determinates the available transport chain and the selection of the optimum transfer points within road, rail and sea transport (de Jong, 2016). The second sub-program, called ChainChoice, is used for optimizing the transport chain (e.g. best route, lowest possible cost coming from (a) cost for loading/unloading process at the sender/receiver, (b) cost for transport and inventory management, (c) corresponding cost by using logistics hubs). The third and final sub-program, called EXTRACT, can aggregate to O-D flows and produce the logistics costs at PC level taking into account the O-D chain pattern (Huber *et al.*, 2015; de Jong, 2016).

As mentioned, the objective is to minimize of the overall cost. Doing that, one of the logistics decisions is to determine the transport chain and chain legs. In Figure 2.3 a representation of a transport chain is provided indicating four options. The first concerns the direct transport (Route 1), the second is via one hub (Routes 2) and the third option is through two hubs (Route 3).

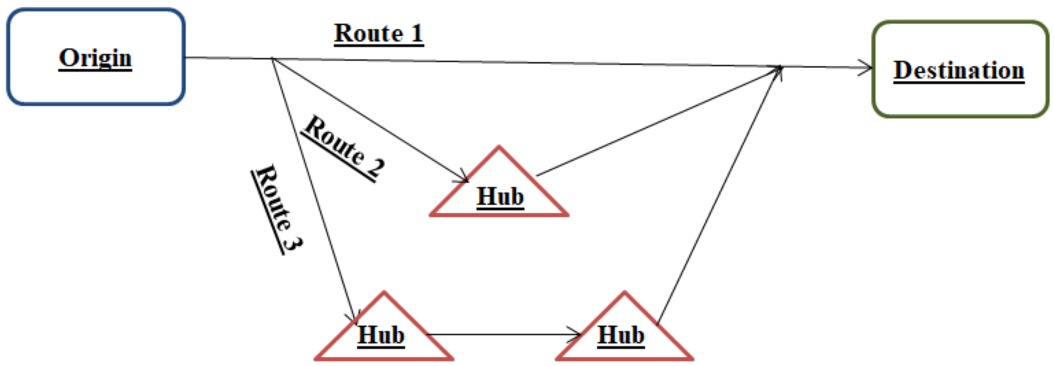

Figure 2.3 Representation of Hubs in SAMGODS and NEMO network models (from Huber *et al*., 2015)

Dutch SMILE (Strategic Model for Integrated Logistic Evaluation)

SMILE was developed during the period 1991-1997 as a joint effort of the Transport Research Centre of the Ministry of Transport and the research organizations NEI (Netherlands Economic Institute) and TNO (Toegepast Natuurwetenschappelijk Onderzoek). It was one of the first models which consider logistical aspects into decision making. Input data used to generate the O-D pairs were found through a clustering process of products based on some characteristics such as value of goods, shipment size etc. (Hober *et al*, 2015; Lorant *et al*, 1998.) For each O-D pair, the locations of hubs facilities are determined. Those decisions are based on lead time, if the hubs are close to activity centers, the overall logistics costs and the availability of modes of transport. (Lorant *et al*, 1998). SMILE distinguishes 5 types of logistics chains Figure 2.4, (a) direct shipment from origin to destination, (b) a chain which consists of the origin and the destination as well a Regional Distribution Center (RDC) for storage or transshipment, (c) similar to chain (b) but the facility is a European Distribution Center (EDC), (d) and (e) are chains that consist of the origin and destination and two facilities (Davydenko, 2015).

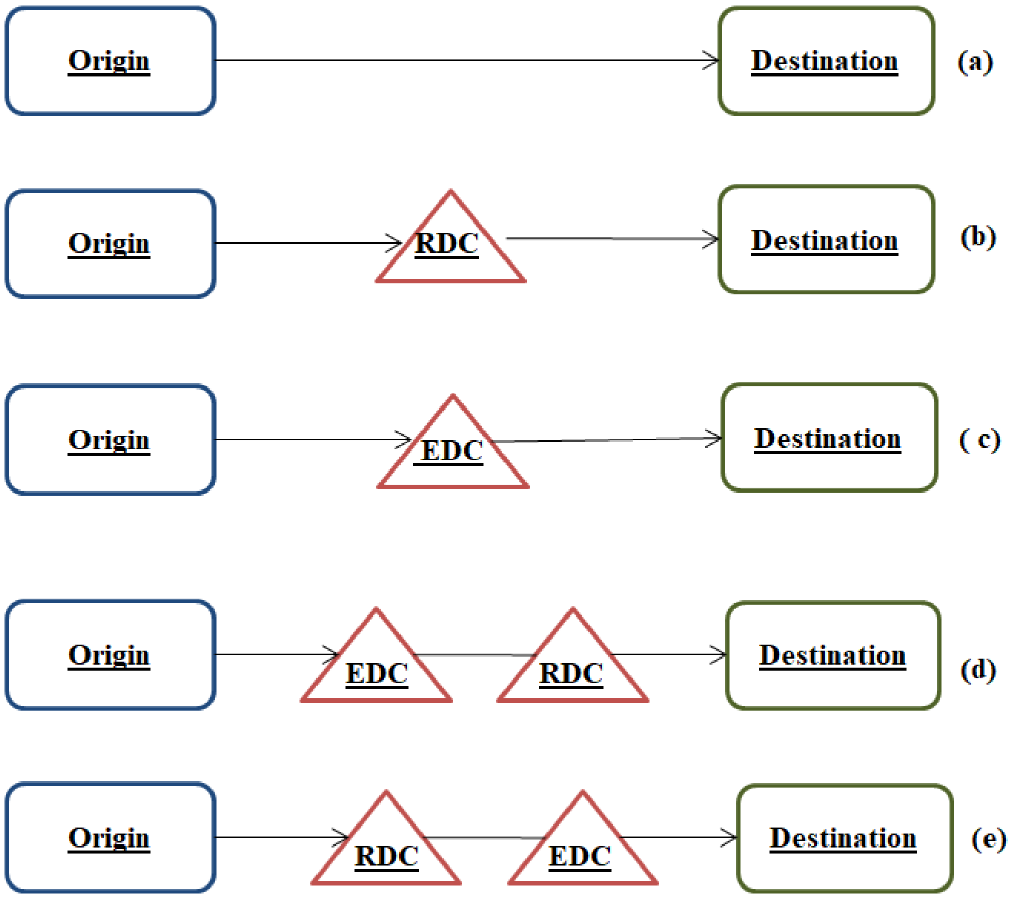

Figure 2.4 The logistics chains in SMILE freight transport model (from Davydenko, 2015).

Spatial Logistic Appended Module (SLAM)

SLAM is part of the European Model SCENES, which is a trans-boundary macroscopic model for the EU (Hober *et al.*, 2015). Major application is the location of distribution centers in Europe. This model receives production and consumption flows (e.g. from SCENES) and generates origin - destination matrices; in those matrices distribution centers are embedded (Hober *et al.*, 2015). That procedure consists of three stages. At the first stage with the help of the PC pair, the locations of distribution centers are selected per region based on economic activity, centrality and accessibility to infrastructures networks (Combes and Leurent, 2007). The second stage is to determinate if the flows will travel through zero, one or two distribution centers based on transport cost (arc cost), inventory cost (uncertainly of the demand) and logistics cost (handling) (Combes and Leurent, 2007). Finally the third stage is to assign the PC pair volume to the chains based on the most attractive regions for distribution centers and logistics chains via these centers (Combes and Leurent, 2007; Hober *et al.*, 2015).

BRITISH EUNET

This is a regional freight transport model of UK. It provides the interrelationship between the growth of freight and economic activity (Hober *et al*, 2015). It covers both national and international supply chains and transportation activities of the UK (Williams, 2003).

Similar to the other models, EUNET uses PC-matrices and O-D matrices. However, it lacked the appropriate survey data in order to create the PC matrices and for that reason it categorized the data with a different formulation. The latter consisted of 5 categories based on the origin of goods (e.g. domestic, imported and exported) and by whom they are consumed (e.g. households, industries and other countries) (Williams, 2003) .

The designed network can be a simple production-consumption logistic chain or more complicated with several numbers of depots and multiple hubs (e.g. primary consolidation center, regional distribution center, local warehouses, major ports etc.) (Williams, 2003).

The logistics hubs are included in the O-D matrices (e.g. flows from Production to depot, Depot to hub and hub to consumption are included in OD matrix).

Despite the complexity of this model, the forecast it provides helps to encounter any changes in transport and economy. Figure 2.4 presents how logistics chain and hubs are represented in this model (Hober *et al.*, 2015).

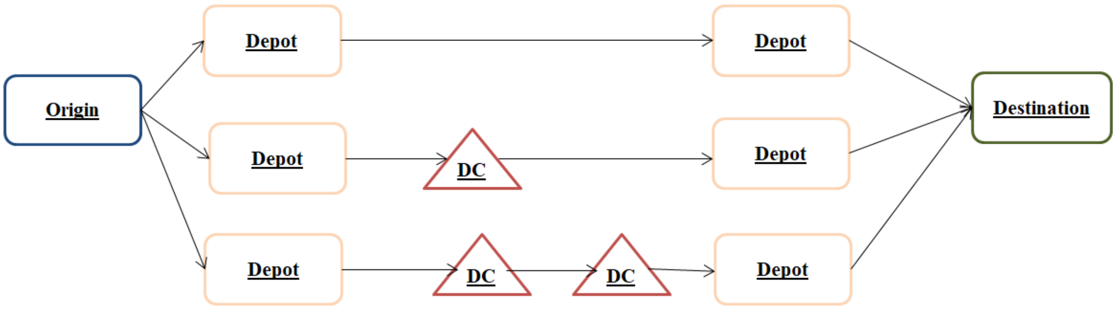

Figure 2.4 Representation of logistic chains and hubs in BRITISH EUNET network model (from Hober *et al.*, 2015)

Los Angeles Freight Forecasting Model (LAMTA)

It is an offshoot of the Los Angeles Metropolitan Area (LAMA) transport model, (Snoble, 2003) mainly focusing on road freight transport and urban transport. LAMTA is a multimodal transport demand model that supports transportation decisions and network design with applications in Los Angeles (Hober *et al.*, 2015).

Like the other models, LAMTA tries to convert the PC flow pairs into O-D flow pairs. Moreover, it uses a specific module that aims at modelling logistics hubs, called Transport Logistics Node Model (TLN). With the help of TLN, logistics facilities can be used at the modelling process and it applies only to long distance freight transport inside or outside LAMA (Hober *et al.*, 2015).

The TLN module is based on two parts. In the first part, the hubs must be characterized by the TLN module (distribution or transport). In the second part, O-D matrices are provided into the TLN, in order to produce separate matrices of different transport modes and commodities. The matrices that are generated are then distinguished into two types related to transport mode and two types related to for commodities. The two transport types examine whether the commodity flows come through a TLN (i.e. if there is a direct transport or not). The first commodity flows examine those that are transported over long distances using three types of transport modes (trucks, rail or ship). The shipments that pass through hubs are estimated based on the product and the direction (inbound and outbound) (Hober *et al.*, 2015). The second type of commodity flow concerns short-distance transport, which is performed by trucks. The final outputs are matrices for all the transport mode and commodity. They main objective of this model is also to minimize the total transportation cost. (Hober *et al.*, 2015)

GOODTRIP

Goodtrip applied in Groningen of Netherlands is an urban freight transport model. It is based on consumer demand and considers the connection of activities between consumers and different kind of suppliers (supermarkets, manufacturers) (Hober *et al.*, 2015). Organization activities, freight flows, transportation and infrastructure are the four components of the model and determine the volume of goods for each chosen zone in the city (Hober *et al.*, 2015). Based on this information an O-D matrix is created as well as the trips on the network. The logistics hubs in that model are defined as loading facilities. This model is suitable for urban transport (Hober *et al.*, 2015).

2.2.2 Freight transport network design in Greece

Although the infrastructure and services of freight transport are critical in the Greek supply chain and contribute significantly to the economy, productivity and competitiveness of Greece, freight transport network design has not attracted the appropriate attention.

Freight transport networks have been designed in Greece by express delivery companies in order to ship their express letters and parcels efficiently and on time. No relevant publications refer to these applications, but it is known that express delivery companies use typically 7 hubs located in Athens, Thessaloniki, Patras, Heraklion, Korinthos, Kozani, Kavala and Larisa. In addition to these actual network implementations, research has been conducted for the design of networks for both international and national freight transport.

Tsekeris' research work (Tsekeris, 2016) analyzed the significance and developments of freight transport in Greece. Moreover, Tsekeris investigated the case of establishing Greece as an international logistics centre, with the help of a supportive freight transport network. During this process, he had to take into consideration factors such as the geographical location, the location of industrial infrastructures, the interregional, regional and international flows and the topology and service of the principal axes of Greece (Tsekeris, 2016). In order to estimate the total number of logistics centers in

Greece, the origin-destination flows for every prefecture of Greece was used together with a cluster analysis, which assembled the prefectures into single trade areas. The number of single trade areas, is the number of the logistics centers. Consequently, the placement of the logistics centers into the single trade areas were selected based on the factors bellow (Tsekeris, 2016):

- The centrality of the prefectures of the clusters. In that process, the centroid origin and destination points were defined as the prefectures' capital cities. There are five types of centralities, and were used to analyze the importance of a prefecture as a node in the network. The centrality study analyzed the importance of a prefecture based on the connections (weighted based on transferred flows and distances), between the said prefectures and the other prefectures. If a prefecture has a high value of centrality, then it is more likely to become a hub. This analysis is done for every prefecture of each single trade areas. (Tsekeris, 2016)

- The population of an urban centre in every single trade area, since it is more likely for a hub to be located in or near an urban centre.

- The volume of freight goods that are transported between prefectures of the single trade areas

- The connectivity of the prefectures in the single trade areas with international networks (e.g. Eastern Mediterranean, trans-European Network, European and Eurasian corridors)

- The current sea and road infrastructure

- The outlook of growth of intermodal transport in every prefecture.

Based on the above, twelve single trade areas and logistics hubs were created. The network that serves these nodes is the current road network of Greece (PATHE, Ionia Road etc.), and the marine network. As far as the transport modes are concerned, these are commercial trucks, the upgraded railway, and ships (Tsekeris, 2016). These hubs will not only be used for international trade but also to support the flows of goods transported within Greece. The resulting logistics hubs are the following: (Tsekeris, 2016)

- Thriaso Pedio in trade area of Attiki and Aegean Islands.

- Thessaloniki in Central Macedonia.
- Patras in trade area of Achaia, Elia and Messenia.
- Igoumenitsa in Epirus. Kavala or Alexandroupoli in Eastern Macedonia and Thrace. Volos in Thessaly.
- Heraklion in Heraklion and Lasithi.
- Astakos in single trade area of Aetolia-Acarnania and Evrytania.
- Industrial zone of Boeotia.
- Kozani, in single trade area of Western Macedonia.
- Tripoli in Peloponnese
- Chania in single trade area of Chania and Rethymno.

In addition to the above, there has been actual implementations of urban distribution centres by companies in order to smooth the traffic of their freight flows. Such distribution centers perform consolidation, separation and storage of freight coming from producers, as well as distribution at points of sale, such as retail stores inside the urban area. Large retailers (e.g. Vassilopoulos) try to locate their distribution centers outside large city centres (e.g. Athens or Thessaloniki) in order to serve their numerous points of sale not only in time but also efficiently.

2.3 Objective and contribution of the thesis

Based on the above, it is obvious that freight transport networks are crucial for the economy and the competitiveness of a country. Considering all processes and actions Greece has taken until now, there is a lot of space for improvement. The objective of this thesis is the design of a freight transport network in Greece through the p-hub median problem formulation (Campbell, 1994b).

The contributions of the thesis include systematic data collection on freight flows in Greece has gathered. Moreover, based on those data and some assumptions, we were able to create reasonable Origin-Destination matrices for the under study network. Lastly, we applied the p-hub median problem formulation to define the hub locations and tested the performance of various configurations resulting from the model.

Chapter 3 Estimation of key aspects of the freight transport network

In this Chapter we identify the nodes and the related transportation connections (i.e. arcs) of the network under study. These nodes and arcs form critical input for the optimization process that is described in detail in Chapter 4. More specifically, Section 3.1 focuses on establishing the nodes that are the possible hub locations of the Greek freight transport network. Section 3.2 defines the relative connections among the aforementioned nodes. Section 3.3 defines the key parameters of the problem (time/cost and transport demand).

3.1 Identification of the nodes of the freight transport network

Greece consists of 13 regions that are the country's first-level administrative entities. Each of these regions comprises second-level administrative entities that are called prefectures, 51 in total. Regions and prefectures relate to both the mainland and island part of Greece. Table 3.1 presents the 13 regions, the corresponding capital cities and the prefectures comprising each region. Figure 3.1 identifies these regions in the map of Greece. Table 3.2 presents the 51 prefectures and the corresponding capital cities and Figure 3.2 shows them on the map.

Table 3.1 The 13 regions of Greece

Region	Capital City	Prefectures
Attica	Athens	Attica
Central Greece	Lamia	Boeotia, Euboea, Evrytania, Phthiotis, Phocis
Central Macedonia	Thessaloniki	Imathia, Thessaloniki, Kilkis Pella, Pieria, Serres, Khalkidhiki
Crete	Heraklion	Heraklion, Lasithi, Rethymno, Chania
Eastern Macedonia and Thrace	Komotini	Evros, Xanthi, Drama, Rhodope, Kavala, Thasos
Epirus	Ioannina	Arta, Preveza, Thesprotia, Ioannina
Ionian Islands	Corfu	Zakynthos, Corfu (Kerkira), Cephalonia/Ithaca, Lefkada
North Aegean	Mytilene	Lesbos/Lemnos, Samos/Ikaria, Chios
Peloponnese	Tripoli	Argolis, Arcadia, Corinthia, Laconia, Messenia
South Aegean	Ermoupoli	Cyclades, Dodecanese
Thessaly	Larissa	Karditsa, Trikala, Larissa, Magnesia
Western Greece	Patras	Aetolia-Acarnania, Achaea, Elis
Western Macedonia	Kozani	Grevena, Kozani, Kastoria, Florina

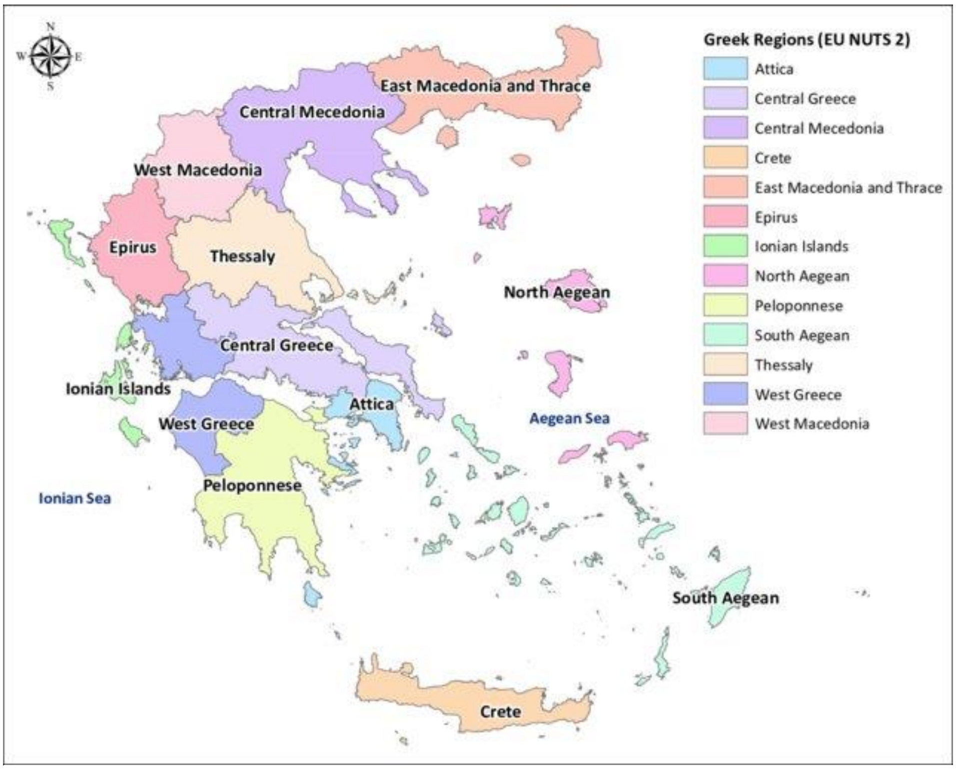

Figure 3.1 Regions of Greece (Source: Research Gate, 2011)

Table 3.2 The 51 prefectures of Greece

Prefecture	Capital City	Prefecture Name	Capital City
Evros	Alexandroupoli	Achaea	Patras
Xanthi	Xanthi	Elis	Pyrgos
Drama	Drama	Boetia	Livadeia
Rhodope	Komotini	Euboea	Chalcis

Prefecture	Capital City	Prefecture Name	Capital City
Kavala, Thasos	Kavala	Evrytania	Karpenisi
Imathia	Veroia	Phthiotis	Lamia
Thessaloniki	Thessaloniki	Phocis	Amfissa
Kilkis	Kilkis	Argolis	Nafplio
Pella	Edessa	Arcadia	Tripoli
Pieria	Katerini	Corinthia	Corinth
Serres	Serres	Laconia	Sparta
Khalkidhiki	Polygyros	Messenia	Kalamata
Grevena	Grevena	Attica	Athens
Kozani	Kozani	Lesbos/Lemnos	Mytilene
Kastoria	Kastoria	Samos/Ikaria	Vathy
Florina	Florina	Chios	Chios
Arta	Arta	Dodecanese	Rhodes
Preveza	Preveza	Cyclades	Ermoupoli
Thesprotia	Igoumenitsa	Heraklion	Heraklion
Ioannina	Ioannina	Lasithi	Agios Nikolaos
Karditsa	Karditsa	Rethymno	Rethymno
Trikala	Trikala	Chania	Chania
Larissa	Larissa		
Magnesia	Volos		
Zakynthos	Zakynthos		
Corfu (Kerkyra)	Corfu (Kerkyra)		
Cephalonia/Ithaca	Argostoli		
Lefkada	Lefkada		
Aetolia-Acarnania	Messolonghi		

Figure 3.2 The 51 prefectures of Greece (Source: NOMAD, 2018)

The nodes of the freight transport network may be located either at the regions' capital cities or the prefectures' capital cities. Obviously the latter choice enhances the network granularity. However, in the p-hub median problem, as the number of nodes increases the complexity of the problem increases in an exponential fashion and the problem becomes very computational expensive. To deal with this complexity, we grouped the aforementioned prefectures performing an analysis that is described in detail below. In this analysis, the number of prefecture groups is reduced to 27. In this way the granularity of the network is acceptable and the complexity of the problem is reduced.

The grouping analysis considers : a) topography, and b) Gross Domestic Product (GDP) of each prefecture. Note that GDP is the numismatic value of all finished goods and services that are produced within a region, a prefecture or a country for a certain period of time (Amadeo, 2018).

A prefecture group includes one or more prefectures. In case a group includes just one prefecture, its capital city represents a node of the network. Otherwise, in case of multiple prefectures in a group the capital city of the prefecture with the highest value of *GDP* is the node of the network.

The estimation process includes the following two steps.

Step 1: Compute grouping parameter for each prefecture

For the grouping parameter computation we need the GDP of each prefecture.

Table 3.3 presents the GDP of each region and prefecture in 2015. The first column of this table includes the regions (**bold**) and prefectures of Greece. The second and the third column contain the GDP value of each region and prefecture, respectively.

Table 3.3 GDP of each region and prefecture (*Source:* ΕΛΣΤΑΤ, 2015)

Regions and Prefecture	Region GDP (million €)	Prefecture GDP (million €)
Attica	**84.374**	84.374
Central Greece	**7.860**	
Boetia		2.334
Euboea		2.771
Evrytania		193
Phthiotis		2.123
Phocis		440
Central Macedonia	**23.716**	
Imathia		1.562
Thessaloniki		15.175
Kilkis		915
Pella		1.550

Regions and Prefecture	Region GDP (million €)	Prefecture GDP (million €)
Pieria		1.416
Serres		1.665
Khalkidhiki		1.432
Western Macedonia	**4.304**	
Grevena		317
Kozani		2.562
Kastoria		520
Florina		905
Eastern Macedonia and Thrace	**6.760**	
Evros		1.785
Xanthi		1.073
Rhodope		1.070
Drama		1.034
Kavala, Thasos		1.798
Thessaly	**9.066**	
Karditsa		1.062
Trikala		1.451
Larissa		3.944
Magnesia		2.608
Western Greece	**8.114**	
Aetolia-Acarnania		2.383
Achaea		4.036
Elis		1.695
Peloponnese	**7.777**	
Argolis		1.436
Arcadia		1.390
Corinthia		1.895
Laconia		1.102
Messenia		1.954
Epirus	**3.887**	
Arta		717
Preveza		690
Thesprotia		550
Ioannina		1.930
North Aegean	**2.481**	
Lesbos/Lemnos		1.319
Samos/Ikaria		523
Chios		638
North Aegean	**6.078**	
Dodecanese		3.335
Cyclades		2.743
Crete	**8.787**	
Heraklion		4.185
Lasithi		1.154
Rethymno		1.179
Chania		2.269
Ionian Islands	**3.107**	
Zakynthos		700
Corfu (Kerkyra)		1.542
Cephalonia/Ithaca		573
Lefkada		292

Prefecture GDP provides an indication of the prefecture’s importance in the economy.

Step 2: Create the prefecture groups

The process occurred groups prefectures that are part of the same region. Grouping was based on the grouping parameter and the geographical location of the prefecture (e.g. prefectures that are close to each other may be grouped together) in order to form prefecture groups with considerable GDP. Prefectures that have high GDP (grouping parameter) are more likely to become a single prefecture group. Lower GDP prefectures are more likely to be grouped with other prefectures to form a prefecture group. This grouping respects to the geographical aspect,which is important in transportation application, and creates prefecture groups with sustainable GDP. Taking these considerations into account we grouped the prefectures ensuring that a) each region includes at least one prefecture group and b) the total number of prefecture groups is 27. A more specialized grouping taking into account three dimensions geography, GDP and population as a result in a more refined/balanced set of nodes. Table 3.4 presents the nodes of the freight transport network that will be used to solve the p-hub median problem.

Table 3.4 Nodes of the Network

Prefectures and prefecture groups	Nodes of the network
Evros	Alexandroupoli
Xanthi, Rhodope, Drama	Komotini
Kavala, Thasos	Kavala
Imathia, Pella, Pieria	Veroia
Thessaloniki, Khalkidhiki	Thessaloniki
Kilkis, Serres	Serres
Kozani	Kozani
Grevena, Kastoria, Florina	Florina
Arta, Preveza, Thesprotia	Arta
Ioannina	Ioannina
Karditsa, Trikala	Trikala
Larissa	Larissa
Magnesia	Volos
Zakynthos, Corfu (Kerkyra), Cephalonia/Ithaca, Lefkada	Corfu (Kerkyra)
Aetolia-Acarnania	Messolonghi
Achaea, Elis	Patras
Boetia	Livadeia
Euboea	Chalcis
Evrytania, Phthiotis, Phocis	Lamia
Argolis, Arcadia, Corinthia	Korinthos

Prefectures and prefecture groups	Nodes of the network
Messenia, Laconia	Kalamata
Attica	Athens
Lesbos/Lemnos, Samos/Ikaria, Chios	Mytilene
Dodecanese	Rhodes
Cyclades	Ermoupoli
Heraklion, Lasithi	Heraklion
Rethymno, Chania	Chania

3.2 The arcs of the freight transport network

Greece comprises the mainland part, where most of the nodes of the freight transport network are located, and the island regions of the Aegean Sea (North Aegean, Cyclades, Dodecanese), the Sea of Crete (Crete) and at the Ionian Sea (Ionian Islands). Thus, there are three types of node connections (arcs):

- Type I. When both nodes in a node pair are located in continental Greece
- Type II. When one node in a node pair is located at the island part of Greece and the other in continental Greece
- Type III: When both nodes in a node pair are located in the island part of Greece.

Type I: Mainland node pairs

This type refers to the node pairs that are located in mainland Greece and the Chania - Heraklion pair in Crete. The connection between the nodes in such a pair uses land transport over the main road network. The latter refers to the motorway network. Thus, the arc connecting such a node pair corresponds to the motorway network route between the two nodes of the pair, and the parameter that characterizes the arcs is the transport time (in hours).

Type II: Mainland-island node pairs

In order to define the arc corresponding to such a pair, we must first identify the ports that connect each node in continental Greece with each node in the island regions. The ports that most of the freight flows pass through are the ports of Piraeus, Igoumenitsa, Thessaloniki, Kavala and Patras. Hence, these ports have been used to connect continental nodes with island nodes. Table 3.5 presents the port used to connect each continental prefecture group to the islands prefecture groups.

Table 3.5 Service Ports ("I" = port of Igoumenitsa, "T" = port of Thessaloniki, "K" = port of Kavala, "PA" = port of Patras and "P" = port of Piraeus)

Prefecture cluster	Ionian Islands	North Aegean	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evros	I	K	P	K	P	P
Xanthi ,Rhodope, Drama	I	K	P	K	P	P
Kavala,Thasos	I	K	P	K	P	P
Imathia, Pella, Pieria	I	K	P	P	P	P
Thessaloniki, Chalkidiki	I	K	P	P	P	P
Kilkis, Serres	I	K	P	P	P	P
Kozani	I	K	P	P	P	P
Grevena, Kastoria, Florina	I	K	P	P	P	P
Arta, Preveza, Thesprotia	I	K	P	P	P	P
Ioannina	I	K	P	P	P	P
Karditsa, Trikala	I	K	P	P	P	P
Larissa	I	K	P	P	P	P
Magnesia	I	K	P	P	P	P
Aetolia-Acarnania	PA	P	P	P	P	P
Achaea, Elis	PA	P	P	P	P	P
Boetia	PA	P	P	P	P	P
Euboea	PA	P	P	P	P	P
Evrytania, Phthiotis, Phocis	PA	P	P	P	P	P
Argolis, Arcadia, Corinthia	PA	P	P	P	P	P
Messenia, Laconia	PA	P	P	P	P	P
Attica	PA	P	P	P	P	P

The selection of the above ports was based also on the availability and frequency of marine connectivity from these ports. It was observed that the transportation from the port of Thessaloniki to the island nodes could only be done with Ro-Ro ships and the schedules of the trips were not frequent. Considering this, as well as the fact the most of sea freight transport is done using passenger ships, we decided to not include the port of Thessaloniki as a service port. For example, if a node pair consists of prefecture group Patras and prefecture group Heraklion/Lasithi, the connection between them will be, from Patras to port of Piraeus using road transport and from port of Piraeus to Heraklion using marine transport. Figure 3.3 shows that example.

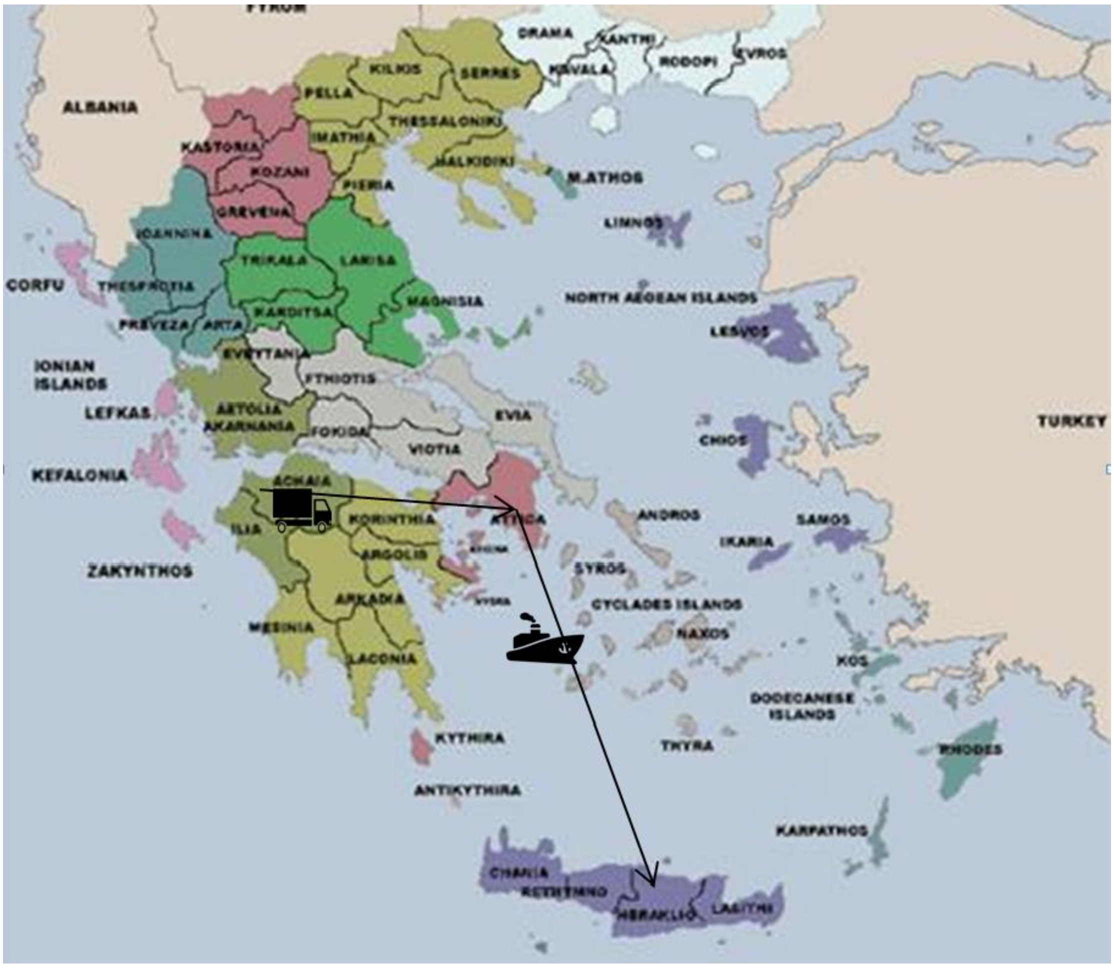

Figure 3.3 Transport between mainland-island node pairs

Type III: Island node pairs

In that case only the nodes of the pairs Dodecanese-Heraklion/Lasithi, Dodecanese-Cyclades and Cyclades-North Aegean have direct trips between them and the related arcs use marine transport solely. In all other cases the island node pairs are connected by combined (road and marine) transport. For example, the connection between Heraklion/Lasithi and Ionian Islands will be from Heraklion/Lasithi to port of Piraus, from port of Piraeus to port of Patras and from port of Patras to Ionian Islands.

3.3 Network parameter

The freight transport network to be used for the application of the p hub median problem was determined in Sections 3.1 and 3.2. In this Section we define the cost corresponding to each arc and the demand between each pair of nodes. These parameters will be used in the objective function of the p-hub median problem.

3.3.1 Estimation of the cost parameter C_{ijkm}

The cost parameter c_{ijkm} is the cost from origin i to destination j via hubs k and m in that order, and is defined from the following Equation:

$$c_{ijkm} = c_{ik} + \alpha c_{km} + c_{mj} \tag{3.1}$$

The formula includes three costs values and the factor a. Each cost value reflects the monetary cost of transport, transport time, or distance between nodes. In this thesis, the cost is defined as the transport time corresponding to the related trip and the unit of measurement is hours.

The transport time between two mainland nodes using road transport is provided by Equation 3.2 below.

$$C_{ij} = \frac{x_{ij}}{u} \tag{3.2}$$

Where C_{ij} cost of transport between nodes i, j

x_{ij} kilometer distance between nodes i, j

u the speed of the vehicle

The transport time between a node in mainland Greece and an island node is the sum of the time corresponding to the road transport leg of the trip and, the time corresponding to marine transport, and an appropriate waiting time.

Transport time between two mainland nodes

To find the distances between the nodes of an arc, we used the tool provided by the Ministry of Infrastructure and Transport (YPOMEDI, 2017), which provides the user with the kilometer distance between two points in mainland Greece. In the tool, the user selects the origin point using the tab “Origin” and the destination point using the tab “Destination”. For example the distance between Athens and Larissa is given as 355.5 km (see Figure 3.4 and Figure 3.5).

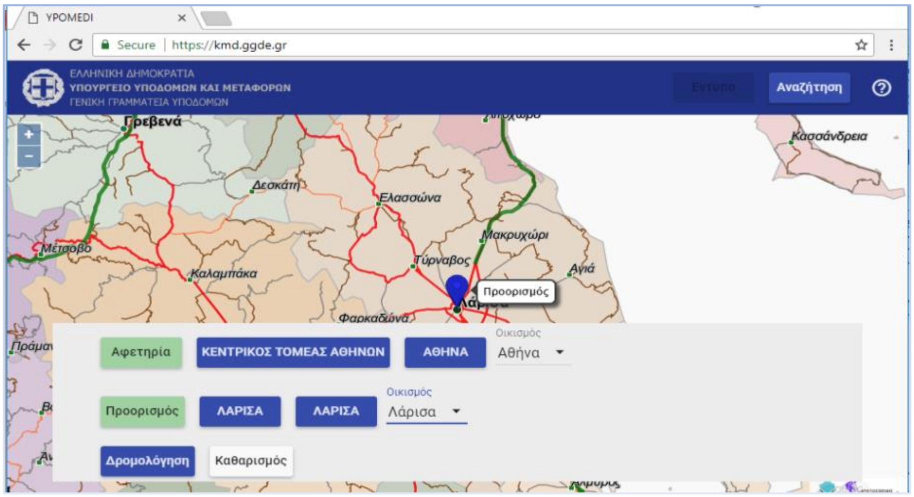

Figure 3.4 Selection of the origin-destination points(*Source*: YPOMEDI, 2017)

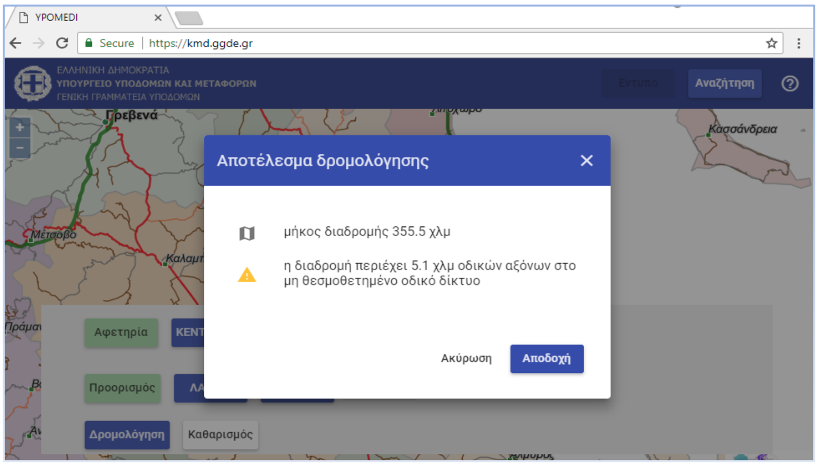

Figure 3.5 Provided distance(*Source*: YPOMEDI, 2017)

In order to convert the distances into transport time, we used the average speed for a truck moving on the Greek motorway network to be $u = 60\ km/h$ also considering Article 20 of the Highway Code- N.2696/1999 (ΦΕΚ A'57/23.03.99, 2001), which stipulates that the maximum permissible speed for truck is 80 km/h. Based on this assumption the transport time is calculated for the above example is :

$$C_{A,L} = \frac{355.5\ km}{60\ km/h} = 6.30\ h$$

Transport time for a mainland-island arc

The procedure for estimating the transport time for such pairs comprises 2 steps:

- The first step provides the transport time by ship from the port corresponding to the mainland node (see Table 3.5 above) to the island node
- The second step provides the entire transport time between the mainland node to the island node.

Step 1: Transport time from the selected port to the islands node

The transport time by ship from the ports that serve all mainland nodes to the island nodes were determined from official ship transport websites. These transport times are presented in the Table 3.6.

Table 3.6 Transport time between service ports and island nodes

	Island nodes					
Service port	Ionian Islands	North Aegean	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Kavala	-	7,15	-	14	-	-
Igoumenitsa	1,3	-	-	-	-	-
Patras	6	-	-	-	-	-
Piraeus	-	9,3	13,1	3,45	8,45	9

Step 2: Estimate the total travel time between the mainland nodes and the island nodes

In order to find the total transport time we remind the reader that each mainland node is connected to the island node through a service port. The connections between the ports, corresponding to the mainland, and the island nodes have been presented in Table 3.5.

Thus, the total travel time between the mainland nodes and the island nodes consists of:

a) The road transport time from the mainland node (e.g. Evros -Alexandroupoli) to the service port that connects it with the island node based on Table 3.5.

b) The transport time from the service port to the island node by ship, based on Table 3.6.
c) A two hour waiting period at the service port.

The resulting total transport times between the mainland nodes and the island nodes are presented in Table 3.7

Table 3.7 Transport Time in hours between mainland and island nodes

Prefecture of Prefecture Clusters	Ionian Islands	North Aegean	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evros	14	12	28,44	19.19	24.20	24.34
Xanthi ,Rhodope, Drama	13.11	11.12	27.55	18.30	23.30	23.45
Kavala,Thasos	11.15	9.19	26.30	16.34	21,34	22.30
Imathia, Pella, Pieria	8	13.20	24	14.36	19.36	19.51
Thessaloniki, Chalkidiki	9.10	12.10	23,56	14.31	19.30	19.46
Kilkis, Serres	10	11.25	25.30	15.25	20.25	21.20
Kozani	6.70	14	23.05	13.40	18.40	19.35
Grevena, Kastoria, Florina	8.40	15.25	24.36	15.11	20.11	20.26
Arta, Preveza, Thesprotia	6	17.30	21.30	11.26	16.26	17.21
Ioannina	5	16.30	22.14	12.49	17.49	18.04
Karditsa, Trikala	6,41	15.18	20.54	11.30	16.30	16.44
Larissa	7.42	14.18	21.03	11.38	16.38	17.33
Magnesia	8.42	15.12	20.47	11.20	16.30	16.37
Aetolia-Acarnania	9.38	16.30	20.13	10.08	15.08	16
Achaea, Elis	8	15.20	19	9.40	14.10	14.53
Boetia	11.16	13.28	17.08	7,43	12.43	13.33
Euboea	13	12.58	16.38	7.13	12.13	12.28
Evrytania, Phthiotis, Phocis	11.13	15.26	19	9.01	14.01	14.56
Argolis, Arcadia, Corinthia	10.20	13.10	16.48	7.23	12.23	12.38
Messenia, Laconia	11.53	15.35	19.15	9.50	14.50	15.05
Attica	11.53	11.35	15.15	5.50	10.50	11.05

Transport time for an island-island case

In most cases, the transport time of an island-island arc considers the time to connect the first island node with its designated service port node, the time corresponding to the land trip from the designated service port to the designated service port of the destination island, and the time for the sea trip from the latter port to the second island node. For example from the Ionian Islands to Chania, the transport time comprises the corresponding time for thetrip from Ionian Islands to Patras, waiting 2 hours at the port, the transport time from Patras to Piraeus, waiting another 2 hours at the port, and, finally, the transport time from Piraeus to Chania.

Exceptions include the cases of Cyclades-Dodecanese, Heraklion/Rethymno-Dodecanese and North Aegean-Cyclades. For these pairs the transport time is estimated considering direct trips.

The transport time between the island nodes are provided in Table 3.8

Table 3.8 Transport time between island nodes in hours

	Ionian Islands	North Aegean	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Ionian Islands	0	23.23	27	17.38	22.30	22.39
North Aegean	23.23	0	26.4	16.74	21.75	22.39
Dodecanese	27	26.4	0	14	17.5	21
Cyclades	17.38	16.74	14	0	15.9	16.54
Heraklion, Lasithi	22.03	21.75	17.5	15.9	0	-
Rethymno, Chania	22.39	22.39	21	16.45	-	0

Travel time matrix

Combining the steps for road transport and marine transport, a 27 x 27matrix is generated - see Table 3.9. The matrix is symmetric. The values of the diagonal are not zero and stand for an intra-group trip.

Table 3.9 Transport time cost matrix (travel time in hours)

	Evros	Xanthi ,Rhodope, Drama	Kavala, Thasos	Imathia , Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis, Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza , Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfu (Kerkyra), Chephalonia/Ithaca, Lefkada	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia, Corinthia,	Messenia Laconia	Attica	Lesbos/ Lemnos, Samos/ Ikaria, Chios	Dodecanese	Cyclades	Heraklion , Lasithi	Rethymno, Chania
Evros	0.046	1.32	2.5	6.1	5.0	4.2	7.0	8.2	10.3	9.3	8.5	7.5	8.4	14	12.05	13.21	12.21	12.46	9.26	14.20	16.34	13.34	12	28.44	19.19	24.20	24.34
Xanthi ,Rhodope, Drama	1.32	0.046	1.58	5.25	4.14	3.28	6.08	7.28	9.41	8.40	8	6.59	7.54	13.11	11.15	12.32	10.32	11.57	8.37	13.31	15.46	12.45	11.12	27.55	18.30	23.30	23.45
Kavala,Thasos	2.46	1.58	0.046	3.7	2.6	1.7	4.5	5.7	7.8	7.20	6.0	5.0	6.0	11.15	9.19	10.35	8.36	10.01	7.21	11.35	14.29	11.29	9.19	226.28	16.30	21.33	22.28
Imathia, Pella, Pieria	6.14	5.25	4	0.046	1.25	2.59	1.36	2.16	4.29	3.28	3.05	3	3.59	7.59	6.03	7.20	6.38	8	4.43	9.11	10.33	8.51	13.20	24	14.36	19.36	19.51
Thessaloniki, Chalkidiki	5.03	4.14	2.58	1.25	0.046	1.48	2.08	3.28	5.41	4.40	4	3	3.54	9.11	7.15	8.32	6.32	7.58	4.37	9.31	11.46	8.46	12.12	23.55	14.30	19.30	19.45
Kilkis, Serres	4.17	3.28	2.10	2.59	1.48	0.046	3.42	5	6.75	6.14	5.34	4.34	5.28	10.05	8.09	9.26	7.26	9.32	5.71	10.25	13.20	10.20	11.26	25.29	15.24	20.24	21.19
Kozani	6.97	6.08	4.52	1.36	2.08	3.42	0.046	1.43	3.40	2.39	2.16	2.02	3.03	6.70	5.14	6.31	5.37	7.07	4.22	8.22	9.45	8.35	14	23.04	13.39	18.39	19.34
Grevena, Kastoria, Florina	8.17	7.28	6.10	2.16	3.28	5	0.5	0.046	5	3.67	3.44	3.33	4.34	8.39	6.03	7.19	7	8.38	5.13	9.11	11.13	9.26	15.26	24.35	15.10	20.10	20.25
Arta, Preveza, Thesprotia	10.30	9.41	8.25	4.29	5.41	7.15	3.40	5	0.046	1.29	3.11	4.13	5.12	6	1.40	2.57	5.28	7.30	4.53	4.48	6.11	6.21	17.36	21.31	11.26	16.26	17.21
Ioannina	9.29	8.40	7.20	3.28	4.40	6.15	2.39	4	1.29	0.046	2.10	3.11	4.11	5	3.03	4.19	6.10	7	4.39	6.11	7.33	7.04	16.36	22.13	12.48	17.48	18.03
Karditsa, Trikala	8.49	8	6.04	3.05	3.60	5.34	2.16	3.44	3.11	2.10	0.046	1.02	2.02	6.41	4.45	6	3.45	4.56	2.30	6.30	9.15	5.44	15.18	20.54	11.19	16.29	16.44
Larissa	7.48	6.59	5.03	3.05	2.60	4.34	2.02	3.33	4.13	3.11	1.02	0.046	1.01	7.43	5.47	5.32	3.35	5.05	2.19	6.38	9.06	6.33	14.18	21.02	11.37	16.37	17.32
Magnesia	8.43	7.54	5.97	3.59	3.54	5.28	3.03	4.34	5.12	4.11	2.02	1.00	0.046	8.42	5.03	5.02	3.45	4.49	2.29	6.32	8.50	5.37	15.12	20.46	11.21	16.21	16.36
Zakynthos, Corfu (Kerkyra), Chephalonia/Ithaca, Lefkada	14	13.21	11.15	7.59	9.21	10.05	7.10	8.30	6	4.59	6.41	7.43	8.42	0.046	9.39	8.00	11.17	13	11.13	10.20	11.53	11.53	23.23	27	17.38	22.30	22.3
Aetolia-Acarnania	11.64	11.15	9.19	6	7.15	8.09	5.15	6.03	1.40	3	4.45	5.47	5.03	9.39	0.046	1.39	4	6.32	3.13	3.30	5.33	5	16.33	18.13	10.08	15.08	16.33
Achaea, Elis	13.21	12.30	10.35	7.20	8.32	9.26	6.30	7.19	2.57	4.20	6	5.32	5.02	8.00	1.39	0.046	3.17	5	3.13	2.20	3.53	3.53	15.23	19	9.38	14.38	14.53
Boetia	11.21	10.30	8.36	6.28	6.32	7.26	5.37	7	5.30	6.10	3.45	3.35	3.45	11.17	4.09	3.17	0.046	1.38	1.56	2.59	5.26	2.38	13.28	17.08	7.431	12.43	13.38
Euboea	12.46	11.57	10.01	8	7.58	9.32	7.07	8.38	7.30	7	4.56	5.05	4.49	13.02	6.12	5	1.38	0.046	3.10	2.5	5.1	1.3	12.58	16.38	7.13	12.13	12.28
Evrytania, Phthiotis, Phocis	9.26	8.37	7.20	4.43	4.37	6.11	4.22	5.13	4.53	4.39	2.30	2.19	2.29	11.13	3.13	3.13	1.56	3.10	0.046	4.02	7	3.56	13.26	19	9.01	14.01	14.56
Argolis, Arcadia, Corinthia	14.20	13.30	11.35	9.21	9.31	10.25	8.22	9.11	4.48	6.11	6.30	6.38	6.22	10.20	3.30	2.20	2.59	2.5	4.02	0.046	3.10	1.4	13.07	16.47	7.22	12.22	12.37
Messenia, Laconia	16.34	15.46	14.30	10.33	11.46	13.20	9.45	11.13	6.11	7.33	9.15	9.06	8.50	11.53	5.33	3.53	5.26	5.1	7.10	3.10	0.046	4.05	15.34	19.14	9.49	14.49	15.04
Attica	13.34	12.45	11.30	8.51	8.46	10.20	8.30	9.26	6.21	7.04	5.44	5.93	5.37	11.53	5.03	3.53	2.38	1.3	3.56	1.4	4.05	0.046	11.3	15.1	5.45	10.50	11
Lesbos/Lemnos, Samos/Ikaria, Chios	12	11.12	9.15	13.20	12.10	11.20	14	15.26	17.30	16.38	15.18	14.18	15.12	23.23	16.33	15.23	13.28	12.58	15.26	13	15.34	11.3	0.046	26.4	17.15	22.15	22.3
Dodecanese	28.44	27.55	26.30	24	23.55	25.20	23	24.35	21.30	22.13	20.54	21.0	20.46	27.03	20.13	19	17.08	16.38	19	16.47	19.14	15.1	26.4	0.046	14	17,5	20
Cyclades	19.20	18.30	16.33	14.30	14.30	15.24	13.39	15.10	11.26	12.48	11.29	11.3	11.21	17.38	10.08	9.38	7.43	7.13	9.01	7.22	9.49	5.45	117.15	14	0.046	16.30	16.45
Heraklion, Lasithi	24.20	23.30	21.33	20.30	19.30	20.24	18.39	20.10	16.26	17.48	16.29	16.3	16.21	22.38	15.08	14.38	12.43	12.13	14.01	12.22	14.49	10.50	22.15	17,5	16.30	0.046	2.36
Rethymno, Chania	24.34167	23.45	22.28	19.51	19.455	21.20	19.34	20.25	17.21	18.03	16.44	17.3	16.36	22.3	16.03	14.53	13.38	12.28	14.56	12.375	15.04	11	22.3	20	16.45	2.36	0.046

3.3.2 Estimation of the demand W_{ij}

The demand parameter W_{ij} corresponds to the freight flows transported between nodes i and j of the network within a period of time (e.g. daily, monthly, yearly). Data on freight flows are not publicly available. Therefore, the DeOPSys (Design, Operations and Production Systems) Laboratory procured the related data from the Hellenic Statistical Authority. The most recent data available relate to the weight (in tones) of freight transported between the regions of Greece for year 2016, and are presented in Table 3.10.

Table 3.10 Weight (in tones) of freight transported between regions of Greece (2016) (*Source:* Hellenic Statistical Authority)

ΒΑΡΟΣ ΜΕΤΑΦΕΡΘΕΝΤΩΝ ΠΡΟΪΟΝΤΩΝ ΜΕ ΦΟΡΤΗΓΑ ΑΥΤΟΚΙΝΗΤΑ ΟΔΙΚΩΝ ΕΜΠΟΡΕΥΜΑΤΙΚΩΝ ΜΕΤΑΦΟΡΩΝ ΚΑΤΑ ΓΕΩΓΡΑΦΙΚΗ ΠΕΡΙΦΕΡΕΙΑ ΕΤΟΥΣ 2016															
ΕΚΦΟΡΤΩΣΕΙΣ σε ΥΠΑ:															
	ΑΝΑΤΟΛΙΚΗ ΜΑΚΕΔΟΝΙΑ & ΘΡΑΚΗ	ΚΕΝΤΡΙΚΗ ΜΑΚΕΔΟΝΙΑ	ΔΥΤΙΚΗ ΜΑΚΕΔΟΝΙΑ	ΗΠΕΙΡΟΣ	ΘΕΣΣΑΛΙΑ	ΙΟΝΙΑ ΝΗΣΙΑ	ΔΥΤΙΚΗ ΕΛΛΑΔΑ	ΣΤΕΡΕΑ ΕΛΛΑΔΑ	ΠΕΛΟΠΟΝΝΗΣΟΣ	ΑΤΤΙΚΗ	ΒΟΡΕΙΟ ΑΙΓΑΙΟ	ΝΟΤΙΟ ΑΙΓΑΙΟ	ΚΡΗΤΗ	ΕΚΤΟΣ ΕΛΛΑΔΟΣ	**ΣΥΝΟΛΟ**
ΦΟΡΤΩΣΕΙΣ από ΥΠΑ:	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι	τόνοι
ΑΝΑΤΟΛΙΚΗ ΜΑΚΕΔΟΝΙΑ ΚΑΙ ΘΡΑΚΗ	13,449,145.9	1,694,627.0	49,959.2	55,548.5	32,911.4		36,480.3	19,119.6		198,434.5	13,318.4			114,667.9	15,664,212.7
ΚΕΝΤΡΙΚΗ ΜΑΚΕΔΟΝΙΑ	1,374,289.8	34,714,578.3	757,712.8	434,483.4	1,226,321.9	69,383.9	298,235.7	231,235.1	166,370.5	2,019,840.2	25,564.1	20,574.4	66,181.5	1,135,976.2	42,540,747.8
ΔΥΤΙΚΗ ΜΑΚΕΔΟΝΙΑ	0.0	1,899,138.2	103,927,685.1	209,146.4	149,547.2		18,727.7	91,902.3		135,608.2					106,431,755.1
ΗΠΕΙΡΟΣ	18,941.0	409,148.7	18,941.0	22,453,789.9	174,344.1	30,580.1	430,244.2	221,382.5	0.0	1,387,549.7				84,432.7	25,229,353.9
ΘΕΣΣΑΛΙΑ	28,296.7	616,273.0	168,868.8	306,729.1	30,824,786.9	70,742.7	228,290.0	877,300.3	180,279.1	693,463.1			0.0	306,752.8	34,301,782.5
ΙΟΝΙΑ ΝΗΣΙΑ		22,712.5		21,216.0	0.0	1,550,070.2	43,481.9		0.0	217,528.0			0.0	7,594.1	1,862,602.8
ΔΥΤΙΚΗ ΕΛΛΑΔΑ	21,430.5	330,867.9	24,849.3	313,308.4	23,454.6	478,613.2	46,460,678.5	343,662.6	385,918.1	1,532,256.1			13,258.1	306,323.5	50,234,620.7
ΣΤΕΡΕΑ ΕΛΛΑΔΑ	19,958.3	317,800.7		122,949.9	156,139.5	16,224.0	480,716.1	191,851.6	12,125,812.3	1,186,341.1		8,767.0	112,879.5	340,167.5	15,079,607.6
ΠΕΛΟΠΟΝΝΗΣΟΣ	40,453.7	586,863.8	0.0	28,425.3	344,243.9	10,560.3	319,485.1	26,855,795.0	127,824.5	3,806,762.8			23,199.3	373,892.9	32,517,506.5
ΑΤΤΙΚΗ	56,209.0	1,651,756.1	67,425.7	745,253.0	809,796.6	236,756.4	1,314,745.7	3,606,936.8	1,328,465.1	39,908,088.5	114,953.5	328,625.0	68,055.7	810,783.4	51,047,850.3
ΒΟΡΕΙΟ ΑΙΓΑΙΟ		0.0								107,582.3	1,663,987.0	60,288.8			1,831,858.1
ΝΟΤΙΟ ΑΙΓΑΙΟ		16,936.7							0.0	92,363.6	0.0	17,192,059.3			17,301,359.6
ΚΡΗΤΗ		56,972.4			10,192.0	16,218.1	12,052.9	12,261.1	0.0	163,935.9			12,692,292.0	111,404.5	13,075,328.9
ΕΚΤΟΣ ΕΛΛΑΔΟΣ	30,867.7	934,284.6	8,113.3	47,337.2	24,543.7		118,666.9	136,430.2	165,473.5	1,342,153.3			35,440.1	52,450.9	2,895,761.4
ΣΥΝΟΛΟ	15,039,592.6	43,251,959.9	105,023,555.0	24,738,187.0	33,776,281.8	2,479,148.9	49,761,805.1	32,587,877.1	14,480,143.0	52,791,907.5	1,817,822.9	17,610,314.5	13,011,306.3	3,644,446.3	410,014,347.7

We used that data of Table 3.10 to estimate the freight flows of the network presented in Section 3.1. That is, from the data related to the 13 regions we estimated the flows among 27 groups of our freight network.

The estimation process distributes the data corresponding to each pair of regions to all pairs between the prefecture groups of the related regions. In order to do so, we determined appropriate distribution drivers. The driver of each prefecture group is the ration of its GDP to the GDP of the region it belongs to.

$$Percent\ GDP\ of\ perfecture\ group = \frac{GDP\ prefecture\ group}{GDP\ of\ the\ region} \qquad (3.3)$$

It is noted, that for regions that have only one prefecture group, the percent GDP of that group is 100%.

The data of the GDP of all regions and prefectures are presented in Table 3.4. The prefecture group GDP is estimated as the sum of the GDP values of the prefectures that comprise it. For example, in the case of group Rhodope/Xanthi/Drama the prefecture group GDP is given as:

$$GDP\ of\ prefecture\ group = GDP(Rhodope) + GDP\ (Xanthi) + GDP(Drama)$$

The percent GDP values per prefecture group are provided in Table 3.11.

Table 3.11 Percent GDP of each prefecture group

Prefecture group	**Region**	**% GDP of Prefecture group**
Evros	Eastern Macedonia and Thrace	26%
Xanthi, Rhodope, Drama		47%
Kavala, Thasos		27%
Imathia, Pella, Pieria	Central Macedonia	19%
Thessaloniki, Khalkidhiki		70%
Kilkis, Serres		11%
Kozani	Western Macedonia	60%
Grevena, Kastoria, Florina		40%

Prefecture group	Region	% GDP of Prefecture group
Arta, Preveza, Thesprotia	Epirus	50%
Ioannina		50%
Karditsa, Trikala	Thessaly	28%
Larissa		44%
Magnesia		29%
Zakynthos, Corfu (Kerkyra), Cephalonia/Ithaca, Lefkada	Ionian Islands	100%
Aetolia-Acarnania	Western Greece	29%
Achaea, Elis		71%
Boetia	Central Greece	30%
Euboea		35%
Evrytania, Phthiotis, Phocis		35%
Argolis, Arcadia, Corinthia	Peloponnese	61%
Messenia, Laconia		39%
Attica	Attica	100%
Lesbos/Lemnos, Samos/Ikaria, Chios	North Aegean	100%
Dodecanese	South Aegean	55%
Cyclades		45%
Heraklion, Lasithi	Crete	61%
Rethymno, Chania		39%

Using these drivers, the transport flow (by weight) W_{ij} for each origin (i)- destination (j) pair of prefecture groups is determined using the following formula:

$$W_{ij}(= \text{ \% GDP (prefecture group i)} * \text{\% GDP (prefecture group j)} * \text{(Flow between Region of prefecture group i and Region of prefecture group j)} \quad (3.4)$$

For example the flow between Larissa and Thessaloniki will be computed as follows:

$$W_{LT} = \text{\% GDP(Larissa)} * \text{\% GDP (Thessaloniki/Khalkidiki)} * \text{(Flow of weight Transport Goods between Thessaly and Central Macedonia))}$$

After the application of this formula, the 27 x 27 matrix of flows was generated – see Table 3.12. Appropriate validations have been performed to ensure that the original data provided by the Hellenic Statistical Agency may be recovered from Table 3.12 and the values obtained are the original ones.

Table 3.12 Demand matrix

	Evros	Xanthi ,Rhodope, Drama	Kavala,Thasos	Imathia, Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis, Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza, Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfy,Lefkada ,Cephalonia	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia,Corithia	Messenia, Laconia	Attica	Lesbos/ Chios, Samos	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evros	937502.5948	1668985.3	944372.500	85434.95	313311.7	48670.84844	7851.49201	5338.788	7382.882594	7283.112481	2408.62724	3780.599563	2500.0716	0	2829.2069	6802.3648	1498.79	1779.432287	1769.7501	0	0	52390.922	3516.34328	0	0	0	0
Xanthi ,Rhodope, Drama	1668985.253	2971204.3	1681215.37	152095.2	557772	86646.08372	13977.5873	9504.356	13143.34728	12965.73193	4287.94902	6730.397286	4450.7426	0	5036.6844	12109.882	2668.22	3167.827229	3150.5905	0	0	93268.731	6259.95609	0	0	0	0
Kavala,Thasos	944372.5005	1681215.4	951292.748	86061.01	315607.7	49027.50254	7909.02679	5377.91	7436.983465	7336.482249	2426.27736	3808.303339	2518.3918	0	2849.9390	6852.2117	1509.78	1792.471752	1782.7186	0	0	52774.837	3542.11062	0	0	0	0
Imathia, Pella, Pieria	69285.08623	123344.5	69792.7989	1265776	4641925	721091.4689	86124.2263	58561.99	41764.77677	41200.37981	64910.0481	101883.3035	67374.382	13248.93451	16728.220	40220.266	13109.9	15564.67839	15479.988	23787.506	7981.14613	385691.06	4881.49171	2155.6043	1773.11115	7679.05496	4958.39055
Thessaloniki, Chalkidiki	254086.0785	452335.73	255947.990	4641925	17023123	2644426.29	315839.499	214761.7	153162.0862	151092.2986	238041.698	373632.0535	247079.04	48587.22125	61346.649	147497.97	48077.6	57079.64454	56769.064	87234.853	29268.8980	1414427.5	17901.6748	7905.1508	6502.45073	28161.0526	18183.6825
Kilkis,Serres	39470.54355	70267.278	39759.7789	721091.5	2644426	410793.6321	49063.5173	33361.78	23792.68801	23471.16059	36978.1582	58041.19741	38382.04	7547.694244	9529.7846	22912.806	7468.53	8866.934423	8818.6879	13551.341	4546.72416	219721.68	2780.90339	1228.0114	1010.11148	4374.62793	2824.71136
Kozani	0	0	0	215862.5	791623	122973.248	0	0	62670.471	61823.56061	24675.2409	38730.4451	25612.045	0	3274.5390	7873.0929	16242.3	19283.60363	19178.678	0	0	80720.571	0	0	0	0	0
Grevena, Kastoria, Florina	0	0	0	146780.3	538280.8	83618.25941	0	0	42614.11151	42038.23689	16778.4516	26335.58485	17415.451	0	2226.5920	5353.4759	11044.3	13112.29392	13040.947	0	0	54887.659	0	0	0	0	0
Arta, Preveza, Thesprotia	2517.423126	4481.6325	2535.87049	39329.47	144231.2	22405.33563	5675.64875	3859.277	5690081.78	5613187.681	24328.0072	38185.42441	25251.629	15394.07048	63620.492	152965.05	33088.9	39284.53089	39070.777	0	0	698494.48	0	0	0	0	0
Ioannina	2483.403407	4421.069	2501.60148	38797.98	142282.1	22102.55649	5598.9497	3807.124	5613187.681	5537332.707	23999.2456	37669.39777	24910.385	15186.03952	62760.743	150897.93	32641.8	38753.65125	38542.786	0	0	689055.24	0	0	0	0	0
Karditsa, Trikala	2070.904227	3686.719	2086.07956	32619.75	119624.9	18582.91943	27863.2868	18946.23	42801.0336	42222.63297	2368480.63	3717585.152	2458400.8	19609.4884	18588.288	44692.494	72203.5	85722.9185	85256.486	37417.975	12554.4191	192224.28	0	0	0	0	0
Larissa	3250.50697	5786.7021	3274.32629	51200.2	187764.2	29167.89117	43734.4262	29738.15	67180.82672	66272.9647	3717585.15	5835149.83	3858724.6	30779.20161	29176.317	70149.678	113331.	134551.3426	133819.22	58731.538	19705.5113	301716.69	0	0	0	0	0
Magnesia	2149.526884	3826.6867	2165.27835	33858.17	124166.5	19288.42694	28921.127	19665.53	44425.99092	43825.63109	2458400.89	3858724.669	2551735.0	20353.96999	19293.999	46389.262	74944.8	88977.42131	88493.280	38838.563	13031.0523	199522.15	0	0	0	0	0
Zakynthos,	0	0	0	4336.981	15904.81	2470.704718	0	0	10680.16431	10535.83569	0	0	0	1550070.24	12772.516	30709.423	0	0	0	0	0	217528.02	0	0	0	0	0
Aetolia-Acarnania	1662.029551	2958.8215	1674.20870	18558.58	68059.04	10572.5087	4344.89405	2954.403	46329.11495	45703.03686	1909.76733	2997.585276	1982.2723	140589.2913	4008857.7	9638642.1	29972.6	35584.72395	35391.101	84881.450	28479.2879	450089.53	0	0	0	2366.45708	1528.02896
Achaea, Elis	3996.077889	7114.0017	4025.36066	44621.06	163636.8	25419.86586	10446.5862	7103.377	111390.7702	109885.468	4591.72281	7207.202924	4766.0492	338023.9287	9638642.0	23174536.	72064.3	85557.64153	85092.108	204083.54	68473.7841	1082166.6	0	0	0	5689.75852	3673.89542
Boetia	1564.540674	2785.2673	1576.00543	18017.85	66076.05	10264.46509	0	0	18376.72669	18128.38899	12850.5932	20170.38847	13338.470	4817.07548	41925.832	100803.79	16912.8	20079.58848	19970.332	2695792.6	904488.015	352237.1	0	1428.2196	1174.79448	20365.2255	13149.8918
Euboea	1857.484176	3306.7788	1871.09559	21391.5	78448.09	12186.37636	0	0	21817.57214	21522.73586	15256.7293	23947.07791	15835.956	5719.021324	49775.996	119678.23	20079.5	23839.27659	23709.563	3200550.9	1073843.71	418189.73	0	1695.6384	1394.76218	24178.3961	15612.0683
Evrytania, Phthiotis, Phocis	1847.377302	3288.7861	1860.91465	21275.11	78021.24	12120.0683	0	0	21698.85917	21405.62715	15173.7149	23816.77795	15749.790	5687.903197	49505.156	119027.04	19970.3	23709.5632	23580.555	3183136.2	1068000.76	415914.29	0	1686.4122	1387.17305	24046.8375	15527.1205
Argolis, Arcadia, Corinthia	6490,02	11553,832	6537,58	68093,92	249717,8	38792	0	0	8694,955288	8577,4542	57982,86	91010,33	60184,2	6416,86	57025,18	137108	4845203	5752416	6E+06	47196,619	30475	2313152,7	0	0	0	8565,881	5531,02
Messenia, Laconia	4190,63	7460,3469	4221,34	43968,46	161243,6	25048	0	0	5614,360664	5538,4898	37439,72	58765,67	38861,13	4143,39	36821,343	88530,9	3128563	3714353	4E+06	30475,009	19677,8	1493610,2	0	0	0	5531,017	3571,4
Attica	14840.36263	26419.496	14949.1110	315404.9	1156670	179680.8614	40135.0109	27290.65	375161.3855	370091.5645	224471.308	352331.8663	232993.44	236756.43	386197.37	928548.32	1070937	1271458.838	1264540.62	994718.70	333746.422	39908088	114953.46	180309.66	148315.285	41353.5618	26702.12819
Lesbos/	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	107582.34	1663987	33079.208	27209.5913	0	0
Dodecanese	0	0	0	1774.472	6507.44	1010.886511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50678	0	5175649.3	4257275.46	0	0
Cyclades	0	0	0	1459.607	5352.751	831.5135093	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41685.63	0	4257275.4	3501859.03	0	0
Heraklion, Lasithi	0	0	0	6610.52	24242.46	3765.901662	0	0	0	0	1716.69354	2694.535189	1781.8684	9854.808426	2151.3255	5172.5100	2212.0932	2626.284029	2611.99399	0	0	99614.504	0	0	0	4686374.76	3026007.29
Rethymno, Chania	0	0	0	4268.434	15653.44	2431.654845	0	0	0	0	1108.47455	1739.870059	1150.5582	6363.281574	1389.1178	3339.9064	1428.3557	1695.800065	1686.57294	0	0	64321.406	0	0	0	3026007.29	1953902.66

The values of the cost and demand matrices (i.e. Tables 3.9 and 3.12)were normalized appropriately in order to support Mathworks Matlab computations. The normalization formula is presented in Appendix A. Applying that formula to the existing demand and cost matrices, new matrices are created with normalized values. Table A.1 presents the new normalized demand dataset and Table A.2 the new normalized cost dataset.

Chapter 4 Design of the national freight transport network in Greece

In this Chapter we apply the p-hub median model of Section 2.1.1, as well as the network, costs/times and freight transport demand of Chapter 3, in order to design the proposed national freight transport network of Greece. To solve the resulting model, we used the commercial solver described in Section 4.1. The selected commercial solver provides optimal solutions within reasonable computational times. In Section 4.2 we present and analyze the results of multiple options for the freight transport network that employ an increasing number of freight hubs. In Section 4.3 we examined a small case scenario for different values of factor α.

4.1. Solving the p-hub median problem

The p-hub median problem, described in Section 2.1.1, is used here to design a national freight transport network in Greece. Specifically, the model is used to identify the most cost-efficient hub locations of the network. Considering the network described in Chapter 3 the set of nodes i, j is $A = \{1, \dots 27\}$. Since each of the identified 27 nodes is a candidate hub, the hub locations k and m belong to this set too. Hence, the p-hub median problem is formulated as follows:

Minimize
$$\sum_{i=1}^{27}\sum_{j=1}^{27}\sum_{k=1}^{27}\sum_{m=1}^{27} W_{ij}\, X_{ijkm}\, C_{ijkm} \quad (4.1)$$

Subject to,

$$\sum_{k=1}^{27} Y_k = p \quad (4.2)$$

$$Y_k \quad \in \{0, 1\}, \forall\, k \in A \quad (4.3)$$

$$X_{ijkm} \in \{0, 1\}, \forall\, i, j, k, \mathrm{m} \in A \quad (4.4)$$

$$\sum_{k=1}^{27}\sum_{m=1}^{27} X_{ijkm} = 1, \forall\, i,\mathrm{j} \in A \quad (4.5)$$

$$X_{ijkm} \leq Y_k\,, \forall i, j, k, \mathrm{m} \in A \quad (4.6)$$

$$X_{ijkm} \leq Y_m, \forall i, j, k, \mathrm{m} \in A \quad (4.7)$$

Furthermore, the p is given exogenously and takes values from 1 to 8. For each value of p a different problem is solved. This problem is modeled as a binary programming mathematical program and solved by the Gurobi optimizer 7.2.0 (Gurobi Optimization Inc., 2018). All experiments were implemented on Mathwork's Matlab 2015a in a PC with a 3.4 GHz Intel Core i7 and 8 GB RAM. The Gurobi optimizer takes as an input the objective function and the relative constraints in the form of matrices and applies various heuristic and exact methodologies. Regarding the p-hub median problem described above, the formulation in the Gurobi optimizer in Mathwork's Matlab interface is as follows:

$$(X, zbest) \;=\; gurobi\;(c, A, b, Aeq, beq) \quad (4.8)$$

Where,

$zbest$: is the optimal value of the objective function (dimensions 1x1)

X: includes the optimal values of the objective function, i.e. the values of the decision variables X_{ijkm} and the variables Y_k. The dimensions of this matrix (vector) are 534.468x1

c: is the vector of the coefficients of the objective function (i.e. the parameters C_{ijkm} and W_{ij} of Equation 4.1). The dimensions are $531.468x1$, the first 531.441 will concern the number of decision variables X_{ijkm} since resulting for all the possible connections of i, j, k, m and the last 27 will concern the Y_k which will be the location of the hubs for all the possible 1... 27 candidates.

A: is the coefficient matrix of the inequality constraints, i.e. of Equations 4.6 and 4.7 - dimensions $1.062.882x531.468$.

b: is the column vector (i.e. right-hand side) of the inequality constraints, i.e. of Equations 4.6 and 4.7 - dimensions $1.062.882x1$.

Aeq: is the coefficients matrix of the equality constraints, i.e. of Equations 4.2 and 4.5 - dimensions $730x531.468$

beq: is the column vector (i.e. right-hand side) of equality constraints, i.e. of Equations 4.2 and 4.5 - dimensions $730x1$

Also, factor α is the discount factor of the inter hub transportation (see Chapter 2). The factor is denoteseconomies of scale through improved load consolidation and truck loading for the line haul routes between the hubs. It takes the values between 0 and 1, $0 \leq a \leq 1$.

4.2. Case description and results

In this Section we present and analyze the results of the national freight network. Specifically, we examined eight different cases considering from one to eight network hubs (i.e.$p = 1, 2 \dots 8$). In this case we used α=0.8.

The one hub case

Applying the p-hub median model with p=1, the results indicate that the unique hub should be established in Attica (see Figure 4.1). This result is considered to be reasonable, since Attica is the highest population prefecture in Greece with the highest GDP indicating very significant freight flow requirements. Furthermore, the available transport infrastructure that connects Attica with the rest of the mainland and island areas in Greece is significant and presents an additional advantage for this hub option. Specifically, regarding the island flows the port of Piraeus (by far the largest port in Greece) is able to support the sea transportation flows between the mainland and the Greek islands. Also, the PATHE motorway is able to support road transport between Attica and the rest of the mainland. Certain commercial and industrial areas in Attica such as Thriaso and Oinofyta, could be possible locations of this unique hub.

Figure 4.1 Proposed location of hub for p= 1

The two hub case

Applying the p-hub median model for p=2, the first hub remains in Attica and the second hub is proposed to be established in Thessaloniki (see Figure 4.2). This result is also reasonable, since Thessaloniki/Khalkidhiki is the second highest population prefecture group in Greece with the second higher GDP, implying considerable freight flows. Additionally, the high freight flows between that prefecture group and the other prefecture groups, especially in Northern Greece, highlight the advantage of this hub location.

In terms of infrastructure, the motorways of PATHE and Egnatia Odos support road transportation between the prefecture group and the rest of mainland Greece. Connectivity with the corresponding island prefecture groups is served through the port of Thessaloniki and the port of Kavala which is close to Thessaloniki.

The two hub locations result in a reasonable network, especially if a line haul service is established between them and feeder services supply the areas connected with these two hubs. For the Thessaloniki hub, commercial and industrial areas in Sindos and Kalochori could be candidate locations.

Figure 4.2 Proposed hub locations for p = 2

The three hub case

This case corresponds to the application of the p-hub median model for p=3. The two hubs remain at the same location and a new hub is located in the prefecture group Achaea/Elia and more specifically in Patras (see Figure 4.3). The relatively high population and GDP imply considerable freight flows related to this area. Additionally, the high freight flows between this and the other prefecture groups, especially in Western Greece and Peloponnese highlight the advantage of this hub location. The PATHE road axis, Ionia Odos, and the national road E9 connect Patras to the other mainland prefecture groups in Peloponnese and Western Greece. Furthermore, the port of Patras supports sea transportation to the Ionian Islands.

The industrial areas of Agios Stefanos could be a possible location for this hub.

Figure 4.3 Proposed hub locations for p = 3

The four hub case

In this case the fourth hub is proposed to be located in prefecture group Heraklion/Lasithi and more specifically in Heraklion (see Figure 4.4). The latter is the fourth largest city of the country based on population and GDP, indicating high freight flow requirements. Furthermore, the hub will serve efficiently the island of Crete and connect it with the mainland hub(s). Within Crete the Northern motorway axis provides connectivity with all four prefectures of the island. The industrial area of Heraklion could be a possible location for the fourth hub.

Figure 4.4 Proposed hub locations for p = 4

The five hub case

In this case the fifth hub is located in the prefecture group of Larissa and specifically in the city of Larissa (see Figure 4.5). The latter is the fifth larger city based on population as well as the GDP, indicating high freight flows. Moreover, this hub may serve the region of Thessaly and possibly parts of Epirus and Central Greece. The PATHE motorway connects Larissa with the other prefecture groups of mainland Greece, also national road E6 connects Larissa with the prefectures groups of the region of Epirus. The fifth hub could be established in the industrial area of Larissa which is located between Larissa and Macrichori.

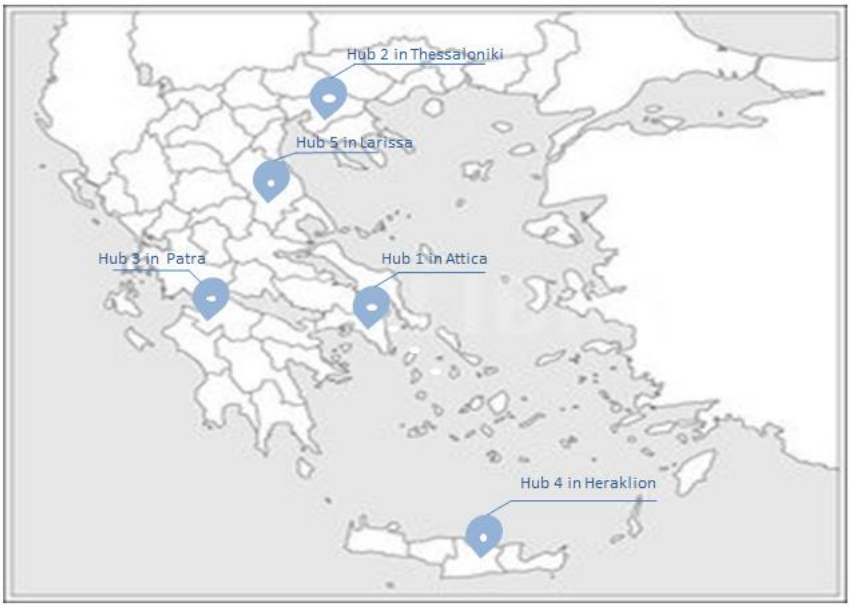

Figure 4.5 Proposed hub locations for p = 5

The six hub case

Applying the p-hub median model for p=6 the locations of the five hubs remain the same as the previous case, and the sixth hub is established in the prefecture group of Dodecanese; more specifically in the island of Rhodes (see Figure 4.6). The freight flows between this and the other prefecture groups of Southern Greece and especially the prefecture group of Cyclades are considerably high. Moreover, the high GDP of Dodecanese, especially in comparison with the other prefecture groups, justify the result as well. The proposed location of the hub could be in the city of Rhodes close to the port.

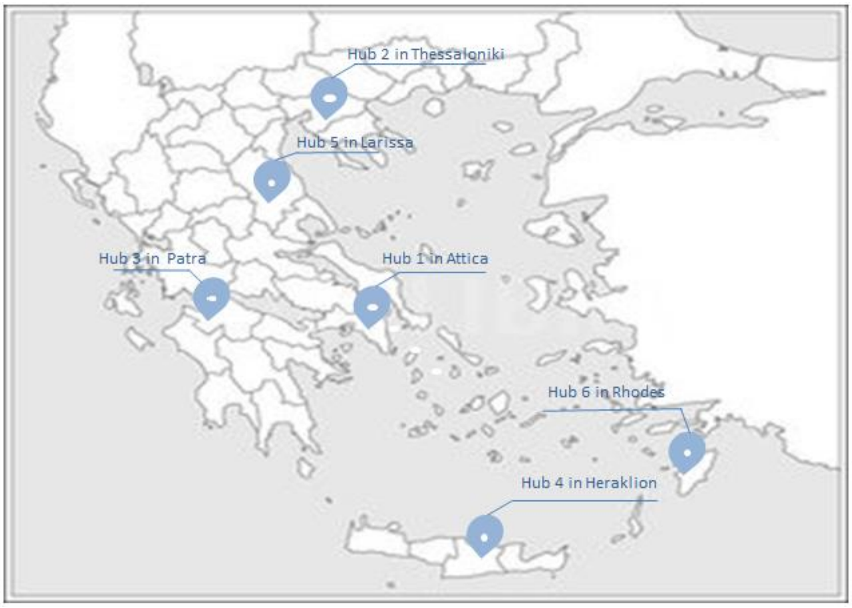

Figure 4.6 Proposed hub locations for p = 6

The seven hub case

In this case the seventh hub is proposed to be established at the prefecture group of Ioannina and specifically at the city of Ioannina (see Figure 4.7). The other six hubs remain invariant with respect to the previous case. Available motorway infrastructure connects the hub to the rest of mainland Greece through the major Egnatia and Ionia Odos motorways. Ionian island connectivity is served through the Igoumenitsa port. The hub may be located at the industrial area of Ioannina.

Figure 4.7 Proposed hub locations for p = 7

The eight hub case

The final scenario corresponds to the application of the p-hub median problem for p=8. While the locations of the seven hubs remain invariant as in the previous case a new hub is proposed in the prefecture group of Xanthi/Rhodope/ Drama and particularly in Komotini (see Figure 4.8). This location could connect Eastern Macedonia and Thrace with the rest of mainland Greece through a line haul service to the Thessaloniki hub. Egnatia Odos facilitates this service. Furthermore, the ports of Alexandroupoli and Kavala provide connectivity to the North Aegean region. The hub may be established in the industrial area of Komotini.

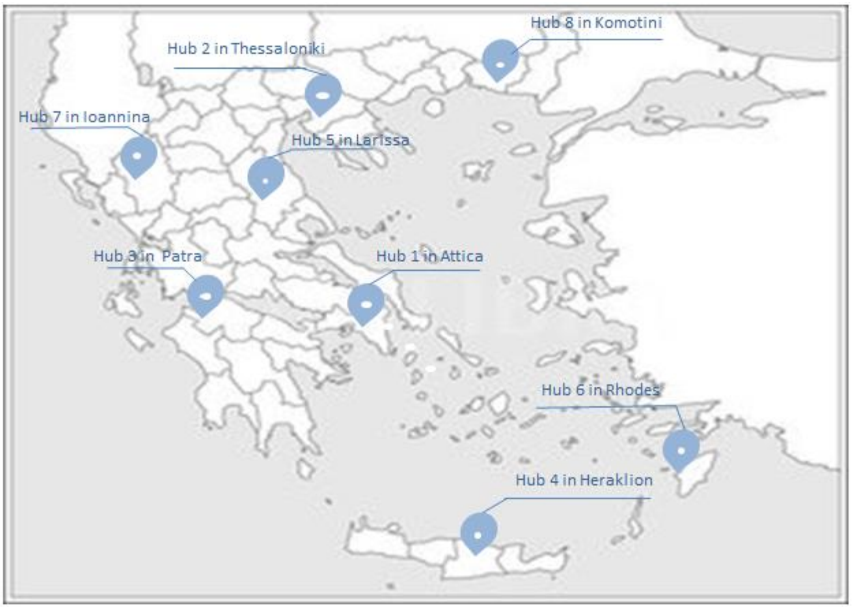

Figure 4.8 Proposed hub location for p=8

Synopsis of cases and related cost analysis

The essential features of the eight cases/scenarios discussed above are captured in Table 4.1.

Table 4.1 Synopsis of the cases

Number of hubs (p)	Location	Comments
1	Athens	▪ Largest city ▪ High GDP and population
2	Athens, Thessaloniki	▪ The two largest cities ▪ Line haul service between Northern and Southern Greece
3	Athens, Thessaloniki, Patras	▪ Hubs located in the three largest cities based on the GDP and population ▪ Patras hub can provide connectivity to Peloponnese and Western Greece
4	Athens, Thessaloniki, Patras, Heraklion	▪ Fourth hub located in Heraklion mainly because of the high freight flows of the region of Crete
5	Athens, Thessaloniki, Patras, Heraklion, Larisa	▪ Fifth hub located in Larisa ▪ Serves Thessaly and Central Greece regions
6	Athens, Thessaloniki, Patras, Heraklion, Larisa, Rhodes	▪ Sixth hub located in Rhodes mainly because of the high freight flows of the region of South Aegean
7	Athens, Thessaloniki, Patras, Heraklion, Larisa, Rhodes, Ioannina	▪ Hub located at Ioannina provides services to Epirus and the Ionian Islands
8	Athens, Thessaloniki, Patras, Heraklion, Larisa, Rhodes, Ioannina, Komotini	▪ Eighth hub located in Komotini; could serve Eastern Macedonia and Thrace as well as the North Aegean islands

4.3 Economies of scale and costs

The cost values of the eight scenarios/cases may be obtained from the values of the objective function. Since these values do not represent actual tone-hours (due to the normalization process described in Appendix A), we provide relative results by considering the highest cost among all cases to be 100. The variation of the total transportation cost with respect to the number of hubs is represented in Figure 4.9.

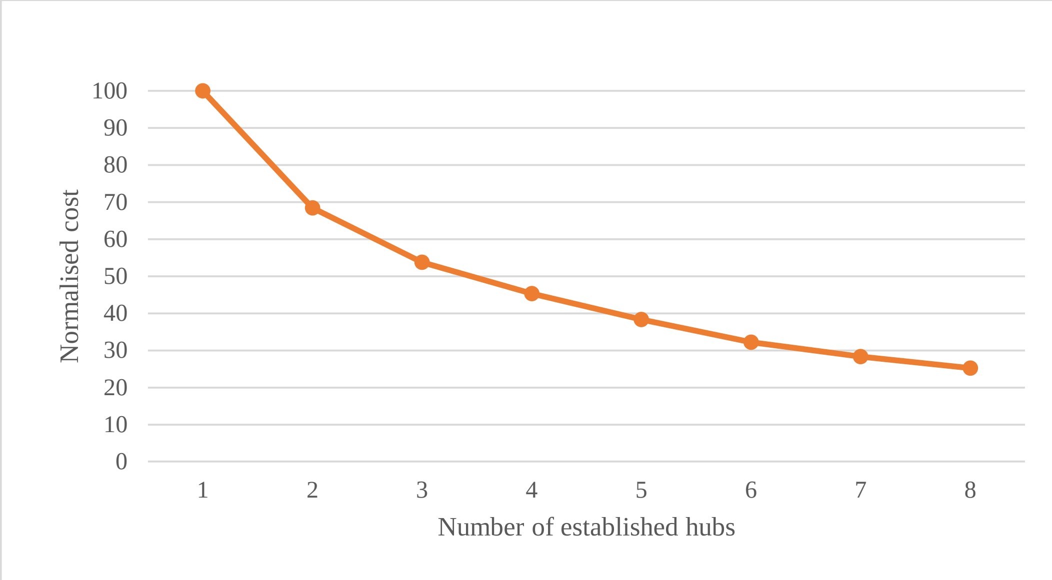

Figure 4.9 Normalized transportation cost as a function of the number of established hubs

As shown in Figure 4.9 increasing the number of established hubs decreases transportation costs significantly. This is due to the fact that the establishment of additional hubs creates more intensive line haul services capitalizing on economies of scale and reducing the number of network links.

Nevertheless, establishing more hubs calls for increased investment and hub operational costs. It also adds transshipment times. These considerations have not been taken into account in the present work. As a result, the most efficient choice may change from p = 8. This analysis presents a great opportunity for future work.

Furthermore, the discount factor plays an important role in the decision, since it denotes the economies of scale for the problem. To study the effect of α, we examined the six hub case with α=0.6, α=0.7, α=0.8 and α=0.9. For all experiments, the results indicate that the locations of the hubs remained the same but the total cost of transportation decreased significantly as the value of α decreased. That is because the cost for the inter-hub transportation was reduced. Figure 4.10 represents the reduction of the total transportation cost as the value of α becomes smaller. As in the previous Figure 4.9, we provide relative results by considering the highest cost among all cases to be 100.

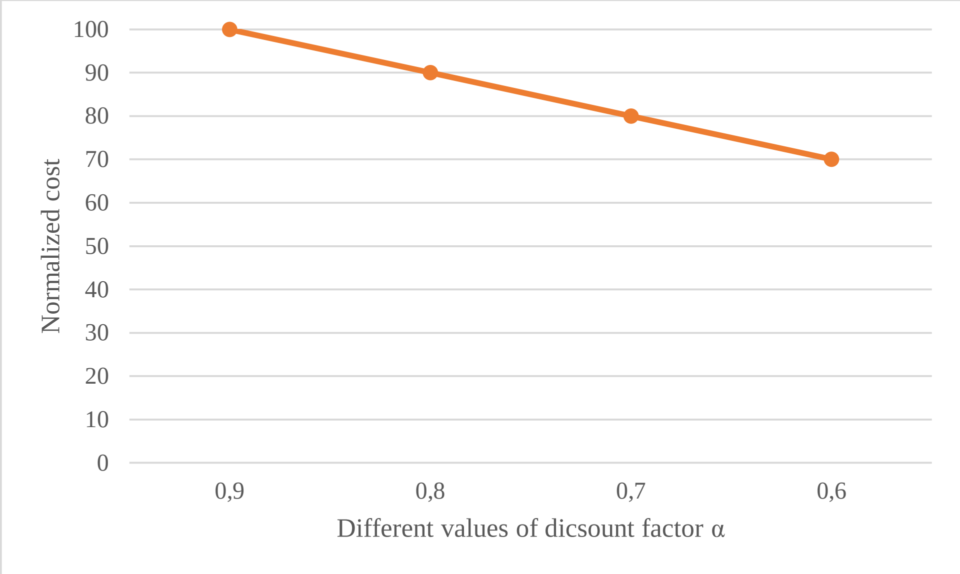

Figure 4.10 Transportation cost with different values of α factor for six hub case.

Chapter 5 Conclusions

In the present thesis, we presented and analyzed the design of a national freight transport network. Specifically, we set out to select the locations of the network hubs and, as a consequence, the line haul services between them. The design was guided by the selection and application of an appropriate mathematical programming problem.

In order to set up the mathematical model, we estimated key aspects of the network such as the nodes and the arcs, as well as important problem parameters. Regarding the nodes of the network, we performed a grouping analysis based on GDP and the geographical location. For the network arcs, we used Greece’s major motorway network, as well as significant marine connections.
Regarding the demand, we used data provided by the Hellenic Statistical Authority regarding freight transport among the 14 regions of Greece. These data were processed further to create a 27 x 27 origin-destination demand matrix. Concerning the cost parameter, we identified the different types of transport between the node pairs of the

network. In a case of mainland-island node connectivity, we determined the service ports that will connect each mainland node with the islands nodes. Concerning road transport, we determined the related distance and estimated the transport time based on an average speed assumption. Concerning marine transport, the estimation of the transport time was based on the times provided in official websites shipping companies, suitably adjusted to consider waiting at origin ports. The cost (time) matrix was created using the above estimates.

Using the network configuration, the estimated demand, and costs, we set up the selected mathematical model in Mathworks Matlab using the Gurobi function. To do so, we formed the input matrices of this function for the objective function and the problem constraints.

A series of experiments was conducted in order to identify the hub locations for different number of hubs. Specifically, we tested cases from 1 to 8 hubs. The results obtained were quite reasonable in all cases with respect to the importance of local market, hub connectivity infrastructure, and reach in the surrounding areas.

In addition to the suitability of the model and its results, significant conclusions of the work include the following:

- Considerable reduction of the transport cost results for increasing number of hubs. For example, the cost reduction resulting when the number of hubs is increased from 1 to 3 hubs is approximately 45%; from 1 to 8 hubs the resulting cost reduction is approximately 75%
- When varying the discount factor α, the location of the hubs remained invariant, but the transportation cost changed, as expected.

Further research may investigate a more advanced grouping of demand areas to define the network nodes. Grouping may take into account three dimensions: geography (proximity), GDP and population and may use an effective clustering method. Furthermore, in this work we didn’t take into consideration the operational and investment cost of establishing a hub. Thus, further research in network design may consider these costs, as well as hub and transport capacities Finally, international transport could be taken into account by setting the gates of the country as nodes of the network and by considering the related flows in the o-d matrix.

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Appendix A. : Min-max normalization of the O-D transport matrices

Min-max normalization is used in statistics and the goal is to change the numeric scale of a data set. Min-max normalization converts the numerical scale of the dataset between 0 and 1. The formula is used to achieve this is the following (Mustaffa, 2011):

$$X_n = \frac{X_o - X_{min}}{X_{max} - X_{min}} \tag{4.1}$$

Where,

X_n: is the new variable within the range 0 and 1

X_o: the current value of variable X

X_{max}: a maximum value of the whole data set

X_{min}: minimum value of the whole data set

Table A.1 Normalized Demand Matrix

	Evros	Xanthi ,Rhodope, Drama	Kavala, Thasos	Imathia, Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis, Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza, Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfy,Lefkada,Cephalonia	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia,Corithia	Messenia, Laconia	Attica	Lesbos/ Chios, Samos	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evros	0.023492	0.041821	0.023664	0.002141	0.007850833	0.00122	0.000197	0.000134	0.000185	0.000182	6E-05	9.47E-05	6.26E-05	0	7.09E-05	0.00017	3.76E-05	4.46E-05	4.43E-05	0	0	0.001313	8.81E-05	0	0	0	0
Xanthi ,Rhodope, Drama	0.041821	0.074451	0.042127	0.003811	0.013976415	0.002171	0.00035	0.000238	0.000329	0.000325	0.00011	0.000169	0.000112	0	0.000126	0.000303	6.69E-05	7.94E-05	7.89E-05	0	0	0.002337	0.000157	0	0	0	0
Kavala,Thasos	0.023664	0.042127	0.023837	0.002156	0.007908363	0.001229	0.000198	0.000135	0.000186	0.000184	6.1E-05	9.54E-05	6.31E-05	0	7.14E-05	0.000172	3.78E-05	4.49E-05	4.47E-05	0	0	0.001322	8.88E-05	0	0	0	0
Imathia, Pella, Pieria	0.001736	0.003091	0.001749	0.031717	0.116315394	0.018069	0.002158	0.001467	0.001047	0.001032	0.00163	0.002553	0.001688	0.000332	0.000419	0.001008	0.000329	0.00039	0.000388	0.000596	0.0002	0.009664	0.000122	5.4E-05	4.44E-05	0.000192	0.000124245
Thessaloniki, Chalkidiki	0.006367	0.011334	0.006413	0.116315	0.426558208	0.066263	0.007914	0.005381	0.003838	0.003786	0.00596	0.009362	0.006191	0.001217	0.001537	0.003696	0.001205	0.00143	0.001422	0.002186	0.000733	0.035442	0.000449	0.000198	0.000163	0.000706	0.000455639
Kilkis, Serres	0.000989	0.001761	0.000996	0.018069	0.066262915	0.010293	0.001229	0.000836	0.000596	0.000588	0.00093	0.001454	0.000962	0.000189	0.000239	0.000574	0.000187	0.000222	0.000221	0.00034	0.000114	0.005506	6.97E-05	3.08E-05	2.53E-05	0.00011	7.07804E-05
Kozani	0	0	0	0.005409	0.019836154	0.003081	0	0	0.00157	0.001549	0.00062	0.00097	0.000642	0	8.21E-05	0.000197	0.000407	0.000483	0.000481	0	0	0.002023	0	0	0	0	0
Grevena, Kastoria, Florina	0	0	0	0.003678	0.013488013	0.002095	0	0	0.001068	0.001053	0.00042	0.00066	0.000436	0	5.58E-05	0.000134	0.000277	0.000329	0.000327	0	0	0.001375	0	0	0	0	0
Arta, Preveza, Thesprotia	6.31E-05	0.000112	6.35E-05	0.000986	0.003614084	0.000561	0.000142	9.67E-05	0.14258	0.140653	0.00061	0.000957	0.000633	0.000386	0.001594	0.003833	0.000829	0.000984	0.000979	0	0	0.017503	0	0	0	0	0
Ioannina	6.22E-05	0.000111	6.27E-05	0.000972	0.003565245	0.000554	0.00014	9.54E-05	0.140653	0.138752	0.0006	0.000944	0.000624	0.000381	0.001573	0.003781	0.000818	0.000971	0.000966	0	0	0.017266	0	0	0	0	0
Karditsa, Trikala	5.19E-05	9.24E-05	5.23E-05	0.000817	0.002997511	0.000466	0.000698	0.000475	0.001072	0.001058	0.05935	0.093154	0.061602	0.000491	0.000466	0.00112	0.001809	0.002148	0.002136	0.000938	0.000315	0.004817	0	0	0	0	0
Larissa	8.14E-05	0.000145	8.2E-05	0.001283	0.004704916	0.000731	0.001096	0.000745	0.001683	0.001661	0.09315	0.146215	0.09669	0.000771	0.000731	0.001758	0.00284	0.003372	0.003353	0.001472	0.000494	0.00756	0	0	0	0	0
Magnesia	5.39E-05	9.59E-05	5.43E-05	0.000848	0.003111313	0.000483	0.000725	0.000493	0.001113	0.001098	0.0616	0.09669	0.06394	0.00051	0.000483	0.001162	0.001878	0.00223	0.002217	0.000973	0.000327	0.005	0	0	0	0	0
Zakynthos,	0	0	0	0.000109	0.000398536	6.19E-05	0	0	0.000268	0.000264	0	0	0	0.038841	0.00032	0.00077	0	0	0	0	0	0.005451	0	0	0	0	0
Aetolia-Acarnania	4.16E-05	7.41E-05	4.2E-05	0.000465	0.001705395	0.000265	0.000109	7.4E-05	0.001161	0.001145	4.8E-05	7.51E-05	4.97E-05	0.003523	0.100452	0.241521	0.000751	0.000892	0.000887	0.002127	0.000714	0.011278	0	0	0	5.93E-05	3.82887E-05
Achaea, Elis	0.0001	0.000178	0.000101	0.001118	0.004100342	0.000637	0.000262	0.000178	0.002791	0.002753	0.00012	0.000181	0.000119	0.00847	0.241521	0.580698	0.001806	0.002144	0.002132	0.005114	0.001716	0.027116	0	0	0	0.000143	9.20589E-05
Boetia	3.92E-05	6.98E-05	3.95E-05	0.000451	0.001655706	0.000257	0	0	0.00046	0.000454	0.00032	0.000505	0.000334	0.000121	0.001051	0.002526	0.000424	0.000503	0.0005	0.06755	0.022664	0.008826	0	3.58E-05	2.94E-05	0.00051	0.000329504
Euboea	4.65E-05	8.29E-05	4.69E-05	0.000536	0.001965719	0.000305	0	0	0.000547	0.000539	0.00038	0.0006	0.000397	0.000143	0.001247	0.002999	0.000503	0.000597	0.000594	0.080198	0.026908	0.010479	0	4.25E-05	3.49E-05	0.000606	0.000391201
Evrytania, Phthiotis, Phocis	4.63E-05	8.24E-05	4.66E-05	0.000533	0.001955023	0.000304	0	0	0.000544	0.000536	0.00038	0.000597	0.000395	0.000143	0.00124	0.002983	0.0005	0.000594	0.000591	0.079762	0.026762	0.010422	0	4.23E-05	3.48E-05	0.000603	0.000389072
Argolis, Arcadia, Corinthia	0.0002	0.000357	0.000202	0.002103	0.007710635	0.001198	0	0	0.000268	0.000265	0.00179	0.00281	0.001858	0.000198	0.001761	0.004234	0.149607	0.17762	0.176653	0.001796	0.000603	0.071424	0	0	0	0.000264	0.000170783
Messenia, Laconia	6.72E-05	0.00012	6.77E-05	0.000705	0.00258706	0.000402	0	0	9.01E-05	8.89E-05	0.0006	0.000943	0.000624	6.65E-05	0.000591	0.00142	0.050196	0.059595	0.05927	0.000603	0.000202	0.023964	0	0	0	8.87E-05	5.7301E-05

	Evros	Xanthi ,Rhodope, Drama	Kavala, Thasos	Imathia, Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis, Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza, Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfy,Lefkada,Cephalonia	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia,Corithia	Messenia, Laconia	Attica	Lesbos/ Chios, Samos	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Attica	0.000372	0.000662	0.000375	0.007903	0.028983355	0.004502	0.001006	0.000684	0.009401	0.009274	0.00562	0.008829	0.005838	0.005933	0.009677	0.023267	0.026835	0.03186	0.031686	0.024925	0.008363	1	0.00288	0.004518	0.003716	0.001036	0.000669091
Lesbos/	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002696	0.041695	0.000829	0.000682	0	0
Dodecanese	0	0	0	4.45E-05	0.000163061	2.53E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00127	0	0.129689	0.106677	0	0
Cyclades	0	0	0	3.66E-05	0.000134127	2.08E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001045	0	0.106677	0.087748	0	0
Heraklion, Lasithi	0	0	0	0.000166	0.000607457	9.44E-05	0	0	0	0	4.3E-05	6.75E-05	4.46E-05	0.000247	5.39E-05	0.00013	5.54E-05	6.58E-05	6.55E-05	0	0	0.002496	0	0	0	0.117429	0.075824411
Rethymno, Chania	0	0	0	0.000107	0.000392237	6.09E-05	0	0	0	0	2.8E-05	4.36E-05	2.88E-05	0.000159	3.48E-05	8.37E-05	3.58E-05	4.25E-05	4.23E-05	0	0	0.001612	0	0	0	0.075824	0.048960067

Table A.2 Normalized Cost Matrix

	Evros	Xanthi ,Rhodope , Drama	Kavala,Thasos	Imathia , Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis , Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza, Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfu (Kerkyra), Chephalonia/Ithaca, Lefkada	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia, Corinthia	Messenia, Laconia	Attica	Lesbos/ Lemnos, Samos/Ikaria, Chios	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evros	0	0.030662	0.08513	0.21461	0.175461	0.145175	0.243781	0.285983	0.361111	0.325425	0.297428	0.261859	0.29508	0.47738505	0.408243	0.449329	0.379072	0.437238	0.324427	0.484311	0.573937	0.468229	0.407363	1	0.660159	0.836243	0.855612
Xanthi ,Rhodope, Drama	0.030662	0	0.053846	0.183326	0.144177	0.113891	0.212497	0.254698	0.329769	0.294082	0.266085	0.230575	0.263796	0.44610093	0.376959	0.418045	0.347788	0.405954	0.293143	0.453027	0.542653	0.436945	0.376079	0.968716	0.628875	0.804959	0.824328
Kavala,Thasos	0.08513	0.053846	0	0.128212	0.089063	0.058894	0.157442	0.199584	0.274713	0.239027	0.21103	0.17552	0.208682	0.39098689	0.321845	0.362931	0.292674	0.35084	0.238088	0.397913	0.487539	0.381831	0.320612	0.913602	0.573761	0.749844	0.769214
Imathia, Pella, Pieria	0.21461	0.183326	0.128212	0	0.042518	0.08965	0.032188	0.074331	0.149459	0.113773	0.105673	0.091704	0.124866	0.26573303	0.196591	0.237677	0.208917	0.267083	0.154272	0.305058	0.362285	0.298074	0.450444	0.829845	0.490004	0.666088	0.685457
Thessaloniki, Chalkidiki	0.175461	0.144177	0.089063	0.042518	0	0.050559	0.071689	0.113832	0.188961	0.153275	0.125277	0.089767	0.12293	0.30523437	0.236151	0.277178	0.20698	0.265146	0.152335	0.312219	0.401845	0.296137	0.411295	0.827908	0.488067	0.664151	0.68352
Kilkis, Serres	0.145175	0.113891	0.058894	0.08965	0.050559	0	0.11888	0.161022	0.236151	0.200465	0.172468	0.136958	0.17012	0.35242467	0.283283	0.324369	0.25417	0.312336	0.199526	0.359409	0.448977	0.343327	0.381126	0.875098	0.535258	0.711341	0.73071
Kozani	0.243781	0.212497	0.157442	0.032188	0.071689	0.11888	0	0.048564	0.118117	0.08243	0.074331	0.069635	0.105086	0.23444892	0.165307	0.206393	0.187435	0.247303	0.13279	0.273715	0.331001	0.278294	0.479674	0.810065	0.470224	0.646308	0.665677
Grevena, Kastoria, Florina	0.285983	0.254698	0.199584	0.074331	0.113832	0.161022	0	0	0.163429	0.127742	0.119643	0.115769	0.15122	0.2797023	0.210619	0.251646	0.23351	0.293437	0.178924	0.319028	0.376313	0.324427	0.521817	0.856199	0.516358	0.692441	0.71181
Arta, Preveza, Thesprotia	0.361111	0.329769	0.274713	0.149459	0.188961	0.236151	0.118117	0.163429	0	0.043692	0.107845	0.143707	0.178748	0.19553453	0.047683	0.088769	0.169885	0.241316	0.15797	0.156151	0.213378	0.202989	0.596946	0.73476	0.394919	0.571003	0.590372
Ioannina	0.325425	0.294082	0.239027	0.113773	0.153275	0.200465	0.08243	0.127742	0.043692	0	0.072159	0.108021	0.143062	0.15996572	0.090882	0.13191	0.213025	0.232805	0.138894	0.199291	0.256577	0.246188	0.561259	0.777959	0.438118	0.614202	0.633571
Karditsa, Trikala	0.297428	0.266085	0.21103	0.105673	0.125277	0.172468	0.074331	0.119643	0.107845	0.072159	0	0.034477	0.069518	0.2241187	0.154977	0.196063	0.11976	0.159027	0.065174	0.2061	0.320671	0.190017	0.533262	0.721789	0.381948	0.558031	0.5774
Larissa	0.261859	0.230575	0.17552	0.091704	0.089767	0.136958	0.069635	0.115769	0.143707	0.108021	0.034477	0	0.033831	0.25998098	0.190839	0.171646	0.11618	0.176048	0.061535	0.223121	0.317267	0.207039	0.497752	0.73881	0.398969	0.575053	0.594422
Magnesia	0.29508	0.263796	0.208682	0.124866	0.12293	0.17012	0.105086	0.15122	0.178748	0.143062	0.069518	0.033831	0	0.29502154	0.175344	0.175285	0.119819	0.156327	0.065057	0.2034	0.297545	0.187317	0.530914	0.719089	0.379248	0.555331	0.5747
Zakynthos, Corfu (Kerkyra), Chephalonia/Ithaca, Lefkada	0.477385	0.446101	0.390987	0.265733	0.305234	0.352425	0.234449	0.279702	0.195535	0.159966	0.224119	0.259981	0.295022	0	0.329006	0.280113	0.377487	0.442755	0.390341	0.357531	0.404428	0.404428	0.802376	0.936199	0.596359	0.772442	0.783711
Aetolia-Acarnania	0.408243	0.376959	0.321845	0.196591	0.236151	0.283283	0.165307	0.210619	0.047683	0.090882	0.154977	0.190839	0.175344	0.3290056	0	0.047272	0.128388	0.199819	0.108726	0.114654	0.171939	0.16155	0.559499	0.693322	0.353481	0.529564	0.548934
Achaea, Elis	0.449329	0.418045	0.362931	0.237677	0.277178	0.324369	0.206393	0.251646	0.088769	0.13191	0.196063	0.171646	0.175285	0.28011316	0.047272	0	0.095754	0.161022	0.108608	0.075798	0.122695	0.122695	0.520643	0.654466	0.314625	0.490709	0.510078
Boetia	0.379072	0.347788	0.292674	0.208917	0.20698	0.25417	0.187435	0.23351	0.169885	0.213025	0.11976	0.11618	0.119819	0.37748718	0.128388	0.095754	0	0.04692	0.053201	0.089591	0.183737	0.068168	0.466116	0.599939	0.260098	0.436182	0.455551
Euboea	0.437238	0.405954	0.35084	0.267083	0.265146	0.312336	0.247303	0.293437	0.241316	0.232805	0.159027	0.176048	0.156327	0.44275535	0.199819	0.161022	0.04692	0	0.092761	0.08513	0.179276	0.043457	0.441405	0.575229	0.235388	0.411471	0.43084

	Evros	Xanthi, Rhodope, Drama	Kavala, Thasos	Imathia, Pella, Pieria	Thessaloniki, Chalkidiki	Kilkis, Serres	Kozani	Grevena, Kastoria, Florina	Arta, Preveza, Thesprotia	Ioannina	Karditsa, Trikala	Larissa	Magnesia	Zakynthos, Corfu (Kerkyra), Chephalonia/Ithaca, Lefkada	Aetolia-Acarnania	Achaea, Elis	Boetia	Euboea	Evrytania, Phthiotis, Phocis	Argolis, Arcadia, Corinthia	Messenia, Laconia	Attica	Lesbos/Lemnos, Samos/Ikaria, Chios	Dodecanese	Cyclades	Heraklion, Lasithi	Rethymno, Chania
Evrytania, Phthiotis, Phocis	0.324427	0.293143	0.238088	0.154272	0.152335	0.199526	0.13279	0.178924	0.15797	0.138894	0.065174	0.061535	0.065057	0.39034125	0.108726	0.108608	0.053201	0.092761	0	0.139834	0.233979	0.123751	0.521699	0.655523	0.315682	0.491765	0.511134
Argolis, Arcadia, Corinthia	0.484311	0.453027	0.397913	0.305058	0.312219	0.359409	0.273715	0.319028	0.156151	0.199291	0.2061	0.223121	0.2034	0.35753108	0.114654	0.075798	0.089591	0.08513	0.139834	0	0.094169	0.046803	0.444751	0.578574	0.238734	0.414817	0.434186
Messenia, Laconia	0.573937	0.542653	0.487539	0.362285	0.401845	0.448977	0.331001	0.376313	0.213378	0.256577	0.320671	0.317267	0.297545	0.40442791	0.171939	0.122695	0.183737	0.179276	0.233979	0.094169	0	0.140949	0.538897	0.67272	0.332879	0.508963	0.528332
Attica	0.468229	0.436945	0.381831	0.298074	0.296137	0.343327	0.278294	0.324427	0.202989	0.246188	0.190017	0.207039	0.187317	0.40442791	0.16155	0.122695	0.068168	0.043457	0.123751	0.046803	0.140949	0	0.396328	0.530151	0.190311	0.366394	0.385763
Lesbos/Lemnos, Samos/Ikaria, Chios	0.407363	0.376079	0.320612	0.450444	0.411295	0.381126	0.479674	0.521817	0.596946	0.561259	0.533262	0.497752	0.530914	0.80237595	0.559499	0.520643	0.466116	0.441405	0.521699	0.444751	0.538897	0.396328	0	0.928099	0.588259	0.764342	0.783711
Dodecanese	1	0.968716	0.913602	0.829845	0.827908	0.875098	0.810065	0.856199	0.73476	0.777959	0.721789	0.73881	0.719089	0.93619919	0.693322	0.654466	0.599939	0.575229	0.655523	0.578574	0.67272	0.530151	0.928099	0	0.722082	0.898165	0.917534
Cyclades	0.660159	0.628875	0.573761	0.490004	0.488067	0.535258	0.470224	0.516358	0.394919	0.438118	0.381948	0.398969	0.379248	0.5963586	0.353481	0.314625	0.260098	0.235388	0.315682	0.238734	0.332879	0.190311	0.588259	0.722082	0	0.558325	0.577694
Heraklion, Lasithi	0.836243	0.804959	0.749844	0.666088	0.664151	0.711341	0.646308	0.692441	0.571003	0.614202	0.558031	0.575053	0.555331	0.7724418	0.529564	0.490709	0.436182	0.411471	0.491765	0.414817	0.508963	0.366394	0.764342	0.898165	0.558325	0	0.081491
Rethymno, Chania	0.855612	0.824328	0.769214	0.685457	0.68352	0.73071	0.665677	0.71181	0.590372	0.633571	0.5774	0.594422	0.5747	0.78371113	0.548934	0.510078	0.455551	0.43084	0.511134	0.434186	0.528332	0.385763	0.783711	0.917534	0.577694	0.081491	0