

SCHEDULING TRANSIT VESSELS IN THE ISTANBUL STRAIT

by

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ABSTRACT

SCHEDULING TRANSIT VESSELS IN THE ISTANBUL STRAIT

Due to its geographical features and unique location, the Istanbul Strait is one of the most significant and critical waterways in the world. Geographical features, meteorological conditions, local maritime traffic, the density of maritime traffic and cargo characteristics make transit vessel navigation difficult in the Istanbul Strait in each passing day. For safe vessel navigation, the Istanbul Strait Vessel Traffic Control Authority (VTCA) has defined some rules and regulations, which can change according to vessel class and meteorological conditions. The objective of this study is to develop and implement an optimization model to schedule the entrances to the Istanbul Strait of the arrived (and waiting) transit vessels, while minimizing and balancing the waiting times of vessel classes against the vessel density and separation (between two consecutive transit vessels) and traffic flow direction requirements in the Istanbul Strait. One of the most significant policies of the VTCA is the minimum pursuit distance between vessels, which differs from one vessel type to another. Minimum pursuit distance rule can be changed by the VTCA based on meteorological conditions or maritime traffic density. Other significant policies of the VTCA are unidirectional traffic flow for transit vessels and not giving permission to some vessel classes to enter the Strait in day time or night time. However, passing through the Strait in bidirectional flow in favorable meteorological conditions is admitted for some vessels. In this study, a mixed integer zero-one formulation is developed and solved for the above defined scheduling problem. In addition to the current situation, parameters such as minimum pursuit distances, number of available pilots and arrival pattern of vessels in the Istanbul Strait are changed for scenario analysis and the effect of change in parameters on performance measures are investigated.

ÖZET

İSTANBUL BOĞAZI'INDA UĞRAKSIZ GEMİ GEÇİŞİ ÇİZELGELEMESİ

İstanbul Boğazı coğrafi özellikleri ve konumu sebebiyle dünyadaki en önemli ve en kritik suyollarından biridir. Coğrafi özellikler, meteorolojik koşullar, yerel deniz trafiği, deniz trafiği yoğunluğu ve taşınan yük özellikleri sebepleriyle her geçen gün İstanbul Boğazı'nda uğraksız gemi geçişi zorlaşmaktadır. Güvenli gemi geçişi için Kıyı Emniyet Müdürlüğü tarafından, gemi tipi ve meteorolojik koşullara göre değişen, bir takım kurallar uygulanmaktadır. Çalışmamızın amacı, gece ve gündüz uğraksız geçiş için İstanbul Boğazı'na gelen ve bekleyen gemilerin Boğaz'a girişlerini, Boğaz'daki deniz trafiği yoğunluğunu çok arttırmadan, gemi özellikleri, en kısa takip mesafesi ve trafik akış yönü gibi deniz trafik kurallarını dikkate alarak, adil bir trafik akışı çerçevesinde, gemilerin bekleme zamanlarını en aza indirecek şekilde çizelgelemeye yönelik bir eniyileme modeli geliştirmek ve uygulamaktır. En önemli deniz trafiği kurallarından biri gemi tiplerine göre değişen iki gemi arasındaki minimum takip mesafesidir. Minimum takip mesafesi hava koşulları ya da trafik yoğunluğuna göre yetkililerce bir miktar değiştirilebilmektedir. Diğer önemli deniz trafiği politikaları ise, uğraksız gemi geçişleri için tek yönlü trafik akışı ve bazı tip gemilerin gece veya gündüz geçişine izin verilmemesidir. Ancak trafik yoğunluğu veya hava koşullarından kaynaklanan istisnai durumlarda, bazı tip gemiler için çift yönlü trafik akışına izin verilebilmektedir. Bu çalışmada, yukarıda tariflenen çizelgeleme problemi için bir karışık tam sayı programlama modeli geliştirilmiş ve çözülmüştür. Mevcut durumun yanı sıra, minimum takip mesafesi, uygun pilot sayısı ve gemilerin İstanbul Boğazı'na geliş biçimleri parametreler değiştirilerek farklı senaryo geliştirilmiş ve performans ölçütlerine etkisi araştırılmıştır.

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LIST OF ACRONYMS/ABBREVIATIONS

ALP	Aircraft Landing Problem
AN	Northbound Class A Vessel
AS	Southbound Class A Vessel
Avg	Average
BN	Northbound Class B Vessel
BS	Southbound Class B Vessel
C1N	Northbound Class C1 Vessel
C1S	Southbound Class C1 Vessel
C2N	Northbound Class C2 Vessel
C2S	Southbound Class C2 Vessel
D1N	Northbound Class D1 Vessel
D1S	Southbound Class D1 Vessel
D2N	Northbound Class D2 Vessel
D2S	Southbound Class D2 Vessel
EN	Northbound Class E Vessel
ES	Southbound Class E Vessel
FIFO	First In First Out
FN	Northbound Class F Vessel
FS	Southbound Class F Vessel
GAMS	General Algebraic Modeling System
LNG	Liquefied Natural Gas
LPG	Liquied Petroleum Gas
Math	Mathematical
Min	Minutes
PN	Northbound Class P Vessel
PS	Southbound Class P Vessel
R&R	Istanbul Strait Maritime Rules and Regulations
SP-1	Sailing Plan1
SP-2	Sailing Plan2
VTCA	Istanbul Strait Vessel Traffic Control Authority

VTS Vessel Traffic Control and Monitoring System

1. INTRODUCTION & STUDY OBJECTIVES

Maritime transport has carried the largest share of transportation throughout history. In this day and age, it has still the most preferred transportation mode because of affordability, as well as transport capacity [1]. However, it requires some rules and regulations for safe, effective and systematic operation. Although risk level is not high while navigating in open seas, it increases while navigating in narrow waterways and nearing land.

Turkish Straits (Canakkale and Istanbul Straits) are two of the most heavily used and treacherous narrow waterways in the world. They are vital for many countries, especially the ones around the Black Sea because they are the only way to reach open seas for those countries. In addition to strategic importance, hard geographical conditions, meteorological conditions, heavy local traffic density, the high share of dangerous cargo carriers, high and increasing number of transits and their changing characteristics make navigation difficult in the Turkish Straits. Hence, it is vital to control and regulate transit vessel traffic in the Turkish Straits [1].

The Istanbul Strait is 31 kilometers long and has an average depth of 45 meters. It is on average 1.5 kilometers wide, while the width is 700 meters at the narrowest point [2]. Due to its narrow and winding nature, a vessel faces with 12 sharp turns while passing through the Istanbul Strait.

Meteorological conditions, particularly fog, rain and wind have adverse effect on the maritime traffic in the Istanbul Strait. Although the severity and frequency of fog, rain and wind change from season to season, they affect visibility and sailing conditions and make navigate difficult on the Strait [1, 3].

Surface and underwater currents also contribute to the difficulty of navigation in the Istanbul Strait. The Istanbul Strait is exposed to four types of currents, which may rise up 6 or 8 knots speed. The first one is the surface current which is the result of water level difference between the Black Sea and the Marmara Sea. Salinity difference between the

Black Sea and the Marmara Sea creates underwater current. Different geographical characteristics of bays and forelands are reasons of reverse current. The last current type is orkoz current which is the consequence of southerly strong winds [1].

Politically and legally, passage and sailing rights in the Istanbul Strait is controlled by the 1936 Montreux Treaty, according to which the Strait is considered to be “international waters”. Nevertheless, the rules and regulations regarding the maritime activities in the Strait are laid out by the Maritime Undersecretariat of the Turkish Government and administered by the Istanbul Strait Vessel Traffic Control Authority (VTCA). 4500 vessels annually passed through the Istanbul Strait in 1936 when Montreux Convention was signed. However, nowadays, around 55000 vessels annually pass through the Istanbul Strait. Moreover, the Maritime Traffic of the Istanbul Strait is four times heavier than the traffic of the Panama Canal and three times heavier that of the Suez Canal [1, 4]. In other words, heavy and increasing demand regarding the usage of the Istanbul Strait for international transportation complicates the navigation in the Strait. In addition, different vessel characteristics such as hazardous cargo, LPG, petroleum carrier vessels impose additional risks onto this critical waterway. Hence, it is inevitable to regulate, plan and control the Maritime traffic in the Istanbul Strait.

Additionally, approximately 2 million people use the Strait every day for their local transportation needs (such as commuting to work) and 2500 local maritime traffic movements are observed in the Istanbul Strait every day [5]. Moreover, the Istanbul Strait is in the middle of one of the largest metropolitans of the world, which means that very large numbers of people and properties could be negatively impacted in case of an undesirable and unexpected maritime incident on the Strait.

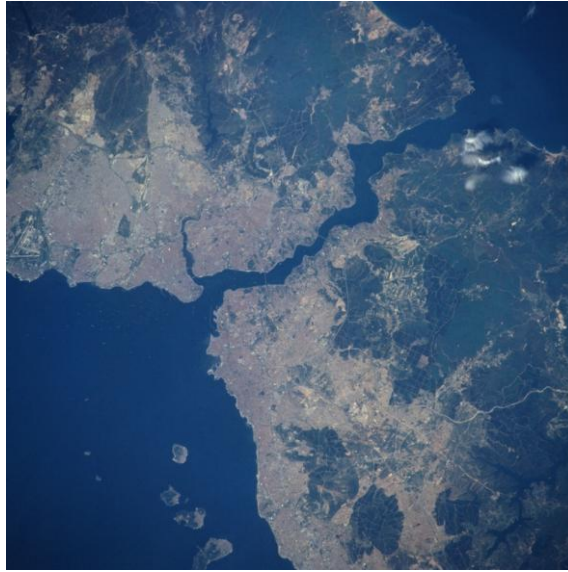


Figure 1.1. The Istanbul Strait.

All these natural and manmade factors indicate that rules and regulations are essential for safe and fair maritime traffic in the Istanbul Strait. In this regard, VTCA administers the rules and regulations (R&R) and manages the maritime traffic in the Istanbul Strait with the help of a sophisticated Vessel Traffic Control and Monitoring System (VTS), which features advanced technical capabilities, such as integrated radar, cameras, sensors and communication systems [1].

To manage the maritime traffic and operations in the Istanbul Strait, the VTCA needs information about the incoming vessels. Sailing Plan 1 (SP – 1) and Sailing Plan 2 (SP – 2), which are essential reports submitted by all vessels (24 hours and 2 hours respectively) before entering the Istanbul Strait, provide detailed information about the vessels to the VTCA. The VTCA operators then set up a safe and fair maritime traffic schedule based on the information coming from the vessels and from the VTS system satisfying the R&R.

Maritime traffic in the Strait flows in one way direction during 24 hours, except for special circumstances determined by the VTCA. Due to one way direction, vessels preferably pass through the Istanbul Strait in a single line without navigating closely and overtaking each other. Vessels enter the Strait from either south or north entrances. If a

vessel enters from the south, it is called northbound vessel because its travel direction is from south to north. Every day, there are a series of decisions are made by the VTCA. The first one is related to the timing and length of the maritime traffic directions in the Istanbul Strait. In other words, duration of direction which is named as time window length is decided. Moreover, since there are different rules regarding daytime and nighttime passage, the scheduling of these two segments are done separately. Although the length and starting time of the nighttime and daytime traffic are naturally dependent on seasons, the length and starting time of the northbound and southbound traffic are decided by the VTCA, in accordance with the number of vessels in queue in both directions.

The second decision is related with the usage of support services such as pilots. In order to promote a safe maritime environment in the Istanbul Strait, the VTCA requires and/or encourages the usage of support services based on vessel types. Due to limited capacities of these support services, the availability level of the support services has impact on vessel scheduling.

The objective of this study is to develop a mathematical model to schedule the entrances to the Istanbul Strait of the arrived (and waiting) transit vessels, while minimizing and balancing the waiting times of vessel classes against the vessel density and separation (between two consecutive transit vessels) requirements in the Istanbul Strait. The mathematical model is based on the R&R determined by the VTCA, while it gives due consideration to meteorological and geographical conditions, support services (pilots), frequency of vessel arrivals and type of vessels.

Another objective of the study is to accomplish extensive scenario analysis through the developed model. The change in parameters associated with minimum pursuit distance rules, the availability level of support services, the length of northbound/southbound traffic time windows are considered and their effects compared in this scenario analysis. Hence, at the end of the study, the effects of potential policy changes associated with the Istanbul Strait Maritime Traffic can be observed, based on the schedule generated by the mathematical optimization model.

One of the significant policies of the VTCA is the minimum pursuit distance between vessels, which differs from one vessel type to another. In the mathematical model, the minimum pursuit distance requirement of the VTCA is applied as a linear timing constraint associated with consecutive vessel entrances to the Strait.

Another policy of the VTCA is the availabilities of support services such as pilots. For safe maritime environment, some kind of vessels should pass through the Istanbul Strait under the guidance of support services. However; support services are in limited numbers so that the support service availability has impact on vessel scheduling. The mathematical model assigns available support services to proper vessels by taking the needs and availabilities into consideration.

Chapter 2 presents literature review on three topics which form the basis of the study. The first one is the vessel scheduling problem faced and how it is treated in various narrow waterways around the globe (including the Istanbul Strait); the second one features various studies on the Strait of Istanbul. The final topic of interest is the Aircraft Landing Problem, which deals with the scheduling of aircraft landings to runways and from which the basic scheduling model developed in this study is derived.

Chapter 3 is on the Istanbul Strait Maritime Environment. Detailed information about the logic of scheduling system managed by the VTCA, the R&R, characteristics and defining features of the Istanbul Strait, natural and manmade factors having effects on vessel scheduling are presented and discussed.

Chapter 4 features the problem definition and the mathematical model. The assumptions, constraints and objectives of the model are presented and discussed.

Chapter 5 focuses on the verification and the validation of the developed model. Basic scenario of the developed model, which schedules the entrances of the waited/arrived vessels to the Istanbul Strait by satisfying the VTCA policies and the R&R, is presented. For verification and validation, the maritime traffic schedule plan of the basic

scenario (output of the basic scenario) is compared with the current maritime traffic schedule plan prepared by the VTCA operators.

Scenario analysis is accomplished in Chapter 6. In this context, scenario results are discussed and compared.

The last two sections contain conclusion and further studies.

2. LITERATURE SURVEY

In this chapter, recent studies related to the aim and contents of this thesis are presented and examined. The examined studies can be divided into three groups. The first group is about how the scheduling problem arises and is dealt with in maritime environments. The second group includes simulation models and other studies about the Istanbul Strait Maritime traffic. The last group discuss the Aircraft Landing Problem (ALP) which is associated with the scheduling of aircraft landings to airports and features the basic scheduling model from which the model developed this study is derived.

Uluscu *et al.* [4], present a scheduling algorithm of day time and night time maritime traffic in the Istanbul Strait while satisfying constraints such as channel traffic Rules and Regulations (R&R), minimum pursuit distance, vessel arrival times, vessel types and vessel priorities. The scheduling algorithm firstly decides which direction should be opened in daytime traffic. Next, it determines how many type A or B vessels (i.e. the hardest to handle) should pass in the active direction during the time window. In the last step, it schedules the vessels in queue (Class A, B, C, D, E, P) based on their class priorities and weighted accumulated waiting times.

Ozbas [3], develops a simulation model including vessel types, vessel arrival times, meteorological conditions, the R&R and pilot services to mimic the maritime transit traffic in the Istanbul Strait, using the Arena software. Average waiting times of vessels, maximum waiting times of vessels, average pilot utilization, average and maximum number of vessels waiting in queue are obtained as outputs. The model analyzes the interactions between the inputs and effects of the inputs on the maritime transit traffic in the Istanbul Strait by comparing the outputs. Based on the study, it is concluded that the pilot utilization is the most important factor, while the vessels arrival rate is the second important factor on the outputs.

Almaz [2], investigates the transit maritime traffic in the Istanbul Strait by developing an Arena simulation model and scenario analysis. In the simulation model; traffic rules and regulations, vessel profiles, vessel arrival rates, pilot availability,

meteorological and geographical conditions are taken into consideration. The parameters are divided into three groups: external and internal parameters, the R&R. External parameters (vessel profiles, vessel arrival rates, speed rate, meteorological conditions etc.) are not controlled by the Strait Authorities. Internal parameters (pilot availability, vessel priorities etc.) are controlled by the Strait Authorities. The last group, the R&R, features policy issues that can only be changed by the Ministry. Through the simulation model, two types of scenario analyses are conducted in the study: basic and integrated scenario analysis. The integrated scenario analysis includes various submodels, such as probabilistic current and visibility submodels, reparametrized minimum pursuit distances, rearranged meteorological and visibility conditions, overtaking rules. The results of basic scenario analysis show that the number of pilots in the service, vessel arrival rate and vessel types have great impact on the outputs. The results of integrated scenario analysis show that current and visibility conditions are more significant parameters than others.

Jackman, Guerra and Olafsson [6], study the issue of scheduling daily transit traffic in the Panama Canal and aim to reduce transit time. In this study, the problem is defined as a capacitated queuing network problem. Then, a metaheuristic approach, based on Nested Partitions, is developed to get an optimal schedule for vessels passing through the Panama Canal. Finally, it is concluded that metaheuristic approaches decrease the transit time in the Panama Canal.

Almaz and Altiok [7], develop a simulation model for the vessel traffic in the Delaware River with the aim of analyzing the navigational efficiency in the River. While building simulation model, vessel profiles, terminal/anchorage properties, operational and navigational rules are taken into consideration. The simulation model is also developed for scenario, policy analysis and risk analysis of the Delaware River. Performance measures such as overall port/terminal utilization, port times and terminal calls, anchorage visits and delays based on various vessel visits, categories and movements are investigated in this study.

Ozlem [5], develops a simulation model for the maritime traffic in the Istanbul Strait, to schedule uni-directional daytime as well as two-directional nighttime maritime

traffic, considering R&R and maritime traffic constraints. Moreover, minimum pursuit distances rule, vessel types, pilot availabilities, vessel arrival rate and visibility conditions are measured through scenario analysis. Minimum pursuit distance, vessel profile, pilot policy and vessel arrival rate are chosen to identify the impact of factors on results. It is concluded that minimum pursuit distance have the largest impact on results. The author intends to use the developed model for further risk analysis studies.

Kose *et al.* [8], develop a simulation model to mimic Istanbul Strait Maritime Traffic and give information about future maritime traffic based on various scenario analysis. The inputs of the model are vessel arrivals, meteorological conditions and flow direction. Vessels in queue at both sides (Marmara and Black Sea) are scheduled based on traffic rules and the FIFO (First In First Out) rule. In the scenario analysis accomplished, effects of increase/decrease in number of vessels and dangerous vessels are investigated and discussed.

Tan and Otay [9], study a physics-based stochastic model with the purpose of researching into vessel casualties resulting from tanker traffic through a narrow waterway. A state-space model is built to show the waterway and the location of the vessels at a given time. There are three steps are in the model; determination of the distribution of the surface current at a given location, determination of the distribution of the angular drift for a given vessel and combination of the drift probabilities and random arrival of vessels into a Markov Chain model. After the Markov model analysis, risk measurements and expected number of casualties are obtained.

Beasley *et al.* [10], study the scheduling of aircraft landings at airports. The study focuses on a static case, meaning that the set of all planes which are going to land are known. In the study, a mixed-integer zero-one formulation is developed to minimize waiting times of planes before landing. The landing times are decided while satisfying separation time and first come first served rule for single and multiple runways. An integer programming solution procedure based on tree search principle is deployed to solve the problem optimally. The study also provides a heuristic algorithm to solve the problem.

Soomer and Franx [11], focus on the scheduling aircraft landings for a static, single runway problem using airlines' preferences. The model decides on the landing time of planes based on their priorities, while minimizing the costs caused by delays. A local search heuristic algorithm is developed to solve the problem.

Chen, Lei and Zhong [12], focus on vessel scheduling problem with bi-directional flows on US ports. An integer mathematical model is developed to solve two special linear cases. The first case is aircraft landing for a static, single runway problem using airlines' preferences. The model decides on the landing time of planes based on their priorities, while minimizing the costs caused from delays. A local search heuristic algorithm is developed to solve the problem.

3. THE ISTANBUL STRAIT MARITIME ENVIRONMENT

In this chapter, the current and actual Istanbul Strait Maritime Environment is described by providing information regarding how the VTCA classifies the vessels, the R&R, the arrival processes of vessels for Istanbul Strait transit, meteorological and geographical factors, pilot services and how the VTCA schedules vessel entrances.

3.1. Vessel Classification

The VTS classifies all transit vessels of the Strait considering two main criteria:

The first one is the length of vessels;

- Less than 75 meters;
- Between 75 meters and 100 meters;
- Between 100 meters and 150 meters;
- Between 150 meters and 200 meters;
- Between 200 meters and 250 meters;
- Between 250 meters and 300 meters;
- Longer than 300 meters.

The second one is the cargo and flag characteristic of vessels;

- Tankers and Hazardous material carrying vessels (LPG-LNG carrying vessels, chemical tankers etc.);
- Other types of cargo vessels (dry cargo vessels, bulk carrier vessels, general cargo vessels etc.);
- Passenger vessels;
- Small Turkish – flagged vessels.

Table 3.1. Vessel Classifications.

Length (m.)	Tankers&Hazardous Material Carrying Vessels		Other Cargo Vessels		Passenger Vessels
	Turkish Flagged Vessels	Other Flagged Vessels	Turkish Flagged Vessels	Other Flagged Vessels	Turkish & Other Flagged Vessels
75>	F		F		P
75 - 100	D				
100 - 150	C				
150 - 200	B		C		
200 - 250	A				
250 - 300			E		
> 300	T6				

Based on the VTCA classification rules, all transit vessels are divided into 8 classes: A, B, C, D, E, F, T6 and P. The vessels in the same class must satisfy the same rules determined by the VTCA, while entering and navigating in the Istanbul Strait. Each class has an “importance weight” based on its own characteristics. In some cases, these importance weights serve as “entrance priorities”, enabling the related vessels faster access to the Strait (for example passenger vessels have priority over other vessels and are routed to the Strait immediately even when there are long queues of other vessel types). Importance weights also serve as “cost multipliers” of accumulated weighting times of different vessel classes.

Passenger (Class P) vessels have the highest priority, among all vessels since they are carrying passengers. Additionally, they are the only class allowed to sail in both directions during the whole day. Although Class T6 vessels pass 4 or 5 times in a year, they are the most critical type because of the risks they generate. They may enter the Istanbul Strait only during day time. Moreover, they are expected not to encounter any vessels moving in the opposite direction while navigating in the Strait. The frequency of Class A vessels is considerably higher than that of Class T6 vessels; however, the entering and navigating rules of class A vessels are similar to that of Class T6. Class A vessels may navigate in the Istanbul Strait only during day time; additionally, they are expected not to encounter any vessels moving in the opposite direction while they are in between the Kanlıca and Vaniköy points. Class E vessels have lesser weight and less strict navigating and entering rules than Class A vessels. Nevertheless, they are only allowed for day time

transit due to their lengths and cargo types. Class B vessels are also critical, but since they are shorter in length, they are allowed to sail only during night time. Class C, Class D and Class F vessels have lesser weights, decreasing in that order, while they may sail in day time or night time. Minimum pursuit distance between vessels, which plays crucial role in vessel scheduling in the Strait, is different for each vessel couple.

In addition, class T6, A, B, E and P vessels are required (by regulations) to deploy support services (pilot captains), while such services are optional for class C, D and F vessels. In the same class, a vessel deploying a support service has higher importance weight compared to a vessel without a support services.

The importance weights of vessel classes are vital in the optimization objective, but not critical for strict scheduling purposes. Minimum pursuit distance, support service availability and other constraints should also be satisfied to have an optimal and fair transit vessel schedule.

3.2. VTCA Rules and Regulations

Vessel scheduling the Istanbul Strait Maritime Traffic is more complex than just the application of the “First Come First Enter” rule. First of all, all waiting vessels are classified based on the criteria in Section 3.1. Secondly, “First Come First Enter” rule is applied separately for vessels in different classes. Lastly, all types of vessels are scheduled by considering their individual minimum pursuit distance requirements, the importance weights of vessels, availability of support services and other rules. If one of the mentioned requirements is not fulfilled for a specific vessel, it is passed over in the scheduling process and it continues waiting in queue until all requirements are satisfied.

3.2.1. Flow Direction of Vessels

There is uni-directional transit vessel traffic in the Istanbul Strait during the full 24 hours. However, this rule is relaxed for Class P vessels and they may enter the Strait from the opposite of the active traffic flow direction, with the condition that they should not

come across with a Class A vessel between the Kanlıca and Vaniköy points. To avoid such a meeting in this critical region, a class P vessel should enter the Strait 30 minutes later than the entrance of last class A vessel from the opposite (active) direction.

3.2.2. Minimum Pursuit Distance of Vessels

One of the most significant transit rules effecting total weighted waiting times of vessels is the minimum pursuit distance requirements. On the other hand, these requirements can be altered (softly interpreted) by the VTCA, in accordance with the prevailing meteorological conditions and the Istanbul Strait traffic density, although this rule is stated explicitly in the written the R&R.

Between two consecutive vessels longer than 300 meters (Class T6), there should be at least 120 minutes and 105 minutes time separation in northbound and southbound traffic flows, respectively. Class T6 involves all vessels longer than 300 meters (without cargo type considerations). These vessels are not permitted to enter the Strait during night time. They are only included in daytime traffic plan.

No matter which type of flags they have, there should be at least 75 minutes time separation in both northbound and southbound directions, between two consecutive class A vessels as shown in Table 3.2. Class A vessels, which are hazardous cargo carriers in the 200 – 300 m. length interval, are allowed to pass through the Strait of Istanbul only during day time. Navigating and entering characteristic of Class A and T6 vessels are similar, except the minimum pursuit distance requirement between two consecutive vessels in these classes.

Class A and Class T6 vessels shape the day time traffic plan because of their high importance weights. No matter which type of flags they have, there should be at least 75 minutes time separation in both northbound and southbound directions, between two consecutive class B vessels as shown in Table 3.2. Class B vessels are tankers or hazardous material carriers in the 150 – 200 m. length interval and they are allowed to pass through the Strait of Istanbul only during night time. They have the highest

importance weights among vessels making night time transit. Therefore, they form the basis of night time traffic planning.

No matter which type of flags they have, there should be at least 20 minutes time separation for both northbound and southbound directions, between two consecutive class C vessels as shown in Table 3.2. Class C vessels, which are tankers or hazardous material carrier vessels in the 100-150 m. length interval and cargo vessels in the length interval 150 – 250 m., may enter the Istanbul Strait in day time or night time.

There should be at least 10 minutes time separation for both northbound and southbound directions, between two consecutive class D vessels as shown in Table 3.2. The class D vessels can be divided into two groups. The first group includes tankers or hazardous material carrier vessels in the 0 – 100 m. and cargo vessels in the length interval 75 – 150 m. The second group includes cargo vessels shorter than 75 meters without Turkish flag. The class D vessels may enter the Istanbul Strait in day time or night time. The arrival frequency of the Class D vessels is considerably higher than others.

No matter which type of flags they have, there should be at least 20 minutes time separation for both northbound and southbound directions, between two consecutive class E vessels as shown in Table 3.2. Class E vessels, which are other cargo vessels 250 - 300 m. length intervals, enter the Istanbul Strait only in day time.

Class F vessels may enter the Strait once an hour, which means that there should be at least 60 minutes time separation for both northbound and southbound directions. Moreover, there should be at least 5 minutes time separation between other vessels. Class F vessels are tankers, hazardous material carriers or cargo vessels in the 0 – 75 m. length interval and carry Turkish flags.

No matter which type of flag they have, there should be at least 10 minutes time separation for both northbound and southbound directions, between two consecutive class P vessels as shown in Table 3.2. They have the highest importance weights among other

vessels and may pass through the Strait both in the active direction and the passive direction.

Between two consecutive class A and class D vessels, there should be at least 10 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class A and class C/E vessels, there should be at least 20 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class B and class C vessels, there should be at least 20 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class B and class D vessels, there should be at least 10 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class C and class D vessels, there should be at least 10 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class C and class E vessels, there should be at least 20 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class D and class E vessels, there should be at least 20 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Between two consecutive class F vessels and the other class vessels, there should be at least 5 minutes time separation for both northbound and southbound directions as shown in Table 3.2.

Table 3.2. Minimum pursuit distance in time between classes (minutes).

Class	A	B	C	D	E	F	P
A	75	75	20	10	20	5	10
B	75	75	20	10	20	5	10
C	20	20	20	10	20	5	10
D	10	10	10	10	10	5	10
E	20	20	20	10	20	5	10
F	5	5	5	5	5	60	5
P	10	10	10	10	10	10	10

3.3. The Arrival Process of Vessels

Transit maritime traffic in the Istanbul Strait is so heavy that approximately 55,000 vessels annually demand to pass through the Strait. Vessels arrive randomly and it is quite safe to assume that the arrival distribution of vessels is exponential [3]. Although, real data is used in this study, the solution approach of this study can be applied in other studies featuring randomly generated vessel arrivals.

Managing and scheduling safe and balanced daily sailing plan for all require checking the availability of vessels for navigating the Istanbul Strait, by satisfying the R&R, natural and manmade conditions, time window availability, availability of support services and minimum pursuit distance requirements. Therefore, vessels have to report their physical and technical properties before their arrival. Hazardous cargo carrier vessels and vessels whose weight are higher than 500 gross tone (GT) have to officially submit their Sailing Plans (SP1) to the VTCA at least 24 hours before arriving at the Strait. Moreover, vessels in the 200 – 300 meters length interval have to submit SP1 at least 48 hours before arriving at the Istanbul Strait. Dangerous cargo carriers and 500 GT or more weight vessels sailing from Marmara harbors have to send SP1 to the VTCA at least 6 hours before. In addition to the SP1, vessels have to submit Sailing Plan 2 (SP2) at least two hours or 20 nautical miles (whichever first) before arriving at the Istanbul Strait [1].

SP1 and SP2 significantly affect daily vessel sailing plans because they provide the technical and physical properties of the involved vessels as shown in Table 3.3. and Table 3.4. The vessels, which do not submit their SP1s/SP2s on time, cannot be accepted into the queues until providing necessary information.

Table 3.3. SP1 Report.

A	Gemi Adı	
A	Çağrı İşareti	
A	Bayrağı	
A	IMO No	
A	MMSI No	
B	Tarih ve Zaman (UTC)	
C	Mevkisi (Enlem - Boylam)	
F	Manevra Sürati (Knots) (Ondalık kısım da yazılacak.)	
G	Kalkış Limanı	
H	Boğaz Girişine Varış Tarihi ve Saati L/T (Türkiye)	
I	Varış Limanı	
J	Kılavuz Kaptan Talebi (Evet/Hayır)	
J	Istanbul Boğazı	
J	Marmara Denizi	
J	Çanakkale Boğazı	
O	Başta Su Çekimi (Boğaz Girişinde)	
O	Kıçta Su Çekimi (Boğaz Girişince)	
O	Azami Hava Çekimi (Boğaz Girişinde)	
P	Yük (Yükün Cinsi ve Miktarı) *	
P	Tehlikeli, Zararlı ve Kirletici Yük ile ilgili Açıklama (IMDG, IGC, IBC, GC, INF)	
P	Silah Sevkiyatı Halinde "Son Kullanıcı Sertifikası" Tarih/No'su ve Kopyası	
Q	Arıza/Hasar/Yetersizlik/Diğer Kısıtlayıcı Nedenler	
T	Geminin Boğaz Acentesi ve/veya Temsilcinin Adı	
T	Vergi No'su	
T	Gemi Kaptanının Adı – Soyadı	
U	Gemi Tipi	
U	Tam Boy (Metre)	
U	Tam En (Metre)	
U	Gros Ton	
U	Net Ton	
U	Tek/Çift Cidarlı (Tankerler)	
U	Geminin İnşa Yılı	
W	Gemideki Personel ve Yolcu Sayısı	
X	P&I Klüp Adı	
X	P&I Poliçe No'su	
X	P&I Geçerlilik Tarihi	
X	Son PSC Tarihi	
X	Gemideki Yağ Yakıtı Miktarı (F/O-D/O-L/O)	
* İhtiyaç duyulması halinde yükle ilgili daha detaylı bilgi istenebilecektir.		

Table 3.4. SP2 Report.

Code	Explanation
A	Gemi Adı/Çağrı İşareti/Bayrağı/IMO No/MMSI No
F	En Yüksek Manevra Sürati
G	Kalkış Limanı

Table 3.4. SP2 Report (continued).

H	Boğaz Girişine Varış Zamanı
I	Varış Limanı
J	Kılavuz Kaptan İsteği (Evet/Hayır) İstanbul Boğazı Marmara Denizi Çanakkale Boğazı
P	Tehlikeli Yük Bilgisi (Varsa)
T	Gemi Acentası/Donatısı
Q	Arıza/Hasar/Yetersizlik/Diğer Kısıtlayıcı Nedenler
X	Boğaz Geçişi İçin Hazır Olup Olmadığı

After the evaluation of all outstanding SP1 and SP2 notifications, while vessels queue up and wait at either entrance of the Strait, the VTCA determines their entrance schedule (i.e. entrance time to the Strait) in accordance with the rules and criteria mentioned in Section 3.2.

3.4. Day Time Vessel Scheduling

In scheduling day time maritime traffic, the numbers southbound and northbound vessels in queue, length and the starting time of day time are considered. Start time and length of a day changes according to months, as displayed in Table 3.5.

Table 3.5. Starting time and maximum day duration of months.

Months	Start Time	Max. Duration (Min.)
January	07:21	583
February	06:54	647
March	06:09	726
April	05:20	808
May	04:41	878
June	04:28	912
July	04:41	895
August	05:11	832
September	05:40	755
October	06:12	673
November	06:50	602
December	07:17	565

Before scheduling any vessel, first initial flow direction of day time traffic and durations of southbound/northbound traffic flow time windows are determined. The starting direction of day time maritime traffic and last direction of the previous night's

time window ought to be the same. For this reason, the VTCA first makes a decision on the duration of both flow directions rather than the initial daytime direction.

Numbers of waiting Class A vessels in both directions are used to determine the sizes of the northbound and southbound traffic flow time windows. This is because of its type and minimum pursuit distance between two consecutive Class A vessels. The total available daytime is allocated to the two time windows in accordance with waiting Class A vessel numbers.

Accordingly, the window length of the first direction of day time traffic is;

$$W_d = \frac{NQ(A)_{t_s}^d}{NQ(A)_{t_s}^d + NQ(A)_{t_s}^{d'}} * Z \quad (3.1)$$

The window length of the opposite direction of day time traffic is;

$$W_{d'} = \frac{NQ(A)_{t_s}^{d'}}{NQ(A)_{t_s}^d + NQ(A)_{t_s}^{d'}} * Z \quad (3.2)$$

where, $NQ(A)_{t_s}^{(d)}$ is the number of Class A vessels in queue in the first direction at $t=t_s$. $NQ(A)_{t_s}^{(d')}$ is the number of Class A vessels in queue in the opposite direction at $t=t_s$. W_d is window length of the first direction. $W_{d'}$ is window length of the opposite direction. Z is maximum day time duration.

After determining the first direction and the time window length of day time, daily vessel sailing plan of the first direction can be scheduled. In addition, the VTCA schedules the maritime traffic plan based on the numbers of vessels in queue in the active direction, the ready time (arrival time) of vessels in queue, the minimum pursuit distance between vessels as well as the vessels' importance weights. Before changing the flow direction, a two hour interlude is necessary in order to "empty out" the Strait of all vessels sailing in the prevailing direction. The daily vessel sailing plan of the opposite direction is scheduled with the same logic of the first direction.

Class A, E and T6 vessels can navigate only during day time. The vessels in Class C, D, F and P may navigate in daytime or night time.

3.5. Night Time Vessel Scheduling

Night time vessel scheduling is similar to the day time vessel scheduling in many aspects, such as determination of the first direction, the time window length and the logic of the scheduling process. The closing direction of day time maritime traffic ought to be first direction of the night time maritime traffic. However, unlike day time maritime traffic, the numbers of Class B vessels in queue are taken into consideration while determining southbound and northbound night time window lengths. This is because of its type and minimum pursuit distance between two consecutive Class B vessels. Therefore, the most critical vessels of night time maritime traffic are Class B vessels.

The window length of the first direction of night time traffic is;

$$W'_d = \frac{NQ(B)_{t_s}^{d'}}{NQ(B)_{t_s}^d + NQ(B)_{t_s}^{d'}} * Z' \quad (3.3)$$

The window length of the opposite direction of night time traffic is;

$$W'_{d'} = \frac{NQ(B)_{t_s}^d}{NQ(B)_{t_s}^d + NQ(B)_{t_s}^{d'}} * Z' \quad (3.4)$$

where, $NQ(B)_{t_s}^{(d)}$ is the number of Class B vessels in queue in the first direction at $t=t_s$, $NQ(B)_{t_s}^{(d')}$ is the number of Class B vessels in queue in the opposite direction at $t=t_s$. W_d is window length of the first direction. $W_{d'}$ is window length of the opposite direction. Z is maximum day time duration.

Although the daily vessel sailing plan logic of day time and night time is substantially the same, the main difference is that class B vessels are permitted to navigate only in night time.

3.6. Pilotage Services

Pilotage services which are provided by the VTCA are momentous for safe and balanced maritime traffic in the Istanbul Strait. Due to the hard natural and the manmade conditions in the Istanbul Strait, using a pilot is mandatory especially for the vessels in 250 meters length and dangerous cargo carrier vessels longer than 150 meters, while navigating in the Strait. For other vessels, it is optional to use a pilot and they can express their support services demand in their SP1 and SP2 plans. Hamsi Limanı and Fil Burnu Lights at the Black Sea entrance, as well as Fenerbahçe Light Tower at the Marmara Sea entrance are pilot embarking and disembarking point [3].

Available number of support services has significant effect on the daily vessel sailing plan. Some vessels can spend more time in queue due to lack of necessary support services. Therefore, the availability of support services should be checked regularly and systematically for safe and balanced sailing plans. Actually, there are 21 available pilots in total. They are respectively assigned the vessels which request their services on first come first served (FCFS) basis. A pilot accompanies a vessel until the vessel leaves the Strait and then the pilot returns to accompany other vessels in queue of active direction. The available time of the pilot is determined based on this assumption; the departing pilots are gathered at the passive entrance to be sent back to the active entrance in groups of ten (if there is still need and time for their service).

3.7. Traffic Lanes & Overtaking

The R&R gives permission for vessel overtaking one another in the Istanbul Strait, except in the section between Kanlıca and Vanikoy (which is the narrowest part of the Strait). However, the VTCA should be consulted before overtaking, while such permissions are routinely granted unless there are some extraordinary vessel characteristics and environmental conditions (such as local traffic density and/or meteorological conditions).

Especially important is that there should not be another vessel in overtaking lane, while a vessel overtakes slower moving vessel. During an overtaking action the faster moving vessel passes through the overtaking lane, and then it continues navigation in the original lane [3].

3.8. The Speed of Vessels

Average speed of vessels in the Istanbul Strait is approximately 10 knots. Vessel speed may change according to vessel features. For example, some vessels are specially designed for fast navigation and their maneuverability is greatly reduced under certain speeds. These vessels are named as high speed vessels and should sail through the Strait at 15 knots optimally. For speed determination; visibility, traffic density, vessel maneuverability, vessel features, meteorological and current conditions are considered by the VTCA. Then, vessels should proceed with their designated speeds during their pass through the Strait.

3.9. Visibility and Wind Conditions

High visibility is important for safe navigation. However, sometimes fog, mist, snow and rain storm may cause decrease in visibility. In reduced visibility, each vessel should prepare themselves according to conditions and its characteristic. Then, it passes through the Istanbul Strait with safe and constant speed. Fog is intensively observed in March and April; while, it is rarely observed in summer. The best visibility conditions are in the evenings of November, December and January.

According to the Strait statistics, many of the past accidents happened under low visibility conditions due to fog, snow and rain. Actually, vessel traffic is stopped when visibility falls below 0.5 mile [1].

Wind conditions also have serious effects on the Istanbul Strait maritime traffic. Especially the points below threaten safety of the traffic.

- Increase in wind force may directly affect vessels and make difficult to navigate in the Strait.
- Strong breezes may change the direction and speed of current. Such conditions are generally observed in January.

For safe vessel transition, visibility and wind conditions are regularly checked and necessary warnings are given by the VTCA.

3.10. Geographical Conditions

Geographical characteristics of the Istanbul Strait contribute significantly to the navigational complexity of the Strait maritime traffic. The Istanbul Strait is 31 kilometers long and has an average depth of 45 meters, while the depth increases from south to north. In the Strait, some parts have high depths as well as other parts have many reefs and shelves. However, depth conditions are not continuous. There are many reefs and shelves. Moreover, it has many narrow and winding regions. A vessel faces 12 sharp turns while passing through the Strait. Four of the turns require more than 45 degrees. Actually, the course change at Yenikoy is 80 degrees.

3.11. Current Conditions

Currents also contribute to the navigational difficulty in the Istanbul Strait. Prevailing currents in the Istanbul Strait can be named as surface currents, underwater currents and reverse currents.

3.11.1. The Surface Current

The water level of the Black Sea is 40 cm. higher than the water level of the Marmara Sea. This water level difference causes the occurrence of a strong southbound surface current. The surface current is more intense in the middle of the Strait. It becomes even more intense from the Kandilli Bay to the southern entrance.

3.11.2. The Underwater Current

The underwater current flows in reverse direction of the surface current. It is caused by the salinity difference between the Black Sea and the Marmara Sea. It is active in 15 – 45 meters depth.

3.11.3. The Reverse Current

Different geographical characteristics of bays and forelands are the instigators of the reverse current. In the bays and forelands, the direction of the surface current is distorted (and even reversed) because of the tendency of water flows to follow the shorelines. The direction and intensity of the reverse current depends on the force of the surface current and is also affected by wind force and meteorological changes. For example, the intensity of the reverse current between Galata and Defterdar Bay increases in the afternoon; while decreasing in the evening [1].

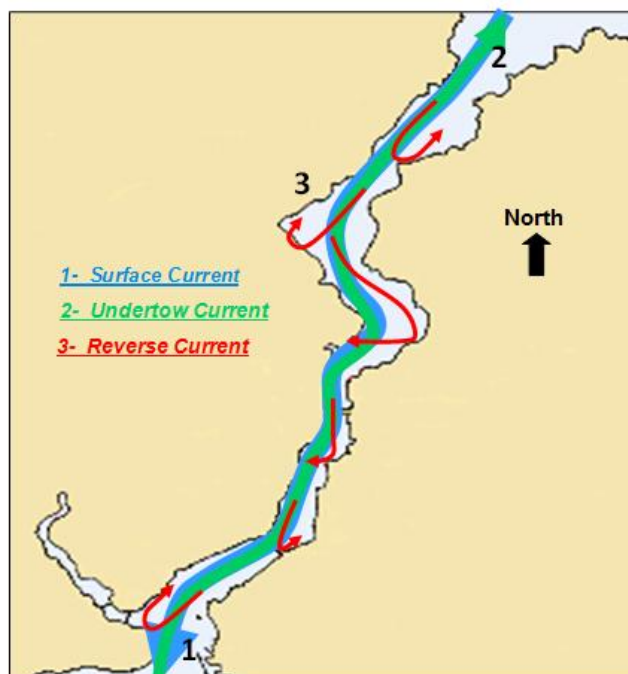


Figure 3.1. Currents in the Istanbul Strait.

3.11.4. The Orkoz Current

Strong winds, especially strong southwest winds, increase the water level of the Istanbul Strait at the south entrance. After the increase in water level, the active surface current changes and the northbound orkoz current occurs (with speeds up 6 – 7 knots). Such strong reverse currents may lead to the suspension of the maritime traffic.

3.12. Current Conditions

In addition to all geographical and meteorological factors, suspension bridges and energy transfer lines have effect on the Istanbul Strait maritime traffic. In the Istanbul Strait, there are two suspension bridges; “Bogazici Bridge” and “Fatih Sultan Mehmet Bridge” as well as two energy transfer lines which are in between Bebek – Kandilli and Rumelikavağı – Anadolukavağı regions. Due to these energy transfer lines, ship borne radars perceive as if there is another vessel although there is no vessel. Therefore, especially uninitiated captains should be cautious and in touch with the VTCA for safe navigation.

4. PROBLEM DEFINITION & THE MATHEMATICAL MODEL

As explained and discussed in the previous chapters, the maritime traffic in the Istanbul Strait is very heavy (and increasing), while environmental and meteorological conditions make navigation quite difficult. Therefore, close control of the maritime activity in the Strait and especially admission (scheduling) of incoming vessels is a very important issue. While considering safety of the Istanbul Strait Maritime Traffic, the VTCA should take regularity and fairness of it into consideration. Regularity and fairness mean that the same rules should always be applied to vessels under the same conditions. Moreover, vessels should be admitted to the Istanbul Strait without waiting too much time. Therefore, this study aims to minimize average weighted waiting time per vessel as well as total weighted waiting time of vessels before entering the Strait, while making sure that general R&R and VTCA policies, such as flow direction time windows, pilot services and requirements, minimum pursuit distance requirements are satisfied. In other words, in this study a model is developed to maximize the number of vessels entering the Istanbul Strait, while satisfying various constraints during daytime and nighttime traffic for southbound and northbound directions.

The developed model features a mixed-integer zero-one formulation to realize the objective of the study and satisfy conditions, the R&R and model assumptions. General Algebraic Modeling System (GAMS) software is used for solving the mathematical formulation. The model gets data from input files and produce outputs while taking constraints into account.

4.1. Model Assumptions

Some assumptions are made to simplify the modeling of the real Istanbul Strait Maritime Traffic.

The first assumption is related with vessel classification. Using support services (pilot captains) is mandatory for Class T6, A, B, E and P vessels while navigating in Istanbul Strait. On the contrary, using support services is optional for Class C, D and F

vessels. Due to having different importance weights and different R&R requirements, vessels which demand support services and vessels which do not demand support services are separately classified for class C and D vessels. Vessels requesting support services are classified as C1 and D1; others are classified as C2 and D2.

Class T6 vessels are quite rare in the Istanbul Strait (Only five or six T6 vessels pass through the Istanbul Strait in a year). Therefore, T6 vessels are ignored in the developed model.

In the developed model, daily vessel arrivals are obtained from 2011 data of the VTCA. In other words, the arrival behavior exemplified in the model is the one actually experienced in real life. It should be noted; however, that the input module of the model could be easily adjusted to accommodate other arrival patterns. Moreover, the logic of the R&R and support services that are represented in the mathematical model are compatible with the logic of the real situation.

The treatment of vessel speeds and overtaking actions are accomplished external to the basic optimization model in order to reduce its size and complexity. Once the set of incoming vessels associated with each time slice is identified; vessels in same classes, Class C (C1 and C2), Class D (D1 and D2), Class E and Class F vessels, are sorted according to their speeds in descending order. In other words, a vessel having higher speed than others in its class is set to enter the Istanbul Strait before the remaining vessels in its subclass having lower speed. Entering list is sorted based on vessel speed. This way, since faster vessel would be scheduled to enter the Strait earlier the need for overpassing would be reduced. Class A and B vessels are not sorted according to their speed. This is because the minimum pursuit distance between these vessels is high, which prevents the overtaking activities among them. After sorting the different vessel types into different queues according to their speeds, these “sorted” queues are inputted the developed optimization model for the final schedule.

Although overtaking is not directly embedded into the mathematical model, it is recognized that vessels have permission to overtake while navigating. In other words, the

fact that “faster” vessels are most likely to “overtake” their “slower” preceding vessels is modeled in the following fashion. Since vessel queues are ordered with respect to speed, more often than not, a preceding vessel is faster than its follower. To cover the cases where this is not true, the faster vessel’s speed is temporarily reduced to its predecessor’s speed, where it is actually following the slower vessel (a situation assumed to occur in 16% of the overall transit) and then set to its actual speed, where it has overtaken the slower vessel (a situation assumed to occur in 84% of the overall transit).

In addition to the pilotage services R&Rs, if pilots are available after start time of 120 time interval and before the end time of it, they are considered available at the beginning of the next time interval.

The effect of meteorological, geographical, visibility and current conditions are considered to be insignificant for the actual scheduling of vessel entrances. Hence, they are ignored in the developed mathematical model.

4.2. The Mathematical Model

In this part, the developed mixed integer zero – one optimization model of the vessel (entrance) scheduling problem of the Istanbul Strait is presented under the assumptions mentioned in Section 4.1.

The mathematical model includes different subclasses, such as parameters, indices, continuous variables and integer variables. Parameter settings can be changed from case to case. The most significant parameter is the duration of the scheduling horizon of a “single” schedule optimization period. In this study, the time length is accepted 2 hours for each run. The reasons why the 2 hours time interval is accepted as planning horizons are;

- Vessels submit their SP2 reports 2 hours earlier before arriving to the Strait; accordingly, a “two hour planning” period would presumably include all vessels requesting transit.
- To create a dynamic model by taking newly arrived vessels into consideration; accordingly, new arrivals would be taken into consideration in the “next” two

hour period. Otherwise, vessels spend more time in queue if they are only taken into consideration at the beginning time of each time window.

- To decrease the computation time in solving the resulting integer optimization problem. This approach drastically reduces the number of variables and constraints in each individual model.

4.2.1. Notations

Notation is explained in four subsets; parameters, indices, continuous variables and integer variables.

4.2.1.1. Indices.

$M(i)$: Number of ready Class M vessels waiting to enter the Istanbul Strait
($i=1, \dots, I_M$) ($M=A, B, C1, C2, D1, D2, E, F, P$)

4.2.1.2. Parameters.

$t_{M(i)}$: Ready time of vessel “ i ” in Class M to enter the Strait ($i = 1, \dots, I_M$; $M=A, B, C1, C2, D1, D2, E, F, P$)

S_{ij} : Minimum pursuit distance between vessel “ i ” in Class M and vessel “ j ” in Class N ($i = 1, \dots, I_M$; $j = 1, \dots, J_M$; $M=A, B, C1, C2, D1, D2, E, F, P$; $N=A, B, C1, C2, D1, D2, E, F, P$)

V is the start of the scheduling planning horizon. W is the end of the scheduling planning horizon. R is available number of pilot captains. b is very large number. T_M is earliest potential entry time of a vessel i in Class M ($M = A, B, C1, C2, D1, D2, E, F, P$) if it can't be scheduled to enter between V and M. α_M is the importance weight of class M ($M = A, B, C1, C2, D1, D2, E, F, P$).

Table 4.1. The importance weights of vessel classes.

	Northbound	Southbound
αA	0.28	0.26
αB	0.28	0.26
$\alpha C1$	0.18	0.18
$\alpha C2$	0.13	0.13
$\alpha D1$	0.09	0.09
$\alpha D2$	0.04	0.04
αE	0.21	0.21
αF	0.08	0.08
αP	0.50	0.50

The importance weights of A, B and T6 classes are taken as 0,26 for southbound vessels and 0,28 for northbound vessels as shown in Table 4.1. The importance weight of northbound vessels is higher because keeping large number of such vessels waiting in the Marmara Sea for long periods is not desired due to the dangerous/hazardous cargo characteristic of such vessels.

Higher importance weight means more consideration in the objective function and (sometimes) higher priority. Class P because of its human cargo is superior to other classes as shown in Tableau 4.1 above. The importance weights of other classes are decreasing in the order below;

Class A = Class B > Class E > Class C1 > Class C2 > Class D1 > Class F > Class D2

4.2.1.3. Decision Variables.

$x_{M(i)}$: Entrance time of i^{th} vessel of class M to the Istanbul Strait ($i = 1, \dots, I_M$; $M=A, B, C1, C2, D1, D2, E, F, P$)

Z: Total weighted waiting times of vessels before entering the Strait

$y_{M(i)}$: Binary variable with a value of 1, if i^{th} vessel of class M enters the Strait during the scheduling planning horizon, and with a value of 0 otherwise ($i = 1, \dots, I_M$; $M=A, B, C1, C2, D1, D2, E, F, P$)

$\theta_{M(i), N(j)}$: Binary variable with a value of 1, if i^{th} vessel of class M enters the Strait before j^{th} vessel of Class N, and with a value of 0 otherwise ($i = 1, \dots, I_M$; $j = 1, \dots, J_N$; $M=A, B, C1, C2, D1, D2, E, F, P$; $N=A, B, C1, C2,$

D1, D2, E, F, P ; M ≠ N)

4.2.2. The Mathematical Model

The following mixed integer programming model is employed to determine a minimum total weighted waiting time of vessels passing through the Istanbul Strait in a defined time interval (the scheduling planning horizon).

$$\text{Min } Z = \sum_M (\alpha_M * \sum_{i=1}^{I_M} (x_{M(i)} - t_{M(i)})) \quad \forall M, \forall i \quad (4.1)$$

s.t.

$$t_{M(i)} \leq x_{M(i)} \quad \forall M, \forall i \quad (4.2)$$

$$\theta_{MN(i,j)} + \theta_{NM(j,i)} = 1 \quad \forall i, \forall j, \forall M, \forall N, M \neq N \quad (4.3)$$

$$x_{M(i)} + S_{MN(i,j)} - b * \theta_{NM(j,i)} \leq x_{N(j)} \quad \forall i, \forall j, \forall M, \forall N, M \neq N \quad (4.4)$$

$$x_{N(j)} + S_{MN(i,j)} - b * \theta_{MN(i,j)} \leq x_{M(i)} \quad \forall i, \forall j, \forall M, \forall N, M \neq N \quad (4.5)$$

$$\sum_{i=1}^{i-1} x_{M(i)} + \sum_{i=1}^{i-1} S_{MM(i)} \leq \sum_{i=1}^{i-1} x_{M(i+1)} \quad \forall i, \forall M, (i-1) \geq 1 \quad (4.6)$$

$$x_{M(i)} \leq W + (1 - y_{M(i)}) * b \quad \forall i, \forall M \quad (4.7)$$

$$x_{M(i)} \geq V \quad \forall i, \forall M \quad (4.8)$$

$$x_{M(i)} \geq (1 - y_{M(i)}) * (W + T_M) \quad \forall i, \forall M \quad (4.9)$$

$$\sum_i y_{M(i)} \leq R \quad \forall i, \forall M, (M = A, B, C1, D1, E, P) \quad (4.10)$$

The aim of the model is to minimize the total weighted waiting time of vessels in queue before they enter the Istanbul Strait. Each such model considers a time horizon of two hours (i.e. minimizes the waiting time/maximizes transits in that time horizon). A sequence of 2 hours models is formulated in tandem to cover longer time horizons (such as 48 hours). In this mathematical model, the objective function (4.1) includes entering time of vessels, ready time of vessels to enter the Istanbul Strait and the importance weight of the each class. A feasible scheduling plan is subject to constraint sets (4.2) to (4.10). The constraint set (4.2) ensures that the entering time of a vessel should be larger than the

ready time of that vessel to enter the Istanbul Strait. The sets of constraints (4.3) to (4.5) compare the relationship between two vessels in different classes regarding precedence and guarantee to satisfy minimum pursuit distance rule between two vessels in different classes. In constraint set (4.3), there are two options: either the i^{th} vessel of class M entering the Istanbul Strait before j^{th} vessel of class N or vice versa. The vessel entering the Strait before gets 1 in the related θ variable. In the case of i^{th} vessel of class M entering the Strait before j^{th} vessel of class N, constraint set (4.4) ensures that j^{th} vessel should enter the Strait after satisfying the required minimum pursuit distance or later (Constraint set (4.5) becomes redundant/nonbinding in this case). In the case of j^{th} vessel of class N entering the Strait before i^{th} vessel of class M, constraint set (4.5) ensures that i^{th} vessel should enter the Strait after satisfying the required minimum pursuit distance or later (Constraint set (4.4) becomes redundant/nonbinding in this case.) The constraint set (4.6) ensures the required minimum pursuit distance between two vessels in the same the class. The set of constraints (4.7) to (4.8) assure that if a vessel is designated to enter the Strait in the time interval under consideration (i.e. [V to W]) than its entrance time should be less than W and greater than V. The constraint set (4.9) ensures that if i^{th} vessel of the class M do not enter the Strait during the time interval under consideration (between V to W), it can enter the Strait after time T_M . The constraint (4.10) requires that the total number of used pilot services should be equal to/less than available number of pilot services during time interval under consideration.

The full open form of the mathematical model is displayed in Appendix A.

5. VERIFICATION AND VALIDATION

The mathematical model developed in this study is a representation of the real traffic system in the Istanbul Channel under the assumptions mentioned in Section 4.1. In order to make sure that the representation is sufficiently realistic, the real 2011 VTS data, is inputted into the mathematical model and outputs obtained are compared with the 2011 real situation results, in terms of vessel entrances, transit activities, and pilot services.

5.1. Verification of the Mathematical Model

Model verification is basically the process of making sure that the mathematical relationships and input/output characteristics of the built model correctly represent the real situation in this study. During the verification process,

- The model logic, the constraints and codes of the model are carefully checked.
- For model consistency, various runs are obtained with a series of test data some of which representing “extreme conditions”.
- Some extreme values are assigned to the input parameters to check whether the outputs are plausible or not.
- To avoid bias and minimize oversights, expert opinions are taken into consideration while building the mathematical model.

5.2. Validation of the Mathematical Model

Model validation is concerned with making sure that outputs obtained from the model show similar behavior to that of the real life system performance being expected. However, it is not possible to get exactly the same results with real life performance so that close results are reasonable. In the validation process,

- The actual 2011 data are provided as inputs of the mathematical model.
- The outputs of the mathematical model (regard in Table 5.1.) are compared with the actual realization (in terms of a confidence interval) and the outputs of the real life are compared whether they are compatible or not.

Table 5.1. The comparison between the mathematical model solution and the real schedule.

Vessel	The Mathematical Solution	The Real Schedule
B_1	27Sep11 03:50	27Sep11 03:23
D1_1	27Sep11 04:00	27Sep11 04:35
C1_1	27Sep11 04:10	27Sep11 03:48
D1_2	27Sep11 04:20	27Sep11 03:34
C1_2	27Sep11 04:30	27Sep11 03:05
D1_3	27Sep11 04:40	27Sep11 03:55
C1_3	27Sep11 04:50	27Sep11 05:19
D1_4	27Sep11 05:00	27Sep11 03:12
C1_4	27Sep11 05:10	27Sep11 04:16
D1_5	27Sep11 05:20	27Sep11 04:24
C1_5	27Sep11 05:30	27Sep11 04:27
D1_6	27Sep11 05:40	27Sep11 04:01

- The outputs of mathematical model are compared with each other whether they show similar behavior or not.

5.3. The Basic Scenario and Output Analysis

The mathematical model is built based on the assumptions which are already mentioned in the Section 4.1. Also, as mentioned in Section 4.1, the mathematical model does not explicitly include overtaking and speed change issues, left out to reduce model complexity. The outputs of the individual 2 hour models are rearranged according to vessels' speed in order to minimize overtaking needs. In other words, the ordering of the vessels in each class, cleared for admittance in each 2 hour period, is revised with respect to vessel speed (faster vessels moved to earlier positions in the respective "admittance lists").

The inputs of the model are;

- The number of vessels in queue;
- The number of different vessel classes in queue;
- The ready time of vessels in queue;
- The minimum pursuit distances between vessels;

- The importance weights of vessel classes;
- The start and the end time of the scheduling planning horizon;
- The number of available pilot captains;

This model is run for 24 conservative two hours periods (totaling 48 hours) at three different times of the year (April, September, and November) which widely represents yearly trends in terms of number of vessels in queue, vessel classes, meteorological conditions, visibility conditions and current conditions. Moreover, the VTCA's opinions are taken in the selection of these three months. After selecting the months, 48 hours time period of each month is assumed to reflect whole month behavior in terms of average number of vessels. For the mentioned months, 15 – 16th of April, 25 – 26th of September, 19 – 20th of November are selected. The average number of arrivals during all months and the selected two day periods are displayed in the tables below.

Table 5.2. Comparison of the number of arrivals by vessel type in April.

	April (All Month)	April (15-16)	
Vessel Type	Avg. Daily No. of Vessels In Queue	Avg. Daily No. of Vessels In Queue	Variation
A	5.2	5.5	-5.1%
B	7.6	8.0	-5.7%
C1	17.4	15.5	10.7%
C2	5.5	5.5	-0.6%
D1	38.5	45.0	-16.8%
D2	45.6	47.5	-4.2%
E	1.8	2.0	-13.2%
F	11.2	11.5	-3.0%
P	1.9	1.5	19.6%
Northbound	67.8	84.5	-24.6%
Southbound	66.8	57.5	13.9%

Table 5.3. Comparison of the number of arrivals by vessel type in September.

	September (All Month)	September (25-26)	
Vessel Type	Avg. Daily No of Vessels In Queue	Avg. Daily No. of Vessels In Queue	Variation
A	5.3	3.5	34.0%
B	6.6	7.0	-6.1%
C1	20.2	20.0	1.0%
C2	5.6	5.5	1.2%

Table 5.3. Comparison of the number of arrivals by vessel type in September (continued).

	September (All Month)	September (25-26)	
Vessel Type	Avg. Daily No of Vessels In Queue	Avg. Daily No. of Vessels In Queue	Variation
D1	34.9	37.0	-6.0%
D2	50.0	47.0	5.9%
E	2.2	2.5	-11.9%
F	10.2	8.5	16.7%
P	2.4	1.5	38.4%
Northbound	71.0	73.0	-2.8%
Southbound	66.4	59.5	10.4%

Table 5.4. Comparison of the number of arrivals by vessel type in November.

	November (All)	November (19-20)	
Vessel Type	Avg. Daily No. of Vessels In Queue	Avg. Daily No. of Vessels In Queue	Variation
A	5.3	6.0	-12.5%
B	6.1	6.5	-6.6%
C1	22.6	28.5	-26.1%
C2	6.3	7.5	-19.0%
D1	34.4	40.5	-17.6%
D2	51.3	59.0	-15.1%
E	1.9	2.0	-5.3%
F	9.7	11.5	-18.2%
P	1.1	1.0	11.8%
Northbound	69.0	93.0	-34.8%
Southbound	69.8	69.5	0.5%

Each the 48 hour period includes two southbound daytime windows, two northbound daytime windows, two southbound nighttime windows and two northbound nighttime windows. The 24 consecutive 2 hour planning horizon runs accomplished in any such 2-day period are set up in tandem. In other words, the input queues of a succeeding run are composed of the vessels remaining waiting from the previous two hour period and new arrivals during those two hours. Accordingly, for each selected the 48 hour period, 20 individual runs covering 70 – 120 minute intervals and related to one another through the input/output relationship described, are accomplished. In the remaining part of the 48 hour period vessel entrances are interrupted to allow for the emptying of the Strait and direction changes (each such direction change requiring 120 minutes).

Each 48 hours period starts with the northbound daytime window at sunrise. The period between the beginning of the first day (at 00:00) and start time of the northbound daytime window is a warm-up period to have vessels in queue before entering the Istanbul Strait. For example, in Table 5.5, the schedule of 48 hour time period is shown for 25-26-27th of September.

Table 5.5. 48 hour time period schedule for 25-26-27th of September.

Date	Time	Date	Time	Period
25.09.2011	00:00	25.09.2011	05:40	Warm-Up Period
25.09.2011	05:40	25.09.2011	10:50	Northbound Day Time Window_1
25.09.2011	05:40	25.09.2011	07:40	Planning Horizon 1
25.09.2011	07:40	25.09.2011	09:40	Planning Horizon 2
25.09.2011	09:40	25.09.2011	10:50	Planning Horizon 3
25.09.2011	10:50	25.09.2011	12:50	Direction Change
25.09.2011	12:50	25.09.2011	18:15	Southbound Day Time Window_1
25.09.2011	10:50	25.09.2011	12:50	Planning Horizon 1
25.09.2011	12:50	25.09.2011	14:50	Planning Horizon 2
25.09.2011	14:50	25.09.2011	16:50	Planning Horizon 3
25.09.2011	16:50	25.09.2011	18:50	Planning Horizon 4
25.09.2011	18:15	25.09.2011	22:20	Southbound Night Time Window_1
25.09.2011	18:50	25.09.2011	20:50	Planning Horizon 5
25.09.2011	20:50	25.09.2011	22:20	Planning Horizon 6
25.09.2011	22:20	26.09.2011	00:20	Direction Change
26.09.2011	00:20	26.09.2011	05:40	Northbound Night Time Window_1
26.09.2011	00:20	26.09.2011	02:20	Planning Horizon 1
26.09.2011	02:20	26.09.2011	04:20	Planning Horizon 2
26.09.2011	04:20	26.09.2011	05:40	Planning Horizon 3
26.09.2011	05:40	26.09.2011	12:40	Northbound Day Time Window_2
26.09.2011	06:20	26.09.2011	08:20	Planning Horizon 4
26.09.2011	08:20	26.09.2011	10:20	Planning Horizon 5
26.09.2011	10:20	26.09.2011	12:20	Planning Horizon 6
26.09.2011	12:20	26.09.2011	12:40	Planning Horizon 7
26.09.2011	12:40	26.09.2011	14:40	Direction Change
26.09.2011	14:40	26.09.2011	18:15	Southbound Day Time Window_2
26.09.2011	14:40	26.09.2011	16:40	Planning Horizon 1
26.09.2011	16:40	26.09.2011	18:40	Planning Horizon 2
26.09.2011	18:15	27.09.2011	01:50	Southbound Night Time Window_2
26.09.2011	18:40	26.09.2011	20:40	Planning Horizon 3
26.09.2011	20:40	26.09.2011	22:40	Planning Horizon 4
26.09.2011	22:40	27.09.2011	00:40	Planning Horizon 5
27.09.2011	00:40	27.09.2011	01:50	Planning Horizon 6
27.09.2011	01:50	27.09.2011	03:50	Direction Change
27.09.2011	03:50	27.09.2011	05:40	Northbound Night Time Window_2
27.09.2011	03:50	27.09.2011	05:40	Planning Horizon 1

In Table 5.5, the start and finish times of time windows and planning horizons are displayed. For example, the start time of the first northbound daytime window is 05:40 and finish time of it is 10:55. It includes two 120 minute and one 75 minute planning horizons. In the third planning horizon, only vessels scheduled between 09:40 – 10:55 are admitted to the Strait due to the fact that this time window should be terminated at 10:55. Remaining vessels continue waiting in queue until the start time of first northbound nighttime window. Note that direction changes are scheduled between 10:50 – 12:50. Two hour prior to these “direction change times”, the previous flow direction window is terminated and a 2-hour “entrance interruption” is scheduled. When there is no change direction, such as southbound daytime window to southbound nighttime window, there is no need to break 2 hour planning horizon and increase the complexity. For example, the start time of forth planning horizon is 16:50 and the finish time of it is 18:50, while 18:15 is the start time of night time window. A constraint regarding that those Class B vessels can enter the Strait after 18:15 is added to the mathematical model. This logic is applied all other two consecutive time windows in same direction.

In order to understand the model logic and the scheduling process, the daytime window of the first day of 25 – 26th September period is explained step by step.

25.09.2011 00:00 – 05:40 is the warm up period, which means vessels are piled up in queue. The daytime vessel scheduling of 25.09.2011 is planned for the time window between 05:40 (sunrise) – 18:15 (sundown).

The first decision should be made for the length of northbound and southbound daytime windows. The numbers of Class A vessels in queue at the end of the warm-up period help to determine the length of the northbound and the southbound daytime windows.

$NQ(A)_{t_s}^{(d)}$: Number of Class A vessels in queue in the northbound direction during
25.09.2011 00:00 – 05:40

$NQ(A)_{t_s}^{(d)}$: Number of Class A vessels in queue in the southbound direction during

25.09.2011 00:00 – 05:40

W_d : Time window length of the northbound direction

$W_{d'}$: Time window length of the southbound direction

Z : Maximum day time duration

$NQ(A)_{t_s}^{(d)} : 1$

$NQ(A)_{t_s}^{(d')} : 1$

$Z : 775 \text{ min.} - 120 \text{ min. (direction change time)} = 635 \text{ min.}$

$$W_d = \frac{NQ(A)_{t_s}^d}{NQ(A)_{t_s}^d + NQ(A)_{t_s}^{d'}} * Z = (1 / (1+1)) * 635 = 317.5 \text{ min.} \quad (5.1)$$

$$W_{d'} = \frac{NQ(A)_{t_s}^{d'}}{NQ(A)_{t_s}^d + NQ(A)_{t_s}^{d'}} * Z = (1 / (1+1)) * 635 = 317.5 \text{ min.} \quad (5.2)$$

Equation 5.1 shows the time window length of the northbound direction as well as Equation 5.2 shows the time window length of the southbound direction.

5.3.1. Northbound Day Time Traffic

Start Time: 25.09.2011 05:40

End Time: 25.09.2011 10:55 (due to Equation (5.1))

5.3.1.1. Planning Horizon 1.

Start Time: 25.09.2011 05:40

End Time: 25.09.2011 07:40

Input: All newly arrived vessels between 25.09.2011 00:00–05:40 (Except Class B vessels)

21 Pilot Services

Output: The vessel schedule for 120 minutes

9 Pilots are used.

12 Pilots are available for the next period (planning horizon).

14 vessels are scheduled to enter the Strait according to the schedule presented in Table 5.6.

2 D2 vessels are not admitted (in this 2 hour period). They are to be included in the waiting queue of the next planning horizon.

The accounting of all vessels allowed to enter the Strait and those not admitted are displayed in Table 5.7.

Table 5.6. The vessel schedule of planning horizon 1 of the northbound daytime window on 25th of September.

Vessel	Entering Time to the Strait
A_1	05:40
F_1	05:45
D1_1	05:50
C1_1	06:00
D2_1	06:10
C1_2	06:20
D1_2	06:30
C2_1	06:40
D1_3	06:50
C1_3	07:00
D1_4	07:10
C2_2	07:20
D1_5	07:30
D2_2	07:40

Table 5.7. The accounting of vessel activities of planning horizon 1 of the northbound daytime window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
A	1	1	0
C1	3	3	0
C2	2	2	0
D1	5	5	0
D2	4	2	2
F	1	1	0
Total	16	14	2

5.3.1.2. Planning Horizon 2.

Start Time: 25.09.2011 07:40

End Time: 25.09.2011 09:40

Input: All newly arrived vessels between 25.09.2011 05:40-07:40 (Except Class B vessels)

The vessels remaining (still waiting) from the previous planning horizon (3 D2 vessels)

12 pilots are available.

Output: The vessel schedule for 120 minutes

8 pilots are used.

4 pilots are available for the next period.

All vessels in queue (13 vessels) are scheduled to enter the Strait

According to the schedule presented in Table 5.8.

The accounting of all vessels allowed to enter the Strait and those not admitted are displayed in Table 5.9.

Table 5.8. The vessel schedule of planning horizon 2 of the northbound daytime window on 25th of September.

Vessel	Entering Time to the Strait
F_2	07:45
E_1	07:50
D1_6	08:00
C1_4	08:10
D2_3	08:20
D1_7	08:30
D2_4	08:40
D1_8	08:50
D2_5	09:00
D1_9	09:10
D1_10	09:20
D1_11	09:30
F_3	09:35

Table 5.9. The accounting of vessel activities of planning horizon 2 of the northbound daytime window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
C1	1	1	0
D1	6	6	0
D2	3	3	0
E	1	1	0
F	2	2	0
Total	13	13	0

5.3.1.3. Planning Horizon 3.

Start Time: 25.09.2011 09:40

End Time: 25.09.2011 10:55

Input: All newly arrived vessels between 25.09.2011 07:40 – 09:40 (Except Class B vessels)

The vessels remaining (still waiting) from the previous planning horizon (no vessel)

4 available pilots

Output: The vessel schedule for 75 minutes

4 pilots are used.

Vessels in the queue (9 vessels) are scheduled to enter the Strait according to the schedule presented in Table 5.10.

The accounting of all vessels allowed to enter the Strait and those not admitted are displayed in Table 5.11.

Table 5.10. The vessel schedule of planning horizon 3 of the northbound daytime window on 25th of September.

Vessel	The Entering Time to the Strait
C1_5	09:40
D1_12	09:50
C1_6	10:00
D2_6	10:10
D1_13	10:20
D2_7	10:30
D2_8	10:40
D2_9	10:50

Since the northbound daytime window has to be closed at 10:55, the planning horizon 3 is run for 75 minutes. The last vessel of the 09:40 – 10:55 period is admitted to the Strait at 10:50. Although there are still 5 min. remaining and some vessels in queue, they are not admitted to the Strait due to non-satisfaction of the minimum pursuit distance rule. The vessels not admitted continue to wait in the queue until the start time of the northbound nighttime window. Then, they become eligible for the night time north bound window together with other newly arrived vessels.

Table 5.11. The accounting of vessel activities of the planning horizon 3 of northbound daytime window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
C1	2	2	0
D1	2	2	0
D2	5	4	1
Total	9	8	1

The northbound daytime window is closed at 10:50 and during this window 35 vessels are allowed to enter the Istanbul Strait and 1 D2 vessel remains unadmitted (This vessel is going to wait until the start time of the night time northbound window). All 21 pilots are used during this window length.

In addition to the vessel activities indicated by the series of 70 – 120 minutes scheduling models, any northbound (active direction) passenger vessels arrived in the warm up period (in the example case 2 such vessels) and any southbound (passive direction) passenger vessels that arrived during (00:00 – 10:55) period (0 such vessels in the example case) are also admitted to the Strait. However, 2 class P vessels entering the Strait during warm up period (25 September 00:00 – 05:40) are out of scope because their entrance time is not in the focused 48 hours period (25 September 05:40 – 27 September 05:40).

The full schedule of the daytime northbound traffic window (which is displayed in Table 5.12) indicates that instead of the basic FIFO rule, importance weights play significant role in the model. For example, although the first vessel of Class F, F1, arrived

at the Istanbul Strait before than the first vessel of Class A, A1, it entered the Strait after the A1 vessel.

Table 5.12. The vessel schedule of the northbound day time window on 25th of September.

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (min)	Weighted Waiting Time (min)
0.28	A1	25Sep11 04:57	25Sep11 05:40	43	12.0
0.08	F1	25Sep11 00:56	25Sep11 05:45	289	23.1
0.09	D1_1	25Sep11 03:14	25Sep11 05:50	156	14.0
0.18	C1_1	25Sep11 00:02	25Sep11 06:00	358	64.4
0.04	D2_1	25Sep11 01:16	25Sep11 06:10	294	11.8
0.18	C1_2	25Sep11 00:14	25Sep11 06:20	366	65.9
0.09	D1_2	25Sep11 03:54	25Sep11 06:30	156	14.0
0.13	C2_1	25Sep11 01:24	25Sep11 06:40	316	41.1
0.09	D1_3	25Sep11 04:12	25Sep11 06:50	158	14.2
0.18	C1_3	25Sep11 04:02	25Sep11 07:00	178	32.0
0.09	D1_4	25Sep11 05:33	25Sep11 07:10	97	8.7
0.13	C2_2	25Sep11 02:19	25Sep11 07:20	301	39.1
0.09	D1_5	25Sep11 05:37	25Sep11 07:30	113	10.2
0.04	D2_2	25Sep11 02:27	25Sep11 07:40	313	12.5
0.08	F2	25Sep11 05:54	25Sep11 07:45	111	8.9
0.21	E1	25Sep11 06:50	25Sep11 07:50	60	12.6
0.09	D1_6	25Sep11 06:17	25Sep11 08:00	103	9.3
0.18	C1_4	25Sep11 07:03	25Sep11 08:10	67	12.1
0.04	D2_3	25Sep11 03:19	25Sep11 08:20	301	12.0
0.09	D1_7	25Sep11 06:47	25Sep11 08:30	103	9.3
0.04	D2_4	25Sep11 04:43	25Sep11 08:40	237	9.5
0.09	D1_8	25Sep11 07:30	25Sep11 08:50	80	7.2
0.04	D2_5	25Sep11 06:37	25Sep11 09:00	143	5.7
0.09	D1_9	25Sep11 07:31	25Sep11 09:10	99	8.9
0.09	D1_10	25Sep11 07:35	25Sep11 09:20	105	9.5
0.09	D1_11	25Sep11 07:40	25Sep11 09:30	110	9.9
0.08	F3	25Sep11 06:59	25Sep11 09:35	156	12.5
0.18	C1_5	25Sep11 07:45	25Sep11 09:40	115	20.7
0.09	D1_12	25Sep11 08:16	25Sep11 09:50	94	8.5
0.18	C1_6	25Sep11 08:45	25Sep11 10:00	75	13.5
0.04	D2_6	25Sep11 08:13	25Sep11 10:10	117	4.7
0.09	D1_13	25Sep11 09:12	25Sep11 10:20	68	6.1
0.04	D2_7	25Sep11 08:14	25Sep11 10:30	136	5.4
0.04	D2_8	25Sep11 09:11	25Sep11 10:40	89	3.6
0.04	D2_9	25Sep11 09:11	25Sep11 10:50	99	4.0

The vessel schedule displayed in Table 5.12 is the direct output of the mathematical model. Accordingly, since vessel speeds and related overtaking actions are not considered

in the mathematical model, they are not included in the schedule displayed in Table 5.12. Nevertheless, they are embedded to the revised vessel schedule after the optimization run: vessels of classes C1, C2, D1, D2, E, F are sorted from the highest speed to the lowest speed and the revised schedule (describing the admittance time of vessels to the Strait) is displayed in Table 5.13 is generated. This way, in most cases, a vessel will be faster than its successors and will sail through the Strait at its own speed. If this is not the case (i.e. a vessel is faster than its predecessor), it is assumed that it has to cruise 5 km. at the speed of its preceding vessel, then it can cruise 25 km. at its own speed.

Table 5.13. The vessel schedule of the northbound day time window on 25th of September after speed sort.

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (min)	Weighted Waiting Time (min)	Speed
0.28	A1	25Sep11 04:57	25Sep11 05:40	43	12.04	11.5
0.08	F1	25Sep11 00:56	25Sep11 05:45	289	23.12	9
0.09	D1_2	25Sep11 03:54	25Sep11 05:50	116	10.44	14
0.18	C1_1	25Sep11 00:02	25Sep11 06:00	358	64.44	15
0.04	D2_4	25Sep11 04:43	25Sep11 06:10	87	3.48	14
0.18	C1_2	25Sep11 00:14	25Sep11 06:20	366	65.88	12
0.09	D1_1	25Sep11 03:14	25Sep11 06:30	196	17.64	11
0.13	C2_1	25Sep11 01:24	25Sep11 06:40	316	41.08	13.5
0.09	D1_3	25Sep11 04:12	25Sep11 06:50	158	14.22	10.5
0.18	C1_3	25Sep11 04:02	25Sep11 07:00	178	32.04	11.1
0.09	D1_4	25Sep11 05:33	25Sep11 07:10	97	8.73	10.5
0.13	C2_2	25Sep11 02:19	25Sep11 07:20	301	39.13	12.5
0.09	D1_6	25Sep11 06:17	25Sep11 07:30	73	6.57	9
0.04	D2_3	25Sep11 03:19	25Sep11 07:40	261	10.44	13
0.08	F2	25Sep11 05:54	25Sep11 07:45	111	8.88	11
0.21	E1	25Sep11 06:50	25Sep11 07:50	60	12.6	18
0.09	D1_9	25Sep11 07:31	25Sep11 08:00	29	2.61	9
0.18	C1_5	25Sep11 07:45	25Sep11 08:10	25	4.5	12.5
0.04	D2_1	25Sep11 01:16	25Sep11 08:20	424	16.96	11
0.09	D1_10	25Sep11 07:35	25Sep11 08:30	55	4.95	9
0.04	D2_6	25Sep11 08:13	25Sep11 08:40	27	1.08	11
0.09	D1_11	25Sep11 07:40	25Sep11 08:50	70	6.3	8.5
0.04	D2_7	25Sep11 08:14	25Sep11 09:00	46	1.84	10
0.09	D1_12	25Sep11 08:16	25Sep11 09:10	54	4.86	8.5
0.09	D1_13	25Sep11 09:12	25Sep11 09:20	8	0.72	10
0.09	D1_5	25Sep11 05:37	25Sep11 09:30	233	20.97	8
0.08	F3	25Sep11 06:59	25Sep11 09:35	156	12.48	10
0.18	C1_4	25Sep11 07:03	25Sep11 09:40	157	28.26	12.2

Table 5.13. The vessel schedule of the northbound day time window on 25th of September after speed sort.

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (min)	Weighted Waiting Time (min)	Speed
0.09	D1_7	25Sep11 06:47	25Sep11 09:50	183	16.47	8
0.18	C1_6	25Sep11 08:45	25Sep11 10:00	75	13.5	12
0.04	D2_8	25Sep11 09:11	25Sep11 10:10	59	2.36	11
0.09	D1_8	25Sep11 07:30	25Sep11 10:20	170	15.3	8
0.04	D2_9	25Sep11 09:11	25Sep11 10:30	79	3.16	10
0.04	D2_2	25Sep11 02:27	25Sep11 10:40	493	19.72	9.5
0.04	D2_5	25Sep11 06:37	25Sep11 10:50	253	10.12	9.5

The vessel schedule plan after speed sort is displayed in Table 5.13. While sorting vessels in the same class, it is important to note the ready time of the vessels (the ready time of a vessel must be smaller than the suggested entering time). For instance, the speed of C1_2 is 12 and C1_5 is 12.5 knots. According to descending speed order, C1_5 should enter the Istanbul Strait at 7:00 and C1_2 should enter at 08:10. However, the ready time of C1_5 is 07:45, so that it is impossible for it to enter the Istanbul Strait at 07:00. Accordingly, the next C vessel, C1_4, which has the closest speed to C1_5 (12.2 knot) is checked; however, its ready time is 07:03. The next C vessel, C1_2 (which has 12 knots speed), features a ready time as 00:14. Accordingly, C1_2 is the vessel to be admitted to the Strait at 07:00.

The day time northbound window is closed at 10:50 and the day time southbound window is started at 12:50.

5.3.2. Southbound Day Time Traffic

Start Time: 25.09.2011 12:50

End Time: 25.09.2011 18:15

5.3.2.1. Planning Horizon 1.

Start Time: 25.09.2011 12:50

End Time: 25.09.2011 14:50

- Input:** All newly arrived vessels between 25.09.2011 00:00-12:50 (Except Class B vessels)
21 Pilots
- Output:** The vessel schedule for 120 minutes
11 pilots are used.
10 pilots are available for the next planning horizon.
15 vessels are scheduled to enter the Strait according to the schedule presented in Table 5.14.
26 vessels are not admitted to the Istanbul Strait in this 2 hours period.
They are to be inputs of the next planning horizon.
The accounting of all vessels allowed to enter the Strait and those not admitted are displayed in Table 5.15.

Table 5.14. The vessel schedule of planning horizon 1 of the southbound daytime window on 25th of September.

Vessel	Entering Time to the Strait
A1	12:50
F1	12:55
D1_1	13:00
C1_1	13:10
D1_2	13:20
C1_2	13:30
D1_3	13:40
E1	13:50
D2_1	14:00
F2	14:05
C2_1	14:10
D1_4	14:20
C1_3	14:30
D1_5	14:40
C1_4	14:50

Table 5.15. The accounting of vessel activities of planning horizon 1 of the southbound daytime window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
A	1	1	0
C1	4	4	0
C2	2	1	1
D1	13	5	8

Table 5.15. The accounting of vessel activities of planning horizon 1 of the southbound daytime window on 25th of September (continued).

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
D2	17	1	16
E	1	1	0
F	3	2	1
Total	41	15	26

5.3.2.2. Planning Horizon 2.

Start Time: 25.09.2011 14:50

End Time: 25.09.2011 16:50

Input: All newly arrived vessels between 25.09.2011 12:50-14:50 (Except Class B vessels)

The vessels remaining from Planning Horizon1 (26 vessels)

10 Available Pilots

Output: The vessel schedule for 120 minutes

9 pilots are used.

1 pilot is available for the next planning horizon.

23 vessels are not admitted to the Istanbul Strait in this 2 hours period.

They are to be inputs of the next planning horizon.

13 vessels are scheduled to enter the Strait according to the schedule presented in Table 5.16.

The accounting of all vessels allowed to enter the Strait and those not admitted are displayed in Table 5.17.

Table 5.16. The vessel schedule of planning horizon 2 of the southbound daytime window on 25th of September.

Vessel	Entering Time to the Strait
F_3	14:55
D1_6	15:00
C2_2	15:10
D1_7	15:20
D1_8	15:30
D1_9	15:40
D1_10	15:50
D2_2	16:00

Table 5.16. The vessel schedule of planning horizon 2 of the southbound daytime window on 25th of September (continued).

Vessel	Entering Time to the Strait
D1_11	16:10
D1_12	16:20
D1_13	16:30
D2_3	16:40
D1_14	16:50

Table 5.17. The accounting of vessel activities of the planning horizon 1 of the southbound daytime window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
C2	1	1	0
D1	10	9	1
D2	24	2	22
F	1	1	0
Total	36	13	23

5.3.2.3. Planning Horizon 3.

Start Time: 25.09.2011 16:50

End Time: 25.09.2011 18:50

Input: All newly arrived vessels between 25.09.2011 14:50-16:50 (Except Class B vessels)

The vessels remaining from planning horizon 2 (23 vessels)

1 available pilot until 18:30

10 available pilots after 18:30

Output: The vessel schedule for 120 minutes

9 pilots are used.

1 pilot is available for the next planning horizon.

23 vessels are not admitted to the Strait in 2 hours period. They are to be inputs of the next planning horizon.

12 vessels are scheduled to enter the Strait according to the schedule presented in Table 5.18 and Table 5.19.

The accounting of all vessels allowed to enter the Strait and those not

admitted are displayed in Table 5.20.

Planning horizon 3 (on 25th of September, southbound window) is in a way special in that it partly covers daytime scheduling (up to 18:15 and then nighttime scheduling (all southbound)). The most significant issue in this dual coverage is that class B vessels should be allowed to enter after 18:15 (which is easily implemented through a simple lowerbound constraint).

Table 5.18. The vessel schedule of planning horizon 3 of the southbound daytime window on 25th of September.

Vessel	Entering Time to the Strait
D2_4	17:00
D2_5	17:10
D2_6	17:20
D2_7	17:30
D2_8	17:40
D2_9	17:50
D2_10	18:00
D2_11	18:10

In the queue, Class B, C1, D1 and D2 vessels wait to enter the Istanbul Strait and all vessels, except Class D2 vessels, need to use a pilot to navigate in the Strait. There is only 1 available support service until 18:30, as a result of this, only class B vessel uses the pilot before 18:30, because of its importance weight.

The B1, D2_12, C1_5, C1_6 vessels are the scheduled vessels of the northbound nighttime traffic as shown in Table 5.19.

Table 5.19. The vessel schedule of the southbound nighttime window vessels on 25th of September.

Vessel	Entering Time to the Strait
B1	18:20
D2_12	18:30
C1_5	18:40
C1_6	18:50

Table 5.20. The accounting of vessel activities of planning horizon 3 of the southbound daytime and night time window on 25th of September.

Vessel Type	Number of vessels in the queue	Number of vessels entering the Strait	Number of vessels not entering the Strait
B	3	1	2
C1	2	0	2
D1	4	0	4
D2	23	8	15
Total	32	9	23

Table 5.21. The vessel schedule of the southbound daytime window on 25th of September.

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (min)	Weighted Waiting Time (min)
0.26	A1	25Sep11 02:04	25Sep11 12:50	646	168.0
0.08	F1	25Sep11 01:38	25Sep11 12:55	677	54.2
0.09	D1_1	25Sep11 02:16	25Sep11 13:00	644	58.0
0.18	C1_1	25Sep11 00:10	25Sep11 13:10	780	140.4
0.09	D1_2	25Sep11 03:37	25Sep11 13:20	583	52.5
0.18	C1_2	25Sep11 07:07	25Sep11 13:30	383	68.9
0.09	D1_3	25Sep11 03:56	25Sep11 13:40	584	52.6
0.21	E1	25Sep11 00:12	25Sep11 13:50	818	171.8
0.04	D2_1	25Sep11 00:15	25Sep11 14:00	825	33.0
0.08	F2	25Sep11 06:56	25Sep11 14:05	429	34.3
0.13	C2_1	25Sep11 09:09	25Sep11 14:10	301	39.1
0.09	D1_4	25Sep11 04:17	25Sep11 14:20	603	54.3
0.18	C1_3	25Sep11 08:41	25Sep11 14:30	349	62.8
0.09	D1_5	25Sep11 05:15	25Sep11 14:40	565	50.9
0.18	C1_4	25Sep11 11:53	25Sep11 14:50	177	31.9
0.08	F3	25Sep11 08:43	25Sep11 14:55	372	29.8
0.09	D1_6	25Sep11 05:30	25Sep11 15:00	570	51.3
0.13	C2_2	25Sep11 10:15	25Sep11 15:10	295	38.4
0.09	D1_7	25Sep11 06:16	25Sep11 15:20	544	49.0
0.09	D1_8	25Sep11 07:36	25Sep11 15:30	474	42.7
0.09	D1_9	25Sep11 09:38	25Sep11 15:40	362	32.6
0.09	D1_10	25Sep11 10:37	25Sep11 15:50	313	28.2
0.04	D2_2	25Sep11 00:20	25Sep11 16:00	940	37.6
0.09	D1_11	25Sep11 11:43	25Sep11 16:10	267	24.0
0.09	D1_12	25Sep11 12:30	25Sep11 16:20	230	20.7
0.09	D1_13	25Sep11 12:46	25Sep11 16:30	224	20.2
0.04	D2_3	25Sep11 02:15	25Sep11 16:40	865	34.6
0.09	D1_14	25Sep11 13:35	25Sep11 16:50	195	17.6
0.04	D2_4	25Sep11 02:37	25Sep11 17:00	863	34.5
0.04	D2_5	25Sep11 04:39	25Sep11 17:10	751	30.0
0.04	D2_6	25Sep11 05:40	25Sep11 17:20	700	28.0
0.04	D2_7	25Sep11 05:59	25Sep11 17:30	691	27.6
0.04	D2_8	25Sep11 06:12	25Sep11 17:40	688	27.5
0.04	D2_9	25Sep11 06:14	25Sep11 17:50	696	27.8
0.04	D2_10	25Sep11 07:04	25Sep11 18:00	656	26.2
0.04	D2_11	25Sep11 08:02	25Sep11 18:10	608	24.3

The outputs of the mathematical model (for the southbound daytime vessel schedule) are displayed in Table 5.21. Then, the vessels in same class are sorted according to their speeds with the same logic of the northbound daytime window.

Table 5.22 displays the “speed adjusted” final schedule. The remaining vessel scheduling models for the respective northbound/southbound daytime/nighttime windows are processed with the same logic.

Table 5.22. The vessel schedule of the southbound day time window on 25th of September after speed sort.

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (Min.)	Weighted Waiting Time (Min.)	Speed
0.26	A_1	25Sep11 02:04	25Sep11 12:50	646	167.96	14
0.08	F_3	25Sep11 08:43	25Sep11 12:55	252	20.16	12
0.09	D1_7	25Sep11 06:16	25Sep11 13:00	404	36.36	12
0.18	C1_2	25Sep11 07:07	25Sep11 13:10	363	65.34	14
0.09	D1_12	25Sep11 12:30	25Sep11 13:20	50	4.5	11.5
0.18	C1_3	25Sep11 08:41	25Sep11 13:30	289	52.02	14
0.09	D1_13	25Sep11 12:46	25Sep11 13:40	54	4.86	11.5
0.21	E_1	25Sep11 00:12	25Sep11 13:50	818	171.78	13
0.04	D2_7	25Sep11 05:59	25Sep11 14:00	481	19.24	14
0.08	F_1	25Sep11 01:38	25Sep11 14:05	747	59.76	10
0.13	C2_1	25Sep11 09:09	25Sep11 14:10	301	39.13	15
0.09	D1_3	25Sep11 03:56	25Sep11 14:20	624	56.16	10
0.18	C1_1	25Sep11 00:10	25Sep11 14:30	860	154.8	12.5
0.09	D1_4	25Sep11 04:17	25Sep11 14:40	623	56.07	10
0.18	C1_4	25Sep11 11:53	25Sep11 14:50	177	31.86	11
0.08	F_2	25Sep11 06:56	25Sep11 14:55	479	38.32	9
0.09	D1_8	25Sep11 07:36	25Sep11 15:00	444	39.96	10
0.13	C2_2	25Sep11 10:15	25Sep11 15:10	295	38.35	10.5
0.09	D1_9	25Sep11 09:38	25Sep11 15:20	342	30.78	10
0.09	D1_10	25Sep11 10:37	25Sep11 15:30	293	26.37	10
0.09	D1_11	25Sep11 11:43	25Sep11 15:40	237	21.33	10
0.09	D1_14	25Sep11 13:35	25Sep11 15:50	135	12.15	10
0.04	D2_5	25Sep11 04:39	25Sep11 16:00	681	27.24	11.5
0.09	D1_5	25Sep11 05:15	25Sep11 16:10	655	58.95	9.5
0.09	D1_1	25Sep11 02:16	25Sep11 16:20	844	75.96	8.5
0.09	D1_2	25Sep11 03:37	25Sep11 16:30	773	69.57	8
0.04	D2_6	25Sep11 05:40	25Sep11 16:40	660	26.4	11.5
0.09	D1_6	25Sep11 05:30	25Sep11 16:50	680	61.2	8
0.04	D2_4	25Sep11 02:37	25Sep11 17:00	863	34.52	11
0.04	D2_10	25Sep11 07:04	25Sep11 17:10	606	24.24	11

Table 5.22. The vessel schedule of the southbound day time window on 25th of September after speed sort (continued).

Weight	Vessel	Ready Time	Entering Time to the Strait	Waiting Time (Min.)	Weighted Waiting Time (Min.)	Speed
0.04	D2_1	25Sep11 00:15	25Sep11 17:20	1025	41	10
0.04	D2_2	25Sep11 00:20	25Sep11 17:30	1030	41.2	9.5
0.04	D2_8	25Sep11 06:12	25Sep11 17:40	688	27.52	9
0.04	D2_3	25Sep11 02:15	25Sep11 17:50	935	37.4	8.5
0.04	D2_9	25Sep11 06:14	25Sep11 18:00	706	28.24	8.5
0.04	D2_11	25Sep11 08:02	25Sep11 18:10	608	24.32	8

The full set of outputs of the basic scenario is the following and they are displayed in Table 5.23 to Table 5.29;

- Total weighted waiting time of vessels until entering the Istanbul Strait;
- Average weighted waiting time per vessel until entering the Istanbul Strait;
- Total weighted waiting time of the vessels entering the Istanbul Strait until entering the Istanbul Strait for each time window in the 48 hour period;
- Average weighted waiting time per vessel entering the Istanbul Strait until entering the Istanbul Strait for each time window in the 48 hour period;
- The numbers of vessels entering the Istanbul Strait for each time window in the 48 hour period;
- Total weighted waiting time of each class vessels for both northbound and southbound time windows until entering the Istanbul Strait;
- Average weighted waiting time per vessel of each class vessels for both northbound and southbound time windows until entering the Istanbul Strait;
- Total waiting time of vessels until entering the Istanbul Strait;
- Number of southbound/northbound vessels not entering the Istanbul Strait;
- Total weighted waiting time of southbound/northbound vessels not entering the Istanbul Strait during 48 hours period;
- Average weighted waiting time per vessel of southbound/northbound vessels not entering the Istanbul Strait during 48 hours period;
- Total number of vessels in queues;
- The Istanbul Strait utilization.

A short set of aggregate outputs are displayed in Table 5.23. Table 5.23 displays the aggregate outputs of the mathematical model. The detailed vessel schedule of time windows are displayed in Appendix B. The numbers of vessels entering the Strait, the total weighted waiting time of vessels and average weighted waiting time per vessel are different in each time window. The numbers of vessels entering the Strait depend on the time window length. For example, the length of second southbound nighttime window is 7 hours 35 minutes and the length of second northbound nighttime window is 1 hour 50 minutes so that the numbers of vessels entering the Strait are 48 and 13, respectively. Total weighted waiting time of time window depends on the vessel classes in the queue, ready time of vessels to enter the Strait, the importance weights of the vessels entering the Strait. Average waiting time per vessel related to weighted waiting time and the numbers of vessels entering the Strait.

Table 5.23. The outputs of the mathematical model for the 48 hour period on 25-26-27th of September.

Time Window	Before Speed Sort		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Northbound Daytime W1	557	16	35
Southbound Daytime W1	1,725	48	36
Southbound Nighttime W1	838	32	26
Northbound Nighttime W1	2,399	71	34
Northbound Daytime W2	746	17	43
Southbound Daytime W2	2,237	86	26
Southbound Nighttime W2	2,714	57	48
Northbound Nighttime W2	1,211	93	13
Total (48 hours period)	12,428	48	261

Table 5.24. The vessel schedule for the 48 hour period on 25-26-27th of September after speed sort.

Time Window	After Speed Sort		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Northbound Daytime W1	557	16	35
Southbound Daytime W1	1,725	48	36
Southbound Nighttime W1	838	32	26
Northbound Nighttime W1	2,399	71	34
Northbound Daytime W2	746	17	43

Table 5.24. The vessel schedule for the 48 hour period on 25-26-27th of September after speed sort (continued).

Time Window	After Speed Sort		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Southbound Daytime W2	2,237	86	26
Southbound Nighttime W2	2,714	57	48
Northbound Nighttime W2	1,211	93	13
Total (48 hours period)	12,428	48	261

After the speed sort, there is no change in the total weighted waiting time and the average weighted waiting time per vessel, as shown in Table 5.24. It is concluded that speed sort doesn't cause significant change in terms of total weighted waiting time or average weighted waiting time per vessel.

Table 5.25. The actual Strait sailing time of all vessels during the selected 48 hours on 25-26-27th of September.

Time Window	Vessel Strait Transit Times	
	Before Speed Sort (hour)	After Speed Sort (hour)
Northbound Daytime W1	101	101
Southbound Daytime W1	105	105
Southbound Nighttime W1	77	76
Northbound Nighttime W1	100	100
Northbound Daytime W2	130	129
Southbound Daytime W2	80	79
Southbound Nighttime W2	143	142
Northbound Nighttime W2	32	32
Total (48 hours period)	769	764

The total sailing time in the Strait naturally changes from time window to time window and it depends on the vessel speeds and vessel schedules. One key observation related to all time windows is that "speed sorted" schedule does lead to faster transits and better utilization of the Strait.

As displayed in Table 5.26, there are more waiting vessels in the southbound queue than in the northbound queue. Accordingly, the vessels in the southbound queue spend more time (in total and in average) in the queue before entering the Strait. In average, class B vessels relatively spend more time in queue compared to other classes.

The highest average waiting times are those of BN, AS, BS and AN vessel types. This is not surprising since transit demand of such vessels (25-26-27th September in the investigated 48 hours) is relatively high with respect to their admittance rate (around 1 per hour). On the other hand, the smallest average waiting times are those of EN, D2N, D1N, FN, PS and PN vessel types. These results are also intuitive since admittance rate of these vessel types are very high enabling their fast processing even though their transit demands are quite high.

Table 5.26. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 25-26-27th of September.

Vessel Type	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
AN	338	113	3
AS	513	171	3
BN	1,447	289	5
BS	1,319	165	8
C1N	1,165	61	19
C1S	1,551	65	24
C2N	251	31	8
C2S	161	40	4
D1N	956	21	45
D1S	1,615	43	38
D2N	685	16	37
D2S	1,744	40	44
EN	13	13	1
ES	223	74	3
FN	157	26	6
FS	368	33	11
PN	2	1	1
PS	20	20	1
Total_Northbound	4,913	39	125
Total_Southbound	7,515	55	136

Table 5.27. The accounting of all class vessels allowed entering the Strait in each time window for the 48 hour period on 25-26-27th of September.

Time Window	A	B	C1	C2	D1	D2	E	F	P	Total
Northbound Daytime W1	1	0	6	2	13	9	1	3	0	35
Southbound Daytime W1	1	0	6	2	17	6	1	3	0	36
Southbound Nighttime W1	0	3	2	0	2	17	0	2	0	26
Northbound Nighttime W1	0	4	4	1	12	10	0	3	0	34
Northbound Daytime W2	2	0	4	5	13	19	0	0	0	43
Southbound Daytime W2	2	0	9	1	8	0	2	4	0	26

Table 5.27. The accounting of all class vessels allowed entering the Strait in each time window for the 48 hour period on 25-26-27th of September (continued).

Time Window	A	B	C1	C2	D1	D2	E	F	P	Total
Southbound Nighttime W2	0	5	7	1	11	21	0	2	1	48
Northbound Nighttime W2	0	1	5	0	6	0	0	0	1	13
Total (48 hours period)	6	13	43	12	82	82	4	17	2	261

Table 5.27 displays the class distribution of the admitted vessels to the Strait in the breakdown of time window during the selected the 48 hour period.

Table 5.28. The accounting of vessels not admitted to the Strait in each direction for the 48 hour period on 25-26-27th of September.

Vessel Type	Southbound	Northbound
A	0	0
B	0	0
C1	0	2
C2	0	1
D1	0	1
D2	10	15
E	0	0
F	0	0
P	0	0

Table 5.29. The waiting times of vessels not admitted to the Strait in each direction for the 48 hour period on 25-26-27th of September.

Vessel Type	Southbound		Northbound	
	Total Weighted Waiting Time (Min)	Avg. Waiting Time Per Vessel (Min)	Total Weighted Waiting Time (Min)	Avg. Waiting Time Per Vessel (Min)
A	0	0	0	0
B	0	0	0	0
C1	0	0	113	57
C2	0	0	59	59
D1	0	0	14	14
D2	139	14	490	33
E	0	0	0	0
F	0	0	0	0
P	0	0	0	0

Table 5.28 displays the accounting of vessels not admitted to the Strait in each direction for the 48 hour period on 25-26-27th of September. Most of these vessels belong to Class D2. The reasons why more class D2 vessels remain unadmitted to the Strait are,

higher number of Class D2 vessels, as well as small importance weights of Class D2 vessels. Table 5.29 displays the total and average waiting times of vessels.

The vessel schedule of the 48 hour period on 25-26-27th of September in the breakdown of time windows are displayed in Appendix A.

The mathematical model solutions and outputs of April / November are displayed in Appendix B.

5.4. Verification and Validation of the Basic Scenario

In order to verify and validate the developed model and the suggested schedule generation, the outputs of the mathematical model and the outputs of the real life are compared.

To make a fair comparison between the outputs of the mathematical model and the outputs of the real life, the vessels entering the Istanbul Strait during the period between 25.09.2011 05:40 and 27.09.2011 05:40 are taken into account. These vessels are inputs of the mathematical model. After the model run, the outputs and the performance measures are compared with that of the real vessel schedule.

Table 5.30. The comparison of the mathematical model solution and the real schedule for the 48 hour period on 25-26-27th of September.

	Before Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
Time Window	Model	Actual	Model	Actual	Model	Actual
Northbound Daytime W1	2,736	2,942	54	58	51	51
Southbound Daytime W1	2,601	2,677	108	96	24	28
Southbound Nighttime W1	4,245	4,812	104	84	41	57
Northbound Nighttime W1	2,552	2,077	128	148	20	14
Northbound Daytime W2	2,188	3,892	64	75	34	52
Southbound Daytime W2	2,313	1,691	66	85	35	20
Southbound Nighttime W2	4,103	4,066	89	95	46	43
Northbound Nighttime W2	1,525	2,063	127	90	12	23
Total (48 hours period)	22,263	24,220	85	84	263	288

Table 5.31. The comparison of the mathematical model solution after speed sort and the real schedule for the 48 hour period on 25-26-27th of September.

Time Window	After Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Model	Actual	Model	Actual	Model	Actual
Northbound Daytime W1	2,736	2,942	54	58	51	51
Southbound Daytime W1	2,601	2,677	108	96	24	28
Southbound Nighttime W1	4,245	4,812	104	84	41	57
Northbound Nighttime W1	2,552	2,077	128	148	20	14
Northbound Daytime W2	2,188	3,892	64	75	34	52
Southbound Daytime W2	2,313	1,691	66	85	35	20
Southbound Nighttime W2	4,103	4,066	89	95	46	43
Northbound Nighttime W2	1,525	2,063	127	90	12	23
Total (48 hours period)	22,263	24,220	85	84	263	288

In the real situation, the period focused starts on 25 September, at 5:40 and finishes on 27 September, at 06:19 for two day time northbound windows; two day time southbound windows; two night time northbound windows and two night time southbound windows. Although the period starts at same time in the mathematical model, it is terminated on 27 September 2011 at 5:40 due to the fact that 5:40 is the start time of day time northbound window. After 05:40 on 27 September 2011, two vessels enter the Strait in the real situation. In other words, 263 vessels enter the Strait based on the mathematical model results, while 286 vessels enter in the real situation during the specified 48 hours period. The main reason for this difference is that in the real situation, the two hours interlude for direction change and the minimum pursuit distance rule are not strictly applied.

When the total weighted waiting time of vessels are compared, it is concluded that the total weighted waiting time of the real situation is higher than that of the mathematical model as shown in Table 5.30. However, the average waited waiting time per vessel is approximately the same in both cases (before the speed sort and after the speed sort). Due to having different northbound/southbound window lengths, the numbers of vessels entering the Strait in two directions also differ as shown in Table 5.31.

Table 5.32. The comparison between the mathematical model and the real situation in terms of the number of vessels entering the Strait for the 48 hour period on 25-26-27th of September.

Vessel Type	The Number of Vessels Entering The Strait		Difference
	The Math. Model	The Real Situation	
A	8	8	0
B	13	13	0
C1	46	46	0
C2	12	13	1
D1	77	81	4
D2	84	103	19
E	3	3	0
F	19	20	1
P	1	1	0
Total	263	288	25

When the vessels and vessel classes which entered the Strait are compared, the vessels having relatively higher importance weight have tendency to enter the Strait earlier in the mathematical model; this situation is displayed in Table 5.32. Most of the vessels remaining waiting in the mathematical model results belong to Class D2, which has the lowest importance weight.

Table 5.33. The Istanbul Strait utilization comparison for the 48 hour period on 25-26-27th of September.

Time Window	The Istanbul Strait Utilization	
	Before Speed Sort (hour)	After Speed Sort (hour)
Northbound Daytime W1	148	146
Southbound Daytime W1	71	71
Southbound Nighttime W1	116	116
Northbound Nighttime W1	61	61
Northbound Daytime W2	99	99
Southbound Daytime W2	107	106
Southbound Nighttime W2	134	134
Northbound Nighttime W2	35	35
Total (48 hours period)	772	768

Although speed sorting the vessels doesn't make a significant change in total weighted waiting time and average weighted waiting time per vessel, it increases the utilization of the Strait. In other words, if the vessels are sorted based on their speed, the vessels leave the Strait earlier. For example, if the vessel schedule is sorted based on speed

according to the mathematical model output, the entered vessels spend 768 hours in the Strait rather than 772 hours, as shown as Table 5.33.

Table 5.34. The comparison between the mathematical model solution and the real situation in terms of waiting times and number of vessels in the breakdown of vessel class for each direction.

Time Window	Total Weighted Waiting Time (Min)		Avg. Weighted Waiting Time Per Vessel (Min)		Number of Passed Vessels	
	Model	Actual	Model	Actual	Model	Actual
AN	507	662	101	132	5	5
AS	769	863	256	288	3	3
BN	763	810	254	270	3	3
BS	3,467	3,465	347	347	10	10
C1N	1,983	2,306	110	128	18	18
C1S	3,740	4,086	134	146	28	28
C2N	682	989	97	124	7	8
C2S	555	551	111	110	5	5
D1N	2,740	3,318	70	79	39	42
D1S	1,917	2,335	50	60	38	39
D2N	1,619	2,059	48	39	34	53
D2S	2,338	1,263	47	25	50	50
EN	280	294	280	294	1	1
ES	205	268	103	134	2	2
FN	427	536	43	54	10	10
FS	271	358	30	36	9	10
PN	0	0	0	0	0	0
PS	0	57	0	57	1	1
Total_Northbound	9,001	10,974	77	78	117	140
Total_Southbound	13,262	13,246	91	89	146	148

As can be observed in the Table 5.34, there are more vessels in the southbound queue. However, due to the relatively high numbers of Class A and Class B vessels waiting (the determiner of the time window length) in the southbound queue, more southbound vessels enter the Strait.

Table 5.35. The comparison between the mathematical model solutions and the real situation in terms of vessel classes entering the Strait.

Vessel Type	Case	North bound Day time W1	South bound Day time W1	South bound Night time W1	North bound Night time W1	North bound Day time W2	South bound Day time W2	South bound Night time W2	North bound Night time W2	Total
A	Model	3	1	0	0	2	2	0	0	8
	Actual	3	1	0	0	2	2	0	0	8
B	Model	0	0	4	2	0	0	6	1	13
	Actual	0	0	4	2	0	0	6	1	13
C1	Model	5	6	9	3	5	3	10	5	46
	Actual	5	6	9	3	5	3	10	5	46
C2	Model	3	0	3	2	2	0	2	0	12
	Actual	3	0	3	0	4	0	2	1	13
D1	Model	10	8	12	11	12	7	11	6	77
	Actual	10	9	12	8	15	7	11	9	81
D2	Model	23	5	11	1	10	19	15	0	84
	Actual	23	8	26	1	22	4	12	7	103
E	Model	0	1	0	0	1	1	0	0	3
	Actual	0	1	0	0	1	1	0	0	3
F	Model	7	3	2	1	2	3	1	0	19
	Actual	7	3	3	0	3	3	1	0	20
P	Model	0	0	0	0	0	0	1	0	1
	Actual	0	0	0	0	0	0	1	0	1

The numbers of vessels in the breakdown of vessel classes are shown in the Table 5.35. It also displays the number of vessels that remain unadmitted. For example, although there are 8 Class D2 vessels in the southbound daytime queue, only 5 of them enter the Strait.

Although the same R&R are applied and same vessels are used as input, there are different numbers of vessels entering the Strait in these two situations: 288 vessels in the real case and 263 vessels in the solution of the mathematical model. After analyzing the results, it is concluded that the minimum pursuit distance rule and the two hours interlude for direction change rule are not strictly applied in the real case. Accordingly, it is decided to “calibrate” the parameters of the mathematical model in order to account for the “rule violations” in the real case. This “calibration” is accomplished by reducing the minimum pursuit distance (between two consecutive vessels) by 10% (thereby allowing/encouraging

more frequent transits). The mathematical argument behind “10% reduction” in pursuit distances is as follows:

During the investigated 48 hours periods, 8 hours are spent for direction change (i.e. without admitting new vessels). In the other words, 40 hours are for the vessel transition. The average minimum pursuit distance between any two vessels can then be calculated by dividing the available time to number of transits. In other words;

$$40 * 60 = 2400 \text{ min. for vessel transition}$$

In the real situation; 288 transits are recorded.

This, the avg. minimum pursuit distance between any two vessels is, $2400/288$; 8,33 min.

On the other hand, in the mathematical model, the avg. minimum pursuit distance between any two vessels is, $2400/263 = 9.12$ min., which is about 10% more than the real case. In other words, at least the “average pursuit distance” conditions of the real case would be reached if the pursuit distances in the model were to be reduced by 10%. After decreasing the minimum pursuit distance 10%, the new minimum pursuit distances between classes are displayed in the Table 5.36.

Table 5.36. The minimum pursuit distance between vessels classes (in minutes) after 10% decrease.

Vessel	A	B	C	D	E	F	P
A	67.5	67.5	18	9	18	4.5	9
B	67.5	67.5	18	9	18	4.5	9
C	18	18	18	9	18	4.5	9
D	9	9	9	9	9	4.5	9
E	18	18	18	9	18	4.5	9
F	4.5	4.5	4.5	4.5	4.5	54	4.5
P	9	9	9	9	9	9	9

Table 5.37. The comparison of the mathematical model solution and real schedule for the 48 hour period on 25-26-27 September after the 10% decrease in minimum pursuit distance.

Time Window	Before Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Model	Actual	Model	Actual	Mode	Actual
Northbound Daytime W1	2,673	2,942	52	58	51	51
Southbound Daytime W1	2,703	2,677	90	96	30	28
Southbound Nighttime W1	3,668	4,812	80	84	46	57
Northbound Nighttime W1	2,620	2,077	114	148	23	14
Northbound Daytime W2	2,273	3,892	61	75	37	52
Southbound Daytime W2	2,340	1,691	59	85	40	20
Southbound Nighttime W2	2,203	4,066	85	95	26	43
Northbound Nighttime W2	2,068	2,063	103	90	20	23
Total (48 hours period)	20,548	24,220	75	84	273	288

Table 5.38. The comparison of the mathematical model solution after speed sort and the real situation for the 48 hour period on 25-26-27 September after 10% decrease in the minimum pursuit.

Time Window	After Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Model	Actual	Model	Actual	Model	Actual
Northbound Daytime W1	2,673	2,942	52	58	51	51
Southbound Daytime W1	2,703	2,677	90	96	30	28
Southbound Nighttime W1	3,668	4,812	80	84	46	57
Northbound Nighttime W1	2,620	2,077	114	148	23	14
Northbound Daytime W2	2,273	3,892	61	75	37	52
Southbound Daytime W2	2,340	1,691	59	85	40	20
Southbound Nighttime W2	2,203	4,066	85	95	26	43
Northbound Nighttime W2	2,068	2,063	103	90	20	23
Total (48 hours period)	20,548	24,220	75	84	273	288

The revised solution, in the case of 10% decrease in the minimum pursuit distance parameters of the model, 273 vessels could enter the Strait, which is only 4% different than the real case. Based on these arguments, it is concluded that if a 10% reduction in the minimum pursuit distance requirements could compensate the “permissive” (i.e. rule violation infested) environment of the real case.

A second “calibration” option tried has been “to reduce all pursuit distances by 5%” and to reduce direction change interludes from 8 hours to 7 hours.

Table 5.39. The comparison between the mathematical model solution and the real situation for the 48 hour period on 25-26-27th of September after 5% decrease in minimum pursuit distance and 12.5% decrease in direction change interlude.

Time Window	Before Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Model	Actual	Model	Actual	Model	Actual
Northbound Daytime W1	2,697	2,942	53	58	51	51
Southbound Daytime W1	2,704	2,677	93	96	29	28
Southbound Nighttime W1	3,713	4,812	86	84	43	57
Northbound Nighttime W1	2,636	2,077	110	148	24	14
Northbound Daytime W2	2,244	3,892	64	75	35	52
Southbound Daytime W2	2,309	1,691	59	85	39	20
Southbound Nighttime W2	2,585	4,066	72	95	36	43
Northbound Nighttime W2	1,972	2,063	99	90	20	23
Total (48 hours period)	20,860	24,220	75	84	277	288

Table 5.40. The comparison between the mathematical model solution after speed sort and the real situation for the 48 hour period on 25-26-27 September, after 5% decrease in min. pursuit distance and 12.5% decrease in direction change time.

Time Window	After Speed Sort					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Model	Actual	Model	Actual	Model	Actual
Northbound Daytime W1	2,697	2,942	53	58	51	51
Southbound Daytime W1	2,704	2,677	93	96	29	28
Southbound Nighttime W1	3,713	4,812	86	84	43	57
Northbound Nighttime W1	2,636	2,077	110	148	24	14
Northbound Daytime W2	2,244	3,892	64	75	35	52
Southbound Daytime W2	2,309	1,691	59	85	39	20
Southbound Nighttime W2	2,585	4,066	72	95	36	43
Northbound Nighttime W2	1,972	2,063	99	90	20	23
Total (48 hours period)	20,860	24,220	75	84	277	288

In this case, 277 vessels enter the Strait and there are available slots for 6 vessels. It means that, 283 vessels, which is less than the number of vessels enter the Strait in the real

situation, can enter the Strait in this case as shown in Table 5.39 and Table 5.40. This case is only 2% different than the real case in terms of the number vessel admitted to the Strait.

In conclusion, it is possible to have similar number of vessels entering the Strait, in both the real case and the mathematical model solution by decreasing 10% minimum pursuit distance.

6. SCENARIO ANALYSIS

In this chapter, some parameters are changed to observe the effects of the levels of the related parameters on performance measures. In the scope of scenario analysis, the number of available pilots, the minimum pursuit distance between vessels and the arrival pattern of vessels (in terms of number of vessels in queue) are changed to investigate their effects on performance measures. In these scenarios only the actual arrival rates observed in the three instances (15-16 April, 25-26 September, 19-20 November) considered are covered. To make more definitive decision on changing minimum pursuit distance rules, total number of pilots available or arrival rates, more instances should be covered.

6.1. Changing the Minimum Pursuit Distances Between Vessels

The current minimum pursuit distance is first decreased 20% and then increased 20%. These changes are applied to the vessel arrival patterns as mentioned Section 3.3. The outputs of these scenarios are compared with the outputs of the basic scenario.

6.1.1. Increasing the Minimum Pursuit Distance by 20%

Due to the increase in minimum pursuit distance values (displayed in Table 6.1), it is expected that 10 vessels can enter the Strait during any determined 120 minutes time interval instead of the 12 vessels observed in the basic scenario (2 vessels remain in the queue). In other words, the 20% increase in minimum pursuit distance leads to 20% decrease in number of entered vessels to the Strait in two hours time period. This trend is repeated in other 120 minutes run, leading to the transit of 224 vessels (compared to 261 in the basic scenario) in the time period 25 – 26 – 27th September. The detailed comparison is displayed in Table 6.2.

Table 6.1. The minimum pursuit distance in time between vessels classes after 20% increase (min.).

Vessel Type	A	B	C1	C2	D1	D2	E	F	P
A	90	90	24	24	12	12	24	6	12
B	90	90	24	24	12	12	24	6	12
C1	24	24	24	24	12	12	24	6	12
C2	24	24	24	24	12	12	24	6	12
D1	12	12	12	12	12	12	12	6	12
D2	12	12	12	12	12	12	12	6	12
E	24	24	24	24	12	12	24	6	12
F	6	6	6	6	6	6	6	72	6
P	12	12	12	12	12	12	12	6	12

Table 6.2. The comparison between the basic scenario and the “20% increase in minimum pursuit distance scenario” for the 48 hour period on 25-26-27 September.

Time Window	20% increase in Minimum Pursuit Distance Scenario			Basic Scenario		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Northbound Daytime W1	605	20	30	557	16	35
Southbound Daytime W1	1,631	53	31	1,725	48	36
Southbound Nighttime W1	856	41	21	838	32	26
Northbound Nighttime W1	2,531	84	30	2,399	71	34
Northbound Daytime W2	1,077	30	36	746	17	43
Southbound Daytime W2	2,109	100	21	2,237	86	26
Southbound Nighttime W2	3,136	71	44	2,714	57	48
Northbound Nighttime W2	1,094	99	11	1,211	93	13
Total (48 hours period)	13,040	58	224	12,428	48	261

Additionally, with the increase in minimum pursuit distance, the weighted average and overall waiting times per vessel increase and the number of vessels entering the Strait decreases in all time windows, as shown in Table 6.2.

Table 6.3. The Vessel Strait Transition Times comparison between the basic scenario and the 20% increase in minimum pursuit distance scenario for the 48 hour period on 25-26-27 September.

Time Window	Vessel Strait Transit Times	
	20% Increase in Minimum Pursuit	The Basic Scenario (Hour)
Northbound Daytime W1	86	101
Southbound Daytime W1	89	105
Southbound Nighttime W1	61	76
Northbound Nighttime W1	86	100
Northbound Daytime W2	108	129
Southbound Daytime W2	60	79
Southbound Nighttime W2	135	142
Northbound Nighttime W2	29	32
Total (the 48 hour period)	653	764

The increase in the minimum pursuit distance leads to decrease in the numbers of vessels admitted to the Strait. However, as displayed in Table 6.3 the decrease in the numbers of vessels entering the Strait also leads to lesser transit times for vessels entering the Strait.

6.1.2. Decreasing in the Minimum Pursuit Distance by 20%

Due to the decrease in minimum pursuit distance values (displayed in Table 6.4), it is expected that 14 vessels can enter the Strait during any determined 120 minutes time interval instead of the 12 vessels observed in the basic scenario (2 more vessels can enter the Strait). In other words, the 20% increase in minimum pursuit distance leads to 16% increase in number of entered vessels to the Strait, in the investigated two hours time period. This trend is repeated in other 120 minutes run, leading to the transit of 277 vessels (compared to 261 in the basic scenario) in the time period 25 – 26 – 27th September. The detailed comparison is displayed in Table 6.5.

Table 6.4. The minimum pursuit distance in time between vessels classes after 20% decrease (min.).

Vessel Type	A	B	C1	C2	D1	D2	E	F	P
A	60	60	16	16	8	8	16	4	8
B	60	60	16	16	8	8	16	4	8
C1	16	16	16	16	8	8	16	4	8

Table 6.4. The minimum pursuit distance in time between vessels classes after 20% decrease (min.) (continued).

Vessel Type	A	B	C1	C2	D1	D2	E	F	P
C2	16	16	16	16	8	8	16	4	8
D1	8	8	8	8	8	8	8	4	8
D2	8	8	8	8	8	8	8	4	8
E	16	16	16	16	8	8	16	4	8
F	4	4	4	4	4	4	4	48	4
P	8	8	8	8	8	8	8	4	8

Table 6.5. The comparison between the basic scenario and the 20% decrease in minimum pursuit distance scenario for the 48 hour period on 25-26-27 September.

Time Window	20% decrease in Minimum Pursuit Distance			Basic Scenario		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait
Northbound Daytime W1	470	13	36	557	16	35
Southbound Daytime W1	1,671	33	51	1,725	48	36
Southbound Nighttime W1	473	23	21	838	32	26
Northbound Nighttime W1	2,331	51	46	2,399	71	34
Northbound Daytime W2	303	14	21	746	17	43
Southbound Daytime W2	2,359	62	38	2,237	86	26
Southbound Nighttime W2	1,485	40	37	2,714	57	48
Northbound Nighttime W2	1,447	54	27	1,211	93	13
Total (48 hours period)	10,540	38	277	12,428	48	261

The decrease in minimum pursuit distance leads to significant decreases in the weighted average and the overall waiting times of vessel while the number of vessels entering the Strait increases, in all time windows, as shown in Table 6.5.

The decrease in the minimum pursuit distance leads to increase in the numbers of vessels admitted to the Strait. However, as displayed in Table 6.6 the increase in the numbers of vessels entering the Strait also leads to more transit times for vessels entering the Strait.

Table 6.6. The Vessel Strait Transit Time comparison between the basic scenario and the scenario of 20% decrease in minimum pursuit distance for the 48 hour period on 25-26-27th September.

Time Window	Vessel Strait Transit Times	
	20% Decrease in Minimum Pursuit Distance Scenario (Hour)	The Basic Scenario (Hour)
Northbound Daytime W1	104	101
Southbound Daytime W1	149	105
Southbound Nighttime W1	63	76
Northbound Nighttime W1	134	100
Northbound Daytime W2	62	129
Southbound Daytime W2	105	79
Southbound Nighttime W2	114	142
Northbound Nighttime W2	72	32
Total (48 hours period)	802	764

6.2. Changing the Total Number of Pilots Available

In the current situation, there are 21 pilots in total to accompany vessels in their transit through the Strait. In related scenarios, first; the total number of pilots is decreased from 21 to 15, then in the second case, the total number of pilots is increased 21 to 24. The aim is to better understand the impacts of pilot captain availability on performance measures.

6.2.1. Decreasing the Number of Pilots

As expected, when there is decrease in total number of pilots, vessels more dependent on the pilotage service end up waiting longer in queue (until the needed pilots become available). Moreover, since such vessels usually have higher importance weights compared to other classes, total and average weighted waiting time of vessels considerably increase compared to the basic scenario, as shown in Table 6.7.

In this case, only 254 vessels are admitted to the Strait; while 9 available vessel slots remain unused. In other words, if there were adequate number of pilots, 263 vessels could have been admitted to the Strait.

Table 6.7. The comparison between the basic scenario and the “reduced pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of time window.

Time Window	The Reduced Pilot Availability Scenario			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait
Northbound Daytime W1	477	16	30	557	16	35
Southbound Daytime W1	1,709	47	36	1,725	48	36
Southbound Nighttime W1	897	35	26	838	32	26
Northbound Nighttime W1	3,285	94	35	2,399	71	34
Northbound Daytime W2	1,290	30	43	746	17	43
Southbound Daytime W2	2,124	85	25	2,237	86	26
Southbound Nighttime W2	2,648	58	46	2,714	57	48
Northbound Nighttime W2	1,216	94	13	1,211	93	13
Total (48 hours period)	13,646	54	254	12,428	48	261

Table 6.8 displays that the vessels more dependent on the pilotage services (Class A, B, C1, D1, E) spend more time in queue until having available pilot and the number of vessels admitted to the Strait of them decrease. Other vessels are more likely to enter the Strait in terms of vessel number and spend less time in queue.

Table 6.8. The comparison between the basic scenario and the “reduced pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of vessel class.

Vessel Type	The Reduced Pilot Availability Scenario (with 15 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
A	873	145	6	851	142	6
B	2,809	216	13	2,765	213	13
C1	3,611	86	42	2,646	62	43
C2	357	30	12	406	34	12
D1	3,083	47	66	2,898	35	83

Table 6.8. The comparison between the basic scenario and the “reduced pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of vessel class (continued).

Vessel Type	The Reduced Pilot Availability Scenario (with 15 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
D2	2,093	23	92	2,185	27	81
E	300	75	4	236	59	4
F	498	29	17	525	31	17
P	21	10	2	21	10	2
Total_A,B,C1,D1,E	10,675	81	131	9,396	63	149
Total_C2,D2,F,P	2,969	24	123	3,136	28	112

Table 6.9 displays the performance measures in terms of time zone. Based on the Table, there is no significant change in terms of time zone. The changes are more related to numbers of available pilots rather than time zone.

Table 6.9. The comparison between the basic scenario and the “reduced pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of time zone.

Time Zone	The Reduced Pilot Availability Scenario (with 15 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Day Time	5,600	42	134	5,265	38	140
Night Time	8,046	67	120	7,162	59	121

6.2.2. Increasing the Number of Pilots

As expected, when there is increase in total number of pilots, vessels more dependent on the pilotage service spend less time in queue (until the needed pilots become available). Moreover, since such vessels usually have higher importance weights, compared to other classes, total and average weighted waiting time of vessels considerably decrease compared to the basic scenario, as shown in Table 6.10.

In both scenarios, the overall and average weighted waiting time of vessels are mostly same. Moreover, the numbers of vessels admitted to the Strait is same, 261.

Table 6.10. The comparison between the “basic scenario” and the “increased pilot availability scenario” for the 48 hour period on 25-26-27th of September.

Time Window	Increased Pilot Availability Scenario (with 24 pilots)			Basic Scenario (with 21 pilots)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering to the Strait
Northbound Daytime W1	525	15	35	557	16	35
Southbound Daytime W1	1,667	46	36	1,725	48	36
Southbound Nighttime W1	842	32	26	838	32	26
Northbound Nighttime W1	2,430	71	34	2,399	71	34
Northbound Daytime W2	632	15	43	746	17	43
Southbound Daytime W2	2,245	86	26	2,237	86	26
Southbound Nighttime W2	2,634	55	48	2,714	57	48
Northbound Nighttime W2	1,179	91	13	1,211	93	13
Total (48 hours period)	12,152	47	261	12,428	48	261

Table 6.11 displays that the vessels more dependent on the pilotage services (Class A, B, C1, D1, E) spend less time in queue until having available pilot and the numbers of vessels admitted to the Strait of them increase. Other vessels are less likely to enter the Strait in terms of vessel number and spend more time in queue.

Table 6.11. The comparison between the basic scenario and the “increased pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of vessel class.

Vessel Type	The Increased Pilot Availability Scenario (with 24 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
A	817	136	6	851	142	6
B	2,756	212	13	2,765	213	13
C1	2,518	60	42	2,646	62	43

Table 6.11. The comparison between the basic scenario and the “increased pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of vessel class (continued).

Vessel Type	The Increased Pilot Availability Scenario (with 24 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
C2	319	40	8	406	34	12
D1	2,587	21	84	2,898	35	83
D2	2,399	28	85	2,185	27	81
E	240	60	4	236	59	4
F	493	29	17	525	31	17
P	18	9	2	21	10	2
Total_A,B,C1,D1,E	8,918	60	149	9,396	63	149
Total_C2,D2,F,P	3,229	29	112	3,136	28	112

Table 6.12 displays the performance measures in terms of time zone. Based on the Table, there is no significant change in terms of time zone. The changes are more related to numbers of available pilots rather than time zone.

Table 6.12. The comparison between the basic scenario and the “reduced pilot availability scenario” for the 48 hour period on 25-26-27th of September in the breakdown of time zone.

Time Zone	The Increased Pilot Availability Scenario (with 24 pilots available)			The Basic Scenario (with 21 pilots available)		
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time Per Vessel (Min.)	Number of Vessels Entering the Strait
Day Time	5,069	36	140	5,265	38	140
Night Time	7,085	59	121	7,162	59	121

6.3. Changes in Arrival Rates

Based on 2011 data, on average 138 vessels arrive daily (5.6 vessels per hour) at the Istanbul Strait. However, the actual number of arrivals and arrival rates vary considerably

around these averages, depending primarily on season and on time of day. In this subsection the impact of vessel arrival rates on waiting times is investigated.

Table 6.13 displays the total and per vessel waiting times of vessels at the three different 48 hour periods (in different seasons) treated in this study via the developed model (note that November and September arrivals are higher than April arrivals).

Table 6.13. The comparison between the focused 48 hour periods when changes in arrival pattern.

Time Window	Total Weighted Waiting Time (Min.)			Avg. Weighted Waiting Time Per Vessel (Min.)			Number of Vessels Entering to the Strait		
	Sept.	April	Nov.	Sept.	April	Nov.	Sept.	April	Nov.
Northbound Daytime W1	557	616	753	16	16	27	35	38	28
Southbound Daytime W1	1,725	1,331	1,800	48	35	64	36	38	28
Southbound Nighttime W1	838	829	845	32	24	22	26	34	39
Northbound Nighttime W1	2,399	1,815	4,267	71	91	50	34	20	43
Northbound Daytime W2	746	1,307	2,242	17	36	66	43	36	34
Southbound Daytime W2	2,237	1,608	2,179	86	38	109	26	42	20
Southbound Nighttime W2	2,714	682	2,210	57	40	42	48	17	53
Northbound Nighttime W2	1,211	3,583	2,914	93	119	117	13	30	25
Total (48 hours period)	12,428	11,771	17,21	48	46	64	261	255	270

Table 6.13 indicates a strong correlation between arrival rates and waiting times (even the slightest increase in arrival rates may cause a considerable increase in waiting times). However, due to the fact that the numbers of vessels admitted to the Strait and total weighted waiting time of vessels change according to the time window length, comparing total values of each 48 hour period make more sense. It is observed that a 2.4% increase in arrival rate (from 255 to 261) leads to 5.6% increase in total waiting times and 4.3% increase in per vessel waiting times. While a 5.9% increase in arrival rate (from 255 to 270) leads to 46% increase in total waiting times and 39% increase in per vessel waiting times.

Table 6.14 indicates a strong correlation between time spent in the Strait and numbers of vessels admitted to the Strait (even the slightest increase in numbers of vessels admitted to the Strait may cause a considerable increase in the time spent in the Strait). However, due to the fact that the numbers of vessels admitted to the Strait change

according to the time window length, comparing total values of each 48 hour period make more sense. It is observed that a 2.4% increase in arrival rate (from 255 to 261) leads to 6.1% increase in total time spent in the Strait. While a 5.9% increase in arrival rate (from 255 to 270) leads to 8.6% increase in total time spent in the Strait.

Table 6.14. The Istanbul Strait utilization comparison between the focused 48 hour periods when changes in arrival pattern.

Time Window	Vessel Strait Transit Times			Number of Vessels Entering to the Strait		
	Sept.	April	Nov.	Sept.	April	Nov.
Northbound Daytime W1	101	110	83	35	38	28
Southbound Daytime W1	105	106	78	36	38	28
Southbound Nighttime W1	76	98	114	26	34	39
Northbound Nighttime W1	100	58	123	34	20	43
Northbound Daytime W2	129	105	100	43	36	34
Southbound Daytime W2	79	118	60	26	42	20
Southbound Nighttime W2	142	41	154	48	17	53
Northbound Nighttime W2	32	83	70	13	30	25
Total (48 hours period)	764	720	782	261	255	270

In conclusion, the increase in the numbers of vessels in queue leads to increase in waiting times of vessels as well as increase in the numbers of vessels admitted to the Strait. When the numbers of vessels admitted to the Strait increase, the time spent in the Strait increases. In other words, the numbers of vessels in queue have effect on performance measures.

7. CONCLUSION

In this study, a mixed integer zero-one formulation is developed with the aim of minimizing the weighted waiting time of transit vessels before entering the Istanbul Strait, while satisfying the Strait maritime R&R and VTCA policies. In the developed mathematical model, minimum pursuit distance rule, vessel classes, importance weights of vessels and pilot requirements are all taken into account. Moreover, overtaking rules are externally handled in order to reduce the model size and complexity. To solve the mathematical model, General Algebraic Modeling System (GAMS) software is used.

In this study, 2011 real data is used as input; however, the logic and solution approach of this study is also applicable for other studies featuring randomly generated vessel arrivals. Before proceeding with the mathematical model, the length of the northbound and southbound traffic flow time windows should be determined. The numbers of Class A or Class B vessels in the northbound and the southbound queues, as well as the length of day time and night time determine the length of the northbound and southbound time windows. The objective function of the mathematical model minimizes the total weighted waiting time of vessels in queue before they enter the Strait. The mathematical model includes nine sets of constraints related the R&R and model assumptions. Each model is run for 120 minutes period. For example, a 48 hour period includes 24 conservative runs. Outputs of a model is inputs of next model. After the getting mathematical model solution, the vessels in individual vessel classes are sorted, in descending order according to their speeds, in order to reduce overtaking needs during their travel through the Strait. The basic scenario outputs are compared with the actual 2011 vessel schedule and quite satisfactory results are obtained, in particular total and average weighted waiting time of vessels, which are the most significant performance measures for the model.

In order to analyze the effects of various factors such as vessel arrival patterns, pilot availability and minimum pursuit distances between vessels, on performance measures, some scenario analysis is accomplished with the mathematical model. It is observed that the numbers of available pilots, the minimum pursuit distance between vessels and vessels

arrival rates have significant effects on total weighted waiting time of vessels, average weighted waiting time per vessel, as well as the number of vessels admitted to the Strait. The increase in the number of available pilots leads to decrease in total weighted waiting time. In case of the increase in minimum pursuit distance between vessels, increase in total weighted waiting time and decrease in the number of vessels admitted to the Strait are observed. Additionally, when the vessel arrival rates increase, the number of vessels admitted to the Strait increase as well as the total and average weighted waiting time of vessels. Finally, the larger number of vessels admitted to the Strait causes the Strait travel times of the vessels to increase.

Recently, there is increasing vessel demand in the Strait, which leads to denser transit vessel traffic in the Strait. VTCA can decrease the minimum pursuit distance vessels or make changes in number of available pilots based on the findings of this study.

8. FURTHER STUDIES

This study includes a zero-one mixed integer mathematical model which schedules the transit vessel entrances to the Strait by satisfying the Istanbul Strait R&R, VTCA policies as well as pilot availability. Moreover, with scenario analysis, the effect of minimum pursuit distance, available number of pilots and arrival pattern on performance measures are evaluated. However, the effects of meteorological and geographical conditions are not considered in this study. They may be integrated to the model and evaluated in an extended study.

The mathematical model standardizes the vessel entrances by satisfying constraints. However, the risk level of parameters and management are out of scope in this study. In an extended version, risk analysis and management may be held.

Only three instances are covered in this study. To make decision on changing parameters, more runs (with randomized vessel arrival sequences) should be covered. Covering more runs will increase reliability of the results.

The “vessel entrance” scheduling approach can be integrated with the Strait vessel passage simulation. This study can be initial step of simulation models.

APPENDIX A: EXTENDED VERSION OF THE MATHEMATICAL MODEL

Table A.1. Indices of Extended Version of The Mathematical Model.

Indice	Indice Explanation
i	Number of ready Class A vessels waiting to enter the Istanbul Strait ($i=1,\dots,I$)
z	Number of ready Class B vessels waiting to enter the Istanbul Strait ($z=1,\dots,Z$)
j	Number of ready Class C1 vessels waiting to enter the Istanbul Strait ($j=1,\dots,J$)
d	Number of ready Class C2 vessels waiting to enter the Istanbul Strait ($d=1,\dots,D$)
k	Number of ready Class D1 vessels waiting to enter the Istanbul Strait ($k=1,\dots,K$)
h	Number of ready Class D2 vessels waiting to enter the Istanbul Strait ($h=1,\dots,H$)
l	Number of ready Class E vessels waiting to enter the Istanbul Strait ($l=1,\dots,L$)
m	Number of ready Class F vessels waiting to enter the Istanbul Strait ($m=1,\dots,M$)
a	Number of ready Class P vessels waiting to enter the Istanbul Strait ($a=1,\dots,A$)

Table A.2. Parameters of Extended Version of The Mathematical Model.

Parameter	Parameter Explanation
$t_{A(i)}$	Ready time of vessel "i" in Class A to enter the Istanbul Strait ($i = 1, \dots, I$)
$t_{B(z)}$	Ready time of vessel "z" in Class B to enter the Istanbul Strait ($z = 1, \dots, Z$)
$t_{C1(j)}$	Ready time of vessel "j" in Class C1 to enter the Istanbul Strait ($j = 1, \dots, J$)
$t_{C2(d)}$	Ready time of vessel "d" in Class C2 to enter the Istanbul Strait ($d = 1, \dots, D$)
$t_{D1(k)}$	Ready time of vessel "k" in Class D1 to enter the Istanbul Strait ($k = 1, \dots, K$)
$t_{D2(h)}$	Ready time of vessel "h" in Class D2 to enter the Istanbul Strait ($h = 1, \dots, H$)
$t_{E(l)}$	Ready time of vessel "l" in Class E to enter the Istanbul Strait ($l=1,\dots,L$)
$t_{F(m)}$	Ready time of vessel "m" in Class F to enter the Istanbul Strait ($m=1,\dots,M$)
$t_{P(a)}$	Ready time of vessel "a" in Class P to enter the Istanbul Strait ($a = 1, \dots, A$)
$S_{AC1(i,j)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "j" in Class C1 ($i = 1, \dots, I$; $j = 1, \dots, J$)
$S_{AC2(i,d)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "d" in Class C1 ($i = 1, \dots, I$; $d = 1, \dots, G$)
$S_{AD1(i,k)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "k" in Class D1 ($i = 1, \dots, I$; $k = 1, \dots, K$)
$S_{AD2(i,h)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "h" in Class D2 ($i = 1, \dots, I$; $h = 1, \dots, H$)
$S_{AE(i,l)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "l" in Class E ($i = 1, \dots, I$; $l = 1, \dots, L$)
$S_{AF(i,m)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "m" in Class F ($i = 1, \dots, I$; $m = 1, \dots, M$)
$S_{AP(i,a)}$	Minimum pursuit distance between vessel "i" in Class A and vessel "a" in Class P ($i = 1, \dots, I$; $a = 1, \dots, A$)

Table A.2. Parameters of Extended Version of The Mathematical Model (continued).

Parameter	Parameter Explanation
$S_{BC1(z,j)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "j" in Class C1 ($z = 1, \dots, Z; j = 1, \dots, J$)
$S_{BC2(z,d)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "d" in Class C1 ($z = 1, \dots, Z; d = 1, \dots, D$)
$S_{BD1(z,k)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "k" in Class D1 ($z = 1, \dots, Z; k = 1, \dots, K$)
$S_{BD2(z,h)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "h" in Class D2 ($z = 1, \dots, Z; h = 1, \dots, H$)
$S_{BF(z,m)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "m" in Class F ($z = 1, \dots, Z; m = 1, \dots, M$)
$S_{BP(z,a)}$	Minimum pursuit distance between vessel "z" in Class B and vessel "a" in Class P ($z = 1, \dots, Z; a = 1, \dots, A$)
$S_{C1C2(j,d)}$	Minimum pursuit distance between vessel "j" in Class C1 and vessel "d" in Class C2 ($j = 1, \dots, J; d = 1, \dots, D$)
$S_{C1D1(j,k)}$	Minimum pursuit distance between vessel "j" in Class D1 and vessel "k" in Class D1 ($j = 1, \dots, J; k = 1, \dots, K$)
$S_{C1D2(j,h)}$	Minimum pursuit distance between vessel "j" in Class C1 and vessel "h" in Class D2 ($j = 1, \dots, J; h = 1, \dots, H$)
$S_{C1E(j,l)}$	Minimum pursuit distance between vessel "j" in Class C1 and vessel "l" in Class E ($j = 1, \dots, J; l = 1, \dots, L$)
$S_{C1F(j,m)}$	Minimum pursuit distance between vessel "j" in Class C1 and vessel "m" in Class F ($j = 1, \dots, J; m = 1, \dots, M$)
$S_{C1P(j,a)}$	Minimum pursuit distance between vessel "j" in Class C1 and vessel "a" in Class P ($j = 1, \dots, J; a = 1, \dots, A$)
$S_{C2D1(d,k)}$	Minimum pursuit distance between vessel "d" in Class C2 and vessel "k" in Class D1 ($d = 1, \dots, D; k = 1, \dots, K$)
$S_{C2D2(d,h)}$	Minimum pursuit distance between vessel "d" in Class C2 and vessel "h" in Class D2 ($d = 1, \dots, D; h = 1, \dots, H$)
$S_{C2E(d,l)}$	Minimum pursuit distance between vessel "d" in Class C2 and vessel "l" in Class E ($d = 1, \dots, D; l = 1, \dots, L$)
$S_{C2F(d,m)}$	Minimum pursuit distance between vessel "d" in Class C2 and vessel "m" in Class F ($d = 1, \dots, D; m = 1, \dots, M$)
$S_{C2P(d,a)}$	Minimum pursuit distance between vessel "d" in Class C2 and vessel "a" in Class P ($d = 1, \dots, D; a = 1, \dots, A$)
$S_{D1D2(k,h)}$	Minimum pursuit distance between vessel "k" in Class D1 and vessel "h" in Class H ($k = 1, \dots, K; h = 1, \dots, H$)
$S_{D1E(k,l)}$	Minimum pursuit distance between vessel "k" in Class D1 and vessel "l" in Class E ($k = 1, \dots, K; l = 1, \dots, L$)
$S_{D1F(k,m)}$	Minimum pursuit distance between vessel "k" in Class D1 and vessel "m" in Class F ($k = 1, \dots, K; m = 1, \dots, M$)
$S_{D1P(k,a)}$	Minimum pursuit distance between vessel "k" in Class D1 and vessel "a" in Class P ($k = 1, \dots, K; a = 1, \dots, A$)
$S_{D2E(h,l)}$	Minimum pursuit distance between vessel "h" in Class H and vessel "l" in Class E ($h = 1, \dots, H; l = 1, \dots, L$)
$S_{D2F(h,m)}$	Minimum pursuit distance between vessel "h" in Class H and vessel "m" in Class F ($h = 1, \dots, H; m = 1, \dots, M$)
$S_{D2P(h,a)}$	Minimum pursuit distance between vessel "h" in Class D2 and vessel "a" in Class P ($h = 1, \dots, H; a = 1, \dots, A$)
$S_{EF(l,m)}$	Minimum pursuit distance between vessel "l" in Class D2 and vessel "m" in Class F ($l = 1, \dots, L; m = 1, \dots, M$)
$S_{EP(l,a)}$	Minimum pursuit distance between vessel "l" in Class D2 and vessel "a" in Class P ($l = 1, \dots, L; a = 1, \dots, A$)
$S_{AA(i)}$	Minimum pursuit distance between two consecutive Class A vessels ($i = 1, \dots, I$)

Table A.2. Parameters of Extended Version of The Mathematical Model (continued).

Parameter	Parameter Explanation
$S_{BB(z)}$	Minimum pursuit distance between two consecutive Class B vessels ($z = 1, \dots, Z$)
$S_{C1C1(j)}$	Minimum pursuit distance between two consecutive Class C1 vessels ($j = 1, \dots, J$)
$S_{C2C2(d)}$	Minimum pursuit distance between two consecutive Class C2 vessels ($d = 1, \dots, D$)
$S_{D1D1(k)}$	Minimum pursuit distance between two consecutive Class D1 vessels ($k = 1, \dots, K$)
$S_{D2D2(h)}$	Minimum pursuit distance between two consecutive Class D2 vessels ($h = 1, \dots, H$)
$S_{EE(l)}$	Minimum pursuit distance between two consecutive Class E vessels ($l = 1, \dots, L$)
$S_{FF(m)}$	Minimum pursuit distance between two consecutive Class F vessels ($m = 1, \dots, M$)
$S_{PP(a)}$	Minimum pursuit distance between two consecutive Class P vessels ($a = 1, \dots, A$)
V	The start of determined time interval
W	The end of determined time interval
R	Available number of pilot captains
B	Very large number
T_A	Class A vessels enter the Strait after T_A time if they do not enter the Strait in the time interval under consideration (between V and W)
T_B	Class B vessels enter the Strait after T_B time if they do not enter the Strait in the time interval under consideration (between V and W)
T_{C1}	Class C1 vessels enter the Strait after T_{C1} time if they do not enter the Strait in the time interval under consideration (between V and W)
T_{C2}	Class C2 vessels enter the Strait after T_{C2} time if they do not enter the Strait in the time interval under consideration (between V and W)
T_{D1}	Class D1 vessels enter the Strait after T_{D1} time if they do not enter the Strait in the time interval under consideration (between V and W)
T_{D2}	Class D2 vessels enter the Strait after T_{D2} time if they do not enter the Strait in the time interval under consideration (between V and W)
T_E	Class E vessels enter the Strait after T_E time if they do not enter the Strait in the time interval under consideration (between V and W)
T_F	Class F vessels enter the Strait after T_F time if they do not enter the Strait in the time interval under consideration (between V and W)
T_P	Class P vessels enter the Strait after T_P time if they do not enter the Strait in the time interval under consideration (between V and W)
α_A	The importance weight of class A
α_B	The importance weight of class B
α_{C1}	The importance weight of class C1
α_{C2}	The importance weight of class C2
α_{D1}	The importance weight of class D1
α_{D2}	The importance weight of class D2

Table A.2. Parameters of Extended Version of The Mathematical Model (continued).

Parameter	Parameter Explanation
α_E	The importance weight of class E
α_F	The importance weight of class F
α_P	The importance weight of class P

Table A.3. Decision Variables of Extended Version of The Mathematical Model.

Decision Variable	Explanation of Decision Variable
$x_{A(i)}$	Entrance time of vessel i in class A to the Istanbul Strait
$x_{B(z)}$	Entrance time of vessel z in class B to the Istanbul Strait
$x_{C1(j)}$	Entrance time of vessel j in class C1 to the Istanbul Strait
$x_{C2(d)}$	Entrance time of vessel d in class C2 to the Istanbul Strait
$x_{D1(k)}$	Entrance time of vessel k in class D1 to the Istanbul Strait
$x_{D2(p)}$	Entrance time of vessel p in class D2 to the Istanbul Strait
$x_{E(l)}$	Entrance time of vessel l in class E to the Istanbul Strait
$x_{F(m)}$	Entrance time of vessel m in class F to the Istanbul Strait
$x_{P(a)}$	Entrance time of vessel a in class P to the Istanbul Strait
Z	Total Weighted Waiting Times of vessels before entering the Strait
$y_{A(i)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{B(z)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{C1(j)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{C2(d)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{D1(k)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{D2(h)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{E(l)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{F(m)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$y_{P(a)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait during the time interval under consideration, and with a value of 0, otherwise
$\theta_{AC1(i,j)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{AC2(i,d)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise

Table A.3. Decision Variables of Extended Version of The Mathematical Model
(continued).

Decision Variable	Explanation of Decision Variable
$\theta_{AD1(i,k)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{AD2(i,h)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel h in Class D2, and with a value of 0 otherwise
$\theta_{AE(i,l)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{AF(i,m)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{AP(i,a)}$	Binary variable with a value of 1, if vessel i in class A enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{BC1(z,j)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{BC2(z,d)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{BD1(z,k)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{BD2(z,h)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel p in Class D2, and with a value of 0 otherwise
$\theta_{BE(z,l)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{BF(z,m)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{BP(z,a)}$	Binary variable with a value of 1, if vessel z in class B enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{C1A(j,i)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{C1B(j,z)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise
$\theta_{C1C2(j,d)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{C1D1(j,k)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{C1D2(j,h)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel h in Class D2, and with a value of 0 otherwise
$\theta_{C1E(j,l)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{C1F(j,m)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{C1P(j,a)}$	Binary variable with a value of 1, if vessel j in class C1 enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{C2A(d,i)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{C2B(d,z)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise
$\theta_{C2C1(d,j)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{C2D1(d,k)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{C2D2(d,h)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel h in Class D2, and with a value of 0 otherwise
$\theta_{C2E(d,l)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{C2F(d,m)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise

Table A.3. Decision Variables of Extended Version of The Mathematical Model
(continued).

Decision Variable	Explanation of Decision Variable
$\theta_{C2P(d,a)}$	Binary variable with a value of 1, if vessel d in class C2 enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{D1A(k,i)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{D1B(k,z)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise
$\theta_{D1C2(k,d)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{D1C1(k,j)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{D1D2(k,h)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel h in Class D2, and with a value of 0, otherwise
$\theta_{D1E(k,l)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{D1F(k,m)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel m in Class F, and with a value of 0, otherwise
$\theta_{D1P(k,a)}$	Binary variable with a value of 1, if vessel k in class D1 enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{D2A(h,i)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{D2B(h,z)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise
$\theta_{D2C2(h,d)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{D2D1(h,k)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel k in Class D1, and with a value of 0, otherwise
$\theta_{D2C1(h,j)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel j in Class C1, and with a value of 0, otherwise
$\theta_{D2E(h,l)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{D2F(h,m)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{D2P(h,a)}$	Binary variable with a value of 1, if vessel h in class D2 enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{EA(l,i)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{EB(l,z)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel z in Class B, and with a value of 0, otherwise
$\theta_{EC2(l,d)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{ED1(l,k)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{ED2(l,p)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel p in Class D2, and with a value of 0 otherwise
$\theta_{EC1(l,j)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{EF(l,m)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{EP(l,a)}$	Binary variable with a value of 1, if vessel l in class E enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{FA(m,i)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{FB(m,z)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise

Table A.3. Decision Variables of Extended Version of The Mathematical Model
(continued).

Decision Variable	Explanation of Decision Variable
$\theta_{FC2(m,d)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{FD1(m,k)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{FD2(m,h)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel h in Class D2, and with a value of 0 otherwise
$\theta_{FE(m,l)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{FC1(m,j)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise
$\theta_{FP(m,a)}$	Binary variable with a value of 1, if vessel m in class F enters the Istanbul Strait before vessel a in Class P, and with a value of 0 otherwise
$\theta_{PA(a,i)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel i in Class A, and with a value of 0 otherwise
$\theta_{PB(a,z)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel z in Class B, and with a value of 0 otherwise
$\theta_{PC2(a,d)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel d in Class C2, and with a value of 0 otherwise
$\theta_{PD1(a,k)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel k in Class D1, and with a value of 0 otherwise
$\theta_{PD2(a,h)}$	Binary variable with a value of 1, if vessel h in class P enters the Istanbul Strait before vessel p in Class D2, and with a value of 0 otherwise
$\theta_{PE(a,l)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel l in Class E, and with a value of 0 otherwise
$\theta_{PF(a,m)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel m in Class F, and with a value of 0 otherwise
$\theta_{PC1(a,j)}$	Binary variable with a value of 1, if vessel a in class P enters the Istanbul Strait before vessel j in Class C1, and with a value of 0 otherwise

A.1 The Mathematical Model

$$\begin{aligned} \text{Min } Z = & \alpha_A * \sum_{i=1}^I (xA(i) - tA(i)) + \alpha_B * \sum_{z=1}^Z (xB(z) - tB(z)) + \alpha_{C1} * \sum_{j=1}^J (xC1(j) - \\ & tC1(j)) + \alpha_{C2} * \sum_{d=1}^D (xC2(d) - tC2(d)) + \alpha_{D1} * \sum_{k=1}^K (xD1(k) - tD1(k)) + \\ & \alpha_{D2} * \sum_{p=1}^P (xD2(p) - tD2(p)) + \alpha_E * \sum_{l=1}^L (xE(l) - tE(l)) + \alpha_F * \sum_{m=1}^M (xF(m) - tF(m)) \\ & + \alpha_P * \sum_{a=1}^A (xP(a) - tP(a)) \end{aligned}$$

s.t.

$$\begin{aligned} t_{A(i)} &\leq x_{A(i)} && \forall i \\ t_{B(z)} &\leq x_{B(z)} && \forall z \\ t_{C1(j)} &\leq x_{C1(j)} && \forall j \\ t_{C2(d)} &\leq x_{C2(d)} && \forall d \\ t_{D1(k)} &\leq x_{D1(k)} && \forall k \end{aligned}$$

$$\begin{array}{ll}
t_{D2(p)} \leq x_{D2(p)} & \forall p \\
t_{E(l)} \leq x_{E(l)} & \forall l \\
t_{F(m)} \leq x_{F(m)} & \forall m \\
t_{P(a)} \leq x_{P(a)} & \forall a \\
\theta_{AC1(i,j)} + \theta_{C1A(j,i)} = 1 & \forall i, \forall j \\
x_{A(i)} + s_{AC1(i,j)} - B^* \theta_{C1A(j,i)} \leq x_{C1(j)} & \forall i, \forall j \\
x_{C1(j)} + s_{AC1(i,j)} - B^* \theta_{AC1(i,j)} \leq x_{A(i)} & \forall i, \forall j \\
\theta_{AC2(i,d)} + \theta_{C2A(d,i)} = 1 & \forall i, \forall d \\
x_{A(i)} + s_{AC2(i,d)} - B^* \theta_{C2A(d,i)} \leq x_{C2(d)} & \forall i, \forall d \\
x_{C2(d)} + s_{AC2(i,d)} - B^* \theta_{AC2(i,d)} \leq x_{A(i)} & \forall i, \forall d \\
\theta_{AD1(i,k)} + \theta_{D1A(k,i)} = 1 & \forall i, \forall k \\
x_{A(i)} + s_{AD1(i,k)} - B^* \theta_{D1A(k,i)} \leq x_{D1(k)} & \forall i, \forall k \\
x_{D1(k)} + s_{AD1(i,k)} - B^* \theta_{AD1(i,k)} \leq x_{A(i)} & \forall i, \forall k \\
\theta_{AD2(i,p)} + \theta_{D2A(p,i)} = 1 & \forall i, \forall p \\
x_{A(i)} + s_{AD2(i,p)} - B^* \theta_{D2A(p,i)} \leq x_{D2(p)} & \forall i, \forall p \\
x_{D2(p)} + s_{AD2(i,p)} - B^* \theta_{AD2(i,p)} \leq x_{A(i)} & \forall i, \forall p \\
\theta_{AE(i,l)} + \theta_{EA(l,i)} = 1 & \forall i, \forall l \\
x_{A(i)} + s_{AE(i,l)} - B^* \theta_{EA(l,i)} \leq x_{E(l)} & \forall i, \forall l \\
x_{E(l)} + s_{AE(i,l)} - B^* \theta_{AE(i,l)} \leq x_{A(i)} & \forall i, \forall l \\
\theta_{AF(i,m)} + \theta_{FA(m,i)} = 1 & \forall i, \forall m \\
x_{A(i)} + s_{AF(i,m)} - B^* \theta_{FA(m,i)} \leq x_{F(m)} & \forall i, \forall m \\
x_{F(m)} + s_{AF(i,m)} - B^* \theta_{AF(i,m)} \leq x_{A(i)} & \forall i, \forall m \\
\theta_{AP(i,a)} + \theta_{PA(a,i)} = 1 & \forall i, \forall a \\
x_{A(i)} + s_{AP(i,a)} - B^* \theta_{PA(a,i)} \leq x_{P(a)} & \forall i, \forall a \\
x_{P(a)} + s_{AP(i,a)} - B^* \theta_{AP(i,a)} \leq x_{A(i)} & \forall i, \forall a \\
\theta_{BC1(z,j)} + \theta_{C1B(j,z)} = 1 & \forall z, \forall j \\
x_{B(z)} + s_{BC1(z,j)} - B^* \theta_{C1B(j,z)} \leq x_{C1(j)} & \forall z, \forall j \\
x_{C1(j)} + s_{BC1(z,j)} - B^* \theta_{BC1(z,j)} \leq x_{B(z)} & \forall z, \forall j \\
\theta_{BC2(z,d)} + \theta_{C2B(d,z)} = 1 & \forall z, \forall d \\
x_{B(z)} + s_{BC2(z,d)} - B^* \theta_{C2B(d,z)} \leq x_{C2(d)} & \forall z, \forall d \\
x_{C2(d)} + s_{BC2(z,d)} - B^* \theta_{BC2(z,d)} \leq x_{B(z)} & \forall z, \forall d
\end{array}$$

$$\begin{array}{ll}
\theta_{BD1(z,k)} + \theta_{D1B(k,z)} = 1 & \forall z, \forall k \\
x_{B(z)} + s_{BD1(z,k)} - B^* \theta_{D1B(k,z)} \leq x_{D1(k)} & \forall z, \forall k \\
x_{D1(k)} + s_{BD1(z,k)} - B^* \theta_{BD1(z,k)} \leq x_{B(z)} & \forall z, \forall k \\
\theta_{BD2(z,p)} + \theta_{D2B(k,p)} = 1 & \forall z, \forall p \\
x_{B(z)} + s_{BD2(z,p)} - B^* \theta_{D2B(p,z)} \leq x_{D2(p)} & \forall z, \forall p \\
x_{D2(p)} + s_{BD2(z,p)} - B^* \theta_{BD2(z,p)} \leq x_{B(z)} & \forall z, \forall p \\
\theta_{BF(z,m)} + \theta_{FB(m,z)} = 1 & \forall z, \forall m \\
x_{B(z)} + s_{BF(z,m)} - B^* \theta_{FB(m,z)} \leq x_{F(m)} & \forall z, \forall m \\
x_{F(m)} + s_{BF(z,m)} - B^* \theta_{BF(z,m)} \leq x_{B(z)} & \forall z, \forall m \\
\theta_{BP(z,a)} + \theta_{PB(a,z)} = 1 & \forall z, \forall a \\
x_{B(z)} + s_{BP(z,B)} - B^* \theta_{PB(B,z)} \leq x_{P(B)} & \forall z, \forall a \\
x_{P(B)} + s_{BP(z,B)} - B^* \theta_{BP(z,B)} \leq x_{B(z)} & \forall z, \forall a \\
\theta_{C1C2(j,d)} + \theta_{C2C1(d,j)} = 1 & \forall j, \forall d \\
x_{C1(j)} + s_{C1C2(j,d)} - B^* \theta_{C2C1(d,j)} \leq x_{C2(d)} & \forall j, \forall d \\
x_{C2(d)} + s_{C1C2(j,d)} - B^* \theta_{C1C2(j,d)} \leq x_{C1(j)} & \forall j, \forall d \\
\theta_{C1D1(j,k)} + \theta_{D1C1(k,j)} = 1 & \forall j, \forall k \\
x_{C1(j)} + s_{C1D1(j,k)} - B^* \theta_{D1C1(k,j)} \leq x_{D1(k)} & \forall j, \forall k \\
x_{D1(k)} + s_{C1D1(j,k)} - B^* \theta_{C1D1(j,k)} \leq x_{C1(j)} & \forall j, \forall k \\
\theta_{C1D2(j,p)} + \theta_{D2C1(p,j)} = 1 & \forall j, \forall p \\
x_{C1(j)} + s_{C1D2(j,p)} - B^* \theta_{D2C1(p,j)} \leq x_{D2(p)} & \forall j, \forall p \\
x_{D2(p)} + s_{C1D2(j,p)} - B^* \theta_{C1D2(j,p)} \leq x_{C1(j)} & \forall j, \forall p \\
\theta_{C1E(j,l)} + \theta_{EC1(l,j)} = 1 & \forall j, \forall l \\
x_{C1(j)} + s_{C1E(j,l)} - B^* \theta_{EC1(l,j)} \leq x_{E(l)} & \forall j, \forall l \\
x_{E(l)} + s_{C1E(j,l)} - B^* \theta_{C1E(j,l)} \leq x_{C1(j)} & \forall j, \forall l \\
\theta_{C1F(j,m)} + \theta_{FC1(m,j)} = 1 & \forall j, \forall m \\
x_{C1(j)} + s_{C1F(j,m)} - B^* \theta_{FC1(m,j)} \leq x_{F(m)} & \forall j, \forall m \\
x_{F(m)} + s_{C1F(j,m)} - B^* \theta_{C1F(j,m)} \leq x_{C1(j)} & \forall j, \forall m \\
\theta_{C1P(j,a)} + \theta_{PC1(a,p)} = 1 & \forall j, \forall a \\
x_{C1(j)} + s_{C1P(j,a)} - B^* \theta_{PC1(a,j)} \leq x_{P(a)} & \forall j, \forall a \\
x_{P(a)} + s_{C1P(j,a)} - B^* \theta_{C1P(j,a)} \leq x_{C1(j)} & \forall j, \forall a \\
\theta_{C2D1(d,k)} + \theta_{D1C2(k,d)} = 1 & \forall d, \forall k
\end{array}$$

$$\begin{aligned}
& X_{C2(d)} + S_{C2D1(d,k)} - B^* \theta_{D1C2(k,d)} \leq X_{D1(k)} && \forall d, \forall k \\
& X_{D1(k)} + S_{C2D1(d,k)} - B^* \theta_{C2D1(d,k)} \leq X_{C2(d)} && \forall d, \forall k \\
& \theta_{C2D2(d,p)} + \theta_{D2C2(k,p)} = 1 && \forall d, \forall p \\
& X_{C2(d)} + S_{C2D2(d,p)} - B^* \theta_{D2C2(p,d)} \leq X_{D2(p)} && \forall d, \forall p \\
& X_{D2(p)} + S_{C2D2(d,p)} - B^* \theta_{C2D2(d,p)} \leq X_{C2(d)} && \forall d, \forall p \\
& \theta_{C2E(d,l)} + \theta_{EC2(l,p)} = 1 && \forall d, \forall l \\
& X_{C2(d)} + S_{C2E(d,l)} - B^* \theta_{EC2(l,d)} \leq X_{E(l)} && \forall d, \forall l \\
& X_{E(l)} + S_{C2E(d,l)} - B^* \theta_{C2E(d,l)} \leq X_{C2(d)} && \forall d, \forall l \\
& \theta_{C2F(d,m)} + \theta_{FC2(m,p)} = 1 && \forall d, \forall m \\
& X_{C2(d)} + S_{C2F(d,m)} - B^* \theta_{FC2(m,d)} \leq X_{F(m)} && \forall d, \forall m \\
& X_{F(m)} + S_{C2F(d,m)} - B^* \theta_{C2F(d,m)} \leq X_{C2(d)} && \forall d, \forall m \\
& \theta_{C2P(d,a)} + \theta_{PC2(a,p)} = 1 && \forall d, \forall a \\
& X_{C2(d)} + S_{C2P(d,a)} - B^* \theta_{PC2(a,d)} \leq X_{P(a)} && \forall d, \forall a \\
& X_{P(a)} + S_{C2P(d,a)} - B^* \theta_{C2P(d,a)} \leq X_{C2(a)} && \forall d, \forall a \\
& \theta_{D1D2(k,p)} + \theta_{D2D1(k,p)} = 1 && \forall k, \forall p \\
& X_{D1(k)} + S_{D1D2(k,p)} - B^* \theta_{D2D1(p,k)} \leq X_{D2(p)} && \forall k, \forall p \\
& X_{D2(p)} + S_{D1D2(k,p)} - B^* \theta_{D1D2(k,p)} \leq X_{D1(k)} && \forall k, \forall p \\
& \theta_{D1E(k,l)} + \theta_{ED1(l,k)} = 1 && \forall k, \forall l \\
& X_{D1(k)} + S_{D1E(k,l)} - B^* \theta_{ED1(l,k)} \leq X_{E(l)} && \forall k, \forall l \\
& X_{E(l)} + S_{D1E(k,l)} - B^* \theta_{D1E(k,l)} \leq X_{D1(k)} && \forall k, \forall l \\
& \theta_{D1F(k,m)} + \theta_{FD1(m,k)} = 1 && \forall k, \forall m \\
& X_{D1(k)} + S_{D1F(k,m)} - B^* \theta_{FD1(m,k)} \leq X_{F(m)} && \forall k, \forall m \\
& X_{F(m)} + S_{D1F(k,m)} - B^* \theta_{D1F(k,m)} \leq X_{D1(k)} && \forall k, \forall m \\
& \theta_{D1P(k,a)} + \theta_{PD1(a,k)} = 1 && \forall k, \forall a \\
& X_{D1(k)} + S_{D1P(k,a)} - B^* \theta_{PD1(a,k)} \leq X_{P(a)} && \forall k, \forall a \\
& X_{P(a)} + S_{D1P(k,a)} - B^* \theta_{D1P(k,a)} \leq X_{D1(k)} && \forall k, \forall a \\
& \theta_{D2E(p,l)} + \theta_{ED2(l,p)} = 1 && \forall p, \forall l \\
& X_{D2(p)} + S_{D2E(p,l)} - B^* \theta_{ED2(l,p)} \leq X_{E(l)} && \forall p, \forall l \\
& X_{E(l)} + S_{D2E(p,l)} - B^* \theta_{D2E(p,l)} \leq X_{D2(p)} && \forall p, \forall l \\
& \theta_{D2F(p,m)} + \theta_{FD2(m,p)} = 1 && \forall p, \forall m \\
& X_{D2(p)} + S_{D2F(p,m)} - B^* \theta_{FD2(m,p)} \leq X_{F(m)} && \forall p, \forall m
\end{aligned}$$

$$\begin{aligned}
x_{D2(p)} + s_{D2F(p,m)} - B^* \theta_{D2F(p,m)} &\leq x_{D2(p)} && \forall p, \forall m \\
\theta_{D2P(p,a)} + \theta_{PD2(a,p)} &= 1 && \forall p, \forall a \\
x_{D2(p)} + s_{D2P(p,a)} - B^* \theta_{PD2(a,p)} &\leq x_{P(a)} && \forall p, \forall a \\
x_{P(a)} + s_{D2P(p,a)} - B^* \theta_{D2P(p,a)} &\leq x_{D2(p)} && \forall p, \forall a \\
\theta_{EF(l,m)} + \theta_{FE(m,l)} &= 1 && \forall l, \forall m \\
x_{E(l)} + s_{EF(l,m)} - B^* \theta_{FE(m,l)} &\leq x_{F(m)} && \forall l, \forall m \\
x_{F(m)} + s_{EF(l,m)} - B^* \theta_{EF(l,m)} &\leq x_{E(l)} && \forall l, \forall m \\
\theta_{EP(l,a)} + \theta_{PE(a,l)} &= 1 && \forall l, \forall a \\
x_{E(l)} + s_{EP(l,a)} - B^* \theta_{PE(a,l)} &\leq x_{P(a)} && \forall l, \forall a \\
x_{P(a)} + s_{EP(l,a)} - B^* \theta_{EP(l,a)} &\leq x_{E(l)} && \forall l, \forall a \\
\theta_{FP(m,a)} + \theta_{PF(a,m)} &= 1 && \forall m, \forall a \\
x_{F(m)} + s_{FP(m,a)} - B^* \theta_{PF(a,m)} &\leq x_{P(a)} && \forall m, \forall a \\
x_{P(a)} + s_{FP(m,a)} - B^* \theta_{FP(m,a)} &\leq x_{F(m)} && \forall m, \forall a \\
\sum_{i=1}^{i-1} x_{A(i)} + \sum_{i=1}^{i-1} s_{AA(i)} &\leq \sum_{i=1}^{i-1} x_{A(i+1)} && (i-1) \geq 1 \\
\sum_{z=1}^{z-1} x_{B(z)} + \sum_{z=1}^{z-1} s_{BB(z)} &\leq \sum_{z=1}^{z-1} x_{B(z+1)} && (z-1) \geq 1 \\
\sum_{j=1}^{j-1} x_{C1(j)} + \sum_{j=1}^{j-1} s_{C1C1(j)} &\leq \sum_{j=1}^{j-1} x_{C1(j+1)} && (j-1) \geq 1 \\
\sum_{d=1}^{d-1} x_{C2(d)} + \sum_{d=1}^{d-1} s_{C2C2(d)} &\leq \sum_{d=1}^{d-1} x_{C2(d+1)} && (d-1) \geq 1 \\
\sum_{k=1}^{k-1} x_{D1(k)} + \sum_{k=1}^{k-1} s_{D1D1(k)} &\leq \sum_{k=1}^{k-1} x_{D1(k+1)} && (k-1) \geq 1 \\
\sum_{p=1}^{p-1} x_{D2(p)} + \sum_{p=1}^{p-1} s_{D2D2(p)} &\leq \sum_{p=1}^{p-1} x_{D2(p+1)} && (p-1) \geq 1 \\
\sum_{l=1}^{l-1} x_{E(l)} + \sum_{l=1}^{l-1} s_{E(l)} &\leq \sum_{l=1}^{l-1} x_{E(l+1)} && (l-1) \geq 1 \\
\sum_{m=1}^{m-1} x_{F(m)} + \sum_{m=1}^{m-1} s_{FF(m)} &\leq \sum_{m=1}^{m-1} x_{F(m+1)} && (m-1) \geq 1 \\
\sum_{a=1}^{a-1} x_{P(a)} + \sum_{a=1}^{a-1} s_{PP(a)} &\leq \sum_{a=1}^{a-1} x_{P(a+1)} && (a-1) \geq 1 \\
x_{A(i)} &\leq W + (1 - y_{A(i)}) * B && \forall i \\
x_{B(z)} &\leq W + (1 - y_{B(z)}) * B && \forall z \\
x_{C1(j)} &\leq W + (1 - y_{C1(j)}) * B && \forall j \\
x_{C2(d)} &\leq W + (1 - y_{C2(d)}) * B && \forall d \\
x_{D1(k)} &\leq W + (1 - y_{D1(k)}) * B && \forall k \\
x_{D2(p)} &\leq W + (1 - y_{D2(p)}) * B && \forall p \\
x_{E(l)} &\leq W + (1 - y_{E(l)}) * B && \forall l \\
x_{F(m)} &\leq W + (1 - y_{F(m)}) * B && \forall m \\
x_{P(a)} &\leq W + (1 - y_{P(a)}) * B && \forall a
\end{aligned}$$

$$\begin{aligned}
x_{A(i)} &\geq V && \forall i \\
x_{B(z)} &\geq V && \forall z \\
x_{C1(j)} &\geq V && \forall j \\
x_{C2(d)} &\geq V && \forall d \\
x_{D1(k)} &\geq V && \forall k \\
x_{D2(p)} &\geq V && \forall p \\
x_{E(l)} &\geq V && \forall l \\
x_{F(m)} &\geq V && \forall m \\
x_{P(a)} &\geq V && \forall a \\
x_{A(i)} &\geq (1 - y_{A(i)}) * (W + T_A) && \forall i \\
x_{B(z)} &\geq (1 - y_{B(z)}) * (W + T_B) && \forall z \\
x_{C1(j)} &\geq (1 - y_{C1(j)}) * (W + T_{C1}) && \forall j \\
x_{C2(d)} &\geq (1 - y_{C2(d)}) * (W + T_{C2}) && \forall d \\
x_{D1(k)} &\geq (1 - y_{D1(k)}) * (W + T_{D1}) && \forall k \\
x_{D2(p)} &\geq (1 - y_{D2(p)}) * (W + T_{D2}) && \forall p \\
x_{E(l)} &\geq (1 - y_{E(l)}) * (W + T_E) && \forall l \\
x_{F(m)} &\geq (1 - y_{F(m)}) * (W + T_F) && \forall m \\
x_{P(a)} &\geq (1 - y_{P(a)}) * (W + T_P) && \forall a \\
\sum_i^I y_{A(i)} + \sum_z^Z y_{B(z)} + \sum_j^J y_{C1(j)} + \sum_k^K y_{D1(k)} + \sum_l^L y_{E(l)} + \sum_a^A y_{P(a)} &\leq A && \forall i, \forall z, \forall j, \forall k, \\
&&& \forall l, \forall a
\end{aligned}$$

APPENDIX B: MATHEMATICAL MODEL SOLUTION

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26 -27th of September.

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W1	0.28	A_1	25Sep11 04:57	25Sep11 05:40	11
Northbound Day Time W1	0.08	F_1	25Sep11 00:56	25Sep11 05:45	9
Northbound Day Time W1	0.09	D1_2	25Sep11 03:54	25Sep11 05:50	14
Northbound Day Time W1	0.18	C1_1	25Sep11 00:02	25Sep11 06:00	15
Northbound Day Time W1	0.04	D2_4	25Sep11 04:43	25Sep11 06:10	14
Northbound Day Time W1	0.13	C2_1	25Sep11 01:24	25Sep11 06:20	13
Northbound Day Time W1	0.04	D2_3	25Sep11 03:19	25Sep11 06:30	13
Northbound Day Time W1	0.13	C2_2	25Sep11 02:19	25Sep11 06:40	12
Northbound Day Time W1	0.09	D1_1	25Sep11 03:14	25Sep11 06:50	11
Northbound Day Time W1	0.18	C1_2	25Sep11 00:14	25Sep11 07:00	12
Northbound Day Time W1	0.04	D2_1	25Sep11 01:16	25Sep11 07:10	11
Northbound Day Time W1	0.18	C1_4	25Sep11 07:03	25Sep11 07:20	12
Northbound Day Time W1	0.09	D1_3	25Sep11 04:12	25Sep11 07:30	10
Northbound Day Time W1	0.09	D1_4	25Sep11 05:33	25Sep11 07:40	10
Northbound Day Time W1	0.08	F_2	25Sep11 05:54	25Sep11 07:45	11
Northbound Day Time W1	0.21	E_1	25Sep11 06:50	25Sep11 07:50	18
Northbound Day Time W1	0.04	D2_5	25Sep11 06:37	25Sep11 08:00	9
Northbound Day Time W1	0.18	C1_5	25Sep11 07:45	25Sep11 08:10	12
Northbound Day Time W1	0.04	D2_7	25Sep11 08:14	25Sep11 08:20	10
Northbound Day Time W1	0.04	D2_6	25Sep11 08:13	25Sep11 08:30	11
Northbound Day Time W1	0.09	D1_6	25Sep11 06:17	25Sep11 08:40	9
Northbound Day Time W1	0.09	D1_9	25Sep11 07:31	25Sep11 08:50	9
Northbound Day Time W1	0.09	D1_10	25Sep11 07:35	25Sep11 09:00	9
Northbound Day Time W1	0.09	D1_11	25Sep11 07:40	25Sep11 09:10	8
Northbound Day Time W1	0.04	D2_8	25Sep11 09:11	25Sep11 09:20	11
Northbound Day Time W1	0.04	D2_9	25Sep11 09:11	25Sep11 09:30	10
Northbound Day Time W1	0.08	F_3	25Sep11 06:59	25Sep11 09:35	10
Northbound Day Time W1	0.18	C1_6	25Sep11 08:45	25Sep11 09:40	12
Northbound Day Time W1	0.09	D1_13	25Sep11 09:12	25Sep11 09:50	10
Northbound Day Time W1	0.18	C1_3	25Sep11 04:02	25Sep11 10:00	11.Oca
Northbound Day Time W1	0.09	D1_12	25Sep11 08:16	25Sep11 10:10	11
Northbound Day Time W1	0.09	D1_5	25Sep11 05:37	25Sep11 10:20	8
Northbound Day Time W1	0.09	D1_5	25Sep11 05:37	25Sep11 10:30	8
Northbound Day Time W1	0.09	D1_7	25Sep11 06:47	25Sep11 10:40	8
Northbound Day Time W1	0.09	D1_8	25Sep11 07:30	25Sep11 10:50	8
2 Hours Interlude for Direction Change					
Southbound Day Time W1	0.26	A_1	25Sep11 02:04	25Sep11 12:50	14
Southbound Day Time W1	0.08	F_3	25Sep11 08:43	25Sep11 12:55	12
Southbound Day Time W1	0.04	D2_7	25Sep11 05:59	25Sep11 13:00	14
Southbound Day Time W1	0.13	C2_1	25Sep11 09:09	25Sep11 13:10	15
Southbound Day Time W1	0.09	D1_7	25Sep11 06:16	25Sep11 13:20	12
Southbound Day Time W1	0.18	C1_2	25Sep11 07:07	25Sep11 13:30	14
Southbound Day Time W1	0.09	D1_12	25Sep11 12:30	25Sep11 13:40	11
Southbound Day Time W1	0.21	E_1	25Sep11 00:12	25Sep11 13:50	13
Southbound Day Time W1	0.09	D1_13	25Sep11 12:46	25Sep11 14:00	11
Southbound Day Time W1	0.08	F_1	25Sep11 01:38	25Sep11 14:05	10
Southbound Day Time W1	0.18	C1_3	25Sep11 08:41	25Sep11 14:10	14

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26 – 27th of September (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Day Time W1	0.04	D2_5	25Sep11 04:39	25Sep11 14:20	11
Southbound Day Time W1	0.18	C1_1	25Sep11 00:10	25Sep11 14:30	12
Southbound Day Time W1	0.04	D2_6	25Sep11 05:40	25Sep11 14:40	11
Southbound Day Time W1	0.18	C1_4	25Sep11 11:53	25Sep11 14:50	11
Southbound Day Time W1	0.08	F_2	25Sep11 06:56	25Sep11 14:55	9
Southbound Day Time W1	0.04	D2_4	25Sep11 02:37	25Sep11 15:00	11
Southbound Day Time W1	0.13	C2_2	25Sep11 10:15	25Sep11 15:10	10
Southbound Day Time W1	0.04	D2_10	25Sep11 07:04	25Sep11 15:20	11
Southbound Day Time W1	0.09	D1_3	25Sep11 03:56	25Sep11 15:30	10
Southbound Day Time W1	0.04	D2_1	25Sep11 00:15	25Sep11 15:40	10
Southbound Day Time W1	0.09	D1_4	25Sep11 04:17	25Sep11 15:50	10
Southbound Day Time W1	0.09	D1_8	25Sep11 07:36	25Sep11 16:00	10
Southbound Day Time W1	0.09	D1_9	25Sep11 09:38	25Sep11 16:10	10
Southbound Day Time W1	0.09	D1_10	25Sep11 10:37	25Sep11 16:20	10
Southbound Day Time W1	0.09	D1_11	25Sep11 11:43	25Sep11 16:30	10
Southbound Day Time W1	0.09	D1_14	25Sep11 13:35	25Sep11 16:40	10
Southbound Day Time W1	0.09	D1_5	25Sep11 05:15	25Sep11 16:50	9
Southbound Day Time W1	0.04	D2_2	25Sep11 00:20	25Sep11 17:00	9
Southbound Day Time W1	0.04	D2_8	25Sep11 06:12	25Sep11 17:10	9
Southbound Day Time W1	0.09	D1_1	25Sep11 02:16	25Sep11 17:20	8
Southbound Day Time W1	0.04	D2_3	25Sep11 02:15	25Sep11 17:30	8
Southbound Day Time W1	0.04	D2_9	25Sep11 06:14	25Sep11 17:40	8
Southbound Day Time W1	0.09	D1_2	25Sep11 03:37	25Sep11 17:50	8
Southbound Day Time W1	0.09	D1_6	25Sep11 05:30	25Sep11 18:00	8
Southbound Day Time W1	0.04	D2_11	25Sep11 08:02	25Sep11 18:10	8
Southbound Night Time W1	0.26	B_1	25Sep11 07:29	25Sep11 18:20	12
Southbound Night Time W1	0.04	D2_1	25Sep11 05:59	25Sep11 18:30	14
Southbound Night Time W1	0.04	D2_2	25Sep11 06:12	25Sep11 18:40	9
Southbound Night Time W1	0.09	D1_1	25Sep11 16:35	25Sep11 18:50	7
Southbound Night Time W1	0.18	C1_2	25Sep11 18:02	25Sep11 19:00	13
Southbound Night Time W1	0.04	D2_7	25Sep11 09:54	25Sep11 19:10	13
Southbound Night Time W1	0.09	D1_2	25Sep11 18:51	25Sep11 19:20	13
Southbound Night Time W1	0.26	B_2	25Sep11 13:27	25Sep11 19:35	13
Southbound Night Time W1	0.04	D2_11	25Sep11 12:11	25Sep11 19:45	12
Southbound Night Time W1	0.18	C1_1	25Sep11 16:55	25Sep11 19:55	11
Southbound Night Time W1	0.04	D2_12	25Sep11 12:52	25Sep11 20:05	12
Southbound Night Time W1	0.04	D2_4	25Sep11 07:04	25Sep11 20:15	11
Southbound Night Time W1	0.04	D2_15	25Sep11 13:54	25Sep11 20:25	11
Southbound Night Time W1	0.04	D2_16	25Sep11 13:57	25Sep11 20:35	11
Southbound Night Time W1	0.26	B_3	25Sep11 15:30	25Sep11 20:50	10
Southbound Night Time W1	0.08	F_1	25Sep11 19:50	25Sep11 20:55	10
Southbound Night Time W1	0.04	D2_8	25Sep11 10:46	25Sep11 21:00	10
Southbound Night Time W1	0.04	D2_9	25Sep11 11:25	25Sep11 21:10	10
Southbound Night Time W1	0.04	D2_10	25Sep11 11:39	25Sep11 21:20	10
Southbound Night Time W1	0.04	D2_13	25Sep11 13:20	25Sep11 21:30	10
Southbound Night Time W1	0.04	D2_3	25Sep11 06:14	25Sep11 21:40	10
Southbound Night Time W1	0.04	D2_14	25Sep11 13:45	25Sep11 21:50	8
Southbound Night Time W1	0.04	D2_17	25Sep11 14:00	25Sep11 22:00	8
Southbound Night Time W1	0.08	F_2	25Sep11 20:02	25Sep11 22:05	10
Southbound Night Time W1	0.04	D2_5	25Sep11 08:02	25Sep11 22:10	8
Southbound Night Time W1	0.04	D2_6	25Sep11 09:01	25Sep11 22:20	8
2 Hours Interlude for Direction Change					
Northbound Night Time W1	0.28	B_1	25Sep11 04:57	26Sep11 00:20	11
Northbound Night Time W1	0.08	F_1	25Sep11 14:38	26Sep11 00:25	10

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26
-27th of September (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Night Time W1	0.09	D1_4	25Sep11 17:34	26Sep11 00:30	12
Northbound Night Time W1	0.18	C1_2	25Sep11 19:50	26Sep11 00:40	15
Northbound Night Time W1	0.09	D1_9	25Sep11 23:19	26Sep11 00:50	12
Northbound Night Time W1	0.18	C1_1	25Sep11 10:47	26Sep11 01:00	12
Northbound Night Time W1	0.04	D2_9	25Sep11 19:17	26Sep11 01:10	12
Northbound Night Time W1	0.18	C1_3	25Sep11 19:50	26Sep11 01:20	12
Northbound Night Time W1	0.08	F_2	25Sep11 15:29	26Sep11 01:25	10
Northbound Night Time W1	0.09	D1_10	26Sep11 01:09	26Sep11 01:30	11
Northbound Night Time W1	0.04	D2_2	25Sep11 11:11	26Sep11 01:40	11
Northbound Night Time W1	0.28	B_2	25Sep11 05:07	26Sep11 01:50	16
Northbound Night Time W1	0.09	D1_11	26Sep11 01:38	26Sep11 02:00	11
Northbound Night Time W1	0.13	C2_1	25Sep11 12:49	26Sep11 02:10	10
Northbound Night Time W1	0.04	D2_5	25Sep11 12:01	26Sep11 02:20	11
Northbound Night Time W1	0.08	F_3	25Sep11 22:39	26Sep11 02:25	9
Northbound Night Time W1	0.18	C1_4	26Sep11 01:32	26Sep11 02:30	10
Northbound Night Time W1	0.04	D2_8	25Sep11 19:03	26Sep11 02:40	11
Northbound Night Time W1	0.09	D1_3	25Sep11 16:53	26Sep11 02:50	10
Northbound Night Time W1	0.28	B_3	25Sep11 09:47	26Sep11 03:05	15
Northbound Night Time W1	0.04	D2_1	25Sep11 09:26	26Sep11 03:15	10
Northbound Night Time W1	0.09	D1_8	25Sep11 22:48	26Sep11 03:25	10
Northbound Night Time W1	0.04	D2_3	25Sep11 11:11	26Sep11 03:35	10
Northbound Night Time W1	0.04	D2_4	25Sep11 11:26	26Sep11 03:45	10
Northbound Night Time W1	0.04	D2_6	25Sep11 12:23	26Sep11 03:55	10
Northbound Night Time W1	0.09	D1_7	25Sep11 18:31	26Sep11 04:05	9
Northbound Night Time W1	0.28	B_4	25Sep11 16:15	26Sep11 04:20	13
Northbound Night Time W1	0.09	D1_5	25Sep11 18:02	26Sep11 04:30	8
Northbound Night Time W1	0.09	D1_6	25Sep11 18:07	26Sep11 04:40	8
Northbound Night Time W1	0.09	D1_1	25Sep11 14:30	26Sep11 04:50	8
Northbound Night Time W1	0.09	D1_2	25Sep11 16:03	26Sep11 05:00	8
Northbound Night Time W1	0.04	D2_7	25Sep11 14:03	26Sep11 05:10	8
Northbound Night Time W1	0.09	D1_12	26Sep11 03:40	26Sep11 05:20	8
Northbound Night Time W1	0.04	D2_10	25Sep11 19:34	26Sep11 05:30	10
Northbound Day Time W2	0.04	D2_1	25Sep11 19:53	26Sep11 05:40	11
Northbound Day Time W2	0.04	D2_2	25Sep11 22:06	26Sep11 05:50	11
Northbound Day Time W2	0.04	D2_3	26Sep11 00:36	26Sep11 06:00	10
Northbound Day Time W2	0.04	D2_4	26Sep11 02:28	26Sep11 06:10	10
Northbound Day Time W2	0.28	A_1	25Sep11 18:33	26Sep11 06:20	12
Northbound Day Time W2	0.04	D2_5	26Sep11 02:58	26Sep11 06:30	11
Northbound Day Time W2	0.04	D2_11	26Sep11 06:20	26Sep11 06:40	11
Northbound Day Time W2	0.18	C1_1	26Sep11 06:10	26Sep11 06:50	14
Northbound Day Time W2	0.09	D1_5	26Sep11 06:49	26Sep11 07:00	11
Northbound Day Time W2	0.18	C1_2	26Sep11 06:14	26Sep11 07:10	13
Northbound Day Time W2	0.09	D1_6	26Sep11 07:14	26Sep11 07:20	11
Northbound Day Time W2	0.13	C2_2	26Sep11 07:06	26Sep11 07:30	12
Northbound Day Time W2	0.04	D2_12	26Sep11 06:44	26Sep11 07:40	11
Northbound Day Time W2	0.04	D2_8	26Sep11 04:54	26Sep11 07:50	10
Northbound Day Time W2	0.28	A_2	26Sep11 00:23	26Sep11 08:00	11
Northbound Day Time W2	0.04	D2_15	26Sep11 07:46	26Sep11 08:10	10
Northbound Day Time W2	0.04	D2_9	26Sep11 04:55	26Sep11 08:20	10
Northbound Day Time W2	0.13	C2_1	26Sep11 05:29	26Sep11 08:30	11
Northbound Day Time W2	0.04	D2_10	26Sep11 04:58	26Sep11 08:40	10
Northbound Day Time W2	0.13	C2_3	26Sep11 07:27	26Sep11 08:50	11

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26 -27th of September (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W2	0.09	D1_3	26Sep11 06:40	26Sep11 09:00	10
Northbound Day Time W2	0.04	D2_13	26Sep11 06:49	26Sep11 09:10	10
Northbound Day Time W2	0.04	D2_14	26Sep11 07:29	26Sep11 09:20	10
Northbound Day Time W2	0.04	D2_16	26Sep11 07:52	26Sep11 09:30	10
Northbound Day Time W2	0.04	D2_17	26Sep11 08:14	26Sep11 09:40	10
Northbound Day Time W2	0.09	D1_4	26Sep11 06:41	26Sep11 09:50	9
Northbound Day Time W2	0.04	D2_18	26Sep11 09:46	26Sep11 10:00	10
Northbound Day Time W2	0.04	D2_19	26Sep11 09:54	26Sep11 10:10	11
Northbound Day Time W2	0.09	D1_10	26Sep11 09:41	26Sep11 10:20	9
Northbound Day Time W2	0.13	C2_4	26Sep11 09:06	26Sep11 10:30	12
Northbound Day Time W2	0.04	D2_6	26Sep11 03:28	26Sep11 10:40	8
Northbound Day Time W2	0.18	C1_3	26Sep11 09:14	26Sep11 10:50	11
Northbound Day Time W2	0.09	D1_12	26Sep11 10:41	26Sep11 11:00	9
Northbound Day Time W2	0.13	C2_5	26Sep11 09:27	26Sep11 11:10	11
Northbound Day Time W2	0.04	D2_7	26Sep11 03:59	26Sep11 11:20	8
Northbound Day Time W2	0.18	C1_4	26Sep11 09:29	26Sep11 11:30	10
Northbound Day Time W2	0.09	D1_8	26Sep11 08:03	26Sep11 11:40	8
Northbound Day Time W2	0.09	D1_11	26Sep11 10:13	26Sep11 11:50	8
Northbound Day Time W2	0.09	D1_13	26Sep11 11:03	26Sep11 12:00	8
Northbound Day Time W2	0.09	D1_7	26Sep11 07:25	26Sep11 12:10	8
Northbound Day Time W2	0.09	D1_9	26Sep11 08:25	26Sep11 12:20	8
Northbound Day Time W2	0.09	D1_1	26Sep11 05:46	26Sep11 12:30	8
Northbound Day Time W2	0.09	D1_2	26Sep11 06:12	26Sep11 12:40	8
2 Hours Interlude for Direction Change					
Southbound Day Time W2	0.26	A_1	26Sep11 02:43	26Sep11 14:40	14
Southbound Day Time W2	0.08	F_2	26Sep11 03:30	26Sep11 14:45	11
Southbound Day Time W2	0.09	D1_1	25Sep11 23:01	26Sep11 14:50	8
Southbound Day Time W2	0.18	C1_8	26Sep11 13:02	26Sep11 15:00	18
Southbound Day Time W2	0.21	E_1	26Sep11 12:05	26Sep11 15:10	17
Southbound Day Time W2	0.18	C1_9	26Sep11 13:42	26Sep11 15:20	16
Southbound Day Time W2	0.09	D1_2	26Sep11 00:24	26Sep11 15:30	15
Southbound Day Time W2	0.18	C1_4	26Sep11 01:43	26Sep11 15:40	14
Southbound Day Time W2	0.08	F_3	26Sep11 09:50	26Sep11 15:45	11
Southbound Day Time W2	0.09	D1_3	26Sep11 00:26	26Sep11 15:55	10
Southbound Day Time W2	0.18	C1_2	25Sep11 23:43	26Sep11 16:05	14
Southbound Day Time W2	0.09	D1_4	26Sep11 01:29	26Sep11 16:15	10
Southbound Day Time W2	0.18	C1_6	26Sep11 09:06	26Sep11 16:25	14
Southbound Day Time W2	0.09	D1_5	26Sep11 02:32	26Sep11 16:35	10
Southbound Day Time W2	0.18	C1_5	26Sep11 07:24	26Sep11 16:45	13
Southbound Day Time W2	0.08	F_4	26Sep11 14:24	26Sep11 16:50	11
Southbound Day Time W2	0.18	C1_3	26Sep11 00:27	26Sep11 17:00	12
Southbound Day Time W2	0.09	D1_6	26Sep11 06:13	26Sep11 17:10	10
Southbound Day Time W2	0.09	D1_7	26Sep11 06:43	26Sep11 17:20	8
Southbound Day Time W2	0.13	C2_1	26Sep11 08:35	26Sep11 17:30	11
Southbound Day Time W2	0.21	E_2	26Sep11 16:30	26Sep11 17:40	11
Southbound Day Time W2	0.18	C1_7	26Sep11 09:13	26Sep11 17:50	11
Southbound Day Time W2	0.08	F_1	26Sep11 00:06	26Sep11 17:55	9
Southbound Day Time W2	0.09	D1_8	26Sep11 06:52	26Sep11 18:00	8
Southbound Day Time W2	0.18	C1_1	25Sep11 23:04	26Sep11 18:10	10
Southbound Day Time W2	0.26	A_2	26Sep11 07:59	26Sep11 18:20	11
Southbound Night Time W2	0.18	C1_1	26Sep11 15:17	26Sep11 18:30	10
Southbound Night Time W2	0.09	D1_2	26Sep11 08:56	26Sep11 18:40	11

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26 -27th of September (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Night Time W2	0.09	D1_1	26Sep11 08:31	26Sep11 18:50	8
Southbound Night Time W2	0.08	F_1	26Sep11 14:56	26Sep11 18:55	5
Southbound Night Time W2	0.18	C1_3	26Sep11 18:42	26Sep11 19:00	13
Southbound Night Time W2	0.04	D2_11	25Sep11 22:27	26Sep11 19:10	15
Southbound Night Time W2	0.04	D2_15	26Sep11 03:57	26Sep11 19:20	15
Southbound Night Time W2	0.26	B_1	26Sep11 01:01	26Sep11 19:30	14
Southbound Night Time W2	0.04	D2_16	26Sep11 04:48	26Sep11 19:40	13
Southbound Night Time W2	0.13	C2_1	26Sep11 18:06	26Sep11 19:50	12
Southbound Night Time W2	0.04	D2_18	26Sep11 09:22	26Sep11 20:00	12
Southbound Night Time W2	0.5	P_1	26Sep11 15:14	26Sep11 20:10	13
Southbound Night Time W2	0.04	D2_21	25Sep11 17:33	26Sep11 20:10	12
Southbound Night Time W2	0.04	D2_5	25Sep11 20:00	26Sep11 20:20	12
Southbound Night Time W2	0.04	D2_8	26Sep11 08:11	26Sep11 20:30	11
Southbound Night Time W2	0.26	B_2	26Sep11 20:26	26Sep11 20:40	13
Southbound Night Time W2	0.18	C1_4	26Sep11 01:14	26Sep11 20:50	16
Southbound Night Time W2	0.04	D2_12	26Sep11 09:07	26Sep11 21:00	11
Southbound Night Time W2	0.04	D2_17	26Sep11 10:33	26Sep11 21:10	11
Southbound Night Time W2	0.04	D2_19	26Sep11 14:12	26Sep11 21:20	11
Southbound Night Time W2	0.09	D1_8	26Sep11 18:02	26Sep11 21:30	10
Southbound Night Time W2	0.18	C1_2	25Sep11 17:11	26Sep11 21:40	10
Southbound Night Time W2	0.04	D2_4	25Sep11 20:39	26Sep11 21:50	10
Southbound Night Time W2	0.04	D2_10	26Sep11 02:04	26Sep11 22:00	10
Southbound Night Time W2	0.04	D2_14	26Sep11 11:09	26Sep11 22:10	10
Southbound Night Time W2	0.04	D2_20	25Sep11 14:12	26Sep11 22:20	10
Southbound Night Time W2	0.04	D2_1	26Sep11 08:43	26Sep11 22:30	9
Southbound Night Time W2	0.26	B_3	26Sep11 14:56	26Sep11 22:40	12
Southbound Night Time W2	0.08	F_1	26Sep11 22:25	26Sep11 22:45	5
Southbound Night Time W2	0.09	D1_11	26Sep11 13:04	26Sep11 22:50	9
Southbound Night Time W2	0.09	D1_7	25Sep11 19:39	26Sep11 23:00	9
Southbound Night Time W2	0.04	D2_6	25Sep11 19:53	26Sep11 23:10	9
Southbound Night Time W2	0.04	D2_7	26Sep11 11:03	26Sep11 23:20	9
Southbound Night Time W2	0.09	D1_3	26Sep11 11:06	26Sep11 23:30	8
Southbound Night Time W2	0.09	D1_4	26Sep11 19:06	26Sep11 23:40	8
Southbound Night Time W2	0.09	D1_10	26Sep11 12:12	26Sep11 23:50	8
Southbound Night Time W2	0.26	B_4	25Sep11 20:03	27Sep11 00:00	13
Southbound Night Time W2	0.04	D2_9	25Sep11 14:20	27Sep11 00:10	8
Southbound Night Time W2	0.04	D2_2	25Sep11 15:09	27Sep11 00:20	8
Southbound Night Time W2	0.04	D2_3	26Sep11 02:01	27Sep11 00:30	8
Southbound Night Time W2	0.04	D2_13	26Sep11 23:15	27Sep11 00:40	8
Southbound Night Time W2	0.18	C1_5	26Sep11 12:56	27Sep11 00:50	12
Southbound Night Time W2	0.09	D1_6	27Sep11 00:03	27Sep11 01:00	7
Southbound Night Time W2	0.18	C1_7	26Sep11 18:48	27Sep11 01:10	12
Southbound Night Time W2	0.09	D1_9	26Sep11 19:55	27Sep11 01:20	7
Southbound Night Time W2	0.26	B_5	26Sep11 12:42	27Sep11 01:30	14
Southbound Night Time W2	0.09	D1_5	26Sep11 23:46	27Sep11 01:40	7
Southbound Night Time W2	0.18	C1_6	26Sep11 23:46	27Sep11 01:50	8
2 Hours Interlude for Direction Change					
Northbound Night Time W2	0.28	B_1	26Sep11 11:12	27Sep11 03:50	12
Northbound Night Time W2	0.09	D1_1	26Sep11 14:18	27Sep11 04:00	12
Northbound Night Time W2	0.18	C1_2	26Sep11 15:02	27Sep11 04:10	11
Northbound Night Time W2	0.09	D1_4	26Sep11 23:01	27Sep11 04:20	8
Northbound Night Time W2	0.5	P_1	27Sep11 04:18	27Sep11 04:30	13
Northbound Night Time W2	0.18	C1_5	26Sep11 19:31	27Sep11 04:30	11
Northbound Night Time W2	0.09	D1_3	26Sep11 15:36	27Sep11 04:40	11

Table B.1. The mathematical model solution for the 48 hour period on 25 – 26 -27th of September (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Night Time W2	0.18	C1_6	26Sep11 22:43	27Sep11 04:50	12
Northbound Night Time W2	0.09	D1_5	27Sep11 00:55	27Sep11 05:00	11
Northbound Night Time W2	0.18	C1_1	26Sep11 12:41	27Sep11 05:10	11
Northbound Night Time W2	0.09	D1_6	27Sep11 01:22	27Sep11 05:20	12
Northbound Night Time W2	0.18	C1_3	26Sep11 19:10	27Sep11 05:30	11
Northbound Night Time W2	0.09	D1_2	26Sep11 14:30	27Sep11 05:40	11

Table B.2. The 48 hour time period schedule for 15-16-17th of April.

Date	Time	Date	Time	Period
15.04.2011	00:00	15.04.2011	05:20	Warm-Up Period
15.04.2011	05:20	15.04.2011	11:05	Northbound Day Time Window_1
15.04.2011	05:20	15.04.2011	07:20	Planning Horizon 1
15.04.2011	07:20	15.04.2011	09:20	Planning Horizon 2
15.04.2011	09:20	15.04.2011	11:05	Planning Horizon 3
15.04.2011	11:05	15.04.2011	13:05	Direction Change
15.04.2011	13:05	15.04.2011	18:50	Southbound Day Time Window_1
15.04.2011	13:05	15.04.2011	15:05	Planning Horizon 1
15.04.2011	15:05	15.04.2011	17:05	Planning Horizon 2
15.04.2011	17:05	15.04.2011	18:50	Planning Horizon 3
15.04.2011	18:50	16.04.2011	00:35	Southbound Night Time Window_1
15.04.2011	18:50	15.04.2011	19:05	Planning Horizon 3
15.04.2011	19:05	15.04.2011	21:05	Planning Horizon 4
15.04.2011	21:05	15.04.2011	23:05	Planning Horizon 5
15.04.2011	23:05	16.04.2011	00:35	Planning Horizon 6
16.04.2011	00:35	16.04.2011	02:35	Direction Change
16.04.2011	02:35	16.04.2011	05:20	Northbound Night Time Window_1
16.04.2011	02:35	16.04.2011	04:35	Planning Horizon 1
16.04.2011	04:35	16.04.2011	05:20	Planning Horizon 2
16.04.2011	05:20	16.04.2011	11:05	Northbound Day Time Window_2
16.04.2011	05:20	16.04.2011	06:35	Planning Horizon 2
16.04.2011	06:35	16.04.2011	08:35	Planning Horizon 3
16.04.2011	08:35	16.04.2011	10:35	Planning Horizon 4
16.04.2011	10:35	16.04.2011	11:05	Planning Horizon 5
16.04.2011	11:05	16.04.2011	13:05	Direction Change
16.04.2011	13:05	16.04.2011	18:50	Southbound Day Time Window_2
16.04.2011	13:05	16.04.2011	15:05	Planning Horizon 1
16.04.2011	15:05	16.04.2011	17:05	Planning Horizon 2
16.04.2011	17:05	16.04.2011	18:50	Planning Horizon 3
16.04.2011	18:50	16.04.2011	22:55	Southbound Night Time Window_2
16.04.2011	18:50	16.04.2011	19:05	Planning Horizon 3
16.04.2011	19:05	16.04.2011	21:05	Planning Horizon 4
16.04.2011	21:05	16.04.2011	22:55	Planning Horizon 5
16.04.2011	22:55	17.04.2011	00:55	Direction Change
17.04.2011	00:55	17.04.2011	05:20	Northbound Night Time window_2
17.04.2011	00:55	17.04.2011	02:55	Planning Horizon 1
17.04.2011	02:55	17.04.2011	04:55	Planning Horizon 2
17.04.2011	04:55	17.04.2011	05:20	Planning Horizon 3

Table B.3. The outputs of the mathematical model for the 48 hour period on 15-16-17th of April.

Time Window	April					
	Total Weighted Waiting Time (Min.)		Avg. Weighted Waiting Time Per Vessel (Min.)		Number of Vessels Entering to the Strait	
	Before Speed Sort	After Speed Sort	Before Speed Sort	After Speed Sort	Before Speed Sort	After Speed Sort
Northbound Daytime W1	616	616	16	16	38	38
Southbound Daytime W1	1,331	1,331	35	35	38	38
Southbound Nighttime W1	829	829	24	24	34	34
Northbound Nighttime W1	1,815	1,815	91	91	20	20
Northbound Daytime W2	1,307	1,307	36	36	36	36
Southbound Daytime W2	1,608	1,608	38	38	42	42
Southbound Nighttime W2	682	682	40	40	17	17
Northbound Nighttime W2	3,583	3,583	119	119	30	30
Total (48 hours period)	11,771	11,771	46	46	255	255

Table B.4. The actual Strait sailing time of all vessels during the selected 48 hours (15-16-17th of April).

Time Window	Vessel Transit Times	
	Before Speed	After Speed
Northbound Daytime W1	111	110
Southbound Daytime W1	107	106
Southbound Nighttime W1	98	98
Northbound Nighttime W1	57	58
Northbound Daytime W2	106	105
Southbound Daytime W2	119	118
Southbound Nighttime W2	41	41
Northbound Nighttime W2	83	83
Total (48 hours period)	723	720

Table B.5. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 15-16-17th of April before speed sort.

Vessel Type	Before Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
AN	350	87	4
AS	887	177	5
BN	1751	292	6
BS	1146	127	9
C1N	1741	97	18
C1S	245	19	13
C2N	219	36	6
C2S	355	59	6

Table B.5. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 15-16-17th of April before speed sort (continued).

Vessel Type	Before Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
D1N	1805	44	41
D1S	788	21	37
D2N	862	25	34
D2S	661	15	44
EN	176	59	3
ES	139	139	1
FN	411	41	10
FS	213	15	14
PN	8	4	2
PS	15	8	2
Total_Northbound Vessels	7,322	59	124
Total_Southbound Vessels	4,450	34	131

Table B.6. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 15-16-17th of April after speed sort.

Vessel Type	After Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
AN	350	87	4
AS	887	177	5
BN	1751	292	6
BS	1146	127	9
C1N	1741	97	18
C1S	245	19	13
C2N	219	36	6
C2S	355	59	6
D1N	1805	44	41
D1S	788	21	37
D2N	862	25	34
D2S	661	15	44
EN	176	59	3
ES	139	139	1
FN	411	41	10
FS	213	15	14
PN	8	4	2
PS	15	8	2
Total_Northbound Vessels	7,322	59	124
Total_Southbound Vessels	4,450	34	131

Table B.7. The accounting of all class vessels allowed entering the Strait in each time window for the 48 hour period on 15-16-17th of April.

Time Window	A	B	C1	C2	D1	D2	E	F	P	Total
Northbound Daytime W1	3	0	4	1	16	11	0	3	0	38
Southbound Daytime W1	3	0	3	4	10	15	0	3	0	38
Southbound Nighttime W1	0	5	3	0	13	9	0	4	0	34
Northbound Nighttime W1	0	2	4	2	7	1	1	3	0	20
Northbound Daytime W2	1	0	3	1	11	16	2	1	1	36
Southbound Daytime W2	2	0	4	1	11	16	1	6	1	42
Southbound Nighttime W2	0	4	3	1	3	4	0	1	1	17
Northbound Nighttime W2	0	4	7	2	7	6	0	3	1	30
Total (48 hours period)	9	15	31	12	78	78	4	24	4	255

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April.

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W1	0.28	A_1	15Apr11 00:35	15Apr11 05:20	12
Northbound Day Time W1	0.09	D1_2	15Apr11 00:35	15Apr11 05:30	17
Northbound Day Time W1	0.18	C1_1	15Apr11 00:31	15Apr11 05:40	11
Northbound Day Time W1	0.09	D1_5	15Apr11 03:10	15Apr11 05:50	14
Northbound Day Time W1	0.18	C1_3	15Apr11 05:55	15Apr11 06:00	12
Northbound Day Time W1	0.09	D1_1	15Apr11 00:15	15Apr11 06:10	13
Northbound Day Time W1	0.09	D1_6	15Apr11 04:12	15Apr11 06:20	13
Northbound Day Time W1	0.09	D1_4	15Apr11 02:59	15Apr11 06:30	12
Northbound Day Time W1	0.28	A_2	15Apr11 03:15	15Apr11 06:40	14
Northbound Day Time W1	0.09	D1_9	15Apr11 06:34	15Apr11 06:50	11
Northbound Day Time W1	0.09	D1_8	15Apr11 05:16	15Apr11 07:00	10
Northbound Day Time W1	0.09	D1_7	15Apr11 05:10	15Apr11 07:10	9
Northbound Day Time W1	0.04	D2_1	15Apr11 02:00	15Apr11 07:20	11
Northbound Day Time W1	0.09	D1_3	15Apr11 02:21	15Apr11 07:30	8
Northbound Day Time W1	0.18	C1_2	15Apr11 00:46	15Apr11 07:40	11
Northbound Day Time W1	0.04	D2_6	15Apr11 05:54	15Apr11 07:50	11
Northbound Day Time W1	0.28	A_3	15Apr11 04:26	15Apr11 08:00	12
Northbound Day Time W1	0.04	D2_7	15Apr11 07:14	15Apr11 08:10	11
Northbound Day Time W1	0.13	C2_1	15Apr11 06:45	15Apr11 08:20	10
Northbound Day Time W1	0.04	D2_2	15Apr11 02:58	15Apr11 08:30	10
Northbound Day Time W1	0.04	D2_3	15Apr11 03:14	15Apr11 08:40	10
Northbound Day Time W1	0.04	D2_4	15Apr11 03:48	15Apr11 08:50	10
Northbound Day Time W1	0.04	D2_8	15Apr11 07:30	15Apr11 09:00	10
Northbound Day Time W1	0.08	F_1	15Apr11 08:34	15Apr11 09:05	10
Northbound Day Time W1	0.18	C1_4	15Apr11 08:44	15Apr11 09:10	10
Northbound Day Time W1	0.09	D1_12	15Apr11 08:45	15Apr11 09:20	10
Northbound Day Time W1	0.09	D1_11	15Apr11 08:31	15Apr11 09:30	10
Northbound Day Time W1	0.09	D1_14	15Apr11 09:12	15Apr11 09:40	10
Northbound Day Time W1	0.09	D1_13	15Apr11 09:06	15Apr11 09:50	8
Northbound Day Time W1	0.09	D1_10	15Apr11 08:27	15Apr11 10:00	8
Northbound Day Time W1	0.08	F_2	15Apr11 09:45	15Apr11 10:05	12
Northbound Day Time W1	0.04	D2_9	15Apr11 09:33	15Apr11 10:10	12
Northbound Day Time W1	0.09	D1_15	15Apr11 09:32	15Apr11 10:20	8
Northbound Day Time W1	0.04	D2_11	15Apr11 10:13	15Apr11 10:30	10
Northbound Day Time W1	0.04	D2_10	15Apr11 10:11	15Apr11 10:40	8
Northbound Day Time W1	0.04	D2_5	15Apr11 04:01	15Apr11 10:50	8
Northbound Day Time W1	0.09	D1_16	15Apr11 10:49	15Apr11 11:00	8

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W1	0.08	F_3	15Apr11 10:13	15Apr11 11:05	10
2 Hours Interlude for Direction Change					
Southbound Day Time W1	0.26	A_1	15Apr11 04:10	15Apr11 13:05	12
Southbound Day Time W1	0.09	D1_2	15Apr11 02:02	15Apr11 13:15	11
Southbound Day Time W1	0.18	C1_1	15Apr11 05:23	15Apr11 13:25	15
Southbound Day Time W1	0.09	D1_4	15Apr11 06:35	15Apr11 13:35	11
Southbound Day Time W1	0.13	C2_1	15Apr11 02:34	15Apr11 13:45	12
Southbound Day Time W1	0.09	D1_7	15Apr11 13:23	15Apr11 13:55	11
Southbound Day Time W1	0.13	C2_2	15Apr11 03:05	15Apr11 14:05	12
Southbound Day Time W1	0.09	D1_3	15Apr11 05:44	15Apr11 14:15	10
Southbound Day Time W1	0.26	A_2	15Apr11 09:23	15Apr11 14:25	15
Southbound Day Time W1	0.09	D1_1	15Apr11 00:06	15Apr11 14:35	8
Southbound Day Time W1	0.13	C2_3	15Apr11 04:22	15Apr11 14:45	11
Southbound Day Time W1	0.09	D1_6	15Apr11 10:29	15Apr11 14:55	8
Southbound Day Time W1	0.04	D2_5	15Apr11 04:34	15Apr11 15:05	17
Southbound Day Time W1	0.08	F_1	15Apr11 14:33	15Apr11 15:10	9
Southbound Day Time W1	0.18	C1_3	15Apr11 15:12	15Apr11 15:15	15
Southbound Day Time W1	0.09	D1_8	15Apr11 15:17	15Apr11 15:25	8
Southbound Day Time W1	0.04	D2_6	15Apr11 05:17	15Apr11 15:35	15
Southbound Day Time W1	0.26	A_3	15Apr11 10:11	15Apr11 15:45	10
Southbound Day Time W1	0.04	D2_7	15Apr11 07:00	15Apr11 15:55	15
Southbound Day Time W1	0.04	D2_4	15Apr11 04:21	15Apr11 16:05	14
Southbound Day Time W1	0.04	D2_15	15Apr11 15:33	15Apr11 16:15	14
Southbound Day Time W1	0.04	D2_2	15Apr11 03:47	15Apr11 16:25	12
Southbound Day Time W1	0.04	D2_10	15Apr11 09:06	15Apr11 16:35	12
Southbound Day Time W1	0.04	D2_3	15Apr11 03:53	15Apr11 16:45	11
Southbound Day Time W1	0.04	D2_11	15Apr11 11:44	15Apr11 16:55	10
Southbound Day Time W1	0.04	D2_8	15Apr11 07:29	15Apr11 17:05	10
Southbound Day Time W1	0.08	F_2	15Apr11 16:00	15Apr11 17:10	10
Southbound Day Time W1	0.18	C1_2	15Apr11 14:38	15Apr11 17:15	14
Southbound Day Time W1	0.09	D1_9	15Apr11 16:11	15Apr11 17:25	11
Southbound Day Time W1	0.13	C2_4	15Apr11 16:25	15Apr11 17:35	10
Southbound Day Time W1	0.09	D1_5	15Apr11 08:26	15Apr11 17:45	8
Southbound Day Time W1	0.09	D1_10	15Apr11 17:02	15Apr11 17:55	8
Southbound Day Time W1	0.04	D2_9	15Apr11 07:31	15Apr11 18:05	12
Southbound Day Time W1	0.04	D2_14	15Apr11 13:34	15Apr11 18:15	10
Southbound Day Time W1	0.08	F_3	15Apr11 17:00	15Apr11 18:20	10
Southbound Day Time W1	0.04	D2_13	15Apr11 13:23	15Apr11 18:25	9
Southbound Day Time W1	0.04	D2_12	15Apr11 12:49	15Apr11 18:35	8
Southbound Day Time W1	0.04	D2_1	15Apr11 01:03	15Apr11 18:45	8
Southbound Night Time W1	0.04	D2_1	15Apr11 17:03	15Apr11 18:55	12
Southbound Night Time W1	0.26	B_1	15Apr11 04:25	15Apr11 19:05	13
Southbound Night Time W1	0.09	D1_3	15Apr11 17:59	15Apr11 19:15	13
Southbound Night Time W1	0.18	C1_1	15Apr11 18:21	15Apr11 19:25	12
Southbound Night Time W1	0.09	D1_2	15Apr11 17:59	15Apr11 19:35	12
Southbound Night Time W1	0.08	F_1	15Apr11 17:13	15Apr11 19:45	10
Southbound Night Time W1	0.09	D1_6	15Apr11 18:49	15Apr11 19:55	12
Southbound Night Time W1	0.04	D2_6	15Apr11 19:51	15Apr11 20:05	11
Southbound Night Time W1	0.09	D1_13	15Apr11 19:53	15Apr11 20:15	11
Southbound Night Time W1	0.09	D1_8	15Apr11 18:57	15Apr11 20:25	10
Southbound Night Time W1	0.09	D1_11	15Apr11 19:26	15Apr11 20:35	10
Southbound Night Time W1	0.09	D1_12	15Apr11 19:44	15Apr11 20:45	10
Southbound Night Time W1	0.26	B_2	15Apr11 15:04	15Apr11 20:55	12

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Night Time W1	0.09	D1_1	15Apr11 17:13	15Apr11 21:05	9
Southbound Night Time W1	0.04	D2_7	15Apr11 20:34	15Apr11 21:15	16
Southbound Night Time W1	0.04	D2_2	15Apr11 17:19	15Apr11 21:25	10
Southbound Night Time W1	0.18	C1_2	15Apr11 19:43	15Apr11 21:35	14
Southbound Night Time W1	0.08	F_4	15Apr11 21:24	15Apr11 21:40	10
Southbound Night Time W1	0.09	D1_9	15Apr11 19:09	15Apr11 21:45	9
Southbound Night Time W1	0.09	D1_5	15Apr11 18:47	15Apr11 21:55	8
Southbound Night Time W1	0.04	D2_5	15Apr11 18:41	15Apr11 22:05	10
Southbound Night Time W1	0.26	B_3	15Apr11 17:07	15Apr11 22:15	14
Southbound Night Time W1	0.04	D2_3	15Apr11 17:30	15Apr11 22:25	9
Southbound Night Time W1					
Southbound Night Time W1					
Southbound Night Time W1					
Southbound Night Time W1					
Southbound Night Time W1	0.09	D1_7	15Apr11 18:51	15Apr11 23:15	8
Southbound Night Time W1	0.26	B_4	15Apr11 17:22	15Apr11 23:25	15
Southbound Night Time W1	0.08	F_3	15Apr11 21:22	15Apr11 23:30	9
Southbound Night Time W1	0.09	D1_10	15Apr11 19:17	15Apr11 23:35	8
Southbound Night Time W1	0.18	C1_3	15Apr11 21:48	15Apr11 23:45	12
Southbound Night Time W1	0.09	D1_4	15Apr11 18:14	15Apr11 23:55	7
Southbound Night Time W1	0.04	D2_8	15Apr11 22:18	16Apr11 00:05	10
Southbound Night Time W1	0.04	D2_9	15Apr11 23:14	16Apr11 00:15	10
Southbound Night Time W1	0.04	D2_4	15Apr11 18:20	16Apr11 00:25	7
Southbound Night Time W1	0.08	F_2	15Apr11 19:22	16Apr11 00:30	8
Southbound Night Time W1	0.26	B_5	15Apr11 22:36	16Apr11 00:35	15.75
2 Hours Interlude for Direction Change					
Northbound Night Time W1	0.26	B_1	15Apr11 03:32	16Apr11 02:35	13
Northbound Night Time W1	0.08	F_1	15Apr11 13:12	16Apr11 02:40	10
Northbound Night Time W1	0.09	D1_3	15Apr11 14:18	16Apr11 02:45	16
Northbound Night Time W1	0.18	C1_1	15Apr11 11:05	16Apr11 02:55	11
Northbound Night Time W1	0.09	D1_2	15Apr11 12:42	16Apr11 03:05	12
Northbound Night Time W1	0.21	E_1	15Apr11 16:07	16Apr11 03:15	16
Northbound Night Time W1	0.09	D1_1	15Apr11 11:56	16Apr11 03:25	11
Northbound Night Time W1	0.13	C2_2	16Apr11 01:22	16Apr11 03:35	19
Northbound Night Time W1	0.08	F_3	15Apr11 15:38	16Apr11 03:40	10
Northbound Night Time W1	0.09	D1_5	15Apr11 15:46	16Apr11 03:45	10
Northbound Night Time W1	0.26	B_2	15Apr11 20:10	16Apr11 03:55	12
Northbound Night Time W1	0.09	D1_4	15Apr11 15:40	16Apr11 04:05	9
Northbound Night Time W1	0.18	C1_4	16Apr11 03:28	16Apr11 04:15	18
Northbound Night Time W1	0.09	D1_6	15Apr11 16:05	16Apr11 04:25	9
Northbound Night Time W1	0.13	C2_1	16Apr11 00:02	16Apr11 04:35	10
Northbound Night Time W1	0.08	F_2	15Apr11 14:44	16Apr11 04:40	7
Northbound Night Time W1	0.18	C1_2	15Apr11 15:19	16Apr11 04:45	8
Northbound Night Time W1	0.04	D2_1	15Apr11 10:57	16Apr11 04:55	14
Northbound Night Time W1	0.18	C1_3	15Apr11 21:01	16Apr11 05:05	8
Northbound Night Time W1	0.09	D1_7	15Apr11 16:06	16Apr11 05:15	8
Northbound Day Time W2	0.18	C1_1	16Apr11 04:18	16Apr11 05:25	13
Northbound Day Time W2	0.09	D1_2	15Apr11 20:26	16Apr11 05:35	9
Northbound Day Time W2	0.08	F_1	15Apr11 15:53	16Apr11 05:40	10
Northbound Day Time W2	0.28	A_1	15Apr11 20:40	16Apr11 05:45	15
Northbound Day Time W2	0.04	D2_4	15Apr11 15:06	16Apr11 05:55	16
Northbound Day Time W2	0.04	D2_1	15Apr11 13:15	16Apr11 06:05	10
Northbound Day Time W2	0.04	D2_2	15Apr11 13:19	16Apr11 06:15	9

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W2	0.04	D2_3	15Apr11 14:21	16Apr11 06:25	8
Northbound Day Time W2	0.09	D1_1	15Apr11 16:19	16Apr11 06:35	7
Northbound Day Time W2	0.21	E_2	16Apr11 06:12	16Apr11 06:45	17
Northbound Day Time W2	0.04	D2_8	15Apr11 21:58	16Apr11 06:55	13
Northbound Day Time W2	0.18	C1_3	16Apr11 06:15	16Apr11 07:05	13
Northbound Day Time W2	0.04	D2_10	15Apr11 22:30	16Apr11 07:15	12
Northbound Day Time W2	0.18	C1_2	16Apr11 04:51	16Apr11 07:25	11
Northbound Day Time W2	0.04	D2_14	16Apr11 01:13	16Apr11 07:35	12
Northbound Day Time W2	0.21	E_1	16Apr11 05:30	16Apr11 07:45	10
Northbound Day Time W2	0.09	D1_5	15Apr11 23:43	16Apr11 07:55	15
Northbound Day Time W2	0.13	C2_1	16Apr11 06:21	16Apr11 08:05	13
Northbound Day Time W2	0.09	D1_9	16Apr11 00:22	16Apr11 08:15	12
Northbound Day Time W2	0.09	D1_11	16Apr11 06:30	16Apr11 08:25	11
Northbound Day Time W2	0.09	D1_8	16Apr11 00:07	16Apr11 08:35	10
Northbound Day Time W2	0.09	D1_7	16Apr11 00:05	16Apr11 08:45	9
Northbound Day Time W2	0.09	D1_4	15Apr11 22:06	16Apr11 08:55	8
Northbound Day Time W2	0.09	D1_3	15Apr11 21:00	16Apr11 09:05	8
Northbound Day Time W2	0.09	D1_6	15Apr11 23:48	16Apr11 09:15	8
Northbound Day Time W2	0.5	P_1	16Apr11 09:17	16Apr11 09:25	12
Northbound Day Time W2	0.09	D1_10	16Apr11 05:27	16Apr11 09:35	8
Northbound Day Time W2	0.04	D2_9	15Apr11 22:14	16Apr11 09:45	11
Northbound Day Time W2	0.04	D2_11	15Apr11 22:35	16Apr11 09:55	11
Northbound Day Time W2	0.04	D2_6	15Apr11 20:04	16Apr11 10:05	10
Northbound Day Time W2	0.04	D2_7	15Apr11 20:36	16Apr11 10:15	10
Northbound Day Time W2	0.04	D2_13	15Apr11 23:56	16Apr11 10:25	10
Northbound Day Time W2	0.04	D2_16	16Apr11 03:10	16Apr11 10:35	10
Northbound Day Time W2	0.04	D2_5	15Apr11 16:07	16Apr11 10:45	9
Northbound Day Time W2	0.04	D2_12	15Apr11 23:13	16Apr11 10:55	9
Northbound Day Time W2	0.04	D2_15	16Apr11 01:14	16Apr11 11:05	9
2 Hours Interlude for Direction Change					
Southbound Day Time W2	0.5	P_1	16Apr11 11:54	16Apr11 11:54	16
Southbound Day Time W2	0.26	A_1	15Apr11 18:18	16Apr11 13:05	13
Southbound Day Time W2	0.08	F_2	16Apr11 07:21	16Apr11 13:10	12
Southbound Day Time W2	0.09	D1_3	16Apr11 04:52	16Apr11 13:15	11
Southbound Day Time W2	0.21	E_1	16Apr11 02:21	16Apr11 13:25	17
Southbound Day Time W2	0.09	D1_4	16Apr11 05:52	16Apr11 13:35	10
Southbound Day Time W2	0.13	C2_1	16Apr11 02:14	16Apr11 13:45	15
Southbound Day Time W2	0.09	D1_8	16Apr11 13:14	16Apr11 13:55	12
Southbound Day Time W2	0.09	D1_1	16Apr11 00:53	16Apr11 14:05	9
Southbound Day Time W2	0.08	F_3	16Apr11 09:16	16Apr11 14:10	10
Southbound Day Time W2	0.09	D1_6	16Apr11 12:01	16Apr11 14:15	9
Southbound Day Time W2	0.26	A_2	15Apr11 19:52	16Apr11 14:25	12
Southbound Day Time W2	0.09	D1_2	16Apr11 02:58	16Apr11 14:35	8
Southbound Day Time W2	0.09	D1_7	16Apr11 12:50	16Apr11 14:45	8
Southbound Day Time W2	0.04	D2_3	16Apr11 01:47	16Apr11 14:55	14
Southbound Day Time W2	0.04	D2_1	16Apr11 01:30	16Apr11 15:05	13
Southbound Day Time W2	0.08	F_5	16Apr11 14:04	16Apr11 15:10	10
Southbound Day Time W2	0.18	C1_2	16Apr11 14:07	16Apr11 15:15	13
Southbound Day Time W2	0.09	D1_9	16Apr11 15:21	16Apr11 15:25	10
Southbound Day Time W2	0.18	C1_3	16Apr11 14:31	16Apr11 15:35	11
Southbound Day Time W2	0.04	D2_16	16Apr11 15:39	16Apr11 15:45	14
Southbound Day Time W2	0.18	C1_1	16Apr11 13:45	16Apr11 15:55	10
Southbound Day Time W2	0.04	D2_4	16Apr11 03:59	16Apr11 16:05	12

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Day Time W2	0.08	F_6	16Apr11 14:33	16Apr11 16:10	10
Southbound Day Time W2	0.04	D2_7	16Apr11 09:39	16Apr11 16:15	12
Southbound Day Time W2	0.04	D2_2	16Apr11 01:43	16Apr11 16:25	11
Southbound Day Time W2	0.04	D2_8	16Apr11 10:11	16Apr11 16:35	11
Southbound Day Time W2	0.04	D2_11	16Apr11 13:33	16Apr11 16:45	11
Southbound Day Time W2	0.04	D2_13	16Apr11 14:05	16Apr11 16:55	11
Southbound Day Time W2	0.04	D2_15	16Apr11 14:38	16Apr11 17:05	11
Southbound Day Time W2	0.08	F_4	16Apr11 10:07	16Apr11 17:10	8
Southbound Day Time W2	0.18	C1_4	16Apr11 15:51	16Apr11 17:15	10
Southbound Day Time W2	0.09	D1_10	16Apr11 16:04	16Apr11 17:25	11
Southbound Day Time W2	0.09	D1_5	16Apr11 09:47	16Apr11 17:35	8
Southbound Day Time W2	0.04	D2_9	16Apr11 10:50	16Apr11 17:45	10
Southbound Day Time W2	0.04	D2_10	16Apr11 13:19	16Apr11 17:55	10
Southbound Day Time W2	0.04	D2_12	16Apr11 13:52	16Apr11 18:05	10
Southbound Day Time W2	0.08	F_1	16Apr11 06:56	16Apr11 18:10	7
Southbound Day Time W2	0.04	D2_14	16Apr11 14:12	16Apr11 18:15	10
Southbound Day Time W2	0.04	D2_5	16Apr11 06:51	16Apr11 18:25	9
Southbound Day Time W2	0.04	D2_6	16Apr11 08:53	16Apr11 18:35	8
Southbound Day Time W2	0.09	D1_11	16Apr11 17:40	16Apr11 18:45	11
Southbound Night Time W2	0.26	B_1	15Apr11 23:50	16Apr11 18:55	13
Southbound Night Time W2	0.04	D2_1	16Apr11 18:10	16Apr11 19:05	9
Southbound Night Time W2	0.18	C1_1	16Apr11 18:21	16Apr11 19:15	10
Southbound Night Time W2	0.09	D1_1	16Apr11 18:14	16Apr11 19:25	11
Southbound Night Time W2	0.18	C1_2	16Apr11 19:25	16Apr11 19:35	14
Southbound Night Time W2	0.09	D1_2	16Apr11 19:15	16Apr11 19:45	12
Southbound Night Time W2	0.13	C2_1	16Apr11 19:37	16Apr11 19:55	15
Southbound Night Time W2	0.09	D1_3	16Apr11 19:39	16Apr11 20:05	13
Southbound Night Time W2	0.26	B_2	16Apr11 10:09	16Apr11 20:15	12
Southbound Night Time W2	0.04	D2_2	16Apr11 19:29	16Apr11 20:25	11
Southbound Night Time W2	0.18	C1_3	16Apr11 19:56	16Apr11 20:35	13
Southbound Night Time W2	0.08	F_1	16Apr11 20:27	16Apr11 20:40	10
Southbound Night Time W2	0.04	D2_3	16Apr11 20:05	16Apr11 20:45	10
Southbound Night Time W2					
Southbound Night Time W2	0.5	P_1	16Apr11 18:55	16Apr11 19:25	13
Southbound Night Time W2					
Southbound Night Time W2					
Southbound Night Time W2	0.26	B_3	16Apr11 16:23	16Apr11 21:35	15
Southbound Night Time W2					
Southbound Night Time W2					
Southbound Night Time W2					
Southbound Night Time W2					
Southbound Night Time W2	0.04	D2_4	16Apr11 22:22	16Apr11 22:35	9
Southbound Night Time W2					
Southbound Night Time W2	0.26	B_4	16Apr11 17:01	16Apr11 22:55	13
2 Hours Interlude for Direction Change					
Northbound Night Time W2	0.28	B_1	16Apr11 05:42	17Apr11 00:55	14
Northbound Night Time W2	0.08	F_1	16Apr11 10:05	17Apr11 01:00	10
Northbound Night Time W2	0.09	D1_1	16Apr11 08:09	17Apr11 01:05	11
Northbound Night Time W2	0.18	C1_6	16Apr11 16:42	17Apr11 01:15	14
Northbound Night Time W2	0.5	P_1	17Apr11 01:18	17Apr11 01:25	10
Northbound Night Time W2	0.13	C2_2	17Apr11 00:25	17Apr11 01:35	15
Northbound Night Time W2	0.09	D1_5	16Apr11 10:51	17Apr11 01:45	11

Table B.8. The mathematical model solution for the 48 hour period on 15-16-17th of April (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Night Time W2	0.18	C1_7	16Apr11 20:33	17Apr11 01:55	14
Northbound Night Time W2	0.09	D1_7	16Apr11 11:43	17Apr11 02:05	11
Northbound Night Time W2	0.08	F_2	16Apr11 12:54	17Apr11 02:10	9
Northbound Night Time W2	0.09	D1_2	16Apr11 09:15	17Apr11 02:15	10
Northbound Night Time W2	0.28	B_2	16Apr11 07:33	17Apr11 02:25	13
Northbound Night Time W2	0.09	D1_6	16Apr11 11:26	17Apr11 02:35	10
Northbound Night Time W2	0.18	C1_5	16Apr11 12:28	17Apr11 02:45	13
Northbound Night Time W2	0.09	D1_3	16Apr11 09:25	17Apr11 02:55	9
Northbound Night Time W2	0.18	C1_3	16Apr11 09:28	17Apr11 03:05	13
Northbound Night Time W2	0.09	D1_4	16Apr11 09:30	17Apr11 03:15	8
Northbound Night Time W2	0.04	D2_3	16Apr11 09:23	17Apr11 03:25	12
Northbound Night Time W2	0.28	B_3	16Apr11 08:24	17Apr11 03:35	13
Northbound Night Time W2	0.18	C1_4	16Apr11 09:51	17Apr11 03:45	11
Northbound Night Time W2	0.04	D2_4	16Apr11 09:50	17Apr11 03:55	11
Northbound Night Time W2	0.13	C2_1	16Apr11 11:19	17Apr11 04:05	10
Northbound Night Time W2	0.04	D2_1	16Apr11 07:04	17Apr11 04:15	10
Northbound Night Time W2	0.18	C1_2	16Apr11 08:03	17Apr11 04:25	10
Northbound Night Time W2	0.04	D2_2	16Apr11 07:30	17Apr11 04:35	10
Northbound Night Time W2	0.04	D2_5	16Apr11 13:03	17Apr11 04:45	9
Northbound Night Time W2	0.28	B_4	16Apr11 10:32	17Apr11 04:55	12
Northbound Night Time W2	0.08	F_3	17Apr11 02:21	17Apr11 05:00	9
Northbound Night Time W2	0.04	D2_6	16Apr11 13:16	17Apr11 05:05	9
Northbound Night Time W2	0.18	C1_1	16Apr11 07:22	17Apr11 05:15	10

Table B.9. The accounting of vessels not admitted to the Strait in each direction for the 48 hour period on 15-16-17th of April.

Vessel Type	Southbound	Northbound
A	0	0
B	1	2
C1	0	1
C2	0	0
D1	1	14
D2	1	15
E	0	0
F	0	0
P	0	0

Table B.10. The waiting times of vessels not admitted to the Strait in each direction for the 48 hour period on 15-16-17th of April.

Vessel Type	Southbound		Northbound	
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)
A	0	0	0	0
B	140	140	35	17
C1	0	0	26	26
C2	0	0	0	0
D1	32	32	724	52
D2	13	13	358	24

Table B.10. The waiting times of vessels not admitted to the Strait in each direction for the 48 hour period on 15-16-17th of April (continued).

Vessel Type	Southbound		Northbound	
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)
E	0	0	0	0
F	0	0	0	0
P	0	0	0	0

Table B.11. The 48 hour time period schedule for 19-20-21th of November.

Date	Time	Date	Time	Period
19.11.2011	00:00	19.11.2011	06:50	Warm-Up Period
19.11.2011	06:50	19.11.2011	10:50	Northbound Day Time Window_1
19.11.2011	06:50	19.11.2011	08:50	Planning Horizon 1
19.11.2011	08:50	19.11.2011	10:50	Planning Horizon 2
19.11.2011	10:50	19.11.2011	12:50	Direction Change
19.11.2011	12:50	19.11.2011	16:50	Southbound Day Time Window_1
19.11.2011	12:50	19.11.2011	14:50	Planning Horizon 1
19.11.2011	14:50	19.11.2011	16:50	Planning Horizon 2
19.11.2011	16:50	19.11.2011	22:50	Southbound Night Time Window_1
19.11.2011	16:50	19.11.2011	18:50	Planning Horizon 3
19.11.2011	18:50	19.11.2011	20:50	Planning Horizon 4
19.11.2011	20:50	19.11.2011	22:50	Planning Horizon 5
19.11.2011	22:50	20.11.2011	00:50	Direction Change
20.11.2011	00:50	20.11.2011	06:50	Northbound Night Time Window_1
20.11.2011	00:50	20.11.2011	02:50	Planning Horizon 1
20.11.2011	02:50	20.11.2011	04:50	Planning Horizon 2
20.11.2011	04:50	20.11.2011	06:50	Planning Horizon 3
20.11.2011	06:50	20.11.2011	12:10	Northbound Day Time Window_2
20.11.2011	06:50	20.11.2011	08:50	Planning Horizon 4
20.11.2011	08:50	20.11.2011	10:50	Planning Horizon 5
20.11.2011	10:50	20.11.2011	12:10	Planning Horizon 6
20.11.2011	12:10	20.11.2011	14:10	Direction Change
20.11.2011	14:10	20.11.2011	16:50	Southbound Day Time Window_2
20.11.2011	14:10	20.11.2011	16:10	Planning Horizon 1
20.11.2011	16:10	20.11.2011	16:50	Planning Horizon 2
20.11.2011	16:50	21.11.2011	01:25	Southbound Night Time Window_2
20.11.2011	16:50	20.11.2011	18:10	Planning Horizon 2
20.11.2011	18:10	20.11.2011	20:10	Planning Horizon 3
20.11.2011	20:10	20.11.2011	22:10	Planning Horizon 4
20.11.2011	22:10	21.11.2011	00:10	Planning Horizon 5
21.11.2011	00:10	21.11.2011	01:25	Planning Horizon 5
21.11.2011	01:25	21.11.2011	03:25	Direction Change
21.11.2011	03:25	21.11.2011	06:50	Northbound Night Time Window_2
21.11.2011	03:25	21.11.2011	05:25	Planning Horizon 1
21.11.2011	05:25	21.11.2011	06:50	Planning Horizon 2

Table B.12. The outputs of the mathematical model for the 48 hour period on 19-20-21th of November.

Time Window	November					
	Total Weighted Waiting Time (Min.)		Average Weighted Waiting Time (Min.)		Number of Vessels Entering to the Strait	
	Before Speed Sort	After Speed	Before Speed Sort	After Speed Sort	Before Speed Sort	After Speed Sort
Northbound Daytime W1	753	753	27	27	28	28
Southbound Daytime W1	1,800	1,800	64	64	28	28
Southbound Nighttime W1	845	845	22	22	39	39
Northbound Nighttime W1	4,267	4,267	55	50	43	43
Northbound Daytime W2	2,242	2,242	66	66	34	34
Southbound Daytime W2	2,179	2,179	109	109	20	20
Southbound Nighttime W2	2,210	2,210	42	42	53	53
Northbound Nighttime W2	2,914	2,914	117	117	25	25
Total (48 hours period)	17,210	17,210	64	64	270	270

Table B.13. The actual Strait sailing time of all vessels during the selected 48 hours (19-20-21th of November).

Time Window	Vessel Strait Transit Times	
	Before Speed Sort (hour)	After Speed Sort (hour)
Northbound Daytime W1	83	83
Southbound Daytime W1	79	78
Southbound Nighttime W1	114	114
Northbound Nighttime W1	123	123
Northbound Daytime W2	100	100
Southbound Daytime W2	60	60
Southbound Nighttime W2	155	154
Northbound Nighttime W2	70	70
Total (48 hours period)	784	782

Table B.14. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 19-20-21th of November before speed sort.

Vessel Type	Before Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
AN	897	179	5
AS	753	188	4
BN	1,191	170	7
BS	711	89	8
C1N	3,118	108	29
C1S	2,253	83	27
C2N	457	46	10
C2S	349	70	5
D1N	2,599	68	38
D1S	1,593	48	33
D2N	1,195	52	23
D2S	1,129	22	51
EN	178	89	2
ES	11	11	1

Table B.14. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 19-20-21th of November before speed sort (continued).

Vessel Type	Before Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
FN	536	36	15
FS	235	24	10
PN	5	5	1
PS	0	0	1
Total_Northbound Vessels	10,176	78	130
Total_Southbound Vessels	7,034	50	140

Table B.15. The accounting of all vessels allowed entering the Strait and their waiting times in queue for the selected the 48 hour period on 19-20-21th of November after speed sort.

Vessel Type	After Speed Sort		
	Total Weighted Waiting Time (Min)	Avg. Weighted Waiting Time Per Vessel (Min)	Number of passed vessels
AN	897	179	5
AS	753	188	4
BN	1,191	170	7
BS	711	89	8
C1N	3,118	108	29
C1S	2,253	83	27
C2N	457	46	10
C2S	349	70	5
D1N	2,599	68	38
D1S	1,593	48	33
D2N	1,195	52	23
D2S	1,129	22	51
EN	178	89	2
ES	11	11	1
FN	536	36	15
FS	235	24	10
PN	5	5	1
PS	0	0	1
Total_Northbound Vessels	10,176	78	130
Total_Southbound Vessels	7,034	50	140

Table B.16. The accounting of all class vessels allowed entering the Strait in each time window for the 48 hour period on 19-20-21th of November.

Time Window	A	B	C1	C2	D1	D2	E	F	P	Total
Northbound Daytime W1	1	0	6	3	9	5	1	3	0	28
Southbound Daytime W1	1	0	6	2	13	2	1	2	1	28
Southbound Nighttime W1	0	3	6	1	5	21	0	3	0	39
Northbound Nighttime W1	0	4	10	3	10	8	1	6	1	43
Northbound Daytime W2	4	0	6	3	9	10	0	2	0	34
Southbound Daytime W2	3	0	5	1	8	0	0	3	0	20
Southbound Nighttime W2	0	5	10	1	7	28	0	2	0	53

Table B.16. The accounting of all class vessels allowed entering the Strait in each time window for the 48 hour period on 19-20-21th of November (continued).

Time Window	A	B	C1	C2	D1	D2	E	F	P	Total
Northbound Nighttime W2	0	3	7	1	10	0	0	4	0	25
Total (48 hours period)	9	15	56	15	71	74	3	25	2	270

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November.

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W1	0.28	A_1	19Nov11 00:02	19Nov11 06:50	13
Northbound Day Time W1	0.08	F_1	19Nov11 04:01	19Nov11 06:55	10
Northbound Day Time W1	0.09	D1_7	19Nov11 05:56	19Nov11 07:00	18
Northbound Day Time W1	0.18	C1_2	19Nov11 04:31	19Nov11 07:10	15
Northbound Day Time W1	0.09	D1_2	19Nov11 00:25	19Nov11 07:20	10
Northbound Day Time W1	0.18	C1_1	19Nov11 02:04	19Nov11 07:30	12
Northbound Day Time W1	0.09	D1_6	19Nov11 05:04	19Nov11 07:40	10
Northbound Day Time W1	0.13	C2_2	19Nov11 07:50	19Nov11 07:50	13
Northbound Day Time W1	0.09	D1_8	19Nov11 07:09	19Nov11 08:00	10
Northbound Day Time W1	0.18	C1_5	19Nov11 07:18	19Nov11 08:10	12
Northbound Day Time W1	0.09	D1_3	19Nov11 00:37	19Nov11 08:20	9
Northbound Day Time W1	0.18	C1_6	19Nov11 08:29	19Nov11 08:30	14
Northbound Day Time W1	0.09	D1_1	19Nov11 00:02	19Nov11 08:40	9
Northbound Day Time W1	0.09	D1_9	19Nov11 08:30	19Nov11 08:50	9
Northbound Day Time W1	0.08	F_2	19Nov11 07:44	19Nov11 08:55	10
Northbound Day Time W1	0.21	E_1	19Nov11 07:20	19Nov11 09:00	11
Northbound Day Time W1	0.09	D1_5	19Nov11 02:35	19Nov11 09:10	8
Northbound Day Time W1	0.18	C1_3	19Nov11 05:27	19Nov11 09:20	9
Northbound Day Time W1	0.09	D1_4	19Nov11 02:18	19Nov11 09:30	8
Northbound Day Time W1	0.18	C1_4	19Nov11 05:27	19Nov11 09:40	8
Northbound Day Time W1	0.04	D2_3	19Nov11 01:11	19Nov11 09:50	11
Northbound Day Time W1	0.08	F_3	19Nov11 08:07	19Nov11 09:55	9
Northbound Day Time W1	0.13	C2_1	19Nov11 03:12	19Nov11 10:00	12
Northbound Day Time W1	0.04	D2_2	19Nov11 00:37	19Nov11 10:10	10
Northbound Day Time W1	0.13	C2_3	19Nov11 08:08	19Nov11 10:20	11
Northbound Day Time W1	0.04	D2_5	19Nov11 02:43	19Nov11 10:30	10
Northbound Day Time W1	0.04	D2_1	19Nov11 00:19	19Nov11 10:40	8
Northbound Day Time W1	0.04	D2_4	19Nov11 01:52	19Nov11 10:50	8
2 Hours Interlude for Direction Change					
Southbound Day Time W1	0.5	P_1	19Nov11 12:16	19Nov11 12:16	16
Southbound Day Time W1	0.26	A_1	19Nov11 01:31	19Nov11 12:50	12
Southbound Day Time W1	0.08	F_2	19Nov11 06:24	19Nov11 12:55	11
Southbound Day Time W1	0.09	D1_8	19Nov11 04:30	19Nov11 13:00	14
Southbound Day Time W1	0.18	C1_4	19Nov11 05:32	19Nov11 13:10	15
Southbound Day Time W1	0.09	D1_7	19Nov11 03:27	19Nov11 13:20	13
Southbound Day Time W1	0.18	C1_5	19Nov11 09:13	19Nov11 13:30	12
Southbound Day Time W1	0.09	D1_3	19Nov11 00:58	19Nov11 13:40	12
Southbound Day Time W1	0.18	C1_6	19Nov11 13:41	19Nov11 13:50	12
Southbound Day Time W1	0.08	F_1	19Nov11 05:08	19Nov11 13:55	8
Southbound Day Time W1	0.09	D1_11	19Nov11 06:57	19Nov11 14:00	11
Southbound Day Time W1	0.18	C1_2	19Nov11 00:54	19Nov11 14:10	12
Southbound Day Time W1	0.09	D1_9	19Nov11 05:33	19Nov11 14:20	10
Southbound Day Time W1	0.13	C2_1	19Nov11 07:02	19Nov11 14:30	10
Southbound Day Time W1	0.09	D1_12	19Nov11 08:01	19Nov11 14:40	10

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Day Time W1	0.18	C1_1	19Nov11 00:26	19Nov11 14:50	11
Southbound Day Time W1	0.09	D1_2	19Nov11 00:34	19Nov11 15:00	9
Southbound Day Time W1	0.21	E_1	19Nov11 14:19	19Nov11 15:10	20
Southbound Day Time W1	0.09	D1_1	19Nov11 00:30	19Nov11 15:20	8
Southbound Day Time W1	0.13	C2_2	19Nov11 11:06	19Nov11 15:30	10
Southbound Day Time W1	0.09	D1_10	19Nov11 06:01	19Nov11 15:40	8
Southbound Day Time W1	0.18	C1_3	19Nov11 00:56	19Nov11 15:50	11
Southbound Day Time W1	0.09	D1_13	19Nov11 09:12	19Nov11 16:00	8
Southbound Day Time W1	0.09	D1_4	19Nov11 01:01	19Nov11 16:10	8
Southbound Day Time W1	0.04	D2_2	19Nov11 02:37	19Nov11 16:20	10
Southbound Day Time W1	0.04	D2_1	19Nov11 01:25	19Nov11 16:30	10
Southbound Day Time W1	0.09	D1_5	19Nov11 01:03	19Nov11 16:40	8
Southbound Day Time W1	0.09	D1_6	19Nov11 01:06	19Nov11 16:50	8
Southbound Night Time W1	0.26	B_1	19Nov11 09:10	19Nov11 17:00	12
Southbound Night Time W1	0.08	F_2	19Nov11 16:27	19Nov11 17:05	10
Southbound Night Time W1	0.04	D2_14	19Nov11 11:51	19Nov11 17:10	11
Southbound Night Time W1	0.04	D2_4	19Nov11 06:21	19Nov11 17:20	11
Southbound Night Time W1	0.04	D2_9	19Nov11 10:01	19Nov11 17:30	11
Southbound Night Time W1	0.04	D2_10	19Nov11 10:12	19Nov11 17:40	11
Southbound Night Time W1	0.18	C1_2	19Nov11 17:47	19Nov11 17:50	12
Southbound Night Time W1	0.09	D1_1	19Nov11 12:11	19Nov11 18:00	11
Southbound Night Time W1	0.08	F_1	19Nov11 15:48	19Nov11 18:05	9
Southbound Night Time W1	0.09	D1_2	19Nov11 13:23	19Nov11 18:10	11
Southbound Night Time W1	0.26	B_2	19Nov11 14:05	19Nov11 18:20	12
Southbound Night Time W1	0.04	D2_20	19Nov11 17:07	19Nov11 18:30	11
Southbound Night Time W1	0.04	D2_1	19Nov11 04:05	19Nov11 18:40	10
Southbound Night Time W1	0.04	D2_12	19Nov11 11:29	19Nov11 18:50	10
Southbound Night Time W1	0.18	C1_3	19Nov11 17:49	19Nov11 19:00	11
Southbound Night Time W1	0.08	F_3	19Nov11 18:39	19Nov11 19:05	10
Southbound Night Time W1	0.09	D1_3	19Nov11 17:11	19Nov11 19:10	9
Southbound Night Time W1	0.18	C1_4	19Nov11 18:02	19Nov11 19:20	13
Southbound Night Time W1	0.04	D2_5	19Nov11 07:03	19Nov11 19:30	10
Southbound Night Time W1	0.04	D2_21	19Nov11 19:40	19Nov11 19:40	11
Southbound Night Time W1	0.18	C1_1	19Nov11 16:03	19Nov11 19:50	10
Southbound Night Time W1	0.04	D2_8	19Nov11 07:57	19Nov11 20:00	10
Southbound Night Time W1	0.04	D2_2	19Nov11 04:47	19Nov11 20:10	9
Southbound Night Time W1	0.04	D2_6	19Nov11 07:05	19Nov11 20:20	9
Southbound Night Time W1	0.04	D2_16	19Nov11 15:15	19Nov11 20:30	9
Southbound Night Time W1	0.04	D2_19	19Nov11 16:49	19Nov11 20:40	9
Southbound Night Time W1	0.04	D2_3	19Nov11 05:58	19Nov11 20:50	8
Southbound Night Time W1	0.26	B_3	19Nov11 19:53	19Nov11 21:00	13
Southbound Night Time W1	0.09	D1_4	19Nov11 20:21	19Nov11 21:10	11
Southbound Night Time W1	0.18	C1_5	19Nov11 20:48	19Nov11 21:20	13
Southbound Night Time W1	0.04	D2_7	19Nov11 07:23	19Nov11 21:30	8
Southbound Night Time W1	0.18	C1_6	19Nov11 20:54	19Nov11 21:40	13
Southbound Night Time W1	0.04	D2_13	19Nov11 11:50	19Nov11 21:50	8
Southbound Night Time W1	0.04	D2_18	19Nov11 16:20	19Nov11 22:00	8
Southbound Night Time W1	0.04	D2_15	19Nov11 13:57	19Nov11 22:10	8
Southbound Night Time W1	0.04	D2_11	19Nov11 11:16	19Nov11 22:20	8
Southbound Night Time W1	0.04	D2_17	19Nov11 15:30	19Nov11 22:30	8
Southbound Night Time W1	0.13	C2_1	19Nov11 21:23	19Nov11 22:40	12
Southbound Night Time W1	0.09	D1_5	19Nov11 21:19	19Nov11 22:50	14
2 Hours Interlude for Direction Change					

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Night Time W1	0.28	B_1	19Nov11 04:58	20.11.2011 00:50	12
Northbound Night Time W1	0.08	F_2	19Nov11 12:19	20.11.2011 00:55	12
Northbound Night Time W1	0.09	D1_5	19Nov11 12:56	20.11.2011 01:00	12
Northbound Night Time W1	0.21	E_1	19Nov11 12:43	20.11.2011 01:10	15
Northbound Night Time W1	0.09	D1_7	19Nov11 14:27	20.11.2011 01:20	12
Northbound Night Time W1	0.18	C1_3	19Nov11 09:36	20.11.2011 01:30	13
Northbound Night Time W1	0.09	D1_9	19Nov11 17:48	20.11.2011 01:40	11
Northbound Night Time W1	0.5	P_1	20Nov11 01:41	20.11.2011 01:50	16
Northbound Night Time W1	0.08	F_4	19Nov11 20:38	20.11.2011 01:55	11
Northbound Night Time W1	0.09	D1_2	19Nov11 11:36	20.11.2011 02:00	10
Northbound Night Time W1	0.28	B_2	19Nov11 05:38	20.11.2011 02:10	12
Northbound Night Time W1	0.09	D1_1	19Nov11 09:07	20.11.2011 02:20	9
Northbound Night Time W1	0.18	C1_6	19Nov11 11:52	20.11.2011 02:30	13
Northbound Night Time W1	0.09	D1_8	19Nov11 15:48	20.11.2011 02:40	9
Northbound Night Time W1	0.18	C1_10	19Nov11 19:53	20.11.2011 02:50	13
Northbound Night Time W1	0.08	F_6	19Nov11 22:54	20.11.2011 02:55	11
Northbound Night Time W1	0.18	C1_4	19Nov11 10:02	20.11.2011 03:00	12
Northbound Night Time W1	0.09	D1_4	19Nov11 12:43	20.11.2011 03:10	9
Northbound Night Time W1	0.09	D1_3	19Nov11 11:36	20.11.2011 03:20	8
Northbound Night Time W1	0.28	B_3	20Nov11 00:42	20.11.2011 03:30	11
Northbound Night Time W1	0.04	D2_6	19Nov11 04:11	20.11.2011 03:40	13
Northbound Night Time W1	0.18	C1_7	19Nov11 14:17	20.11.2011 03:50	12
Northbound Night Time W1	0.08	F_3	19Nov11 19:09	20.11.2011 03:55	10
Northbound Night Time W1	0.09	D1_10	19Nov11 19:05	20.11.2011 04:00	8
Northbound Night Time W1	0.18	C1_8	19Nov11 18:38	20.11.2011 04:10	11
Northbound Night Time W1	0.04	D2_2	19Nov11 03:34	20.11.2011 04:20	12
Northbound Night Time W1	0.18	C1_1	19Nov11 09:00	20.11.2011 04:30	10
Northbound Night Time W1	0.04	D2_1	19Nov11 03:00	20.11.2011 04:40	11
Northbound Night Time W1	0.28	B_4	20Nov11 02:00	20.11.2011 04:50	13
Northbound Night Time W1	0.08	F_1	19Nov11 10:27	20.11.2011 04:55	8
Northbound Night Time W1	0.13	C2_2	19Nov11 18:27	20.11.2011 05:00	22
Northbound Night Time W1	0.04	D2_5	19Nov11 03:50	20.11.2011 05:10	11
Northbound Night Time W1	0.13	C2_3	20Nov11 02:08	20.11.2011 05:20	11
Northbound Night Time W1	0.04	D2_4	19Nov11 03:42	20.11.2011 05:30	9
Northbound Night Time W1	0.13	C2_1	19Nov11 11:50	20.11.2011 05:40	10
Northbound Night Time W1	0.04	D2_3	19Nov11 03:37	20.11.2011 05:50	9
Northbound Night Time W1	0.08	F_5	19Nov11 20:49	20.11.2011 05:55	8
Northbound Night Time W1	0.18	C1_5	19Nov11 10:16	20.11.2011 06:00	10
Northbound Night Time W1	0.04	D2_8	19Nov11 04:25	20.11.2011 06:10	9
Northbound Night Time W1	0.18	C1_2	19Nov11 09:23	20.11.2011 06:20	10
Northbound Night Time W1	0.04	D2_7	19Nov11 04:12	20.11.2011 06:30	8
Northbound Night Time W1	0.18	C1_9	19Nov11 18:51	20.11.2011 06:40	10
Northbound Night Time W1	0.09	D1_6	19Nov11 13:02	20.11.2011 06:50	7
Northbound Day Time W1	0.28	A_1	19Nov11 18:21	20.11.2011 07:00	14
Northbound Day Time W1	0.08	F_1	20Nov11 01:13	20.11.2011 07:05	10
Northbound Day Time W1	0.18	C1_1	19Nov11 21:58	20.11.2011 07:10	14
Northbound Day Time W1	0.09	D1_6	20Nov11 00:52	20.11.2011 07:20	14
Northbound Day Time W1	0.18	C1_3	20Nov11 04:17	20.11.2011 07:30	14
Northbound Day Time W1	0.09	D1_9	20Nov11 00:52	20.11.2011 07:40	14
Northbound Day Time W1	0.18	C1_4	20Nov11 05:05	20.11.2011 07:50	12
Northbound Day Time W1	0.04	D2_4	19Nov11 06:54	20.11.2011 08:00	12
Northbound Day Time W1	0.08	F_2	20Nov11 04:55	20.11.2011 08:05	10
Northbound Day Time W1	0.09	D1_7	20Nov11 02:08	20.11.2011 08:10	11

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Day Time W1	0.28	A_2	19Nov11 21:17	20.11.2011 08:20	11
Northbound Day Time W1	0.09	D1_3	19Nov11 22:50	20.11.2011 08:30	9
Northbound Day Time W1	0.18	C1_2	20Nov11 00:24	20.11.2011 08:40	11
Northbound Day Time W1	0.09	D1_8	20Nov11 02:28	20.11.2011 08:50	9
Northbound Day Time W1	0.13	C2_1	20Nov11 04:01	20.11.2011 09:00	12
Northbound Day Time W1	0.09	D1_1	19Nov11 19:14	20.11.2011 09:10	8
Northbound Day Time W1	0.13	C2_3	20Nov11 08:22	20.11.2011 09:20	11
Northbound Day Time W1	0.09	D1_2	19Nov11 22:29	20.11.2011 09:30	8
Northbound Day Time W1	0.28	A_3	19Nov11 23:00	20.11.2011 09:40	14
Northbound Day Time W1	0.09	D1_4	19Nov11 22:55	20.11.2011 09:50	7
Northbound Day Time W1	0.04	D2_7	19Nov11 11:42	20.11.2011 10:00	11
Northbound Day Time W1	0.09	D1_5	20Nov11 00:45	20.11.2011 10:10	6
Northbound Day Time W1	0.13	C2_2	20Nov11 05:56	20.11.2011 10:20	10
Northbound Day Time W1	0.04	D2_3	19Nov11 06:28	20.11.2011 10:30	10
Northbound Day Time W1	0.04	D2_6	19Nov11 10:51	20.11.2011 10:40	10
Northbound Day Time W1	0.04	D2_8	19Nov11 13:07	20.11.2011 10:50	10
Northbound Day Time W1	0.04	D2_9	19Nov11 13:42	20.11.2011 11:00	10
Northbound Day Time W1	0.04	D2_1	19Nov11 05:28	20.11.2011 11:10	9
Northbound Day Time W1	0.28	A_4	19Nov11 23:08	20.11.2011 11:20	15
Northbound Day Time W1	0.04	D2_2	19Nov11 05:52	20.11.2011 11:30	9
Northbound Day Time W1	0.18	C1_5	20Nov11 09:10	20.11.2011 11:40	11
Northbound Day Time W1	0.04	D2_10	19Nov11 15:30	20.11.2011 11:50	8
Northbound Day Time W1	0.18	C1_6	20Nov11 10:00	20.11.2011 12:00	10
Northbound Day Time W1	0.04	D2_5	19Nov11 08:46	20.11.2011 12:10	8
2 Hours Interlude for Direction Change					
Southbound Day Time W2	0.26	A_1	19Nov11 22:11	20.11.2011 14:10	11
Southbound Day Time W2	0.08	F_1	20Nov11 02:35	20.11.2011 14:15	10
Southbound Day Time W2	0.18	C1_4	20Nov11 03:42	20.11.2011 14:20	17
Southbound Day Time W2	0.09	D1_2	19Nov11 21:36	20.11.2011 14:30	10
Southbound Day Time W2	0.13	C2_1	19Nov11 21:31	20.11.2011 14:40	12
Southbound Day Time W2	0.09	D1_8	20Nov11 10:16	20.11.2011 14:50	9
Southbound Day Time W2	0.18	C1_1	19Nov11 23:38	20.11.2011 15:00	13
Southbound Day Time W2	0.09	D1_1	19Nov11 21:28	20.11.2011 15:10	8
Southbound Day Time W2	0.08	F_2	20Nov11 03:51	20.11.2011 15:15	10
Southbound Day Time W2	0.09	D1_3	19Nov11 22:42	20.11.2011 15:20	8
Southbound Day Time W2	0.26	A_2	20Nov11 03:55	20.11.2011 15:30	13
Southbound Day Time W2	0.09	D1_5	20Nov11 01:44	20.11.2011 15:40	8
Southbound Day Time W2	0.18	C1_2	20Nov11 00:55	20.11.2011 15:50	13
Southbound Day Time W2	0.09	D1_6	20Nov11 01:54	20.11.2011 16:00	8
Southbound Day Time W2	0.18	C1_3	20Nov11 01:38	20.11.2011 16:10	12
Southbound Day Time W2	0.08	F_3	20Nov11 09:49	20.11.2011 16:15	9
Southbound Day Time W2	0.09	D1_4	20Nov11 00:53	20.11.2011 16:20	8
Southbound Day Time W2	0.18	C1_5	20Nov11 04:52	20.11.2011 16:30	12
Southbound Day Time W2	0.09	D1_7	20Nov11 04:19	20.11.2011 16:40	8
Southbound Day Time W2	0.26	A_3	20Nov11 07:28	20.11.2011 16:50	12
Southbound Night Time W2	0.09	D1_2	20Nov11 13:43	20.11.2011 17:00	13
Southbound Night Time W2	0.13	C2_1	20Nov11 02:40	20.11.2011 17:10	9
Southbound Night Time W2	0.09	D1_1	20Nov11 13:30	20.11.2011 17:20	11
Southbound Night Time W2	0.18	C1_1	20Nov11 06:17	20.11.2011 17:30	13
Southbound Night Time W2	0.09	D1_3	20Nov11 14:34	20.11.2011 17:40	8
Southbound Night Time W2	0.04	D2_2	19Nov11 21:28	20.11.2011 17:50	12
Southbound Night Time W2	0.04	D2_1	19Nov11 21:08	20.11.2011 18:00	8
Southbound Night Time W2	0.26	B_1	20Nov11 08:22	20.11.2011 18:10	13

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Southbound Night Time W2	0.04	D2_11	20Nov11 09:29	20.11.2011 18:20	13
Southbound Night Time W2	0.04	D2_16	20Nov11 15:43	20.11.2011 18:30	13
Southbound Night Time W2	0.04	D2_15	20Nov11 15:05	20.11.2011 18:40	12
Southbound Night Time W2	0.04	D2_19	20Nov11 17:34	20.11.2011 18:50	12
Southbound Night Time W2	0.04	D2_20	20Nov11 17:39	20.11.2011 19:00	12
Southbound Night Time W2	0.04	D2_6	20Nov11 04:05	20.11.2011 19:10	11
Southbound Night Time W2	0.09	D1_4	20Nov11 14:48	20.11.2011 19:20	10
Southbound Night Time W2	0.26	B_2	20Nov11 12:13	20.11.2011 19:30	12
Southbound Night Time W2	0.09	D1_6	20Nov11 17:26	20.11.2011 19:40	10
Southbound Night Time W2	0.18	C1_7	20Nov11 16:53	20.11.2011 19:50	14
Southbound Night Time W2	0.09	D1_5	20Nov11 14:49	20.11.2011 20:00	9
Southbound Night Time W2	0.18	C1_8	20Nov11 18:08	20.11.2011 20:10	12
Southbound Night Time W2	0.04	D2_8	20Nov11 08:24	20.11.2011 20:20	11
Southbound Night Time W2	0.18	C1_5	20Nov11 12:09	20.11.2011 20:30	12
Southbound Night Time W2	0.04	D2_12	20Nov11 10:19	20.11.2011 20:40	11
Southbound Night Time W2	0.26	B_3	20Nov11 16:33	20.11.2011 20:50	12
Southbound Night Time W2	0.04	D2_14	20Nov11 11:34	20.11.2011 21:00	11
Southbound Night Time W2	0.18	C1_3	20Nov11 09:27	20.11.2011 21:10	11
Southbound Night Time W2	0.04	D2_24	20Nov11 21:16	20.11.2011 21:20	12
Southbound Night Time W2	0.18	C1_2	20Nov11 06:38	20.11.2011 21:30	11
Southbound Night Time W2	0.04	D2_21	20Nov11 19:16	20.11.2011 21:40	11
Southbound Night Time W2	0.18	C1_4	20Nov11 09:54	20.11.2011 21:50	11
Southbound Night Time W2	0.04	D2_22	20Nov11 19:55	20.11.2011 22:00	11
Southbound Night Time W2	0.04	D2_9	20Nov11 08:36	20.11.2011 22:10	10
Southbound Night Time W2	0.26	B_4	20Nov11 16:52	20.11.2011 22:20	12
Southbound Night Time W2	0.04	D2_10	20Nov11 09:23	20.11.2011 22:30	10
Southbound Night Time W2	0.18	C1_10	20Nov11 19:41	20.11.2011 22:40	11
Southbound Night Time W2	0.04	D2_18	20Nov11 17:11	20.11.2011 22:50	10
Southbound Night Time W2	0.18	C1_9	20Nov11 18:37	20.11.2011 23:00	10
Southbound Night Time W2	0.04	D2_13	20Nov11 11:18	20.11.2011 23:10	9
Southbound Night Time W2	0.18	C1_6	20Nov11 14:32	20.11.2011 23:20	7
Southbound Night Time W2	0.04	D2_26	20Nov11 23:12	20.11.2011 23:30	11
Southbound Night Time W2	0.26	B_5	20Nov11 18:06	20.11.2011 23:40	15
Southbound Night Time W2	0.04	D2_5	20Nov11 02:59	20.11.2011 23:50	9
Southbound Night Time W2	0.04	D2_23	20Nov11 19:57	21.11.2011 00:00	9
Southbound Night Time W2	0.04	D2_17	20Nov11 17:07	21.11.2011 00:10	8
Southbound Night Time W2	0.04	D2_25	20Nov11 22:01	21.11.2011 00:20	8
Southbound Night Time W2	0.09	D1_7	21Nov11 00:03	21.11.2011 00:30	8
Southbound Night Time W2	0.08	F_1	21Nov11 00:21	21.11.2011 00:35	12
Southbound Night Time W2	0.04	D2_28	21Nov11 00:28	21.11.2011 00:40	10
Southbound Night Time W2	0.04	D2_27	20Nov11 23:41	21.11.2011 00:50	8
Southbound Night Time W2	0.04	D2_4	20Nov11 02:39	21.11.2011 01:00	8
Southbound Night Time W2	0.04	D2_7	20Nov11 07:25	21.11.2011 01:10	8
Southbound Night Time W2	0.04	D2_3	20Nov11 02:00	21.11.2011 01:20	7
Southbound Night Time W2	0.08	F_2	21Nov11 00:45	21.11.2011 01:25	9
2 Hours Interlude for Direction Change					
Northbound Night Time W2	0.28	B_1	20Nov11 08:24	21.11.2011 03:25	14
Northbound Night Time W2	0.08	F_1	20Nov11 10:51	21.11.2011 03:30	10
Northbound Night Time W2	0.09	D1_7	20Nov11 06:16	21.11.2011 03:35	15
Northbound Night Time W2	0.18	C1_3	20Nov11 12:41	21.11.2011 03:45	14
Northbound Night Time W2	0.09	D1_1	20Nov11 02:53	21.11.2011 03:55	12
Northbound Night Time W2	0.18	C1_4	20Nov11 17:08	21.11.2011 04:05	13
Northbound Night Time W2	0.09	D1_2	20Nov11 03:17	21.11.2011 04:15	12

Table B.17. The mathematical model solution for the 48 hour period on 19-20-21th of November (continued).

Time Window	Weight	Vessel	Ready Time	Entering Time to the Strait	Vessel Speed (knots)
Northbound Night Time W2	0.18	C1_7	20Nov11 19:33	21.11.2011 04:25	13
Northbound Night Time W2	0.08	F_2	20Nov11 20:57	21.11.2011 04:30	10
Northbound Night Time W2	0.09	D1_4	20Nov11 04:52	21.11.2011 04:35	11
Northbound Night Time W2	0.28	B_2	21Nov11 00:52	21.11.2011 04:45	10
Northbound Night Time W2	0.09	D1_5	20Nov11 04:57	21.11.2011 04:55	11
Northbound Night Time W2	0.18	C1_5	20Nov11 19:25	21.11.2011 05:05	12
Northbound Night Time W2	0.09	D1_3	20Nov11 04:12	21.11.2011 05:15	10
Northbound Night Time W2	0.18	C1_1	20Nov11 10:36	21.11.2011 05:25	11
Northbound Night Time W2	0.08	F_3	20Nov11 21:55	21.11.2011 05:30	10
Northbound Night Time W2	0.09	D1_6	20Nov11 05:51	21.11.2011 05:35	10
Northbound Night Time W2	0.13	C2_1	20Nov11 22:05	21.11.2011 05:45	11
Northbound Night Time W2	0.09	D1_10	20Nov11 12:46	21.11.2011 05:55	9
Northbound Night Time W2	0.28	B_3	21Nov11 04:06	21.11.2011 06:05	15
Northbound Night Time W2	0.09	D1_8	20Nov11 07:30	21.11.2011 06:15	8
Northbound Night Time W2	0.18	C1_6	20Nov11 19:25	21.11.2011 06:25	11
Northbound Night Time W2	0.08	F_4	20Nov11 23:40	21.11.2011 06:30	9
Northbound Night Time W2	0.09	D1_9	20Nov11 09:46	21.11.2011 06:35	7
Northbound Night Time W2	0.18	C1_2	20Nov11 10:56	21.11.2011 06:45	10

Table B.18. The accounting of vessels not admitted to the Strait in each direction for the 48 hour period on 19-20-21th of November.

Vessel	Southbound	Northbound
A	0	0
B	0	0
C1	0	4
C2	0	0
D1	0	17
D2	0	49
E	0	0
F	0	0
P	0	0

Table B.19. The waiting times of vessels not admitted to the Strait in each direction for the 48 hour period on 19-20-21th of November.

Vessel Class	Southbound		Northbound	
	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)	Total Weighted Waiting Time (Min.)	Avg. Weighted Waiting Time (Min.)
A	0	0	0	0
B	0	0	0	0
C1	0	0	184	46
C2	0	0	0	0
D1	0	0	871	51
D2	0	0	2,308	47
E	0	0	0	0
F	0	0	0	0
P	0	0	0	0

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