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Assessing the potential for development and competitiveness of gateway ports

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To my Family

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Abstract

This thesis focuses on the evaluation and ranking of competing gateway cargo ports in view of their development potential. For port evaluation we have identified 27 suitable and interesting criteria form the literature. In order to evaluate the standing of the port after future investments, one would need to estimate the potential demand that the port will serve, given these investments (Demand is one of the 27 aforementioned criteria). For this purpose, we have developed a model that estimates this future demand by optimizing logistics cost and handling/transportation time of cargo to/from the hinterland area using Goal Programming. In order to arrive to a fair comparison between competing ports using the above criteria, we computed appropriate criteria weights, with the use of four different weight determination methods, namely AHP, BWM, Entropy and CRITIC. For ranking the competing ports using the selected criteria and their weights, we employed four MCDM (Multi – Criteria Decision Making) methods, namely PROMETHEE II, TOPSIS, VIKOR and WASPAS.

The method has been applied to the Port of Alexandroupolis, currently under privatization, and we considered as competing ports those of Thessaloniki, Kavala, Burgas, Varna and Constanza that may serve the same hinterland of SE Europe. Alexandroupolis was evaluated under two states: Current state and future state after investments. The results indicated a significant variability of the results among weight determination criteria and evaluation methods. To address this issue we applied the most consistent methods for criteria weight determination and port evaluation. Using this approach, it appears that after investments, Alexandroupolis' rank increases from 5^{th} to 2^{nd} among the six competing ports. This indicates that investing in the port of Alexandroupolis will significantly enhance the port's demand, function and reputation in Eastern Mediterranean.

Περίληψη

Η παρούσα διπλωματική εργασία επικεντρώνεται στην αξιολόγηση και κατάταξη ανταγωνιστικών λιμένων - πύλης, με βάση τις αναπτυξιακές τους δυνατότητες. Για την αξιολόγηση των λιμένων εντοπίσαμε 27 κατάλληλα και ενδιαφέροντα κριτήρια από τη βιβλιογραφία. Για να αξιολογηθεί η κατάσταση ενός λιμένα μετά από πιθανές επενδύσεις, θα πρέπει αρχικά να πραγματοποιηθεί η εκτίμηση της πιθανής ζήτησης που θα εξυπηρετήσει το λιμάνι, έπειτα από τις αντίστοιχες επενδύσεις (Η ζήτηση αποτελεί ένα από τα 27 προαναφερθέντα κριτήρια). Για το σκοπό αυτό, έχουμε αναπτύξει ένα μοντέλο που εκτιμά αυτήν τη πιθανή μελλοντική ζήτηση μέσω βελτιστοποίηση του κόστους και χρόνου διακίνησης/μεταφοράς φορτίου προς/από την ενδοχώρα χρησιμοποιώντας την μέθοδο του Προγραμματισμού Στόχων. Για να φτάσουμε σε μια δίκαιη σύγκριση μεταξύ των ανταγωνιστικών λιμένων χρησιμοποιώντας τα παραπάνω κριτήρια, υπολογίσαμε τα κατάλληλα βάρη των προαναφερόμενων κριτηρίων, με τη χρήση τεσσάρων διαφορετικών μεθόδων προσδιορισμού βάρους, συγκεκριμένα AHP, BWM, Entropy και CRITIC. Για την κατάταξη των ανταγωνιστικών λιμένων χρησιμοποιώντας τα επιλεγμένα κριτήρια και τα βάρη τους, χρησιμοποιήσαμε τέσσερις μεθόδους MCDM (Multi – Criteria Decision Making), συγκεκριμένα PROMETHEE II, TOPSIS, VIKOR και WASPAS.

Η μέθοδος εφαρμόστηκε στο λιμάνι της Αλεξανδρούπολης, που βρίσκεται υπό ιδιωτικοποίηση, και θεωρήσαμε ως ανταγωνιστικά λιμάνια αυτά της Θεσσαλονίκης, της Καβάλας, του Μπουργκάς, της Βάρνας και της Κωνστάντζα που ενδέχεται να εξυπηρετούν την ίδια ενδοχώρα της ΝΑ Ευρώπης. Η Αλεξανδρούπολη αξιολογήθηκε σε δύο καταστάσεις: Τρέχουσα κατάσταση και πιθανή μελλοντική κατάσταση μετά από επενδύσεις. Τα αποτελέσματα έδειξαν μια σημαντική μεταβλητότητα των αποτελεσμάτων μεταξύ των κριτηρίων προσδιορισμού βάρους και των μεθόδων αξιολόγησης. Για την αντιμετώπιση αυτού του ζητήματος, εφαρμόσαμε τις πιο σταθερές μεθόδους για τον προσδιορισμό βάρους κριτηρίων και την αξιολόγηση λιμένων. Με την πραγματοποίηση αυτής της μεθοδολογίας, αποδεικνύεται ότι μετά από επενδύσεις, ο λιμένας της Αλεξανδρούπολης αυξάνεται σε βαθμό προτίμησης συγκριτικά με τους ανταγωνιστικούς λιμένες από 5η στον 2η μεταξύ των έξι ανταγωνιστικών λιμένων. Αυτό δείχνει ότι η επένδυση στο λιμάνι της

Αλεξανδρούπολης θα ενισχύσει σημαντικά τη ζήτηση, τη λειτουργία και τη φήμη του λιμανιού στην Ανατολική Μεσόγειο.

Table of Contents

Table of Figures

List of Tables

Chapter 1 Introduction

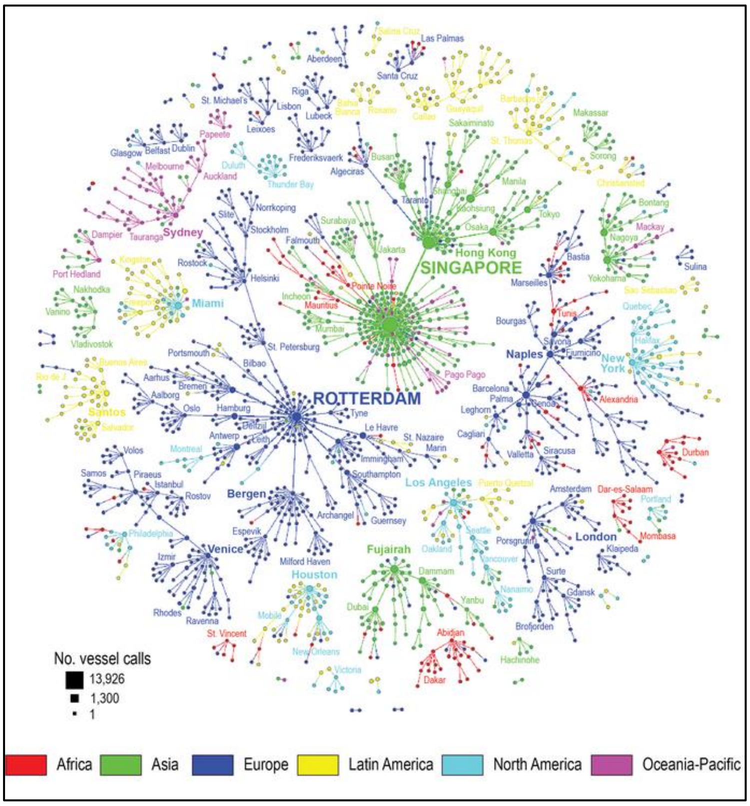

Figure 1.1 – Maritime Network example (world-seastems.cnrs.fr)

Maritime transportation is extensively used in global trade for transporting high amounts of cargo between countries. The underlying maritime transportation network consists of nodes (ports) and arcs (routes). The routes are the paths that cargo vessels follow between ports while transporting cargo or on their way to a port from which they will pick up cargo.

The routes change over the years in order to increase the efficiency and quality of transportation. In recent years, special emphasis is placed, in addition to cost, to customer service and sustainability.

The selection of routes and the related ports has attracted significant research interest, given the evolving importance of different markets, as well as geopolitical changes, including the strengthening of the Asian production base. The importance of ports depends on the region of interest, type of port, and the perspective of selection. Regions around the world have different characteristics (e.g. exporting regions, regions that support access to major markets, regions that act as global trade hubs, etc.) Concerning the type of ports, the latter may be classified as follows (Ducruet *et al.*, 2018):

- Transhipment ports
- Gateway ports
- Local cargo-based ports.

Transhipment ports are hubs where there is a transfer of cargo between line haul vessels and distribution vessels. Gateway ports supply a hinterland region. Local cargo ports serve smaller, local communities.

The perspective of port selection relates to the users of the port. For example, shippers are mainly interested in cost efficiency and transport times, while shipping liners are more interested in the port's location, operations efficiency and network reach. Investors are also interested in port location, state of the port in terms of equipment, workforce, reputation among liners, and return on investment.

In this thesis we focus on the assessment of gateway ports from the perspective of the investor. To do so we develop a novel methodology that includes

- Analysis of port development strategies
- Development of port selection criteria with respect to two perspectives
- Analysis of candidate ports based on proposed criteria
- Prediction of future transport flows based on multi-criteria optimization process
- Selection of the most appropriate methods to assess competing ports (in their current and future state)

The proposed methodology has been applied to assess the investment opportunity for the Port of Alexandroupolis (currently in the process of privatization), taking into account the characteristics and state of competing gateway ports in the Balkans and Southeastern Europe, such as Thessaloniki, Kavala, Varna, Burgas and Constanza.

The contributions of this thesis are the following:

- The method of goal programming was used in order to estimate the potential cargo handled by the port of Alexandroupolis. The results have been used in the port assessment process
- An original set of port assessment criteria were developed focusing on the interests of investors when selecting a potential port for investment
- A plethora of weight determination methods and Multi-Criteria Decision Making methods were applied to the case study when assessing the ports. Methods that led to inconsistent results were identified and eliminated from the final ranking.

The structure of the remainder of the thesis is as follows: Chapter 2 analyzes the relevant literature and introduces how port development strategies are reviewed as well as related case studies. Chapter 3 introduces the assessment method of a port as a major gateway with original port assessment criteria from the perspective of investors, which are analyzed using various Multi Criteria Decision Making methods. In Chapter 4, the hinterland targets and transportation routes of the aforementioned ports are introduced, and the maritime network is constructed. Furthermore, in this Chapter, the potential cargo flows between the hinterland and the related ports are estimated for a possible state of the Alexandroupolis port, based on the proposed mathematical programming model. Chapter 5 introduces an approach to select the most appropriate methods for this assessment and the application of the case study. Finally, in Chapter 6 we summarize the conclusions of this work and propose directions for further research.

Chapter 2 Background

2.1 Relevant Literature

Cargo port development has been a topic of discussion for almost a century. However with the prevalence of globalization, significant changes are transforming the maritime industry. New generation competitive ports are being developed (e.g. Tangier Med, Morocco), while the importance of some mature ports is reducing (e.g. Gioia Tauro).

Ducruet *et al.* (2018) discuss port development strategies that lead to the rise of new generation ports, as well as cases of declining ports, which do not follow the appropriate development strategy. Based on this reference, there are three types of development strategies for a port, namely:

- Transhipment hub strategy
- Hinterland expansion strategy
- Local cargo base expansion strategy.

Each strategy has different characteristics that indicate the port's potential. For example, key characteristics of a port that is appropriate to become a transshipment hub are the favorable location and appropriate infrastructure for efficient handling of cargo. Other aspects are also considered in the literature as important when selecting the development strategy for a port. For example, shipper companies prefer ports that deliver fast transportation times with the lowest possible cost.

Table 2.1 presents important research papers that focus on criteria to assess the value of a port with respect to different perspectives, as well as the methods used for port comparison. Columns 3-5 of the Table indicate the perspective for assessing the value of a port; that is the shipper's, forwarder's or ship operator's perspective. Column 6 presents the related port strategy as discussed above, and the last column, column 7, notes the multicriteria method used for port assessment.

Table 2.1 – Port selection criteria per perspective and evaluation methods

		PERCPECTIVE				
AUTHORS	ARTICLE	SHIPPER	FORWARDER	DEEP - SEA OPERATOR	STRATEGY	MCDM METHOD
Kurt et.al (2015)	An AHP Decision Support Model for the Hub port choice for the Shipping Liners in the Mediterranean region	X			Transshipment hub	AHP
Chen et. al (2017)	Transshipment hub selection from a shipper's and freight forwarder's perspective	X	X		Transshipment hub	AHP
Ugboma et.al (2006)	An Analytic Hierarchy Process (AHP) Approach to Port Selection Decisions – Empirical Evidence from Nigerian Ports	X			Transshipment hub	AHP
Kramberger et.al (2015)	Port Hinterland Modelling Based on Port Choice				Hinterland expansion	-
Weigmans et.al (2008)	Port and terminal selection by deep-sea container operators			X	Transshipment hub	-
Chang et.al (2008)	Port selection factors by shipping lines: Different perspectives between trunk liners and feeder service providers	X			Transshipment hub	-
Ergin et.al (2015)	Selection of Container Port Using ELECTRE Technique	X			Transshipment hub	ELECTRE
Chou (2009)	Application of FMCDM model to selecting the hub location in the marine transportation: A case study in southeastern Asia	X			Transshipment hub	Fuzzy MCDM
Van Dyck and Ismael (2015)	Multi-Criteria Evaluation of Port Competitiveness in West Africa Using Analytic Hierarchy Process (AHP)	X			Transshipment hub	AHP
Kavirantha et. al (2018)	Transshipment Hub Port Competitiveness of the Port of Colombo against the Major Southeast Asian Hub Ports	X			Transshipment hub	Discrete Choice Model
Gharakani et. al (2016)	A multi criteria decision-making model for selecting hub port for Iranian marine industry	X			Transshipment hub	AHP - TOPSIS
Sumner and Rudan (2018)	A Hybrid MCDM approach to port selection	X			Transshipment hub	BWM - ABC Algorithm
Icaza and Parnell (2018)	Container Port Selection in West Africa: A Multi-Criteria Decision Analysis	X			Transshipment hub	MAVT with VFT and AFT
Rezaei et. al (2019)	Port performance measurement in the context of port choice: an MCDA approach	X	X	X	Hinterland expansion	BWM
Lirn et. al (2003)	Transhipment Port Selection and Decision-making Behaviour: Analysing the Taiwanese Case	X			Transshipment hub	AHP - FMCDM

Kurt *et al.* (2015) compares three Mediterranean ports (Giao Tauro, Piraeus and Candarli) using Analytic Hierarchy Process (AHP) with the following criteria:

- Location
- Connectivity
- Port operation performance
- Capacity

- Investment opportunity, as well as their respective sub-criteria.

Given that the current study performs an extensive analysis of a Mediterranean port and of the related investment opportunities, we adopted some appropriate criteria from this study (see Chapter 6).

Chen *et al.* (2017) compared transhipment hub ports in Asia. Note that the importance of attributes of European, Asian, American and African ports may differ, and these differences are reflected in the weights of the relevant criteria. For example, while in Asian ports berth length is an important attribute, in European ports, efficiency is very significant from the perspective of the shipper and freight forwarder. A high number of criteria were examined in the above study, and stakeholders indicated appropriate and, oftentimes different, weights for each criterion. Some of the criteria of the study were deemed suitable for the current work; i.e.

- Natural factors
- Catchment area
- Stability of government policies.

Ugboma *et al.* (2006) uses the Analytic Hierarchy Process (AHP) to compare four Nigerian ports, from a shipper's perspective. Some criteria used in this work, provide a solid basis for assessment. For example, the criterion "adequate infrastructure" may describe:

- Infrastructure condition
- Container capacity or container yard size
- Rail terminal capacity.

Selected criteria from this work have been used in our study.

Chang *et al.* (2008) focuses on shipping liners and feeder service providers and proposes some interesting assessment criteria that are important from an investor's point of view, such as:

- Possibility of niche market
- Customs and government regulations

- Management and worker relationship (Labor relations)
- IT ability and availability

The above criteria were used in our study.

Ergin *et al.* (2015) compares three Turkish ports with respect to their container terminals using the Multi – Criteria Decision Making (MCDM) method ELECTRE. We have used some of their criteria to assess the port value for investors, i.e:

- Infrastructure condition
- Port facilities and equipment
- Port berthing time
- Container handling efficiency
- Container yard efficiency
- Port container charge
- EDI computer system
- Good reputation related to damage and delays
- Personnel quality.

Chou (2009) used Fuzzy Multi – Criteria Decision Making methods (MCDM) to solve the problem of marine hub location selection in southeastern Asia. Even though many of the proposed criteria are related to transhipment ports, some are also important for a gateway port and have been adopted in this thesis; i.e:

- Closeness to main route
- Frequency of ship calls
- Infrastructure condition
- Container yard and customs efficiency.

Van Dyck and Ismael (2015) used Analytic Hierarchy Process (AHP) to evaluate port competitiveness in West Africa, between six ports. Very interesting and original criteria were proposed in this study, such as peace and conflict instability, indicating the different attributes that may be relevant in different geopolitical locations.

Kavirantha *et al.* (2018) assesses the competitiveness of the port of Colombo with other major ports in the area. The author in this study organizes the criteria within two main categories. First, there are quantitative criteria, comprising Monetary and Time sub criteria (and each with their individual lower level criteria). Secondly there are non – quantitative criteria, comprising the location, operation and liner related sub-criteria, each with their own lower level criteria. We have adopted a subset of appropriate criteria in our study.

Gharakani *et al.* (2016) applies a combination of Multi – Criteria Decision Making (MCDM) methods for the evaluation of six transshipment hubs in Iran. First, the criteria, extracted from the literature, are weighted using Analytic Hierarchy Process. Subsequently, the six ports of Abbas, Imam, Assaluyeh, Bushehr, Chabahar and Khorramshahr are evaluated using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method.

Sumner and Rudan (2018) consolidated a large number of criteria from previous studies. The criteria weights were calculated using the Best – Worst Method (BWM), while port evaluation was completed using the Artificial Bee Colony (ABC) algorithm.

Icaza and Parnell (2018) studied container port selection in West Africa. Given the difference in the economic status of African ports when compared to the rest of the world, more emphasis is put on criteria that rely on economic stability, infrastructure condition and political stability. Rather than using data from surveys, this study creates a decision analysis model using Multi Attribute Value Thinking (MAVT) with Value Focused Thinking (VFT) and Alternative Focused Thinking (AFT) based on quantitative data extracted from port authorities in order to identify the best and worst performing ports in the region.

Lirn *et al.* (2003) assessed transhipment ports in Taiwan, using similar criteria to previous studies. The weights of the criteria were first calculated using the Analytic Hierarchy Process (AHP) and subsequently the ports were compared using a Fuzzy Multi – Criteria Decision Making (MCDM) method.

The aforementioned articles refer to port selection from the perspective of shipper and carriers, whilst targeting the selection of the best possible transhipment hub port in the area. Limited literature exists regarding the selection of gateway ports, especially from the perspective of deep-sea operators or forwarders. Examples include the studies of Weigmans (2008) and Rezaei (2019). Kramberger (2015), focused on port hinterland modelling and selection; they proposed criteria that are more relevant to gateway ports.

Inspired by this latter study, our thesis contributes to the selection of criteria important to gateway ports, from the perspective of possible port investors, which in many cases can be deep-sea operators (like COSCO or Evergreen). We have applied the proposed criteria and selection methodology to an extensive case study of the port of Alexandroupolis.

2.2 Port Development in the Mediterranean

In this Section we explain the process of port development in the Mediterranean, that is the steps to be performed in case a port is to evolve from a local coastal port to potentially a port of international importance. The basis of the material presented her is the book of Ducruet *et al.* (2018)- *Maritime Networks, Port Efficiency, and Hinterland Connectivity in the Mediterranean*. That is, although the material is not original, it is important in setting some fundamental concepts for the thesis and, thus, it has been deemed necessary to included it here.

2.2.1 Port development strategies

There are two main components that should be considered for the successful development of a port, i.e.:

1. The strategy and the roadmap that the port needs to follow in order to achieve its goals
2. The characteristics of the port, for example its deviation from the trunk line (main route) or the berth depth (Ducruet *et al.*, 2018).

The development strategy is unique to each port, since each is different in many aspects (target market, location, continent, etc.). Thus, the port authority has to apply the appropriate strategy that corresponds to the needs of the relevant market in order to increase the attraction of the port. There are also other parameters that may affect the evolution of a port. For example, if a port authority sees an opportunity to develop the port as a transhipment hub, criteria such as location or berth depth are considered very important by shippers and freight forwarders. On the contrary, if the authority considers development as a hinterland port, other criteria are deemed more important.

Based on Ducruet *et al.*, 2018, three main markets for a port emerge, i.e.

- its Local cargo base
- the Hinterland
- other ports, through Transhipment.

An important factor that must be taken into consideration is that these three markets are interrelated, that is, the expansion of one of those can affect the others. For example, an important port for cargo transhipment can develop a large hinterland, since a strong cargo base can be considered suitable to expand the port's hinterland connections. Of course, the ability of a port to serves a large hinterland area is based on the existence of the required infrastructure and logistics facilities.

The port authority may focus in either one of those markets or in all three of them; however, the development of each market has a different time frame.

- Transhipment attraction, for example, requires less time, since it can be implemented by attracting shipping alliances to increase the port's connectivity, without major investments being involved. Note, however, that in the Mediterranean, hub ports are very competitive and, therefore, it is easy to lose important connections to other ports
- To expand a port's hinterland reach, major investments must be made in order to construct the required infrastructure and connect the port to its hinterland

(rail, roads). This, of course, is more time consuming than attracting shipping alliances as in the transhipment case

- In order to upgrade a port's local cargo base, land for logistics and manufacturing must be either leased or constructed, in order to increase its attractiveness.

2.2.1.1 Typology of connectivity based on market served

In order to further to identify the strategy that best suits a port, based on the markets that it will serve, Fig. 2.1, proposed by Ducruet *et al.* (2018) shows the types of connectivity that a port can achieve, based on its maritime and hinterland connections.

Different types of port development, Carruthers 2018

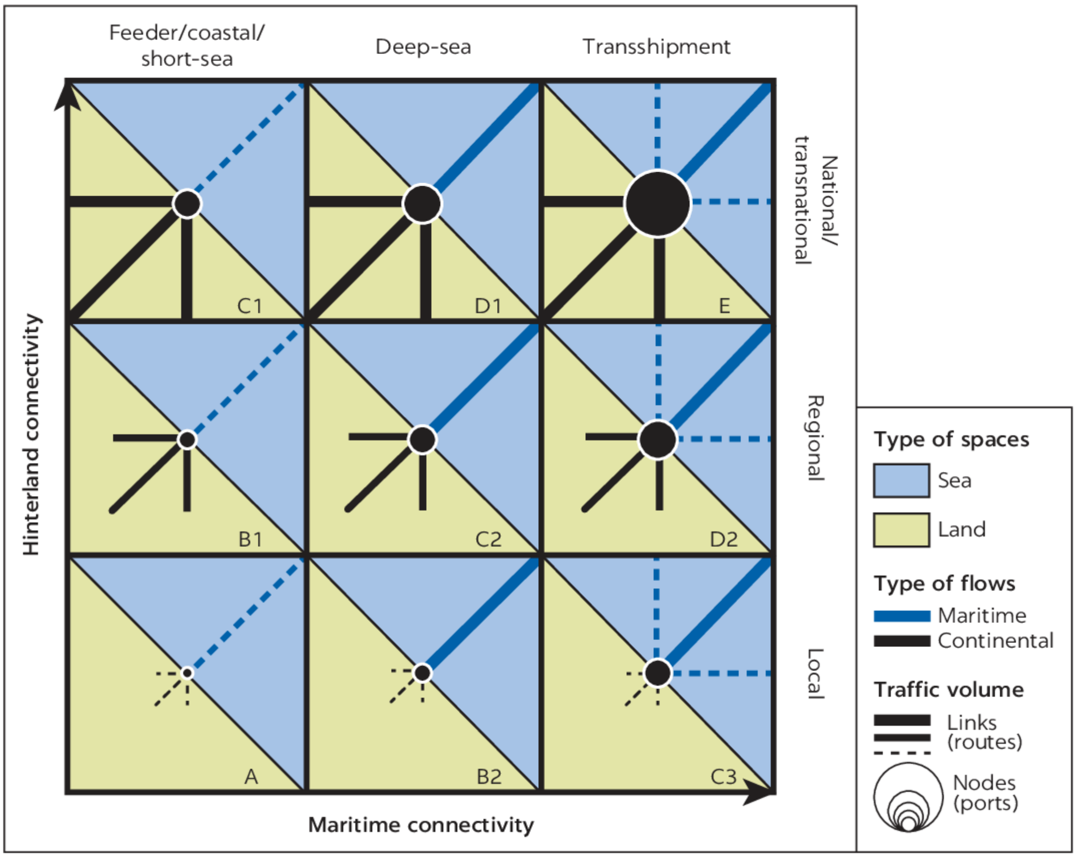

Figure 2.1 – Ducruet 2018 - Maritime Networks, Port Efficiency and Hinterland Connectivity in the Mediterranean

The figure includes two axes, *maritime connectivity* and *hinterland connectivity.*

- Maritime connectivity refers to the number of connections of a port has with other ports. For example, a transhipment hub (e.g., Valencia, Spain) has multiple connections a) with other ports of the main trunk line and b) with feeder ports. The main goal of this type of port is the distribution of cargo as efficiently as possible to many final destinations. A small port that only serves its cargo base does not have many connections (e.g., Chios, Greece) and mainly depends on its main cargo supplier. As is shown in Fig. 2.1 the more connections a port has, it is located further in the *x* axis and the less connections it has, it is located at the initial part of the *x* axis.

- Hinterland connectivity refers to the number of inland landlocked (and not only) destinations supplied by a port and is related to the level of modal connectivity of the port (rail, road, airport). For example, the port of Barcelona, in addition to its local cargo base, serves the cities of Zaragoza and Madrid among others and has extensive rail connections with international cities, including Lyon, from where the port is connected to even further hinterlands (Van den Berg and De Langen, 2011). Again, a small port like Chios, Greece for example, does not have the influence to supply distant hinterlands, since it is located on an island and can mainly serve its local cargo base. In Fig. 2.1 the more extensive hinterland connections a port has, the further is located along the *y* axis; ports with limited hinterland connectivity are located at the beginning part of the *y* axis.

Figure 2.2 – Ducruet, 2018 - Maritime Networks, Port Efficiency and Hinterland Connectivity in the Mediterranean (port Barcelona example)

Figure 2.1 also indicates the intensity of the port’s links and connectivity. The line width represents the intensity of connections that a port has (the thicker the line, the more the connections) and the circle (nodes) represent the intensity of connections that a port has on both types of connectivity (maritime & hinterland).

<u>Examples of ports in every cell category:</u>

Cell A: Ports with very low hinterland and maritime connectivity with low demand, limited investments in infrastructure, possibly an unfavourable location, limited berths, limited depth and limited land area. Examples are: Chios – Greece, Alghero - Italy. These ports are considered local feeder/coastal ports.

Cell B2: Ports in cell B2 have improved maritime connections in contrast with ports of cell A; i.e. some deep-sea cargo transportation is served by these ports. However hinterland connectivity is still underdeveloped. Examples are: Iraklion – Greece, Ceuta – Spain. These ports can be characterized as local deep-sea ports.

Cell C3: Ports with fully developed maritime connectivity, which are full-fledged transhipment hubs, with many connections and shipping alliances involved. However, due to various reasons, their hinterland is limited or inexistent for certain reasons, including:

- the port is located on an island
- the transhipment strategy has been selected for the port's development
- investments were not made to increase modal connectivity.

Examples are: Marsaxlokk – Malta, Colombo – Sri Lanka. These ports are characterized as local transhipment ports.

Cell B1: Ports with increased hinterland connectivity in comparison to category A ports. Thus, there is some form of modal connectivity with other hinterlands; however the maritime connectivity is weak. Examples are: Alexandroupoli – Greece, Ploce – Croatia. These ports are considered regional short-sea ports.

Cell C2: Ports with the same level of connectivity as B1 ports. However, the maritime connectivity of these ports is more developed. A port that falls into this category is: Thessaloniki – Greece. These ports are described as regional deep-sea ports.

Cell D2: Ports with the same level of hinterland connectivity as ports in C2 and B1. Their maritime connectivity is fully developed, to the point where they can be considered to be transhipment hubs. Examples of ports that fall into this category are: Piraeus – Greece, Valencia - Spain, Giao Tauro – Italy. All these ports are competing in the Mediterranean as the most dominant transhipment hubs is the region.

Cell C1: Ports with fully expanded hinterland connectivity to the point that these ports are connected to the market of other competing ports; however, the maritime connectivity is still limited, for reasons such as:

- The port still focuses on its hinterland's expansion, mainly investing in the attractiveness of its services and in infrastructure to increase of maritime connectivity
- The port's location is not ideal.

Examples of ports that fall into this category are Algiers – Algeria, Varna – Bulgaria. These ports are considered transnational short-sea shippers.

Cell D1: Ports with both fully developed hinterland connectivity and, in contrast to the C1 ports, with increased maritime operations. Examples of ports in this category are: Tanger Med – Morocco, Marseilles – France. These ports can be considered transnational deep-sea ports.

Cell E: In this final E category belong ports that are fully developed from every aspect of connectivity. These ports are connected with an expanded hinterland and have fully developed infrastructure and logistics facilities, so their services are efficient. They are targets of the major shipping companies. Examples of ports in this category are: Rotterdam – Netherlands, Antwerp – Belgium, Shanghai – China. These ports can be considered as transnational transhipment or gateway ports.

Of course, ports do not have a permanent position in the above matrix since their state evolves over time. For example, Tangier Med – Morocco some years ago was in cell C1 and in B1 prior to that; however it used the hinterland expansion strategy in order to reach its current state in cell D. Obviously, as ports may improve their position, they may also be downgraded, if the port authority does not take appropriate actions.

2.2.1.2 Possible port strategies for development

A port's starting and desired ending state greatly affect the strategy that will be followed. Below we are discussing some strategic path examples.

<u>The Transhipment Hub Strategy</u>

The transhipment hub strategy aims to rapidly develop the transhipment services of a port (by improving port efficiency, connectivity, attracting shipping alliances etc.) and use its position as a popular hub to increase its hinterland connections, as well as its cargo base. In Fig. 2.1 above, this can be presented by the path from A=>B2=>C3 and then D2=>E. However, this is not easy to achieve, since:

- constructing the required infrastructure will take years and investments.
- most transhipment hubs are located near the trunk line.

Additionally, the transhipment hub strategy poses a risk since the competition between Mediterranean ports is fierce. Consider for example the port of Djen-Djen – Algeria (Cherif, 2011): Even though it attracted the global terminal operator DP World, this did not produce sought after economic benefits, since:

- the port ’s Hinterland is limited
- the port faced fierce competition by neighbouring hubs.

The Hinterland Expansion Strategy

The hinterland expansion strategy aims to make the port reach more extensive hinterland areas. Extensive investments must be made in order to build the required infrastructure and increase the intermodal connectivity between the port and its hinterland (since the majority of hinterland areas are served through rail and road). By having an extensive number of intermodal connections, a port can become an attractive target for shipping alliances, who aim to transport their cargo further into the hinterland. This case is especially relevant in the Mediterranean, where competition between ports is fierce.

Interesting examples concern the ports of Antwerp and Hamburg, which in order to compete Rotterdam’s extensive intermodal network, invested in the development of their infrastructure and intermodal connectivity. This action resulted in the attraction of more shipping liners and forwarders to the ports.

Cargo Base Expansion Strategy

The cargo base expansion strategy aims to the development of a strong cargo local base, which can support logistics and manufacturing activities in the area. The strategy depends on the economic size as well as the population of the local city/area. However, creating a successful local cargo base can prove difficult if the markets are not adjacent or the port is outside the optimal range from the main shipping route.

The government also has an important role here, since if it intervenes and achieves to attract terminal operations, invests in the improvement of the local transportation network, as well as in the value-added services that the port offers, it will support considerably the development of the port as a prominent cargo base.

2.2.2 Characteristics of a successful port

As was mentioned in the beginning of Section 2.2, the two factors that must be taken into consideration when planning a port's development are:

- The strategy the port authority chooses to apply
- The criteria that make the port stand out amongst its competitors.

The factors that determine if a port can develop more efficiently are the characteristics of the port. Not every port can be equally effective as transhipment hub and not every port has the potential to be a great gateway port. The differences in criteria when selecting a suitable port development strategy are introduced in this Section.

2.2.2.1 Transhipment hub port indicators

Many authors have elaborated on the deciding factors when choosing a suitable hub port. However, those factors differ based on the perspective from which a port is analyzed. The majority of studies examine the hub port selection problem from a shipper's perspective, although there is literature that examines a freight forwarders point of view, or even a mix of both perspectives in order to achieve a more complete result.

In order for a port to attract shippers, its authority must understand and match their needs and develop a unique positioning strategy. Positioning involves the differentiation of the port and its services compared to its competitors.

- Shippers will choose those ports, which can act as transhipment nodes for their cargo and can handle those goods reliably and efficiently
- From the forwarders' perspective, the hub selection is the core to strategic route optimization, which could considerably affect on-time delivery, operational efficiency, and service quality in cargo handling and customs clearance (Chen *et al.*, 2017).

After analyzing seminal articles of the literature (Ugboma *et al.*,2006 – Chen *et al.*, 2017 – Kurt *et al.*, 2015), it can be said that the criteria for hub port selection are common. Typical criteria include:

Table 2.1 – Common transhipment hub selection criteria

Main Criteria	Sub - criteria
Location	Distance from main route
	Distance from other markets/ports
Port Service Charges	-
Port Operation Performance	Crane Number and Performance
	Loading / Discharging Time
	Port Woring Hours
	Modal Connectivity
	Port Capacity
	Berth Depth
Port traffic	Availability of Captive Cargo (availability of import/export from the port's hinterland)
	Frequency of ship visit
Investment Opportubity	Government Strategies
	Port Authority Strategies
Efficient Customs Procedure	-

2.2.2.2 Indicators of hinterland-oriented ports

In the case of ports that target to increase their influence over more distant hinterlands, not much literature exists. In order to increase hinterland influence and competitiveness, considerable investments that range from infrastructure to intermodal connectivity upgrades may be necessary. Even in this case, many decision makers may choose competing ports for hinterland supply, because of intrinsic criteria (such as port location). For example, during his research, Kramberger (2014) pointed out that the eastern part of Germany is supplied by the port of Rotterdam, even though the port of Hamburg is closer and with an equal level of infrastructure and connectivity. This case study highlights the importance of selecting the most suitable strategy for the port’s development.

Of course, ports that focus on increasing transhipment flows will have a much more limited hinterland than gateway ports, since their first target is to establish their dominance over other ports in the sea and gain as many maritime connections as possible, while the target of the second category is to attract cargo flows in order to distribute the goods into the mainland.

From observations made on large gateway ports of the Mediterranean (e.g. Marseilles – France, Valencia – Spain), some indicators could be revealed (Ducruet *et al.*, 2018):

Table 2.2 – Common gateway port selection criteria

Main Criteria	Sub - criteria
Hinterland Volume (describes the volume of containers that arrive and depart from the hinterland)	-
Modal Split (the percentage of the total hinterland volume that is transported by train/barge)	-
Intermodal Connectivity	Frequency of Service
	Capacity of Servive
	Number of Competing Service Providers
	Number of Intermediate Stops
	Transit Time
Road Congestion	-
Linkage with Inland	-
Efficient Customs Procedure	-

2.2.2.3 Indicators for ports with a developed local cargo base

Again, as in the case of ports that target to increase their hinterland reach, not much literature exists for ports that try to increase their local cargo base operations. However, there are examples of ports that achieved radical growth following the enhancement of their local cargo base services.

Maybe the most successful example of a port that started form a local cargo base is the port of Barcelona. Since Barcelona is the main supplier for the Catalonia region, it means it already had a captive regional market and was connected to four rail corridors (Iberian, Ebro, Southern France, European), with the first two being connected with Zaragoza. In order to increase the port's strength, investments were made by the Barcelona Port Authority (APB) that included the upgrade of the rail connection with Zaragoza, a new intermodal terminal located in the area of Figueras and a logistics cluster in Perpignan. After these investments, a platform was provided for the development of logistics services in the nearby area, which ultimately attracted maritime flows to Barcelona. (Van den Verg and De Langen, 2011)

.

Other examples include Alexandria – Egypt, Izmir – Turkey, Naples – France, Rades – Tunisia. (Ducruet *et al.*, 2018)

Ultimately, some criteria were consolidated from references in the literature, that successful local cargo base ports share, which are presented in Table 2.3:

Table 2.3 – Common local cargo base port selection criteria

Local cargo base Criteria
Available land for leasing / rent / selling for logistics operators or manufacturers
Economic size and population of the local region
Frequency of ship calls
Modal connectivity
Investments
Government interventions, through which terminal operators could be attracted and have a positive effect on value added activities

Port selection criteria will be introduced Chapter 3 in further analyzed in Chapter 5, where a case study will be presented comparing the prospect of development of port Alexandroupolis, facing competition from nearby developed ports.

Chapter 3 Proposed Approach for Assessing a Port's Potential as a Gateway

3.1 Introduction

In this Chapter we provide the blueprint for the assessment of ports as potential major gateways, specifically in the Mediterranean and Black Sea regions. As was mentioned in Chapter 2, when assessing a port, it is important to understand its selected strategy for development. Not every port can be a good transhipment hub and not every port can be a good hinterland gateway. Given that in this thesis the main focus is the assessment of gateway ports, the criteria presented in the Section 3.2 are selected from the existing literature for cases of hinterland expansion strategies of ports.

However, criteria selection for gateway ports is only one aspect of the analysis. An assessment methodology must be constructed in order to efficiently evaluate one or several ports based on the above (multiple) criteria. In Section 3.3, the detailed analysis of the methodology and the evaluation method, which will be based on Multi-Criteria Decision Making, will be introduced.

3.2 Port Assessment Criteria

There are many different perspectives from which port characteristics can be analysed, for example, the perspectives of shipping liners, freight forwarders, deep-sea operators, investors etc. Each stakeholder category has different expectations and criteria when selecting a port to satisfy their needs. For example, shippers look for efficient transportation times and low costs, investors on the other hand look for ports with a favourable location and land for investment opportunities.

In this case, the analysis of the criteria will be conducted through the perspective of investors, however the criteria of shipping liners will also be presented to highlight their differences. Many authors have researched the reasoning behind the selection of certain ports for either transhipment or gateway functionality. Focusing on gateway ports, there is a plethora of commonly used criteria (e.g. water depth) as well as unique criteria, which differ based on each study. For example, when comparing ports in Africa, political stability can be considered a critical criterion for the final decision, in contrast with European port selection, where the aforementioned criterion has little to no weight. In Table 3.1 below, criteria consolidated from various studies are presented.

Table 3.1 – Gateway port selection criteria

Criteria	**Kurt *et al.* (2015)**	**Ugboma *et al.* (2006)**	**Chang *et al.* (2008)**	**Ergin *et al.* (2015)**	**Chen *et al.* (2017)**	**Chou (2009)**	**Van Dyck & Ismael (2015)**	**Kavirantha *et al.* (2018)**	**Sum of authors per criterion**
Location	✓	✓	✓		✓	✓	✓	✓	**7**
Catchment Area					✓				**1**
Port Connectivity	✓								**1**
Crane Number & Performance	✓	✓		✓	✓	✓	✓		**6**
Vessel Turnaround Time	✓			✓		✓	✓	✓	**5**
Container Throughput	✓		✓	✓		✓			**4**
Container Capacity	✓						✓	✓	**3**
Water Depth	✓		✓				✓		**3**
Berth Length	✓		✓				✓	✓	**4**
Infrastructure Condition		✓		✓	✓	✓		✓	**5**
Frequency of vessel calls		✓			✓	✓		✓	**4**
Inland Intermodal Connectivity			✓		✓	✓			**3**
Reputation for cargo damage & delays			✓	✓				✓	**3**
Possibility of niche market			✓						**1**
IT availability			✓	✓	✓	✓	✓	✓	**6**
Customs & Government regulations			✓		✓	✓		✓	**4**

Criteria	Kurt *et al.* (2015)	Ugboma *et al.* (2006)	Chang *et al.* (2008)	Ergin *et al.* (2015)	Chen *et al.* (2017)	Chou (2009)	Van Dyck & Ismael (2015)	Kavirantha *et al.* (2018)	Sum of authors per criterion
Labor Relations			✓	✓				✓	**3**
Stability of Government Policies					✓		✓		**2**
Investment plan						✓		✓	**2**

For the course of this thesis, the criteria selected for major gateway port assessment from an investor's perspective are a consolidation of unique and common criteria pinpointed throughout the literature and presented in Table 3.2.

Table 3.2 – Investor port criteria consolidated

Main Criteria	Sub - Criteria	Comment
Port Location	Distance from main poles of attraction	Distance from ports to the selected hinterland through roads
	Distance from main route (rail)	Distance from ports to the selected hinterland through rail
	Distance from main route (road)	Distance from ports to the selected hinterland through road
	Catchment area	The hinterland area which the ports supplies or has the potential to supply
	Natural Factors	The grade of the natural conditions of the port (ex. ice free)
Port Infrastructure	Infrastructure condition	Condition of installed infrastructure
	Container yard size	-
	Available land for expansion (seaside)	The existence of available sea area, to increase the port's size seaside
	Available land for expansion (portside)	The existence of available land for the port's expansion from the port side.
	Water depth	-
	Berth length	-
	Inland intermodal airport connectivity	The distance from the port to the closest airport
	Inland intermodal rail connectivity	Existence of rail connection with the port
	Reliability of rail connectivity	State of railway's network infrastructure
	Reliability of road connectivity	State of road's network infrastructure
	Container capacity	Container capacity is the amount of TEUs that can be stored in the port simultaneously
	Rail terminal capacity	The number of trains that can be simultaneously stationed at the port

Main Criteria	Sub - Criteria	Comment
Port Management	Possibility of niche market	Insight on whether the examined port has the potential to serve a niche (rare) market
	Labour relations	-
	Stability of government policies	This index represents the level of political stability
	Port reputation	-
	Customs & government regulations	This index describes the complexity of the handling of customs
Port Efficiency	Ship turnaround time	The time between the arrival and departure of a vessel
	Loaded (Export) cargo	Ths. tons of cargo that loaded in the examined port
	Unloaded (Import) cargo	Ths. tons of cargo that unloaded in the examined port
	Number of port calls	The number of times that vessels called to the port
	Road congestion	Time to drive from the port to the main national road
	IT availability	Use or not of information technology in the port

Table 3.3 presents the selection criteria for a gateway port from the liners' perspective, based on the literature analysed in Chapter 2 (Table 2.1). When comparing the criteria of Tables 3.2 and 3.3, there are very noticeable differences between the two perspectives (investor perspective vs. shipping liner perspective). While in both cases, port location, infrastructure, management and efficiency play an important part in port selection, for liners there are two additional main categories: port costs and cargo volume processed. Slight differences may be noted in the other main criteria.

Table 3.3 – Shipping liner port criteria consolidated

Main Criteria	Sub Criteria
Port Location	Distance from main poles of attraction
	Distance from main route (rail)
	Distance from main route (road)
	Catchment area
	Natural Factors
Port Infrastructure	Crane number and type
	Inland intermodal connectivity

Main Criteria	Sub Criteria
	Rail terminal cargo capacity
	Water depth
	Berth length
	Container Yard Size
	Infrastructure condition
Port Management	Cargo loss
	Cargo damage
	24 hour operation
	Port future development plan
	Communication with port
	Personnel quality
	Labor relations
	Stability of government policies
Port Costs	Un/loading fee from vessels
	Un/loading fee from truck
	Internal handling charge
	Warehousing charge
Port Cargo Volume	Transshipment share vs hinterland share
	Annual container throughput
	Import and Export balance
Port Efficiency	Ship turnaround time
	Container dwell time
	Truck processing time
	Container handling efficiency
	Service reliability
	Information technology availability
	Free Trade Zone
	Simplicity of customs procedure

3.3 Port Assessment Method

As already discussed, the port assessment method will be based on Multi – Criteria Decision Making (MCDM). Since the beginning of the 1960's, many advances have been made in MCDM methods. As a result, Important methods include:

- Analytic Hierarchy Process (AHP)
- (ELimination Et Choice Translating Reality) ELECTRE
- Decision making trial and evaluation laboratory (DEMATEL)
- Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE)
- The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)
- Analytic Network Process (ANP)
- Multi Criteria Optimization and Compromise Solution (VIKOR)
- Aggregation Decision Making (DM) Methods (Abbas Mardani, 2015)
- and many more.

There have been many instances, where a plethora of MCDM methods were used to compare and rank alternatives. The use of multiple methods in decision making is called Hybrid MCDM.

Gharakani *et al.* (2016), for example use the AHP and TOPSIS methods to evaluate six hub ports in Iran. First, five criteria (Port location, Port infrastructure, Hinterland economy, Port efficiency, Cost, Other criteria) and their respective sub – criteria are weighted using AHP. The results place the existence of a Free Trade Zone as the most important criterion and port berthing time length as the least important criterion. Subsequently, using the criteria weights, the TOPSIS method is used to evaluate six Iranian ports.

Sumner and Rudan (2018) also analyse transhipment hub port selection using the Hybrid MCDM approach of the Best-Worst method for weight determination and the ABC algorithm for port ranking. In this study, fifty criteria were identified and weighted, relevant to transhipment hub port selection for liner shippers.

Zavadskas (2014) also used hybrid MCDM methods for the evaluation of deep-sea ports in the Eastern Baltic Sea. First, twelve criteria, including efficiency of land use, accessibility to the marine terminals by rail, conservation of the natural sand beach and many more, are weighted and compared using Fuzzy – AHP. Additive Ration Assessment (ARAS) is used to compare four alternatives with seven decision makers.

De Icaza and Parnell (2018) apply a Multi Attribute Value Theory (MAVT) with Value – Focused Thinking (VFT) and Alternative Focused Thinking (AFT) to determine the most favourable port in West Africa out of six. The criteria used for this problem were consolidated from the existing literature and divided in main criteria and sub – criteria.

Rezaei (2019) use the Best – Worst Method to evaluate the weights of important port selection criteria following a very interesting approach. Using the calculated weights and grading them from the perspective of forwarders, shippers and carriers, port performance was assessed for different hinterland locations using different transportation.

There have been many more instances in which hybrid MCDM methods where used, not only in the marine sector. For example, Kusumawardani and Agintiara (2015) use the fuzzy AHP and TOPSIS methods in human resources, to determine the best possible candidate for the position of manager. Dadras (2014) utilize Fuzzy AHP for weight determination and Fuzzy TOPSIS to evaluate the most suitable lands for urban development in Iran. Komchornrit (2017) uses CFA-MACBETH and PROMETHEE for the selection of a dry – port location in southern Thailand.

In this case, as with the majority of case studies in the marine logistics sector, a combination of multiple MCDM methods will be used, to provide a result as objective as possible. The main addition that this thesis offers to the existing literature is the application of more than one criteria weight determination methods and MCDM methods in the port assessment process.

For weight determination of the selected criteria, four methods will be used:

- AHP

- Best – Worst method (BWM)
- CRITIC
- Entropy

For each set of criteria weights computed by the four aforementioned methods, four MCDM methods will be used for port evaluation:

- PROMETHEE II
- TOPSIS
- VIKOR
- WASPAS

Appendices A and B provide a detailed analysis with examples of the selected criteria weight determination and Multi Criteria Decision Making methods.

For a candidate port, two comparisons will be made, one concerning the current state of the port when compared to the other ports, and one including the potential state of the port, after investments. If the candidate port increases considerably its ranking when compared to the other ports after investments, it is then deemed worthy for investment.

The steps of the assessment method are the following:

Step 1: Determine values to the assessment criteria (Table 3.2). In the case of the candidate port, where the values of some criteria will be used after investment, a forecast must be made to estimate these values (as will be done in Chapter 4, where the potential imports and exports of Alexandroupolis are estimated)

Step 2: Apply the criteria weight determination methods for the current state of the competing ports, as well as and future state of the reference port. In order to compute the criteria weights, in this thesis we used the four methods mentioned above.

In AHP and BWM the final weight values are based on human judgment, in contrast with Critic and Entropy, for which the criteria weight values are based on each criterion’s contrast intensity (the deviation the of criterion compared with the rest of the criteria) and conflict (correlation of each criterion with other criteria). The fusion of contrast intensity and conflict provides the amount of information of each criterion (See Appendix A).

Step 3: Apply the Multi Criteria Decision Making (MCDM) methods for both states (current and possible after investments) of the candidate port. For every different weight value calculated in step 2, we apply the four MCDM methods mentioned above.

In total, there will be 16 results (8 for the current state and 8 for the possible future state).

Step 4: Selection of the most efficient assessment method. The results that will be provided by the application of Steps 2 and 3 will possibly yield inconsistencies. For example, TOPSIS may provide varying results for different weight determination methods and similarly AHP may provide varying results for every MCDM method. In order to arrive to a robust result, only the more consistent methods will be selected for the final decision (as shown in Chapter 5.6), whether to invest in the candidate port or not.

Chapter 4 Port of Alexandroupolis: Potential cargo flows of competing ports

4.1 Introduction

In the previous Chapter, a methodology was proposed for the assessment of ports as major gateways, that will be applied on Alexandroupolis port as a case study. However, before applying this methodology, the potential import and export cargo flows that may be handled by Alexandroupolis must be estimated, in order to provide the values to the corresponding criteria for the future (To be) state of the port. On the process of forecasting this demand of import and export flows, one should consider the ports that compete for the same hinterland and its import and export; i.e. the ports of:

- Thessaloniki
- Kavala
- Varna
- Burgas
- Constanta

All cargo flows that are handled by the competing ports (and Alexandroupolis) are published or will be estimated (from Eurostat or the respective port authorities). In this we will estimate the potential cargo flows that Alexandroupolis may take away from its competing ports, given the investments that will be applied and the new private management to take charge.

It is noted that the hinterland targets of all aforementioned ports are the following:

- Bulgaria
- Romania
- Moldova

- Ukraine
- Russia.

These countries, given their difference in size, GDP per capita, population, and seaport use (Ukraine for example transports the majority of its cargo via oil pipelines and trucks) have different demand in import and export of maritime cargo. For some countries, like Romania and Bulgaria, maritime demand is easily accessed via Eurostat while for other, like Russia and Ukraine, estimations need to be made. For Moldova, which is a landlocked country, an estimation was also made regarding maritime demand.

Given the knowledge of a port’s imports and exports, a linear goal programming Multi – Criteria Decision Making (MCDM) method was proposed to calculate the best possible distribution from port to hinterland and vice versa, using as criteria the time and cost of transportation. The results of the problem provide insight to:

- The amount of imported and exported cargo handled between the ports and the examined hinterland.
- The preference of use and amount of cargo transported via either rail or truck
- The potential cargo flows of Alexandroupolis port, which will be used in Chapter 5 for port comparison as per the methods presented in Chapter 3.

4.2 A Model for Estimating Cargo Demand per Port

In this Section, the model of the linear programming problem will be introduced and later applied on the case study in Section 4.5. The main objective is the solution of two problems:

- Amount of cargo transported from each port to the hinterland (Port cargo dispatching)
- Amount of cargo transported from the hinterland to each port (Port cargo attraction)

The solution of the aforementioned problems will provide insight to the potential cargo loaded (outgoing) and unloaded (incoming) in each competing port and in the process of making so, will indicate the Alexandroupolis port's potential to be a major gateway in the area of Eastern Europe and the Black Sea.

It should be noted that during this evaluation, the infrastructure of Alexandroupolis port is assumed to be appropriately upgraded.

4.2.1 Port cargo dispatching estimation model

In order to estimate the dispatched cargo from each of the competing ports to each of the hinterland regions, we developed a novel linear programming model described below.

- Objective: The objective of the problem is the minimization of transportation times and costs from the ports to the hinterland
- Decision variables: The decision variables are the amount of cargo to be transported from each port to each region of the hinterland
- Parameters: The parameters of the problem are:
    - Maximum capacity of dispatched cargo per port
    - Demand for import per hinterland region

The imports and exports per hinterland region are provided by either their respective Statistical Institutes or are estimations by the author. For example, Moldova is a landlocked country, thus there are no maritime imports and exports; however, there is a strong possibility that the imported/exported cargo will at some point use maritime transportation. All relevant parameters are calculated in Section 4.4.

As was mentioned, the main goal is the minimization of transportation times and costs between the ports and the hinterland. This translates to the problem below.

<u>Main Goal:</u>

$$\min \sum_{k=1}^{2} \sum_{i=1}^{6} \sum_{j=1}^{14} x_{ijk}{}^{p}, \qquad p = 1\ (time), 2\ (cost)$$

Where:

- k represents the mode of transport used for intermodal connectivity, where
    - k =1 is rail
    - k =2 is truck
- i represents the port of origin for the 6 ports introduced in Chapter 4.2, where:
    - i =1 is Alexandroupolis
    - i =2 is Thessaloniki
    - i =3 is Kavala
    - i =4 is Varna
    - i =5 is Burgas
    - i =6 is Constanta
- j represents the hinterland regions of each country (14 in total) that the cargo is exchanged with, introduced in Chapter 4.3, where:
    - j =1 is North Bulgaria
    - j =2 is South Bulgaria
    - j =3 is North Romania
    - j =4 is South Romania
    - j =5 is North Moldova
    - j =6 is Central Moldova
    - j =7 is South Moldova
    - j =8 is Independent Moldova
    - j =9 is North-west Ukraine
    - j =10 is South – east Ukraine
    - j =11 is Central Russia
    - j =12 is Southern Russia
    - j =13 is Northwestern Russia
    - j =14 is Volga Russia

- ${x_{ijk}}^p$ is the decision variable, that is the amount of cargo transported from port i to hinterland j using mode of transportation k for the parameter p (time or cost).

The problem constraints are:

$$\sum_{k=1}^{2}\sum_{j=1}^{14} x_{ijk}{}^{p} \leq c_i, \quad i = 1, \dots, 6$$

i.e. the amount of cargo transported from port $\boldsymbol{i}$ cannot exceed the capacity $\boldsymbol{c_i}$ of that port.

$$\sum_{k=1}^{2}\sum_{i=1}^{6} x_{ijk}{}^{p} \geq d_j, \quad j = 1, \dots, 14$$

i.e. the amount of cargo transported to hinterland region $\boldsymbol{j}$ must at least be equal to the demand $\boldsymbol{d_j}$ of this region.

$$\sum_{j=1}^{14} x_{ij1}{}^{p} \leq 2.920, \quad i = 1, 2, 4, 5, 6 \ (no\ Kavala)$$

i.e. the cargo transported using rail from port $\boldsymbol{i}$ towards hinterland $\boldsymbol{j}$ cannot exceed the capacity of 2.920 thousand tonnes per year (assumption that up to 10 trains depart the port daily, each transporting 800 tons of cargo).

It is noted that the cost minimization problem will provide a different result than the time minimization problem. Since both cost and time are important, the two objectives need to be considered in the same model, leading to a multi-objective model. We have selected to use goal programming to address the multi-objective problem (Supply Chain Management II Lecture, 2020). Under the goal programming method, first each problem must be solved individually to acquire the best result per each criterion. The application of goal programming introduces an additional constraint to the problem, which is essentially the normalized values (with the way of Tamiz *et al.,* 1998) of the time and cost parameters. Additionally, extra decision variables are added to the problem (s_i), that represent the difference between the optimal solutions per criterion and the new proposed solution of the multi-objective problem

Main Goal:

$$\min \sum_{p=1}^{2} ({s_p}^- + {s_p}^+)$$

Where:

- p is the number of evaluated criteria. In this case, there are two (2) criteria evaluated in time and cost
- ${s_p}^-$ is the deviation between the ideal value and the new value, computed after considering the p^{th} non – beneficial criteria. In this case study, both time and cost are non – beneficial criteria
- ${s_p}^+$ is the deviation between the ideal value and the new value, computed after considering the p^{th} beneficial criteria. In this case study there are no beneficial criteria, as time and cost are both non – beneficial

Additionally, another set of constraints is created, based on the number of criteria. Since in this case study the examined criteria are two (time and cost of transportation), a set of two constraints is created, where:

$$\sum_{k=1}^{2} \sum_{i=1}^{6} \sum_{j=1}^{14} {x_{ijk}}^p + {s_p}^- = B_p, \qquad for\ p = 1\ (time), 2\ (cost)$$

Essentially, the previous objective function now serves as a constraint where:

- ${x_{ijk}}^p$ is the objective function of the p^{th} criterion
- ${s_p}^-$ is the deviation between the ideal value and the new value, computed after considering the p^{th} non – beneficial criteria. In this case study, both time and cost are non – beneficial criteria.
- B_p is the optimal value of the p^{th} criterion

Given the introduction of the new constraints, the optimal values (B_p) must be normalized, in order to calculate the problem on the same scale. The normalization will be completed as suggested by Tamiz *et al.* (1998) and shown below.

$$\min \sum_{l=1}^{2} (\widehat{s_p^-} + \widehat{s_p^+})$$

$$f_p(x)\big/ n_p + \widehat{s_p^-} + \widehat{s_p^+} = 100, \qquad p = 1,2$$

$$\widehat{s_p^-}, \widehat{s_p^+} \geq 0, \qquad p = 1,2$$

Where:

$$\widehat{s_p^-} = \frac{s_p{}^-}{n_p}, \qquad \widehat{s_p^+} = \frac{s_p{}^+}{n_p}, \;\; n_p = \frac{B_p}{100}$$

and $f_p(x)$ is the objective function of the p^{th} parameter.

4.2.2 Port cargo attraction estimation model

For the estimation of cargo attracted by the competing ports from the examined hinterland, the main goal and decision variables remain the same with the previous problem, thus:

- Main goal: The reduction of transportation times and costs from the hinterlands to the ports
- Decision variables: Amount of cargo that will be transported from each hinterland to each port

The parameters change slightly, since now the evaluation is regarding cargo attraction. Thus, the parameters of this problem are:

  - Maximum capacity of loaded (imported) cargo per port
  - Exports of each hinterland.

The imports and exports per hinterland are provided by either their respective Statistical Institutes or are estimations by the author. All parameters are calculated in Section 4.4.

The main difference of the port cargo dispatching estimation model compared to the port cargo attraction estimation model are the constraints, that will be modified to fit the new problem. These are:

$$\sum_{k=1}^{2}\sum_{i=1}^{6} x_{jik}{}^{p} \leq \hat{c}_j, \quad j = 1, \dots, 14$$

Where:

- $\boldsymbol{x_{jik}{}^{p}}$ is the amount of cargo transported from hinterland $\boldsymbol{j}$ to port $\boldsymbol{i}$ and cannot exceed the exports $\boldsymbol{\hat{c}_j}$ of the hinterland $\boldsymbol{j}$.

$$\sum_{k=1}^{2}\sum_{j=1}^{14} x_{jik}{}^{p} \geq \hat{d}_i, \quad i = 1, \dots, 6$$

Where:

- $\boldsymbol{x_{jik}{}^{p}}$ is the amount of cargo transported from hinterland $\boldsymbol{j}$ to port $\boldsymbol{i}$ and must satisfy the demand $\boldsymbol{\widehat{d}_i}$ of port $\boldsymbol{i}$.

$$\sum_{i=1}^{5} x_{ji1}{}^{p} \leq 2.920, \quad j = 1, \dots, 14 \quad (excluding\ Kavala\ port)$$

Where:

- $\boldsymbol{x_{jik}{}^{p}}$ is amount of cargo transported using rail from hinterland $\boldsymbol{j}$ towards port $\boldsymbol{i}$ and cannot exceed the capacity of 2.920 th. tonnes (assumption that 10 trains reach the port daily, each transporting 800 tons of cargo)

The goal programming model and the normalization by Tamiz *et al.* (1998) remain unchanged from the previous problem of port cargo dispatching estimation model.

4.3 Targeted Catchment Area and Competitors

What the hinterland countries of interest have in common is that they are located on the most eastern part of Europe and are adjacent to the Black Sea (except Moldova, which is a landlocked country).

Every port in the list of competing ones for the same hinterland area has a different route of cargo flow when supplying each individual country of this hinterland. In the following Sections, each port's network with every country of the hinterland will be presented, as well as the different transportation times and costs it takes to supply the hinterland countries and regions from these ports and vice versa. It should be noted that the transportation times and costs will be calculated from a common reference point in the Mediterranean Sea (Fig. 4.1) where cargo vessels pass while a) travelling to (or from) the Dardanelles Strait to pass through Marmara Sea and reach the Black Sea ports or b) headed to the Greek ports of Thessaloniki, Kavala or Alexandroupolis.

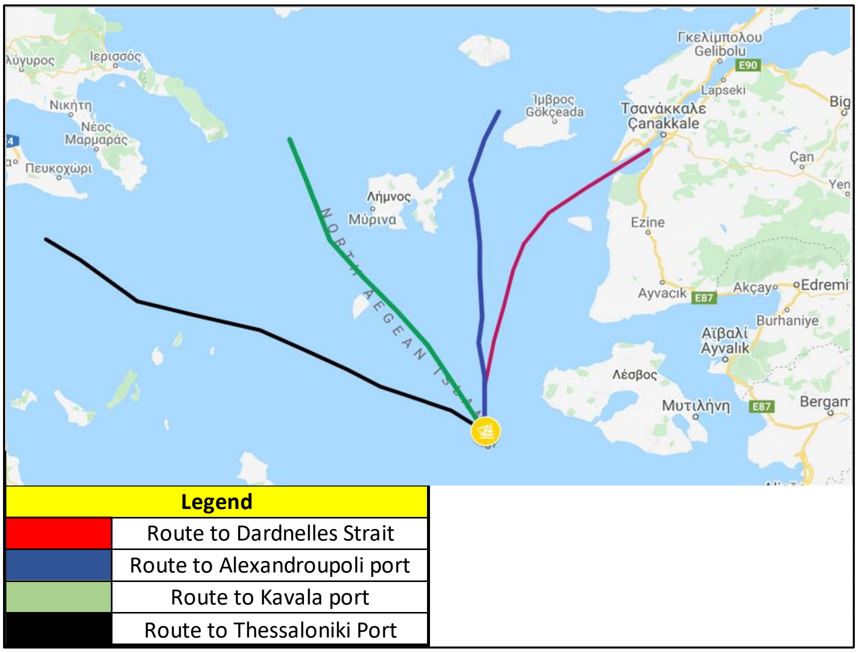

Figure 4.1 – Reference route location

Starting from the reference point in the Mediterranean, the total transportation times and costs from every port to every hinterland region can be estimated. The assumption is that transportation is completed when the shipped cargo enters the borders of each respective country of the hinterland.

Time calculation

We have estimated the time it takes for cargo to be transported from the reference point in the Mediterranean sea (Fig. 4.1) to the borders of each targeted hinterland region. Of course, not only transportation time is included, since there are other parameters that affect the total time, including for example the turnaround time of the port, the time of train loading/ unloading and so on. These parameters are:

Turnaround time: The time between the arrival of a ship vessel until its departure from the port (Marine Traffic).

Rail time indicators which include:

- Hours for loading/unloading: The time it takes to fully inspect and load a commercial train (ec.europa.eu)
- Hub waiting time: The time that a train spends mainly upon entering a different country for cargo inspection and transit (author's estimation)
- Train average speed: The average speed of train in Eastern Europe (author's estimation)

Maritime indicators include:

- Vessel speed: The average speed of a cargo vessel (ec.europa.eu)
- Time to pass Bosphorous: The average time that it takes for the crossing from the Dardanelles strait to the Black Sea and vice-versa. (Marine Traffic)

Truck time indicators include:

- Time for loading/unloading: The time it takes to fully load a truck (reutersevents.com)
- Average truck speed: The average speed of truck movement (cga.ct.gov)

The values of all parameters are presented in Table 4.1.

Table 4.1 – Transportation time indicators and values (hours)

Turnaround times	
Alexandroupoli	24
Thessaloniki	18
Kavala	48
Varna	56
Burgas	41
Constanta	72
Novorrosyisk	32,4
Illychovsk	45,56

Rail time indicators	
Hours for loading / unloading	6
Hub waiting time	24
Train average speed	100
Maritime time indicators	
Vessel speed	37,04
Time to pass Vosporos	96
Truck time indicators	
Hours for loading / unloading	0,1
Average truck speed	70

Given these indicators and the distances between all ports and hinterland regions, the total transportation times are calculated and presented for both rail and truck transport in Tables 4.2 and 4.3 respectively.

Table 4.2 – Rail total transportation times

Rail Total Time (hrs)					
Hinterland/ Port	Bulgaria	Romania	Moldova	Ukraine	Russia
Alexandroupoli	37,37	65,14	136,70	128,62	127,76
Thessaloniki	34,04	64,33	136,22	128,14	127,54
Varna	160,94	169,16	226,19	218,11	215,99
Burgas	144,94	154,35	212,72	204,64	202,23
Constanta	185,97	179,02	187,69	233,05	231,91

Table 4.3 – Truck total transportation times

Truck Total Time (hrs)					
Hinterland/ Port	Bulgaria	Romania	Moldova	Ukraine	Russia
Alexandroupoli	30,74	36,19	95,56	94,24	91,95
Thessaloniki	28,37	33,62	95,45	94,14	92,24
Kavala	56,04	61,83	121,03	119,71	117,99
Varna	160,94	163,06	219,42	218,11	215,99
Burgas	144,94	148,52	205,96	204,64	202,23
Constanta	180,01	179,02	182,10	233,05	231,91

Cost calculation

We have estimated the time it takes for cargo to be transported from the reference point in the Mediterranean sea (Fig. 4.1) to the borders of each targeted hinterland. There are other parameters other than transportation costs included that affect the total cost, namely:

Maritime cost indicators include:

- Cost of TEU per day: the daily transportation cost of a twenty foot equivalent unit (transportgeography.org)
- Vessel speed: The average speed of a cargo vessel. The cost per day is multiplied with the appropriate times. For example, if transportation from Varna to Burgas via sea takes 8 hours, travelling with the average vessel speed, the cost of transportation is ${}^{8}/_{24} * 168 = 56$ € per container (ec.europa.eu)
- Time to pass Bosphorous: The average time that it takes for the crossing from the Dardanelles to the Black Sea and vice-versa. It is estimated to be 96 hours (or 4 days) including waiting time, making the transportation cost $4 * 168 = 672$ € per container. (Marine Traffic)

Rail cost indicator is the cost of commercial train use per km (Di Foggia & Arrigo, 2014)

Truck cost indicator is the cost of truck use per km (della.eu)

The values of all parameters are presented in Table 4.4.

Table 4.4 - Transportation cost indicators and values (€)

Rail cost indicators	
Cost for rail use per km	0,48
Maritime cost indicators	
Cost of TEU per day	168
Vessel speed	37,04
Time to pass Vosporos	96
Truck cost indicators	
Cost for truck use per km	1,67

Given these indicators and the distances between all ports and hinterland targets, the total transportation costs per TEU are calculated and presented in Tables 4.5 and 4.6 for rail and truck transportation respectively.

Table 4.5 – Rail total transportation costs per TEU

Total Rail Cost (euro)					
Hinterland/ Port	Bulgaria	Romania	Moldova	Ukraine	Russia
Alexandroupoli	124,56	305,52	501,50	401,66	447,60
Thessaloniki	126,42	428,34	640,17	540,33	598,75
Varna	734,55	841,11	915,66	815,82	893,11
Burgas	727,56	891,24	926,43	826,59	901,81
Constanta	794,71	749,11	877,27	808,45	892,55

Table 4.6 – Truck total transportation costs per TEU

Total Truck Cost (euro)					
Hinterland/ Port	Bulgaria	Romania	Moldova	Ukraine	Russia
Alexandroupoli	161,70	798,97	1.114,53	972,08	782,83
Thessaloniki	247,70	862,26	1.465,07	1.322,62	1.180,13
Kavala	204,09	881,11	1.176,64	1.034,19	911,74
Varna	734,55	971,69	958,27	815,82	893,11
Burgas	727,56	1.135,04	969,04	826,59	901,81
Constanta	853,48	749,11	1.098,14	808,45	892,55

4.3.1 Alexandroupolis routes

Alexandroupolis port location is very favorable for the distribution of commodities in the targeted hinterland, since:

- Cargo transported to the Black Sea countries from the port will bypass the Dardanelles and Boshporous, significantly decreasing transportation costs and time, given that there is a high level of congestion in the straits and especially in Bosphorous
- It is very close to the borders of Bulgaria, making intermodal connectivity to Russia, Ukraine and Moldova through the ports of Varna and Burgas efficient.

Figures 4.2 and 4.3 present all the connections of Alexandroupolis with the examined hinterland and the time and costs of each route per transportation type. It is assumed that the hinterland is supplied when the truck/train/ship enters the border of each respective country.

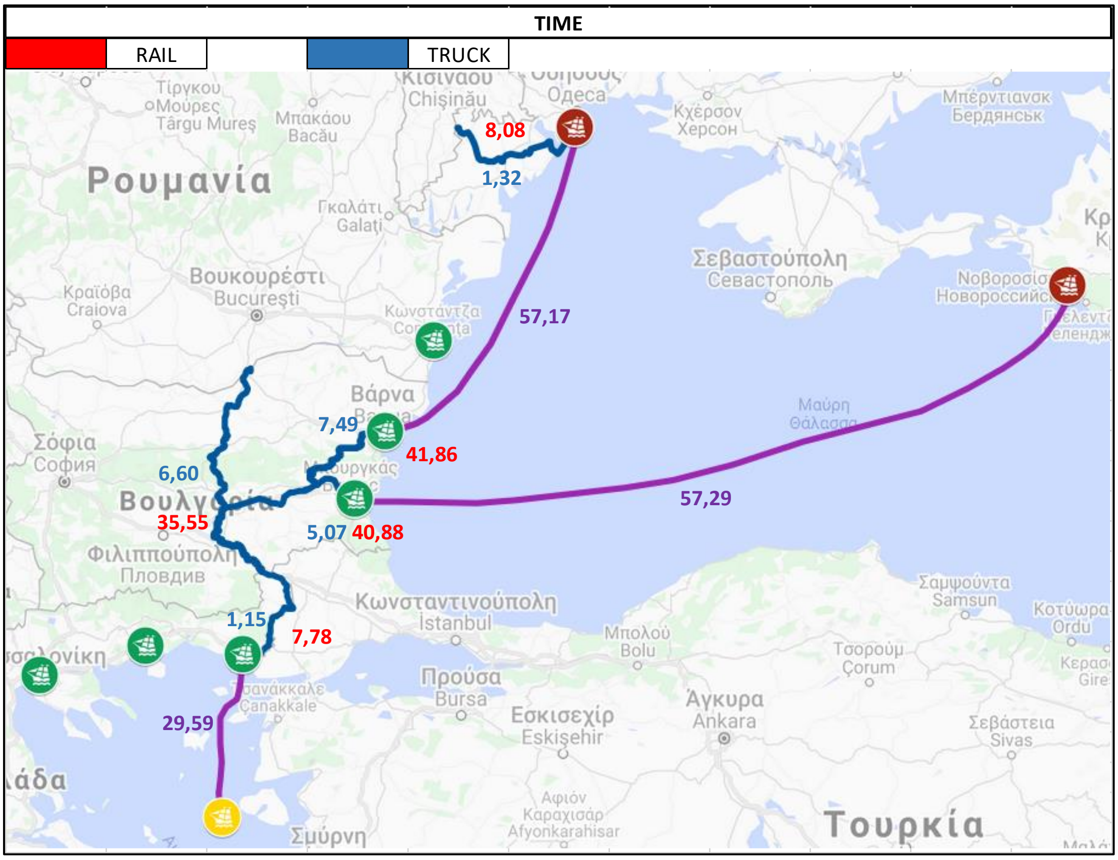

Figure 4.2 – Alexandroupolis transportation routes (blue for inland routes and purple for maritime routes) and time in hours (red for train and blue for truck) per TEU.

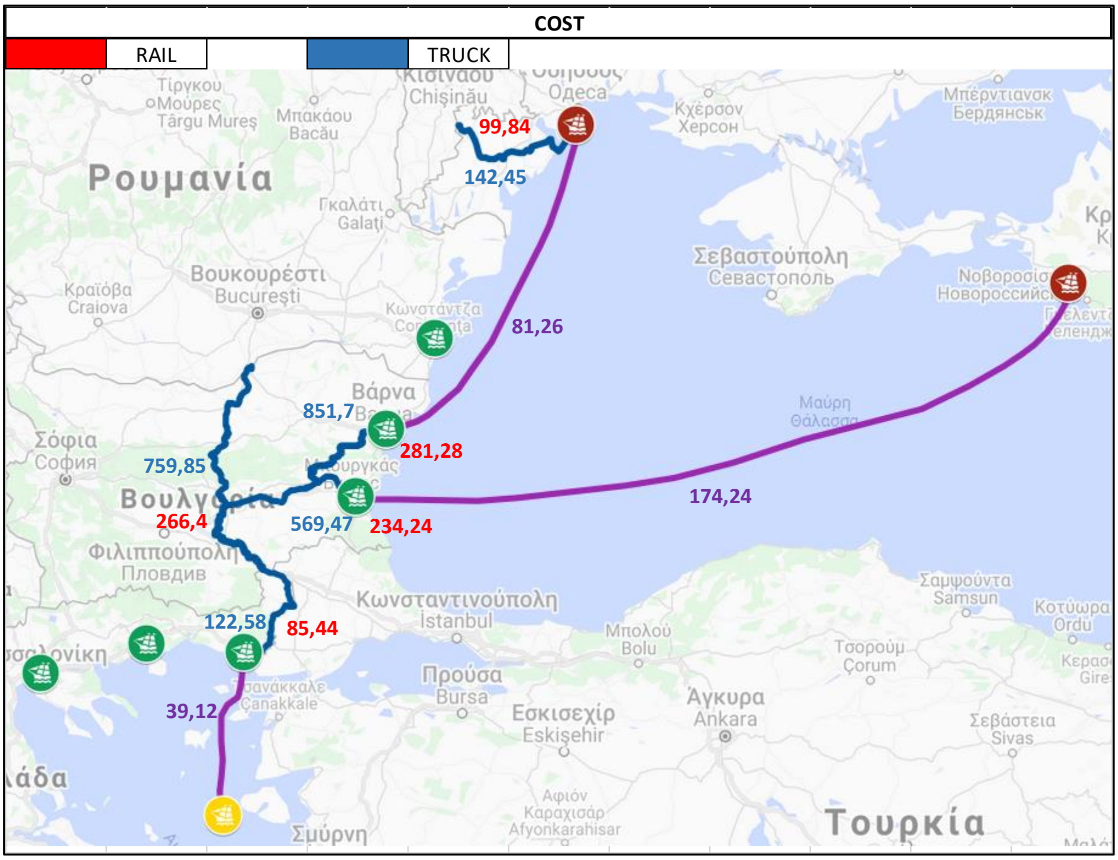

Figure 4.3 – Alexandroupolis transportation routes (blue for inland routes and purple for maritime routes) and cost in euros (red for train and blue for truck) per TEU.

As evident in Figs. 4.2 and 4.3, transport to/from the port of Alexandroupolis uses intermodal connectivity to each country of the hinterland. The transportation network is as follows:

<u>Alexandroupolis – border of Bulgaria</u>: After the cargo is unloaded at the port, it can reach the country either by rail through the Svilengrad border - which takes 7.78 hours and costs 85.44 € per container, or by truck - which takes 1.15 hours and costs 122.58€.

<u>Alexandroupolis – border of Romania:</u> Similarly with Bulgaria, after the cargo is unloaded at the port, it can reach the border Ruse of Romania via rail after passing through Bulgarian soil - which takes 35.55 hours and costs 266.4€ per container, or via truck – which takes 6.60 hours and costs 759.85€.

<u>Alexandroupolis – border of Moldova:</u> Given Moldova's distance and still underdeveloped rail/road network, it is more efficient to use other modes of transport to supply the country rather than use the direct rail or road network connection from

Alexandroupolis. Thus, after the cargo is unloaded at the Alexandroupolis port, it can reach Varna port in Bulgaria via rail – which takes 40.88 hours and costs 234.24€ - or via truck – which takes 5.07 hours and costs 569.47€. Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€. Finally, from Ilyichevsk port, the cargo can reach Moldova using either rail through the border of Basarabeaska – which takes 8.08 hours and costs 99.84€, or truck – which takes 1.32 hours and costs 142.45€.

Alexandroupolis – border of Ukraine: The transportation from Alexandroupolis towards Ukraine has already been described when presenting the Moldova case and the commodities reaching the Ilyichevsk port. Specifically, after the cargo is unloaded at the port of Alexandroupolis, it can reach the port of Varna via rail – which takes 40.88 hours and costs 234.24€, or via truck – which takes 5.07 hours and costs 569.47€. Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€.

Alexandroupolis – border of Russia: The transportation route from Alexandroupolis towards Russia also includes transit operations, with the final location being the port of Novorossiysk. After the cargo is unloaded in the port of Alexandroupolis, it is transported towards Burgas port via either rail – which takes 41.48 hours and costs 281.28€ - or by truck – which takes 7.49 hours and costs 851.7€. From there, it will be sent to Novorossiysk port and reach Russia – which takes 57.29 hours and costs 174.24€.

In Table 4.7, the total time and cost it takes to supply every country of the hinterland from Alexandroupolis (and vise-versa) for every transportation method is captured.

Table 4.7 – Alexandroupolis total transportation time and costs per TEU.

Alexandroupoli		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	37,37	65,14	136,70	128,62	127,76
	Truck	30,74	36,19	95,56	94,24	91,95
Cost (€)	Rail	124,56	305,52	501,50	401,66	447,60
	Truck	161,70	798,97	1114,53	972,08	782,83

4.3.2 Thessaloniki routes

Thessaloniki is a gateway port not only for the Balkans, but also for countries in Central Europe, given its already established railway and road connections with the capitals of these countries (Fig. 4.4).

Figure 4.4 – Thessaloniki's port connection with central Europe route (Source: mapsofeurope.com)

This explains the port authority's focus on that market and not exclusively on Eastern Europe. Note that the port's location is the most western with respect to all other competing ports, making the port competitive for Western Balkan supply and Central

Europe supply, and, perhaps, less competitive for Eastern Balkan and Black Sea countries supply. It is also noted that Thessaloniki port handles a substantial amount of cargo annually.

Figures 4.5 and 4.6 represent the time and cost respectively for the transport of cargo between Thessaloniki and the countries of the hinterland.

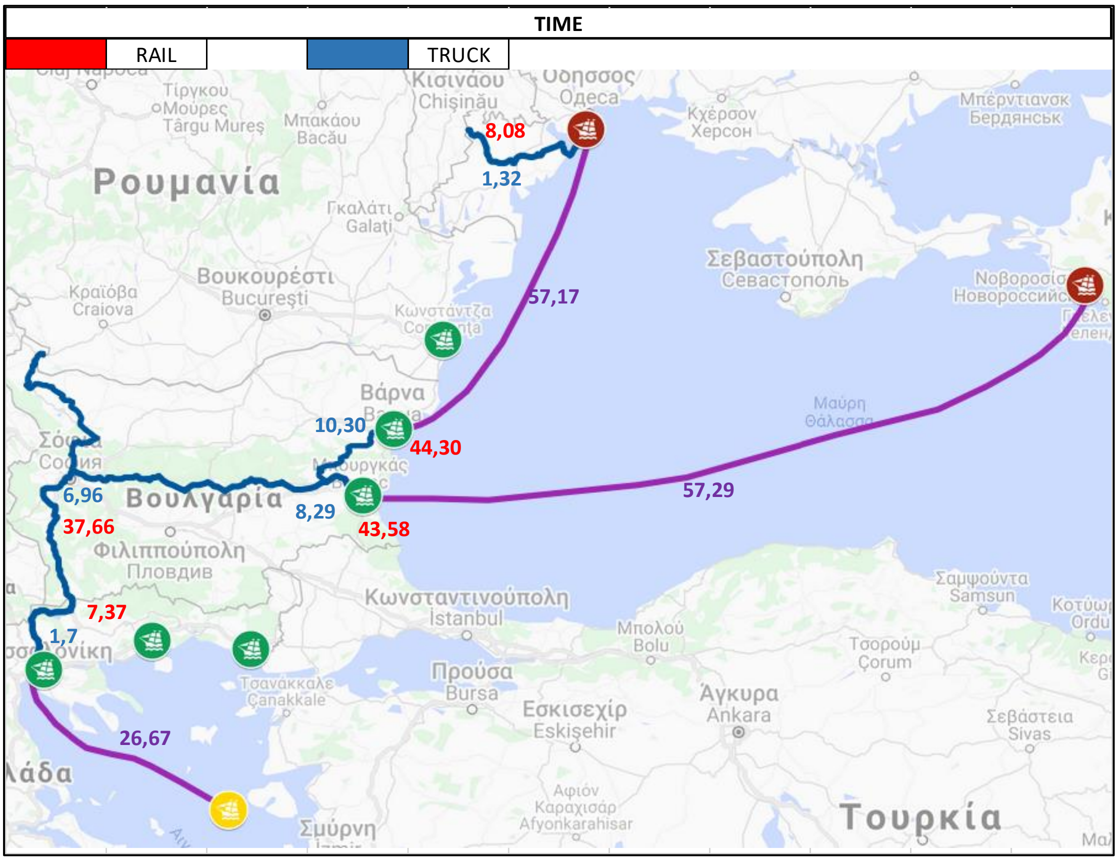

Figure 4.5 – Thessaloniki transportation routes (blue for inland routes and purple for maritime routes) and time in hours (red for train and blue for truck) per TEU.

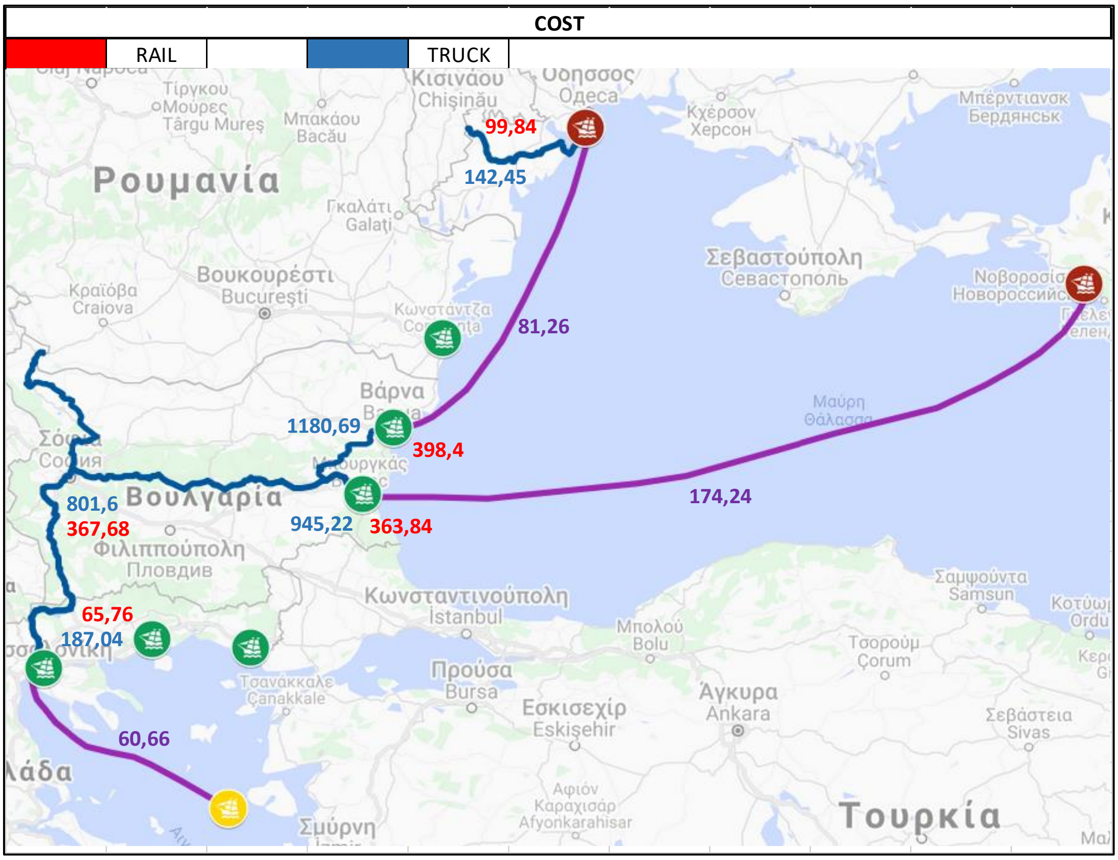

Figure 4.6 – Thessaloniki transportation routes (blue for inland routes and purple for maritime routes) and costs in euros (red for train and blue for truck) per TEU

Similarly with the Alexandroupolis port, Thessaloniki uses intermodal connectivity to supply all hinterland regions, as seen in Figs. 4.5 and 4.6. The details of time and costs of transportation between Thessaloniki and every country in the hinterland per transportation type is provided below:

<u>Thessaloniki – border of Bulgaria</u>: After the cargo is unloaded at the port, it can reach the country either by rail through the Kulata border - which takes 7.37 hours and costs 65.76€ per container - or by truck - which takes 1.7 hours and costs 187.04€.

<u>Thessaloniki – border of Romania:</u> Similarly with Bulgaria, after the cargo is unloaded at the port, it can reach the border Calafat of Romania via rail after passing through Bulgarian soil - which takes 37.66 hours and costs 387.68€ per container - or via truck – which takes 6.96 hours and costs 801.6€.

<u>Thessaloniki – border of Moldova:</u> Again, like with the case of Alexandroupolis, because of Moldova's distance and still underdeveloped rail/road network, it is more efficient to use many modes of transport to supply the country rather than use the

direct rail or road network connection from Thessaloniki. In the examined case, after cargo is unloaded at the port, it can reach port Varna of Bulgaria via rail – which takes 44.30 hours and costs 398.4€ - or via truck – which takes 10.30 hours and costs 1180.69€. Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€. Finally, from Ilyichevsk port, the commodities can reach Moldova using either rail through the border of Basarabeaska – which takes 8.08 hours and costs 99.84€ - or truck – which takes 1.32 hours and costs 142.45€.

<u>Thessaloniki – border of Ukraine:</u> The transportation from Thessaloniki towards Ukraine was already included when describing the Moldova case, when the commodities reached port Ilyichevsk. First, after the cargo is unloaded at Thessaloniki port, it can reach Varna port via rail – which takes 44.30 hours and costs 398.4€ - or via truck – which takes 10.30 hours and costs 1180.69€. Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€.

<u>Thessaloniki – border of Russia:</u> The transportation route from Thessaloniki towards Russia also happens with multiple transits, with the final location being port Novorossiysk. After the cargo is unloaded at port Thessaloniki, it is transported towards Burgas port via either rail – which takes 43.58 hours and costs 363.84€ - or by truck – which takes 8.29 hours and costs 945.22€. From there, it will be sent to Novorossiysk port and reach Russia – which takes 57.29 hours and costs 174.24€.

In Table 4.8, the total time and cost it is required for the exchange of cargo between Thessaloniki and the examined hinterland countries for every transportation method is consolidated.

Table 4.8 – Thessaloniki total transportation time and costs per TEU.

Thessaloniki		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	34,04	64,33	136,22	128,14	127,54
	Truck	28,37	33,62	95,45	94,14	92,24
Cost (€)	Rail	126,42	428,34	640,17	540,33	598,75
	Truck	247,70	862,26	1465,07	1322,62	1180,13

4.3.3 Kavala routes

Kavala is a Greek port located between the ports of Thessaloniki and Alexandroupolis. Its location is also favorable when considering major gateway ports of the Balkans and Eastern Europe, given its close proximity to the borders of Bulgaria, and the potential to bypass Bosphorous.

However, in contrast to all the other competing ports, Kavala has no established railway connection. This is a disadvantage. There are many instances that a cargo trains are preferred to trucks, given the economies of scale achieved in long distances (> 500 km). In spite of this disadvantage, the port has the potential to offer efficient transportation options for the supply of Eastern European and Balkan countries, as seen in Figs. 4.7 and 4.8, where the network of Kavala with the hinterland targets is depicted.

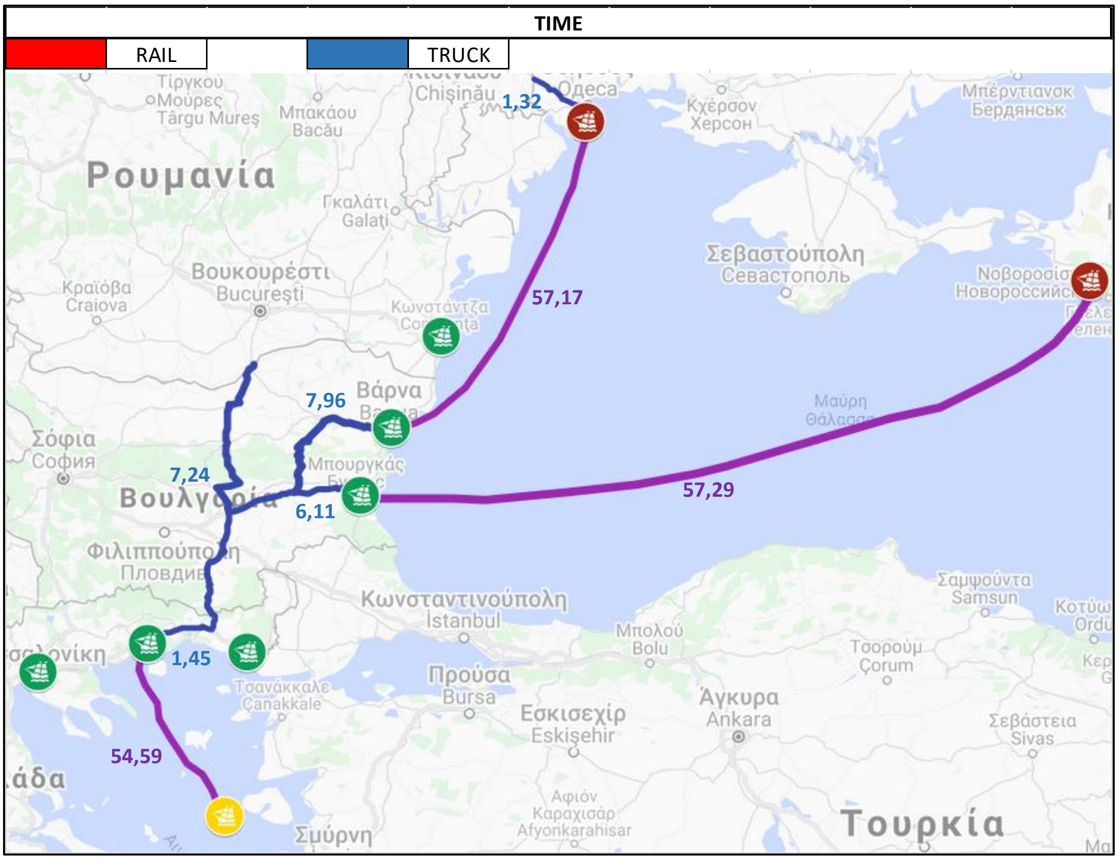

Figure 4.7 – Kavala transportation routes (blue for inland routes and purple for maritime routes) and time in hours (red for train and blue for truck) per TEU.

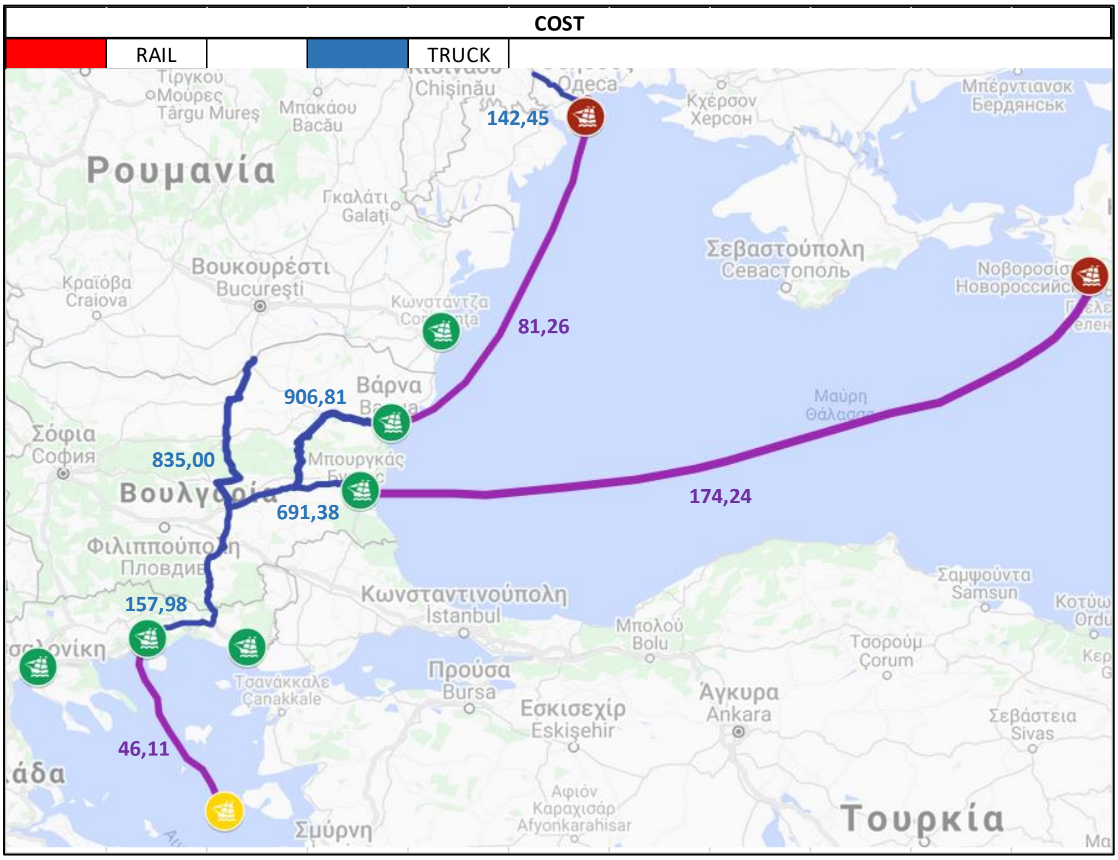

Figure 4.8 - Kavala transportation routes (blue for inland routes and purple for maritime routes) and costs in euros (red for train and blue for truck) per TEU.

Similarly to the cases of the two other Greek ports of Alexandroupolis and Thessaloniki, connectivity between Kavala and every hinterland region involves the use of intermodal connectivity, achieved only by truck. The detailed explanation of the network connectivity between Kavala and the countries of the hinterland time wise and cost wise is:

Kavala – border of Bulgaria: After the cargo is unloaded at the port, it reaches the country by truck - which takes 1.45 hours and costs 159.98€.

Kavala – border of Romania: Similarly with Bulgaria, after the cargo is unloaded at the port, it can reach the border Ruse of Romania via truck – which takes 7.24 hours and costs 835.00€.

Kavala – border of Moldova: Like in the case of Alexandroupolis and Thessaloniki, Moldova will be supplied by Kavala through transit in Varna and then Ukraine and not directly through the road network. Specifically, after cargo is unloaded at the port, it reaches Varna port in Bulgaria via truck – which takes 7.96 hours and costs 906.81€.

Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€. Finally, from Ilyichevsk port, the commodities can reach Moldova using truck – which takes 1.32 hours and costs 142.45€.

Kavala – border of Ukraine: The transportation from Kavala towards Ukraine was already included when describing the Moldova case, when the commodities reached port Ilyichevsk. First, after the cargo is unloaded at Kavala port, it reaches Varna port via truck – which takes 7.96 hours and costs 906.81€. Afterwards, the cargo is loaded in a vessel and is transported from Varna port to Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€.

Kavala – border of Russia: The transportation route from Kavala towards Russia happens with multiple transits, with the final location being port Novorossiysk. After the cargo is unloaded in port Kavala, it is transported towards Burgas port via truck – which takes 6.11 hours and costs 691.38€. From there, it will be sent to Novorossiysk port and reach Russia – which takes 57.29 hours and costs 174.24€.

The total transportation time and cost of all routes of Kavala with the targeted hinterland are consolidated and presented in Table 4.9.

Table 4.9 – Kavala total transportation time and costs per TEU.

Kavala		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	-	-	-	-	-
	Truck	56,04	61,83	121,03	119,71	117,99
Cost (€)	Rail	-	-	-	-	-
	Truck	204,09	881,11	1176,64	1034,19	911,74

4.3.4 Varna routes

The port of Varna in Bulgaria is just one out of three ports in this study that are located in the Black Sea (the other two been Burgas and Constanta). Historically, the first port of Bulgaria, it currently imports the majority of Bulgaria's liquid and dry bulk cargo. As far as international connectivity goes, being located in the Black Sea, its only access with the other seas is through the Bosphorous channel. Nevertheless, Varna, as well as the other two ports of Constanta and Burgas, have been traditionally supplying their surrounding hinterland. The network connectivity of the port is illustrated in Figs. 4.9 and 4.10 (including transportation times and costs, respectively).

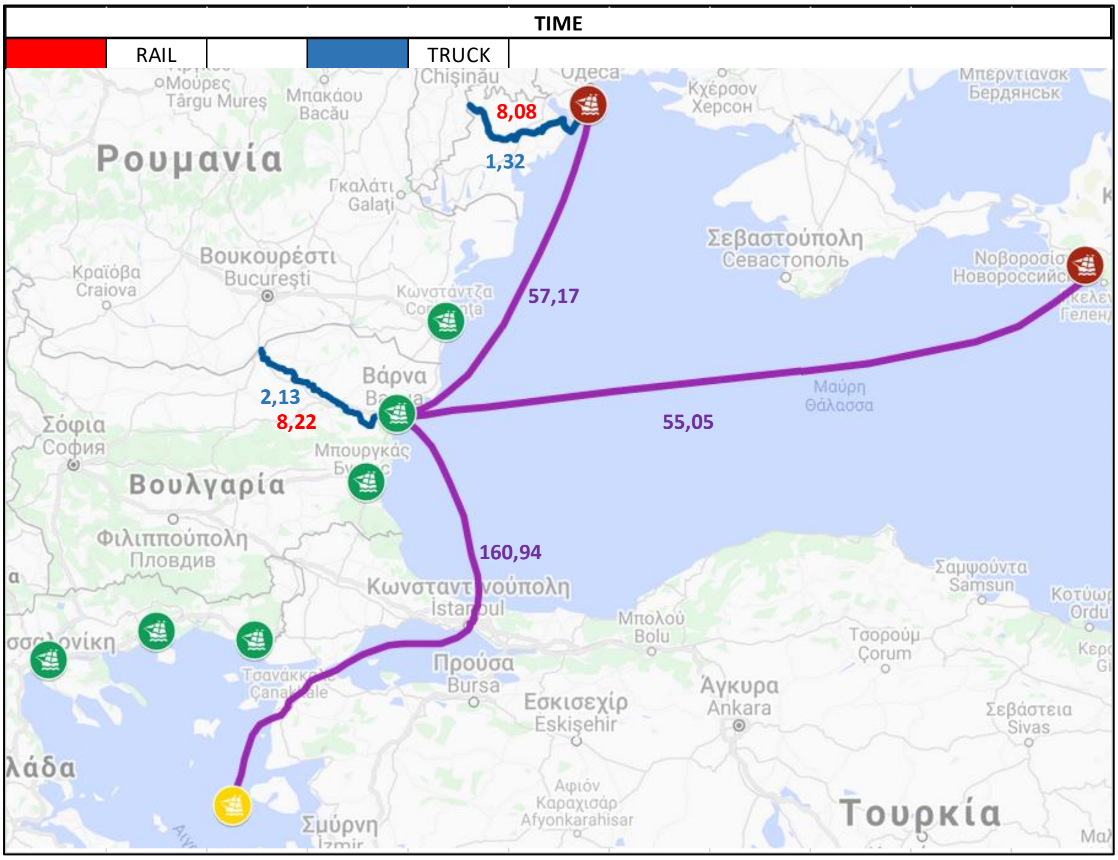

Figure 4.9 - Varna transportation routes (blue for inland routes and purple for maritime routes) and times in hours (red for train and blue for truck) per TEU.

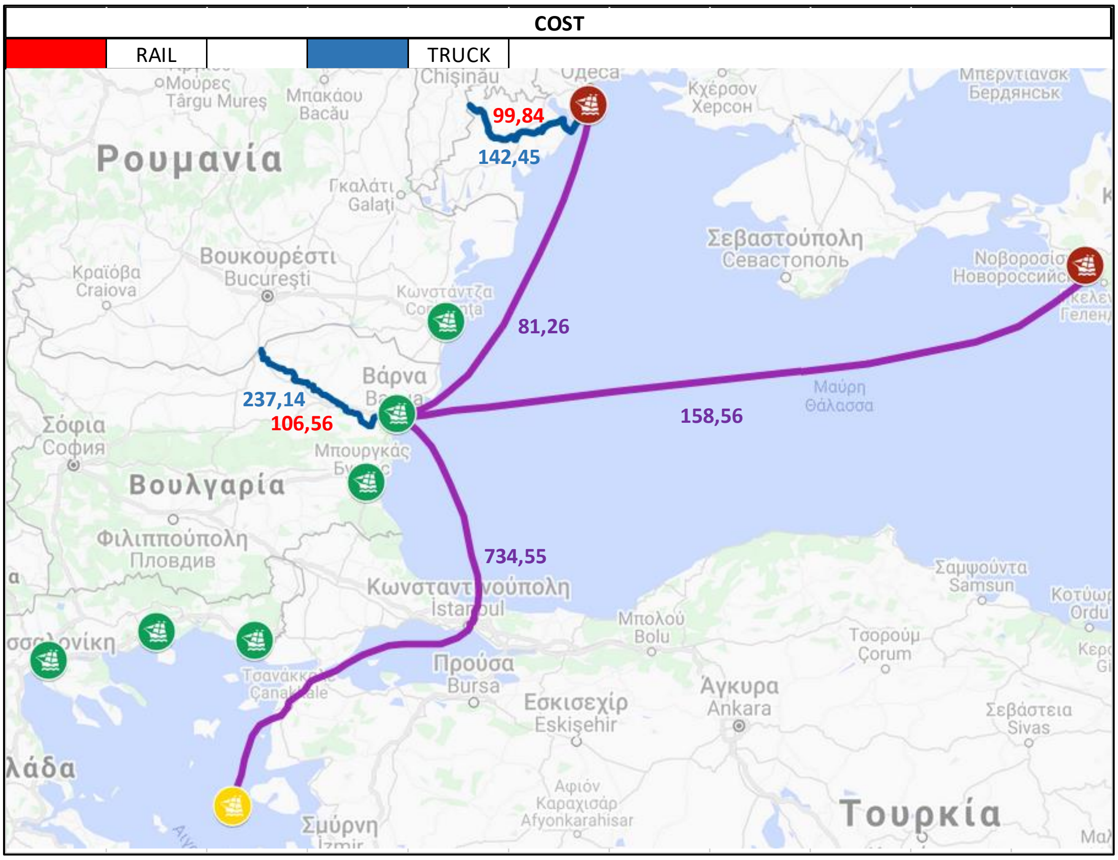

Figure 4.10 - Varna transportation routes (blue for inland routes and purple for maritime routes) and costs in euros (red for train and blue for truck) per TEU.

The connectivity of the port with all hinterland targets is explained below:

Varna – border of Bulgaria: Since the port of Varna is located in Bulgaria, the port is considered to supply the country when cargo enters the port. In this case, the ship takes 160.94 hours to arrive and the cost per cargo unit is 734.55 euros from the reference point in the Mediterranean (Fig. 4.1).

Varna – border of Romania: In order for the port to supply Romania, intermodal connectivity is required. When the cargo is unloaded at the port, it is transported to Romania either via rail through the border of Ruse – which takes 8.22 hours and costs 106.56€ - or via truck – which takes 2.13 hours and costs 237.14€.

Varna – border of Moldova: When exchanging commodities with Moldova, again intermodal connectivity is used, since more than two transportation methods are included. In this case, after the cargo is unloaded at the port of Varna, it is transhipped towards Ilyichevsk port, Ukraine – which takes 57.17 hours and costs 81.26€. From Ilyichevsk, the cargo is loaded on either train or truck and shipped towards Moldova.

It takes 8.08 hours and costs 99.84€ for trains to reach Moldova from Ukraine through the borders of Basarabeaska and 1.32 hours with a cost of 142.45€ for trucks.

Varna – border of Ukraine: The transportation from Varna towards Ukraine was already included when describing the Moldova case - without however using more transportation types other than the ship - when the commodities reached port Ilyichevsk. First, the cargo is unloaded at Varna port, and through transhipment reaches port Ilyichevsk, Ukraine which takes 57.17 hours and costs 81.26€ per unit.

Varna – border of Russia: The transportation from Varna towards Russia happens only via maritime connection. After the cargo is unloaded at port Varna, it is transhipped towards Novorossiysk port and reaches Russia – which takes 55.05 hours and costs 158.56€.

All transportation times and costs between port Varna and the examined hinterland for every transportation type are presented in Table 4.10

Table 4.10 – Varna total transportation time and costs per TEU.

Varna		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	160,94	169,16	226,19	218,11	215,99
	Truck	160,94	163,06	219,42	218,11	215,99
Cost (€)	Rail	734,55	841,11	915,66	815,82	893,11
	Truck	734,55	971,69	958,27	815,82	893,11

Some values are the same for truck and rail transportation for Varna, since in those cases all of the transportation is completed via maritime connectivity.

4.3.5 Burgas routes

Burgas is the second Bulgarian port in this case study, located south of the port of Varna. Currently, the port handles more cargo traffic than the port of Varna, with its main focus been containerized cargo. Also, the port's close location to the entrance of the Black Sea makes it an interesting case for transhipment activities throughout the Black Sea, as well as an interesting port for bypassing the Bosphorous using land-based intermodal connectivity.

As far as inland connectivity of the port with the surrounding area, the port traditionally supplies its hinterland, including the countries of this case study. In Figs. 4.11 and 4.12 the connectivity network of port Burgas and the hinterland are illustrated time wise and cost wise respectively.

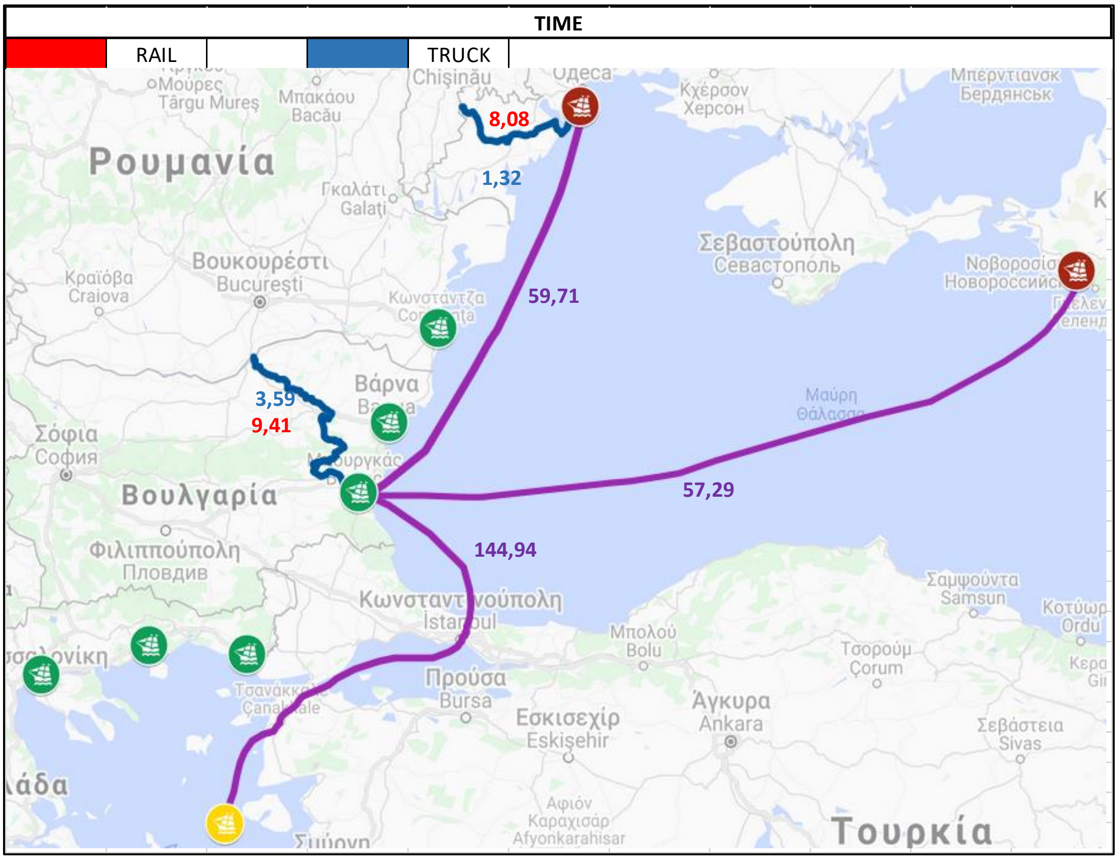

Figure 4.11 - Burgas transportation routes (blue for inland routes and purple for maritime routes) and time in hours (red for train and blue for truck) per TEU.

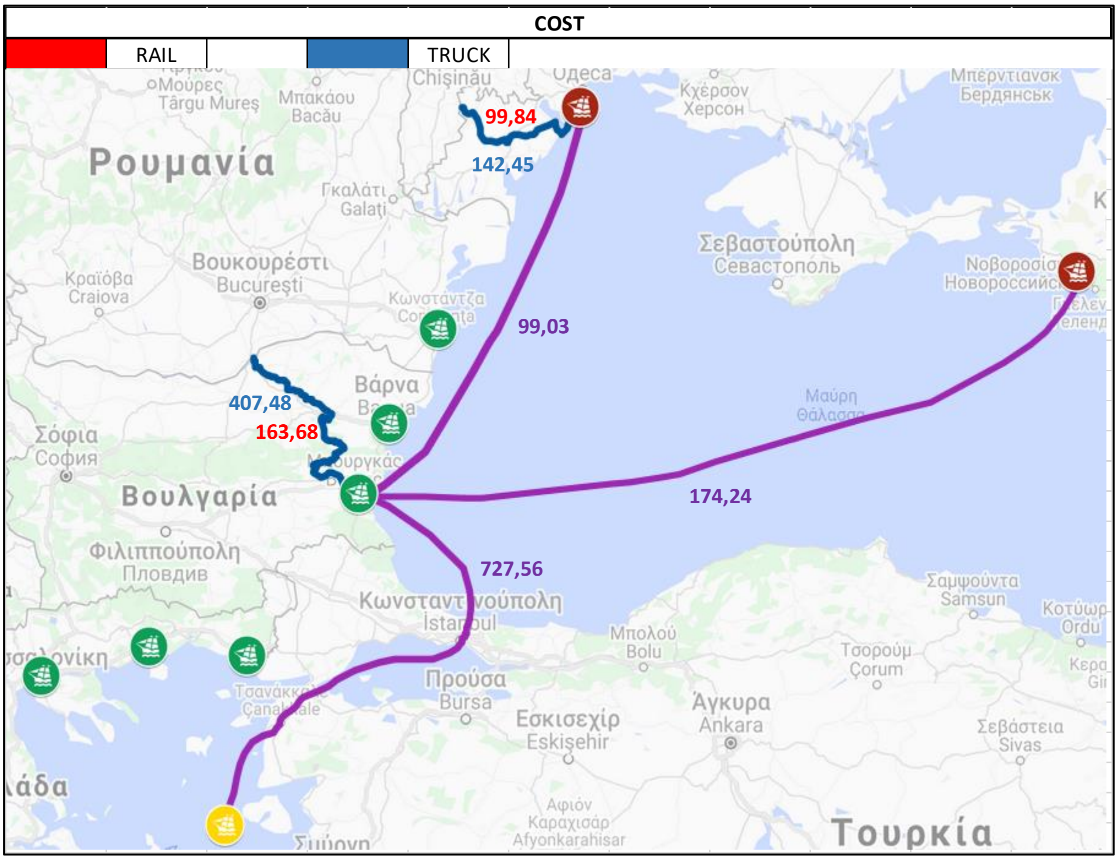

Figure 4.12 - Burgas transportation routes (blue for inland routes and purple for maritime routes) and costs in euros (red for train and blue for truck) per TEU.

Like in the case of Varna, intermodal connectivity is not required in all cases, since transportation may be achieved using only one transportation method (sea). Below, the connectivity of the port with every hinterland target is explained.

<u>Burgas - border of Bulgaria:</u> Since the port of Burgas is located in Bulgaria, the port is considered to supply the country when cargo enters the port. In this case, the ship takes 144.94 hours to arrive and the cost per cargo unit is 727.56 euros from the reference point.

<u>Burgas – border of Romania:</u> In order for the port to supply Romania, intermodal connectivity is needed. When the cargo is unloaded at the port, it is transported to Romania either via rail through the border of Ruse – which takes 9.41 hours and costs 163.68€ - or via truck – which takes 3.59 hours and costs 407.48€.

<u>Burgas – border of Moldova:</u> When exchanging commodities with Moldova, again intermodal connectivity is used, since more than two transportation vessels are used. In this case, after cargo is unloaded at the port of Burgas, it is transhipped towards

port Ilyichevsk port, Ukraine – which takes 59.71 hours and costs 99.03€. From Ilyichevsk, the cargo is loaded on either train or truck and shipped towards Moldova. It takes 8.08 hours and costs 99.84€ for trains to reach Moldova from Ukraine through the borders of Basarabeaska and 1.32 hours with a cost of 142.45€ for trucks.

Burgas – border of Ukraine: The transportation from Varna towards Ukraine was already included when describing the Moldova case, when the commodities reached port Ilyichevsk. First, the cargo is unloaded at Burgas port, and through transhipment reaches port Ilyichevsk, Ukraine which takes 59.71 hours and costs 99.03€ per unit.

Burgas – border of Russia: The transportation route from Burgas towards Russia happens only through maritime connectivity. After the cargo is unloaded at port Burgas, it is transhipped towards Novorossiysk port and reaches Russia – which takes 57.29 hours and costs 174.24€.

All transportation times and costs for the exchange of cargo between port Burgas and the examined hinterland are consolidated in Table 4.11.

Table 4.11 – Burgas total transportation time and costs per TEU.

Burgas		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	144,94	154,35	212,72	204,64	202,23
	Truck	144,94	148,52	205,96	204,64	202,23
Cost (€)	Rail	727,56	891,24	926,43	826,59	901,81
	Truck	727,56	1135,04	969,04	826,59	901,81

4.3.6 Constanta routes

The port of Constanta is the most developed in terms of infrastructure and cargo handled annually. It is an important gateway port of Europe, supplying Central European hinterlands as far as Hungary, Czech Republic, etc. As far as inland connectivity of the port with the surrounding area, the port traditionally supplies its hinterland, including the countries of this case study. In Figs. 4.13 and 4.14, the connectivity network of port Constanta is illustrated time-wise and cost wise respectively.

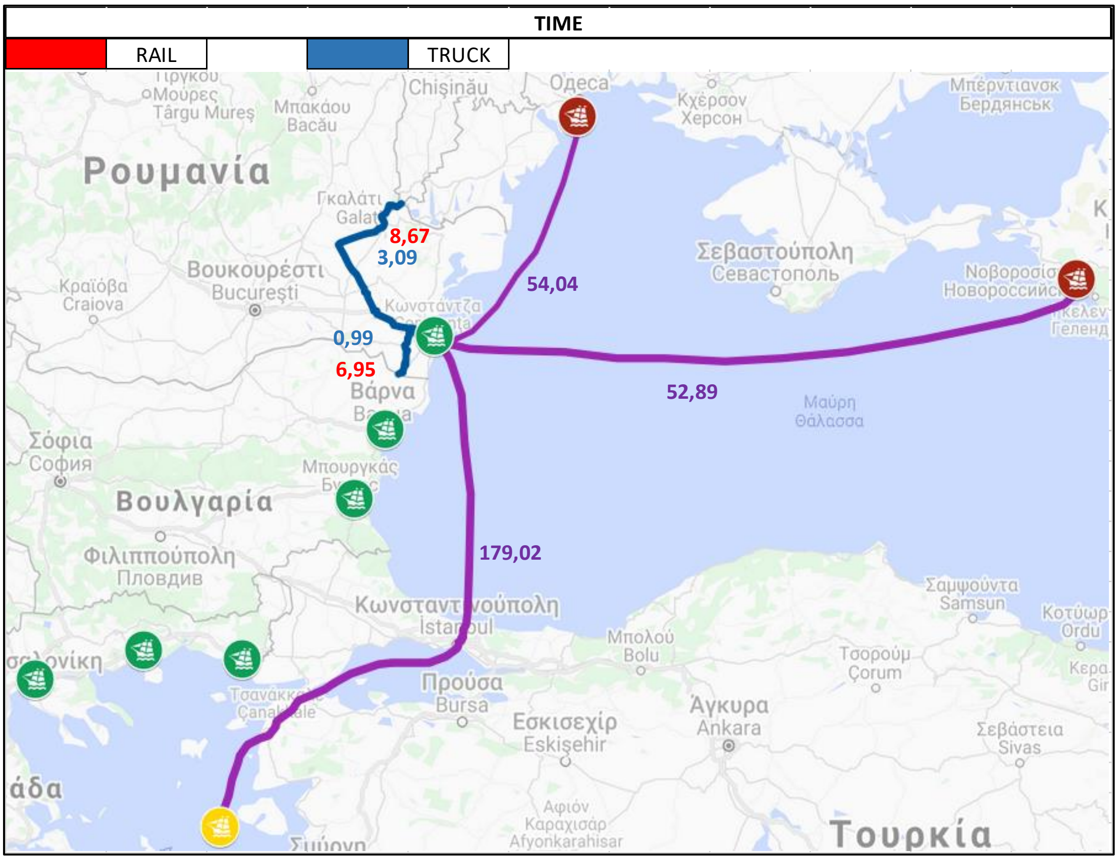

Figure 4.13 - Constanta transportation routes (blue for inland routes and purple for maritime routes) and time in hours (red for train and blue for truck) per TEU.

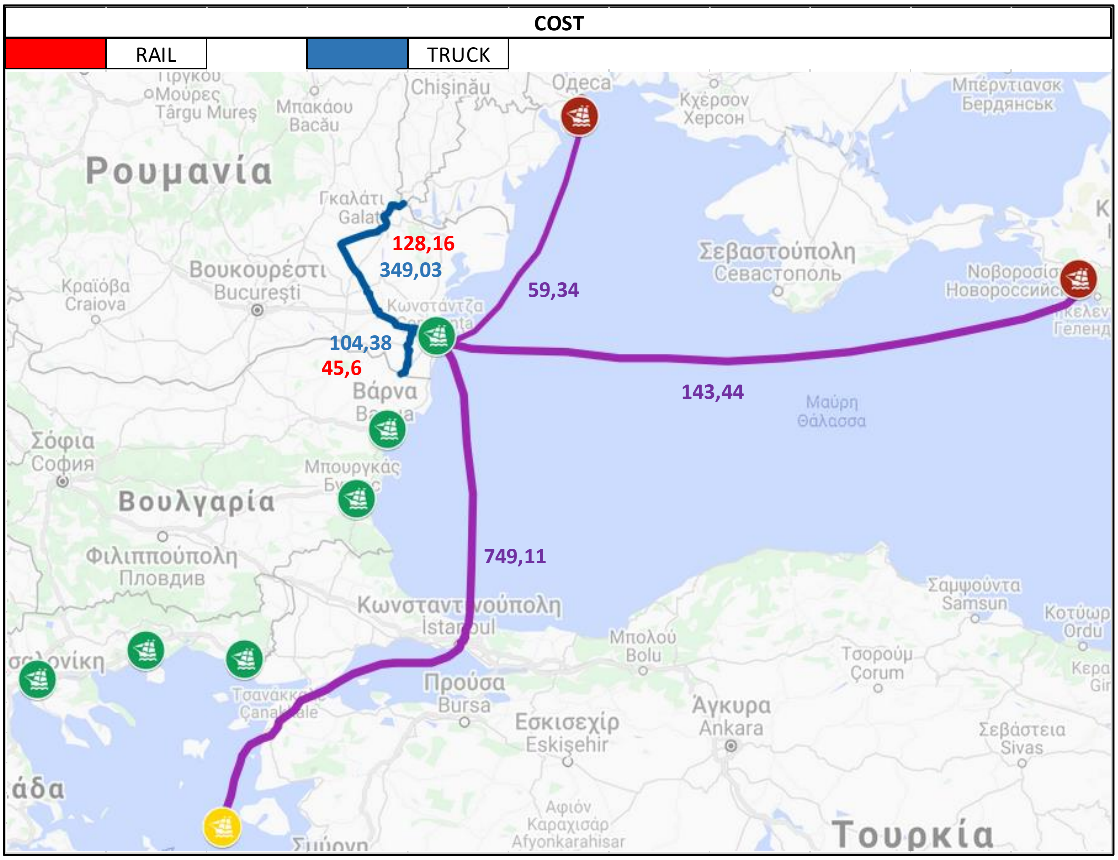

Figure 4.14 - Constanta transportation routes (blue for inland routes and purple for maritime routes) and costs in euros (red for train and blue for truck) per TEU.

<u>Constanta – border of Bulgaria:</u> In order for the port to supply Bulgaria, intermodal connectivity is needed. When the cargo is unloaded at the port, it is transported to Bulgaria either via rail through the border of Kardam – which takes 6.95 hours and costs 45.6€ - or via truck – which takes 0.99 hours and costs 104.38€.

<u>Constanta – border of Romania:</u> Since the port of Constanta is located in Romania, it is considered to supply the country when cargo enters the port. In this case, the ship takes 179.02 hours to arrive and the cost per cargo unit is 749.11 euros

<u>Constanta – border of Moldova:</u> In order for the port to supply Moldova, intermodal connectivity is needed. In contrast with the other ports, it is more efficient to use the rail/road network to supply Moldova, given that Romania and Moldova are neighbouring countries. When the cargo is unloaded at the port, it is transported to Moldova either via rail through the border of Giurgulesti – which takes 8.67 hours and costs 128.16€ - or via truck – which takes 3.09 hours and costs 349.03€.

Constanta – border of Ukraine: The transportation route from Constanta towards Ukraine happens only through maritime connection. After the cargo is unloaded at port Constanta, it is transhipped towards Ilyichevsk port and reaches Ukraine – which takes 54.04 hours and costs 59.34€.

Constanta – border of Russia: The transportation route from Constanta towards Russia happens only through maritime connection. After the cargo is unloaded at port Constanta, it is transhipped towards Novorossiysk port and reaches Russia – which takes 52.89 hours and costs 143.44€.

All transportation times and costs for cargo exchange between port Constanta and the examined hinterland with every transportation method is presented in Table 4.12.

Table 4.12 – Constanta total transportation time and costs per TEU.

Constanta		Bulgaria	Romania	Moldova	Ukraine	Russia
Time (hrs)	Rail	185,97	179,02	187,69	233,05	231,91
	Truck	180,01	179,02	182,10	233,05	231,91
Cost (€)	Rail	794,71	749,11	877,27	808,45	892,55
	Truck	853,48	749,11	1098,14	808,45	892,55

4.4 Demand of Imports and Exports of the Hinterland

As was already mentioned in the beginning of this Chapter, the main goal is to estimate the potential cargo that can be handled by the port of Alexandroupolis, which includes the dispatchment of incoming and attraction of outgoing cargo, when appropriate investments and management initiatives have been implemented. Given that the main goal is the minimization of transportation time and costs, it is important to present here the parameters based on which the linear programming model of the problem will be set. These parameters include the estimation of hinterland demand in imports and exports per country/region of the hinterland.

4.4.1 Maritime imports of catchment area

For each country we have examined its regions in order to understand the export and import capacity of different areas per country.

Bulgaria

Bulgaria, as a country that belongs to the European Union, is already divided into NUTS (Nomenclature of Territorial Units for Statistics) sub – regions. Currently, as per NUTS 2, the country is divided into 6 regions, as shown in Fig. 4.15; however, for simplicity but without loss of generality, in this study we use two super-regions, North and South, distinguished by the red line in Fig. 4.15. Since the linear problem will be solved using Excel Solver, it was necessary to reduce the number of decision variables due to restrictions of Excel. Of course, it would be possible to solve the same linear problem and use all NUTS 2 regions using Matlab or another similar tool.

The maritime import demand of the country is provided by Eurostat statistics (ec.europa.eu) and is 13.015 thousand tonnes for all types of maritime cargo annually (average from 2010 – 2019). The estimates of the import demand of each super-region are based on population. For example, North Bulgaria consists of 36% of the total population of Bulgaria, thus the import demand is:

$0.36 * 13.015 = 4.726{,}23$ th. tonnes

All calculations for Bulgaria's import demand are presented in Table 4.13.

Figure 4.15 – Division of Bulgaria into sub – regions (Source: Wikipedia)

Table 4.13 – Import demand of Bulgaria per region (ths. tonnes) (Source: Eurostat)

Bulgaria	Population	Total Demand	Percentage of total population	County Demand
North	2.674.347,00	13.015,00	0,36	4.726,23
South	4.690.223,00		0,64	8.288,77
Total	7.364.570,00		1,00	13.015,00

Romania

Similarly to Bulgaria, Romania is already divided into 8 NUTS regions (as shown in Fig. 4.16). As with Bulgaria and for simplicity, in this thesis we consider 2 super-regions, as distinguished by the red line in Fig. 4.16.

The maritime import demand for the country is provided by Eurostat (the average from 2010 – 2019) and the calculation per region is given in Table 4.14.

Figure 4.16 – Division of Romania into sub – regions (Source: Czech Statistical Office)

Table 4.14 – Import demand of Romania per region (ths. tonnes) (Source: Eurostat)

Romania	Population	Total Demand	Percentage of total population	County Demand
North	8.263.154,00	20.690,00	0,41	8.496,56
South	11.858.487,00		0,59	12.193,44
Total	20.121.641,00		1,00	20.690,00

Moldova

Moldova is divided into 5 administrative divisions, including 2 autonomous ones (Fig. 4.17). Again, for simplicity, we use four super– regions, considering the autonomous districts as one region.

Given that Moldova is landlocked, there is no direct cargo exchange with ports, however some of the cargo imported and exported are transported by sea as part of their journey. We assumed that approximately one fourth (1/4) of the total imports and exports of Moldova are transported by sea.

Figure 4.17 – Division of Moldova into sub – regions (Source: Wikipedia)

The import demand of each region is shown in Table 4.15.

Table 4.15 – Import demand of Moldova per region (ths. tonnes) (Source: Moldovan Statistical Institute)

Moldova	Population	Total Demand	Percentage of total population	County Demand
North	724.319,00	5.128,00	0,20	1.046,74
Central	1.765.526,00		0,50	2.551,43
South	455.066,00		0,13	657,63
Independent regions	603.535,00		0,17	872,19
Total	3.548.446,00		1,00	5.128,00

Ukraine

Ukraine is divided in 27 oblasts, contained for this study in 2 super – regions; Northwestern (blue and red) and Southeastern (yellow and green) as seen in Fig. 4.18.

The majority of transportation in Ukraine uses truck, followed by rail and then oil pipelines. Maritime transportation is the least popular choice for imports and exports (Ukraine Statistical Databases), since only the 0.36% of the total transportation occurs via maritime connectivity.

Figure 4.18 – Division of Ukraine into sub – regions (Source: Wikipedia with modifications by author)

The import demand of each super-region is shown in Table 4.16.

Table 4.16 – Import demand of Ukraine per region (ths. Tonnes) (Source: Ukrainian Statistical Institute)

Ukraine	Population	Total Demand	Percentage of total population	County Demand
North West	17.706.925,00	999,00	0,45	445,69
South East	21.982.422,00		0,55	553,31
Total	39.689.347,00		1,00	999,00

Russia

For Russia we have considered only the European part. European Russia is divided into 5 regions, which for simplicity we reduced to 4 (Fig. 4.19).

Maritime imports and exports are limited (Table 4.17) due to the supply and exports of the country through other modes, especially rail from/to Western Europe and pipelines.

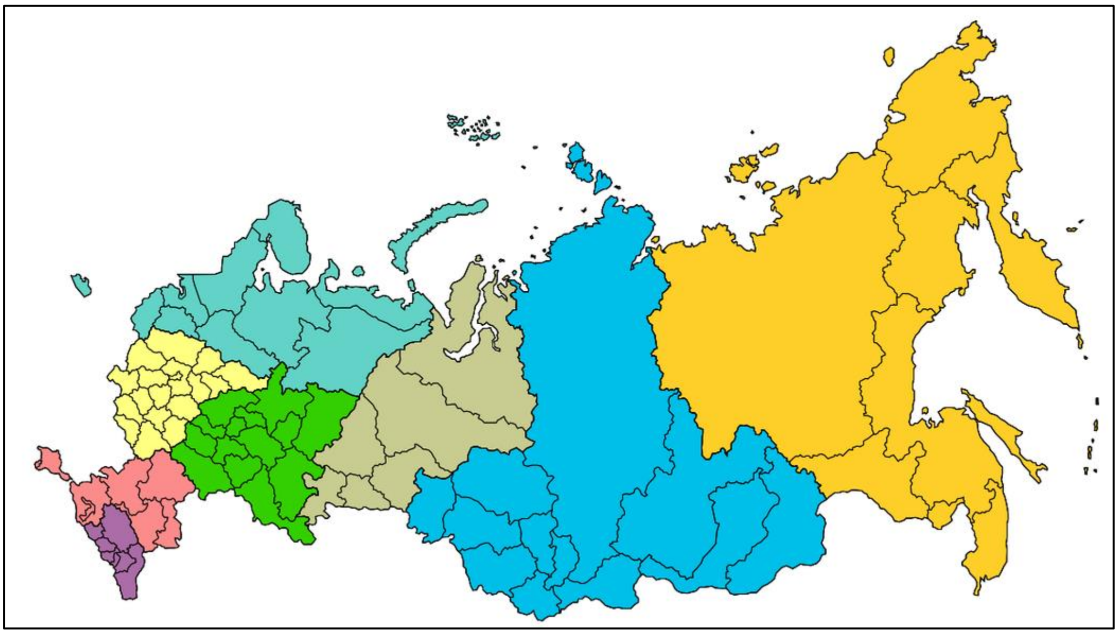

Figure 4.19 – Division of Russia into sub – regions (Source: Wikipedia)

The regions considered are the following:

- Central (Light Blue)
- North-western (Yellow)
- Volga (Green)
- Southern and Caucasia (Red and Purple)

The demand of each region is shown in Table 4.17.

Table 4.17 – Import demand of Russia per region (ths. Tonnes) (Source: Russian Statistical Institute)

European Russia	Population	Total Demand	Percentage of total population	County Demand
Central	39.209.582,00	7.555,00	0,36	2.718,95
Northwestern	13.899.310,00		0,13	963,83
Southern+Caucasian	26.204.228,00		0,24	1.817,10
Volga	29.636.574,00		0,27	2.055,12
Total	108.949.694,00		1,00	7.555,00

4.4.2 Catchment area maritime exports

The division of each country to regions was already discussed in the previous Section. For these regions, in this Section we used the same sources to map the amount of exported cargo per country and super-region. The next five Tables (4.18 through 4.22) present the export of each country per respective region, using the same methodology as applied in Section 4.4.1.

Bulgaria

Table 4.18 – Exports of Bulgaria per region (ths. tonnes) (Source: Eurostat)

Bulgaria	Population	Total Productivity	Percentage of total population	County Productivity
North	2.674.347,00	14.574,30	0,36	5.292,47
South	4.690.223,00		0,64	9.281,83
Total	7.364.570,00		1,00	14.574,30

Romania

Table 4.19 – Exports of Romania per region (ths. tonnes) (Source: Eurostat)

Romania	Population	Total Productivity	Percentage of total population	County Productivity
North	8.263.154,00	24.247,20	0,41	9.957,36
South	11.858.487,00		0,59	14.289,84
Total	20.121.641,00		1,00	24.247,20

Moldova

Table 4.20 – Exports of Moldova per region (ths. tonnes) (Source: Moldovan Statistical Institute)

Moldova	Population	Total Productivity	Percentage of total population	County Productivity
North	724.319,00	2.873,00	0,20	586,45
Central	1.765.526,00		0,50	1.429,46
South	455.066,00		0,13	368,44
Independent regions	603.535,00		0,17	488,65
Total	3.548.446,00		1,00	2.873,00

Ukraine

Table 4.21 – Exports of Ukraine per region (ths. tonnes) (Source: Ukrainian Statistical Institute)

Ukraine	Population	Total Productivity	Percentage of total population	County Productivity
North West	17.706.925,00	892,60	0,45	398,22
South East	21.982.422,00		0,55	494,38
Total	39.689.347,00		1,00	892,60

Russia

Table 4.22 – Exports of Russia per region (ths. tonnes) (Source: Russian Statistical Institute)

European Russia	Population	Total Productivity	Percentage of total population	County Productivity
Central	39.209.582,00	12.919,00	0,36	4.649,38
Northwestern	13.899.310,00		0,13	1.648,15
Southern+Caucasian	26.204.228,00		0,24	3.107,24
Volga	29.636.574,00		0,27	3.514,24
Total	108.949.694,00		1,00	12.919,00

4.5 Goal Programming results

We used the parameters of Sections 4.3 and 4.4 in the models of Section 4.2 and solved the latter with Excel solver. The results are presented in this Section for the cases of:

- Port cargo dispatching to the Hinterland
- Port cargo attraction from the Hinterland

4.5.1 Port cargo dispatching estimates

The transportation **time** minimization problem for port dispatching yields the results indicated in Table 4.23.

Table 4.23 – Time minimization results for cargo dispatched per port

From port to hinterland (Time)					
Loaded	**Destination**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	North	Truck	4.726,23	5.600,00
	Bulgaria	South	Truck	873,77	
Thessaloniki	Bulgaria	South	Truck	6.638,50	9.446,00
	Romania	North	Truck	534,06	
	Romania	South	Truck	2.273,44	
Kavala	Bulgaria	South	Truck	776,50	776,50
Varna	Romania	North	Truck	3.988,50	3.988,50
Burgas	Romania	South	Truck	9.920,00	9.920,00
Constanta	Russia	Northwestern	Rail	963,83	17.656,00
	Russia	Volga	Rail	1.956,17	
	Romania	North	Truck	3.974,00	
	Moldova	North	Truck	1.046,74	
	Moldova	Central	Truck	2.551,43	
	Moldova	South	Truck	657,63	
	Moldova	Independent	Truck	872,19	
	Ukraine	Northwestern	Truck	445,69	
	Ukraine	Southeastern	Truck	553,31	
	Russia	Central	Truck	2.718,95	
	Russia	Southern	Truck	1.817,10	
	Russia	Volga	Truck	98,95	

Judging from Table 4.23, it is more efficient timewise when cargo is exchanged between:

PORT	REGION	TRANS. TYPE
Alexandroupoli	Bulgaria	Truck
Thessaloniki	Southern Bulgaria	Truck
Thessaloniki	Romania	Truck
Kavala	Southern Bulgaria	Truck
Varna	Northern Romania	Truck
Burgas	Northern Romania	Truck
Constanta	Russia	Truck & Rail
Constanta	Northern Romania	Truck
Constanta	Moldova	Truck
Constanta	Ukraine	Truck

It should come as no surprise that the majority of intermodal connectivity for the time parameter occurs via truck, given its much faster transportation times when compared to commercial trains.

The transportation **cost** minimization problem yields visibly different results for cargo dispatching, as shown in Table 4.24.

Table 4.24 – Cost minimization results for cargo dispatching

From port to hinterland (Cost)					
Loaded	**Destination**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	South	Rail	112,50	5.600,00
	Romania	North	Rail	2.807,50	
	Bulgaria	North	Truck	2.680,00	
Thessaloniki	Bulgaria	South	Rail	2.920,00	9.446,00
	Bulgaria	North	Truck	1.269,73	
	Bulgaria	South	Truck	5.256,27	
Kavala	Bulgaria	North	Truck	776,50	776,50
Varna	Moldova	Central	Rail	2.047,81	3.988,50
	Moldova	Independent	Rail	872,19	
	Ukraine	Northwestern	Truck	445,69	
	Ukraine	Southeastern	Truck	553,31	
	Russia	Central	Truck	69,50	
Burgas	Moldova	North	Rail	1.046,74	9.348,00
	Moldova	Central	Rail	503,62	
	Moldova	South	Rail	312,13	
	Russia	Central	Truck	2.649,45	
	Russia	Southern	Truck	1.817,10	
	Russia	Northwestern	Truck	963,83	
	Russia	Volga	Truck	2.055,12	
Constanta	Romania	South	Rail	2.574,50	18.228,00
	Moldova	South	Rail	345,50	
	Romania	North	Truck	5.689,06	
	Romania	South	Truck	9.618,94	

Based on the results from Table 4.24, it is more efficient cost – wise when cargo is exchanged between:

PORT	REGION	TRANS. TYPE
Alexandroupoli	Southern Bulgaria	Rail
Alexandroupoli	Northern Bulgaria	Truck

PORT	REGION	TRANS. TYPE
Alexandroupoli	Northern Romania	Rail
Thessaloniki	Bulgaria	Truck
Thessaloniki	Southern Bulgaria	Rail
Kavala	Northern Bulgaria	Truck
Varna	Central Moldova	Rail
Varna	Independent Moldova	Rail
Varna	Ukraine	Truck
Varna	Central Russia	Truck
Burgas	North Moldova	Rail
Burgas	Central Moldova	Rail
Burgas	South Moldova	Rail
Burgas	Central Russia	Truck
Burgas	Southern Russia	Truck
Burgas	North-western Russia	Truck
Burgas	Volga Russia	Truck
Constanta	Romania	Truck
Constanta	Southern Romania	Rail
Constanta	Moldova	Rail

In the cost minimization problem, all ports, excluding Burgas, use all of their rail capacity for cargo transportation to each hinterland region. This result is to be expected, given the lower cost of rail as compared to truck.

After the calculation of the optimal transportation values for time and cost, we applied the goal programming method to obtain the final results for the multi-criteria problem. The results are shown in Table 4.25, and they indicate that:

- ${s_1}^- = 4.5$
- ${s_2}^- = 0.5$

Thus more importance was placed on the minimization of cost (${s_2}^-$) since its deviation from the optimal value is lower than in the case of the time parameter (${s_1}^-$).

Table 4.25 – Results of the Goal Programming problem for port cargo dispatching

From port to hinterland					
Loaded	**Destination**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	South	Rail	112,00	5.600,00
	Romania	North	Rail	2.808,00	
	Bulgaria	North	Truck	2.680,00	
Thessaloniki	Bulgaria	North	Rail	1.269,23	9.446,00
	Bulgaria	South	Rail	1.650,77	
	Bulgaria	South	Truck	6.526,00	
Kavala	Bulgaria	North	Truck	777,00	777,00
Varna	Romania	North	Rail	2.574,00	3.416,00
	Moldova	North	Rail	346,00	
	Ukraine	North West	Truck	445,69	
	Ukraine	South East	Truck	50,31	
Burgas	Moldova	Central	Rail	1.862,00	9.920,00
	Ukraine	South East	Truck	503,00	
	Russia	Central	Truck	2.718,95	
	Russia	Southern	Truck	1.817,10	
	Russia	Northwestern	Truck	963,83	
	Russia	Volga	Truck	2.055,12	
Constanta	Moldova	North	Rail	700,74	18.228,00
	Moldova	Central	Rail	689,43	
	Moldova	South	Rail	657,63	
	Moldova	Independent	Rail	872,19	
	Romania	North	Truck	3.114,56	
	Romania	South	Truck	12.193,44	

The conclusion to be drawn from this process is that:

- Alexandroupolis port can potentially dispatch 5.600 th. tons of cargo to its hinterland, which consists of:
  - Bulgaria and
  - Romania
- Alexandroupolis uses all of its rail capacity for transportation, which emphasizes the need to invest into rail infrastructure.

4.5.2 Port cargo attraction estimates

The transportation **time** minimization problem for port cargo attraction yields the results indicated in Table 4.26.

Table 4.26 – Time minimization problem for port cargo attraction

From hinterland to port (Time)					
Unloaded	**Origin**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	North	Truck	3.035,00	3.035,00
Thessaloniki	Bulgaria	North	Truck	2.257,47	5.121,00
	Bulgaria	South	Truck	2.863,53	
Kavala	Bulgaria	South	Truck	1.064,50	1.064,50
Varna	Romania	South	Truck	7.446,50	7.446,50
Burgas	Bulgaria	South	Rail	2.920,00	7.928,00
	Bulgaria	South	Truck	2.433,80	
	Romania	North	Truck	2.574,20	
Constanta	Russia	Central	Rail	2.920,00	22.634,50
	Romania	North	Truck	7.383,16	
	Romania	South	Truck	6.843,34	
	Moldova	North	Truck	586,45	
	Moldova	Central	Truck	1.429,46	
	Moldova	South	Truck	368,44	
	Moldova	Independent	Truck	488,65	
	Russia	Central	Truck	966,85	
	Russia	Northwestern	Truck	1.648,15	

Based on the results of the linear problem, it is more efficient time – wise when the following hinterland regions supply the following ports:

REGION	PORT	TRANS. TYPE
Bulgaria	Alexandroupoli	Truck
Bulgaria	Thessaloniki	Truck
Southern Bulgaria	Kavala	Truck
Southern Bulgaria	Varna	Truck
Southern Bulgaria	Burgas	Truck
Southern Bulgaria	Burgas	Rail
Northern Romania	Burgas	Truck
Central Russia	Constanta	Truck
Central Russia	Constanta	Rail
Romania	Constanta	Truck
North Moldova	Constanta	Truck
Central Moldova	Constanta	Truck
South Moldova	Constanta	Truck

REGION	PORT	TRANS. TYPE
Independent Moldova	Constanta	Truck
North – western Russia	Constanta	Truck

Similarly to the export distribution problem, the majority of intermodal transportation occurs via truck when examining the imports of the ports timewise, as can be seen in Table 4.26. This result is to be expected, given the smaller transportation times of the truck when compared to the rail.

The transportation **cost** minimization problem for port cargo attraction yields visibly different results, as can be judged from Table 4.27.

Table 4.27 – Cost minimization problem for port cargo attraction

From hinterland to port (Cost)					
Unloaded	**Origin**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	North	Rail	2.858,67	3.035,00
	Bulgaria	South	Rail	61,33	
	Bulgaria	South	Truck	115,00	
Thessaloniki	Bulgaria	South	Rail	2.920,00	5.121,00
	Bulgaria	South	Truck	2.201,00	
Kavala	Bulgaria	South	Truck	1.064,50	1.064,50
Varna	Romania	South	Rail	1.612,70	7.446,50
	Ukraine	Northwestern	Truck	398,22	
	Ukraine	Southeastern	Truck	494,38	
	Russia	Central	Truck	4.649,38	
	Russia	Southern	Truck	291,82	
Burgas	Bulgaria	South	Rail	2.920,00	7.928,00
	Bulgaria	North	Truck	2.433,80	
	Russia	Southern	Truck	2.574,20	
Constanta	Romania	South	Rail	2.920,00	22.634,50
	Romania	North	Truck	9.957,36	
	Romania	South	Truck	9.757,14	

Judging from Table 4.27, it is most efficient cost – wise when the following hinterland regions supply the following ports:

REGION	PORT	TRANS. TYPE
North Bulgaria	Alexandroupoli	Rail
Southern Bulgaria	Alexandroupoli	Rail

REGION	PORT	TRANS. TYPE
Southern Bulgaria	Alexandroupoli	Truck
Southern Bulgaria	Thessaloniki	Truck
Southern Bulgaria	Thessaloniki	Rail
Southern Bulgaria	Kavala	Truck
Southern Romania	Varna	Rail
Ukraine	Varna	Truck
Central Russia	Varna	Truck
Southern Russia	Varna	Truck
Bulgaria	Burgas	Truck
Bulgaria	Burgas	Rail
Southern Russia	Burgas	Truck
Southern Romania	Constanta	Rail
Romania	Constanta	Truck

Additionally, all ports except Varna, use all the capacity that a railway connection can offer (2.920 th. tons) to receive cargo from the examined hinterland. Again, this result is to be expected, given the smaller transportation costs and higher volume of commercial trains compared to trucks.

After the calculation of the optimal transportation time and costs, the goal programming methodology for port cargo attraction (Section 4.2.2) can be applied to the problem. The results, depicted in Table 4.28, indicate that:

- ${s_1}^- = 1.2$
- ${s_2}^- = 0.9$

Which, similarly with the previous problem, means that more importance was put on the minimization of cost (${s_2}^-$), since its deviation from the optimal value is smaller than in the case of the time parameter (${s_1}^-$).

Table 4.28 – Goal Programming problem for port cargo attraction

From hinterland to port					
Unloaded	**Origin**	**Region**	**Transport Type**	**Amount (th. tonnes)**	**Sum**
Alexandroupoli	Bulgaria	South	Rail	2.920,00	3.035,00
	Bulgaria	South	Truck	115,00	
Thessaloniki	Bulgaria	South	Rail	2.920,00	5.121,00
	Bulgaria	South	Truck	2.201,00	
Kavala	Bulgaria	South	Truck	1.064,50	1.064,50
Varna	Romania	North	Rail	2.920,00	7.446,50
	Ukraine	North West	Rail	398,22	
	Ukraine	South East	Rail	494,38	
	Russia	Southern	Truck	119,66	
	Russia	Volga	Truck	3.514,24	
Burgas	Bulgaria	North	Rail	1.354,30	7.928,00
	Romania	North	Truck	1.565,70	
	Bulgaria	North	Truck	3.938,17	
	Bulgaria	South	Truck	61,33	
	Russia	Southern	Truck	1.008,50	
Constanta	Romania	North	Rail	47,00	22.634,50
	Moldova	North	Rail	586,45	
	Moldova	Central	Rail	1.429,46	
	Moldova	South	Rail	368,44	
	Moldova	Independent	Rail	488,65	
	Romania	North	Truck	5.424,66	
	Romania	South	Truck	14.289,84	

The conclusion to be drawn from this process is that:

- Alexandroupolis port can potentially import 3.035 th. tons of cargo from its hinterland, which consists of only Bulgaria.
- Alexandroupolis uses all of its rail capacity for transportation, which emphasizes the need to invest into rail infrastructure.
- The amount of cargo dispatched from the hinterland exceeds the import capacity of the selected ports, which explains why hinterland regions located further from the ports of examination (like Russia or Ukraine) do not send their maximum amount of cargo units to the ports.

4.6 Concluding Remarks

In this Chapter we studied the potential of cargo demand related to the ports of Alexandroupolis, Thessaloniki, Kavala, Varna, Burgas and Constanta. The targeted markets were countries in Eastern Europe, including Bulgaria, Romania, Moldova, Ukraine and Russia. The main goal of the analysis was to understand the potential cargo exchanged between the port of Alexandroupolis and the examined hinterland, should Alexandroupolis develop the infrastructure and management systems to handle these cargo volumes.

To do so, we developed a new multi-objective linear programming model that evaluates the most efficient transportation routes and amount of cargo between the ports under study and the countries/regions of the hinterland, with the main objective of simultaneous time and cost minimization. We applied the model in two cases: one related to the amount of cargo transported from the ports to the hinterland (dispatched cargo) and the other related to the amount of cargo transported from the hinterland regions to the ports (attracted cargo).

The model's parameters were estimated:

- From the statistical databases of the ports and the countries under consideration, where we obtained the maritime cargo movement of ports and counties
- We computed the cost and time to transport cargo between ports and hinterland regions

From the solution of the problem, it was deduced that the port of Alexandroupolis has the potential to:

- Dispatch 5.600 th. tons to its hinterland, which includes Bulgaria and Romania
- Attract 3.035 th. tons from its hinterland, which includes Bulgaria

Chapter 5 Current and potential role of Alexandroupolis as a gateway port in the Balkans and Eastern Europe

5.1 Introduction – Why the hinterland expansion strategy is preferred

Considering Fig. 2.1 of Chapter 2, the current state of the port of Alexandroupolis places it in cell B1, meaning that the port is still underdeveloped in marine connectivity, with limited infrastructure for hinterland connectivity, thus serving as a regional short-sea port. However, with appropriate investment, the port may have the potential of becoming a transnational gateway for short-sea or even deep-sea cargo flows (cells C1 and D1) (Ducruet *et al.,* 2018). Additionally, the local cargo base may also be developed, due to the enhanced logistics capabilities of the area, and the related economies of scale (de Langen, 2011). In this Chapter we will test this thesis.

To do so, first, Alexandroupolis and the competing ports in the area will be evaluated on each criterion established in Chapter 3. For Alexandroupolis, we will evaluate both the current state and the potential state of the port after appropriate investments. Subsequently, using various Multi-Criteria Decision Making methods (MCDM), the weights of the criteria will be calculated, and the final port ranking will be derived. If, after investments, the Alexandroupolis port manages to improve its ranking significantly compared to the current state, it may prove beneficial and profitable for investors to invest in this port.

5.2 Criteria values of competing ports

The values of the criteria used in this Section are extracted from:

- Eurostat, transport database (ec.europa.eu)
- Alexandroupolis port Master Plan (ola-sa.gr)
- Port authority websites (portfocus.com)
- European commission (2009) - East Mediterranean region flow patterns and

key tendencies related to future MoS development (ec.europa.eu)

5.2.1 Alexandroupolis port criteria values before and after investments

For the future state of Alexandroupolis port, the values are selected by the author depending on the potential for improvement of the port and the market needs.

The following two Tables, 5.1 and 5.2, present the criteria parameters for the current state of the port and the possible future state after investments, respectively.

Table 5.1 – Criteria values for current state of Alexandroupolis port

Port Location	Distance to main poles of attraction (road km)	758,6
	Distance to main poles of attraction (rail km)	967,2
	Distance from main route (km)	1334
	Natural Factors (scale 1:10)	5
Port Infrastructure	Infrastructure condition (scale 1:10)	5
	Water depth (m)	14,13
	Berth length (m)	2.515
	Container yard size (sq.m)	180.000
	Available land for expansion seaside (sq.m)	0
	Available land for expansion port side (sq.m)	470.000
	Inland intermodal connectivity (distance airport km)	6,3
	Inland intermodal connectivity rail use (0 or 1)	1
	Reliability of inland rail connectivity (scale 1:5)	1
	Reliability of inland road connectivity (scale 1:5)	2
	Container capacity (TEUs)	4.500
	Rail terminal capacity (number)	1
Port Management	Possibility of niche market	1
	Labor relations (scale 1:5)	5
	Stability of government policies (scale 1:5)	2
	Port reputation (scale 1:5)	1
	Customs and government regulations (scale 1:5)	4
Port Efficiency	Ship turnaround time (hours)	24
	Loaded (Outgoing) cargo (th. tonnes)	194,12
	Unloaded (Incoming) cargo (th. tonnes)	165,91
	Number of port calls	127
	Road congestion (minutes)	15
	Information technology availability	0

Table 5.2 – Criteria values for future state of Alexandroupolis port

Port/		Alexandroupoli
Port Location	Distance to main poles of attraction (road km)	758,6
	Distance to main poles of attraction (rail km)	967,2
	Distance from main route (km)	1334
	Natural Factors (scale 1:10)	5
Port Infrastructure	Infrastructure condition (scale 1:10)	8
	Water depth (m)	17
	Berth length (m)	3.675
	Container yard size (sq.m)	550.000
	Available land for expansion seaside (sq.m)	0
	Available land for expansion port side (sq.m)	470.000
	Inland intermodal connectivity (distance airport km)	6,3
	Inland intermodal connectivity rail use (0 or 1)	1
	Reliability of inland rail connectivity (scale 1:5)	4
	Reliability of inland road connectivity (scale 1:5)	5
	Container capacity (TEUs)	13.750
	Rail terminal capacity (number)	6
Port Management	Possibility of niche market	1
	Labor relations (scale 1:5)	5
	Stability of government policies (scale 1:5)	4
	Port reputation (scale 1:5)	5
	Customs and government regulations (scale 1:5)	5
Port Efficiency	Ship turnaround time (hours)	24
	Loaded (Outgoing) cargo (th. tonnes)	3.035
	Unloaded (Incoming) cargo (th. tonnes)	5.600
	Number of port calls	1.160
	Road congestion (minutes)	15
	Information technology availability	1

5.2.2 Criteria values for the other ports

The parameter values for the ports of Thessaloniki, Kavala, Varna, Burgas and Constanta are presented in Table 5.3.

Table 5.3 – Criteria values for the other four ports

	Thessaloniki	Kavala	Varna	Burgas	Constanta
Distance to main poles of attraction (road)	893,2	785,1	447	508,4	347,9
Distance to main poles of attraction (rail)	1112	-	630,2	754,2	430
Distance from main route	1390	1340	1885	1793	1905
Natural Factors	5	8	6	8	8
Infrastructure condition	9	6	7	7	10
Water depth	12	11,5	11,5	14,6	19
Berth length	6.200	2.860	5.775	4.570	30.000
Container yard size	254.000	50.000	168.000	53.200	818.842
Available land for expansion seaside	325.000	2.388.000	1.214.000	2.890.000	0
Available land for expansion port side	497.000	3.048.000	11.300.000	2.313.000	6.550.000
Inland intermodal connectivity (airport)	17	24,4	15,25	13,7	39,2
Inland intermodal connectivity rail use	1	0	1	1	1
Reliability of inland rail connectivity	4	0	3	3	5
Reliability of inland road connectivity	5	4	5	5	5
Container capacity (TEUs)	6.350	1.251	4.200	1.330	20.472
Rail terminal capacity	11	0	10	6	24
Possibility of niche market	1	0	1	1	1
Labor relations	3	5	2	2	4
Stability of government policies	2	2	2	2	4
Port reputation	5	1	4	3	5
Customs and government regulations	5	4	5	5	5
Ship turnaround time	18	48	56	41	72
Loaded (Outgoing) cargo (th. tonnes)	5.121	1.064,50	7.446,50	7.928	22.634,50
Unloaded (Incoming) cargo (th. tonnes)	9.446	776,5	3.989	9.920	18.228
Number of port calls	1.929	369	1.560	1.692	4.542
Road congestion	25	3	16,5	23	24
IT availability	1	0	1	1	1

5.3 Criteria weight determination

Step 2 of the assessment methodology presented in Chapter 3 will be applied. Note that not every criterion of Table 3.2 (Chapter 3) has the same weight in the assessment process. In order to efficiently compute the criteria weights that will be used in this case study, four methods have been used (analyzed in Appendix A):

- Analytic Hierarchy Process (AHP)
- Best – Worst Method (BWM)
- CRITIC
- ENTROPY

5.3.1 Criteria weights using the Analytical Hierarchy Process (AHP)

For the steps of AHP, see Appendix A.

Step A: Definition of relative criteria importance

By applying Saaty's scale, compare criterion i to criterion j to obtain the a_{ij} value and create the pairwise comparison matrix (or reciprocal matrix) of Table 5.4. The pairwise comparison matrix is based on the author's judgement.

Table 5.4 – AHP main criteria pairwise comparison matrix

	Port Location	Port Infrastructure	Port Management	Port Efficiency
Port Location	*1*	*4*	*6*	*3*
Port Infrastructure	*0,25*	*1*	*3*	*0,33*
Port Management	*0,17*	*0,33*	*1*	*0,33*
Port Efficiency	*0,33*	*3,00*	*3*	*1*
Sum	**1,75**	**8,33**	**13**	**4,67**

Step B: Criteria Weight Calculation:

The normalized pairwise comparison matrix is computed and provided in Table 5.5.

Table 5.5 – AHP main criteria normalized pairwise comparison matrix

	Port Location	**Port Infr/cture**	**Port Man/ment**	**Port Efficiency**	**Criteria Weight**
Port Location	*0,57*	*0,48*	*0,46*	*0,64*	**0,54**
Port Infr/cture	*0,14*	*0,12*	*0,23*	*0,07*	**0,14**
Port Man/ment	*0,10*	*0,04*	*0,08*	*0,07*	**0,07**
Port Efficiency	*0,19*	*0,36*	*0,23*	*0,21*	**0,25**

The criteria weights are the average values of each row.

Step C: Consistency check:

For computing the Consistency Index ($C.I$) of the normalized pairwise comparison matrix, we use Eq. (5.1).

$$C.I = \frac{\lambda_{max} - m}{m - 1}, \qquad (5.1)$$

Where λ_{max} is 4.1625.

$$C.I = \frac{4.1625 - 4}{4 - 1} = 0.05419$$

For four criteria, the Random Consistency Index ($R.C.I$) equals 0.9, based on the Random Consistency Index by Saaty (see Appendix A). Finally, the Consistency Ratio ($C.R$) is calculated by dividing $C.I$ with $R.C.I$ to obtain

$$C.R = \frac{0.05419}{0.9} = 0.06021 \leq 0.1$$

Thus, the reciprocal matrix is consistent.

According to these results, investors are giving more importance to intrinsic characteristics, since these are hard to change through investments. Port management, for example, is the most unimportant criterion based on AHP, since it is directly affected by the investors' decisions. On the other hand, no matter the amount of investment, the port cannot change location, making this criterion very important for gateway port selection.

After calculating the weights of all main criteria and their respective sub-criteria (in similar fashion to the computation of the main criteria weights), the final step is to compute the final weights of every criterion, using Eq. (5.2)

$$Final\ weight = Main\ criteria\ weight * sub\ criterion\ weight, \qquad (5.2)$$

The results of Table 5.6 indicate that the most important criterion for port selection based on AHP is the distance of the port from the main poles of attraction via rail. Even though there are 27 criteria, approximately a quarter (23.7%) of the final decision for gateway port selection depends on this criterion.

Table 5.6 – AHP results for case study

Criterion	Final Weight	Rank
Distance to main poles of attraction (road)	*0,073*	**4**
Distance to main poles of attraction (rail)	*0,237*	**1**
Distance from main route	*0,193*	**2**
Natural Factors	*0,036*	**8**
Infrastructure condition	*0,006*	**23**
Water depth	*0,009*	**18**
Berth length	*0,006*	**21**
Container yard size	*0,006*	**22**
Available land for expansion seaside	*0,019*	**13**
Available land for expansion port side	*0,021*	**11**

Criterion	Final Weight	Rank
Inland intermodal connectivity (airport)	*0,002*	**27**
Inland intermodal connectivity rail use	*0,036*	**7**
Reliability of inland rail connectivity	*0,005*	**24**
Reliability of inland road connectivity	*0,003*	**26**
Container capacity	*0,009*	**19**
Rail terminal capacity	*0,019*	**12**
Possibility of niche market	*0,027*	**9**
Labor relations	*0,004*	**25**
Stability of government policies	*0,007*	**20**
Port reputation	*0,018*	**14**
Customs and government regulations	*0,015*	**16**
Ship turnaround time	*0,027*	**10**
Loaded (Outgoing) cargo	*0,053*	**5**
Unloaded (Incoming) cargo	*0,092*	**3**
Number of port calls	*0,012*	**17**
Road congestion	*0,050*	**6**
Information technology availability	*0,015*	**15**

5.3.2 BWM (Best – Worst Method)

Based on the hierarchical model of the problem, the following steps will be followed for the calculation of the criteria weights:

- Comparison of the four main criteria (Port Location, Port Infrastructure, Port Management and Port efficiency)
- Comparison of the sub – criteria of each of the main criteria

<u>Main criteria weight calculation:</u>

Step A: Identification of the criteria (see above).

Step B: Selection of best and worst criterion

Port Location was selected as the best criterion (based on the AHP analysis above). For the same reason, Port Management was selected as the worst criterion.

Step C: Comparison of the best criterion with the other criteria.

Based on a nine point scale, Table 5.7 below represents the importance of Port Location (best criterion) in comparison to the other criteria:

Table 5.7 – BWM comparison of the best main criterion

	Port Location	Port Infrastructure	Port Management	Port Efficiency
Port Location	*1*	*4*	*6*	*3*

Step D: BWM Comparison of the worst main criterion

Based on a nine-point scale, Table 5.8 below presents the comparison of Port Management to the other criteria:

Table 5.8 – BWM comparison of the worst main criterion

	Port Management
Port Location	*6*
Port Infrastructure	*3*
Port Management	*1*
Port Efficiency	*3*

Step E: Based on Appendix A and Rezaei (2014), the appropriate linear programming problem is constructed to calculate the criteria weights for the four main criteria. After solving the problem using Excel solver, the resulting weights are:

- $w_1 = 0.5526$
- $w_2 = 0.1578$
- $w_3 = 0.0789$
- $w_4 = 0.2105$

Based on Appendix A, the Consistency Ratio for this problem is $0.02631 \leq 0.2922$, thus the pairwise comparison is consistent, and the results are valid for further evaluation.

Following the weight calculation of the main criteria and sub – criteria (in a similar fashion to the one used for the main criteria), the final weights of each individual criterion are calculated by applying the same Eq. (5.2) as in the AHP case, with the results presented in Table 5.9.

Table 5.9 – BWM weights for case study

Criterion	Final Weight	Rank
Distance to main poles of attraction (road)	*0,102*	**3**
Distance to main poles of attraction (rail)	*0,256*	**1**
Distance from main route	*0,154*	**2**
Natural Factors	*0,041*	**6**
Infrastructure condition	*0,010*	**23**
Water depth	*0,013*	**17**
Berth length	*0,010*	**21**
Container yard size	*0,010*	**22**
Available land for expansion seaside	*0,013*	**17**
Available land for expansion port side	*0,017*	**14**
Inland intermodal connectivity (airport)	*0,003*	**27**
Inland intermodal connectivity rail use	*0,039*	**7**
Reliability of inland rail connectivity	*0,007*	**24**
Reliability of inland road connectivity	*0,006*	**25**
Container capacity	*0,013*	**19**
Rail terminal capacity	*0,017*	**13**
Possibility of niche market	*0,030*	**9**
Labor relations	*0,004*	**26**
Stability of government policies	*0,013*	**15**
Port reputation	*0,019*	**12**
Customs and government regulations	*0,013*	**15**
Ship turnaround time	*0,020*	**11**
Loaded (Outgoing) cargo	*0,033*	**8**
Unloaded (Incoming) cargo	*0,077*	**4**
Number of port calls	*0,011*	**20**
Road congestion	*0,050*	**5**
Information technology availability	*0,020*	**10**

5.3.3 CRITIC

Unlike the two previous methods (AHP & BWM), in the CRITIC criteria weight determination method there is no hierarchical model, thus there is no categorization of Main criteria and sub – criteria.

Furthermore, given that in this case study there are two states, the current and possible future state of the ports, different criteria weights will be generated for each respective perspective, since the importance of each criterion is based on the state (see Appendix A).

Step A: Determine the values of each criterion for every alternative:

All values for the current and potential state of the ports are provided in Tables 5.1 to 5.3 in Section 5.2.

Step B: Matrix normalization (see Appendix A)

For **Steps 3**, **4** and **5** we performed the computations for Contrast Intensity (Standard Deviation), Conflict (Correlation) and the final criteria weights calculations respectively for both the current and the possible future state. The results provided two different sets of criteria weights, each for a different state of the ports, depicted in Tables 5.10 and 5.11.

Table 5.10 – CRITIC criteria weights for the current state

Criteria	w_j	Rank
Distance to main poles of attraction (road)	*0,051*	**6**
Distance to main poles of attraction (rail)	*0,056*	**2**
Distance from main route	*0,065*	**1**
Natural Factors	*0,049*	**7**
Infrastructure condition	*0,025*	**24**
Water depth	*0,029*	**19**
Berth length	*0,027*	**20**

Criteria	w_j	Rank
Container yard size	*0,026*	**22**
Available land for expansion seaside	*0,054*	**4**
Available land for expansion port side	*0,036*	**12**
Inland intermodal connectivity (airport)	*0,045*	**9**
Inland intermodal connectivity rail use	*0,032*	**13**
Reliability of inland rail connectivity	*0,030*	**17**
Reliability of inland road connectivity	*0,032*	**15**
Container capacity (TEUs)	*0,026*	**21**
Rail terminal capacity	*0,024*	**26**
Possibility of niche market	*0,032*	**13**
Labor relations	*0,055*	**3**
Stability of government policies	*0,029*	**18**
Port reputation	*0,031*	**16**
Customs and government regulations	*0,037*	**10**
Ship turnaround time	*0,046*	**8**
Loaded (Outgoing) cargo (th. tonnes)	*0,024*	**25**
Unloaded (Incoming) cargo (th. tonnes)	*0,025*	**23**
Number of port calls	*0,023*	**27**
Road congestion	*0,053*	**5**
IT availability	*0,037*	**10**

Table 5.11 – CRITIC criteria weights for possible future state

Criteria	w_j	Rank
Distance to main poles of attraction (road)	*0,049*	**7**
Distance to main poles of attraction (rail)	*0,047*	**8**
Distance from main route	*0,060*	**2**
Natural Factors	*0,060*	**3**
Infrastructure condition	*0,024*	**25**

Criteria	w_j	Rank
Water depth	*0,030*	**13**
Berth length	*0,029*	**14**
Container yard size	*0,027*	**21**
Available land for expansion seaside	*0,062*	**1**
Available land for expansion port side	*0,042*	**9**
Inland intermodal connectivity (airport)	*0,040*	**11**
Inland intermodal connectivity rail use	*0,028*	**18**
Reliability of inland rail connectivity	*0,053*	**5**
Reliability of inland road connectivity	*0,028*	**15**
Container capacity (TEUs)	*0,027*	**20**
Rail terminal capacity	*0,023*	**27**
Possibility of niche market	*0,028*	**18**
Labor relations	*0,050*	**6**
Stability of government policies	*0,038*	**12**
Port reputation	*0,025*	**23**
Customs and government regulations	*0,028*	**15**
Ship turnaround time	*0,041*	**10**
Loaded (Outgoing) cargo (th. tonnes)	*0,027*	**22**
Unloaded (Incoming) cargo (th. tonnes)	*0,024*	**24**
Number of port calls	*0,024*	**26**
Road congestion	*0,054*	**4**
IT availability	*0,028*	**15**

5.3.4 Entropy

Similarly to CRITIC, different criteria weights will be computed for each of the two port states since the importance of each criterion is changes based on those state - (see Appendix A).

Step A: Determine the values of each criterion for every alternative.

All values are provided in Tables 5.1 to 5.3 in Section 5.2.

Step B: Matrix normalization

For **Steps 3** and **Step 4** we performed all computations for Entropy and the final criteria weights for the current and the possible state of the ports after investments. The results of the Entropy methodology provided two different sets of criteria weights, each for a different state of the ports, depicted in Tables 5.12 and 5.13.

Table 5.12 - Entropy criteria weights for the current state

Criteria	w_j	Rank
Distance to main poles of attraction (road)	*0,034*	**21**
Distance to main poles of attraction (rail)	*0,037*	**10**
Distance from main route	*0,036*	**12**
Natural Factors	*0,036*	**13**
Infrastructure condition	*0,034*	**22**
Water depth	*0,040*	**5**
Berth length	*0,045*	**2**
Container yard size	*0,041*	**4**
Available land for expansion seaside	*0,039*	**7**
Available land for expansion port side	*0,039*	**6**
Inland intermodal connectivity (airport)	*0,032*	**24**
Inland intermodal connectivity rail use	*0,031*	**26**
Reliability of inland rail connectivity	*0,036*	**16**
Reliability of inland road connectivity	*0,031*	**25**
Container capacity (TEUs)	*0,041*	**3**
Rail terminal capacity	*0,036*	**15**
Possibility of niche market	*0,031*	**26**
Labor relations	*0,036*	**11**
Stability of government policies	*0,061*	**1**

Criteria	w_j	Rank
Port reputation	*0,036*	**18**
Customs and government regulations	*0,035*	**19**
Ship turnaround time	*0,033*	**23**
Loaded (Outgoing) cargo (th. tonnes)	*0,037*	**9**
Unloaded (Incoming) cargo (th. tonnes)	*0,036*	**14**
Number of port calls	*0,036*	**17**
Road congestion	*0,038*	**8**
IT availability	*0,035*	**19**

Table 5.13 - Entropy criteria weights for the possible future state

Criteria	w_j	Rank
Distance to main poles of attraction (road)	*0,035*	**17**
Distance to main poles of attraction (rail)	*0,038*	**10**
Distance from main route	*0,038*	**13**
Natural Factors	*0,038*	**14**
Infrastructure condition	*0,035*	**19**
Water depth	*0,041*	**4**
Berth length	*0,046*	**2**
Container yard size	*0,040*	**8**
Available land for expansion seaside	*0,040*	**7**
Available land for expansion port side	*0,040*	**5**
Inland intermodal connectivity (airport)	*0,033*	**21**
Inland intermodal connectivity rail use	*0,032*	**23**
Reliability of inland rail connectivity	*0,043*	**3**
Reliability of inland road connectivity	*0,032*	**23**
Container capacity (TEUs)	*0,040*	**6**
Rail terminal capacity	*0,035*	**18**
Possibility of niche market	*0,032*	**23**
Labor relations	*0,038*	**12**

Criteria	w_j	Rank
Stability of government policies	*0,049*	**1**
Port reputation	*0,033*	**22**
Customs and government regulations	*0,032*	**23**
Ship turnaround time	*0,034*	**20**
Loaded (Outgoing) cargo (th. tonnes)	*0,038*	**11**
Unloaded (Incoming) cargo (th. tonnes)	*0,035*	**16**
Number of port calls	*0,036*	**15**
Road congestion	*0,039*	**9**
IT availability	*0,032*	**23**

From the above results (see Table 5.14), it is concluded that each method provides different criteria weights, with similarities between a) AHP & BWM and b) CRITIC & Entropy.

Table 5.14 – Synopsis of criteria weights for all methods

Methods/ Criteria	AHP	BWM	CRITIC		ENTROPY	
			Current	Possible	Current	Possible
Distance to main poles of attraction (road)	0,073	0,102	0,051	0,049	0,034	0,035
Distance to main poles of attraction (rail)	0,237	0,256	0,056	0,047	0,037	0,038
Distance from main route	0,193	0,154	0,065	0,060	0,036	0,038
Natural Factors	0,036	0,041	0,049	0,060	0,036	0,038
Infrastructure condition	0,006	0,010	0,025	0,024	0,034	0,035
Water depth	0,009	0,013	0,029	0,030	0,040	0,041
Berth length	0,006	0,010	0,027	0,029	0,045	0,046
Container yard size	0,006	0,010	0,026	0,027	0,041	0,040
Available land for expansion seaside	0,019	0,013	0,054	0,062	0,039	0,040
Available land for expansion port side	0,021	0,017	0,036	0,042	0,039	0,040
Inland intermodal connectivity (airport)	0,002	0,003	0,045	0,040	0,032	0,033
Inland intermodal connectivity rail use	0,036	0,039	0,032	0,028	0,031	0,032
Reliability of inland rail connectivity	0,005	0,007	0,030	0,053	0,036	0,043
Reliability of inland road connectivity	0,003	0,006	0,032	0,028	0,031	0,032
Container capacity (TEUs)	0,009	0,013	0,026	0,027	0,041	0,040
Rail terminal capacity	0,019	0,017	0,024	0,023	0,036	0,035
Possibility of niche market	0,027	0,030	0,032	0,028	0,031	0,032
Labor relations	0,004	0,004	0,055	0,050	0,036	0,038
Stability of government policies	0,007	0,013	0,029	0,038	0,061	0,049
Port reputation	0,018	0,019	0,031	0,025	0,036	0,033
Customs and government regulations	0,015	0,013	0,037	0,028	0,035	0,032
Ship turnaround time	0,027	0,020	0,046	0,041	0,033	0,034
Loaded (Outgoing) cargo (th. tonnes)	0,053	0,033	0,024	0,027	0,037	0,038
Unloaded (Incoming) cargo (th. tonnes)	0,092	0,077	0,025	0,024	0,036	0,035
Number of port calls	0,012	0,011	0,023	0,024	0,036	0,036
Road congestion	0,050	0,050	0,053	0,054	0,038	0,039
IT availability	0,015	0,020	0,037	0,028	0,035	0,032

5.4 Application of the port evaluation methods

As was already mentioned in **Step 3** during the analysis of the assessment methodology (Chapter 3), four Multi Criteria Decision Making (MCDM) methods will be used for the assessment of the potential gateway ports, namely:

- PROMETHEE II
- TOPSIS
- VIKOR
- WASPAS

Every MCDM method will be applied twice: for their current state and for the state after potential investments in Alexandroupolis port. In each application we will use the weights resulting from the above four weight determination methods.

5.4.1 PROMETHEE II

Step A: Determine the values of each criterion for every alternative. The application of PROMETHEE II will be illustrated using the AHP weights as a reference, while for the remaining weights we will only provide the results, since the application steps are identical.

Step B: Matrix normalization

Normalization depends on whether the criterion is beneficial or non – beneficial (see Appendix B). Beneficial criteria are those that benefit the decision maker through maximization e.g. quality, since the higher the quality, the better. Non – beneficial criteria have the opposite effect. For example, the lower the value of Price of an alternative, the better.

Step C: Comparison of alternatives per criterion

Having calculated the Normalized matrix, the comparison of the alternatives is performed, which essentially provides the deviation of one alternative from the others.

Step D: Calculation of the preference function and weighted matrix

The preference function (or p_j) is then applied to the previously computed Deviation of the Normalized matrix $d_j(a, b)$, which essentially represents the preference of alternative a over b with respect to the j^{th} criterion. Following the computation of the Preference Function (p_j), the newly formed matrix is multiplied with the criteria weights to obtain the Weighted Preference matrix (WP_j)

Step E: Weighted Aggregated Preference Function

In this step, the Weighted Aggregated Preference Function (or $\pi(a, b)$) is calculated, in order to consolidate the values of the Weighted Preference Matrix into a compact form. Table 5.15 presents the Weighted Aggregated Preference matrix for the current port state for the AHP criteria weights.

Table 5.15 – Preference matrix of PROMETHEE using the weights resulting from AHP

PORTS	Al/polis	Thessaloniki	Kavala	Varna	Burgas	Constanta
Alexandroupolis	*0,00*	*0,01*	*0,43*	*0,17*	*0,11*	*0,24*
Thessaloniki	*0,25*	*0,00*	*0,66*	*0,29*	*0,20*	*0,31*
Kavala	*0,08*	*0,07*	*0,00*	*0,08*	*0,05*	*0,08*
Varna	*0,35*	*0,23*	*0,61*	*0,00*	*0,07*	*0,10*
Burgas	*0,36*	*0,22*	*0,65*	*0,14*	*0,00*	*0,15*
Constanta	*0,56*	*0,39*	*0,74*	*0,23*	*0,22*	*0,00*

Step F: Positive and Negative outranking flows and alternative ranking

In order to evaluate the alternatives from best to worst, there are two values that must be calculated for every alternative:

- the leaving flow (φ^+), which describes the strength of an alternative over the other alternatives

- the entering flow (φ^-), which describes the weakness of an alternative with respect to the other alternatives

For the current state of the ports using AHP weights, the entering and leaving flows are presented in Table 5.16.

Table 5.16 – PROMETHEE flows for AHP weights in the current state

PORTS	Al/polis	Thessaloniki	Kavala	Varna	Burgas	Constanta	φ^+
Alexandroupolis	*0,00*	*0,01*	*0,43*	*0,17*	*0,11*	*0,24*	**0,19**
Thessaloniki	*0,25*	*0,00*	*0,66*	*0,29*	*0,20*	*0,31*	**0,34**
Kavala	*0,08*	*0,07*	*0,00*	*0,08*	*0,05*	*0,08*	**0,07**
Varna	*0,35*	*0,23*	*0,61*	*0,00*	*0,07*	*0,10*	**0,27**
Burgas	*0,36*	*0,22*	*0,65*	*0,14*	*0,00*	*0,15*	**0,30**
Constanta	*0,56*	*0,39*	*0,74*	*0,23*	*0,22*	*0,00*	**0,43**
φ^-	**0,32**	**0,18**	**0,62**	**0,18**	**0,13**	**0,18**	

The final rankings are calculated after subtracting these flows and are presented in Table 5.17.

Table 5.17 – PROMETHEE current state with AHP weights

Ports	$\varphi^+(\alpha)$	$\varphi^-(\alpha)$	$\varphi(\alpha)$	Rank
Alexandroupolis	*0,193*	*0,319*	*-0,126*	**5**
Thessaloniki	*0,342*	*0,183*	*0,160*	**3**
Kavala	*0,072*	*0,618*	*-0,546*	**6**
Varna	*0,271*	*0,181*	*0,090*	**4**

Ports	$\varphi^{+}(\alpha)$	$\varphi^{-}(\alpha)$	$\varphi(\alpha)$	Rank
Burgas	*0,303*	*0,129*	*0,174*	**2**
Constanta	*0,426*	*0,177*	*0,249*	**1**

The same methodology is applied for the results of every criteria weight determination method for both the current state and the possible future state. Table 5.18 presents the results of PROMETHEE for the current port state.

Table 5.18 – PROMETHEE port rankings in the current state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*5*	*5*	*5*	*5*
Thessaloniki	*3*	*1*	*3*	*3*
Kavala	*6*	*6*	*6*	*6*
Varna	*4*	*4*	*4*	*4*
Burgas	*2*	*3*	*2*	*2*
Constanta	*1*	*2*	*1*	*1*

Despite the differences in the criteria weights of the four weight determination methods, the rankings of the ports are quite similar. In particular, what is common in all methods is that Alexandroupolis and Kavala rankings stay the same (5th and 6th respectively), which is to be expected, since these two ports are currently the most underdeveloped. For the majority of most methods (except BWM), Constanta was ranked as the top port, followed by Burgas, followed by Varna and Thessaloniki in a virtual tie. On the other hand, the rankings for the possible future state of Alexandroupolis differ, as can be seen in the results of PROMETHEE II of Table 5.19.

Table 5.19 – PROMETHEE port rankings in the potential future state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*5*	*4*	*3*	*2*
Thessaloniki	*3*	*1*	*4*	*3*
Kavala	*6*	*6*	*6*	*6*
Varna	*4*	*5*	*5*	*5*
Burgas	*2*	*3*	*2*	*4*
Constanta	*1*	*2*	*1*	*1*

Despite the changes and investments made to the Alexandroupolis port, AHP and BWM still rank the port low. On the other hand, with CRITIC, Alexandroupolis is ranked third, while with Entropy, Alexandroupolis is ranked second, after Constanta.

5.4.2 TOPSIS

The detailed analysis of the TOPSIS Multi Criteria Decision Making method is presented in Appendix B. Essentially, the main concept of the method is that the best alternative has:

- the closest Euclidean distance to the ideal solution
- the highest Euclidean distance from the non – ideal solution

Step A: Determine the values of each criterion for every alternative (see Tables 5.1 through 5.3 in Section 5.2).

Step B: Matrix normalization

Step C: Weighted Normalized Decision Matrix and ideal – non ideal values

Following the calculation of the Weighted Normalized matrix, the ideal and non – ideal values are determined, based on whether the criterion is beneficial or non – beneficial.

Step D: Euclidean Distance

Compute the distances from the ideal and non – ideal values for each alternative. The results are provided in Table 5.20 below.

Table 5.20 – TOPSIS AHP ideal and non – ideal distances per port

Ports	${S_i}^+$	${S_i}^-$
Alexandroupolis	*0,073*	*0,084*
Thessaloniki	*0,060*	*0,105*
Kavala	*0,169*	*0,071*
Varna	*0,098*	*0,044*
Burgas	*0,077*	*0,064*
Constanta	*0,101*	*0,086*

Step E: Alternative Rankings

In this last step of TOPSIS evaluation, the performance of each alternative based on the ideal and non – ideal solution is provided. Table 5.21 is obtained for the AHP criteria weights.

Table 5.21 – TOPSIS current state with AHP weights

Ports	${S_i}^+$	${S_i}^-$	${S_i}^+ + {S_i}^-$	P_i	Rank
Alexandroupolis	*0,095*	*0,081*	*0,176*	*0,463*	**3**
Thessaloniki	*0,061*	*0,106*	*0,167*	*0,636*	**1**
Kavala	*0,170*	*0,071*	*0,241*	*0,295*	**6**
Varna	*0,099*	*0,046*	*0,145*	*0,317*	**5**
Burgas	*0,077*	*0,067*	*0,144*	*0,463*	**4**
Constanta	*0,101*	*0,092*	*0,193*	*0,477*	**2**

The application of this methodology with different criteria weights for the current port state are provided in Table 5.22.

Table 5.22 – TOPSIS port rankings in the current state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*3*	*2*	*6*	*5*
Thessaloniki	*1*	*1*	*4*	*3*
Kavala	*6*	*6*	*5*	*6*
Varna	*5*	*5*	*3*	*2*
Burgas	*4*	*3*	*2*	*4*
Constanta	*2*	*4*	*1*	*1*

The results indicate significant differences depending on the weight determination method used. When applying the AHP and BWM criteria weights, which are based on judgment, much emphasis is placed into intrinsic criteria, such as distance to main poles or natural factors. As a result, the Mediterranean ports, especially Alexandroupolis, even though has underdeveloped infrastructure, places higher than the Black Sea ports. On the other hand, the other two methods (CRITIC and Entropy) rank the Black Sea ports in better position, since they have a much more developed infrastructure and intermodal connectivity, especially when compared to Alexandroupolis and Kavala.

As expected, when the port of Alexandroupolis, which already has a favorable location as a gateway port, enhances its connectivity and infrastructure through investments, its preference as a gateway port changes as seen in Table 5.23.

Table 5.23 – TOPSIS port rankings in the potential future state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*2*	*2*	*4*	*2*
Thessaloniki	*1*	*1*	*6*	*5*
Kavala	*6*	*6*	*5*	*6*
Varna	*5*	*5*	*3*	*3*
Burgas	*4*	*3*	*2*	*4*
Constanta	*3*	*4*	*1*	*1*

The results of TOPSIS indicate that, after potential investments, Alexandroupolis may become a prominent gateway port in the area, as was also deduced by PROMETHEE II.

5.4.3 VIKOR

The VIKOR (from Serbian as Multi Criteria Optimization and Compromise Solution) method resembles TOPSIS, in the context that the best alternative is the one that is as close as possible to the ideal solution. Again, below we apply the method using the AHP criteria weights. A similar process is followed for the weight values resulting from the remaining methods.

Step A: Determine the values of each criterion for every alternative (see Tables 5.1 through 5.3 in Section 5.2).

Step B: Matrix normalization and distance to the ideal solution

Step C: Individual Regret

Unity measure S_i indicates how close each alternative is to the ideal solution. The closer S_i is to 0, the closer to the best solution alternative i it is. Let R_i be the individual regret for each alternative, which represents the normalized value of the criterion which deviates the most from the ideal solution. Both the individual regret (R_i) and the unity measure (S_i) of each port are illustrated in Table 5.24.

Table 5.24 – S_i and R_i for AHP weights in current state

Port	S_i	R_i
Alexandroupolis	*0,441*	*0,096*
Thessaloniki	*0,289*	*0,050*
Kavala	*0,396*	*0,237*
Varna	*0,617*	*0,186*
Burgas	*0,515*	*0,155*
Constanta	*0,518*	*0,193*

Step D: Final alternative rankings

The last step is to provide the rankings of the alternatives (ports). In Table 5.25, the VIKOR results for AHP criteria weights is presented.

Table 5.25 – VIKOR current state with AHP weights

Ports	S_i	R_i	Q_i	Rank
Alexandroupolis	*0,441*	*0,096*	*0,354*	**2**
Thessaloniki	*0,289*	*0,050*	*0,000*	**1**
Kavala	*0,396*	*0,237*	*0,664*	**4**
Varna	*0,617*	*0,186*	*0,864*	**6**
Burgas	*0,515*	*0,155*	*0,625*	**3**
Constanta	*0,518*	*0,193*	*0,731*	**5**
S^* , R^*	*0,289*	*0,050*	-	-
S^- , R^-	*0,617*	*0,237*	-	-

The application of the VIKOR evaluation for all criteria weight methods for the current state of the ports is provided in Table 5.26.

Table 5.26 – VIKOR rankings in the current state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*2*	*2*	*6*	*6*
Thessaloniki	*1*	*1*	*1*	*2*
Kavala	*4*	*6*	*5*	*5*
Varna	*6*	*5*	*4*	*4*
Burgas	*3*	*3*	*3*	*3*
Constanta	*5*	*4*	*2*	*1*

In general, it is observed that weight determination techniques that are based on judgement (AHP & BWM) place the Black Sea ports last, given their distance from the trunk lines. On the other hand, techniques that weight each criterion based on the amount of information (CRITIC & Entropy) and provide more balanced weight values, place the Black Sea ports higher given their developed infrastructure (with the exception of Thessaloniki, which is a very modern port). When the same methodology is applied to the possible future state of the ports, the results of VIKOR produce Table 5.27.

Table 5.27 – VIKOR rankings in the potential future state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*2*	*2*	*2*	*2*
Thessaloniki	*1*	*1*	*3*	*3*

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Kavala	*6*	*6*	*6*	*6*
Varna	*5*	*5*	*5*	*5*
Burgas	*3*	*3*	*4*	*4*
Constanta	*4*	*4*	*1*	*1*

After infrastructure upgrades, the port Alexandroupolis increased its appeal to investors. In addition to its favorable location, which will allow the port to supply Eastern Europe, the improved infrastructure makes it an efficient port, ranking second for all of weight determination methods.

5.4.4 WASPAS

WASPAS (Weighted Aggregated Sum Product Assessment) is the fusion of two very commonly used MCDM methods, the Weighted Sum Model, and the Weighted Product Model. As with every port ranking method, a step by step analysis will be presented for the current state using the weights calculated with AHP. Afterwards, the results of every weight determination criteria will be provided and discussed for both the current and possible future state of the ports.

Step A: Determine the values of each criterion for every alternative (see Tables 5.1 through 5.3 in Section 5.2). The application of WASPAS will be illustrated using the AHP weights as a reference, while for the remaining weights we will only provide the results, since the application steps are identical.

Step B: Matrix normalization

Step C: Weighted Sum Model (WSM) Rankings

WSM is provided by multiplying each normalized value with the respective criterion weight (see Appendix B).

Step D: Weighted Product Model (WPM) Rankings

The weighted normalized matrix for this case is computed by raising each normalized value to the power of the respective criterion weight (see Appendix B)

Step E: Final Rankings

After containing the preference scores from both WSM and WPM methods, the WASPAS (Weighted Aggregated Sum Product Assessment) model can be constructed. The results of the evaluation for AHP criteria weights for the current state of the ports is provided in Table 5.28.

Table 5.28 - WASPAS current state with AHP weights

Ports	WSM (Q_i^1)	WPM (Q_i^2)	WASPAS (Q_i)	Rank
Alexandroupolis	*0,621*	*0,334*	*0,477*	**5**
Thessaloniki	*0,769*	*0,641*	*0,705*	**1**
Kavala	*0,418*	*0,519*	*0,469*	**6**
Varna	*0,564*	*0,507*	*0,535*	**4**
Burgas	*0,630*	*0,562*	*0,596*	**3**
Constanta	*0,658*	*0,594*	*0,626*	**2**

The port rankings, when the same steps of the WASPAS evaluation are applied for different criteria weights of the current state of the ports, are provided in Table 5.29.

Table 5.29 - WASPAS rankings in the current state

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*5*	*5*	*6*	*6*
Thessaloniki	*1*	*1*	*2*	*2*
Kavala	*6*	*6*	*5*	*5*
Varna	*4*	*4*	*4*	*3*
Burgas	*3*	*3*	*3*	*4*
Constanta	*2*	*2*	*1*	*1*

Given the similarities in the weights of AHP and BWM, it should come as no surprise that the rankings are the same between these two methods.

Surprisingly, even with the weights of CRITIC and ENTROPY, the rankings of the ports did not change dramatically as was seen in the previous methods. Constanta replaced Thessaloniki as the most appealing port for investors, followed by the now second ranked Thessaloniki. Varna and Burgas retained their position as medium tier ports, ranked third and fourth, followed by the Kavala which replaced Alexandroupolis as the fifth port.

The same steps are applied to the possible future state of the ports, after potential investments in Alexandroupolis. The results are depicted in Table 5.30.

Table 5.30 - WASPAS rankings in the potential future states

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Alex/polis	*2*	*2*	*2*	*2*
Thessaloniki	*1*	*1*	*3*	*3*

Ports	AHP Rank	BWM Rank	CRITIC Rank	Entropy Rank
Kavala	*6*	*6*	*6*	*6*
Varna	*5*	*5*	*5*	*4*
Burgas	*4*	*4*	*4*	*5*
Constanta	*3*	*3*	*1*	*1*

After using AHP weights, the results indicate that, similarly to the current state of the ports, Thessaloniki remains as the most appealing port, now followed by the developed Alexandroupolis and then Constanta, Burgas, Varna and lastly Kavala. For BWM, even though the performance scores differ slightly compared to AHP, the rankings remain the same for the two methods. In the CRITIC and ENTROPY methods, similarly to the current state analysis, the results do not differ significantly. Constanta remains the top port, as was the case with the current state, followed by a now developed Alexandroupolis and then Thessaloniki, Varna and Burgas retaining fourth and fifth place ahead of Kavala.

5.5 Addressing inconsistencies of the results of the MCDM methods

The results of the above analysis are consolidated in Table 5.31. In this Table we notice a high level of inconsistency among the different a) criteria weight determination and b) port evaluation methods. For example, in the current state for the TOPSIS method, Alexandroupolis port's rank ranges from 2nd to 6th, depending on the criteria weight determination method.

Table 5.31 – Current and possible state results

Current State																
Criteria Weight methodology:	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM
Evaluation methodology:	PROMETHEE II				TOPSIS				VIKOR				WASPAS			
Ports	Port Ranks:															
Alexandroupolis	5	5	5	5	6	5	3	2	6	6	2	2	6	6	5	5
Thessaloniki	4	3	3	1	4	3	1	1	1	2	1	1	2	2	1	1
Kavala	6	6	6	6	5	6	6	6	5	5	4	6	5	5	6	6
Varna	3	4	4	4	3	2	5	5	4	4	6	5	4	3	4	4
Burgas	2	2	2	3	2	4	4	3	3	3	3	3	3	4	3	3
Constanta	1	1	1	2	1	1	2	4	2	1	5	4	1	1	2	2

Possible State																
Criteria Weight methodology:	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM	CRITIC	Entropy	AHP	BWM
Evaluation methodology:	PROMETHEE II				TOPSIS				VIKOR				WASPAS			
Ports	Port Ranks:															
Alexandroupolis	3	2	5	4	4	2	2	2	2	2	2	2	2	2	2	2
Thessaloniki	4	3	3	1	6	5	1	1	3	3	1	1	3	3	1	1
Kavala	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6
Varna	5	5	4	5	3	3	5	5	5	5	5	5	5	4	5	5
Burgas	2	4	2	3	2	4	4	3	4	4	3	3	4	5	4	4
Constanta	1	1	1	2	1	1	3	4	1	1	4	4	1	1	3	3

To address this problem, we propose a new post processing step in both the weight determination and the port evaluation methods, which is presented in the following Sections.

Thus, the problem is to select:

- The most consistent weight determination method (i.e. AHP, BWM, CRITIC, Entropy) across all evaluation methods (i.e. PROMETHEE, TOPSIS, VIKOR, WASPAS)
- The most consistent evaluation method (i.e. PROMETHEE, TOPSIS, VIKOR, WASPAS) across all weight determination methods (i.e. AHP, BWM, CRITIC, Entropy)

Then, the most consistent evaluation method with the weights of the most consistent weight determination method will be selected for the gateway port assessment problem.

5.5.1 Selecting the most consistent weight determination method

We define as a consistent weight determination method, the one that gives similar port rankings across all evaluation methods. Let's start with some notation. By applying each weight determination method w and each evaluation method e we get the ranking r_{we}^{p} of port p. For example, for the current port state and for $w =$ CRITIC, $e =$ PROMETHEE II and $p =$ Alexandroupolis, $r_{we}^{p} = 5$ (see Table 5.31).

In order to identify the most consistent method, the following steps are proposed.

Step A: Determine the average port rankings per criteria weight determination method

For weight determination method w, we calculate the average ranking ($\overline{r_w^p}$) of port p across the four evaluation methods. For example, for the current port state and for $w =$ CRITIC, and $p =$ Alexandroupolis, we obtain

$$\overline{r_w^p} = \frac{5+6+6+6}{4} = 5.75$$

Step B: Distance from average ranking

In this step we determine the L_2 distance of ranking (r_{we}^{p}) of port p under criteria determination method w and evaluation method e of from the average port ranking ($\overline{r_w^p}$), as shown in Eq. (5.4).

$$d(p,w) = \sqrt{\sum_{e} (r_{we}^{p} - \overline{r_w^p})^2}\,, \qquad (5.4)$$

For example, when applying Eq. (5.4) for the current state and for w = CRITIC and p = Alexandroupolis, the distance is:

$$d(p,w) = \sqrt{(5-5.75)^2 + (6-5.75)^2 + (6-5.75)^2 + (6-5.75)^2} = 0.87$$

The closer the distance of $d(p,w)$ to 0, the more consistent is the w criteria weight determination method since the rankings of the method are closer to the average rank.

Step C: Consistency measure

The consistency measure (c) of criteria determination method (w) is calculated by the summation of the distances of the previous step for all ports. The idea is that the criteria weight determination method whose rankings are closer to the average ranking for all ports is the most consistent, as indicated by Eq. (5.5)

$$c(w) = \sum_{p} d(p, w)\,, \qquad (5.5)$$

Note that in our case we have the current and future states, thus for the evaluation of the consistency of a weight determination method we add the above consistency measures for both states. That is, for the total consistency of a weight determination method we evaluate $c(w)$ for the current state, $c(w)$ for the future state and add them.

Table 5.32 presents the distances $d(p, w)$ per port p for the current and future states, as well as the corresponding values of the consistency measures.

That is in the case of $w =$ CRITIC:

$$c(w) = 7.20 \ + 8.70 = 15.90$$

By applying the aforementioned method to the assessment problem at hand, we conclude that the most consistent criteria weight determination method is *BWM*, since it provides the most consistent results out of all criteria weight determination methods (Table 5.32). A close second is *Entropy* , which also demonstrates a high level of consistency amongst its results.

Table 5.32 - $d(p, w)$ and $c(w)$ for the current and future states for all weight determination methods

$d(p,w)$	**Weight Determination Methods**							
	AHP		BWM		CRITIC		Entropy	
Ports	Current	Future	Current	Future	Current	Future	Current	Future
Alexandroupolis	2,60	2,60	3,00	1,73	0,87	1,66	1,00	0,00
Thessaloniki	1,73	1,73	0,00	0,00	2,60	2,45	1,00	1,73
Kavala	1,73	0,00	0,00	0,00	0,87	0,87	1,00	0,00
Varna	1,66	0,87	1,00	0,00	1,00	1,73	1,66	1,66
Burgas	1,41	1,66	0,00	0,87	1,00	2,00	1,66	0,87
Constanta	3,00	2,18	2,00	1,66	0,87	0,00	0,00	0,00
$c(w)$	21,17		10,26		15,90		10,57	

5.5.2 Most consistent gateway port evaluation method

A similar methodology will be applied for the consistency check of the port evaluation methods, in order to identify which is the most consistent for the assessment of gateway ports in the Mediterranean – Black Sea region in the current and future state of the ports. The steps of this methodology are the same as previously, with small exceptions.

Step A: Determine the average port rankings per port evaluation method

For the port evaluation method of e, we calculate the average ranking ($\overline{r_e^p}$) of a port across all criteria weight determination methods. For example, for the current port state and for $e =$ TOPSIS, and $p =$ Alexandroupolis, we obtain

$$\overline{r_e^p} = \frac{6 + 5 + 3 + 2}{4} = 4$$

Step B: Distance from average ranking

In this step we determine the L_2 distance of ranking (r_{we}^p) of port p under criteria determination method w and evaluation method e of from the average port ranking ($\overline{r_e^p}$), as shown in Eq. (5.6).

$$\hat{d}(p, e) = \sqrt{\sum_w (r_{we}^p - \overline{r_e^p})^2}, \qquad (5.6)$$

Take for example the application of Eq. (5.6) for the current state for w = TOPSIS and p = Alexandroupolis. The distance is:

$$\hat{d}(p, e) = \sqrt{(6 - 4)^2 + (5 - 4)^2 + (3 - 4)^2 + (2 - 4)^2} = 3.16$$

Step C: Consistency measure

The consistency measure (c) of port evaluation method (e) is calculated by the summation of the distances of the previous step, as indicated in Eq. (5.7).

$$\hat{c}(e) = \sum_{p} \hat{d}(p,e)\,, \qquad (5.7)$$

Note that similarly to the criteria weight consistency analysis, we have the current and future states, thus for the evaluation of the consistency of a port evaluation method we add the above consistency measures for both states. Table 5.33 presents the distances $\hat{d}(p,e)$ per port p for the current and future states, as well as the corresponding values of the consistency measures.

The final consistency measure is the summation of the consistency measures of the two individual states. That is in the case of w = TOPSIS:

$$\hat{c}(e) = 13.33 + 13.41 = 26.74$$

Table 5.33 - $\hat{d}(p,e)$ and $\hat{c}(e)$ for the current and future states for all weight determination methods

$\hat{d}(p,e)$	Port Evaluation Methods							
	PROMETHEE II		TOPSIS		VIKOR		WASPAS	
Ports	Current	Future	Current	Future	Current	Future	Current	Future
Alexandroupolis	0,00	2,24	3,16	1,73	4,00	0,00	1,00	0,00
Thessaloniki	2,18	2,18	2,60	4,56	0,87	2,00	1,00	2,00
Kavala	0,00	0,00	0,87	0,87	1,41	0,00	1,00	0,00
Varna	0,87	0,87	2,60	2,00	1,66	0,00	0,87	0,87
Burgas	0,87	1,66	1,66	1,66	0,00	1,00	0,87	0,87
Constanta	0,87	0,87	2,45	2,60	3,16	3,00	1,00	2,00
$\hat{c}(e)$	12,58		26,74		17,10		11,46	

By applying the aforementioned methodology to the isolate the most consistent port evaluation method, we conclude that the most consistent port evaluation method is *WASPAS*, provided that it shows the most consistent results out of all criteria weight determination methods (Table 5.33).

5.5.3 Final port rankings assessment

Based on the methodology described in the two previous Sections, Tables in 5.34 and 5.35 are generated, showcasing the criteria weight consistency measure $c(w)$ and the port evaluation consistency measure $\hat{c}(e)$ respectively of every method of the gateway port assessment problem.

Table 5.34 – Criteria weight methods consistency measure $c(w)$

Criteria Weight Method	AHP	BWM	CRITIC	Entropy
$\boldsymbol{c(w)}$	*21,17*	*10,26*	*15,90*	*10,57*

Table 5.35 – Port evaluation methods consistency measure $\hat{c}(e)$

Port Evaluation Method	PROMETHEE II	TOPSIS	VIKOR	WASPAS
$\boldsymbol{\hat{c}(e)}$	*12,58*	*26,74*	*17,10*	*11,46*

Based on the consistency results presented above, for the final gateway port assessment we will use the *BWM* weight determination method and the *WASPAS* Multi – Criteria Decision Making port evaluation method. The final results of the gateway port assessment methodology are depicted in Tables 5.35 and 5.36 for the current and future state of the ports respectively.

Table 5.36 – Final port current state rankings

Criteria Weight Determination Method	BWM
MCDM Port Evaluation Method	WASPAS
Ports	**Ranks**
Alexandroupolis	*5*
Thessaloniki	*1*
Kavala	*6*

Criteria Weight Determination Method	BWM
MCDM Port Evaluation Method	WASPAS
Varna	*4*
Burgas	*3*
Constanta	*2*

Table 5.37 – Final Port potential future state rankings

Criteria Weight Determination Method	BWM
MCDM Port Evaluation Method	WASPAS
Ports	**Ranks**
Alexandroupolis	*2*
Thessaloniki	*1*
Kavala	*6*
Varna	*5*
Burgas	*4*
Constanta	*3*

Based on the above results, the port of Alexandroupolis can potentially increase its ranking from 5^{th} preferred gateway port of the Mediterranean / Black Sea region to 2^{rd}, following a proper investment plan, thus surpassing the ports of Varna, Burgas and Thessaloniki. Note that this ranking concerns the gateway aspect of the ports. The results indicate that an investment in Alexandroupolis port may increase considerably its value, establishing the port as one of the top gateway ports in the region.

Chapter 6 Conclusions and recommendations for further research

The purpose of this thesis is to assess the potential for development and competitiveness of gateway ports, with a focus on Mediterranean and Black Sea ports. Case studies from the literature have indicated that the targeted investments in port infrastructure and rail/road connectivity can directly influence a port's development as a gateway for its hinterland area and increase its cargo flow, securing a profitable road map for future development.

To assess and compare the competitiveness of gateway ports, we distinguished two perspectives: The investor perspective and the shipping liner one. We focused our work on the investor's perspective. Our port evaluation approach comprises two stages: a) port assessment based on various criteria, and b) competitiveness evaluation against peer ports. For the port assessment stage, we established a comprehensive set of 27 criteria. Th weights of these riteria were estimated using four multi criteria evaluation methods: AHP, BWM, Entropy and CRITIC. For the comparison between peers, we used four Multi – Criteria Decision Making methods, namely PROMETHEE II, TOPSIS, VIKOR and WASPAS.

Note that in case of a port that an investor is evaluating for further development, one has to perform the assessment and competitiveness evaluation for two states of the port under study, namely:

- The current state of the port
- The possible future state of the port, after potential investments

One of the criteria that may determine gateway port selection relates to cargo flows (incoming and outgoing) of the port. While the current cargo flows of every port can be extracted from existing data, the potential future flows need to be estimated. In order to estimate the cargo flows for the future state of a port after investments, we proposed a new method that is based on a novel linear goal programming model, which minimizes the required transportation times and costs of exchanged cargo between the ports and the regions of the hinterland.

We have applied the proposed port evaluation approach to the port of Alexandroupolis, with competing ports those of Thessaloniki, Kavala, Varna, Burgas, Constanta.

First, we estimated the cargo flows that Alexandroupolis may attract after appropriate investments. Our proposed model indicated that Alexandroupolis can potentially process *8.635* thousand tons of cargo annually in total, which is a vast improvement from its current cargo flows (*360* thousand tons).

Having calculated the potential cargo flows of the candidate port, the assessment methodology was applied to evaluate the preference ranking of the ports from the perspective of investors. After applying the criteria weight determination methods, it was concluded that there were similarities between a) AHP and BWM and b) CRITIC and Entropy. While the first set of criteria weight evaluation methods provided results that showed increased preference for intrinsic criteria, the second set resulted in a more even distribution amongst criteria weights. Subsequently, the port evaluation Multi – Criteria Decision (MCDM) methods were applied for the current and possible future state of the ports, for every criteria weight determination method.

The rankings generated by the application of the methodology yielded different results per port evaluation method and weight determination method for each state. It is noted, however, that a plethora of inconsistencies were observed in the port rankings obtained by the four methods. In order to address the inconsistencies between the results, we proposed a new post processing step to quantify the inconsistency within each method and select the most consistent criteria weight determination and port evaluation method.

As a result, the BWM criteria weight determination method and the WASPAS port evaluation MCDM method were considered consistent enough for the Alexandroupolis case.

Based on the results from these methods, Alexandroupolis can potentially improve its ranking among the competitive ports from 5^{th} (among 6) to 2^{nd} after investments, thus surpassing the ports of Varna, Burgas and Thessaloniki. Consequently, its case is very interesting and should be examined further.

Directions for further research in this work include two areas: Port evaluation research, and further work on the specific case of Alexandroupolis.

In terms of port evaluation:

- There is a plethora of port evaluation methods in the literature besides the Multi – Criteria Decision Making methods, which include:
    - Spatial analysis (Sutomo and Soemardjito, 2012)
    - Quality function deployment (Duru *et al.*,2020)
    - In a following research, a promising area is the study of the most relevant methods and establishment of selection criteria upon which the right choice per case may be made.
    - Inconsistency among the results of the various methods should be studied further. The source of this inconsistency should be investigated, and appropriate improvements should be proposed

In terms of the Alexandroupolis port case:

- The pairwise comparison matrices for AHP and BWM could be generated based on the judgment of experts in the field of marine transportation (forwarders, shippers etc.)
- An investment plan for Alexandroupolis, and the related business case, is certainly necessary to further examine the potential of the port to serve as a major gateway for Eastern Europe and the Black Sea.
- The port of Alexandroupolis can also be evaluated as a transshipment hub port that consolidates and transships commodities heading from and towards Black Sea ports.

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Appendix A Weight determination methods for port selection

In this Appendix, a detailed analysis of the criteria weight determination methods to be applied for the gateway port assessment is presented. These methods are:

- Analytic Hierarchy Process (AHP)
- Best – Worst Method (BWM)
- Critic
- Entropy

To illustrate each method, we use a simple example of the best possible car selection. Let’s consider five different alternatives to compare when choosing a car, namely:

- Toyota
- Audi
- Honda
- Mercedes
- Dodge.

The characteristics of interest for the comparison are the following:

- Quality
- Price
- Safety
- Style
- Comfort.

These different criteria are key in deciding the most preferable car.

A.1 Analytic Hierarchy Process (AHP)

The following description of AHP is based on two courses of Paraskevopoulos and Saaty (1987). The essence of AHP is the construction of a matrix that provides information regarding the importance of a criterion, by comparing it with the other criteria using Saaty's nine – point scale (see Fig. A.1). The resulting pairwise comparison matrix will be used to assess the weight of each criterion. The steps of the method are presented using the best possible car selection example.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

Figure A.1 – Saaty's nine – point ratio scale

Step 1: Definition of relative criteria importance

Consider the above five criteria used when selecting a car. By applying Saaty's scale, compare criterion i with criterion j to obtain the a_{ij} value and create the pairwise comparison matrix (or reciprocal matrix) of Table A.1. For example, when comparing Quality (criterion 1) with Price (criterion 2) the decision maker postulates that Price is weakly more important than Quality, and rates the importance based on Saaty's nine-point scale ratio as 2 ($a_{21} = 2$). Since the ratings are inversely proportional and $a_{21} = 2$, the importance of Quality compared to Price should be $a_{12} = 1/2$, for the pairwise comparison matrix to be consistent.

Table A.1 – AHP Pairwise comparison matrix

Criteria	Pairwise Comparison Matrix				
	Quality	Price	Safety	Style	Comfort
Quality	1,00	0,50	0,33	2,00	3,00
Price	2,00	1,00	0,50	3,00	4,00
Safety	3,00	2,00	1,00	5,00	6,00
Style	0,50	0,33	0,20	1,00	2,00
Comfort	0,33	0,25	0,17	0,50	1,00
Sum	6,83	4,08	2,20	11,50	16,00

Step 2: Criteria Weight Calculation

The above matrix must be first normalized to calculate the criteria weights on the same scale. The normalization process is as follows:

- Calculate the sum of each criterion of the reciprocal matrix (red colour of Table A.1). The higher the value, the less important the criterion for the alternative selection
- Divide each value with the corresponding sum, to compute the normalized value, as per Eq. (A.1):

$$\hat{a}_{ij} = \frac{a_{ij}}{\sum_i a_{ij}}, \qquad for\ j = 1, \dots, 5 \qquad (A.1)$$

The resulting pairwise comparison matrix is presented in table A.2

Table A.2 – AHP Normalized Pairwise Comparison Matrix

Criteria	Normalized Pairwise Comparison Matrix					
	Quality	Price	Safety	Style	Comfort	Criteria Weights
Quality	0,146	0,122	0,152	0,174	0,188	0,156
Price	0,293	0,245	0,227	0,261	0,250	0,255
Safety	0,439	0,490	0,455	0,435	0,375	0,439
Style	0,073	0,082	0,091	0,087	0,125	0,092
Comfort	0,049	0,061	0,076	0,043	0,063	0,058

Compute the average value of each row of the normalized reciprocal matrix, as per Eq. (A.2).

$$w_j = \sum_{j=1}^{m} \hat{a}_{ij}/m \ , \qquad i = 1,..,m \ and \ j = 1,\dots,m \qquad (A.2)$$

Where m is the number of criteria.

These average values provide the weights of the corresponding criteria.

Step 3: Consistency check

Considering that AHP is a method that depends on human judgment, inconsistencies may arise in the comparison matrix. Saaty (1987) has explained in detail the method for assessing consistency of the AHP weights. For the purpose of the thesis, the methodology is presented in a simplified manner.

The consistency index (C.I) of a matrix is calculated using Eq. (A.3)

$$C.I = \frac{\lambda_{max} - m}{m - 1}, \qquad (A.3)$$

The steps for calculating λ_{max} are:

- Compute the Weighted Sum Value, as per Eq. (A.4)

$$WSM_j = \sum_{i=1}^{m} a_{ij} * w_j \ , \qquad for \ j = 1,\dots,m \qquad (A.4)$$

- Divide the WSM with the respective criterion weight for every j as per Eq. (A.5)

$$\lambda_j = \frac{WSM_j}{w_j}, \qquad for \ j = 1,\dots,m \qquad (A.5)$$

- The average of all λ_j provides the value for λ_{max}

$$\lambda_{max} = \frac{\sum_{j=1}^{m} \lambda_j}{m} \qquad (A.6)$$

For the best car selection problem, the steps for the calculation of the λ_{max} variable are presented in Table A.3.

Table A.3 - λ_{max} calculation

Criteria	Weighted Sum Value	Criteria Weights	Weighted Sum Value/ Criteria Weights
Quality	0,788	0,156	5,042
Price	1,295	0,255	5,076
Safety	2,226	0,439	5,074
Style	0,459	0,092	5,016
Comfort	0,293	0,058	5,024

The final Consistency Ratio ($C.R$) is obtained when comparing $C.I$ to a Random Consistency Index ($R.I$) given by Saaty (Fig. A.2) using Eq. (A.7)

$$C.R = {}^{C.I}/_{R.I} \qquad (A.7)$$

If $C.R > 0.1$, then the matrix is considered fully inconsistent.

Using the consistency index Eq. (A.3) for the best car selection example

$$C.I = \frac{\lambda_{max} - n}{n-1} = \frac{5.04643 - 5}{5-1} = 0.011607$$

n	1	2	3	4	5	6	7	8	9
$R.C.I$	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Figure A.2 – Random Consistency Index by Saaty

In this problem, there are five criteria being evaluated. So, the Consistency Ratio is

$$C.R = \frac{Consistency\ Index}{Random\ Consistency\ Index} = \frac{0.011607}{1.12} = 0.010364 \ \leq 0.1$$

and the pairwise comparison matrix is fairly consistent. Having validated that the reciprocal matrix of Table A.2 is consistent, the criteria weights as per AHP are:

- Quality = 0.16
- Price = 0.25
- Safety = 0.44
- Style = 0.09
- Comfort = 0.06

A.2 Best – Worst Method (BWM)

The description of the Best - Worst Method will be based on Rezaei (2014). The main idea behind this method is that, instead of comparing each criterion with all other criteria as in AHP, the decision maker selects the Best criterion and the Worst criterion. Then, every other criterion in the problem is compared with the Best and Worst criteria based on a nine point scale (as with AHP). Of course, the Best criterion has to be more important, or at least of equal importance, to the other criteria, and similarly the Worst criterion must be the least important criterion out of all. Otherwise, the problem will be inconsistent and the result unreliable.

By definition, the comparisons made between a criterion with the best or the worst ones are called reference comparisons. By making these comparisons, the criteria outside the best and worst ones are scaled between themselves. For example, if there are five trees for comparison, where tree B is the tallest and C is the shortest, when the decision maker rates tree B by a score 5 compared to tree A (in a nine point scale comparison) and 3 compared to tree E, an argument can be made that tree A is by 5/3 taller than tree E. These types of comparisons are called secondary comparisons and are created by the relation between two criteria when compared to the best or worst criterion. Since these comparisons are not directly influenced by the decision maker, there is a higher risk of inconsistency if the pairwise comparison matrix is not properly scaled.

Rezaei (2014) proposes five steps for BWM:

Step 1: Determine the criteria to be used in the assessment. For the car selection example, the criteria are:

- Quality
- Price
- Safety
- Style
- Comfort

Step 2: Determine the best and worst criterion out of all selected criteria. The best criterion is the one that, based on the decision maker is the most important to consider for the final selection; the worst on the other hand is the least important. For example, for in the car selection example, the best criterion is Safety, while the worst is Comfort.

Step 3: Compare all criteria with the best selected criterion, using the nine point scale. The end result is a vector with the preference scale related to the best criterion - Table A.4.

Table A.4 – Best criterion comparison

Best Criterion (Safety)	Quality	Price	Safety	Style	Comfort
Safety	3	2	1	5	6

It is important to note that when comparing the best criterion with the worst one, the difference in scale must be noticeable compared with the other criteria. If for example comfort is not rated as the lowest criterion in this step, inconsistencies will be generated.

Step 4: Compare all criteria with the worst criterion, using the nine point scale. The end result is a column with the preference scale related to the worst criterion- Table A.5.

Table A.5 – Worst criterion comparison

Worst Criterion (Comfort)	Comfort
Quality	3
Price	4
Safety	6
Style	4
Comfort	1

Again, it is important to rate the best criterion with the highest value, or there will be inconsistencies.

Step 5: The final step is to calculate the optimal weight values. As per Rezaei (2014), the optimal weights are calculated as per Eq. (A.8) and Eq. (A.9) for every j :

- $\frac{w_{Best1}}{w_{j1}} = a_{Bestj}, \qquad j = 1, \dots, m \qquad\qquad (A.8)$
- $\frac{w_{j2}}{w_{Worst2}} = a_{jWorst}, \qquad j = 1, \dots, m \qquad\qquad (A.9)$

Where:

- $w_{Best} = the\ weight\ of\ the\ best\ selected\ criterion$
- $w_{Worst} = the\ weight\ of\ the\ worst\ selected\ criterion$
- $w_{jk} = the\ weight\ of\ the\ j^{th}\ criterion\ for\ the\ k^{th}\ table$

  $where$:

  $k = 1\ is\ the\ best\ criterion\ comparison\ \&$

  $k = 2\ is\ the\ worst\ criterion\ comparison$
- $a_{Bestj} = the\ scale\ of\ the\ best\ criterion\ compared\ to\ the\ j^{th}\ criterion$
- $a_{jWorst} =$

  $the\ scale\ of\ the\ j^{th}\ criterion\ compared\ to\ the\ worst\ criterion$

For example, for the calculation of the style criterion's optimal weight, Eq. (A.8) and Eq. (A.9) are respectively:

$$\frac{w_{31}}{w_{41}} = a_{34} = 5$$

$$\frac{w_{42}}{w_{52}} = a_{45} \; = 4$$

Where:

- $w_3 = the\ weight\ of\ the\ 3rd\ and\ Best\ criterion\ (safety)$
- $w_5 = the\ weight\ of\ the\ 5th\ and\ Worst\ criterion\ (comfort)$
- $w_{41} = the\ weight\ of\ the\ 4th\ and\ evaluated\ criterion\ (style)\ for:$
  $the\ best\ criterion\ comparison\ (1)\ \&$
  $the\ worst\ criterion\ comparison\ (2)$
- $a_{34} =$
  $the\ scale\ of\ the\ Best\ criterion\ (safety)\ compared\ to\ the\ evaluated\ criterion\ (style)\ =$
  $= 5\ based\ on\ Table\ A.8$
- $a_{45} =$
  $the\ scale\ of\ the\ evaluated\ criterion\ (style)\ compared\ to\ the\ Worst\ criterion\ (comfort)$
  $= 4\ based\ on\ Table\ A.9$

Note, however, that w_j should be a unique value for each j. To satisfy this requirement for all j, an approach is proposed by Rezaei (2014), where the maximum absolute differences of Eq. (A.10) and Eq. (A.11) are minimized for all j.

$$\left|\frac{w_{Best1}}{w_{j1}} - a_{Bestj}\right|, \qquad j = 1, \dots, m \qquad (A.10)$$

$$\left|\frac{w_{j2}}{w_{Worst2}} - a_{jWorst}\right|, \qquad j = 1, \dots, m \qquad (A.11)$$

If we consider non negativity (since the weights must be ≥ 0) and that the sum of the weights should equal 1, the following Problem 1 is constructed:

<u>Problem 1</u>

$$\min max_{j=1}^{n} \left\{\left|\frac{w_{best}}{w_{j1}} - a_{bestj}\right|, \left|\frac{w_{j2}}{w_{worst}} - a_{jworst}\right|\right\}$$

s.t.

$$\sum_j w_{jk} = 1\,, \qquad for\ k = 1{,}2$$

$$w_{jk} \geq 0, \qquad for\ j = 1, \dots, n\ and\ k = 1{,}2$$

Problem 1 is translated into Problem 2, where the ξ variable is introduced. ξ is essentially the deviation of the optimal value of $\frac{w_{best}}{w_j}$ and $\frac{w_j}{w_{worst}}$ from the decision maker's values of choice a_{Bestj} and $a_{jWorst.}$ The goal of Problem 2 is to minimize the ξ value (related to inconsistency).

<u>Problem 2</u>

$$\min \xi$$

s.t

$$\left|\frac{w_{best1}}{w_{j1}} - a_{bestj}\right| \leq \xi, \qquad for\ all\ j$$

$$\left|\frac{w_{j2}}{w_{worst2}} - a_{jworst}\right| \leq \xi, \qquad for\ all\ j$$

$$\sum_j w_{jk} = 1\,, \qquad for\ k = 1{,}2$$

$$w_{jk} \geq 0, \qquad for\ j = 1, \dots, m\ and\ k = 1{,}2$$

Problem 2 is not linear, and, thus, cannot be solved using Simplex.

Using the example of the best car selection, it will be demonstrated how the problem could be converted into a linear one and solved using linear programming.

In **Step 1**, the criteria of the best possible car selection were introduced.
In **Step 2**, the best and worst criteria were selected and then compared with the rest of criteria using **Steps 3** and **4**. For Step 5, we first need to convert the optimization problem into a linear one. For Problem 2 to be linear, the following constraints of must be modified.

$$\left|\frac{w_{best1}}{w_{j1}} - a_{bestj}\right| \le \xi,\ for\ all\ j \qquad (A.12)$$

$$\left|\frac{w_{j2}}{w_{worst2}} - a_{jworst}\right| \le \xi,\ for\ all\ j \qquad (A.13)$$

First, Constraint 1 (Eq. (A.12)) will be converted into a linear equation. Consider the third criterion (w_3 = safety) to be the best criterion. Thus.

$$\frac{w_{31}}{w_{11}} - a_{31} \le \xi \rightarrow w_{31} - a_{31}w_{11} \le \xi w_{11} \qquad (A.14)$$

$$\frac{w_{31}}{w_{21}} - a_{32} \le \xi \rightarrow w_{31} - a_{32}w_{21} \le \xi w_{21} \qquad (A.15)$$

$$\frac{w_{31}}{w_{31}} - a_{33} \le \xi \rightarrow w_{31} - a_{33}w_{31} \le \xi w_{31} \qquad (A.16)$$

$$\frac{w_{31}}{w_{41}} - a_{34} \le \xi \rightarrow w_{31} - a_{34}w_{41} \le \xi w_{41} \qquad (A.17)$$

$$\frac{w_{31}}{w_{51}} - a_{35} \le \xi \rightarrow w_{31} - a_{35}w_{51} \le \xi w_{51} \qquad (A.18)$$

If Eqs. (A.14) to Eq. (A.18) are summed, the following Eq. (A.19) is constructed:

$$5w_{31} - a_{31}w_{11} - a_{32}w_{21} - \cancel{a_{33}w_3} - a_{34}w_{41} - a_{35}w_{51} \le \xi\cancel{(w_{11} + w_{21} + w_{31} + w_{41} + w_{51})} \rightarrow$$

$$4w_{31} - a_{31}w_{11} - a_{32}w_{21} - a_{34}w_{41} - a_{35}w_{51} \le \xi \qquad (A.19)$$

Since a_{33} equals to 1 and the sum of all weights is 1.

Inequality (A.19) is satisfied if Eq. (A.20) to (A.23) are satisfied:

$$w_{31} - a_{31}w_{11} \le {}^{\xi}/_{4} \rightarrow w_{31} - 3w_{11} \le {}^{\xi}/_{4} \qquad (A.20)$$

$$w_{31} - a_{32}w_{21} \le {}^{\xi}/_{4} \rightarrow w_{31} - 2w_{21} \le {}^{\xi}/_{4} \qquad (A.21)$$

$$w_{31} - a_{34}w_{41} \le {}^{\xi}/_{4} \rightarrow w_{31} - 6w_{41} \le {}^{\xi}/_{4} \qquad (A.22)$$

$$w_{31} - a_{35}w_{51} \le {}^{\xi}/_{4} \rightarrow w_{31} - 5w_{51} \le {}^{\xi}/_{4} \qquad (A.23)$$

Eqs. (A.20) through (A.23) are linear, since there are no products between w_j values and the ξ value. Similarly, Constraint 2 (Eq. (A.13)) is linear, if the same process is applied, which results to Eq. (A.24) through (A.27)

$$w_{12} - a_{15}w_{52} \leq {}^{\xi}/_{4} \rightarrow w_{12} - 3w_{52} \leq {}^{\xi}/_{4} \qquad (A.24)$$

$$w_{22} - a_{25}w_{52} \leq {}^{\xi}/_{4} \rightarrow w_{22} - 4w_{52} \leq {}^{\xi}/_{4} \qquad (A.25)$$

$$w_{32} - a_{35}w_{52} \leq {}^{\xi}/_{4} \rightarrow w_{32} - 6w_{52} \leq {}^{\xi}/_{4} \qquad (A.26)$$

$$w_{42} - a_{45}w_{52} \leq {}^{\xi}/_{4} \rightarrow w_{42} - 4w_{52} \leq {}^{\xi}/_{4} \qquad (A.27)$$

Through this conversion we may obtain linear Problem 3 that can be solved by Simplex. Note, however, that although any solution of Problem 3 is a feasible solution of Problem 2, the reverse does not hold. This is because the feasible space of Problem 3 is a subset of the feasible space of Problem 2, and the optimal solution of Problem 3 may not be optimal for Problem 2 (i.e. there may be better weights that the ones obtained by solving Problem 3 instead of 2.

Problem 3		
Obj. Function:	$\min \xi$	
Subject to:	$\lvert w_{31} - 3w_{11}\rvert \leq {}^{\xi}/_{4}$	Constraint 1 (Eq. (A.12))
	$\lvert w_{31} - 2w_{11}\rvert \leq {}^{\xi}/_{4}$	
	$\lvert w_{31} - 6w_{41}\rvert \leq {}^{\xi}/_{4}$	
	$\lvert w_{31} - 5w_{51}\rvert \leq {}^{\xi}/_{4}$	
	$\lvert w_{12} - 3w_{52}\rvert \leq {}^{\xi}/_{4}$	Constraint 2 (Eq. (A.13))
	$\lvert w_{22} - 4w_{52}\rvert \leq {}^{\xi}/_{4}$	
	$\lvert w_{32} - 6w_{52}\rvert \leq {}^{\xi}/_{4}$	
	$\lvert w_{42} - 4w_{52}\rvert \leq {}^{\xi}/_{4}$	

Problem 3		
Obj. Function:	$\min \xi$	
	$w_1 + w_2 + w_3 + w_4 + w_5 = 1$	
	$w_{1,} w_{2,} w_{3,} w_{4,} w_5 \geq 0$	

Problem 3 can be solved with many tools, including Excel's Solver, Matlab and many others.

The resulting criteria weights computed for the best car selection problem by the Best – Worst method are:

- Quality = 0.18
- Price = 0.27
- Safety = 0.39
- Style = 0.11
- Comfort = 0.06

The ξ value is 0.1415. Based on Rezaei (2014), the value of ξ will aid with the calculation of the Consistency Ratio, provided by Eq. (A.28).

$$Consistency\ Ratio = {}^{\xi}/_{Consistency\ Index} \qquad (A.28)$$

As per Rezaei *et al.*(2019) ,the thresholds of the Consistency Ratio are considered in Table (A.6). If the computed Consistency Ratio of the best car selection problem is higher than the respective case described in Table (A.6) then the pairwise comparison matrix is deemed inconsistent and the results unreliable for further evaluation.

Table A.6 – Threshold of different combinations for consistency measurements (Rezaei *et al.* (2019))

	Criteria						
Scales	3	4	5	6	7	8	9
3	*0.2087*	*0.2087*	*0.2087*	*0.2087*	*0.2087*	*0.2087*	*0.2087*
4	*0.1581*	*0.2352*	*0.2738*	*0.2928*	*0.3102*	*0.3154*	*0.3273*
5	*0.2111*	*0.2848*	*0.3019*	*0.3309*	*0.3479*	*0.3611*	*0.3741*
6	*0.2164*	*0.2922*	*0.3565*	*0.3924*	*0.4061*	*0.4168*	*0.4225*
7	*0.2090*	*0.3313*	*0.3734*	*0.3931*	*0.4035*	*0.4108*	*0.4298*
8	*0.2267*	*0.3409*	*0.4029*	*0.4230*	*0.4379*	*0.4543*	*0.4599*
9	*0.2122*	*0.3653*	*0.4055*	*0.4225*	*0.4445*	*0.4587*	*0.4747*

The Consistency Index depends on the ratio of the Best criterion over the Worst criterion. For the best car selection, the importance of the Best criterion (safety) is 6 over the Worst criterion (comfort) (Table A.4). Thus, as per Table. A.7, the $C.I$ is 3.00.

Table A.7 – BWM Consistency Index

$\boldsymbol{a_{BW}}$	1	2	3	4	5	6	7	8	9
Consistency Index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

The application of Eq. (A.28) to the best car example provides the following result:

$$Consistency\ Ratio = {}^{0.1415}/_{3.00} = 0.0471 \leq 0.3309$$

Since the comparisons are consistent, the results of the criteria weights are reliable and can be used for further evaluation.

A.3 CRITIC

The description of the CRITIC method below is based on Diakoulaki *et al.* (1993). In contrast with the two previous MCDM methods (AHP & BWM), which rely on the decision maker's judgment to calculate and compare criteria weights, this method views criteria as information sources and weighs them based on information importance (which is provided by the conflict and contrast intensity of each criterion, as described later in this Section) .

In older studies, criteria were scaled based on their standard deviation or entropy, since this way it is possible to quantify their contrast intensity. For example, the more diverse the score of a criterion for all alternatives the bigger the contrast; this means that this criterion plays an important part in decision making. On the other hand, a criterion with no apparent difference between alternatives is a criterion without informational importance.

For this method, an additional dimension is added, aside from contrast intensity, to determine the informational importance of criteria. Thus dimension is the conflict between different criteria. The premise is that the more correlated a criterion is with other criteria, the less important it is. On the other hand, the more discordant a criterion is, the higher its informational importance and, thus, its weight. Essentially, the CRITIC method is the combination of these two dimensions: contrast intensity and conflict.

The steps of the CRITIC method are illustrated through the best possible car selection example.

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker's Judgment.

For the best car selection example, the values are provided based on judgment in Table A.8 (on a scale from 1 – 10).

Table A.8 – The five cars rated for five criteria.

		Criteria				
		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	6	3	5	2	6
	Audi	8	7	4	7	4
	Honda	7	4	6	4	5
	Mercedes	9	8	7	8	8
	Dodge	8	7	5	5	5
	f_j*	9	3	7	8	8
	f_{j*}	6	8	4	2	4

Step 2: Matrix normalization

In order for the criteria weight calculation to be on an equal scale, the matrix of Table A.8 is normalized. Normalization is performed by calculating the following ratio.

$$x_{aj} = \frac{f_j(a) - f_{j*}}{f_j * - f_{j*}}, \qquad (A.29)$$

Where:

- x_{aj} is the normalized value of the alternative (car) a for the criterion j
- $f_j(a)$ is the value of the alternative (car) a for the criterion j given in Table A.8.
- f_{j*} is the non – ideal value of the j^{th} criterion
- $f_j *$ is the ideal value of the j^{th} criterion

The resulting normalized matrix is provided in Table A.9

Table A.9 – CRITIC Normalized matrix

x_{aj}		Criteria				
		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,00	1,00	0,33	0,00	0,50
	Audi	0,67	0,20	0,00	0,83	0,00
	Honda	0,33	0,80	0,67	0,33	0,25
	Mercedes	1,00	0,00	1,00	1,00	1,00
	Dodge	0,67	0,20	0,33	0,50	0,25
	σ_j	0,38	0,43	0,38	0,40	0,38

Step 3: Contrast intensity calculation

After normalization, the standard deviation is calculated for each criterion, which is the measure of contrast intensity:

$$s_j = \sqrt{\frac{\sum_{i=1}^{n}(x_{ij} - \hat{x}_{ij})^2}{n-1}}, \qquad for\ j = 1, \dots, 5 \qquad (A.30)$$

Applying Eq. (A.30) to the normalized matrix yields the following values for every criterion:

- Quality = 0.38
- Price = 0.43
- Safety = 0.38
- Style = 0.40
- Comfort = 0.38

The higher the value of contrast intensity, the higher the importance of the criterion.

Step 4: Conflict calculation

In order to calculate conflict, a symmetric mxm matrix must be formed, where m is the number of criteria. Next, the correlation of one criterion over the other must be calculated. Let r_{jk} be the linear correlation coefficient between vectors x_j (blue criteria of Table A.10) and x_k (yellow criteria of Table A.10). Essentially, the correlation of each criteria with the other must be calculated using the values of the normalized matrix (Table A.9). The results are provided in Table A.10. The further the value of each criterion is from 1 (with the minimum value being -1, which means total uncorrelation), the more uncorrelated a criterion is and the more important it is considered according to the conflict dimension.

Table A.10 – Correlation calculation

r_{jk}		Criteria				
		Quality	Price	Safety	Style	Comfort
Criteria	Quality	1,00	-0,97	0,35	0,96	0,32
	Price	-0,97	1,00	-0,14	-0,93	-0,20
	Safety	0,35	-0,14	1,00	0,24	0,84
	Style	0,96	-0,93	0,24	1,00	0,23
	Comfort	0,32	-0,20	0,84	0,23	1,00

The total conflict of a criterion is calculated as follows:.

$$con_{jk} = \sum_{k=1}^{m} (1 - r_{jk}), \qquad (A.31)$$

Where:

con_{jk} is the conflict between criterion j and criterion k

r_{jk} is the correlation of criterion j with criterion k

According to Eq. (A.31), the higher the value of con_{jk}, the more discordant the criterion (with 0 being fully correlated and 2 fully discordant). After applying Eq. (A.31) to Table A.10, the final conflict values are presented in Table A.11. The last column of Table A.11 provides the total conflict of each criterion, where the higher the value the more important the criterion for the decision making.

Table A.11– Final conflict matrix

$1 - r_{jk}$		Criteria					$\sum_{k=1}^{m} (1 - r_{jk}).$
		Quality	Price	Safety	Style	Comfort	
Criteria	Quality	0,00	1,97	0,65	0,04	0,68	3,35
	Price	1,97	0,00	1,14	1,93	1,20	6,24
	Safety	0,65	1,14	0,00	0,76	0,16	2,72
	Style	0,04	1,93	0,76	0,00	0,77	3,50
	Comfort	0,68	1,20	0,16	0,77	0,00	2,81

Step 5: CRITIC criteria weight calculation

Having calculated both contrast intensity (standard deviation) and conflict (correlation) of the criteria, their multiplication provides the amount of information of each criterion j (C_j), as is shown in Eq. (A.32)

$$C_j = \sigma_j * \sum_{k=1}^{m} (1 - r_{jk}), \qquad (A.32)$$

The higher the value of C_j, the higher the amount of information of criterion j and thus the more important the criterion for the decision making. In order to calculate the weights of all criteria, Eq. (A.33) is used:

$$w_j = \frac{C_j}{\sum_{j=1}^{m} C_j}, \qquad (A.33)$$

In the car selection example, the final criteria weights are depicted in Table A.12.

Table A.12– Final Weights

	Quality	Price	Safety	Style	Comfort
Cj	1,27	2,70	1,03	1,39	1,06
$\sum_{k=1}^{m} C_k$	7,47				
wj	0,17	0,36	0,14	0,19	0,14

Based on the results of CRITIC, the weights of each criterion are:

- Quality = 0.17
- Price = 0.36
- Safety = 0.14
- Style = 0.19
- Comfort = 0.14

A.4 ENTROPY

The Entropy method will be described based on Jati (2014) and Isik and Adali (2017). This method bares a lot of similarities with the previous method, CRITIC, however with a simpler approach. While in Critic the aspects of contrast intensity and conflict are used, in Entropy, contrast intensity is used only. Thus, similarly to CRITIC, the ENTROPY method evaluates and rates higher those criteria with the higher amount of information compared to the other criteria.

The steps of the method as proposed by Shanon and Weaver (1949) are applied to the best car selection example.

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker's Judgment.

For the best car selection example, the values are provided based on judgment in Table A.13 (on a scale from 1 – 10).

Table A.13 – Score of each alternative for each criterion

		Criteria				
		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	6	3	5	2	6
	Audi	8	7	4	7	4
	Honda	7	4	6	4	5
	Mercedes	9	8	7	8	8
	Dodge	8	7	5	5	5

Step 2: Matrix normalization

Normalization depends on whether the criterion is beneficial or non – beneficial and uses Eq. (A.34) or (A.35), respectively. Beneficial criteria are those that benefit the decision maker through maximization. Quality is an example, since the higher the quality, the better. Non – beneficial criteria have the opposite effect. For example, the lower the value of Price, the better.

$$r_{ij} = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})}, \qquad i = 1, \dots, 5 \text{ and } j = 1, \dots, 5 \qquad (A.34)$$

$$r_{ij} = \frac{\max_i(x_{ij}) - x_{ij}}{\max_i(x_{ij}) - \min_i(x_{ij})}, \qquad i = 1, \dots, 5 \text{ and } j = 1, \dots, 5 \qquad (A.35)$$

where i are the alternatives and j are the criteria.

The application of Eq. (A.34) and (A.35) results in the normalized matrix of Table A.14.

Table A.14– Entropy Normalized matrix

Normalized Matrix						
r_{ij}		Criteria				
		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,00	1,00	0,33	0,00	0,50
	Audi	0,67	0,20	0,00	0,83	0,00
	Honda	0,33	0,80	0,67	0,33	0,25
	Mercedes	1,00	0,00	1,00	1,00	1,00
	Dodge	0,67	0,20	0,33	0,50	0,25
	Sum =	2,67	2,20	2,33	2,67	2,00

Step 3: Entropy values

Entropy is based on the contrast intensity of a criterion, similarly to the standard deviation in CRITIC. For criterion j

$$e_j = -\frac{\sum_{i=1}^{n} f_{ij} * \ln(f_{ij})}{\ln(m)}, \qquad i = 1, \dots, 5 \text{ and } j = 1, \dots, 5 \quad (A.36)$$

$$where, \qquad f_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \; and\; r_{ij}\; is\; the\; normalized\; matrix\; value$$

If f_{ij} is 0, then $f_{ij} * \ln(f_{ij})$ is also 0 (Wu *et al.*, 2011). The smaller the entropy value, the higher the criterion's weight, since this means the criterion provides more important information compared to the other criteria.

Step 4: Entropy criteria weights calculation

Finally, entropy weights for criterion j are provided from :

$$w_j = \frac{1 - e_j}{n - \sum_{i=1}^{m} e_j} \quad where \sum_{j=1}^{n} w_j = 1\,, \qquad (A.37)$$

The application of Eq. (A.37) on the best car selection example is illustrated in Table A.15.

Table A.15– Final Weights

$f_{ij} * \ln(f_{ij})$		Criteria				
		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,00	-0,36	-0,28	0,00	-0,35
	Audi	-0,35	-0,22	0,00	-0,36	0,00
	Honda	-0,26	-0,37	-0,36	-0,26	-0,26
	Mercedes	-0,37	0,00	-0,36	-0,37	-0,35
	Dodge	-0,35	-0,22	-0,28	-0,31	-0,26
	$\sum_{i=1}^{m} fij * \ln(fij)$	-1,32	-1,16	-1,28	-1,31	-1,21
	e_{ij}	0,82	0,72	0,79	0,81	0,75
	w_j	0,16	0,25	0,19	0,17	0,22

Based on the results of Entropy, the weights of each criterion are:

- Quality = 0.16
- Price = 0.25
- Safety = 0.19
- Style = 0.17
- Comfort = 0.22

A.5 Weights comparison among methods

Overall, all four criteria weight determination methods produced the results depicted in Table A.16.

Table A.16 – Criteria Weight Determination Methods Consolidation

		Weights based on different methods			
		AHP	BWM	CRITIC	ENTROPY
Criteria	Quality	0,16	0,18	0,17	0,16
	Price	0,26	0,27	0,36	0,25
	Safety	0,44	0,39	0,14	0,19
	Style	0,09	0,11	0,19	0,17
	Comfort	0,06	0,06	0,14	0,22

Judging from Table A.16, there are many similarities between the final results from each method, with a small amount deviation on some criteria (Table A.17). When comparing AHP & BWM, it can noticed that the criteria weights are very similar, which is to be expected, given that both of these methods depend on human judgment and the pairwise comparison matrix was generated by the same author. An equivalent deduction can be made about CRITIC and Entropy methods since both criteria weight determination methods are based on the same concept of conflict (standard deviation or entropy) and contrast intensity (correlation).

However, as can be noticed in Table A.18, there is a low amount of correlation between the criteria weight determination methods based on the decision makers (AHP and BWM) and the other methods of CRITIC and Entropy. This was to be expected, given the major differences in the weights of:

- Safety
- Style
- Comfort

Table A.17 – Standard deviation of criteria weights between methods

		Standard Deviation
Criteria	Quality	0,009
	Price	0,052
	Safety	0,148
	Style	0,047
	Comfort	0,079

Table A.18 – Correlation between criteria weight determination methods (Correlation ranges between -1 and 1, where -1 is total uncorrelation and 1 is total correlation).

	AHP	BWM	CRITIC	ENTROPY	Correlation Sum
AHP	1,000	0,992	0,090	0,054	2,137
BWM	0,992	1,000	0,182	0,067	2,241
CRITIC	0,090	0,182	1,000	0,672	1,944
ENTROPY	0,054	0,067	0,672	1,000	1,793

Appendix B Multi Criteria Decision Making (MCDM) port assessment methods

In this Appendix we present a detailed analysis of the Multi Criteria Decision Making (MCDM) methods used in gateway port assessment. The methods used more frequently when comparing ports in the marine logistics sector are the following:

- PROMETHEE II
- TOPSIS
- VIKOR
- WASPAS

Following Appendix A, the car selection example will be used to illustrate each method. The criteria weights to be used are those computed by CRITIC in Appendix A, i.e.:

Criteria	Weights
Quality	0,1706
Price	0,3622
Safety	0,1383
Style	0,1864
Comfort	0,1425
sum=	1

B.1 PROMETHEE II

PROMETHEE II was proposed by Jean – Pierre Brans (1982). This method is characterized as an outranking MCDM method and in contrast with other aggregation methods, enables the decision maker to highlight the main alternatives of the problem, through reasonable comparison between all alternatives. There are many PROMETHEE method stages, each describing a different aspect of the problem. Namely:

- PROMETHEE I provides partial ranking to the problem

- PROMETHEE II provides complete rankings
- PROMETHEE IV provides sensitivity analysis and
- PROMETHEE V provides the decision of multiple alternatives under constraints.

For the candidate port assessment, PROMETHEE II will be used. The steps of PROMETHEE II are described based on the article of Brans *et al.* (2005) and the example of the best car selection.

Table B.1 – Car selection example values and weights

		Beneficial	Non - Beneficial	Beneficial	Beneficial	Beneficial
Criteria Weights		0,1706	0,3622	0,1383	0,1864	0,1425
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	6	3	5	2	6
	Audi	8	7	4	7	4
	Honda	7	4	6	4	5
	Mercedes	9	8	7	8	8
	Dodge	8	7	5	5	5

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker's Judgment.

For the best car selection example, the values are provided based on judgment in Table B.1(on a scale from 1 – 10).

Step 2: Matrix normalization

The normalization depends on the whether the criterion is beneficial on non – beneficial, by applying the respective Eqs. (B.1) and (B.2). Beneficial criteria are those that benefit the decision maker through maximization. Quality is an example, since the higher the quality, the better. Non – beneficial criteria are the opposite. For example, the lower the value of Price, the better for the selection.

$$r_{ij} = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})}, \qquad i = 1, \dots, 5 \; and \; j = 1, \dots, 5 \qquad (B.1)$$

$$r_{ij} = \frac{\max_i(x_{ij}) - x_{ij}}{\max_i(x_{ij}) - \min_i(x_{ij})}, \qquad i = 1, \dots, 5 \; and \; j = 1, \dots, 5 \qquad (B.2)$$

Where i are the alternatives and j are the criteria.

Applying Eqs. (B.1) and (B.2) leads to Table B.2.

Table B.2 – PROMETHEE II Normalized Matrix

Normalized Matrix		Beneficial	Non - Beneficial	Beneficial	Beneficial	Beneficial
Criteria Weights		0,17	0,36	0,14	0,19	0,14
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,00	1,00	0,33	0,00	0,50
	Audi	0,67	0,20	0,00	0,83	0,00
	Honda	0,33	0,80	0,67	0,33	0,25
	Mercedes	1,00	0,00	1,00	1,00	1,00
	Dodge	0,67	0,20	0,33	0,50	0,25

Step 3: Comparison of alternatives per criterion

The comparison of alternatives is performed by applying Eq. (B.3) to the normalized matrix, which essentially provides the deviation of one alternative from the other.

$$d_j(a, b) = g_j(a) - g_j(b), \qquad (B.3)$$

Where d_j is the deviation of alternatives a and b in the j^{th} criterion and g_j represents the normalized value of the alternative in the j^{th} criterion. In the car selection example, the alternative values and the j values are designated by the rows and columns of the matrix in Table B.2. For example, the application of Eq. (B.3) when comparing Toyota (1) with Audi (2) in the Quality criterion is:

$$d_1(1,2) = g_1(1) - g_1(2) = 0 - 0.67 = -0.67.$$

Another example, when comparing Honda (3) with Mercedes (4) in the Price criterion, as per Eq. (B.3), the value is:

$$d_2(3,4) = g_2(3) - g_2(4) = 0.8 - 0 = 0.80$$

The application of Eq. (B.3) for all alternatives leads to Table B.3 below:

Table B.3 – Deviation of pairwise comparisons

Criteria	Quality_**d1(k,l)**	Price_**d2(k,l)**	Safety_**d3(k,l)**	Style_**d4(k,l)**	Comfort_**d5(k,l)**
k=1 , l=2	-0,67	0,80	0,33	-0,83	0,50
k=1 , l=3	-0,33	0,20	-0,33	-0,33	0,25
k=1 , l=4	-1,00	1,00	-0,67	-1,00	-0,50
k=1 , l=5	-0,67	-0,80	0,00	-0,50	0,25
k=2 , l=1	0,67	-0,80	-0,33	0,83	-0,50
k=2 , l=3	0,33	-0,60	-0,67	0,50	-0,25
k=2 , l=4	-0,33	0,20	-1,00	-0,17	-1,00
k=2 , l=5	0,00	0,00	-0,33	0,33	-0,25
k=3 , l=1	0,33	-0,20	0,33	0,33	-0,25
k=3 , l=2	-0,33	0,60	0,67	-0,50	0,25
k=3 , l=4	-0,67	0,80	-0,33	-0,67	-0,75
k=3 , l=5	-0,33	0,60	0,33	-0,17	0,00
k=4 , l=1	1,00	-1,00	0,67	1,00	0,50
k=4 , l=2	0,33	-0,20	1,00	0,17	1,00
k=4 , l=3	0,67	-0,80	0,33	0,67	0,75
k=4 , l=5	0,33	-0,20	0,67	0,50	0,75
k=5 , l=1	0,67	-0,80	0,00	0,50	-0,25
k=5 , l=2	0,00	0,00	0,33	-0,33	0,25
k=5 , l=3	0,33	-0,60	-0,33	0,17	0,00
k=5 , l=4	-0,33	0,20	-0,67	-0,50	-0,75

Step 4: Calculation of the preference function and weighted matrix

The preference function (or p_j) essentially presents the preference of alternative a over b with respect to the j^{th} criterion:

$$p_j(a,b) = 0, \quad if\ r_{aj} \leq r_{bj}\ or$$

$$(B.4)$$

$$p_j(a,b) = r_{aj} - r_{bj}, \quad if\ r_{aj} > r_{bj}$$

Where

- p_j is the non-negative deviation of alternative a from alternative b in the j^{th} criterion
- r_{aj} is the importance of alternative a in the j^{th} criterion
- r_{bj} is the importance of alternative b in the j^{th} criterion. If in the Deviation of Pairwise Comparison (Table B.3) the value of a cell is positive, it suggests that alternative a is more important that alternative b (thus $r_{aj} > r_{bj}$)

Applying Eq. (B.4) to the deviation matrix of Table B.3, we obtain Table B.4:

Table B.4 – Preference function matrix

Criteria	Quality_**p1(k,l)**	Price_**p2(k,l)**	Safety_**p3(k,l)**	Style_**p4(k,l)**	Comfort_**p5(k,l)**
k=1 , l=2	0,00	0,80	0,33	0,00	0,50
k=1 , l=3	0,00	0,20	0,00	0,00	0,25
k=1 , l=4	0,00	1,00	0,00	0,00	0,00
k=1 , l=5	0,00	0,00	0,00	0,00	0,25
k=2 , l=1	0,67	0,00	0,00	0,83	0,00
k=2 , l=3	0,33	0,00	0,00	0,50	0,00
k=2 , l=4	0,00	0,20	0,00	0,00	0,00
k=2 , l=5	0,00	0,00	0,00	0,33	0,00
k=3 , l=1	0,33	0,00	0,33	0,33	0,00
k=3 , l=2	0,00	0,60	0,67	0,00	0,25
k=3 , l=4	0,00	0,80	0,00	0,00	0,00
k=3 , l=5	0,00	0,60	0,33	0,00	0,00
k=4 , l=1	1,00	0,00	0,67	1,00	0,50
k=4 , l=2	0,33	0,00	1,00	0,17	1,00
k=4 , l=3	0,67	0,00	0,33	0,67	0,75
k=4 , l=5	0,33	0,00	0,67	0,50	0,75
k=5 , l=1	0,67	0,00	0,00	0,50	0,00
k=5 , l=2	0,00	0,00	0,33	0,00	0,25
k=5 , l=3	0,33	0,00	0,00	0,17	0,00
k=5 , l=4	0,00	0,20	0,00	0,00	0,00

It can be noted that this matrix is derived directly from the previous one, by converting all negative elements to 0 using Eq. (B.4).

The criteria weights is multiplied with the elements of the preference function matrix, as follows:

$$WP_j(a,b) = w_j * p_j(a,b), \qquad (B.5)$$

to obtain the weighted preference matrix (Table B.5).

Table B.5 – Weighted Preference Matrix

Criteria	Quality_WP1(k,l)	Price_WP2(k,l)	Safety_WP3(k,l)	Style_WP4(k,l)	Comfort_WP5(k,l)
k=1 , l=2	0,00	0,29	0,05	0,00	0,07
k=1 , l=3	0,00	0,07	0,00	0,00	0,04
k=1 , l=4	0,00	0,36	0,00	0,00	0,00
k=1 , l=5	0,00	0,00	0,00	0,00	0,04
k=2 , l=1	0,11	0,00	0,00	0,16	0,00
k=2 , l=3	0,06	0,00	0,00	0,09	0,00
k=2 , l=4	0,00	0,07	0,00	0,00	0,00
k=2 , l=5	0,00	0,00	0,00	0,06	0,00
k=3 , l=1	0,06	0,00	0,05	0,06	0,00
k=3 , l=2	0,00	0,22	0,09	0,00	0,04
k=3 , l=4	0,00	0,29	0,00	0,00	0,00
k=3 , l=5	0,00	0,22	0,05	0,00	0,00
k=4 , l=1	0,17	0,00	0,09	0,19	0,07
k=4 , l=2	0,06	0,00	0,14	0,03	0,14
k=4 , l=3	0,11	0,00	0,05	0,12	0,11
k=4 , l=5	0,06	0,00	0,09	0,09	0,11
k=5 , l=1	0,11	0,00	0,00	0,09	0,00
k=5 , l=2	0,00	0,00	0,05	0,00	0,04
k=5 , l=3	0,06	0,00	0,00	0,03	0,00
k=5 , l=4	0,00	0,07	0,00	0,00	0,00

Step 5: Weighted Aggregated Preference Function

In this step, the Weighted Aggregated Preference Function (or $\pi(a,b)$) is calculated, in order to consolidate the values of Table B.5:

$$\pi(a,b) = \frac{\sum_{j=1}^{m}[w_j * p_j(a,b)]}{\sum_{j=1}^{m} w_j} = \frac{\sum_{j=1}^{m} WP_j(a,b)}{\sum_{j=1}^{m} w_j}, \qquad (B.6)$$

Where:

- $\pi(a,b)$ is the weighted aggregated preference of alternative a over alternative b
- $WP_j(a,b)$ is the weighted preference of alternative a over alternative b (Table B.5)

- w_j are the CRITIC weights for the criterion j

The Weighted Aggregated Preference Function Matrix for the example is presented in Table B.6:

Table B.6 – Weighted Aggregated Preference Function Matrix

π(a,b)		Alternatives				
		Toyota	Audi	Honda	Mercedes	Dodge
Alternatives	Toyota	0,00	0,41	0,11	0,36	0,04
	Audi	0,27	0,00	0,15	0,07	0,06
	Honda	0,17	0,35	0,00	0,29	0,26
	Mercedes	0,52	0,37	0,39	0,00	0,35
	Dodge	0,21	0,08	0,09	0,07	0,00

Step 6: Positive and Negative outranking flows and alternative ranking

In order to evaluate the alternatives from best to worst, there are two values that must be calculated for every alternative:

- the leaving flow (φ^+), which describes the strength of an alternative over the other alternatives
- the entering flow (φ^-), which describes the weakness of an alternative with respect to the other alternatives

Equations (B.7) and (B.8) provide the leaving and entering flows respectively.

$$\varphi^+ = \frac{1}{n-1}\sum_{b=1}^{n} \pi(a,b) \quad a \neq b, \qquad (B.7)$$

$$\varphi^- = \frac{1}{n-1}\sum_{a=1}^{n} \pi(a,b) \quad a \neq b, \qquad (B.8)$$

For example, Toyota's leaving flow (φ^+) is:

$$\varphi^{+} = \frac{1}{5-1}\sum_{b=1}^{5}\pi(1,b) = \frac{1}{4} * (0 + 0.4070 + 0.1020 + 0.3621 + 0.3562)$$
$$= 0.2282$$

And its entering flow (φ^{-}) is:

$$\varphi^{+} = \frac{1}{5-1}\sum_{a=1}^{5}\pi(a,1) = \frac{1}{4} * (0 + 0.2690 + 0.1651 + 0.5204 + 0.2069)$$
$$= 0.2903$$

If applied for all alternatives, the resulting matrix is in Table B.7:

Table B.7 – Aggregated Preference Function with positive and negative flows

π(a,b)		Alternatives					
		Toyota	Audi	Honda	Mercedes	Dodge	ϕ^{+}
Alternatives	Toyota	0,00	0,41	0,11	0,36	0,04	0,23
	Audi	0,27	0,00	0,15	0,07	0,06	0,14
	Honda	0,17	0,35	0,00	0,29	0,26	0,27
	Mercedes	0,52	0,37	0,39	0,00	0,35	0,41
	Dodge	0,21	0,08	0,09	0,07	0,00	0,11
	ϕ^{-}	0,29	0,30	0,18	0,20	0,18	

Finally, to calculate the net outranking flow of each alternative, Eq. (B.9) is used to obtain the ranking of each alternative:

$$\varphi(\alpha) = \varphi^{+}(\alpha) - \varphi^{-}(\alpha), \qquad (B.9)$$

The final matrix that depicts the ranking of each alternative is provided in Table B.8.

Table B.8 – Final alternative rankings

		ϕ(a)$^+$	ϕ(a)$^-$	ϕ(a)	Rank
Alternatives	Toyota	0,23	0,29	-0,06	4
	Audi	0,14	0,30	-0,16	2
	Honda	0,27	0,18	0,08	5
	Mercedes	0,41	0,20	0,21	1
	Dodge	0,11	0,18	-0,07	3

The higher the value of $\varphi(a)$, the higher the rank of the alternative (the higher the leaving flow (φ^+) and the lower the entering flow (φ^-), the better). In this context, the best ranked automobile out of the five is Mercedes, followed by Audi, Dodge, Toyota and Honda for the five selected criteria (quality, price, safety, style, comfort)

B.2 TOPSIS

A widely used method, especially when evaluating ports, is TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution). This method, which is presented in an article of Chen and Huang (1992), with a reference to Hwang and Yoon (1982), uses as basic principle that the optimal alternative has the smallest possible Euclidean distance from the best solution and, at the same time, it has the largest possible Euclidean distance from the worst solution.

The description of the method is based on Kim (2015), and it is illustrated using the best car selection example.

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker’s Judgment.

For the best car selection example, the values are provided based on judgment in Table B.1 on the PROMETHEE II example (on a scale from 1 – 10).

Step 2: Matrix normalization

As with every method, in order to rank the alternatives on the same scale, the values must be normalized. For TOPSIS, the values are normalized using the Euclidean distance function, which is given by Eq. (B.10).

$\sqrt{\sum_{i=1}^{n} x_{ij}^2}$, $(B.10)$ (B.10)

Where:

- i is the number of alternatives
- j is the number of criterion
- x_{ij} is the value of alternative i for criterion j

For example, the Euclidean distance for the Price ($j = 2$) criterion is:

$$\sqrt{\sum_{i=1}^{n} x_{i2}^2} = \sqrt{x_{12}^2 + x_{22}^2 + x_{32}^2 + x_{42}^2 + x_{52}^2} = \sqrt{3^2 + 7^2 + 4^2 + 8^2 + 7^2}$$

$$= 13.67$$

Following the application of Eq. (B.10), the Euclidean distance of all criteria are:

- Quality = 17.1464
- Price = 13.6747
- Safety = 12.2882
- Style = 12.5698
- Comfort = 12.8840

The TOPSIS normalized matrix of Table B.9 is given by:

$$\hat{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^{2}}}, \qquad (B.11)$$

Table B.9 – TOPSIS Normalized Matrix

Normalized Mat.		Beneficial	Non - Beneficial	Beneficial	Beneficial	Beneficial
Criteria Weights		0,17	0,36	0,14	0,19	0,14
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,35	0,22	0,41	0,16	0,47
	Audi	0,47	0,51	0,33	0,56	0,31
	Honda	0,41	0,29	0,49	0,32	0,39
	Mercedes	0,52	0,59	0,57	0,64	0,62
	Dodge	0,47	0,51	0,41	0,40	0,39

Step 3: Weighted Normalized Decision Matrix and ideal – non ideal values

In Step 3 is the CRITIC criteria weights are multiplied by the elements of the normalized decision matrix to obtain the weighted normalized decision matrix (Table B.10).

$$v_{ij} = \hat{x}_{ij} * w_j, \qquad (B.12)$$

Table B.10 – TOPSIS Weighted Normalized Decision Matrix

Weighted Norm. Mat.		Beneficial	Non - Beneficial	Beneficial	Beneficial	Beneficial
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,06	0,08	0,06	0,03	0,07
	Audi	0,08	0,19	0,05	0,10	0,04
	Honda	0,07	0,11	0,07	0,06	0,06
	Mercedes	0,09	0,21	0,08	0,12	0,09
	Dodge	0,08	0,19	0,06	0,07	0,06

Based on the above matrix, the ideal and non – ideal values can be calculated for each criterion. For beneficial criteria (e.g. quality), the highest value of v_{ij} for every criterion j is the ideal value ($v_{ij}{}^{+}$), while the lowest value of v_{ij} for every criterion j is the non – ideal value ($v_{ij}{}^{-}$). The opposite applies to non – beneficial criteria (e.g. price). The ideal and non – ideal values for the example are provided in Table B.11:

Table B.11 – Ideal and Non – Ideal values

Criteria		Quality	Price	Safety	Style	Comfort
Ideal Value	${v_{ij}}^{+}$	0,090	0,079	0,079	0,119	0,088
Non - Ideal Value	${v_{ij}}^{-}$	0,060	0,212	0,045	0,030	0,044

Step 4: Euclidean Distance

In order to compute the distances from the ideal and non – ideal values for each alternative, we use the Equations below.

$$ {S_i}^{+} = \left[\sum_{j=1}^{m} (v_{ij} - {v_{ij}}^{+})^2 \right]^{0.5} , \qquad (B.13) $$

$$ {S_i}^{-} = \left[\sum_{j=1}^{m} (v_{ij} - {v_{ij}}^{-})^2 \right]^{0.5} , \qquad (B.14) $$

For example, if applied to Toyota, the distance of the ideal value (Eq. B.13) and the non – ideal value (Eq. B.14) should be respectively:

$$ {S_{Toyota}}^{+} = [(0.0597 - 0.0895)^2 + (0.0795 - 0.0795)^2 + (0.0563 - 0.0788)^2 + (0.0297 - 0.1187)^2 + (0.0664 - 0.0885)^2]^{0.5} = 0.099 $$

$$ {S_{Toyota}}^{-} = [(0.0597 - 0.0597)^2 + (0.0795 - 0.2119)^2 + (0.0563 - 0.045)^2 + (0.0297 - 0.0297)^2 + (0.0664 - 0.0442)^2]^{0.5} = 0.13473 $$

In Table B.12, the ideal and non – ideal Euclidean distances of every alternative are presented.

Table B.12 – Alternative distances from ideal and non – ideal solution

		S_i+	S_i-	$S_i^+ + S_i^-$	P_i
Alternatives	Toyota	0,10	0,13	0,23	0,58
	Audi	0,12	0,08	0,20	0,40
	Honda	0,08	0,11	0,19	0,60
	Mercedes	0,13	0,11	0,24	0,45
	Dodge	0,12	0,06	0,18	0,32

Step 5: Alternative Rankings

In the last step of TOPSIS evaluation, the closeness of each alternative to the ideal solution is provided from:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} , \qquad (B.15)$$

P_i stands for Performance value of alternative i. The closer P_i is to 1, the better the alternative (since the largest the S_i^- - distance to the non – ideal solution - the better). By applying Eq. (B.15) to each alternative, Table B.13 is obtained:

Table B.13 – TOPSIS Alternatives Performance Values

		S_i+	S_i-	$S_i^+ + S_i^-$	P_i	Rank
Alternatives	Toyota	0,10	0,13	0,23	0,58	2
	Audi	0,12	0,08	0,20	0,40	4
	Honda	0,08	0,11	0,19	0,60	1
	Mercedes	0,13	0,11	0,24	0,45	3
	Dodge	0,12	0,06	0,18	0,32	5

The results indicate that the closest alternative to the ideal solution is Honda, followed by Toyota, Mercedes, Audi and Dodge.

For comparison, when the Entropy weights were assigned to this same problem, the ranks changed, having Mercedes as the most preferred alternative, followed by Honda, Toyota, Audi and lastly Dodge.

B.3 VIKOR

The VIKOR (from Serbian as Multi Criteria Optimization and Compromise Solution) method resembles TOPSIS; the best alternative is the one as close as possible to the ideal solution. However, some notable differences exist between the two methods. TOPSIS provides two reference points to the problem, the distances to the ideal and non – ideal solution. Thus the alternative that is closer to the ideal solution may not be the best ranked alternative, which is not the case in VIKOR, where only the closeness to the ideal solution is calculated.

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker's Judgment.

For the best car selection example, the values are provided based on judgment in Table B.1 on the PROMETHEE II example (on a scale from 1 – 10).

Step 2: Matrix normalization and distance to the ideal solution

In order to normalize the initial matrix, the best and worst values are identified for each criterion. - Table B.14:

Table B.14 – VIKOR Best and Worts values per criterion

		Beneficial	Non - Beneficial	Beneficial	Beneficial	Beneficial
Criteria Weights		0,1705771	0,362174551	0,1383367	0,1864293	0,1424823
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	6	3	5	2	6
	Audi	8	7	4	7	4
	Honda	7	4	6	4	5
	Mercedes	9	8	7	8	8
	Dodge	8	7	5	5	5
	Best x_i+	9	3	7	8	8
	Worst x_i-	6	8	4	2	4

In the normalization step of VIKOR, the weighted normalized matrix is calculated immediately, using Eq. (B.16), leading to the value of S_i, the unity measure.

$$S_i = \sum_{j=1}^{m} (w_j \frac{x_{ij}{}^{+} - x_{ij}}{x_{ij}{}^{+} - x_{ij}{}^{-}}), \qquad i = 1, .., n \qquad (B.16)$$

Where:

- w_j is the weight of criterion j
- $x_{ij}{}^{+}$ is the best value of an alternative i for criteria j
- $x_{ij}{}^{-}$ is the worst value of an alternative i for criteria j
- x_{ij} is the value of alternative i for criteria j

The application Eq. (B.16) to the best car leads to Table B.15.

Table B.15 – VIKOR Weighted Normalized Matrix and Unity Measure

Criteria		Quality	Price	Safety	Style	Comfort	Si
Alternatives	Toyota	0,17	0,00	0,09	0,19	0,07	0,52
	Audi	0,06	0,29	0,14	0,03	0,14	0,66
	Honda	0,11	0,07	0,05	0,12	0,11	0,46
	Mercedes	0,00	0,36	0,00	0,00	0,00	0,36
	Dodge	0,06	0,29	0,09	0,09	0,11	0,64

Step 3: Individual Regret

S_i indicates how close each alternative is to the ideal solution. The closer S_i is to 0, the closer to the best solution alternative i is. Let R_i be the individual regret for each alternative, that is the worst normalized value of an alternative for a criterion j. For example, based on Table B.15, the individual regret (R_i) of Honda is Style, with a value of 0.12, since for this criterion Honda deviates most from the ideal solution.

$$R_i = \max_{j} \left(w_j \frac{x_i{}^{+} - x_i}{x_i{}^{+} - x_i{}^{-}} \right), \qquad (B.17)$$

For every alternative, R_i is presented in Table B.16.

Table B.16 – VIKOR Weighted Normalized Matrix and Individual Regret

Criteria		Quality	Price	Safety	Style	Comfort	Ri
Alternatives	Toyota	0,17	0,00	0,09	0,19	0,07	0,19
	Audi	0,06	0,29	0,14	0,03	0,14	0,29
	Honda	0,11	0,07	0,05	0,12	0,11	0,12
	Mercedes	0,00	0,36	0,00	0,00	0,00	0,36
	Dodge	0,06	0,29	0,09	0,09	0,11	0,29

Step 4: Final alternative rankings

Compute S^*, S^-, R^* and R^- as follows:

$$S^* = \min_i S_i$$

$$S^- = \max_i S_i$$

$$(B.18)$$

$$R^* = \min_i R_i$$

$$R^- = \max_i R_i$$

S^* and R^* represent the best values of unity measure (S_i) and individual regret (R_i) between all alternatives, while S^- and R^- represent the worst values of unity measure (S_i) and individual regret (R_i) between all alternatives.

Table B.17 – Best and Worst S_i & R_i

		Si	Ri
Alternatives	Toyota	0,52	0,19
	Audi	0,66	0,29
	Honda	0,46	0,12
	Mercedes	0,36	0,36
	Dodge	0,64	0,29
	S* , R*	0,36	0,12
	S^- , R^-	0,66	0,36

Table B.17 indicates that, the best S_i relates to Mercedes while the worst S_i relates to Audi. For the R_i, the alternative with the smallest individual regret is Honda while the one with the highest is Mercedes.

The following Equation provides the function used to evaluate the alternatives.

$$Q_i = u * \left(\frac{S_i - S^*}{S^- - S^*}\right) + (1-u) * \left(\frac{R_i - R^*}{R^- - R^*}\right), \qquad (B.19)$$

Parameter *u* takes values between 0 and 1 and essentially provides the weight as to the preference of either the unity measure (S_i) or the individual regret (R_i) for the final decision making. For example, if *u = 1,* then the evaluation will be solely dependent on the unity measure (S_i). On the other hand, if *u = 0,* then the evaluation will depend solely on the individual regret (R_i) for each alternative. In most cases, the u value is 0.5, so that both S_i and R_i have the same weight in the evaluation. For the example, using Eq. (B.19) with $u = 0{,}5$ provides the results of Table B.18.

Table B.18– VIKOR Final alternative rankings

Criteria		Quality	Price	Safety	Style	Comfort	Si	Ri	Qi	Rank
Alternatives	Toyota	0,17	0,00	0,09	0,19	0,07	0,52	0,19	0,40	2
	Audi	0,06	0,29	0,14	0,03	0,14	0,66	0,29	0,85	5
	Honda	0,11	0,07	0,05	0,12	0,11	0,46	0,12	0,17	1
	Mercedes	0,00	0,36	0,00	0,00	0,00	0,36	0,36	0,50	3
	Dodge	0,06	0,29	0,09	0,09	0,11	0,64	0,29	0,81	4

The smaller the value of Q_i, the better the alternative, since it is closer to the ideal solution. Based on VIKOR and the CRITIC criteria weights, the best selection is Honda, followed by Toyota, Mercedes, Dodge and finally Audi

B.4 WASPAS

WASPAS (Weighted Aggregated Sum Product Assessment) is the fusion of two very commonly used MCDM methods, the Weighted Sum Model, and the Weighted Product Model. The description that follows is based on Zavadskas *et al.* (2012)

Step 1: Determine the values of each criterion for every alternative. These may be provided by:

- National Statistical Institutes
- Statistical Organizations (such as Eurostat)
- Company websites
- Decision Maker's Judgment.

For the best car selection example, the values are provided based on judgment in Table B.1 on the PROMETHEE II example (on a scale from 1 – 10).

Step 2: Matrix normalization

Normalization is performed using Eqs. (B.20) or (B.21), based on whether the criterion is beneficial or non – beneficial respectively.

$$\hat{x}_{ij} = \frac{x_{ij}}{\max\limits_i(x_{ij})}, \qquad for\ i = 1,\dots,n\ and\ j = 1,\dots,m \quad (B.20)$$

$$\hat{x}_{ij} = \frac{\min\limits_i(x_{ij})}{x_{ij}}, \qquad for\ i = 1,\dots,n\ and\ j = 1,\dots,m \quad (B.21)$$

Where:

- $\hat{x}_{ij}$ is the normalized value of alternative i for criterion j
- $\min(x_{ij})$ minimum value of alternative i for criterion j
-

The normalized matrix for the example is given in Table B.19

Table B.19 – WASPAS Normalized Matrix

Criteria		Quality	Price	Safety	Style	Comfort	Preference Score	Rank
Alternatives	Toyota	0,11	0,36	0,10	0,05	0,11	0,73	2
	Audi	0,15	0,16	0,08	0,16	0,07	0,62	4
	Honda	0,13	0,27	0,12	0,09	0,09	0,71	3
	Mercedes	0,17	0,14	0,14	0,19	0,14	0,77	1
	Dodge	0,15	0,16	0,10	0,12	0,09	0,61	5

Step 3: WSM Rankings

WSM is provided by multiplying each normalized value with the respective criterion weight. Then the preference score Q_{i^1} of alternative i is computed from Eq. (B.22).

$$Q_{i^1} = \sum_{j=1}^{m} (w_j * \hat{x}_{ij}), \qquad (B.22)$$

the alternative with the highest score is preferred.

For example, when applying the WSM equation for the Toyota alternative, its preference score is:

$$Q_{1^1} = \sum_{j=1}^{5} (w_j * \hat{x}_{ij}) = w_1 * \hat{x}_{11} + w_2\hat{x}_{12} * +w_3\hat{x}_{13} * +w_4\hat{x}_{14} * +w_5 * \hat{x}_{15} =$$

$$0.1705 * 0.667 + 0.3621 * 1 + 0.1383 * 0.714 + 0.1864 * 0.250 + 0.1424 * 0.752 = 0.7821$$

By applying Eq. (B.22) is to all alternatives, Table B.20 is obtained.

Table B.20 – WSM Rankings

Normalized Matrix						
Criteria Weights		0,17	0,36	0,14	0,19	0,14
Criteria		Quality	Price	Safety	Style	Comfort
Alternatives	Toyota	0,67	1,00	0,71	0,25	0,75
	Audi	0,89	0,43	0,57	0,88	0,50
	Honda	0,78	0,75	0,86	0,50	0,63
	Mercedes	1,00	0,38	1,00	1,00	1,00
	Dodge	0,89	0,43	0,71	0,63	0,63

As can be noted, WSM rates Mercedes with the highest preference score of 0.774, followed by Toyota, Honda. Audi and lastly Dodge.

Step 4: WPM Rankings

The weighted normalized matrix for this case is computed by using Eq. (B.23). The alternative with the highest preference score Q_{i^2} is preferred.

$$Q_{i^2} = \prod_{j=1}^{m} \hat{x}_{ij}{}^{w_j}, \qquad (B.23)$$

For example, when applying the WPM equation to the Audi alternative, its preference score is:

$Q_{2^2} = \prod_{j=1}^{5} \hat{x}_{2j}{}^{w_j} = \hat{x}_{21}{}^{w_1} * \hat{x}_{22}{}^{w_2} * \hat{x}_{23}{}^{w_3} * \hat{x}_{24}{}^{w_4} * \hat{x}_{25}{}^{w_5} = 0.889^{0.1705} * 0.429^{0.3617} * 0.571^{0.1383} * 0.875^{0.1864} * 0.5^{0.1424} = 0.590$

When the Eq. (B.23) is applied for all alternatives, Table (B.21) is obtained.

Table B.21 – WPM Rankings

Criteria		Quality	Price	Safety	Style	Comfort	Preference Score	Rank
Alternatives	Toyota	0,93	1,00	0,95	0,77	0,96	0,66	3
	Audi	0,98	0,74	0,93	0,98	0,91	0,59	4
	Honda	0,96	0,90	0,98	0,88	0,94	0,69	2
	Mercedes	1,00	0,70	1,00	1,00	1,00	0,70	1
	Dodge	0,98	0,74	0,95	0,92	0,94	0,59	4

In the case of WPM, Mercedes is still ranked the highest with a score of 0.701, followed now by Honda, Toyota and the last place is shared among Dodge and Audi.

Step 5: Final Rankings

After getting the preference scores from both WSM and WPM methods, the WASPAS (Weighted Aggregated Sum Product Assessment) model can be constructed based on Eq. (B.24)

$$Q_i = \lambda \sum_{j=1}^{n} (w_j * \hat{x}_{ij}) + (1-\lambda) \prod_{j=1}^{n} \hat{x}_{ij}{}^{w_j}, \qquad or$$

$$Q_i = \lambda Q_{i^1} + (1-\lambda) Q_{i^2}, \qquad (B.24)$$

Where λ is a variable between 0 and 1, that determines the weight given to either WSM or WPM.

In the car selection example, with $\lambda = 0.5$, the final preference scores are provided in Table B.22.

Table B.22 – WASPAS Final Rankings

Q_i		Performance Score	Rank
Alternatives	Toyota	0,694	3
	Audi	0,605	4
	Honda	0,700	2
	Mercedes	0,737	1
	Dodge	0,600	5

The final resulting performance scores of WASPAS using the criteria weights of the CRITIC method indicate that Mercedes remains the top alternative, followed by Honda, Toyota, Audi and lastly Dodge.

B.5 Selection results comparison

All computed alternative rankings were consolidated in Table B.23.

Table B.23 – Multi Criteria Decision Making methods results consolidation

		Rankings based on different methods			
		PROMETHEE	**TOPSIS**	**VIKOR**	**WASPAS**
Alternatives	Toyota	4	2	2	3
	Audi	2	4	5	4
	Honda	5	1	1	2
	Mercedes	1	3	3	1
	Dodge	3	5	4	5

What can be extracted from Table B.23 is that, depending on the method of assessment, there are different rankings per alternative in most cases. This is also evident in Table B.24, where the standard deviation of each alternative was calculated for every assessment method and the values are quite high. However, it can be also deducted that these results were caused by PROMETHEE, which has the most different rankings from all other methods. It was noticed that if the method is removed when calculating the standard deviation, the results become much less deviated (Table B.24). This theory was further confirmed, when the correlation between the ranking was calculated in Table B.25 and PROMETHEE has a very high level of discordance compared with every other method. Of course, the method will still be applied to the case study, since maybe it was not suitable for the computation of this specific example and will produce more expected results for the case study of this Thesis.

Table B.24 – Standard deviation between MCDM methods results

	PROMETHEE	TOPSIS	VIKOR	WASPAS
PROMETHEE	1	-0,6	-0,7	0,1
TOPSIS	-0,6	1	0,9	0,7
VIKOR	-0,7	0,9	1	0,6
WASPAS	0,1	0,7	0,6	1

Table B.25 – Correlation between MCDM methods results

		Standard Deviation (with PROMETHEE)	Standard Deviation (no PROMETHEE)
Alternatives	Toyota	0,957	0,577
	Audi	1,258	0,577
	Honda	1,893	0,577
	Mercedes	1,155	1,155
	Dodge	0,957	0,577