Transatlantic Maritime Transportation Between the Czech Republic and the United States

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TRANSATLANTIC MARITIME TRANSPORTATION BETWEEN THE
CZECH REPUBLIC AND THE UNITED STATES

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Dedication

I would like to use this opportunity and dedicate this thesis to the special memory of Doc. Ing. Ladislav Bína, CSc., thanks to mainly him I had this great opportunity to study and live in El Paso which was very exciting and enriching.
TRANSATLANTIC MARITIME TRANSPORTATION BETWEEN THE CZECH REPUBLIC AND THE UNITED STATES

by

PETR TOMAN, Bc.

THESIS

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Special thank belongs to my parents and family for their support during all my life.
Declaration

This thesis is an output of the Transatlantic Dual Masters Degree Program in Transportation Science and Logistics Systems, a joint project between Czech Technical University in Prague, Czech Republic, The University of Texas at El Paso, USA and University of Zilina, Slovak Republic.

This thesis is jointly supervised by the following faculty members:

Ruey Long Cheu, Ph.D., The University of Texas at El Paso
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Abstract

Maritime transportation is the backbone of today’s world trade and therefore there special attention should be paid to all subjects concerning this mode of transportation. It is also necessary to complement maritime transportation by other modes, such as rail and/or truck (road). This thesis deals with the problems of maritime transportation and provides the summary of recent developments, trends and statistics mainly on Transatlantic maritime routes (Europe to U.S.). Besides maritime transportation, this thesis also reviews the trends and statistics of rail and truck (road) transportation in U.S. and Europe.

The second part of thesis seeks to create a mathematical model of transportation between Europe and U.S. The line haul is maritime transportation and the complementary modes of transportation from the ports to/from cities (points of destination/origin) are rail and truck (road). The models are formulated for shipping goods from Europe to U.S. The first model, Transatlantic Multi-Mode Container Routing Problem (TMMCRP), is developed by author himself. The second one, Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP), already existed in a different formulation and the author adjusted it to be applicable to the case study.

The last part of the thesis deals with a case study. The author considers four Czech biggest cities (points of origin), five European ports, eight U.S. ports and 10 biggest cities in U.S. (points of destination). The adapted Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP) is applied to this case study and it seeks to solve the transportation of a set of five shipments with unique O-D pairs and volume. The end of the thesis summarizes the results and analyses the average costs, optimal set volume, optimal shipment routing and port analysis.
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Chapter 1: Introduction

Chapter 1 is the introduction of whole thesis. It consists of the background, the description of main thesis objectives and the organization of the thesis.

1.1. Background

Maritime transportation is undeniably one of the most important and one of the most widespread transportation modes in the world.

Chyba! Nenalezen zdroj odkazů. shows the gross weight of seaborne goods handled in European ports in the years 2002-2011. There is an obvious increasing trend in years 2002-2007. In year 2008 the gross weight became steady and in 2009 it fell rapidly. This was caused by the economic recession which hit Europe in 2008 and its aftermaths can be seen in 2009. From year 2009 there has been a continuing growth.

Figure 1.1 The gross weight of seaborne goods handled in European ports 2002-2011

Source: EC (2014a)
In U.S., 1.478 billion tons of freight was transported by sea in year 2011. It was almost 75% of all U.S. international merchandise trade weight in that year. Figure 1.2 shows the weight of U.S. international merchandise trade by mode of transportation in year 2011.

![Figure 1.2 Weight of U.S.-International merchandise trade by mode of transportation: 2011 Total Modal (%)](image)

Source: RITA (2012b)

Figure 1.3 shows the value of U.S. international merchandise trade by mode of transportation in year 2011. In that year, the value of U.S. international trade was $3.688 billion. It was almost 47% of all U.S. international merchandise trade value. In comparison the value of freight transported trade by sea (46.90 %) with weight of freight transported trade by sea (74.96%) it is obvious that sea transportation mode is being used mainly for transportation of the goods of lower value where time does not play a crucial role.
Figure 1.3 Value of U.S.-International trade by mode of transportation: 2011 Total Modal (%)
Source: RITA (2012a)

With the increase of the international trade across the continents maritime transportation has developed technologically over the last 20 years.

There are several ways where maritime transportation has developed in the last decades. The first one is indisputably containerization. The container was firstly used in transportation process in 1956. Since that time it has been developed into today’s different variety of containers. Container sizes were standardized so the handling and stacking of containers become much easier and faster. The faster growth of containerization was recorded in the years 1990-2008 and during those years the containerization had the biggest impact on world trade. It was particularly connected with the entry of China in the global economy. Detailed information about containerization will be reviewed in Chapter 2.

Another trend in maritime transportation is the development of ships. Container ships became bigger and their capacity has been increased. The largest container ships have the
maximum capacity up to 18,270 Twenty-foot Equivalent Units (TEUs). More information concerning maritime ships is in Chapter 2.

One of the most important features of the maritime transportation is its network and its connection with highway and railway systems. The maritime network has three main routes: transpacific, transatlantic and Europe-Asia. Figure 1.4 shows the main maritime shipping routes and main ports in the world maritime network.

![Main Maritime Shipping Routes](image)

Figure 1.4 World maritime network
Source: Rodrigue et al. (2013)

Almost every time when sea transportation is used in shipping goods it is necessary to connect it with one of the inland modes of transportation (truck, railway or inland waterborne). Ports play the crucial role of intermodal transportation. Therefore they have to be adequately equipped to be able to handle transshipment from ships to inland modes of transportation (truck, train, barge) and conversely. The maximum truck capacity is limited to 40 ft (to carry two TEU
containers). In most countries the range of capacity of trains differs from 50 to 100 TEUs. In some countries (e.g. U.S.) double stacking is being used and it increases the capacity of trains up to 400 TEUs (PPIAF 2014a). The intermodal transportation segment is quite important, because it grows most rapidly compared to the other freight businesses. In the years 1988 and 2008 the international combined transportation (in tons) had increased by 215% and between 2002 and 2015 it is expected to grow by 135% (UIRR 2014).

The principle of intermodal transportation is shown on the Figure 1.5. In international shipping the “first mile” and “last mile” are usually trucks or trains while the line haul transportation is usually maritime transportation.

![Intermodal transportation chain](Image)

**Figure 1.5 Intermodal transportation chain**
Source: Rodrigue et al. (2013)

### 1.2. Thesis Motivation

Maritime transportation is essential for international trade. There is no other mode, except perhaps for air transportation, on how to transport goods between two or more countries which do
not have any land connections between them. Air transportation is fast transportation but it is indisputably much more expensive in comparison with other modes. For example, the comparison of air, road, rail and sea transportation can be seen in Figure 1.6. These modes of transportation are compared according to the following criteria: transit time and cost of transportation of 40-ft container from China to western Europe.

![Figure 1.6 Comparison of transportation modes for transportation of 40´ container from China to western Europe](image)

Source: Container Transportation (2014a)

Even though maritime transportation is not the fastest mode of transportation, it is the cheaper option. Thus it is crucial for world trade and its development. More than 90% of European Union’s (EU’s) external trade is transported by maritime transportation (EP 2009). Therefore it is necessary to continuously look for better solutions and improvements of that transportation to find more economical and faster ways for the transport of goods. This thesis
focuses on the transatlantic route, specifically transportation between the Czech Republic and U.S. with the aim on maritime transportation as the line haul.

1.3. Thesis Objectives

There are several objectives in this thesis.

The first objective is to analyze maritime transportation between U.S. and EU. Included in the discussions are different ways of goods transportation between the U.S. and Europe focusing on the Czech Republic. Another issue which the thesis deals with is the description of major ports of both U.S. and Europe. The ports are classified by the location, depth and capacity.

The second objective is to review the main problems of today’s maritime transportation and highlight the recent developments, including vessel’s classification, parameters, capacities, size categories, etc.

The third objective of this thesis is to develop a general model of multimodal freight transportation between EU and U.S. The model of freight transportation will be applied to four main Czech cities (Prague, Brno, Ostrava and Pilsen) and 10 biggest cities in U.S. as the origins and destinations. Since this thesis concerns with freight transportation between the main cities in EU and U.S., inland transportation by truck and rail from the Czech Republic to the most important ports of Europe are also included. The same is done also for U.S. continent.

1.4. Thesis Organization

This thesis is organized into the following chapters:

- Chapter 1 describes the background, objectives and organization of this thesis.
- Chapter 2 reviews maritime transportation. It mentions world maritime routes. It reviews maritime ships, their parameters, classification, capacities, and etc. Major ports in both- U.S.
and European continent and the inland truck and rail connections from these ports to main cities are also discussed.

- Chapter 3 presents two mathematical models which serve as the optimization tool of a freight transportation between Europe and the U.S.
- Chapter 4 presents the application of the model of multimodal freight transportation between the Czech Republic and U.S. adjusted the author and a case study.
- Chapter 5 outlines the main findings of the thesis and gives a summary.
Chapter 2: Review of Maritime Transportation

2.1. World Trade

2.1.1. Merchandise Trade

The development of the maritime transportation and international seaborne trade are highly connected with worldwide macroeconomic conditions. World merchandise trade and world seaborne trade have been continuously shaped by the shape of the curve of world GDP. Moreover, global merchandise trade has been growing much faster than GDP (UNCTAD 2013). Figure 2.1 shows the close connection of world GDP, world merchandise trade and seaborne trade.

![Graph showing the connection between world GDP, world merchandise trade, world seaborne trade, and OECD Industrial Production Index.](source-unctad-2013)

Figure 2.1 The OECD Industrial Production Index and indices for world GDP, world merchandise trade and world seaborne trade (1975-2013) (1990 = 100)

Source: UNCTAD (2013)
For example, 90% of the EU’s external trade and over 40% of its internal trade is transported by sea. Europe controls 40% of world merchant fleet. Every year over 3.5 billion tons of cargo passes through the European ports. Globalization, the elimination of trade barriers, the unprecedented growth of containerization and the increase in seaborne trade level have had an impact on maritime transportation and therefore it has shaped the changes in the 20 years (EP 2009).

2.1.2. World Seaborne Trade

The amount of world merchandise trade and international seaborne trade has been continuously increasing since the year 1985 (UNCTAD 2013). The only exception is in year 2009, when the international seaborne trade was influenced by the economic recession that hit U.S. and Europe in 2008. During these years international seaborne trade decreased by 6%. Figure 2.2 illustrates above mentioned trend.
2.2. World Maritime Routes

Since maritime transportation is essential for world merchandise trade including world seaborne trade, several maritime routes and corridors have been heavily used. As can be seen on Figure 2.3, there exist three main maritime routes, which are crucial for the world maritime network. Figure 2.3 shows the density of these corridors (in number of journeys) in 2010. The three most occupied routes are connecting Europe and North America (transatlantic route), North America and Far East (transpacific route) and Europe and Far East (Europe-Asia-Europe route).
2.2.1. Types of Maritime Routes

There exist three main types of maritime routes which are shown on Figure 2.4:

- **Port-to-port**
  
  This type of maritime route usually consists of regular service between two ports. The disadvantage of this route structure is limited connectivity. It is used mainly by the movements of raw materials.

- **Pendulum**
  
  This type of maritime route is the characteristic of transportation of containerized cargo and involves a sequence of ports where the maritime shipping line seeks to optimize their ship’s movement. The most significant pendulum routes are between western Europe, North America and East Asia.
• **Round-the-World**

  This type involves a sequence of ports which makes a trip around the world.

![Diagram of maritime routes](image)

**Figure 2.4 Three main types of maritime routes**
Source: Rodrigue et al. (2013)

### 2.2.2. Statistics

Figure 2.5 shows how the containerized cargo flows have been increasing since the year 1995 to 2012. The flow on the transatlantic route has been increasing slowly and not as rapidly as the flows on the transpacific route and the Europe-Asia-Europe route. While the transatlantic flow has been more or less the same and has been about 5 millions TEUs per year, other two flows have been practically increasing by one million TEUs per year before 2009. In 2009 cargo flows on all these routes recorded sharp declines. The global container trade dropped by almost 10%. It was first negative annual percentage change.

From Figure 2.5 it is also obvious that the busiest routes are transpacific and Europe-Asia-Europe. The busiest one had been the transpacific route before 2009 but after that the transpacific route was exceeded by the Europe-Asia-Europe route.
2.2.3. Transpacific Route

This route started in 1968 between Seattle and Yokohama. It connects the west coast of North America and industrial parts of Japan (Keihin ports, Hanshin ports) and the Far East (Shanghai, Singapore, Hon Kong, Shenzhen, Busan, and etc.).

The long distance transport services on the transpacific route have been adapted to the realities of production along U.S. and Far East. Pendulum routes consists of port calls (five to seven) within Asia Pacific and couple of calls along U.S. west coast. The average time for such services ranges between 35 and 50 days. It depends on the number of port calls, the time spent at ports and the port locations. There are also a few direct routes, which round trips time is about 25 days (Rodrigue et al. 2013).
Figure 2.6 Two major transpacific pendulum routes provided by OOCL
Source: Rodrigue (2007)

Figure 2.6 shows the two most important pendulum services lines provided by Orient Overseas Container Line (OOCL). The Northwest Express route (NWX) links Japan, Central / Northern China and South Korea. Japanese parts (automobile) are shipped to coastal China assembly plants. The finished or semi-finished goods are shipped from the Chinese ports across the Pacific to the U.S. with a stop in South Korea where Korean exports are loaded. Similar arrangement is repeated for the South China Express route (SCX). The trading flows most usually involve finished goods for the North American retailing distribution centers. This pendulum service line is often called “Wal-Mart” line, because this corporation buys about 12% of all Chinese exports and this trade is associated with the SCX route (Rodrigue 2007).
2.2.4. Europe-Asia-Europe Route

For many years the second most important route after the transpacific one was the Europe-Asia-Europe route. In the years 2009-2011 it overtook the transpacific route and became the most important maritime route in terms of volume of transported TEUs. This route connects mainly western Europe and Far East as can be seen in the Figure 2.7 (UNCTAD 2013).

![Figure 2.7 Europe - Asia - Europe maritime route and its alternatives](source: Rodrigue et al. (2013))

The artery between Asia and Europe is the Suez route. It goes through locations such as Strait of Malacca, Bab el-Mandab, the Suez Canal and the Strait of Gibraltar. Maritime shipping companies can use container ships with a capacity to 12,500 TEUs (SuezMax) due to draft of the Suez Canal (Rodrique et al. 2013).
There are two alternatives from the Suez route. The first alternative route is sailing along the Cape of Good Hope (Cape route). This route is approximately 4,900 nautical miles (8,900 km) or 10 days longer than the Suez route (WSC 2014).

The second alternative is the Northern Sea Route. Since the polar ice cap has been rapidly reduced and further ice cap reductions would open this new possibility of connecting western Europe with the Far East. The disadvantages of this alternative are the necessity of ice-classed ships, ice breaker assistance, slower sailing speed, navigation difficulties and Russian transit fees. Together they have caused non-regularity of the liner services. This route is used mainly during summer months due to lower sea ice concentration (NSR 2014).

2.2.5. Transatlantic Route

This route connects the main ports in the east coast of North America (New York-New Jersey, Savannah, Norfolk, Charleston and Miami) with main ports of western Europe (Rotterdam, Antwerp, Hamburg and Bremerhaven).

Since EU has proposed to U.S. in March 2013 and the U.S. on a trade and investment agreement called Transatlantic Trade and Investment Partnership (TTIP) the transatlantic route could become increasing more important for the global trade. The total U.S. investment in the EU is three times higher than in all of Asia and EU investment in U.S. is approximately eight times the amount of EU investment in India and China together. Therefore these investments are real driver of the transatlantic trade relationship, contributing to growth on both sides of the Atlantic. Thus the volume of transported cargo on the transatlantic route could to increase (EC 2013a).
Figure 2.8 shows the statistics of EU-U.S. trade in goods value. It is obvious that EU export is higher than U.S. export. The statistic also shows the growing trend of EU-U.S. trade.

Nowadays the route does not only connect the European ports with the ports on east coast of the U.S. but also the ports on west coast of U.S. Instead of sailing pass the shore of South America there is a possibility to sail through the Panama Canal which shortens the distance necessary to reach the ports on west coast by approximately 7,000 nautical miles (13,000 km). The time shortened by this is about 14 days compared to sailing pass South Africa (Rodrigue et al. 2013).

The pendulum route structure also exists in the transatlantic route. One of them is being provided by OOCL and it can be seen in Figure 2.9. Atlantic Express (ATX) takes in a total 27 days (including time spent in the ports) and it serves four European ports (Hamburg, Rotterdam, Le Havre and Southampton) and three ports on east coast of the U.S. (New York, Norfolk and Charleston).
2.3. Maritime Ships

One of the most important things of the maritime transportation is maritime ships. There exist several types of maritime ships used for different purposes. The differentiation depends mainly on the type of transported goods. Maritime ships differ also in vessel size, vessel speed and generally vessel parameters. All these features are being discussed in the following subsections of the thesis.

2.3.1. Parameters of Maritime Ships

Length Overall (LOA)

Length Overall (LOA) means the maximum length of a ship’s hull. This distance is measured parallel to the waterline and it is commonly used method to express the size of a ship.
This parameter is also important for docking of ship in a port because it is used for calculating the cost of marina berth.

**Beam**

The beam of a ship is the width measured at the widest point and at the ship’s nominal waterline. Beam is one of the most important parameters of vessels for sailing through canals (e.g., the Panama Canal).

**Draft**

The draft is the vertical distance between the waterline and the bottom of the hull. The thickness of the hull is included. Draft also represents the minimum depth of water a ship can be safely navigated. Draft is another significant factor of vessel for navigating through waterways such as canals (e.g., the Panama Canal, the Suez Canal) and straits (e.g., Strait of Malacca). It is also crucial for vessel’s docking in ports. Figure 2.10 shows range and average draft of container ships according their capacity in TEU.
Figure 2.10 Range of draft and average draft of container ships
Source: Rodrigue et al. (2013)

Speed

The average speed of ships is about 15 knots (1 knot = 1 marine mile per hour = 1.853 km per hour). Nowadays, ships are capable to sail up to 30 knots but it is very uncommon for ships to sail faster than 25 knots because the energy requirements are high.

According to the energy requirements and fuel consumption the speed can be divided as the following:

- **Normal** (20-25 knots; 37.0-46.3 km/hr) - this is the optimal cruising speed a container ship and its engine have been design to travel at. Most of the containerships are designed to travel at 24 knots.
- **Slow steaming** (18-20 knots; 33.3-37.0 km/hr) - this speed saves fuel, but at the expense of additional travel time. It became important mainly after the recession hit the world trade in 2009. In 2011, more than 50% of containerships travel at this speed.

- **Extra slow steaming** (15-18 knots; 27.8-33.3 km/hr) - is also known as economical speed. By this speed is possible to reach a minimal level of fuel consumption and maintaining a commercial service at the same time.

- **Minimal cost** (12 - 15 knots; 22.2 - 27.8 km/hr) - this lower speeds do not lead to any significant additional fuel save. The level of service is unacceptable at this speed (Rodrique et al. 2013).

**Capacity**

There exist two main ways to formulate a vessel’s capacity: by **DeadWeight Tonnage (DWT)** and by **Twenty-foot Equivalent Unit (TEU)**. DWT is a measure of how much can a vessel carry and can still safely sail. It is the summation of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers and crew.

**Volume**

There are two basic ways of volume formulation: **Gross Register Tonnage (GRT)** and **Net Register Tonnage (NRT)**. GRT is a vessel’s total internal volume (non-revenue-earning and revenue-earning space) expressed in register tons (1 RT = 100 cubic feet = 2.83 m³). NRT is calculated from GRT by excluding of non-revenue-earning spaces.

**2.3.2. Classification by Vessel Type**

There exist several vessel types according to different types of transported goods. The main vessel types are: oil tankers, bulk carriers, general cargo ships, container ships, liquefied gas...
Carriers, offshore supply ships, ferries and passenger ships. The four most widespread vessel types are oil tankers, bulk carriers, general cargo ships and container ships.

Figure 2.11 provides a relatively good overview of common types of merchant vessels.

![Merchant ships diagram](image)

**Figure 2.11 Overview of merchant ship types**

*Source: GDV (2014)*

Figure 2.12 provides a good overview of world fleet by vessel types and their capacity in DWT. It can be seen that two most widespread vessel types have been oil tanker and dry bulk carriers. The total capacity of both these vessel types has been continuously increasing while the total capacity of general cargo ship remains the same.
2.3.2.1. Oil Tankers

This vessel is designed for the bulk transport of oil. There are two basic types of oil tanker: crude tanker and product tanker. Crude tankers are used for transportation of large quantities of unrefined crude oil from the point of its extraction to refineries. While product tankers are ships supposed to transport petrochemicals from refineries to places of consumption. Generally they are much smaller than crude tankers (capacity up to 550,000 DWT of crude oil) and they are able to move from 10,000-80,000 DWT of petrochemicals.
2.3.2.2. Bulk Carriers

Bulk carriers are ships which are designed to carry solid bulk cargoes. In DWT, bulk carriers carry almost 41% of the world’s sailing fleet as can be seen from Figure 2.12. It is the most widely used vessel type (UNCTAD 2013).

Currently more than 7,000 bulk carriers (which is more than a third of the entire merchant fleet in the world) sail the seas carrying the majority of the world’s dry bulk cargoes, including bulk cargoes such as coal, grain, iron ore, bauxite, alumina, steel products, phosphate, cement, pet coke, forest products, and sulphur. They range from small vessels of under 500 DWT to huge carriers of 365,000 DWT. Bulk carriers have to be carefully designed and maintained because they may carry cargo that can be very dense, corrosive and abrasive (DNV-GL 2014, Maritime Connector 2014).

There are also several types of bulk carriers such as basic bulk carriers, combined carriers, gearless carriers, self-dischargers, lakers, and BIBO (“Bulk In, Bags Out”).

Basic bulk carriers are usually equipped by series of holds (from 5 for a 35,000 DWT vessel to 9 for a 250,000 DWT vessel) covered by prominent hatch covers. They are also equipped by on-board cranes allowing them to discharge cargo in ports without necessity of shore-based cranes. They are also flexible with respect to cargoes they can carry and the routes they can sail through.

Gearless carriers are bulkers without any cranes or conveyors. Therefore they can’t go to the ports without any loading or unloading facilities. They are usually of big size thus they can only dock at the largest and most equipped ports. The main reason why such bulk carriers are used is to avoid the costs of installing, operating and maintaining cranes in the vessels. In contrary, self-dischargers are such bulk carriers with on-ship conveyor belts allowing them to discharge their cargo efficiently and quickly.
2.3.2.3. General Cargo Ships

General cargo ships are vessels arranged for lift on/lift off cargo handling and they are used for carriage of general dry cargoes. The cargo holds of these multi-purpose vessels are able to handle both containers and all sorts of cargo. These vessels carry packaged items like chemicals, foods, furniture, machinery, motor- and military vehicles, and etc (MARIN 2014).

The traditional ships are less than 10,000 DWT, because of extremely slow loading and off-loading. These ships have been replaced by container ships because they can be loaded and unloaded faster and efficiently.

From Figure 2.12 it can be seen that absolute value of transported DWT has practically fluctuated around the value of 110 millions of DWT per year since 1980. But in comparison with other vessel types the relative value of general cargo vessel has continuously decreased since the other vessel types have been increasing in DWT. In 2012, general cargo vessels carry 6.9% of all the world maritime trade (UNCTAD 2013).

2.3.2.4. Container Ships

Nowadays, about 90% of non-bulk cargo in the world is transported in containers and the capacity of vessels capable to carry containers is continuously increasing. Ships of latest generation Post New Panamax are able to carry up to 15,000 TEUs. The principle of economies of scale is fundamental to the economics of maritime transportation. Therefore the capacity of container ships had been continuously increased because larger the ship is the lower cost per transported unit is. Continuous development of container ship capacity is obvious from Figure 2.13 (Container Transportation 2014b).
Figure 2.13 Graph of development of container vessel’s capacity

Source: Rodrigue et al. (2013)

It is possible to say that generally the higher the vessel capacity the smaller the total number of vessel is. In 2011, there were a total of 5,000 purpose-built container vessels. An aggregate capacity of those vessels was 17.77 million TEUs. The distribution of vessel number according the vessel capacity can be seen in Table 2.1 (Container Ships 2014b).
Containerization and Containers

The history of containerization goes back to 20th century. Entrepreneur named Malcom McLean was the first one who put the idea of container into practice. On 26 April 1956 McLean’s prototype, a modified Second World War tanker, sailed from Newark to Houston and it carried 58 truck bodies with removed wheels. This shipment started a revolution in transportation even though in 1950s it still took up five days to load and unload a standard conventional cargo vessel. Therefore bulk cargo ships spent more time in ports than at sea (Tomlinson 2009).

Freight containers started to be rapidly used in the 1960s for the consignment of goods by sea and it also began the development of vessels specialized for container transportation. Therefore the International Maritime Organization (IMO) published ISO standards for containers.
between 1968 and 1970. Loading, transporting and unloading of goods in ports became more consistent and efficient due to those standards. It saved time and resources (IMO 2014).

Establishing standard containers was crucial for the following development of container transportation and the number of containers in the world started to continuously grow as Table 2.2 shows.

Table 2.2 Number of containers in the world

<table>
<thead>
<tr>
<th>End of the year</th>
<th>Number of containers (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>18 000</td>
</tr>
<tr>
<td>1965</td>
<td>54 000</td>
</tr>
<tr>
<td>1970</td>
<td>500 000</td>
</tr>
<tr>
<td>1975</td>
<td>1 300 000</td>
</tr>
<tr>
<td>1980</td>
<td>3 150 000</td>
</tr>
<tr>
<td>1985</td>
<td>4 850 000</td>
</tr>
<tr>
<td>1990</td>
<td>6 400 000</td>
</tr>
<tr>
<td>1995</td>
<td>9 600 000</td>
</tr>
<tr>
<td>2000</td>
<td>13 800 000</td>
</tr>
<tr>
<td>2005</td>
<td>19 100 000</td>
</tr>
<tr>
<td>2008</td>
<td>25 000 000</td>
</tr>
</tbody>
</table>

Source: Container Transportation (2014c)

A freight container is a shipping equipment with length suitable to withstand shipment, storage, handling and used to transport cargo. According to ISO 668:1995(E), a shipping container is an article of transport equipment which is:

a) of a permanent character and accordingly strong enough to be suitable for repeated use;

b) specially designed to facilitate the carriage of goods, by one or more mode of transport, without intermediate reloading;
c) fitted with devices permitting its ready handling, particularly its transfer from one mode of transport to another;

d) so designed as to be easy to fill and empty;

e) stackable; and,

f) having an internal volume of 1 cubic meter or more (Container Transportation 2014d).

According to ISO 6346 (1996) (Container Transportation 2014e), freight containers are divided into following main categories:

1. General purpose container
2. Bulk container
3. Named cargo container (livestock container, automobile container, etc.)
4. Thermal container
5. Open-top container
6. Platform container
7. Tank container

Nowadays, the most widely used containers are 20 ft and 40 ft long. Table 2.3 shows the dimensions of ISO container standards of the three most used containers in shipping. All ISO containers have width of 8 ft (2.438 m). The standard container height is 8 ft 6 inches (2.591 m) while a high container’s height is 9 ft 6 inches (2.896 m). The length of 20-ft container is 19 ft 10.5 inches (6.058 m) while length of a 40-ft containers is exactly 40 ft (12.192 m) (Container Transportation 2014f).
Table 2.3 ISO dimensions of three most used containers

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Container 20’ (20’DC)</th>
<th>40’ standard (40’DC)</th>
<th>40’ high (40’HC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>imperial</td>
<td>metric</td>
<td>imperial</td>
</tr>
<tr>
<td>External</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>19' 10,5&quot;</td>
<td>6,058 m</td>
<td>40'</td>
</tr>
<tr>
<td>Width</td>
<td>8’</td>
<td>2,438 m</td>
<td>8’</td>
</tr>
<tr>
<td>Height</td>
<td>8'6&quot;</td>
<td>2,591 m</td>
<td>8'6&quot;</td>
</tr>
<tr>
<td>Internal (min)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>5,867 m</td>
<td>11,998 m</td>
<td>11,998 m</td>
</tr>
<tr>
<td>Width</td>
<td>2,330 m</td>
<td>2,330 m</td>
<td>2,330 m</td>
</tr>
<tr>
<td>Height</td>
<td>2,350 m</td>
<td>2,350 m</td>
<td>2,350 m</td>
</tr>
<tr>
<td>Gross mass</td>
<td>52900 lb</td>
<td>24000 kg</td>
<td>67200 lb</td>
</tr>
</tbody>
</table>

Source: Container Transportation (2014f)

2.3.2.5. Other

Other types of vessels are liquefied gas carriers, offshore supply, ferries and passenger ships, etc. Figure 2.12 shows that in the last three years the amount of DWT for all other vessels has almost been the same as the general cargo ships. In 2012, it was 100 million DWT which was 6.5% of all volume.

2.3.3. Classification of Containerships by Vessel Capacity

Figure 2.14 is a good overview of the classification of container ships according vessel capacity. This figure shows how ships are called according to their capacity in TEU, the year since they have been in operation, their dimensions (length, width and draft) in meters. The
schemes on the right side of Figure 2.14 show how many layers of containers it is possible to stack below and above the deck and in how many rows they can be stacked.

![Classification of container ships according vessel capacity](image)

All dimensions are in meters. LOA: Length overall.

Figure 2.14 Classification of container ships according vessel capacity
Source: Rodrigue et al. (2013)

2.3.3.1. Early Containerships and Fully Cellular

The first generation of vessels which were able to transport containers was modified bulk carriers or tankers and they were able to carry up to 1,000 TEUs. In 1960s most vessels transporting containers had to be equipped by their own onboard cranes because most port terminals were not equipped to handle containers. Ships were relatively slow with speeds of about 18 to 20 knots. Those ships were able to carry containers only on their decks.
Carrying containers below the deck became possible by the construction of fully cellular containerships (FCC; second generation) in the beginning of the 1970s. Since that time all containerships consist of cells lodging containers in stacks of different heights depending on the vessel capacity. The advantage of such ships is that whole ship can be used for carrying containers (including below deck) and in addition, cranes we removed so more containers could be carried. Ports all around the world started to be equipped by container terminals with cranes. The speed of such containerships is between 20 and 24 knots and the capacity is in the range of 1,000 - 2,500 TEUs (Rodrigue et al. 2013).

2.3.3.2. Panamax and Panamax Max

In the 1980s the economies of scale rapidly pushed for the construction of larger containerships. The size limit for such ships was the Panama Canal and its dimensions. That size limit became to be known as the Panama standard and it was achieved in 1985 with a capacity of about 4,000 TEUs. Panamax containership designs were evolving to take maximum advantage of the limitation in beam (Panamax Max) (Rodrigue et al. 2013).

Figure 2.15 shows that lock chambers at Panama Canal are 33.5 m (110 ft) wide, 304.8 m (1,000 f) long, and on average are 12.8 m (42 ft) deep. Therefore the maximum dimensions allowed for ships sailing through Panama Canal are: length 294.13 m (965 ft), beam 32.31 m (106 ft), draft 12.04 m (39.5 ft) in tropical fresh water (ACP 2014).

2.3.3.3. Post Panamax and Post Panamax Plus

Going beyond Panamax had been for long time perceived as a risk in terms of configuration of the networks, necessity of better handling infrastructure of ports and their draft limitations. In 1988 American President Lines (APL) introduced first containership which
exceeded the 32.2 m width limit of the Panama Canal. Then in 1996 Post Panamax containerships were introduced and their capacities reached 6,600 TEUs.

Those containerships needed a substantial amount of cargo to be profitable. In the 1990s the rapid growth of global trade enabled that those ships were competitive and could be profitable. Vessel capacity increased quickly and reached 8,000 TEUs (Post Panamax Plus; “SSovereign Class”).

One of the requirements of Post Panamax containerships is deep water ports. Draft necessary for those ships is at least 13.1 m (43 ft). Another requirement is the highly efficient, but costly, so-called portainers (container cranes) (Rodrigue et al. 2013).

2.3.3.4. New Panamax

These new containerships should come into operation in 2014 (or later) as can be seen in Figure 2.14. This date depends on the opening of the expanded Panama Canal which was expected to be opened in 2014. Nowadays it is known that the completion date is delayed and the earliest completion date of the expanded Panama Canal will be in the fourth quarter of 2015 (Labrut 2013).

New Panamax ships are constructed to fit exactly to the locks chambers of the expanded Panama Canal. Their vessel capacity reaches 12,500 TEUs. Those ships will be a specific class of vessel which will be effectively serving the Americas and the Caribbean, either from Europe and Asia.

The New Panamax lock complexes will have three chambers on both the Pacific and Atlantic sides and each chamber will have water-saving basins, a lateral filling and emptying system and rolling gates. As Figure 2.15 shows, the new locks chambers will be 55 m (180 ft)
wide, 427 m (1400 ft) long and 18.3 m (60 ft) deep. It will allow ships to sail through of these dimensions: length 366 m (1,200 ft), beam 49 m (160 ft) and draft 15.2 m (49.9 ft) (ACP 2010).

Figure 2.15 Dimensions of existing locks and new locks of the Panama Canal
Source: ACP (2010)

2.3.3.5. Post New Panamax and Triple E

In 2006, the maritime shipper Maersk introduced a ship class having a vessel capacity in the range of 11,000-14,500 TEUs, the Emma Maersk ("E Class"). This class of ships is called Post New Panamax, because dimensions of those ships are even bigger than the specifications of the expanded Panama Canal. Those ships are 393 m (1290 ft) long, 56 m (184 ft) wide and their draft is 15.5 m (51 ft). Their speed is 25.5 knots (Rodrigue et al. 2013).

In July 2013 Maersk introduced Maersk Triple-E ("Triple-E Class") which is able to carry up to 18,000 TEUs. It is the largest commercially feasible ship class for containers. Its sizes: length 400 m (1312 ft), beam 59 m (194 ft) and draft 15.5 m (51ft), imply that only few ports in
the world can handle it. The speed of Triple-E is 23 knots but optimal and most efficient speed is 19 knots (Maersk 2013).

2.4. U.S. Continent

The first part of this section describes the most important U.S. maritime ports. Those ports are discussed from the point of view of their parameters and capacities. The second part of the section is the description and summary of U.S. inland transportation and the connections from the most important U.S. ports to main U.S. cities. There are discussed two main modes of transportation: road and rail.

2.4.1. Ports

Maritime ports are very important in logistic chain and they play crucial role in transportation of goods to and from U.S. As can be seen in Figure 1.2 Weight of U.S.-International merchandise trade by mode of transportation: 2011 Total Modal (%)

Source: RITA (2012b) 74.96% of weight of U.S. international merchandise trade in 2011 was transported by sea. This was 46.90% of the total value of that international U.S. trade as shown in Figure 1.3 Value of U.S.-International trade by mode of transportation: 2011 Total Modal (%)

Source: RITA (2012a) Those statistics and the fact that between U.S. and Europe does not have any land connection, prove the importance of the ports on the both sides of Atlantic ocean.

Figure 2.16 Top 25 U.S. water ports by containerized cargo in 2010

Source: FHWA (2012) shows 25 most important U.S. water ports with export and import going through those ports in thousands of TEUs. As can be seen in Figure 2.16 Top 25 U.S. water ports by containerized cargo in 2010
Source: FHWA (2012) the most important water ports are Los Angeles, Long Beach, Seattle and Oakland in the west coast and New York, Savannah, Norfolk and Houston in the east coast.

Figure 2.16 Top 25 U.S. water ports by containerized cargo in 2010
Source: FHWA (2012)

2.4.1.1. Parameters

A maritime port has several crucial things. First it is the location. Second it is its parameters. And finally it is the equipment of the port and its capability to handle cargo and transfer it from ship to other means of transportation for inland movement to its final destinations.
Talking about ports parameters, the most important one is the maximum berth depth. It is the most important parameter for ships to enter and anchor in the ports. The deeper the ports the bigger ships they can serve.

![Figure 2.17 U.S. water ports and their maximum berth depth](image)

Source: Rodrigue et al. (2013)

As can be seen in Figure 2.17, the four most important ports in the west coast Los Angeles, Long Beach, Oakland and Seattle are able to serve ships up to the capacity of 12,000 TEUs because their depth of berth is 49-60 ft. In the east coast, only ports in New York and Norfolk are able to
serve such ships. Ports in Houston and Savannah are able to serve ships of size up to 5,000 TEUs because their berth depth is 39-45 ft.

2.4.1.2. Capacities

In 2004-2009 the number of containership calls at U.S. ports had remained fairly steady, averaging about 18,000 calls per year. Then, it started to grow by almost 13% per year and in 2011 the number of calls reached 22,100. Likewise, the volume of containerized freight cargo has been increasing as well (MARAD 2013).

![Figure 2.18 Average containership size per call at U.S. ports in TEUs, 2006-2011](image)

Source: MARAD (2013)

Table 2.4 shows calls, capacities and average vessel size per call of top 10 U.S. container ports. U.S. maritime ports are handling larger container vessels than in the past. The average size per call of container vessels that docked at U.S. ports in 2011 was 3,950 TEUs. This is an increase of 22.3% from about 3,500 TEUs in 2006, as can be seen in Figure 2.18. The average size of containerships has increased as carriers increased the use of post-Panamax containerships
in U.S. trade. In 2009, the top five U.S. container ports handled 55% of container cargo capacity (MARAD 2013).

Table 2.4 Top 10 U.S. container ports by port calls and vessel type, 2009

<table>
<thead>
<tr>
<th>Rank</th>
<th>Port/State</th>
<th>All vessel types</th>
<th>Containership</th>
<th>Average vessel size per call (dwt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cells (total vessels)</td>
<td>Capacity (dwt, thousands)</td>
<td>Calls per year</td>
</tr>
<tr>
<td>1</td>
<td>Los Angeles/Long Beach, CA</td>
<td>4,312</td>
<td>285,194</td>
<td>2,442</td>
</tr>
<tr>
<td>2</td>
<td>New York/New Jersey, NY/NJ</td>
<td>4,430</td>
<td>220,616</td>
<td>2,319</td>
</tr>
<tr>
<td>3</td>
<td>San Francisco, CA</td>
<td>3,275</td>
<td>190,668</td>
<td>1,859</td>
</tr>
<tr>
<td>4</td>
<td>Savannah, GA</td>
<td>2,219</td>
<td>112,557</td>
<td>1,714</td>
</tr>
<tr>
<td>5</td>
<td>Virginia Ports, VA</td>
<td>2,502</td>
<td>134,680</td>
<td>1,615</td>
</tr>
<tr>
<td>6</td>
<td>Charleston, SC</td>
<td>1,665</td>
<td>65,748</td>
<td>1,312</td>
</tr>
<tr>
<td>7</td>
<td>Seattle, WA</td>
<td>920</td>
<td>53,190</td>
<td>676</td>
</tr>
<tr>
<td>8</td>
<td>Houston, TX</td>
<td>6,153</td>
<td>277,117</td>
<td>931</td>
</tr>
<tr>
<td>9</td>
<td>Tacoma, WA</td>
<td>1,149</td>
<td>55,253</td>
<td>576</td>
</tr>
<tr>
<td>10</td>
<td>Miami, FL</td>
<td>893</td>
<td>30,463</td>
<td>591</td>
</tr>
</tbody>
</table>

Source: BTS (2011)

2.4.2. Inland Transportation

The freight inland transportation system of U.S. consists of an extensive network of highways, railroads, waterways, pipelines and airways. Increasing number of freight vehicles, vessels, and other conveyances on both public and private infrastructure requires higher system capacity, better maintenance and threaten system performance. The following subsections of the thesis focus on two main transportation modes: road and rail.

2.4.2.1. Road

A vast number of vehicles move goods over the transportation network. Table 2.5 shows that since 1990, road infrastructure has increased slowly despite a large increase in the volume of
traffic. This table also shows the distribution of U.S. road network system, length of roads of each group of highway and number of trucks. As can be seen on Table 2.5 the number of commercial trucks has been relatively stable in recent years (FHWA 2012).

Table 2.5 Road network system - miles, vehicles

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2000</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public roads, route - miles</td>
<td>3 866 926</td>
<td>3 951 101</td>
<td>4 048 523</td>
<td>4 069 343</td>
<td>NA</td>
</tr>
<tr>
<td>National Highway System (NHS)</td>
<td>N 181 189</td>
<td>163 746</td>
<td>164 096</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Interstates</td>
<td>45 074</td>
<td>46 673</td>
<td>46 934</td>
<td>47 013</td>
<td>NA</td>
</tr>
<tr>
<td>Other NHS</td>
<td>N 114 516</td>
<td>116 812</td>
<td>117 083</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>N 3 789 912</td>
<td>3 884 775</td>
<td>3 895 246</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Strategic Highway Corridor Network (STRAHNET)</td>
<td>N 62 066</td>
<td>62 698</td>
<td>62 253</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>N 46 875</td>
<td>46 937</td>
<td>47 013</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Non-Interstate</td>
<td>N 15 389</td>
<td>16 031</td>
<td>15 240</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Highway - vehicles</td>
<td></td>
<td></td>
<td>254 403 081</td>
<td>255 917 664</td>
<td>254 212 619</td>
</tr>
<tr>
<td>Truck, single-unit 2-axle 6-tire or more</td>
<td></td>
<td></td>
<td>8 116 672</td>
<td>8 288 046</td>
<td>8 356 097</td>
</tr>
<tr>
<td>Truck, combination</td>
<td></td>
<td></td>
<td>2 635 347</td>
<td>2 585 229</td>
<td>2 617 118</td>
</tr>
<tr>
<td>Truck, total</td>
<td></td>
<td></td>
<td>10 752 019</td>
<td>10 873 275</td>
<td>10 973 215</td>
</tr>
<tr>
<td>Trucks as percent of all highway vehicles</td>
<td></td>
<td></td>
<td>4.2</td>
<td>4.2</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Key: N = not applicable; NA = not available.

*Based on a new methodology, FHWA revised its annual vehicle miles traveled, number of vehicles, and fuel economy data beginning with 2007.

Source: FHWA (2012)

As can be seen on Figure 2.19, the long-haul freight truck traffic in U.S. is mainly concentrated on major routes connecting population centers, ports, border crossings, and other major hubs of activity. Most of the heaviest traveled routes are on the Interstate System, except for Route 99 in California and a few toll roads and border connections (FHWA 2012).
2.4.2.2. Rail

Table 2.6 shows the length of U.S. railroads and also the number of rail vehicles. Since 1990, rail miles have declined by 21% while road infrastructure has slowly increased. While the number of trucks has been practically stable in recent years, the number of freight cars has declined. That is mainly due to improved utilization and the deployment of larger cars.
### Table 2.6 Railroad network system - miles, vehicles

<table>
<thead>
<tr>
<th></th>
<th>1990</th>
<th>2000</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Railroad - miles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class I</td>
<td>175 909</td>
<td>170 512</td>
<td>140 134</td>
<td>139 326</td>
<td>139 118</td>
</tr>
<tr>
<td>Regional</td>
<td>133 189</td>
<td>120 597</td>
<td>94 313</td>
<td>94 082</td>
<td>93 921</td>
</tr>
<tr>
<td>Local</td>
<td>18 375</td>
<td>20 978</td>
<td>16 930</td>
<td>16 690</td>
<td>12 804</td>
</tr>
<tr>
<td><strong>Railroad - vehicles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class I, locomotive</td>
<td>18 835</td>
<td>20 028</td>
<td>24 143</td>
<td>24 003</td>
<td>24 045</td>
</tr>
<tr>
<td>Class I, freight cars ¹</td>
<td>658 902</td>
<td>560 154</td>
<td>460 172</td>
<td>450 297</td>
<td>416 180</td>
</tr>
<tr>
<td>Nonclass I, freight cars ¹</td>
<td>103 527</td>
<td>132 448</td>
<td>120 463</td>
<td>109 487</td>
<td>108 233</td>
</tr>
<tr>
<td>Car companies and shippers freight cars ¹</td>
<td>449 832</td>
<td>688 194</td>
<td>805 074</td>
<td>833 188</td>
<td>839 020</td>
</tr>
</tbody>
</table>

¹Beginning with 2001 data, Canadian-owned U.S. railroads are excluded. Canadian-owned U.S. railroads accounted for over 46,000 freight cars in 2000.

Source: FHWA (2012)

### 2.4.2.3. Comparison of Road and Rail Transportation

As Figure 2.20 shows trucks carry most of the tonnage and value of freight in U.S., but railroads carry significant volumes over long distances. It is also obvious that higher volume of freight is transported in the east coast than the west coast of U.S.
The fact that the railroads are used mainly for long-distances transportation is caused mainly by the prices of truck and rail intermodal transportation. Figure 2.21 shows that for distances greater than 500 kilometers, rail transportation of containers costs about 20% less than road transportation and the cost advantage increases as distance increases (PPIAF 2014b).
In U.S., the road and rail transportation do not only compete against each other but they are also complementary connected and take an advantage from each other as an intermodal transportation. Therefore they frequently work together to move high-value, time-sensitive cargo. The principle of intermodal transportation is described in more detail in Section 1.1 Background.

The classic forms of rail intermodal transportation are trailer-on-flatcar and container-on-flatcar and these are spread throughout U.S. Figure 2.22 shows that the largest concentrations are on routes between Pacific Coast ports and Chicago, southern California and Texas, and Chicago and New York (FHWA 2012).
Figure 2.22 Tonnage of trailer-on-flatcar and container-on-flatcar rail intermodal moves, 2010
Source: FHWA (2012)

2.5. European Continent

This section describes the most important European maritime ports, their parameters and capacities. This section discusses European inland transportation and the road and rail connections from the most important European ports to main European cities.

2.5.1. Ports

European ports are gateways to the European continent and they are definitely crucial for European transportation business and its competitiveness. Seventy four percent of EU goods are shipped through ports. Over 1200 commercial seaports operate along some 70,000 kilometers of
EU’s coast. Therefore, Europe is one of the densest port regions in the world. In 2011, around 3.7 billion tons of cargo (more than 60,000 port calls of merchant ships) transited through European ports. Bulk traffic represented 70% of it, container traffic 18%, Ro-Ro traffic 7% and the rest was other general cargo (EC 2013b).

Figure 2.23 shows the top 20 European cargo ports in 2011. Three most important European ports have been: Rotterdam (NE), Antwerpen (BG) and Hamburg (GE). It is also worth to mention ports in Le Havre (FR), Bremerhaven (GE) and Zeebrugge (BG).
Figure 2.23 Top 20 European cargo maritime ports and number of tons handled in 2011
Source: EC (2013b)

Port of Rotterdam

The Port of Rotterdam is one of the main ports and the largest logistic and industrial hubs in Europe. The port of Rotterdam is the largest seaport of Europe with an annual throughput of 450 million tons of cargo. The port occupies an area of 10,570 ha, the total length of Rotterdam port area is 40 km, maximum berth depth is 23 m, but for container ships it is 19.65 m as can be
seen in Table 2.7. Table 2.7 shows all the six container terminals of the port of Rotterdam, their parameters (quay length, draught and area), their equipment (gantry cranes, plugs for reefer) and annual capacity in TEU (Port of Rotterdam 2014a).

Table 2.7 Rotterdam container terminals - parameters, equipment and capacity

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Quay length (m)</th>
<th>Draught (m)</th>
<th>Area (m²)</th>
<th>Cranes</th>
<th>Reeferplugs</th>
<th>Capacity per year (TEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotterdam World Gateway</td>
<td>1,700</td>
<td>19.5</td>
<td>1,080,000</td>
<td>14</td>
<td>1,700</td>
<td>2,350,000</td>
</tr>
<tr>
<td>APM Terminals Maasvlakte II</td>
<td>1,000 (barge - 500)</td>
<td>19.65 (barge 9.65)</td>
<td>860,000</td>
<td>8 deepsea, 2 barge, 2 rail</td>
<td>4,500</td>
<td>2,700,000</td>
</tr>
<tr>
<td>Euromax Terminal Rotterdam</td>
<td>1,500</td>
<td>16.8</td>
<td>840,000</td>
<td>15</td>
<td>2,135</td>
<td>-</td>
</tr>
<tr>
<td>APM Terminals Rotterdam</td>
<td>1,600</td>
<td>16.65</td>
<td>1,000,000</td>
<td>14</td>
<td>2,250</td>
<td>3,250,000</td>
</tr>
<tr>
<td>ECT Delta Terminal</td>
<td>3,600</td>
<td>16.65</td>
<td>2,650,000</td>
<td>38</td>
<td>3,387</td>
<td>-</td>
</tr>
<tr>
<td>ECT City Terminal</td>
<td>1,400</td>
<td>14.1</td>
<td>593,000</td>
<td>9</td>
<td>1,359</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: Port of Rotterdam (2014b)

Port of Hamburg

The Port of Hamburg, the largest seaport in Germany, lies between the North Sea and the Baltic Sea. Nowadays, it is the second biggest container port in Europe and the 11th biggest in the world. The port features four container terminals capable of high-performance handling. Three of the terminals are operated by Hamburger Hafen und Logistik (HHLA), a port logistics group based in Europe. Capacity of the terminals is being continually expanded to meet the growing demand. Table 2.8 shows all four container terminals of the port of Hamburg, their parameters (number of berths, quay length, draught and area), their equipment (gantry cranes, plugs for reefer) and annual capacity in TEU (Kable 2014).
Bremen ports

The Port of Bremen actually contains two ports: Bremen and Bremerhaven. Together, the Port of Bremen and the Port of Bremerhaven include 33.9 km of quays. The combined Port of port handled a total of 4,876 TEUs in 2010 holding over 51.9 million gross tons of containerized cargo. As the primary port for containers is the Port of Bremerhaven (the port of Bremen handled only 17 TEUs in 2010) (WPS 2014a).

With the fourth largest container port in Europe, Bremerhaven is one of the major handling hubs for intermodal traffic in import and export. In the Port of Bremerhaven there are total three container terminals which are shown in Table 2.9. Bremerhaven container terminals have in total 14 berths which have a total length of 4,920 m and 12-15 m draught (HMPB 2013).

### Table 2.8 Hamburg container terminals - parameters, equipment and capacity

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Number of berths</th>
<th>Quay length (m)</th>
<th>Draught (m)</th>
<th>Area (m²)</th>
<th>Cranes</th>
<th>Reeferplugs</th>
<th>TEU capacity per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHLA Container Terminal Burchardkai</td>
<td>10</td>
<td>2,850</td>
<td>15.2</td>
<td>1,400,000</td>
<td>25</td>
<td>700</td>
<td>5,200,000 (after future expansion)</td>
</tr>
<tr>
<td>HHLA Container Terminal Altenwerder</td>
<td>4</td>
<td>1,400</td>
<td>16.7</td>
<td>1,000,000</td>
<td>15</td>
<td>2,100</td>
<td>-</td>
</tr>
<tr>
<td>Eurogate Container Terminal Hamburg</td>
<td>6</td>
<td>2,080</td>
<td>15.2</td>
<td>1,200,000</td>
<td>24</td>
<td>-</td>
<td>4,000,000</td>
</tr>
<tr>
<td>HHLA Container Terminal Tollerort</td>
<td>4</td>
<td>1,240</td>
<td>15.2</td>
<td>600,000</td>
<td>12</td>
<td>320</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: HHLA (2014)
Table 2.9 Bremerhaven container terminals - parameters and equipment

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Number of berths</th>
<th>Area (m²)</th>
<th>Cranes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTB North Sea Terminal Bremerhaven</td>
<td>6</td>
<td>1,050,000</td>
<td>18 Super-Post-Panamax</td>
</tr>
<tr>
<td>MSC Gate</td>
<td>4</td>
<td>472,000</td>
<td>10 Super-Post-Panamax + 3 Post-Panamax</td>
</tr>
<tr>
<td>Eurogate Container Terminal Bremerhaven</td>
<td>4</td>
<td>1,131,000</td>
<td>20</td>
</tr>
</tbody>
</table>

Source: YES Logistics (2014)

Port of Antwerp

The Port of Antwerp is a gateway to the European continent. For international freight shipping, the Port of Antwerp is the second busiest port in Europe. It is located centrally in northwest Europe in Netherlands. In 2010, the Port of Antwerp handled a total of 178.2 million of cargo by almost 14,800 vessels. Containerized cargo represented 8.5 million TEUs (containing 102.5 million tons) out of that total amount of cargo. Table 2.10 shows all five container terminals, their parameters (quay length, draught and area), their equipment (gantry cranes, plugs for reefer) and annual capacity in TEU (WPS 2014).

Table 2.10 Antwerp container terminals - parameters, equipment and capacity

<table>
<thead>
<tr>
<th>Terminal</th>
<th>Quay length (m)</th>
<th>Draught (m)</th>
<th>Area (m²)</th>
<th>Cranes</th>
<th>Reeferplugs</th>
<th>Capacity per year (TEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa Terminal</td>
<td>1,180</td>
<td>14.5</td>
<td>720,000</td>
<td>7</td>
<td>-</td>
<td>1,700,000</td>
</tr>
<tr>
<td>Deurganck Terminal (actual situation)</td>
<td>1,780</td>
<td>15.5</td>
<td>1,020,000</td>
<td>11</td>
<td>820</td>
<td>2,600,000</td>
</tr>
<tr>
<td>Deurganck Terminal (final situation)</td>
<td>2,750</td>
<td>17</td>
<td>2,000,000</td>
<td>24</td>
<td>2,130</td>
<td>5,700,000</td>
</tr>
<tr>
<td>Noordzee Terminal</td>
<td>1,125</td>
<td>15.5</td>
<td>790,000</td>
<td>8</td>
<td>850</td>
<td>2,000,000</td>
</tr>
<tr>
<td>MSC Home Terminal</td>
<td>2,900</td>
<td>16</td>
<td>1,670,000</td>
<td>24</td>
<td>1,730</td>
<td>5,400,000</td>
</tr>
<tr>
<td>Churchill Terminal</td>
<td>2,260</td>
<td>14</td>
<td>840,000</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: PSA (2014)
2.5.2. Inland Transportation

The inland transportation network of Europe consists of three main transportation modes: road, rail and inland waterway. This sub sections focuses mainly on first two mentioned: road and rail. Nevertheless as Figure 2.24 shows, in some countries of EU (Netherlands 37%, Romania 21%, Belgium 19%, etc.) Inland WaterWay (IWW) transportation plays indisputable role. In EU-27 road transportation represented 76%, railway 18% and inland waterway 6% in 2011.

A comparison between road and rail goods freight transportation shows that in 2010 the quantities of goods transported by road in the EU-28 equaled nine times the amount transported by rail (EC 2013c).

![Figure 2.24 Modal split of European inland freight transportation in 2011 - % of total inland freight ton-km](image)

Source: EC (2013c)
2.5.2.1. Road

In 2011, approximately 14,933 million tons of goods were transported by road in the EU-28. Of this amount, 20% was transported in the roads of Germany, followed by France (14%), United Kingdom (10%) and Spain (10%). Between 2006 and 2011, the volume of goods transported by road fell in all member states, except for Poland (47% increase), Luxembourg (14%) and Germany (2%).

![Figure 2.25 Goods freight transportation in EU by road - thousand tons](image)

Source: EC (2013c)

2.5.2.2. Rail
The EU railway transportation network is part of the Trans-European Transport Networks (TEN-T). TEN-T is supposed to coordinate improvements and project primary to roads, railways, inland waterways, airports, seaports, inland ports and traffic management systems, providing integrated and intermodal long-distance, high-speed routes. The Trans-European Rail network includes the Trans-European High-Speed Rail Network as well as the Trans-European Conventional Rail Network as can be seen on Figure 2.27 (EC 2014b).

In 2010, EU-28 goods freight transportation by rail amounted to 1,589 million tons. In the years 2007-2010, the volume of freight transportation by rail in EU-28 fell by 13% which was mainly caused by lingering economic recession which hit Europe in 2008. Among Member States the largest quantities of goods were transported by German railways (356 million tons in 2010), followed by Poland (249 in 2011), Austria (108) and United Kingdom (100) (EC 2013c).
Figure 2.26 Goods freight transportation in EU by rail -million tons
Source: EC (2013c)

Figure 2.27 shows the railway freight network, ports and road-rail terminals (RRT) in countries of western and central Europe, which is crucial for connection to the most important European ports and Czech Republic (CR). In 2011, CR was the leader in total length of rail lines operated with 124 km per 1,000 km² in EU-27, followed by Germany (106), Hungary (83) and Slovakia (74) (UNECE 2013).
Figure 2.27 EU railway freight network, ports and rail-road terminals
Source: EC (2011)

2.6. Cost of Maritime Transportation

Maritime transportation has one of the highest entry costs of the transport sector and therefore the main advantage of it have to be economies of scale, making it the cheapest per unit of all transport modes.

Maritime and shipping costs are usually expressed in terms of cost per unit (e.g. cost of transportation for one TEU per day). For calculation of shipping costs it is essential to know some of the following parameters: operating costs, fuel consumption, capital value, depreciation period, interest rate, capital cost, average bunker price and bunker unit cost per TEU. Operating costs and fuel costs are the most important components, as can be seen on Figure 2.28. Since container ships navigate higher speed than bulk vessels, the bunker costs of those ships are
significantly higher and therefore fuel consumption is a particularly important variable (Stopford, 2004).

Maritime transportation costs are highly sensitive to bunker fuel costs. Fuel costs represent 45-50% of all operating costs as is shown in Figure 2.28. The only exception is slow steaming when the fuel cost is not that significantly high. Even with this, from a comparative perspective maritime transportation has smaller fuel price sensitivity than trucking and rail (Rodrigue et al. 2013).

As can be seen on Figure 2.28, the operating costs are definitely dependent on the size of containership. Among the most significant elements of operating costs are fuel, port charges,
insurance, repair and maintenance. It is also obvious that fuel cost, port charges and insurance are dependent on the size of a ship. All other elements of operating costs are practically same, no matter the size of ship.

Fuel cost is the most significant operating costs of a ship. Fuel consumption by a containership is mostly a function of ship size and cruising speed as can be seen in Figure 2.29. That cost function follows an exponential curve above the speed of 14 knots. Ship speed is divided into several main classes. Those classes are: normal, slow steaming and extra slow steaming. All those speed classes are described more in detail in Section 2.3.1.

![Figure 2.29 Fuel consumption according to cruising speed and ship size](Source: Rodrigue et al. (2013))
The second most significant operating cost is port charges. Those costs are beyond the control of the ship-owner. Since they depend on the ship’s tonnage, then economies of scale are very important. These costs mainly include following: pilotage, towage, dockage, wharfage, harbor, tonnage, light, buoy, mooring, customs, watchman, canal fee and others.

2.7. **Trade between the Czech Republic and the U.S.**

Foreign trade between the CR and U.S. has had a different development trend during the last several years. The development of the international trade between CR and U.S. from 1993 to July 2013 is shown in Figure 2.30. Data from the charts was obtained on the basis of information on the international trade within the CR-U.S.

The development of international merchandise trade progressed at an exceedingly dynamic rate during the postwar period. Between 1950 and 2000, trade volume increased at an average of 6% annually. Following a drop in merchandise trade in 2001, positive trend has continued in the past few years (Grossmann 2007).

As can been seen in Figure 2.30, export from CR to U.S. and import from U.S. to CR were nearly at the same level in 1990s. In 2000, significant difference between export and import started. Then import decreased for two years (2001 and 2002) and since those years export to U.S. has been twice higher than import to CR. Since 2003, the trend has practically been the same for both, export and import. The international trade between CR and U.S. recorded significant drop caused the economic recession in 2008 and its aftermaths can be seen in 2009.
Figure 2.30 Volume of export and import CR-U.S. in millions of USD

Source: CENSUS (2014a)

According to the statistic of U.S. Census Bureau to the most exported items from CR to U.S. are: electric apparatus and parts; industrial machinery; medicinal, dental and pharmaceutical preparations; generators, transformers and accessories; iron and steel products; engines and engine parts; automotive tires and tubes. The most imported items from U.S. to CR are following: civilian aircraft engines, equipment and parts; electric apparatus; computers and computer accessories; telecommunication equipment; industrial engines and machines (CENSUS 2014b).
Chapter 3: Models of Freight Transportation between Europe and the U.S.

Chapter 3 introduces the formulation of the models of maritime freight transportation between Europe and the U.S. Section 3.1 introduces the Transatlantic Multi-Mode Container Routing Problem (TMMCRP). After that, the Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP) is introduced in Section 3.2. The last section of this chapter provides some concluding comments.

3.1. Transatlantic Multi-Mode Container Routing Problem (TMMCRP)

3.1.1. Introduction

The following model was developed by the author himself and it is mainly focused on maritime freight transportation across the Atlantic Ocean between Europe and the U.S. When one wants to transport or ship any shipment by maritime transportation it is usually necessary to complement it by another mode of transportation: road, railway and/or inland waterway. Therefore the author also implemented some of those modes of inland transportation into the model.

Therefore the model consists of network of maritime shipping lines between the ports and then networks of road and railway transportation on both sides of the Atlantic Ocean.

3.1.2. Problem Description and Assumptions

The problem could be described as the selecting of routes for each shipment to minimize the total transportation costs of all shipments. Each shipment has its origin and destination point of transportation. Therefore the developed model seeks to determine the routing for each O-D pair of the predefined set of network and at the same time it assigns the volume to each route that minimizes the total transportation costs.
In the model, the points of origin are European cities and points of destination are cities in the U.S. Maritime transportation is considered as the main and only line haul mode of transportation between the two continents. The transportation of shipments between the origin cities and the main European ports, and between the main U.S. ports and destination cities can be by: road or railway. There is no transshipment point between those cities and ports in the same continent. So, there is only direct transportation between those points of origin (destination) and ports in the same continent.

In the model there are several assumptions: (i) there is only one type of commodity and it is heterogeneous, (ii) each O-D demand can be split into multiple shipments using different routes and/or modes, (iii) there is no time dependency, and (iv) the O-D demand is known. Therefore the problem is deterministic in the sense that the demand is known. By contrast, a stochastic version would be the unknown and time dependent demand, which would make problem much more complicated but it is out of the scope of this thesis.

3.1.3. Problem Formulation

3.1.3.1. Sets

Define \( i \in I \) which is point of origin (European city) and \( j \in J \) which represents destination (city in the U.S.). Also, define \( k \in K \) which is the shipment number. A shipment \( k \in K \) will enter the network though an origin point \( O(k) \) and exit through a destination point \( D(k) \). For each shipment \( k \in K \) there is its O-D pair that origins in the city \( O(k) \) and directs to the destination city \( D(k) \).

The point \( m \in M \) is the European port which belongs to the set \( M \)- set of European ports. The point \( n \in N \) is the U.S port which belongs to the set \( N \)- set of U.S. ports.
In the European continent, define \( a \in A \) as an European rail operator which belongs to \( A \) - set of European rail operators and \( b \in B \) as an European truck (road) operator which belongs to \( B \) - set of European truck (road) operators. The same is done for the U.S. part of transportation network, therefore \( d \in D \) is a U.S. rail operator and \( e \in E \) is a U.S. truck (road) operator. Then, define \( c \in C \) as a shipping line operating between European and U.S. ports.

3.1.3.2. Parameters

Each shipment \( k \in K \) has its uniquely associated O-D pair (European city \( i \in I \) and U.S. city \( j \in J \)) and its known demand \( W_{ijk} \) (in terms of TEU). Then there are five different cost parameters. The cost to transport one TEU between European city \( i \in I \) and European port \( m \in M \) via European rail operator \( a \in A \) is the cost rate \( \alpha_{ima} \) (in $/TEU). The cost to transport one TEU between European city \( i \in I \) and European port \( m \in M \) via European truck (road) operator \( b \in B \) is the cost rate \( \beta_{imb} \) (in $/TEU). The cost to transport one TEU between European port \( m \in M \) and U.S. port \( n \in N \) via shipping line \( c \in C \) is the cost rate \( \gamma_{mnc} \) (in $/TEU). The cost to transport one TEU between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. rail operator \( d \in D \) is the cost rate \( \delta_{njd} \) (in $/TEU). The cost to transport one TEU between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. truck (road) operator \( e \in E \) is the cost rate \( \varepsilon_{nje} \) (in $/TEU).

Besides cost parameters there are capacity parameters. The capacity of European port \( m \in M \) is \( O_m \) (in TEU). The capacity of U.S. port \( n \in N \) is \( P_n \) (in TEU).

Besides capacities of ports it is also important to consider the capacities of operators on each link of the network. Therefore the capacity of European rail operator \( a \in A \) on the link between European city \( i \in I \) and European port \( m \in M \) is \( Q_{ima} \) (in TEU). The capacity of European truck (road) operator \( b \in B \) on the link between European city \( i \in I \) and European port
The capacity of shipping line \( c \in C \) on the link between European port \( m \in M \) and U.S. port \( n \in N \) is \( S_{mnc} \) (in TEU). The capacity of U.S. rail operator \( d \in D \) on the link between U.S. port \( n \in N \) and U.S. city \( j \in J \) is \( T_{njd} \) (in TEU). The capacity of U.S. truck (road) operator \( e \in E \) on the link between U.S. port \( n \in N \) and U.S. city \( j \in J \) is \( L_{nje} \) (in TEU).

3.1.3.3. **Decision Variables**

If shipment \( k \in K \) takes place on the link between European city \( i \in I \) and European port \( m \in M \) via European rail operator \( a \in A \), one defines \( X_{imak} \) which is the number of transported TEUs between European city \( i \in I \) and European port \( m \in M \) via European rail operator \( a \in A \) of shipment \( k \in K \).

If shipment \( k \in K \) takes place on the link between European city \( i \in I \) and European port \( m \in M \) via European truck (road) operator \( b \in B \), one defines \( Y_{mbk} \) which is the number of transported TEUs between European city \( i \in I \) and European port \( m \in M \) via European truck (road) operator \( b \in B \) of shipment \( k \in K \).

If shipment \( k \in K \) takes place on the link between European port \( m \in M \) and U.S. port \( n \in N \) via shipping line \( c \in C \), one defines \( Z_{mnc} \) which is the number of transported TEUs between European port \( m \in M \) and U.S. port \( n \in N \) via shipping line \( c \in C \) of shipment \( k \in K \).

If shipment \( k \in K \) takes place on the link between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. rail operator \( d \in D \), one defines \( U_{njd} \) which is the number of transported TEUs between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. rail operator \( d \in D \) of shipment \( k \in K \).

If shipment \( k \in K \) takes place on the link between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. truck (road) operator \( e \in E \), one defines \( V_{nje} \) which is the number of transported TEUs
between U.S. port \( n \in N \) and U.S. city \( j \in J \) via U.S. truck (road) operator \( e \in E \) of shipment \( k \in K \).

### 3.1.3.4. Constraints

The model consists of three sets of constraints. Constraints (3.2) and (3.3) are the shipment specific origin and destination constraints. They ensure that all transported TEUs of shipment \( k \in K \) are equal to demand of shipment \( k \in K \). Constraint (3.2) ensures this consistency for the point of origin \( i \in I \) and constraint (3.3) ensures the same for the point of destination \( j \in J \).

The second set of constraints is formulated in (3.4) and (3.5). These constraints ensure the conservation of flow in the network. Constraint (3.4) ensures that all freight going to port \( m \in M \) from city \( i \in I \) of shipment \( k \in K \) has to be equal to all the freight from this shipment \( k \in K \) that is going out from this port \( m \in M \). Constraint (3.5) ensures that all freight going from port \( n \in N \) to city \( j \in J \) of shipment \( k \in K \) has to be equal to all freight from this shipment \( k \in K \) that is going to this port \( n \in N \).

The last set of constraint (3.6; 3.7; 3.8; 3.9; 3.10; 3.11; 3.12) is the set of capacities. The first two constraints (3.6 and 3.7) of this set are capacity constraints of ports and the rest are the capacity constraints of operators (rail, road and shipping line).

\[
\sum_{m \in M} \sum_{a \in A} X_{mak} + \sum_{m \in M} \sum_{b \in B} Y_{mbk} = W_{ijk} \quad \forall k \in K \tag{3.2}
\]

\[
\sum_{n \in N} \sum_{d \in D} U_{ndk} + \sum_{n \in N} \sum_{e \in E} V_{nejk} = W_{ijk} \quad \forall k \in K \tag{3.3}
\]

\[
\sum_{a \in A} X_{mak} + \sum_{b \in B} Y_{mbk} = \sum_{n \in N} \sum_{c \in C} Z_{mnc} \quad \forall m \in M, \forall k \in K \tag{3.4}
\]
The objective function (3.1) of model seeks to minimize the total transportation cost of the whole network between the European cities and the U.S. cities for all shipments. The objective function is represented as follow:

\[
\begin{align*}
\sum_{d \in D} U_{ndk} + \sum_{e \in E} V_{nejk} &= \sum_{m \in M} \sum_{c \in C} Z_{mnck} && \forall n \in N, \forall k \in K \quad (3.5) \\
\theta &\leq \sum_{n \in N} \sum_{c \in C} \sum_{k \in K} Z_{mnck} \leq O_m && \forall m \in M \quad (3.6) \\
\theta &\leq \sum_{m \in M} \sum_{c \in C} \sum_{k \in K} Z_{mnck} \leq P_n && \forall n \in N \quad (3.7) \\
\theta &\leq \sum_{k \in K} X_{ima} \leq Q_{ima} \quad (3.8) \\
\theta &\leq \sum_{k \in K} Y_{imbk} \leq R_{imb} \quad (3.9) \\
\theta &\leq \sum_{k \in K} Z_{mnck} \leq S_{mnc} \quad (3.10) \\
\theta &\leq \sum_{k \in K} U_{ndk} \leq T_{nd} \quad (3.11) \\
\theta &\leq \sum_{k \in K} V_{nejk} \leq L_{nej} \quad (3.12)
\end{align*}
\]

3.1.3.5. Objective Function

The objective function (3.1) of model seeks to minimize the total transportation cost of the whole network between the European cities and the U.S. cities for all shipments. The objective function is represented as follow:

\[
\text{Min } \sum_{i \in I} \sum_{m \in M} \sum_{a \in A} \sum_{k \in K} \alpha_{ima} \cdot X_{ima} + \sum_{i \in I} \sum_{m \in M} \sum_{b \in B} \sum_{k \in K} \beta_{imb} \cdot Y_{imbk} \\
+ \sum_{m \in M} \sum_{n \in N} \sum_{c \in C} \sum_{k \in K} \gamma_{mnc} \cdot Z_{mnck}
\]
The objective function consists of five parts. The first one represents the total cost of European rail mode of transportation. The second one represents the total cost for European road mode of transportation. The third one is the total cost of maritime transportation between Europe and the U.S. The fourth one is the total cost of U.S. rail mode. Finally the fifth one represents the total cost of U.S. road mode.

Since, this is the first attempt to formulate such a problem. The problem may be solved by the branch-and-cut algorithm (see CPLEX). As was already mentioned additional dimensions such as time-dependency or stochastic demand would require more sophisticated approaches as meta-heuristics (e.g., genetic algorithms, tabu search, ant colony, etc.).

### 3.2. Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP)

#### 3.2.1. Introduction

The following model was originally developed by Hernández and Peeta. The author used it as a framework and adopted it so the adjusted model is mainly focused on maritime freight transportation across the Atlantic Ocean between Europe and the U.S. Author also implemented some modes of inland transportation in the model which complement the maritime transportation.

The model consists of network of maritime shipping lines between the ports and then networks of road and railway transportation on both sides of the Atlantic Ocean.

#### 3.2.2. Problem Description and Assumptions

This chapter presents a mathematical formulation for a Transnational Collaborative Multi-mode Shipping Problem (TCMMSP). It is a problem where logistic companies want to transport

\[ + \sum_{n \in N} \sum_{j \in J} \sum_{d \in D} \sum_{k \in K} \delta_{njd} \cdot U_{njdk} + \sum_{n \in N} \sum_{j \in J} \sum_{e \in E} \sum_{k \in K} \varepsilon_{nje} \cdot V_{nje} \]
shipments to another continent. The formulation includes three modes of transportation, truck, rail and maritime vessel, and is from the perspective of a logistics operator.

The formulation consists of the total costs incurred by different collaborative transportation modes. In addition, the formulation assumes the following: (i) the logistics operator does not prefer any mode of transportation, (ii) selected modes meet all the necessary requirements for transporting goods (e.g., refrigeration equipment, the conditions for dangerous goods and etc.), (iii) the shipment is not split to multiple vehicles or vessels routes (arcs) of the same mode during a transfer, and (iv) the total loaded shipment transported by a vessel must not exceed the ship’s capacity.

Therefore the problem is deterministic in the sense that the demand is known. By contrast, a stochastic version would be the unknown and time dependent demand, which would make problem much more complicated but it is out of the scope of this thesis.

### 3.2.3. Problem Formulation

This section describes the mathematical programming formulation. The notation, constraints, and objective function are discussed, followed by the characterization of the formulation properties.

#### 3.2.3.1. Sets

Let a shipment $q \in Q$ (in TEUs) be served by a set of fixed transshipment facilities $i \in N$ (also labeled facilities or nodes) which are interconnected by links in network $a \in A$ (also labeled arcs). The links in network $a \in A$, those incident from facility $i \in N$, are depicted as $a \in \Gamma(i)$ and those incident to facility $i \in N$ are $a \in \Gamma^{-1}(i)$. A shipment $q \in Q$ may be served by a link in the network $a \in A$ only by collaborative modes of transportation $m \in M$ (Truck, Rail, and Vessel)
operating in this transnational network. Fixed transshipment facilities \( i \in N \) and collaborative mode of transportation \( m \in M \) form our transportation network. A shipment \( q \in Q \) will enter the transportation network through an origin facility \( O(q) \) (either U.S. or EU) and exit through a destination node \( D(q) \) in a different continent across the Atlantic Ocean. For each shipment \( q \in Q \), its origin facility \( O(q) \) and its destination node \( D(q) \) constitutes its origin-destination pair.

### 3.2.3.2. Parameters

Each shipment \( q \in Q \) has the demanded volume \( w_q \). The unit cost incurred by collaborative transportation mode \( m \in M \) for transporting a shipment on arc \( a \in A \) is \( \theta_{am} \) and the fixed cost of transferring for collaborative transportation mode \( m \in M \) on arc \( a \in A \) is \( \varphi_{am} \).

The available transportation capacity by transportation mode \( m \in M \) for link in the network \( a \in A \) is \( r_{am} \). If a collaborative transportation mode \( m \in M \) does not have sufficient capacity for link in the network \( a \in A \), it is assumed without loss of generality that its transportation capacity \( r_{am} \) is 0.

### 3.2.3.3. Decision Variables

If a shipment \( q \in Q \) is served through link in the network \( a \in A \) by collaborative transportation mode \( m \in M \), we define \( x_{amq} \) to take the value of 1, and 0 otherwise. This variable represents binary variable indicating what kind of transportation is suitable.

If a transfer takes place on link in the network \( a \in A \) by collaborative transportation mode \( m \in M \), we define \( y_{am} \) to take the value of 1, and 0 otherwise. It represents the decision variable for the chose a transportation mode.

### 3.2.3.4. Constraints

In this section the TCMMS problem is formulated, which consists of two sets of
constraints. The first set of constraints (3.13a, 3.13b, 3.13c) model the independent transshipment of shipments through the collaborative transnational multi-mode network. The second set of constraints (3.14, 3.15) establishes upper bounds on the available collaborative multimode capacity (in terms of volume). The constraints are as follows:

\[- \sum_{m \in M} \sum_{a \in \Gamma(i)} X_{amq} = -1 \quad \forall i \in O(q), q \in Q \quad (3.13a)\]

\[\sum_{m \in M} \sum_{a \in \Gamma^+(i)} X_{amq} - \sum_{m \in M} \sum_{a \in \Gamma^-(i)} X_{amq} = 0 \quad \forall i \in N \setminus \{O(q), D(q)\}, q \in Q \quad (3.13b)\]

\[\sum_{m \in M} \sum_{a \in \Gamma^-(i)} X_{amq} = 1 \quad \forall i \in D(q), q \in Q \quad (3.13c)\]

\[\sum_{a \in \Gamma^+(i)} Y_{am} \leq 1 \quad \forall i \in N, m \in M \quad (3.14)\]

\[\sum_{q \in Q} w_q X_{amq} \leq r_{am} Y_{am} \quad \forall a \in A, m \in M \quad (3.15)\]

\[X_{amq} \in \{0,1\} \quad \forall a \in A, q \in Q, m \in M \quad (3.16)\]

\[Y_{am} \in \{0,1\} \quad \forall a \in A, m \in M \quad (3.17)\]

Constraint set (3.13) represents the mass balance constraints and ensures the node flow propagation conservation for transportation mode shipment decisions; at most one decision unit of transportation mode for a shipment is propagated at that facility. It consists of (3.13a), (3.13b), and (3.13c), which correspond to the origin, intermediate, and destination nodes/facilities in the network, respectively.

Constraint (3.14) ensures that at most one arc/corridor is assigned to a collaborative transportation mode at a facility for a transfer, implying that a shipment is not split to multiple
transportation mode routes (arcs) during a transfer. Constraint (3.15) represents the collaborative transportation mode capacity constraint; it ensures that the capacity acquired from the collaborative transportation mode (left-hand side of (3.15)) is less than its available capacity (right-hand side of (3.15)) on that transit corridor. Constraint sets (3.16) and (3.17) represent the 0-1 integrality conditions for the decision variables.

3.2.3.5. Objective Function

The objective function of the TCMMSP problem seeks to minimize the total costs incurred in supply chain during transnational transportation and is represented as follows:

\[
\text{Minimize } \sum_{a \in A} \sum_{m \in M} \sum_{q \in Q} \theta_{am} w_q X_{amq} + \sum_{a \in A} \sum_{m \in M} \phi_{am} Y_{am} \tag{3.18}
\]

It consists of two parts. The first term represents collaborative transportation routing cost of the modes, and the second part denotes the fixed cost of transferring where transfers occur between modes. The overall collaborative transportation routing cost of modes are obtained as the summation of the product of the collaborative transportation modes total costs incurred for transporting a shipment \(\theta_{am}\), the demand \(w_q\), and \(X_{amq}\) (the decision on whether a shipment is transported on a link in the network). The overall fixed costs of transferring are obtained as the summation of the fixed transfer cost by mode \(\phi_{am}\) for a link in the network and \(Y_{am}\) (the decision on the whether a transfer takes place on that link in network). Equation (3.18) subject to constraints (3.13) through (3.17) represents the formulation of the TCMMSP problem.
3.2.4. Classification

The proposed formulation of the TCMMSP belongs to the class of binary (0-1) multi-commodity minimum cost flow problems. It is because the constraints (3.13a), (3.13b), and (3.13c) are balance node flow constraints on which "flow" propagates.

The classification is further substantiated by the structure of the physical network in which the collaborative transportation modes operate; that is, the static nodes of the collaborative transportation mode network are fixed transshipment facilities (such as, ports, depots, warehouses, and/or distribution centers) and the static arcs are links in network corresponding to the collaborative transportation modes. It can be noted that constraints (3.13a), (3.13b), and (3.13c) can be written independently for each shipment. Constraint set (3.14) and (3.15) are the transfer arc assignment and the equivalent capacity transportation mode constraints respectively, which bind the rest of the formulation together (Hernández and Peeta 2013).

3.3. Summary

The both models provide a tool of network optimization in transportation science. The developed models allow users to determine the optimal collaborative routing in a network system that achieves the minimization of costs for a company that ships a single commodity from multiple origins to multiple destinations. The input parameters are the demand, cost parameters and the network data. The model provides as its output data the volume carried by each segment and modes and the total costs generated by the whole system.
Chapter 4: Application of Model

4.1. Introduction

This chapter discusses computational experiments performed with TCMMSP model presented in the Chapter 3. It evaluates the case study results as well as the implication for practical applications.

Section 4.2 describes the case study which the model is applied to. Then, Section 4.3 is about all data generation which is necessary as the model inputs. Section 4.4 describes the computational resources and software used for generating the model solutions. Section 4.5 provides the analysis of results. Section 4.6 summarizes the whole chapter and points out the most important findings.

4.2. Case Study

The case study is about the transportation of several shipments of same kind of product from the Czech Republic to U.S. Those shipments consist of a single commodity and there are five shipments in total. For the exporting company, the most important factor is the total cost of transportation of all shipments. Therefore the minimization of cost is crucial and time is not considered. Thus, there is no time-dependency.

For the case study purposes there are four Czech biggest cities as the points of origin. They are: Prague, Brno, Ostrava and Pilsen. There are five European ports: Rotterdam (Netherlands), Hamburg (Germany), Antwerpen (Belgium), Bremerhaven (Germany) and Le Havre (France).

In U.S., eight ports are considered. Four ports are on the East coast: Los Angeles (California), Long Beach (California), Oakland (California) and Seattle (Washington), and four
on the West coast: New York (New York), Savannah (Georgia), Norfolk (Virginia) and Houston (Texas). The points of destination are the 10 biggest cities in U.S. according to the population in 2012 (City Mayors Statistics 2014). The destinations are: New York (New York), Los Angeles (California), Chicago (Illinois), Houston (Texas), Philadelphia (Pennsylvania), Phoenix (Arizona), San Antonio (Texas), San Diego (California), Dallas (Texas) and San Jose (California). Table 4.1 shows the assigned node number of each city and port of the transportation network.

Table 4.1 Nodes and cities in the network

<table>
<thead>
<tr>
<th>Node</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prague, CZE</td>
</tr>
<tr>
<td>2</td>
<td>Brno, CZE</td>
</tr>
<tr>
<td>3</td>
<td>Ostrava, CZE</td>
</tr>
<tr>
<td>4</td>
<td>Pilzen, CZE</td>
</tr>
<tr>
<td>5</td>
<td>Rotterdam, NL</td>
</tr>
<tr>
<td>6</td>
<td>Hamburg, GE</td>
</tr>
<tr>
<td>7</td>
<td>Antwerp, BE</td>
</tr>
<tr>
<td>8</td>
<td>Bremerhaven, GE</td>
</tr>
<tr>
<td>9</td>
<td>Le Havre, FR</td>
</tr>
<tr>
<td>10</td>
<td>Los Angeles, CA</td>
</tr>
<tr>
<td>11</td>
<td>Long Beach, CA</td>
</tr>
<tr>
<td>12</td>
<td>New York, NY</td>
</tr>
<tr>
<td>13</td>
<td>Savannah, GA</td>
</tr>
<tr>
<td>14</td>
<td>Oakland, CA</td>
</tr>
<tr>
<td>15</td>
<td>Norfolk, VA</td>
</tr>
<tr>
<td>16</td>
<td>Houston, TX</td>
</tr>
<tr>
<td>17</td>
<td>Seattle, WA</td>
</tr>
<tr>
<td>18</td>
<td>New York, NY</td>
</tr>
<tr>
<td>19</td>
<td>Los Angeles, CA</td>
</tr>
<tr>
<td>20</td>
<td>Chicago, IL</td>
</tr>
<tr>
<td>21</td>
<td>Houston, TX</td>
</tr>
<tr>
<td>22</td>
<td>Philadelphia, PA</td>
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<tr>
<td>23</td>
<td>Phoenix, AZ</td>
</tr>
<tr>
<td>24</td>
<td>San Antonio, TX</td>
</tr>
<tr>
<td>25</td>
<td>San Diego, CA</td>
</tr>
<tr>
<td>26</td>
<td>Dallas, TX</td>
</tr>
<tr>
<td>27</td>
<td>San Jose, CA</td>
</tr>
</tbody>
</table>
4.3. **Data Generation**

The data necessary for running the model are mainly the unit cost, fixed cost of transfer (at nodes) and capacity matrices for each transportation mode and link.

4.3.1. **Distance Matrices**

For the creation of distance matrices between Czech cities and European ports, and U.S. ports and U.S. cities, data from www.ecotransit.org were used. The data taken were rail distances and road distances.

The maritime distances between the European ports and U.S. ports were taken at www.searates.com. Those distances were in nautical miles therefore it was necessary to recalculate them into kilometers by the conversion factor of 1 nautical mile = 1.852 km.

4.3.2. **Cost Data**

4.3.2.1. **Rail Data**

Figure 4.1 shows the cost per ton-mile for four shipping modes (truck, rail, air and water) in the U.S. in 2002 (Torian 2012). The Consumer Price Index (CPI) was used to adjust the cost from 2002 to 2014 dollar. The CPI in March 2002 was 178.000 and in March 2014 was 236.293 (CPI 2014). Therefore the prices in 2002 were multiplied by the factor of $\frac{\text{CPI}_{2014}}{\text{CPI}_{2002}}$ which is 1.327.
Based on the data presented in Figure 4.1, the following calculation shows the costs of transportation of 1 TEU per km of rail mode: ($0.03*1.327*25) / 1.609 = $0.618 /km. It is necessary to make an assumption that 1 TEU = 25 tons and 1 mile = 1.609 km. Then, the cost of transportation of 1 TEU of rail mode in U.S. is $0.618 /km.

The cost data per 1 TEU of rail mode for the European continent is 0.467 EUR/km (Tylich 2012). The exchange rate of 1 EUR = $1.382 was used to recalculate that value. Therefore, the cost of transportation of 1 TEU of rail mode in Europe is: 0.467 * 1.382 = $0.645 /km.

4.3.2.2. Truck (Road) Data

For the calculation of trucking cost in U.S., data from Figure 4.1 was used. The following calculation shows the costs of transportation of 1 TEU per km for truck (road) mode: ($0.37*1.327*25) / 1.609 = $7.628 /km.
The cost data per 1 TEU of truck (road) mode for European continent is 1.254 EUR/km (Tylich 2012). The equivalent cost of transportation of 1 TEU of rail mode in Europe is: $1.254 * 1.382 = $1.733 /km.

4.3.2.3. Liner Shipping Data

The cost data per 1 TEU of liner shipping mode is considered to be $1.54 /nautical mile which gives $0.83 /km.

4.3.3. Cost Matrices

Cost matrices are created by multiplying the distance matrices by the cost of transportation of 1 TEU per 1 km by specific mode. To simulate stochastic price fluctuation, each cell of the cost matrices is multiplied by a random number (uniform distribution) between 0.95-1.05 for rail transportation, 0.90-1.10 for truck (road) transportation and 0.85-1.15 for liner shipping.

4.3.4. Capacity Data

The capacity of railway depends on the railway line, train size, weight load and other parameters. The author assumes the range of rail capacity for Europe is in the range of 110-200 TEUs and for U.S. 110-400 TEUs. The capacity of road is considered to be in the range of 110-450 TEUs in Europe and 160-700 TEUs in U.S. Finally, the capacity of liner shipping transportation is assumed to be distributed in a range of 1,200-8,000 TEUs. For each link and mode, the capacity is randomly generated according to a uniform distribution.

4.4. Computational Resources

The computing environment consists of a Dell XPS machine with an Intel Core™ 2 Duo processor T8300, under the Windows Vista™ operating system with 2.40GHz and 4GB of RAM.
The TCMMSP problem was solved using the branch-and-cut algorithm in GAMS/CPLEX optimization software version 22.9.2 with ILOG CPLEX 11.0.

4.5. Experiment Setup

The experiment consists of 20 different sets of shipments. Each set consists of five shipments with specific O-D pairs. These O-D pairs can be the same or can differ for the different shipments. Each O-D pair has a number of TEUs or quantity to be shipped.

The total volume of a set was selected from the range of 20-1,580 TEUs. The upper limit was estimated from several initial experiments. It was found that, for the case study setup, the maximum total set volume for having a feasible solution is approximately 1,600 TEUs. GAMS is not able to find a feasible solution for total volume higher than 1,600 TEUs. It is mainly caused by the link capacities for this particular case study. Table 4.2 shows all the sets, the O-D pairs of five shipments in each set and demand volume in each shipment.

<table>
<thead>
<tr>
<th>Shipment Set</th>
<th>Total Set Volume</th>
<th>q1</th>
<th>q2</th>
<th>q3</th>
<th>q4</th>
<th>q5</th>
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<td>2-24</td>
<td>5</td>
<td>1-23</td>
<td>5</td>
<td>1-20</td>
</tr>
</tbody>
</table>
4.6. Analysis of Results

4.6.1. Average Costs

Figure 4.2 shows cost analysis of 19 sets of shipments. It shows the graph of total costs per TEU, routing costs per TEU, transferring costs per TEU and polynomial regression curve of the third order of total costs per TEU. The first sample set 1 had infeasible solution due to demand that exceeded capacity.

The minimum of total costs, derived from the fitted polynomial function, is $7118 /TEU. It is necessary to mention that this is not the absolute minimum cost. It always depends on the selection of different O-D pairs and the shipment volumes.
4.6.2. Optimal Volume

Figure 4.3 shows the analysis of 19 sample sets of shipments. It shows the graph of total costs per TEU against total set volume, and polynomial regression curve of the third order.

The minimum total cost per TEU, derived from the fitted function, is obtained at 540 TEUs. It is necessary to mention again that this quantity is not the absolute minimum. It always depends on the O-D pairs. On the other hand, the maximum total cost per TEU is obtained with set volume of 1,594 TEUs. This is because, as the total volume is approaching the capacity of 1,600 TEUs, all the links and modes (including those with the highest costs) have been used.
4.6.3. Optimal Route

One of the outputs of the model is the optimal routing between each O-D pair. The model is designed to optimally route each shipment.

As an example, one particular demand set (set 7) is presented here. The total volume of this set is 1075 TEUs and the particular volumes and O-D pairs of shipments are shown in Table 4.3.

Table 4.3 Demand set no.7

<table>
<thead>
<tr>
<th>Shipment q</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-D pair</td>
<td>1-22 Prague - Philadelphia</td>
<td>2-21 Brno - Houston</td>
<td>1-20 Prague - Chicago</td>
<td>3-19 Ostrava - Los Angeles</td>
<td>4-26 Pilsen - Dallas</td>
</tr>
<tr>
<td>Volume (TEU)</td>
<td>250</td>
<td>150</td>
<td>45</td>
<td>280</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 4.4 shows the optimal routing obtained for demand set 7. As can be seen, shipments 1 and 3 were shipped as the whole whereas shipments 2, 4 and 5 had to be split.

For example, shipment (q2) is originated in Brno with a demand of 150 TEUs is shipped to the port of Antwerpen (23 TEUs by truck and 127 TEUs by rail). Then, the whole shipment of 150 TEUs is shipped by vessel to port of Houston and from there to the city Houston (point of destination) by truck (150 TEUs).
### Table 4.4 Optimal routing of shipments in demand set no.7

<table>
<thead>
<tr>
<th>$q_1$</th>
<th>1</th>
<th>8</th>
<th>15</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prague</td>
<td>Bremerhaven</td>
<td>Norfolk</td>
<td>Philadelphia</td>
<td></td>
</tr>
<tr>
<td>Truck 250 TEU</td>
<td>Vessel 250 TEU</td>
<td>Truck 250 TEU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_2$</th>
<th>2</th>
<th>7</th>
<th>16</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brno</td>
<td>Antwerpen</td>
<td>Houston</td>
<td>Houston</td>
<td></td>
</tr>
<tr>
<td>Truck 23 TEU</td>
<td>Vessel 150 TEU</td>
<td>Truck 150 TEU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_3$</th>
<th>1</th>
<th>9</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prague</td>
<td>Le Havre</td>
<td>Los Angeles</td>
<td>Chicago</td>
<td></td>
</tr>
<tr>
<td>Rail 45 TEU</td>
<td>Vessel 45 TEU</td>
<td>Rail 45 TEU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_4$</th>
<th>3</th>
<th>6</th>
<th>13</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ostrava</td>
<td>Hamburg</td>
<td>Savannah</td>
<td>Los Angeles</td>
<td></td>
</tr>
<tr>
<td>Truck 242 TEU</td>
<td>Vessel 242 TEU</td>
<td>Rail 242 TEU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_5$</th>
<th>4</th>
<th>7</th>
<th>16</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilsen</td>
<td>Antwerpen</td>
<td>Houston</td>
<td>Dallas</td>
<td></td>
</tr>
<tr>
<td>Rail 156 TEU</td>
<td>Vessel 156 TEU</td>
<td>Rail 156 TEU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 4.6.4. Analysis of Ports Use

The essential part of maritime transportation is indisputably the ports. This section analyses the ports and their utilizations in the case study.
Table 4.5 Number of use of each port

<table>
<thead>
<tr>
<th>Set of shipments</th>
<th>European ports</th>
<th>U.S. ports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotterdam (NL)</td>
<td>Hamburg (GE)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>26</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.5 shows the number of use of each port of the transportation network, irrespective of the shipment volumes. The number in each cell represents the number of shipments. A shipment between the same O-D pair that is split between two ports is counted as two entries of 1 in two different ports. Therefore, for each demand set, the sum of European port uses can be more than 5. Similarly, for each demand set, the sum of U.S. port use can also be more than 5. It can be observed that the demand sets of higher volume are served practically by all ports (except Long Beach and Seattle). But, once the volume of shipment set decreases to approximately under 1,000 TEUs, three more ports are not used anymore (Le Havre, Los Angeles and Oakland). The four main European ports are used almost all the time. The same can be said about U.S. ports in the East Coast. The busiest port in Europe is Antwerpen and in U.S. it is the port in Houston.
Ports in the west coast of U.S. are not used because of their geographical position and long sailing distance.

A test was conducted to see what happens when some of ports are removed from the network. This can happen when there is a disaster or political event that closes a port for a long period. This test was performed for three cases: the ports in Antwerpen, Houston and both ports were removed from the network.

Table 4.6 Port removal analysis

<table>
<thead>
<tr>
<th>Description</th>
<th>Set of shipments</th>
<th>Volume of set (TEU)</th>
<th>Routing costs (USD)</th>
<th>Transferring costs (USD)</th>
<th>Total costs (USD)</th>
<th>Average routing costs (USD/TEU)</th>
<th>Average transferring costs (USD/TEU)</th>
<th>Average total costs (USD/TEU)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All ports available</td>
<td>7</td>
<td>1075</td>
<td>8959979</td>
<td>74420</td>
<td>9034399</td>
<td>8335</td>
<td>69</td>
<td>8404</td>
<td>-</td>
</tr>
<tr>
<td>Antwerpen removal</td>
<td>7</td>
<td>1075</td>
<td>9673745</td>
<td>60554</td>
<td>9734299</td>
<td>8999</td>
<td>56</td>
<td>9055</td>
<td>7.75</td>
</tr>
<tr>
<td>Houston removal</td>
<td>7</td>
<td>1075</td>
<td>10089174</td>
<td>59532</td>
<td>10148706</td>
<td>9385</td>
<td>55</td>
<td>9441</td>
<td>12.33</td>
</tr>
<tr>
<td>Houston and Bremerhaven removal</td>
<td>7</td>
<td>1075</td>
<td>12048297</td>
<td>48242</td>
<td>12096539</td>
<td>11208</td>
<td>45</td>
<td>11253</td>
<td>33.89</td>
</tr>
</tbody>
</table>

Table 4.6 summarizes the result of port removal analysis for demand set 7. It can be seen that the removal of port in Antwerpen from the network causes an increase in total cost per TEU by 7.75 %. The lost of port of Houston by increases the total cost per TEU by 12.33 % and the removal of both ports has the effect of increasing of total cost per TEU by 33.89 %.

4.7. Summary

In this chapter, an application of the Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP) was presented. The problem was solved for 19 different demand sets each consisting of five shipments of different volumes and O-D pairs. Several analyses of the solutions have been performed. The first one is the cost analysis and it shows the average routing, transferring and total costs per TEU at the different demand volumes. The second one is the
analysis of volumes and determination of the optimal set volume. The third one is the optimal route analysis for one specific demand set of five shipments. The last one is port use analysis and identification of the most important ports in the network. It also proves that the removal of one of those ports will increase the total transportation cost per TEU.
Chapter 5: Conclusions

This chapter summarizes the findings of this thesis and research performed. It highlights the contributions and also suggests possible directions of future research. Section 7.1 summarizes the research and its results. Section 7.2 highlights the contributions of the thesis, and Section 7.3 proposes possible extensions of the work in future research.

5.1. Summary of Research

The thesis presents a recent review of maritime transportation. It includes the description of world maritime routes, maritime ships and the costs of maritime transportation. It also discusses the inland rail and road transportation in U.S. and the European continent as the complementary modes for maritime transportation. Included in the analyses are the trends and statistics of the trade between the Czech Republic and U.S.

The second part of the research focuses on mathematical models of freight transportation between Europe and U.S. One model, named Transatlantic Multi-Mode Container Routing Problem (TMMCRP), is formulated by the author himself and another one, named Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP) is adopted from Hernandez (2013). The TCMMSP model is then applied in the case study concerning the transportation of a set of five different shipments of a single commodity from Czech cities to U.S. cities.

Twenty different demand sets, each with five shipments of a unique O-D pair and volume, were generated and the solutions analyzed. Four different analyses were conducted: total cost per TEU, optimal set volume, optimal route and port use analysis.

5.2. Contributions of the Thesis

The contributions of the thesis could be summarized in following points:
1) Summary of the recent problems and developments of maritime transportation.
2) Review of maritime transportation, including world maritime routes, maritime ships and costs of maritime transportation. This review includes statistics, parameters and classification of maritime routes and ships.
3) Discussions on ports and inland transportation on both sides of the Atlantic Ocean.
4) Introduction of two models of freight transportation between Europe and U.S. The first one, Transatlantic Multi-Mode Container Routing Problem (TMMCRP), is developed by the author himself and the second one, Transnational Collaborative Multi-Mode Shipping Problem (TCMMSP), is adapted by the author.
5) The case study on the application of TCMMSP.

It is essential to mention that the models include only the basic constraints and parameters. There are many other directions on how the models could be extended. This should definitely be part of future research.

5.3. Future Research

Both mentioned models work with basic constrains and parameters and both of them are time independent. The future research could focus on bringing the time dependency into them.

In the TCMMSP model, the cost of transfer is fixed regardless of the TEUs. The cost could be changed to unit cost and then multiply by the number of TEUs transferred.

Future research could also include the inland waterborne transportation in the European continent, because this mode of transportation is becoming more important.

One of the next crucial steps is to obtain more accurate input data, such as transportation costs of all modes, capacities of links and nodes of the transportation network.
List of References


<http://www.containerhandbuch.de/chb_e/stra/index.html?/chb_e/stra/stra_01_01_00.htm l> (4/6, 2014).


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Vita

Petr Toman was born in Tabor, Czech Republic, on April 7th, 1989, as the second son of Marie and Bronislav Toman. After graduating from Gymnázium Sobeslav in Sobeslav, Czech Republic, he entered the Czech Technical University in Prague, the Faculty of Transportation Sciences, in 2008. He achieved his Bachelor degree in Technology in Transportation and Telecommunications - Management and Economy of Transportation and Telecommunications in Prague, Faculty of Transportation Sciences, in June 2012. In September 2012, he joined the Transatlantic Dual Masters Program in the Transportation and Logistic Systems which was jointly offered by the Czech Technical University in Prague, the Faculty of Transportation Sciences, and The University of Texas at El Paso.

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