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Studying the selection of ports on liner routes

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STUDYING THE SELECTION OF PORTS ON LINER ROUTES

By

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

………………………………
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Abstract

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With any shipping line, the operational success not only depends on the operation of their fleet but also the organization of a network in which ships operate. A reasonable choice of ports determines the efficiency of any network. On the one hand, it influences operational cost of shipping lines, on the other hand, it affects customer services. The objective of this research is to study the port selection in liner shipping from a logistics perspective, a port activity concerns with both sea side and land side.

It starts by giving a brief look into previous studies which provide us general understandings about the development of liner networks as well as methods applied in studying liner network problems with regard to port selection.

The central work of this study is to set up a model to deal with port choice decision. The model solves three matters: ports on ship's route, their order & loading/unloading ports for each shipment. Its objective is to minimize total cost including ship cost, port tariff, inland transport cost and inventory cost. The model has been applied in real data, with cargo flows between the USA and Northern Europe.

Afterwards, two sensitive analyses are considered. The first assesses the impact of a number of port calls to the total cost which relates closely to the viability of service patterns, multi ports and hub & spoke. The second analyzes the efficiency of large vessels when put into the scope of a logistics network.

The overriding result of this study is to indicate influences of logistics networks in the decision of port choice. Traditionally, people often concentrate on the sea side when studying about this subject. This study emphasizes the necessary to combine different factors and aspects when dealing with this topic, or else a result can be one-sided.

Keywords: port selection, liner route, model, mega vessel, logistics, container.

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List of Abbreviations

CI :Containerisation International
EU : European Union
PIERS : Port Import Export Reporting Service
TEU : Twenty-foot equivalent unit
UNCTAD : United Nations Conference on Trade and Development
UN : United Nations
UK : United Kingdom
USA : United States of America
USD : United States Dollar

Chapter 1 Introduction

1.1 Background

Shipping plays an important role in world trade. Approximately 90 percent of the world total trade of goods is carried by sea. In the shipping industry, there are three operational modes: industrial, tramp and liner operation. About volume, liner shipping constitutes the smallest part among these modes, general cargo carried by liner trade is about 15% of the world total traffic. However, in value terms, it creates more than 70% of the world total, 50% of the world total freight is from liner. (Ma, 2006). Compared with two other transportation modes, liner shipping is quite complicated. Industrial ships are only concerned with internal transportation demand of companies. In tramp shipping, ships mainly operate from port to port with a flexible schedule based on the demand of shippers. In liner shipping, a ship is not only involved with port to port voyage alone but also a network including many ports, it operates in accordance with a published itinerary and schedule like bus activity. Therefore, the routing problem is an intricate issue in liner shipping.

Container transportation has been started since the 1950s. With the advantages of productivity, cost, safety, containers are taking a bigger share of general cargo in liner trade. On a global basis, the containerization ratio is about 75%. (Ma, 2006). All of the major liner routes and most of the minor ones have been containerized. (Stopford, 1997, p 342). Worldwide container port throughput increased from 38.8 million TEU in 1980 to 382 million TEU in 2005. (Baird, 2003; CI, 2007). Over the past 20 years, the average growth demand for container transportation is about 8.7% p.a. (Maersk, 2007). The total number of full container worldwide trade routes (excluding transhipment) amounted to 77.8 million TEUs in 2002, compared to

28.7 million TEUs in 1990. This figure is expected to reach 177.6 million TEUs in 2015. (Rodrigue & Notteboom, 2007). In 2002, Stopford forecasted the average growth of container transportation around 6% p.a until 2023. ISL (2006) estimated this rate is 4.9% through 2024. Global Insight anticipated close to 200 million moves in 2017. (CI, 1/2007). UK-based consultant MDS expected intercontinental container traffic grows 7% p.a from 2006 to 2014. (CI, 3/2007).

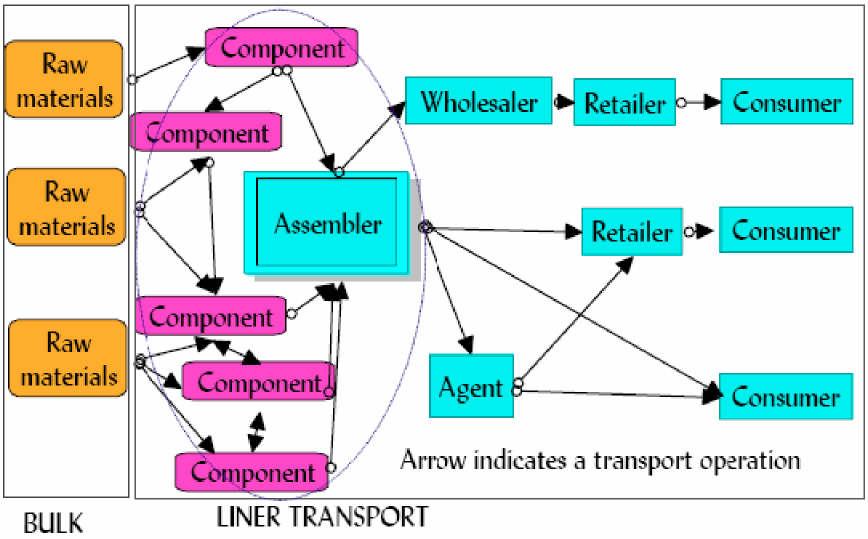

Figure 1: The international transport system
Source: Stopford, M. (2002). Is the drive for ever bigger containership irrestible? *Proceedings of Lloyds List Shipping Forecasting Conference.*

In January 2000, the market share of top 10 shipping lines was 49.3%, after 7 years, it has increased to 60%. With the top 25, it has increased from 74.6% to 84%. (Axs-Alphaliner, 2007). The Herfindahl index has increased from 0.03 to 0.06. [1] These figures can reflect the concentration in liner shipping as seen in the comments of McLellan (2006, p 522), Ma (2006, p 56) or Unctad (2006, p 63). Many well-known shipping lines such as Sea-Land, P&O Nedloyd, US Lines …, used to be market leaders, have gone or acquired by others. The number of companies reduces, however, on trade routes, the number of lines increase which makes the competition become more and more fierce. (UN, 1998, p 11). To exist and grow in such a competitive market, shipping lines must be much more proactive to face the

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[1] Calculated based on data about market share of AXS-Alphaliner

challenges. In recent years, we have observed many strategies applied, from horizontal to vertical integration, merge and acquisition, strategic alliances, exploiting economies of scale by mega-containers, emergence into logistics activities, stevedore industry, and inland transportation.

In any circumstances, the routing problem is always the core interest of shipping lines which determine their success or failure. They must decide ports on their route as well as a reasonable sequence of port calls. It is not as simple as organizing a voyage from the origin to destination port. It is concerned with designing a shipping network. On the one hand, shipping routes directly influence the operational cost of carriers, on the other hand, they affect services provided to customers. A sound selection of ports will create a competitive service for carriers. It is very important for carriers, especially in the circumstance of fierce competition in the liner market.

1.2 Research problems

The study focuses on answering three fundamental questions:

- *Research question 1*: What are the groups, schools in studying liner network problems, particularly in accordance with port selection matters? What is the gap in previous researches which this topic can elaborate on?
- *Research question 2*: What should be the suitable model for the port selection problem? Which factors should be included in the model?
- *Research question 3*: What is the influence of the number of port calls on a ship's route? What is the viability of deploying mega vessels?

1.3 Objectives

- To review the development of liner shipping networks, the tendencies which influence the organization of liner network.
- To review the methods, schools in solving the liner network problem, particularly in accordance with port selection matters.
- To realize the gaps which should contribute in the study of port choice.

- To set up a new model, which inherits the advantages of previous work, on the other hand, to overcome the gaps.
- To apply a model for specific data, and from that, verify the suitability of the new model, draw conclusions, and make analyses from the results.

1.4 Methodology

This topic will be carried out in five phases as shown below:

Phase 1 - *Determine issues addressed in the topic:* This is the foundation phase which determines the main contents for the topic. The knowledge acquired from lectures, books, articles provides a theoretical background for the topic. Information from field trips, seminars, discussions with experts from shipping lines, forwarders, ports gives a good view about practical things.

Phase 2 – *Review of literature:* This phase elaborates the previous studies. A lot of data, information, tools can be found in this work. This phase contributes a deep understanding of the selected topic. A lot of work provides the foundation for a constructed model. We can also detect some gaps which the research should concentrate on more.

Phase 3 – *Modelling:* The questions concerning port selection problems will be answered by a non-linear programming model. This model will try to take full advantage of the previous models as well as overcoming some previous gaps. One important thing in this phase is to find a solution approach for this model.

Phase 4 – *Data collection and application in model:* This is the testing phase of the suggested model. The primary data, which are suitable for applying in our model, are collected from Piers (US). Besides, some secondary data are also supplemented to support the application. After classification, combination and adjustment, these data will be executed in our model to find solutions through a computer program coded by Turbo Pascal 7.0 language. The result of this phase is also a source for later analyses.

Phase 5 – *Analysis:* From the outcomes of the prior phase, we can understand more about the influence of various factors on port selection. Moreover, the efficiency of the hub& spoke system, economies of deploying mega containers, which are still debatable, will be evaluated in this part.

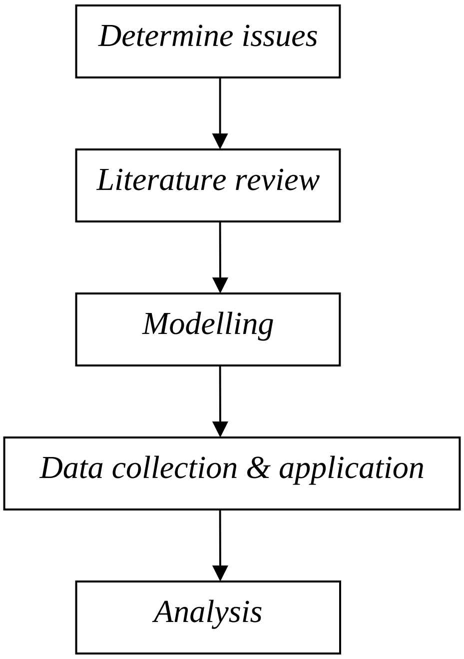


Figure 2: Research methodology
Source: the author

1.5 Scope of the study

The study is presented in five main chapters as follows:

Chapter 1 – Introduction: This chapter gives an overview of the whole research. It describes the background, structure of the study, identifies the main research objectives as well as methodology applied in this study.

Chapter 2 – Literature review: In this chapter, we survey the previous studies in two main groups. One concerns the liner network development. The other includes economic models applied in solving liner network issues.

Chapter 3 – Model formulation: A network model will be presented in chapter 3. The model aims to minimize total cost including: inland transportation cost, ship cost, port tariff and inventory cost of cargo. It deals with three questions: which port should be selected on a ship's route? What is the sequence of port calls in the voyage? Among selected ports, what should be the loading and unloading ports of shipments? Four algorithms are also suggested to approach an optimal solution.

Chapter 4 – Model application and analyses: This chapter includes three parts. The first introduces the input data and phases to process data for application. The second gives an overview of computational programming for running a model with real data and describes the results of a running program. Based on these results, the last analyzes the relationship between the number of port calls and the optimal route as well as the efficiency of mega vessels.

Chapter 5 – Conclusion: This is the wrap-up part of the thesis. The chapter summarizes the whole work and draws general conclusions. It also mentions the limitations of the study, indicates some possible research later which can improve and extend the contemporary topic.

Chapter 2 Literature review

Literature that contributes to our background comes from two main directions. The first are studies about the evolution of liner shipping network. They provide general knowledge about the development, tendency of container shipping network, the organization of the liner system in the global as well as specific regions. The second are economic models established to solve specific problems with regard to port selection in liner shipping. They provide with various kinds of tools to setting up a new model, the way to deal with data and information in a concrete case.

2.1 Container shipping network development

This section will discuss various aspects of container shipping network. Firstly, the theory of Ashar (2002a) will be mentioned to give the overall scene of the development of container shipping system. After that, four aspects will be elaborated upon: transhipment in liner shipping, theories of hub port, network structures of some regions and container service patterns. Two remain parts introduce two common trends in liner shipping which influence a lot the shipping network: the deployment of large container vessels and the evolvement into logistics activities of shipping lines.

The recent history of liner shipping was described as one evolution and three revolutions. (Ashar, 2002a). The evolution refers to the gradual growth in size of ports and vessels whereas revolutions are the changes in the system's linkage and related expansion of its scope. The first revolution was the container invention in 1956 which focused on improving ship-to-shore handling. The second was concerned with intermodal ship-rail transport which further expanded land penetration of containers by creating landbridges. Unlike two previous revolutions originating in the USA, the third, transshipment revolution began in the Far East to tackle shortages in port infrastructure. Later, it spread worldwide, created a system of hub and feeder ports.

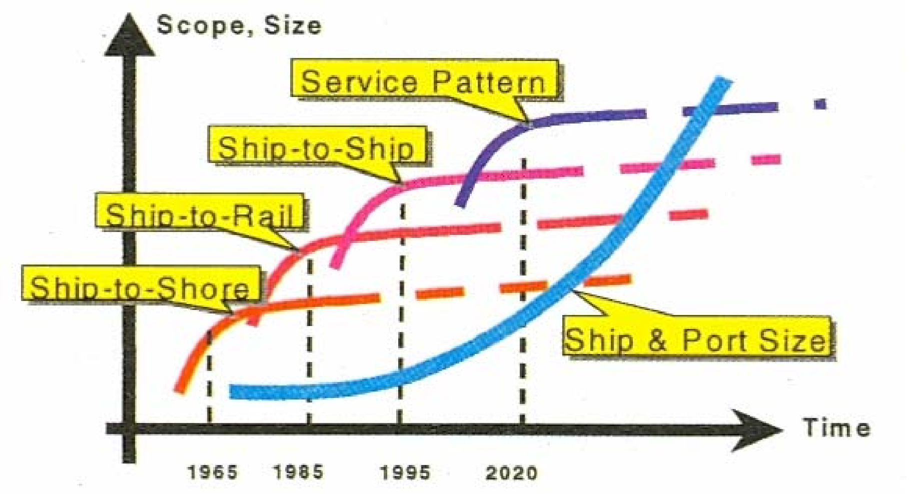


Figure 3: Evolution & revolution in Liner shipping

Source: Ashar, A. (2002a). The fourth revolution. *Proceedings of The IFPCD 6th regular conference,* Antwerp. Belgium.

Transhipment in liner shipping:

Containerisation has changed the way shipping lines organize their activities. In previous periods, carriers operated port-to-port services. Each port had its own captive cargo. To get this cargo, liner services must have called this port in their voyages. Once containerisation has introduced, cargo could be easily transported from one port to others by barges, trucks or small ships. Shipping lines will decide to serve some ports with direct-call, others with feeder service. (Stopford, 1997). With some ports, the physical and equipment constraints also prevent direct call of mainline vessel. Besides, there will be a trade-off between transhipment and direct call. Transhipment can be costly in terms of feeder cost, handling cost, transit time cost. However, direct call may be much more expensive due to the higher daily cost of mother vessels and higher capital cost for both ship and cargo. (Ma, 2006).

Jansson & Shneerson (1987) summarized the feeder transport problem in a particular trade by asking three questions:

- Which ports are to be included in the liner services? (conference ports)
- Of these ports, which ports should be called at by trunk liners?
- How to organize feeder transport for ports in conference not called by trunk liners?

They suggested three solutions for this three-phase problem: (a) multi port calling at all conference ports; (b) a shuttle service between two ‘base ports’ at each end, supported by feeder service to/ from outports; (c) mixed system: liner calls more than one port at each end, but not all conference ports, feeder services to other ports.

In the era of containerisation, transshipment has become a significant part of overall transport activities. Unctad (1990) distinguished various forms of transshipment: scattering/feedering, inter-line, switching, catch-up, by pass and land bridges & mini land bridges. Involved with transhipment operations, ports may be divided into 4 categories: dedicated hub ports, hub and load-centre ports, direct call ports and feedered ports.

Frankel (2004) noted the continual growth of transhipment or multiple handling containers from origin to destination ports. This trend is expected to continue, especially with the increase of globalisation, interregional trade. In 1960, the average number of transfer between ship and shore and vice versa was 2.0, went up to 2.1 in 1970, 2.3 in 1980, 2.7 in 1990 and 3.2 in 2000. The result is the increasing portion of transfer operation in door-to-door time and costs. Economies of liner networks will depend a lot on the efficiency of transfer activities. The savings from improvement in port to port transport are marginal. In this circumstance, it is necessary to pay more attention in port activities, especially the development of more effective, cheaper container loading and unloading operation.

Table 1: Estimated development of global transhipment container volumes, 1980-2002

Year	Total Port Handling (m teu)	Full Container Handling (m teu)	Empty Container Handling (m teu)	Transhipment Port Handling (m teu)	Transhipment Incidence (%)
1980	38.8	30.3	8.4	4.3	11
1990	87.9	70.1	17.8	15.9	18.1
2000	236.2	186.4	49.8	62.3	26.4
2001	246.4	193.1	53.3	65.9	26.7
2002	272.8	214.4	58.4	74.4	27.3
Change 1980/2002	603%	608%	595%	1630%	

Source: Baird, A.J. (2003). *Global Strategy in the Maritime Sector: Perspectives for the Shipping and Ports Industry.* Paper Presented at the Third Meeting of the Inter-American Committee on Ports (CIP).

Hub port development:

A hub port in liner shipping is the same as hub airports for airlines. Such networks have been applied extensively in transportation. Hubs or central transhipment facilities allow setting up a network where fewer, indirect connections can be used instead of many direct connections. This configuration can reduce and simplify network construction cost, centralize commodity handling and sorting, allow carriers to take advantage of scale economies. Kelly & Miller (1994) divided hub and spoke networks into 8 protocols which are distinguished by the types of connections between hub & hub, hub & spoke and spoke & spoke. Fleming & Hayuth (1994) classified hubs by spatial characteristics: centrality and intermediacy. The former hub concerns with the initial origins or ultimate destinations of cargo flow whereas the latter can be a waystop, route junction, gateways … between origin and destination. “One is locally generated and stimulated by the port’s centrality with respect to a regional hinterland. The other is distantly generated by the interaction of widely separated places and stimulated by the port’s en route location or intermediacy.”

Hayut (1981) introduced a five-phase model to illustrate the growth process of a load center:

Phase 1 – Preconditions for change: In this phase, the present port confronts with inefficient handling methods, high cost, and low quality. There are new requirements and demands from customers as well as technical feasibility for changes.

Phase 2 – Initial container port development: Limited to some large ports or a port with favourable site and location.

Phase 3 – Diffusion, consolidated and port concentration: Ports specialize in operation system. Large ports penetrate beyond the traditional hinterland which enlarge their hinterland at the expenses of smaller ports. A new spatial arrangement of the system emerges, based on center-sub-center relations.

Phase 4 – The load center: The concentration of container traffic at the limited number of larger ports.

Phase 5 – The challenge of the periphery: The development of load center faces with many constraints: diseconomies of scale, lack of space for expansion, congestion. Peripheral ports exploit the limitation of load center, take full advantage of flexibility, adapt with new requirements, intensify their activities and challenge with existing hub ports.

Some authors have also used this theoretical model to examine the development of load centers in some regions: Notteboom (1997) in the scope of European ports, Wang (1998) with the case of Hongkong. Both of them more or less agreed with Hayut's theory about concentration process of load centers. However, they deviated from the previous model about deconcentration process (challenge from peripheral ports). Notteboom (1997) considered locational factors (closeness to a main route) as a primary reason for the emergence of new ports. Wang (1998) explained the challenge to Hongkong port from penetrations of hub operators into Chinese ports.

Baird (1996) addressed the influence of containerisation to upstream urban ports in the context of Europe. He argued the physical constraints of these ports in the development, especially the limitation of depth water prevents them to serve big vessels. The role of upstream load centers would become weaker. Notteboom et al (1997) disagree about this argument, they claimed that inland location can not always be a disadvantage. Despite limited draught conditions of maritime access channel, other elements such as substantial hinterland, high productivity, competitive cost, and infrastructure play an essential role in becoming or maintaining a load-centre position.

Tzong (2001) explored the key success factors of Singapore as a leading transhipment hub in the world. The most important factors include: strategic location, high level of operational efficiency, high port connectivity, adequate infrastructure and a wide range of port services. Besides that, the appropriate policy of Singapore government plays a vital role in that success.

Coulter (2002) approached the matter of hub ports from another view, the risk of them. Similar to the chokepoint concept, he considered a hub port as a vulnerable link in the chain of the free and orderly flow of maritime commerce. The more scale a hub port is, the more risk the overall system is. Any disruption in a hub port caused by strike, disaster or IT disconnection could influence not only the port itself but also other ports, factories in the global supply chain.

Regional network structure:

Robinson (1998) studied the dynamic restructuring of Asian hub/feeder nets under conditions of rapid regional growth. He speculated the transformation of the simple mainline/feeder networks into more complex patterns of hierarchical networks reflecting cost/efficiency level in the market. High efficiency/high cost hubs sustaining with high efficiency/high cost shipping would be regarded as first order network. Based on market segmentation, lower cost/lower efficiency ports and shipping would be second, third or subsequent order networks.

The Mediterranean region has a strategic position in world sea transport. It is an articulation between East-west and North-south route, a transit area between the world's biggest markets. After a long time of stagnation, from 1990s, the Mediterranean container market has experienced a fast growth, become central in the network strategies of major carriers. From a niche market, it has become a back door of Europe. Genco & Pitto (2000) went into details the restructuring of transhipment and liner networks which created a complex hierarchical structure based upon the interaction between mega and niche hubs, direct & feeder ports in this area. They classified significant trends which have re-shaped the Mediterranean liner market: the development of hub-and-spoke operation; increasing degree of integration of the Mediterranean market within global network; wider adoption of multi-leg operation and growth in relay transhipment.

Fremont & Soppe (2004) examined the evolution of North European networks in the 1990s. As mentioned above, the period has observed the radical changes of Mediteranean networks. This development has lightened the role of North European ports. Instead of transferring through these ports, a lot of inland cargo has been deviated to Mediteranean ports. Inside the region, shipping lines have reorganized their networks, concentrated on different hubs. On the side of ports, there was fierce inter-competition between ports. The good transportation system made ports accessible from any inland points, no port could ensure about its captive hinterland. The market share gaps between pivot ports have become smaller and smaller.

McCalla et al (2004) described the complex container shipping networks of the Caribbean and Mediterranean Sea at three geographical scales: intra-basin, regional and global between 1994 and 2002 as well as the role alliances played in the network structure. Economic factors were the explanations for the more developed and stable in the network of Mediterranean sea.

Notteboom (2000) approached the transformation in the order of port systems by the concept of the “peripheral port challenges” (PPC). The concept was used to study the reinforcement of new terminal or former non-hubs at the expense of the existing large load centres in the context of the West Mediterranean and the Rhine-Scheldt. The analysis demonstrated that the developments of the former port system were a prime example of PPC triggered from the need to reduce diversion distances. However, the impact of PPC to the latter was rather limited. The difference can stem from the nature of transshipment hubs in these regions. The West Mediterranean hubs are almost pure transshipment terminals for “intermediacy”-based sea-sea flow which are easily detrimental. With Rhine-Scheldt hubs, they concern mainly with “centrality”-based flows which can rely on some strong cargo-generating regional hinterlands.

Service patterns:

The liner shipping system can be defined as a network including nodes (ports) and links (routes between two consecutive ports in a specific service). In that network, there are many services with different patterns. Stopford (1997) mentioned thirty-two maritime coastal regions in the world with 1,024 potential liner services connecting these areas. Notteboom (2006) indicated three inter-related components for setting a service: service frequency; fleet size, vessel size and fleet mix; number of port call. Carriers design a service on the one hand convenient and efficient for them, on the other hand, it must satisfy their customer’s requirement about frequency, accessibility and transit times. Ma (2006) noted six distinguished major types of liner shipping patterns: End-to-end (or point-to-point), Hub-spoke, Pendulum, Double-dipping, Triangle and Round-the-world (RTW).

Of these service patterns, RTW can be the most complicated, with a lot of debates about its feasibility. Lim (1996) provided an in-depth study about this kind of service from basic concepts, advantages and disadvantages, economics to the success and failure of US Lines and Evergreen in operating it. Through his paper, he concluded the viability of RTW about operational and economic aspects compared with end-to-end or pendulum service. The success or failure completely depends on the marketing and management ability of the users.

Ashar (2002a) argued about the underutilization of ship capacity in end-to-end or pendulum services as well as long transit time, small ship size of RTW services. He predicted that the fourth revolution, also the last, triggered by the expansion of Panama Canal, would be the restructuring of liner shipping and port system, a massive conversion of service patterns into new Equatorial RTW. This new service could overcome the weakness of the contemporary system. New equatorial RTW can get shortest possible route, use 15,000 TEU vessels, and only call in some pure transshipment ports.

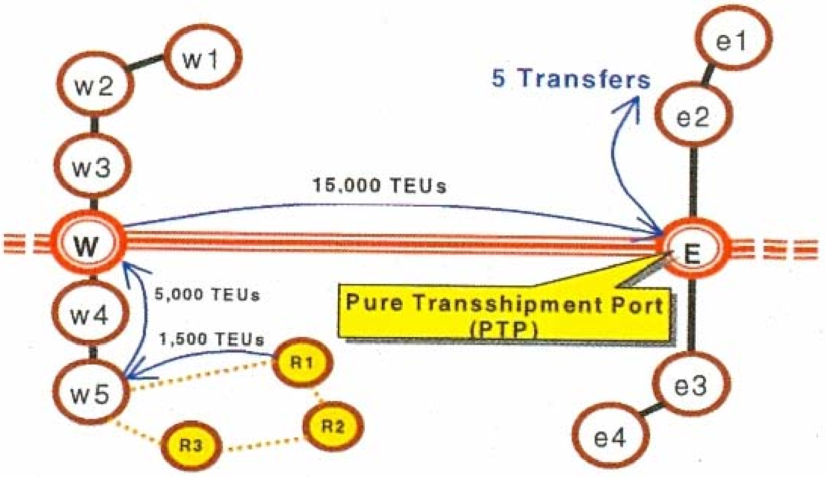


Figure 4: Equotarial Round-the-world service
Source: Ashar, A. (2002a). The fourth revolution. *Proceedings of The IFPCD 6th regular conference*, Antwerp. Belgium.

Sartini (1999) compared transhipment and direct calls by referring two opposite strategies of Maersk and Evergreen in the Mediterranean sea. Maersk concentrated their cargo flow on two mega hub ports, Algeciras and Gioia Tauro. Meanwhile, Evergreen continued to be faithful with a traditional service pattern in this region, end to end service. Sartini noted that in the scope of the Mediterranean sea, hub & spoke system is less economic than multi port calls due to high feeder and terminal cost. The success of Maersk stemmed from their control of terminal operations and clockwork vessel scheduling. Moreover, from these hubs, Maersk combined routes from Asia to Europe with routes to West Africa and America which made double-dipping utilization and optimized the use of their mainline vessel.

Deployment of large container vessels:

It is difficult for carriers to control freight rates. To maintain profits, it is better to keep control on the cost rather than revenue side. (Midoro et al, 2005, p 95). Operating bigger vessels have become a strategy of shipping lines to reduce average cost per slot. The average of ship size continuously goes up. In 1990, this figure is 1,378 TEU, it increases to 1,727 TEU in 2007, then 2,693 in 2010. (BRS-Alphaliner, 2007). The size of largest containership has almost grown 6 times within two last decades, from 2,500 TEU in 1980 to more than 12,000 TEU in 2006. (Dragovic et al, 2007).

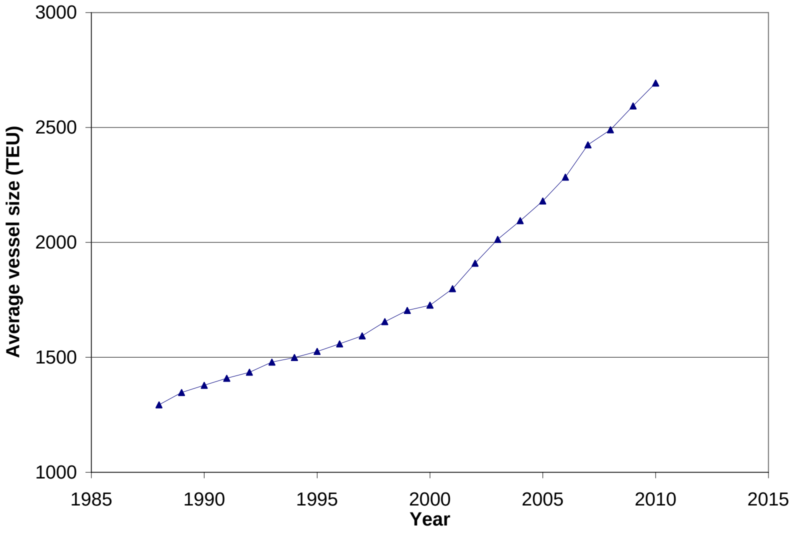


Figure 5: Development of average vessel size
Source: Calculated from data of BRS-Alphaliner (2006).

Many papers have focused on the operation of large mainline vessels. Economies of ship size are provided by the works of Jansson & Shneerson (1987), Talley (1990), Lim (1994), Lim (1998), Cullinane & Khanna (1998), Gilman (1999), Wijnost et al (2000) based on econometric analysis or cost estimation. Jansson & Shneerson (1987) and Talley (1990) tried to find an optimal size by trade-offs analysis between cost in port (increasing with ship size) and cost at sea (decreasing with ship size).

Related to the network efficiency of large containerships, Gilman (1999) argued for the efficiency of a pure hub & spoke system based on a small number of transhipment ports. The high percentage of transhipment containers can make this system more expensive than multi port calls. Therefore, hub & spoke system can not be an alternative for multi port operations, it is just a part of the overall scene.

Ircha (2001) provided solutions for enhancing Canadian ports to take opportunity of the development of bigger vessels. Payer (2002), Yang (2004) and Midoro et al (2005) realized impacts of mega-container vessels for container shipping. There would be new challenges for ports (high-productivity handling facilities, berth length, water depth, and new logistics requirements for container terminals) as well as ship operations (technical aspects, change of port calling schedules, service patterns).

McLellan (1997), Ashar (2002b), Frankel (2004), Imai (2007) and Dragovic et al (2007) consider handling operation as one of the most obstacles for deploying mega container vessels. They mention some solutions for mega terminals to tackle this bottleneck: placement of cranes in adjacent bays (Fantuzzi’s Octopus), handling from both sides (Ceres’s ship-in-slip), multiple hoist gantries, direct ship-to-ship transfer, floating terminal…

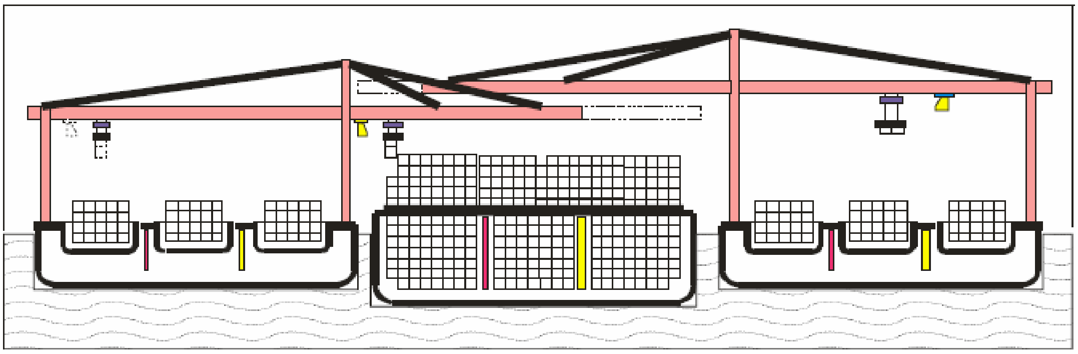


Figure 6: Floating terminal

Source: Dragovic, B. Ryoo, D.K. Park, N.K and Radmilovic, Z (2007). Container ship development: a review of state-of-the-art. *Proceedings of IAME annual conference*, Athens. Greece.

The evolvement of shipping lines into logistics services:

Companies are concerned more and more about managing the supply chain. Instead of working with various parties, shippers tend to negotiate with a few global coverage providers who can provide integrated services with predetermined price. It will be easier for them to control all supply chain. The relationships between shipping lines and shippers have become closer. A survey of CI (11/2006) indicated that many shippers tend to choose direct contact with carriers instead of forwarders. Especially, more than 70% shippers in the survey want ocean carriers to execute their supply chain on a door-to-door basis. There are many opportunities for shipping lines to expand logistics services.

With carriers, the potential cost-saving in sea-leg become smaller. Increasing ship size from 1,000 TEU to 2,000 TEU saves 20% transport unit cost, the rate is 7% from 4,000 TEU to 6,000 TEU and only 4% from 4,000 TEU to 6,000 TEU. Beyond 8,000 TEU, the saving is rather small, only 2% ($4 per TEU). (Stopford, 2002, pp 8-9). Carriers are pressed to find solutions elsewhere. (Notteboom, 2004, p 92). Cariou (2001, 2004), Haralambides et al (2002), Midoro et al (2005), Slack & Fremont (2005), Oliver (2005) and Oliver et al (2007) studied the vertical integration process of carriers into terminal operations. Heaver et al (2001), Heaver (2002), Junior et al (2003), Parola et al (2006) and Fremont (2006) went further with the entry into the international logistics market of shipping lines which extend their activities beyond sea-side.

Providing a logistics service can increase a shipping lines's service, approach closer with customers, on the other hand, they can reduce cost by using shared resources, better combination and control among integrated chain. The levels of entry into the logistics activities of shipping lines are different. Some of them go directly into logistics activities through subsidiaries (e.g. Maersk, NYK, K-line), or simply a part of this activities by keeping close relationship with freight forwarders (e.g. Evergreen, MSC). In any case, they are increasingly involved with the supply chain. A liner shipping network can not stand alone but becomes a component of an overall logistics network.

Inland cost accounts for a much larger portion in total cost than sea-transport cost, their portion could range from 40% to 80%. (Notteboom, 2002, p 5). Landside operation has become a main interest of shipping lines. Load centres are competitive if they have a good inland and relay connection. Scale economies of ship size can only be exploited if there is the guarantee about terminal efficiency as well as reliable connection with hinterland. There is the interdependence between liner shipping and hinterland networks. The efficiency and economy of overall chain depend upon the combination between two above networks. Notteboom (2002, 2004) gave prominence to the combination in designing an optimal network. He suggested basic combination models between 7 types of liner services and 4 types of hinterland services.

Parola et al (2006) studied liner network restructuring in Asia as a consequence of the change in logistics system. They noted that the changes of economic environment, especially the shift of many mobile, automobile, machinery and high-tech electronics manufactures from Japan, Korea to China, have influence the logistics network in this region. Chinese ports such as Shanghai, Qingdao, Tianjin have replaced some other ports in the role of regional distribution centers. To cope with the needs of customers, the shift of cargo flows, especially the restructuring of logistics networks, carriers have adjusted shipping routes. Some routes have deviated from Taiwan, Japan to new logistics platforms in China. These movements are described clearly in the below figure.

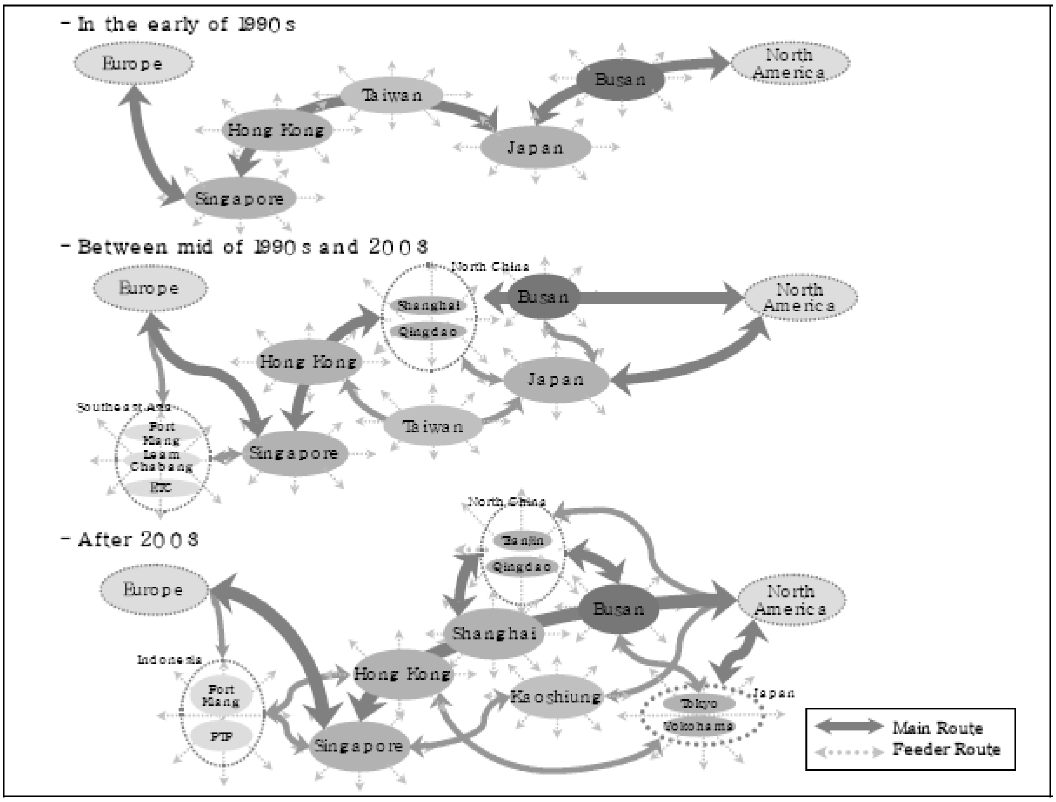


Figure 7: The trend of shipping routes in the Far East

Source: Parola, F. Lee, S.W. Ferrari, C. (2006). Economic integration and logistics restructuring: Rising opportunities for shipping lines in East Asia. *Proceedings of IAME Conference.* Melbourne, Australia.

2.2 Economic models applied in solving liner network problems

Much research has focused on solving liner network matters. In this section, we divide them into three groups. The first group studies factors which influence to the decisions of port choice from various directions: carriers, shippers, forwarders…Analytic hierarchy process and multinomial logit are two main models using in analysing factors. The second concentrates on choosing hub ports, mainly by cost models. The last concerns with designing routes with problems such as port calls, port sequences, service patterns, fleet deployment, empty container in a network. In this group, many different kinds of models are applied, the majority of them are based on linear and non-linear programming.

Port selection factors:

Analytic hierarchy process (AHP) introduced by Saaty has evolved into a flexible and popular method for decision-making in many fields. (Wedley et al, 2001, p 1). This method has been applied recently to evaluate and quantify important port criteria. These criteria can be the basis for assessing port attractiveness.

After two rounds of the Delphi survey, Lirn et al (2004) determined 4 major criteria and 12 sub criteria used in selection of transshipment ports. The next surveys occured with two groups: global carriers and major world ports. They had the agreement of the priorities of major criteria: carrier’s cost, geographical location, physical & technical infrastructures and port management and administration. With sub criteria, there are some differences between them. Song and Yeo (2004) studied the competitiveness of Chinese ports from the view of shipowners, shippers, port operators and researchers. Four most influential factors were selected and quantified: Port location, port facility, cargo volume and service level. The result was also applied to evaluate Chinese ports. HongKong was the most competitive, then Shanghai and Yantian. The criteria, assessment between two above researches are not alike. This can be because of the difference of main objectives, perspectives, interviewees. However, in both cases, location is always considered the most significant. A good location is a big advantage for a port to attract shipping lines.

Guy and Urli (2006) adapted the criteria as well as their weights from the research of Lirn et al (2004) to analyse the port choice of a global carrier between Montreal and New York. They changed the factor weights to be suitable for different objectives of carriers. Transit cost and turn-around time factors are also altered to observe the fluctuation with different port performances. Totally, there are 49 scenarios in their model. New York is mostly preferable choice. To be selected, Montreal must have a big advantage in port performances. Ugboma et al (2006) studied the port selection behaviour of Nigierian shippers. There were six criteria used in their model, among them, port efficiency and frequency of ship visits were the most prioritised. Based on these criteria, Lagos Port Complex was evaluated to be the most preferred whereas Roro port was the least. The research finding indicated key factors for ports to improve their attractiveness. With carriers, they could find appropriate port calls to satisfy shippers's requirements. An advanced version of AHP, fuzzy multiple criteria decision making method (FMCDM), was used by Chou (2007) for solving marine transshipment container port selection problems in Taiwan.

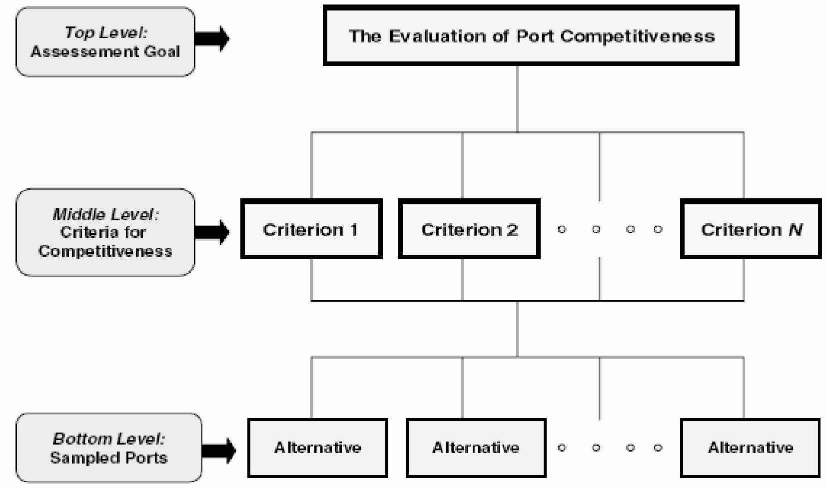


Figure 8: Analytic hierarchy process

Source: Song, D.W and Yeo, K.T. (2004). A competitive analysis of Chinese container ports using the Analytic hierarchy process. *Maritime Economics & Logistics, 6,* 34-52.

The multinomial logit model (MLM) provides a functional form for a discrete choice probability of an alternative. Some papers have adapted this model in assessing the impact of other factors on port choice decision. Malchow (2001) and Malchow & Kanafani (2001) studied how carriers selected ports for their shipments. Of the four variables in their models, oceanic distance and inland distance had significant impact whereas sailing frequency and vessel capacity were not so important. Veldman & Buckman (2003) and Veldman et al (2005) went into details the influence to market share of West European container hub ports of some policies, projects such as Maasvlakte-2 or deepening the Scheldt river. Tiwary et al (2003) suggested 14 port-carrier alternatives in their model to explore Chinese shippers's behaviour. Distance from destination (export cargo), distance from origin (import cargo), port congestion, shipping lines's fleet size affect a lot to the choice of shippers. Although coming from a different size, there is the similarity between this work and those of Malchow (2001) and Malchow & Kanafani (2001) about the effects of oceanic and inland distance to cargo flows.

Also considering key factors which influence port attractiveness, Hong & Menachof (2004) addressed by another approach, a system dynamics model. Three major factors: port revenue, port investment and competitive port investment were simulated in their model to find out about the relative attractiveness as well as the eligibility of new investment of port of Busan. Ng (2006) investigated North European container transshipment port through a Likert-style questionnaire directed towards the top 30 shipping lines. Besides monetary cost, time efficiency, geographical location and service quality should also be taken into consideration when explaining port attractiveness. Tzong (2001) surveyed forwarders from Malaysia, Thailand and Singapore to observe the tendency in port choice. A regression analysis asserted the high correlation between a port's throughput and three most important factors: port efficiency, shipping frequency and port infrastructure. In this case, port location does not play an important role as others

(Lirn et al, 2004; Song and Yeo, 2004). The author argued that a port with disadvantage location could compensate it by higher efficiency and infrastructure.

Hub port selection:

Baird (2001) expanded the containership cost model of Cullinane & Khanna (1999) to compare Hubportship and Multiportship total shipping cost on the Europe-Asia route. Francesetti & Foschi (2002) analyzed the viability of hub and spoke system in the Mediteranean by applying Baird’s model with some adjustments on Mediteranean – Far East itinerary. By changing ship size from 4,000 TEU to 10,000 TEU, both of works have the same result that hub and spoke system has smaller total cost compared with point to point sytem, however the difference tends to be noticeable mitigated when ship size goes up. The sensitivity analysis of Francesetti & Foschi indicated that handling tariff, crane productivity and captive cargo of a hub port had a big impact on the economics of hub and spoke system.

Two later papers of Baird (2002, 2005) supported Orkney (UK) as a new transshipment port in North Europe. By using mainline vessel “deviation cost” model, he indicated cost saving of carriers when using a new hub. The former paper focused on the comparison between a single hub and multi port calls in Northern Europe whereas the latter mainly concerned which port was the best choice for a single hub.

Applying P-hub median problem, Aversa et al (2005) created a mixed integer programming model for selecting a hub port in North America. In this model, Santos (Brazil) was the best choice. The model took into account of port costs (dues and terminal handling charges), shipping costs (feeder, mainline), inland transport costs, tried to find a solution with minimum cost. Some simulations were also taken to studied in which conditions a port can become a hub port, the change of total cost when increasing the number of hub port. However, this model didn’t concern with inventory cost which can partly explain why total cost always declines when the number of hub port goes up.

Zijian and Hong (2001) used theory of neural network to set up and optimize a hub and spoke system in Chinese ports. Zeng & Zang (2002) designed Chinese container network as a hierarchized system embracing four levels: hinterlands, feeder ports, feeder hubs and trunk hub. Dynamic programming was employed to determine hub ports of each level.

Route design:

Lane et al (1987) presented a dynamic cost-based model for providing liner services to serve some trade routes with the aim to minimize total costs of operating cost, port cost and inventory cost. The model not only took into account voyage options but also fleet deployment in each option. The constraint is it is only applicable for end to end route, not suitable for patterns concerning transhipment activities.

Perakis and Jaramillo (1991) developed a linear programming model for fleet deployment to minimize total operating and lay-up costs. This model was implemented by Jaramillo and Perakis (1991) based on the fleet and routing data from a large liner company, Flota Mercate Grancolumbiana (FMG). A drawback of this model is the number of ships allocated in routes in some cases is non-integer numbers. It requires the rounding of these numbers which makes deviate final results. Powell and Perakis (1997) introduced an integer programming model which has eliminated rounding errors of previous works. Also involving with ship assignment, Mourao et al (2001) put their model under constraints of hub and spoke about ship schedule.

Cho and Perakis (1996) suggested the concept of flow-route incident matrix which was used very efficiently in two optimisation models. One is linear programming model of profit maximization. It could be used to select routes, service frequencies in the constraints of fleets. The second is a mixed integer programming model with binary variables involving with new ship investment to meet expected increasing demand in some ports. The objective is to minimize cost including operating cost, lay-up cost and capital cost.

Fagerholt (2004) considered the problem of deciding weekly liner routes as a multi-trip vehicle routing problem. There are two phases addressed to solve this problem. Phase 1 generates all feasible routes together with their duration and cost for each ship by using Travelling Salesman Problem (TSP). In phase 2, integer programming is applied to choose optimal routes in the constraint of fleets with the objective to minimize total transportation cost and ensure all demands in ports are served.

There is always a conflict between carrier's cost and customer's cost. A service with high quality can take advantage for shippers, on the other hand, shipping cost will increase. A complete optimal solution which aims to minimize both of them can not exist. Imai and Papadimitriou (1997) tried to find a set of noninferior solutions for routing problem (included primary and secondary route, hub or feeder port, ship size) by a multiobjective model. From this set, they realized solutions which could be accepted by cost objectives of both carriers and shippers. Hsu and Hsieh (2005) found a Pareto optimal solution (POS) in their two-objective model based on trade-off between these costs. By comparing POSs between different routes, they determined the cargo from an origin port should be transhipped or carried directly to a destination. This model has been enhanced and generalized in their later work. (Hsu and Hsieh, 2007). Authors have also made sensitive analyses to study the effect of charges and efficiency of a hub port to routing decision. Fagerholt (2000) addressed the relationship between transportation cost and service level involving with time window of cargo in ship scheduling and routing problem. Hard time window in which the cargo must have been loaded or unloaded was transformed into soft time window. Operation outside hard time constraint would be penalized by inconvenience cost. By trade-off analysis between transportation and inconvenience cost, it is possible to find an appropriate service. Ting and Tzeng (2003) tried to design an optimal port sequences, vessel speed, and port operation. On the one hand, they satisfied port time constraint (including both hard and soft window), and on the other hand, yielded cost savings.

The network of Malacca-max was presented sophisticatedly by Wijnolst et al (2000). The ship would operate in Far East – Europe with some limited port calls. Some methods was applied to find the most appropriate hub ports including Rotterdam (North Europe), Gioia Toro (Mediterranean), Singapore and Hongkong (Asia). Imai & Mioajia (2004) and Imai et al (2006) studied the economic viability of container mega-ships. Game theory was used to find appropriate ship deployments (mega-ship or ordinary ship) and routing strategies (hub and spoke, pendulum or multi port call network) of shipping lines in the context of competition.

Almost all network models concentrate on one specific area, Song et al (2005) could be an exception with a model to solve a global network problem. They tried to figure out a cost-efficiency network of container shipping worldwide. With realistic input data, besides designed routes, the model could provide other results about incomes, costs of each shipping line; port incomes, utilization of services, each port’s total throughput and transshipment movements.

Lee et al (2006) developed a multicommodity flow model to predict variations of cargo flows among Asian ports with respect to port turnaround time, terminal handling charge, lank link efficiency. One salient feature of this model is that authors separated container flow by commodities which can give a more precise evaluation of inventory cost.

The imbalance trade among regions makes empty container distribution a problem of shipping lines. In designing container network, most paper focus on loaded container, few of them concern with empty container. Imai & Rivera (2001) dealt with fleet size planning for refrigerated containers taking into account emty container flow among ports as well as inside port hinterland. Ting and Tzeng (2004) planned optimal containership slot allocation (for loaded and empty container) in a pre-defined route. Shintani et al (2005) found an optimal route (set of calling ports and calling sequence) for cargo flow incorporating with the problem of repositioning and leasing of empty containers.

2.3 Conclusion

In this chapter, we have an overview of liner networks which are very diversified and complex due to the different characteristics of the regions. Together with the development of containerisation, especially the trend of using bigger vessels, transhipment ports have become more and more crucial in the entire system. However, the feasibility of the pure hub & spoke pattern, which depends on a small number of regional load centres, is still debatable. Multi port call routes are proven to be efficient, even in the case of mega vessels.

Traditionally, ports are only considered as the origin/destination of transport activities. The development of logistics has changed the view, ports now become nodes in logistics chains. Therefore designing liner networks should be put in the context of logistics networks. There are various studies involving with network problems, particularly route designs. Most of them focus on the sea leg with the most interest about transportation cost. There is a gap in the combination between liner shipping and the hinterland network. This is the direction that we will try to elaborate on.

This topic concentrates on an optimal liner network connecting both the sea and land network, the concern is not only the transportation cost for shipping lines but also the inventory cost on the side of shippers. The most appropriate method, especially with the routing problem in this case, is to build a mathematical model based on non-linear programming, with a heuristics approach for finding solutions.

The previous works of Imai & Papadimitriou (1997), Fagerholt (2004), Shintani et al (2005), Imai et al (2006), Aversa et al (2005) provide us with a good basis to set up a new model as well the use of heuristics algorithms. Besides, some previous results will be used to support for this model such as ship cost model, port cost and inland cost estimation from the studies of Wijnost et al (2000), Baird (2001), or Dong et al (2005).

Chapter 3 Model formulation

In the previous chapter, we have mentioned that it is essential to put liner networks inside logistics networks. Designing liner networks should combine with other components of logistics chains. Among a lot of factors, in the scope of this topic, we are concerned with three of them in the model: inland transport, sea transport and inventory of cargo in transport process. This chapter includes two main parts. In the first part, the port selection model based on non linear programming model is introduced. The second presents some algorithms for finding a solution to this model.

3.1 Problem description

Let two regions A and B be separated by sea. In our problem, we deal only with the import/export of cargo between two regions. Each region is divided into some hinterland areas. Flows of import/export cargo between a hinterland area in A and another in B have been classified. There are some ports in both regions which can be used to serve mainline ships. Our task is to organize the cargo transportation network, which involves not only sea transportation but also inland transportation.

Questions:

- Among candidate ports in two regions, which ports should be included in the itinerary of mainline ships?
- What is the sequence of port calls along a ship's route?
- With any cargo transportation demand (from an area in A to another in B or vice versa), which should be the loading and unloading ports?

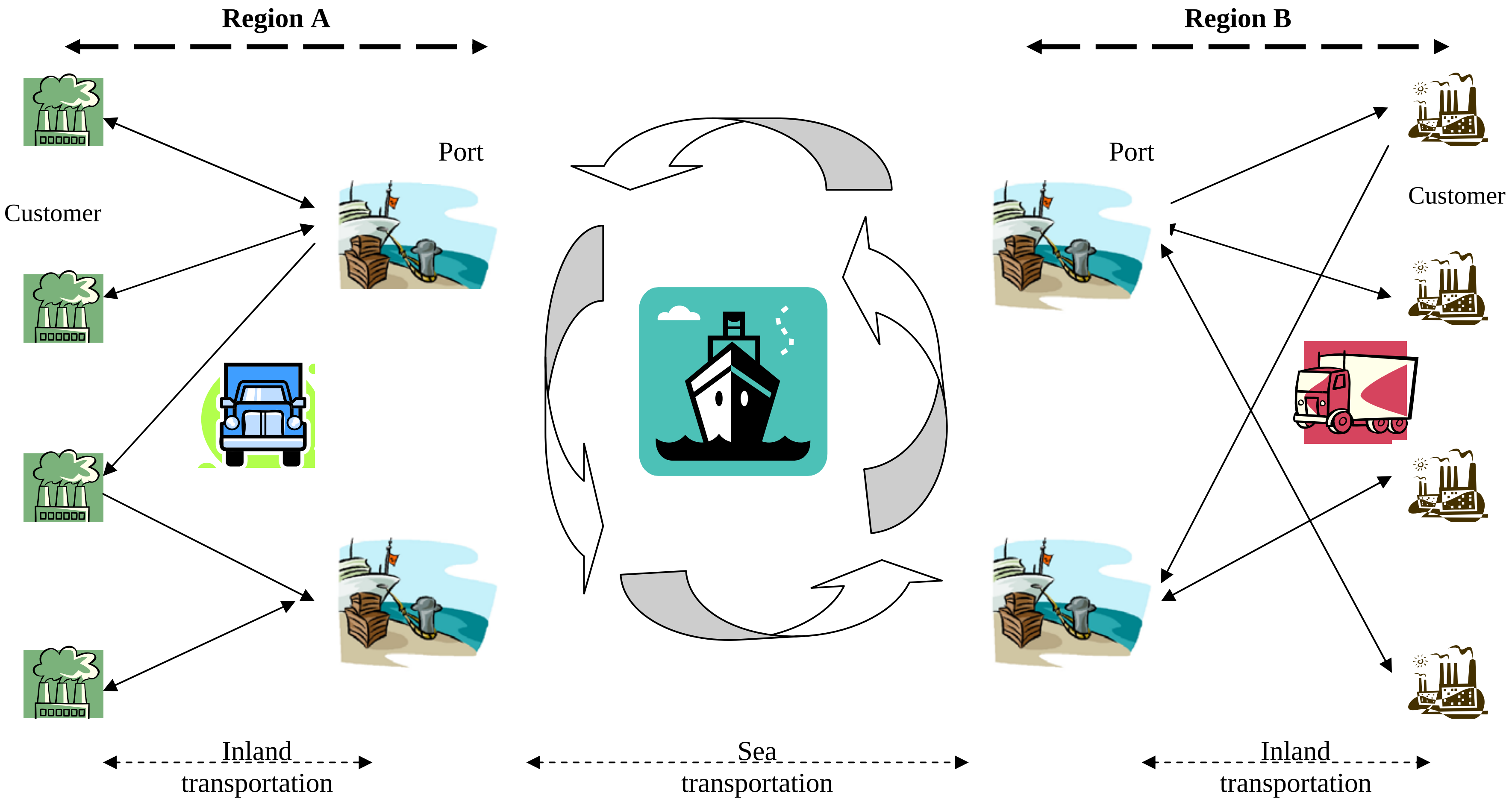


Figure 9: Transportation network in the model

Objective: minimum total transportation cost (sea cost and inland cost), port tariff (port due and handling charge) and inventory cost of cargo.

Assumptions:

- Liner service between A and B is end-to-end service. In a round voyage, a ship only calls a port maximum one time (no double-dipping). Besides, a ship will visit all ports in the same region before moving to other ports in another region.
- Ship size and number of voyages in a specific period of time are predetermined.
- Mainline ship is only concerned with cargo from A to B (and B to A), no domestic cargo (cargo between two areas in the same region).
- There is only one loading and one unloading port for cargo flow from area i to area j. (A to B or B to A).
- There is no limitation from the side of ports. Any candidate port can serve a mainline ship.
- In reality, port time includes waiting time (WT), manoeuvring time (MT) and berth time. In this study, we assume that WT is zero (berth window). With berth time, we only consider it with productive time. We calculate port time depending only on manoeuvring time together with loading and unloading time.
- Dwell time in the container yard will be reduced to the smallest level as possible. (just-in-time system). The containers will be transported to ports at the latest time accepted by ports and withdrawn as soon as possible.

3.2 Model formulation

Our problem deals with complex questions. The value of total cost is defined by variables: selected ports, port call sequence, loading and unloading port choices. Among them, there are a lot of interconnections, a change of one can possibly influence others. The relationships between total cost and these variables are not simply linear but much more complicated. Also, constraints can not be expressed by linear functions. The linear programming model (LPM) is rather simple, it is easy and takes less time to find a solution. However, in our case, it is impossible to build a model based on this kind of model due to the lack of linear conditions. Although extremely sophisticated, Non-LPM is the good option to construct our model.

3.2.1 Model variables

Input variables: their values are specified by input data.

N: number of hinterland areas in region A.

M: number of hinterland areas in region B.

Hinterland areas in A are numbered from 1 to N, areas in B from N+1 to N+M.

r[i]=1: area i belongs region A.

r[i]=0: area i belongs region B.

K: number of candidate ports in region A.

T: number of candidate ports in region B.

Ports in A are numbered from 1 to K, ports in B from K+1 to K+T.

p[i]=1: port i belongs region A.

p[i]=0: port i belongs region B.

Q[i,j]: number of TEUs from inland area i to inland area j in a specific period of time.

box[i,j]: number of containers from i to j in a specific period of time.

v[i,j]: average inventory cost per day per TEU for cargo from i to j. (unit: USD/hour/TEU).

OD: set of cargo flow. OD = {(i,j), Q[i,j] > 0}.

ship_size: the capacity of ship. (unit: TEUs).

voyage_number: number of round voyage in a specific period of time.

fuel_price: the price per tonne of HFO. (unit: USD per tonne).

port_due[i]: port due (ship due, pilotage, towage …) per ship call in port i. (unit: USD/ship).

THC[i]: terminal handling charge in port i. (unit: USD/move).

handling_rate[i]: handling rate in port i. (unit: moves per hour)

pre_dwell[i]: minimum dwell time of cargo (time in container yard) before ship operation. (unit: hours)

post_dwell[i]: minimum dwell time of cargo after ship operation. (unit: hours)

MT[i]: manoeuvring time per entry/exit in port i. (unit:hours)

distance[i, j]: the distance between port i and port j. (unit: miles).

inland_cost[i, s]: inland transportation cost per TEU between area i and port s. (unit: USD/TEU).

inland_time[i, s]: inland transportation time between area i and port s. (unit: hours).

Decision variables: Their values influence the result of this model, these are the values we need to find.

load[i, j, s] = 1: a shipment from i to j will be loaded by port s
or else load[i, j, s] = 0

unload[i, j, d] = 1: a shipment from i to j will be unloaded by port d
or else unload[i, j, d] = 0

select[i] =1: port i is selected in ship's route, or else select[i] = 0.

next[i, j] =1: after port i, port j will be the next call in ship's round voyage or there is an one-way sea connection from port i to port j. Otherwise next[i,j] = 0.

Intermediate variables: These variables are calculated based on variables in two above groups. The purpose of using these variables is to support the calculation process by making it simple and clear.

hubA: set of selected hub port in region A.

hubA = {i: P[i]=1, hub[i]=1}

hubB: set of selected hub port in region B.

hubB = {i: P[i]=0, hub[i]=1}

hub: set of selected hub port in both regions: hub = hubA $\cup$ hubB.

v: ship speed. (unit: knots per hour). This speed is determined based on ship size with a formula of Wijnolst et al (2000): $v = 5.4178 * \text{ship\_size}^{0.1746}$

ExpA: Total loading cargo in region A per voyage (unit: TEUs).

ExpB: Total loading cargo in region B per voyage (unit: TEUs).

$$\text{ExpA} = \frac{\sum_{i=1}^{N} \sum_{j=N+1}^{N+M} Q[i,j]}{\text{voyage\_number}} \qquad \text{ExpB} = \frac{\sum_{j=N+1}^{N+M} \sum_{i=1}^{N} Q[j,i]}{\text{voyage\_number}}$$

Time variables

port_time[t]: total time ship spends in port t, includes manoeuvring time and unloading and loading time. (unit: hours).

port_time[t] =2*MT[t]+

$$\frac{\sum_{(i,j)\in OD} \text{box}[i,j] * \text{load}[i,j,t] + \sum_{(i,j)\in OD} \text{box}[i,j] * \text{unload}[i,j,t]}{\text{handling\_rate}[t] * \text{voyage\_number}}$$

sailing_time[s,d]: total time the ship spend at sea when sailing from port s to port d. (unit: hours).

$$\text{sailing\_time}[s,d] = \sum_{i\in R} \sum_{j\in R} \frac{\text{distance}[i,j] * \text{next}[i,j]}{2 * v}$$

R: set of port in the voyage from s to d.

$$\begin{cases} \sum_{j\in R} \text{next}[i,j] = 1 \qquad \forall i \in R - \{d\} \\ \text{/* Except } \mathbf{d}\text{, each port has exactly one port after it in the voyage from } \mathbf{s} \text{ to } \mathbf{d} \\ \sum_{i\in R} \text{next}[i,j] = 1 \qquad \forall j \in R - \{s\} \\ \text{/* Except } \mathbf{s}\text{, each port has exactly one port before it in the voyage from } \mathbf{s} \text{ to } \mathbf{d} \end{cases}$$

mainline_time[s,d]: time from a ship arrives port s until it leaves port d. It includes the sailing time between ports as well as the time a ship spends in ports on the voyage from port s to port d. (unit: hours).

$$\text{mainline\_time}[s,d] = \text{sailing\_time}[s,d] + \sum_{i \in R} \text{port\_time}[i]$$

time[i, j]: total time for a shipment, from cargo leaves area i until arriving area j. More details of the time component are described in the figure below. (unit: hours).

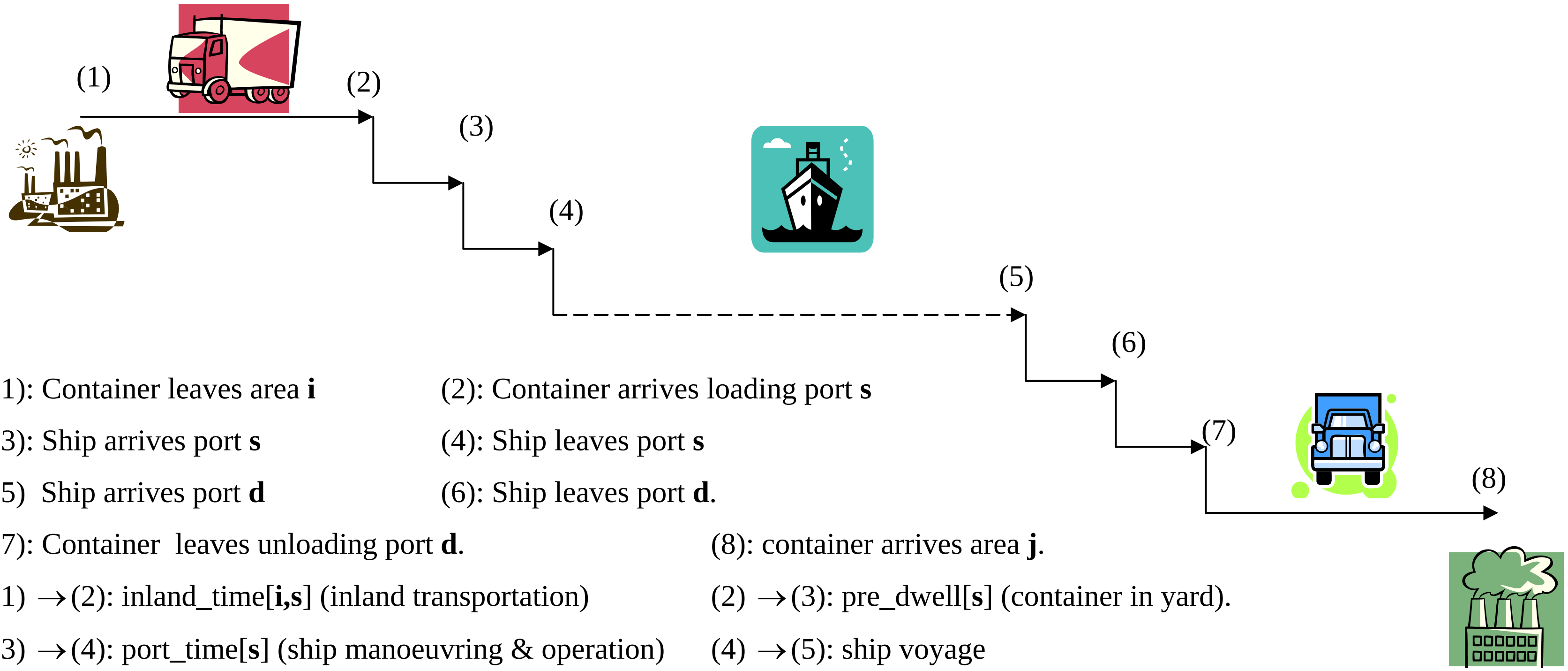
$$\text{time}[i, j] =$$

$$\sum_{s \in hub} \text{inland\_time}[i, s] * \text{load}[i, j, s] + \sum_{s \in hub} \text{pre\_dwell}[s] * \text{load}[i, j, s]$$

$$+ \sum_{s \in hub} \sum_{d \in hub} \text{mainline\_time}[s, d] * \text{load}[i, j, s] * \text{unload}[i, j, d]$$

$$+ \sum_{d \in hub} \text{post\_dwell}[d] * \text{unload}[i, j, d] + \sum_{d \in hub} \text{inland\_time}[j, d] * \text{unload}[i, j, d]$$

Figure 10: Time line of cargo flow from area i to area j.



(1): Container leaves area **i**

(2): Container arrives loading port **s**

(3): Ship arrives port **s**

(4): Ship leaves port **s**

(5) Ship arrives port **d**

(6): Ship leaves port **d**.

(7): Container leaves unloading port **d**.

(8): container arrives area **j**.

(1) →(2): inland_time[**i,s**] (inland transportation)

(2) →(3): pre_dwell[**s**] (container in yard).

(3) →(4): port_time[**s**] (ship manoeuvring & operation)

(4) →(5): ship voyage

(5) →(6): port_time[**d**] (ship manoeuvring & operation)

(6) →(7): post_dwell[**d**] (container in yard)

(7) →(8): inland_time[**j,d**] (inland transportation)

(3) →(6): mainline_time[**s, d**]

(1) →(8): time[**i, j**] (total time for cargo voyage)

voyage_time: total time for a round voyage. It embraces time a ship spends at sea and turnaround time in port.

$$\text{voyage\_time} = \sum_{i\in hub}\sum_{j\in hub}\frac{\text{sailing\_time}[i,j] * \text{next}[i,j]}{2} + \sum_{i\in hub}\text{port\_time}[i]$$

Cost variables

total_inland_cost[i,j]: inland transportation cost for cargo flow from **i** to **j** with two components: inland cost from area **i** to loading port **s**, and from unloading port **d** to area **j**. (unit: USD).

total_inland_cost[i, j] =

$$Q[i,j] * \left(\sum_{s\in hub}\text{inland\_cost}[i,s] * \text{load}[i,j,s] + \sum_{d\in hub}\text{inland\_cost}[i,s] * \text{unload}[i,j,d]\right)$$

tariff[t]: port tariff in port **t** per ship call. It includes port dues for ship and handling cost for cargo. (unit: USD).

total handling cost in port **t** =

$$\frac{\sum_{(i,j)\in OD}\text{box}[i,j] * \text{load}[i,j,t] + \sum_{(i,j)\in OD}\text{box}[i,j] * \text{unload}[i,j,t]}{\text{voyage\_number}} * \text{THC}[t]$$

tariff[t] = port_due[t] + total handling cost in port **t**.

ship_cost: cost per day for ship operation during sailing time and port time. (unit:USD/ day). In this model, we consider time charter rate (TCR) and fuel cost (FC) in ship cost. The calculations of these costs are adapted from the model of Wijnolst et al (2000).

$\text{TCR} = 108.05 * \text{ship\_size}^{0.6257}$ (unit: USD/ day).

FC = fuel_price * (0.0392*ship_size + 5.582) (unit: USD/ day).

TSC: total ship cost in a voyage. (unit: USD). TSC = ship_cost * voyage_time

TPC: total port tariff in a voyage. (unit: USD). $\text{TPC} = \sum_{t \in \text{hub}} \text{tarrif}[t]$

TLC: total inland transportation cost for all shipments to port/ from port serving for a voyage. (unit: USD).

$$\text{TLC} = \frac{\sum_{(i,j) \in OD} \text{total\_inland\_cost}[i, j]}{\text{voyage\_number}}$$

TIC: total inventory cost for all shipments in a voyage. (unit: USD).

$$\text{TIC} = \frac{\sum_{(i,j) \in OD} Q[i, j] * V[i, j] * \text{time}[i, j]}{\text{voyage\_number}}$$

3.2.2 Non linear programming model

<u>Objective</u>:

Minimum total cost TC = TSC + TPC + TLC + TIC

<u>By changing *binary* variables:</u>

load[i, j, s]	i = 1 .. N+M; j= 1 .. N+M; s = 1.. K+T.
unload[i, j, d]	i = 1 .. N+M; j= 1 .. N+M; d = 1.. K+T.
select[i]	i = 1 .. K+T.
next[i, j]	i = 1 .. K+T, j = 1 .. K+T.

<u>Subject to constraints:</u>

$$\sum_{i=1..K} \text{select}[i] \geq 1 \qquad (1)$$

/* *at least one port in region A must be selected.*

$$\sum_{i=K+1..K+T} \text{select}[i] \geq 1 \qquad (2)$$

/* *at least one port in region B must be selected.*

$$\sum_{j \in hub} \text{next}[i,j] = 1 \qquad \forall\, i \in hub \qquad (3)$$

/* *each selected port has exactly one port after it in the voyage.*

$$\sum_{i \in hub} \text{next}[i,j] = 1 \qquad \forall\, j \in hub \qquad (4)$$

/* *each selected port has exactly one port before it in the voyage.*

$$\text{next}[i,i] = 0 \qquad \forall\, i = 1..\, K+T \qquad (5)$$

/**no self- connection from a port to itself.*

$$\sum_{j=1..K+T} \text{next}[i,j] = 0 \qquad \forall\, i \notin hub \qquad (6)$$

/* *non-selected port has no one-way sea connection with other ports.*

$$\sum_{i=1..K+T} \text{next}[i,j] = 0 \qquad \forall\, j \notin hub \qquad (7)$$

/* *no port has one-way sea connection with non-selected ports.*

$$\sum_{i \in hubA} \sum_{j \in hubA} \text{next}[i,j] = \sum_{i \in hubA} \text{select}[i] - 1 \qquad (8)$$

/* *the ship will call all selected port in region A, one of them has one-way sea connection with a selected port in region B.*

$$\sum_{i \in hubB} \sum_{j \in hubB} \text{next}[i,j] = \sum_{i \in hubB} \text{select}[i] - 1 \qquad (9)$$

/* *the ship will call all selected port in region B, one of them has one-way sea connection with a selected port in region A.*

$$\sum_{s \in hub} \text{load}[i,j,s] = 1 \qquad \forall\, (i,j) \in OD \qquad (10)$$

/* *cargo from i to j is loaded by exactly one port*

$$\sum_{s \in hub} load[i,j,s] * (1 - |r[i] - p[s]|) = 1 \quad \forall\ (i,j) \in OD \tag{11}$$

/* *origin i and loading port s are in the same region.*

$$\sum_{d \in hub} unload[i,j,d] = 1 \quad \forall\ (i,j) \in OD \tag{12}$$

/* *cargo from i to j is unloaded by exactly one port*

$$\sum_{d \in hub} unload[i,j,d] * (1 - |r[j] - p[d]|) = 1 \quad \forall\ (i,j) \in OD \tag{13}$$

/* *destination j and unloading port d are in the same region.*

$$\sum_{s \notin hub} load[i,j,s] = 0 \quad \forall\ (i,j) \in OD. \tag{14}$$

/* *non-selected ports are not loading ports for any shipment.*

$$\sum_{d \notin hub} load[i,j,d] = 0 \quad \forall\ (i,j) \in OD. \tag{15}$$

/* *non-selected ports are not unloading ports for any shipment.*

$$\sum_{s=1..K+T} load[i,j,s] = 0 \quad \forall\ (i,j) \notin OD \tag{16}$$

/* *there is no loading port for any pair (i,j) with no cargo transportation demand,.*

$$\sum_{d=1..K+T} load[i,j,d] = 0 \quad \forall\ (i,j) \notin OD \tag{17}$$

/* *there is no unloading port for any pair (i,j) with no cargo transportation demand.*

$$\text{ExpB} + \sum_{s \in R_k} \left(\frac{\sum_{(i,j) \in OD} Q[i,j] * \text{load}[i,j,s]}{\text{voyage\_number}} - \frac{\sum_{(i,j) \in OD} Q[i,j] * \text{unload}[i,j,s]}{\text{voyage\_number}} \right) \leq \text{ship\_size}$$

$\forall\, k \in \text{hubA}$ **(18)**

R_k: set of ports in region A a ship visits from the first port to port **k** in the voyage.

/ volume of cargo a ship carries is always equal or less than ship capacity.*

$$\text{ExpA} + \sum_{s \in R_k} \left(\frac{\sum_{(i,j) \in OD} Q[i,j] * \text{load}[i,j,s]}{\text{voyage\_number}} - \frac{\sum_{(i,j) \in OD} Q[i,j] * \text{unload}[i,j,s]}{\text{voyage\_number}} \right) \leq \textbf{ship\_size}$$

$\forall\, k \in \text{hubB}$ **(19)**

R_k: set of ports in region B a ship visits from the first port to port **k** in the voyage.

/ volume of cargo a ship carries is always equal or less than ship capacity.*

3.3 Solution algorithm

We have proposed a non linear programming (NLP) model for the network problem. The next step, which is very important, is to find the solution. There is some specialized software for solving the NLP model, in that, Solver in Excel is perhaps one of the most popular. The restriction is that there is no software which is efficient or suitable for all kinds of NLP models.[2] There are limits about the number of decision variables and constraints in these softwares. The standard Microsoft Excel Solver has a limit of 200 decision variables, 100 constraints. With Premium Solver Platform, these numbers are 500 and 250. A powerful software, Large-Scale GRG Solver can handle up to 12,000 variables and 12,000 constraints.[3] These limits are rather small compared with our expectation. Besides, our model constraints are very complex and not easy to perform on software interfaces. Therefore, it is better to construct a computer program in a programming language to find the solution. The program can be designed to meet the particularities of the model which makes it very efficient and appropriate for this

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[2] http://www-unix.mcs.anl.gov/otc/Guide/faq/nonlinear-programming-faq.html#Q2
[3] http://www.solver.com/technology4.htm

specific case. In any programming language, the success of a program depends absolutely on the algorithm. In a later part, we will demonstrate some algorithm approaches to our problem.

Table 2: Estimate the number of decision variables in the model

Region A		Region B		Number of decision variables
Number of hinterlands	Number of candidate ports	Number of hinterlands	Number of candidate ports	
5	2	5	2	820
10	5	10	5	8,110
15	5	15	5	18,110
20	5	20	5	32,110
25	5	25	5	50,110
30	5	30	5	72,110
35	5	35	5	98,110
40	5	40	5	128,110
45	5	45	5	162,110
50	5	50	5	200,110
60	5	60	5	288,110
70	5	70	5	392,110
80	5	80	5	512,110
90	5	90	5	648,110

Source: Calculated by the author

3.3.1 Approach 1

Our problem belongs to the NP (nondeterministic polynomial) class which has no efficient algorithm. One simple approach for solving it is to use a brute-force algorithm, a straightforward method in optimization problem. By applying this method, we try to enumerate all possible solutions, deciding afterwards which solution is the best.[4]

The brute-force algorithm can be described in 4 steps:

Step 1: Generation

In our model, each state of network is specified by values of decision variables in 4 groups: select[i] (ports in the voyage), next[i,j] (port call orders), load[i,j,s] and unload[i,j,d] (direction of cargo between inland points and ports). The combination of values from these variables will generate all states of network. Decision variables are

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[4] http://www.vias.org/tmdatanaleng/cc_optim_meth_brutefrc.html

binary, by changing their values (0 or 1) we create all possible solutions (totally 2^x possibilities, with x: the number of decision variables).

Step 2: Checking

With each possible solution created above, we check whether it satisfies all constraints of the model or not. If yes, go to step 3.

Step 3: Total cost calculation

After the two above steps, we have selected ports on a ship's voyage, the sequence of port call, loading and unloading port of each shipment from area i to area j. Combined with input information, we can calculate the total cost for each shipment, then for all shipments.

Step 4: Update

If the total cost of a solution is smaller than our record, we update the new record and new optimal solution.

This enumeration method is rather simple to implement, and of course, it can ensure the optimal solution. However, the number of possible states is very large and increases exponentially with the number of decision variables. It requires a lot of calculations and time for solving. For example, with a case including 8,110 decision variables (in the figure above), the number of possibilities are $2^{8,110}$. In a computer with a processor Intel Core 2 Duo, it can execute approximately 250 million calculations per second.[5] Assuming that each solution needs 10,000 calculations, it means that every day, a computer can only deal with about 2.16 billion solutions (less than 2^{32}). It takes million of years to finish our model making it impossible to apply this algorithm.

3.3.2 Approach 2

The previous approach tries to enumerate solution space, then *checks* the suitability with model constraints. In the second approach, we come from another direction

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[5] Tested directly in computer with a processor Intel Core 2 Duo.

although the main idea is also from a brute-force algorithm. We will try to generate solution space which *satisfies* constraints. This approach will help reduce a lot of possible solutions as well as calculations.

Step 1: Port selection

In this step, we create all possibilities of port choice in region A and region B. This step is rather similar to the first step in approach 1. However, we only consider with port choice, more specifically, values of decision variables select[i]. In region A, there is 2^K – 1 possibilities of port choice, [6] in region B, it is 2^T – 1. Totally, there are (2^K – 1) * (2^T – 1) possible solutions for *port selection* in both regions. Table 3 illustrates all cases of port choice when each region has 4 candidate ports (15 cases per region). Combining port choice in two regions, we have 225 (15*15) ways to select port in ship's voyage.

Table 3: Set of port choice solutions

Region A				Region B			
	Port choice		Port choice		Port choice		Port choice
1	1	9	2	1	5	9	6
2	1,2	10	2,3	2	5,6	10	6,7
3	1,2,3	11	2,3,4	3	5,6,7	11	6,7,8
4	1,2,3,4	12	2,4	4	5,6,7,8	12	6,8
5	1,2,4	13	3	5	5,6,8	13	7
6	1,3	14	3,4	6	5,7	14	7,8
7	1,3,4	15	4	7	5,7,8	15	8
8	1,4			8	5,8		

Source: calculated by the author

Step 2: Port call sequence

With each solution of port choice, this step will enumerate all possible sequences of port calls (values of next[i,j]). A port call order in a region is a permutation of selected ports. Assumed that in a particular state, we select x ports in region A, y ports in region B. We have x!*y! solutions for ship voyage in this port choice state. With all cases from Table 3, we have totally 4,225 voyage solutions. Table 4 figures out all port sequences with selected ports in region A: (1, 3, 4); region B: (5, 8) whereas table 5

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[6] In region A, there are K candidate ports, we have 2^K ways to select port. There is one case, when no port is selected, which does not satisfy our constraint, so there are only 2^K -1 satisfied possibilities.

indicates all possible voyages of a ship which are the combinations between port orders in region A and region B.

Table 4: Set of port sequence solutions each region in a particular state

Region A		Region B	
1	1→3 →4	1	5→8
2	1→4 →3	2	8→5
3	3→1 →4		
4	3→4 →1		
5	4→3 →1		
6	4→1 →3		

Source: calculated by the author

Table 5: Set of ship voyage solutions

1	1→3 →4→5→8→1	7	3→4 →1→5→8→3
2	1→3 →4→8→5→1	8	3→4 →1→8→5→3
3	1→4 →3→5→8→1	9	4→3 →1→5→8→4
4	1→4 →3→8→5→1	10	4→3 →1→8→5→4
5	3→1 →4→5→8→3	11	4→1 →3→5→8→4
6	3→1 →4→8→5→3	12	4→1 →3→8→5→4

Source: calculated by the author

<u>Step 3</u>: Selection of loading and unloading port

After steps 1 and 2, we can determine all possible ship voyages. The last task is to arrange the loading and unloading ports for cargo flow from i to j from the group of port choice in each region. (values of load[i, j,s] and unload[i,j,d]). With each particular ship voyage (x ports in region A, y in region B), there are x*y ways to select a pair of loading and unloading ports for a shipment (from A to B or B to A). Table 6 presents all possibilities of loading and unloading ports of a shipment from A to B from selected ports (1, 3, 4, 5, 8). After this step, we have all possible solutions which satisfy model constraints.

Table 6: Set of possible loading and unloading ports for a shipment from A to B

	Loading port (A)	Unloading port (B)
1	1	5
2	3	8
3	4	5
4	1	8
5	3	5
6	4	8

Source: calculated by the author

Step 4: Checking

After step 3, we have created possible solutions satisfying all constraints about selected port, route and inland connection (constraints from 1 to 17). There are only two last constraints which need checking. These are constraints ensuring that volume of cargo transported is always within the limit of ship capacity. If a solution satisfies them, we go to step 5.

Step 5: Total cost calculation - It is the same as Step 3 in the previous approach.

Step 6: Update - It is the same as Step 4 in the previous approach.

Compared with the previous algorithm, this one can reduce solution space a lot. In the circumstances with 5 ports, 10 hinterland areas in each region, the previous method must assess $2^{8,110}$ solution possibilities whereas this number is about 2^{122} with the second. The second approach is much more efficient. Nevertheless, the size of solution space is still very huge which limits the implementation.

Number of possible solutions = $\sum_{x=1}^{K}\sum_{y=1}^{T}\frac{K!}{(K-x)!}*\frac{T!}{(T-y)!}*D^{X*Y}$

K: number of candidate ports in region A.

T: number of candidate ports in region B.

x: number of selected ports in region A.

y: number of selected ports in region B.

D: number of shipments from A to B or B to A.

$\frac{K!}{(K-x)!}*\frac{T!}{(T-y)!}$: number of possible voyages with x ports in A, y ports in B.

D^{X*Y}: number of possible loading and unloading ports for all D shipment with x ports in A, y ports in B.

It is better if we use a heuristic approach based on this algorithm to find a good solution. The result can not be the optimality but it can be acceptable and feasible to be found. In routing studies, heuristic method is the most popular way scholars use to solve their problems.

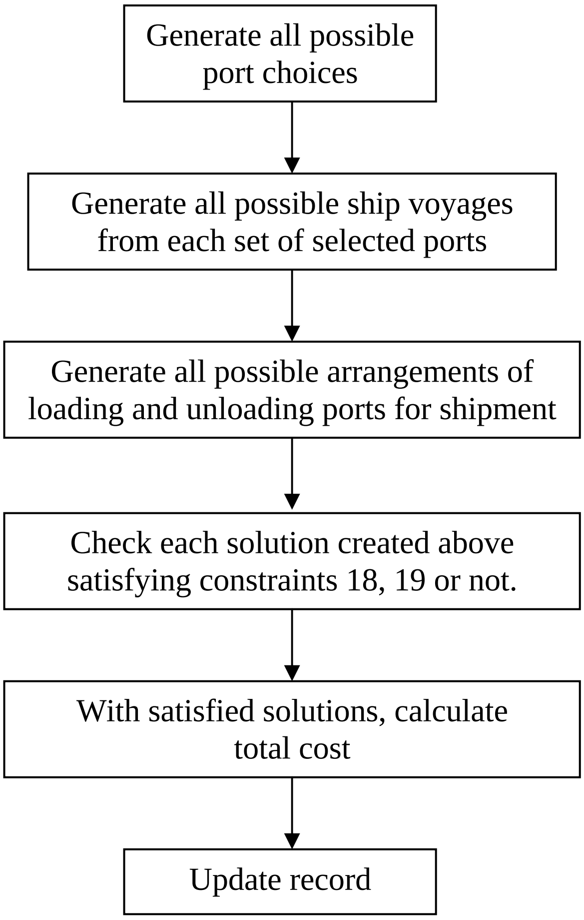

Figure 11: The second algorithm diagram

Source: the author

3.3.3 Approach 3

The third approach will improve ideas from the second. The change is from step 3. In this step, the second method will *try* to generate all possibilities of loading and unloading port whereas the third will *define* loading and unloading port for shipments from a particular set of port choice and port call order by a greedy idea. In that way, approach 3 is only concerned with generating states of port choice and port call order (values of select[i], next[i,j]).

With each state of port choice and port call order created by steps 1 and 2, there are two cost components in total cost we can determine: one is total ship cost during sailing time, and another is total port due. There are 7 sub-components which have not calculated yes. Our tactic in this algorithm is not try to find a minimum total of these undefined costs (global optimal) but only five of them (local optimal) by using a greedy model.

Table 7: Components of total cost

	Component	Sub-component	Defined
1	Total ship cost (TSC)	Port time	No
2		Sailing time	Yes
3	Total port tariff (TPC)	Port due	Yes
4		Handling cost	No
5	Total inland transportation cost (TLC)	Origin to loading port	No
6		Unloading port to destination	No
7	Total inventory cost (TIC)	Port time	No
8		Sailing time	No
9		Inland time	No

Source: the author

Greedy model – try to find a suitable loading and unloading ports for all cargo flow in order to minimize:

total greedy cost = (4) + (5) + (6) + (8) + (9) (*)

= total handling cost + total inland transportation cost + total inventory cost (during inland transport and sailing time).

Our greedy idea comes from an observation that there is a *positive linear relationship* between the total greedy cost (*) and total handling cost, inland transportation cost, inventory cost (inland transport and sailing time) of *each shipment*. The optimal of (*) is determined by that of each shipment. Therefore, instead of solving a big problem with all shipments, we work with smaller ones, each concerned with a separate shipment which is much simpler than the former. Obviously, ship cost and inventory cost during time ship in port is outside the new model, they are the error of greedy model. If we put them in model (*), the big problem can not divide into smaller and simpler ones, the algorithm will return the second algorithm.

Selection of loading and unloading port for a shipment:

It is assumed that cargo from i to j will be loaded by port s, unloaded by port d. We call the total of inland transportation costs from area **i** to port **s**, port **d** to area **j**, handling cost in port **s** and **d**, inventory cost (in sailing time and inland transport time) as a greedy cost. With each pair of ports, the greedy cost is different. We calculate this cost for all pairs. A pair (s,d) will be selected as loading and unloading ports for cargo flow from i to j if it has minimum greedy cost.

Greedy time: t[i, j, s, d] = inland_time[i, s] + sailing_time[s, d] + inland_time[j, d]

$$\text{Greedy cost: } f[i, j, s, d] = \left(\text{inland\_cost}[i, s] + \text{inland\_cost}[j, d]\right) * \frac{Q[i, j]}{\text{voyage\_number}}$$

$$+\ t[s, d] * V[i, j] * \frac{Q[i, j]}{\text{voyage\_number}}$$

$$+ (\text{handling\_cost}[s] + \text{handling\_cost}[d]) * \frac{\text{box}[i, j]}{\text{voyage\_number}}$$

/* *s and i are in the same region, d and j are in the same region*

(s,d): selected loading and unloading ports of cargo from i to j

if $f[i, j, s, d] \le f[i, j, s', d']$ $\forall s', d' \in$ set of selected ports.

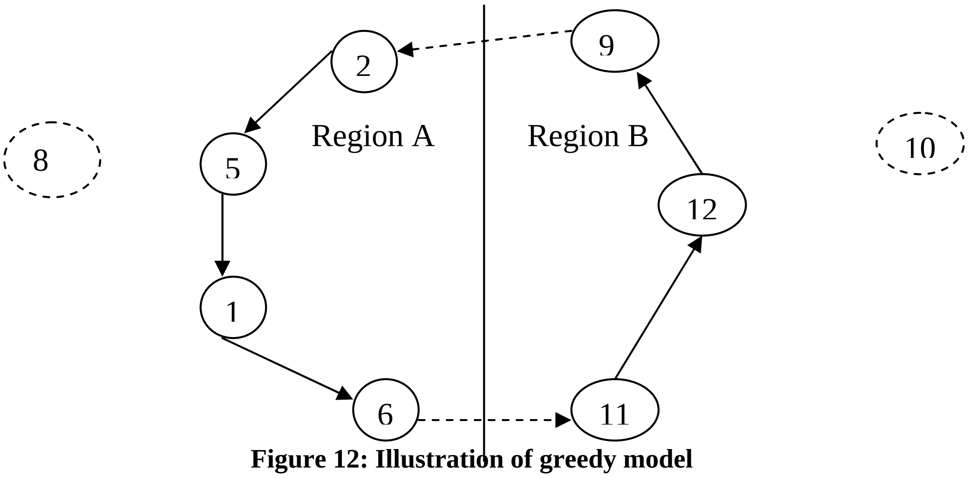

Figure 12: Illustration of greedy model
Source: The author

In the figure above, we have a round voyage: (2) → (5) →(1) → (6)→ (11) → (12) →(9) →(2) . We concern with cargo routine from (8) to (10). Greedy cost corresponding with a pair of ports (5) and (12) will include: inland and inventory cost from (8) to (5) and (12) to (10); inventory cost during *sailing time* from (5) to (1), (1) to (6), (6) to (11) and (11) to (12); handling cost in port (5) and (12).

Adjust of shipments:

After the previous step, we have a list of loading and unloading ports for all shipments. It is possible that, in some ports, the cargo carried by a ship will exceed her capacity. Therefore, in this step, we will re-arrange some shipments in some ports to make sure of two last model constraints.

Supposed in port k, cargo carried exceed ship capacity, there are two ways for adjustment excessive volume:

- Some loading shipments in port **k** will be changed to other ports in the same region called by a ship later than **k**.
- Some shipments will be discharged earlier in port **k** instead of later in other ports in the region.

With this greedy algorithm, the number of possible solutions do not depend on the number of cargo flows between two regions, they only depend on the number of candidate ports in each region. Solution space will be reduced considerably. Therefore, it is feasible to find a good solution to our problem.

Number of possible solutions = $\sum_{x=1}^{K}\sum_{y=1}^{T}\frac{K!}{(K-x)!}*\frac{T!}{(T-y)!}$

K: number of candidate ports in region A.

T: number of candidate ports in region B.

x: number of selected ports in region A.

y: number of selected ports in region B.

Table 8: Estimation solution space in the third algorithm

Number of candidate ports in A	Number of candidate ports in B	Number of possible solutions
4	4	4,096
5	5	105,625
6	6	3,825,936
7	7	187,662,601
8	8	12,012,160,000

Source: calculated by author

The error of the algorithm means we only assess local optimality (greedy cost), it does not mean that it is global optimality (total cost). The efficiency of this approach depends on the ratio between ship cost, inventory cargo cost during time ship in port and total cost. If it is small, it means that there is only a small difference compared with the optimal result. In the next chapter, when applying the model in real data, we can check this matter and assess the appropriateness of this method as well.

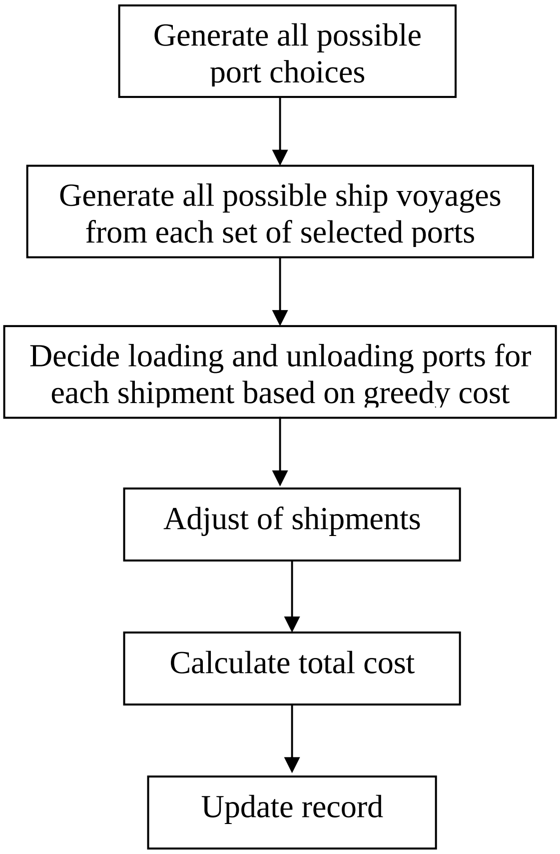

Figure 13: The third algorithm diagram

Source: the author

3.3.4 Approach 4

In the last approach, we are only concerned with generating possibilities of port choice. From each state of port choice, we will determine a corresponsive port call order by finding a minimum sailing time round voyage going through all selected ports, each port one time. After that, the algorithm is the same with the third one.

The problem of finding a round voyage with minimum sailing time is a classical Traveling Salesman Problem (TSP). In solving it, we use the “Nearest-Neighbor” method, which is adapted from Imai et al (2006). The method is as follows:

Step 1: Select one port as the starting node.

Step 2: Proceed to unvisited port, which is the nearest to the present port.

Step 3: Repeat Step 2 until all ports are visited.

Step 4: Go back to the starting node to form one round trip.

The distance between two ports in different regions is often much longer than that between two ports in the same region which ensures that a ship will visit all ports in a region before sailing to ports on another side.

Obviously, the result of the last approach is not as good as the above approach. However, with smaller solution space, it can be more effective when the number of candidate ports increases. Generally, the last approach deals with $2^K * 2^T$ cases (K, T: number of candidate ports in regions A and B).

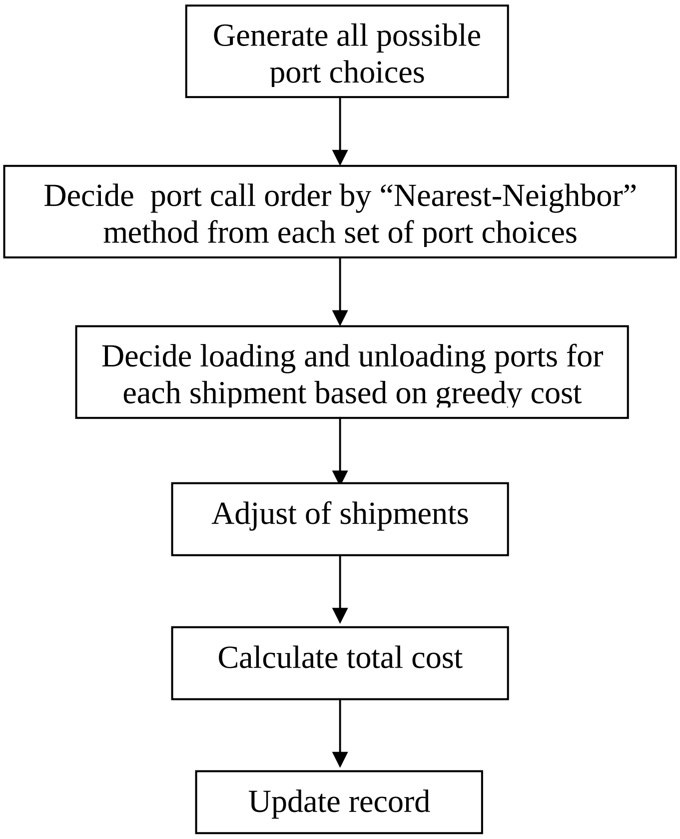

Figure 14: The fourth algorithm diagram
Source: The author

Table 9: Comparison of the four approaches

	Solution space	Result	Generation	Heuristic process	Application
Approach 1	$2^{2*(N+M)^2 * (K+T) + (K+T) + (K+T)^2}$	Optimal	select[i] next[i, j] load[i, j, s] unload[i, j, d]	No	Theoretical
Approach 2	$\sum_{x=1}^{K}\sum_{y=1}^{T}\frac{K!}{(K-x)!}*\frac{T!}{(T-y)!} * D^{X*Y}$	Optimal	select[i] next[i, j] load[i,j,s] unload[i,j,d]	No	Theoretical
Approach 3	$\sum_{x=1}^{K}\sum_{y=1}^{T}\frac{K!}{(K-x)!}*\frac{T!}{(T-y)!}$	Close optimal, better than the last.	select[i] next[i, j]	Define load[i,j,s] & unload[i,j,d]	Effective with $K,T< 8$
Approach 4	$2^K * 2^T$	Close optimal	select[i]	Define next[i,j]; load[i,j,s] & unload[i,j,d]	Effective with $16 \geq K,T \geq 8$

N: number of hinterland areas in region A. M: number of hinterland areas in region B.

K: number of candidate ports in region A. T: number of candidate ports in region B. D: number of shipments.

3.4 Conclusion

In chapter 3, we have introduced a non linear programming model to solve a network problem with the objective to minimize total cost including ship cost, inland transportation cost, port tariff and inventory cost of cargo. There are 4 groups of decision variables and 19 constraints in this model. By solving it, we can find an optimal ship voyage as well as inland cargo direction. However, the complexity of an NP-class problem makes it difficult to get an optimal solution. We suggest four approaches to deal with the solution matters. The main idea of these approaches are to generate solution space, then decide which is best. The first two are only theoretical. Applying them, we can have optimal solution, but a very huge number of calculations prevent us to receive results in an acceptable time frame. The last two are heuristic algorithms, which are improved from the second approach combined with greedy ideas. The selection between them depends on the size of data. If the number of total candidate ports is less than 15, it is feasible to apply the third method, on the contrary, the last is a better choice.

Chapter 4 Model application and analyses

We have presented a port selection model in the previous chapter. In chapter 4, it will be put into real data. On the one hand, the trial tests the suitability of the suggested model, on the other hand, from the results, we can get analyses about factors which influence port choice decision. This chapter is structured in three sections. The first introduces data used in the model as well as the processes of solving them. The second mentions a computational programme based on the previous algorithm to find a solution. The last section takes into account sensitive analyses to consider the impact of number of port calls on a ship's voyage as well as that of mega vessels.

4.1 Data description

We deal with container flows between the USA and Northern Europe which go through ports on the East Coast (USA) and Le Havre – Hamburg range (Europe) on the Transpacific route. The application result will give us a possible optimal ship voyage for this particular case. To execute these data in our model, we must carry out some processes to adjust them to be suitable with the model's patterns as well as to find some additional data. There are six phases in processing the input data.

Phase 1: Collect raw data

The initial data are provided by the branch of Piers (USA)[7] in the UK. They include all seaborne trade profiles between two regions in October, 2005. In Northern Europe, it is impossible to cover all but only 8 main countries are playing a big part

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[7] PIERS - the Port Import Export Reporting Service: a center which maintains a database of import, export information on the cargoes moving through ports in the U.S., Mexico, Latin America, and Asia

in good transactions with the USA: France, United Kingdom, Netherlands, Germany, Belgium, Norway, Sweden and Denmark. In 2005, the value trade of these countries constituted more than 74% total value trade between EU and US.[8] Each profile has basic information about a shipment: origin, destination, loading and discharging ports, number of containers, TEUs and estimated value. Totally, there are 43,693 shipments from the USA to Europe, and 76,800 ones in reverse direction. In Europe, information about the starting/ultimate point of a cargo flow is a city /town. Meanwhile in the USA, this is mostly a state, rarely does a record have information about the city. Some records also have blanks on this field of information. In this case, a shipment will be assumed to have the same original or final state as USA loading port or unloading port. Origins and destinations are bases for us to divide hinterland areas. In Europe, the unit is a city/town whereas in the USA, this is a state.

Table 10: Sea-freight flow between US and Northern Europe in October, 2005

	Europe to US	US to Europe
Total number of shipment	76,800	43,693
Total containers	76,051	44,761
Total TEUs	125,072	78,487
Total value (USD)	6,646,365,201	4,124,036,815

Source: combined from data of Piers

Phase 2: Filter and synthesize data

The scope of application is only the Transpacific route with the East Coast (USA) and North European port systems. With cargo between the USA and North Europe, besides two systems, it can be transported through ports in the Mediterranean Sea, West Coast (USA) or taken round-the-world, pendulum service passing Suez canal. We are only concerned with captive cargo of two above port systems, more precisely, cargo loaded and unloaded by them. The filter process has been done to get rid of un-satisfied shipments. After that, there are 66,786 (Europe to US) and 41,701 (US to Europe) shipments left.

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[8] Calculated based on figures retrieved from the website: http://www.eurunion.org/profile/facts.htm

Table 11: Filtered sea-freight flow between US and Northern Europe

	Europe to US	US to Europe
Total number of shipment	66,786	41,701
Total containers	66,270	44,559
Total TEUs	108,547	78,487
Total value (USD)	6,016,375,530	4,093,756,649

Source: combined from data of Piers

In processed data, there are 3,179 different starting/final points of shipments in Northern Europe, this figure in the USA is 46. Each point is defined as a hinterland area. Shipments are combined based on hinterland areas. After combining, we have 2940 cargo flows from US to Europe, 5,371 from Europe to US. The synthesization process helps reduce considerably the amount of input data, making the problem become less complicated.

Table 12: Number of hinterland areas in the application

Country	Hinterland areas	Country	Hinterland areas
Belgium	181	Denmark	100
France	653	Germany	1,019
Netherlands	232	Norway	45
Sweden	114	UK	835
US	46		

Source: combined from data of Piers

Phase 3: Select candidate ports

There are twelve ports selected as candidate ports in running the application: Rotterdam, Antwerp, Bremerhaven, Le Havre & Felixstowe (Europe); New York, Charleston, Houston, Norfolk, Savannah and Baltimore (US). These are main ports on the Trans-Atlantic route. In our specific data, containers going through these ports in reality occupy nearly 90% of the total cargo throughput on this route.

Table 13: Cargo through EU candidate ports in October, 2005

Port	Container	Value	TEU
ROTTERDAM	26,931	2,208,964,364	46,706
ANTWERP	26,463	2,466,987,906	44,519
BREMERHAVEN	22,819	2,204,395,462	38,291
HAMBURG	7,337	690,919,511	11,862
LE HAVRE	7,053	628,476,353	11,524
FELIXSTOWE	6,859	543,999,027	11,361
Total	97,462	8,743,742,623	164,263

Source: combined from data of Piers

Table 14: Cargo through US candidate ports in October, 2005

Port	Container	Value	TEU
NEW YORK	32,671	2,855,103,007	54,371
CHARLESTON	23,763	2,327,109,313	39,995
HOUSTON	18,282	1,377,447,048	29,717
NORFOLK	15,706	1,634,499,795	27,670
SAVANNAH	4,707	286,163,912	8,521
BALTIMORE	4,011	495,223,059	7,345
Total	99,140	8,975,546,134	167,618

Source: combined from data of Piers

Between USA ports and inland points, we use the transportation modes of railroad and truck. These modes are also used for transportation in continental Europe. Between continental Europe and UK, Scandinavian Countries, feeder services will be used in the model to carry containers.[9] In these regions, there are many ports which can function as feeder ports. However, in the scope of this research, it is very difficult to cover all cases. We assumed that, in UK, all containers will be loaded and unloaded through port of Felixstowe, in Norway, port of Oslo, in Sweden, port of Goteborg, and Denmark, port of Aarhus. With containers in Belgium, Germany, Netherlands and France which are transhipped by port of Felixstowe, feeder ports will be selected among ports of Rotterdam, Le Havre, Antwerp, Bremerhaven and Hamburg based on the smallest transportation cost of a shipment between origin/destination and transhipment port.

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[9] These transportation modes results from the discussions with Mr Jacob Hansen, Schenker - Denmark; Mr Steffen Saltofte, Maersk Line and Professsor Pierre Cariou, WMU.

Phase 4: Estimate sea and inland distance

Sailing distances between ports are retrieved from the database - Veson Nautical Distance 2004. There are 66 distance records for mainlines and 23 for feeder routes (in Europe) which are presented in appendix 2. Inland distances and transport times between hinterland areas and ports are calculated through the website of ViaMichelin[10] with 11,795 records totally.

Table 15: Summary of inland connections

Hinterland area	Port	Connection
US (46 areas)	New York, Charleston, Houston, Norfolk, Savannah & Baltimore	276
Belgium, Netherlands, France, Germany (2085 areas)	Le Havre, Rotterdam, Antwerp, Bremerhaven, Hamburg	10,425
UK (835 areas)	Felixstowe	835
Norway (45 areas)	Oslo	45
Denmark (100 areas)	Aarhus	100
Sweden (114 areas)	Goteborg	114
Total		11,795

Source: combined by the author

Phase 5: set up operational configuration:

* Number of round voyage = $\frac{\text{total TEUS of shipments}}{2 * \text{ship\_size} * \text{slot utilisation}}$

Slot utilisation is set up at rate 70%.

* Handling operation: in all ports, mainline vessels are served by 6 gantry cranes with productivity 33 moves per hour. [11]

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[10] http://www.viamichelin.com/viamichelin/gbr/dyn/controller/Driving_directions#

[11] Together with slot utilization, these figures are retrieved from Baird (2001) as well as after discussion with Mr Ton Van Hoorn, APM Terminal – Rotterdam.

* Manoeuvring time: for the entry and exit in each port, three hours per call is taken. (adapted from the supposition of Wijnolst et al, 2000).

* Minimum dwell time before loading or after discharging: 24 hours. This assumption originates from experience in receipt/delivery container activities of APM terminal, Rotterdam.

* Ship speed: speed = 5.4178 * ship_size$^{0.1746}$ (knots/hour)

In our model, fuel cost having strict relationship with ship speed is calculated by the formula of Wijnolst et al (2000). To make sure the unification and rationalisation in calculation process, ship speed will continue to be worked out by their model. Thus, the result may be higher than practical ship speed (often around 25 knots per hour).

Phase 6: Estimate cost

a. Port tariff: The calculation of port tariffs for candidate ports is quite sophisticated. Each port has many ways to levy a vessel and cargo with different port due and terminal handling charge (THC) systems. Moreover, they also depend considerably on a contract between a port and a shipping line. In this model, we assume that THC is 100 USD per movement (this charge is used in most papers concerning with handling charge) whereas port dues is adapted from cost model of Baird (2001).

Cost model:

- Ship dues: 0.1884 USD per grt
- Towage: 5,356 USD per tug, a mainline ship uses 2 tugs, a feeder ship uses 1 tug per entry/exit.
- Mooring/unmooring: 0.044 USD per grt
- Pilotage: 0.1612 USD per grt. With feeder ship, due to short trip, they can enjoy partial pilot exemption, thereby avoiding 75% normal pilot costs.
- Other charges assessed at 5% of the above charges.

* Gross tonnage (grt) is converted from ship size:

GRT = 12.556 * ship_size + 1087.2 (Wijnolst et al, 2000).

b. Ship cost: adapted from Wijnolst et al (2000).

Time charter rate = 108.05 * ship_size$^{0.6257}$ (USD/ day).

FC = fuel_price * (0.0392*ship_size + 5.582) (USD/ day).

Fuel price in this case is used as the price of Heavy Fuel Oil (HFO). We get the price per tonne of HFO 375USD. (the average price of HFO in Rotterdam during time from 19/07/2007 to 27/07/2007). [12]

c. Inland transportation cost:

Road cost = 40 + 1.2 per km (USD/TEU).

Rail cost = 70 + 0.5 per km (USD/TEU). (MDS, 2006). [13]

Inland transport in our case is a combination of both rail and road modes. Hence, the cost of inland transportation will be calculated based on the ratio of cargo carried between two transportation modes. In Europe, from the latest figures in 2005, the ratio of tonne-km good transport by road and by rail is 4.74:1.[14] In the USA, with the statistics of two transportation modes in 1993, 1997 and 2002 from BTS (2007), there is only a little difference in tonne-mile figures between two modes, we assume the ratio is 1:1.

Inland transportation cost in Europe:

$$\frac{40*4.74+70*1}{5.74} + \frac{1.2*4.74+0.5*1}{5.74} \text{ per km} = 45 \text{ USD} + 1 \text{ USD per km.}$$

Inland transportation cost in US:

$$\frac{40*1+70*1}{2} + \frac{1.2*1+0.5*1}{2} \text{ per km} = 55 \text{ USD} + 0.8 \text{ USD per km.}$$

d. Feeder cost:

Feeder ship size: 1,000 TEU.

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[12] Information is retrieved from website: http://www.bunkerworld.com/markets/prices/nl/rtm/

[13] In MDS's model, the currency is British pound, we have converted into USD. (1 pound = 2 USD)

[14] Calculated based on figures from website of Eurostat: http://epp.eurostat.ec.europa.eu

Slot utilisation: 70%.

Time in port: 24 hours.

Speed: 18 knots per hour.

Port due: 16,886 USD per call.

$\Rightarrow$ Port due per TEU: 24 USD per call.

Ship cost: 24,935 USD per day.

$\Rightarrow$ Ship cost per TEU: 35 USD per day.

Feeder cost from port i to port j for a shipment: (U containers and Q Teus)

$$= \text{Terminal handling charges} * 2 * U + \text{Port due (per TEU)} * Q$$

$$+ \text{Ship cost (per TEU)} * \frac{\text{sea distance between port i and port j}}{24 * \text{speed}} * Q$$

$$= 200 * U + 24 * Q + 35 * \frac{\text{sea distance between port i and port j}}{432} * Q \text{ (USD)}$$

For transshipment cargo, their transportation cost to hub ports includes two parts: inland transportation cost to feeder port, and feeder cost to hub ports. In our suggested model, we only mention the inland transportation process, in this case, it will be also extended to the feeder process. This implementation does not influence the previous model and makes our problem more practical and reasonable. We also suppose that besides inland transportation time to feeder port, sailing time between feeder and hub ports, these shipments spend totally two days in feeder and hub ports before being loaded on board mother vessels.

e. Inventory cost of cargo:

Notteboom (2006) assessed one day delay of cargo would result in two following costs: opportunity cost (3% - 4% per year), economic depreciation (10-30% per year). We assume inventory cost in our application is 23.5% per year (approximately 0.06% per day) including 3.5% opportunity cost and 20% economic depreciation.

Inventory cost per TEU per day = its value * 0.06%.

Table 16: Operational configuration of different ship sizes

Ship size (TEU)	GRT	Speed (knot/h)	Number of voyage	Ship cost ($/day)	Port due ($)
6,000	76,423	24.75	22.6	115,274	54,079
7,000	88,979	25.42	19.4	132,504	59,269
8,000	101,535	26.02	17.0	149,601	64,458
9,000	114,091	26.56	15.1	166,589	69,647
10,000	126,647	27.05	13.6	183,483	74,836
11,000	139,203	27.51	12.3	200,296	80,025
12,000	151,759	27.93	11.3	217,038	85,214
13,000	164,315	28.32	10.4	233,718	90,403
14,000	176,871	28.69	9.7	250,341	95,593
15,000	189,427	29.04	9.0	266,914	100,782
16,000	201,983	29.37	8.5	283,440	105,971
17,000	214,539	29.68	8.0	299,924	111,160
18,000	227,095	29.98	7.5	316,369	116,349
1,000 (feeder)	13,643	18.10		24,935	16,886

Source: calculated by author

4.2 Computational experiments

Programs for finding solutions are written in the programming language Turbo Pascal 7.0. We apply the third algorithm presented in chapter 3 as the basis for them. On the one hand, this algorithm can provide us results in acceptable time with input data in our case, on the other hand, it reduces the error in the calculation process. The model will be tried with different ship sizes from 6,000 TEU (Post panamax) to 18,000 TEU (Malacca-max). 13 programme packages have been created in correspondence with various ship capacities. Each package has 10 component files divided into three sets. The first is database files which contain all input data about cargo and transport profiles. They are the same for all packages. The second are executing files distinguished from packages by different ship sizes. They retrieve data from the first one, process and provide results to the last set, output files.

Table 17: Computational program package

	File name	Description
Set 1: Database files		
1	export.txt	*store* 2,940 cargo flow profiles from US to Europe: origin, destination, total box, TEU and value.
2	import.txt	*store* 5,371 cargo flow profiles from Europe to US: origin, destination, total box, TEU and value.
3	eurocost.txt	*store* 19,074 transport records between Europe hinterland and candidate ports: total cost, time.
4	uscost.txt	*store* 276 transport records between US hinterland and candidate ports: total cost, time.
5	sea_dis.txt	*store* 144 sailing distances between any two candidate ports.
Set 2: executing files		
6	generate.pas	*generate* all possible voyages in the problem. (ports in ship's voyage, their orders).
7	main.pas	*calculate* total cost for all possible voyages. This is the main program of the package.
8	filter.pas	*select* optimal voyages with smallest total cost.
Set 3: output files		
9	voyage.out	*store* 3,852,936 possible voyages in the problem.
10	result.out	*store* optimal voyage records. Each record includes: cost, time indicators, voyage specification, cargo statistics for each ports in the voyage, loading, unloading ports for each shipment.

Source: the author

Each computational program package is run in 4 computers with processors Intel Core 2 Duo for the duration of 20 hours. It calculates total cost for all 3,825,936 possible solutions for a particular ship size. Solution space is divided into 11 groups by the number of visited ports on a ship’s route (from minimum 2 ports to maximum 12 ports). The program will find solutions with the smallest total cost in each group. Afterwards, it determines optimal solution for this type of ship: ports in ship’s voyage, port call sequence, loading and unloading ports for cargo flows. In appendix 3, with each ship size, we provide details of 11 optimal voyages corresponding with each group.

Table 18: Summary of computational results

Ship size (TEUs)	Voyage	Voyage time (hours)	Average cost per TEU (USD)	Error of heuristic algorithm*
6,000	(1)	522	1,617.43	4.2%
7,000	(2)	536	1607.17	4.9%
8,000	(2)	533	1699.32	5.3%
9,000	(2)	533	1695.58	5.7%
10,000	(2)	534	1594.22	6.2%
11,000	(2)	534	1592.12	6.5%
12,000	(2)	537	1594.55	6.9%
13,000	(3)	554	1594.74	7.6%
14,000	(3)	559	1599.57	8.0%
15,000	(3)	562	1601.36	8.4%
16,000	(3)	565	1604.17	8.8%
17,000	(3)	573	1613.39	9.3%
18,000	(3)	576	1616.26	9.6%

Source: calculated by author.

* Error is calculated by ratio between inventory cost (during time ship in port) and total cost. As proposed in chapter 3, inventory cost and ship cost (during time ship in port) are two missing costs we do not put into the greedy model, these are error of algorithm. In this particular case, by comparing voyages in each group, we can eliminate error from ship cost in port time. This cost is unchanged for all voyages having the same number of port calls, so it does not influence the optimal solution.

Voyage (1) includes 7 ports:

Felixstowe → Antwerp → Bremerhaven → New York → Norfolk → Charleston → Houston → Felixstowe.

Total sea distance: 10,797 miles.

Voyage (2) includes 8 ports:

Felixstowe → Antwerp → Rotterdam → Bremerhaven → New York → Baltimore → Charleston → Houston → Felixstowe.

Total sea distance: 11,081 miles.

Voyage (3) includes 10 ports:

Le Havre → Felixstowe → Antwerp → Rotterdam → Bremerhaven → New York → Norfolk → Charleston → Savannah → Houston → Le Havre.

Total sea distance: 11,175 miles.

To present results of a computational program, we illustrate a case in accordance with 6,000 TEU ship. In the optimal routine, a ship visits 7 ports with a total time 522 hours, in that, sailing time is 437 hours, the remaining 85 hours belong to port times. The figure below provides detailed description of the voyage. Table 19 indicates cargo information going through ports in each voyage: total number of shipments, values, containers and TEUs. The next table contains all cost compositions for transporting one TEU cargo from an origin to a destination with this particular size of a vessel.

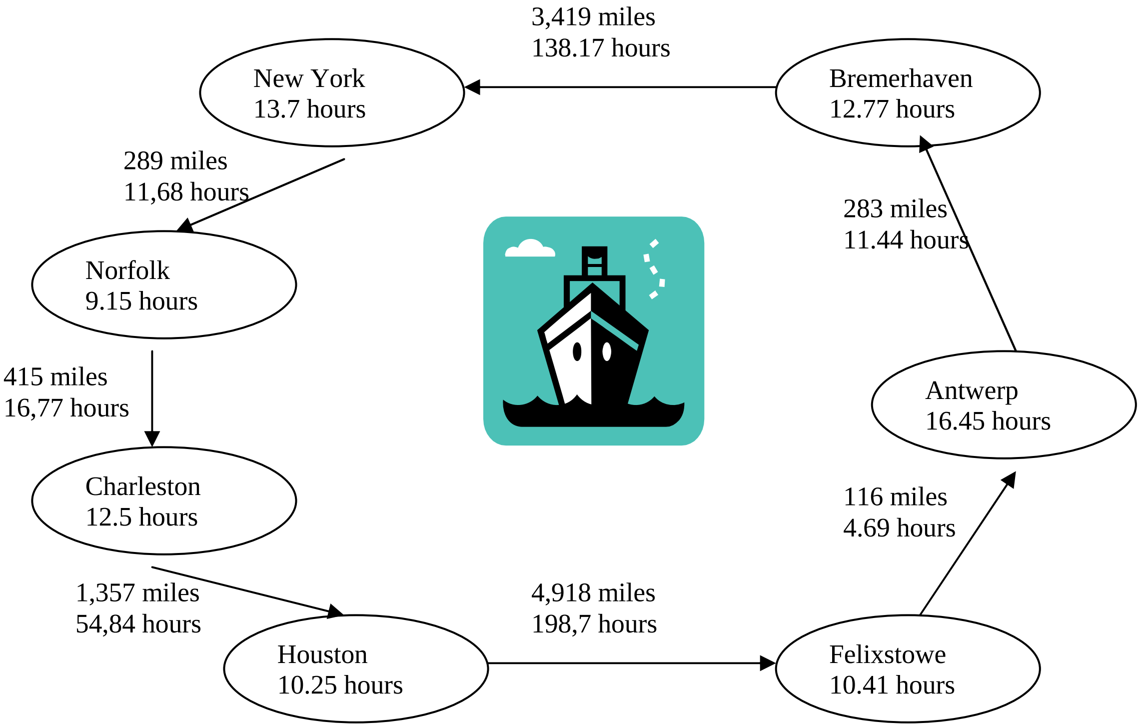

Figure 15: Optimal route with ship size 6,000 TEU.
Source: the author

Table 19: Cargo through ports in ship's voyage (ship size 6,000 TEU)

Port	Loading cargo				Unloading cargo			
	Shipments	TEUs	Boxes	Value ($)	Shipments	TEUs	Boxes	Value ($)
Felixstowe	1,653	924	587	54,312,868	1,239	955	533	46,418,139
Antwerp	2,521	2,202	1,336	108,953,634	1,134	1,800	1,034	95,411,924
Bremerhaven	1,197	1,747	1,053	106,938,671	567	770	434	42,027,182
New York	789	798	457	41,646,457	2,305	2,173	1,322	116,993,047
Norfolk	498	607	334	41,511,169	645	644	385	38,800,456
Charleston	930	1,253	696	55,083,357	1,493	1,313	801	80,215,943
Houston	723	867	514	45,616,262	928	743	468	34,195,729
Total	8,311	8,398	4,978	454,062,418	8,311	8,398	4,978	454,062,418

Source: calculated by the author

Table 20:Cost composition per TEU (ship size 6,000 TEU)

	Component	Sub-component	Value (USD)	Percentage
1	Ship cost	Port time	69.78	4.30%
		Sailing time	251.45	15.51%
2	Total port tariff	Port due	72.57	4.48%
		Handling cost	200	12.34%
3	Total transportation cost between hinterland points and ports	Inland transport	563.57	34.77%
		Feeder transport	13	0.80%
4	Total inventory cost	Port time	153.79	9.49%
		Sailing time	282.02	17.40%
		Inland time	8.25	0.51%
		Feeder time	6.48	0.40%
	Total cost		1,620.91	100%

Source: Calculated by the author

The error in our heuristic calculation is less than 10%, but actually, this figure is smaller. It means that our result is rather close to the optimality. Between elements of total cost in all cases of ship size, we realize that, inland and feeder transport cost represent the biggest part (nearly 40%), then inventory cost of cargo (more than 25%), ship cost and port tariff only plays a smaller part (each less than 20%). Two former costs are often missing in routing problems. Obviously, without the presence of the two important parts, we can not observe the full effect of factors to operational efficiency. The final results can be good in one aspect but possibly not in general. In the following section, impacts of these costs will be taken into consideration.

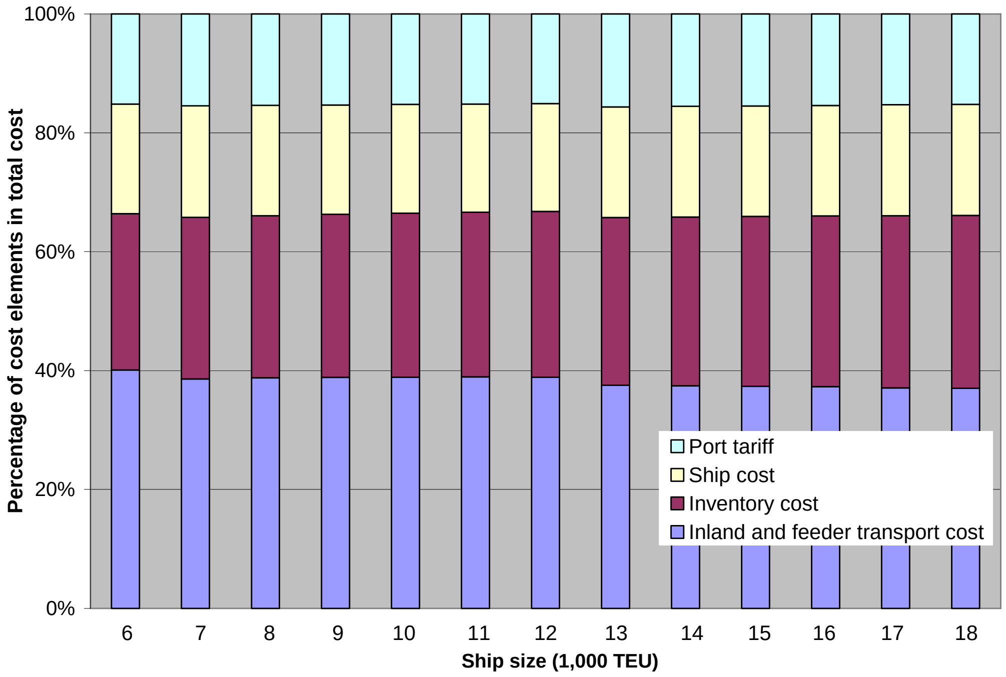

Figure 16: Percentage of cost elements in total cost of different ship sizes
Source: the author

4.3 Sensitive analyses

Results from computational programs provide us with materials to elaborate into sensitive analyses. In this section, firstly, we focus on the relationship between the number of port calls and an optimal voyage which involves a lot of the feasibility of service patterns: hub and spoke or multi ports. Secondly, the efficiency of bigger vessel will be assessed when put in an entire network. Some simulations are also taken to consider the impacts of operational factors to optimal voyage and ship size as well.

Dilemma of determining number of ports in ship's voyage:

To study the relationship between number of visited ports and optimal solution for each kind of ship, we divide total cost (per TEU) into four groups: transport and inventory cost in inland and feeder process (1); total ship cost, inventory cost during sailing and port time (2); port due and handling cost (3). For each ship type, regression functions between each cost group and number of port calls have been calculated by the Microsoft Excel software. Cost figures for running regression are retrieved from previous outcomes. (presented in appendix 3). Correlation coefficients R^2 of these functions are more than 0.9 showing strong relationships between these variables. The next table will include detailed correlations in correspondence with 8 different ship sizes.

Table 21: The regression between cost elements (y) and number of port calls (x)

Ship size	Total inland and feeder cost	Total ship cost and inventory cost in voyage time	Port tariff
6,000 TEU	$y = -362*Ln(x) + 1424.7$ $R^2 = 0.9095$	$y = 129.7*Ln(x) + 443.43$ $R^2 = 0.9389$	$y = 6.4*x + 200$ $R^2 = 1$
8.000 TEU	$y = -366*Ln(x) + 1425.7$ $R^2 = 0.9032$	$y = 120.5*Ln(x) + 457.5$ $R^2 = 0.9294$	$y = 5.8*x + 200$ $R^2 = 1$
10,000 TEU	$y = -370*Ln(x) + 1431.1$ $R^2 = 0.9099$	$y = 113.5*Ln(x) + 474.7$ $R^2 = 0.941$	$y = 5.3*x + 200$ $R^2 = 1$
12,000 TEU	$y = -370*Ln(x) + 1431.1$ $R^2 = 0.9097$	$y = 103.7*Ln(x) + 498.4$ $R^2 = 0.9362$	$y = 5.1*x + 200$ $R^2 = 1$
14,000 TEU	$y = -289*Ln(x) + 1218.7$ $R^2 = 0.9463$	$y = 72.7*Ln(x) + 581.9$ $R^2 = 0.9352$	$y = 4.9*x + 204.9$ $R^2 = 1$
16,000 TEU	$y = -289*Ln(x) + 1218.7$ $R^2 = 0.9463$	$y = 66.7*Ln(x) + 600.7$ $R^2 = 0.9264$	$y = 4.7*x + 204.7$ $R^2 = 1$
18,000 TEU	$y = -289*Ln(x) + 1218.7$ $R^2 = 0.9463$	$y = 59.9*Ln(x) + 628.3$ $R^2 = 0.9118$	$y = 4.6*x + 204.6$ $R^2 = 1$

Source: Calculated by the author from data in appendix 3

+ Correlations between group (1) and number of port calls (x) are expressed by logarithm functions $y = a* \ln(x) + b$, with **a** always negative, indicating the tendency of *decreasing* cost involving with transportation process between origins/destinations and loading/unloading ports when the number of port calls go up, the level of decrease becomes smaller and smaller.

+ Correlations between group (2) and number of port calls (x) are expressed by logarithm functions $y = a* \ln(x) + b$, with **a** always positive, indicating the tendency of *increasing* ship cost and inventory cost during voyage time when the number of port calls go up, the level of increase becomes smaller and smaller.

+ Correlations between group (4) and number of port calls (x) are expressed by linear functions y = a* x + b, with **a** always positive, indicating the tendency of *increasing* port tariff when the number of port calls go up.

From regression analyses, we have concluded that with higher number of port calls, we get the benefit from lower cost concerning with container transportation between hinterland points and loading/unloading ports, on the other hand, we suffer higher port tariff, ship cost, inventory cost during voyage time. There is a conflict between cost group (1) and groups (2), (3). The optimal number of ports on a ship's voyage will depend upon the trade-off analysis between them.

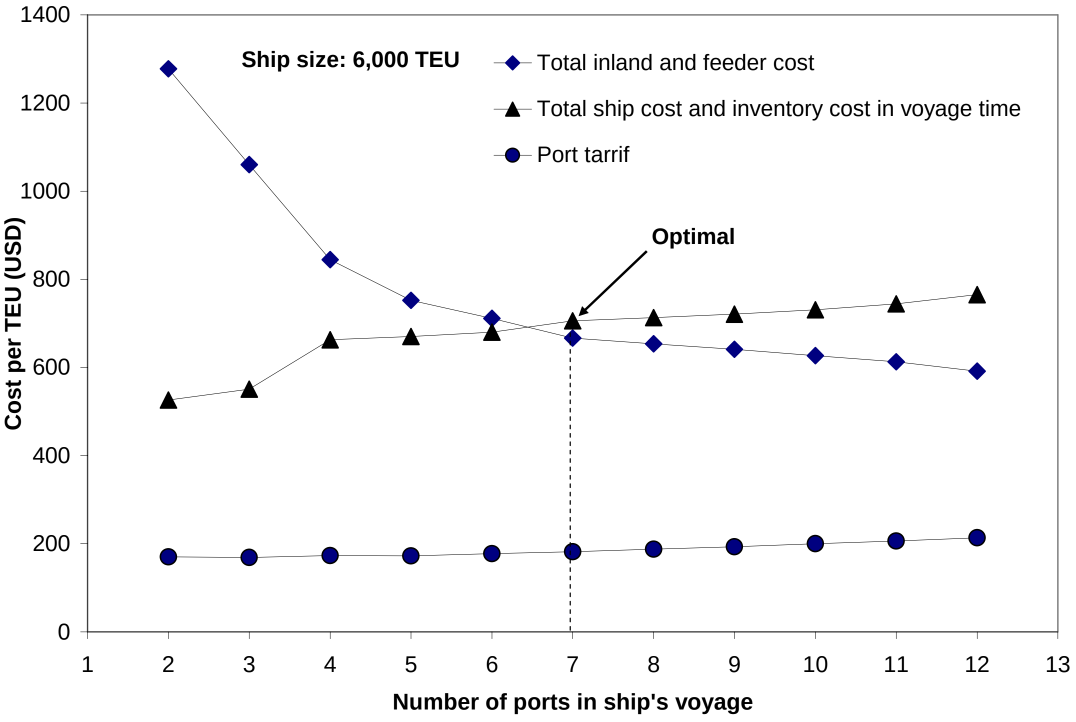

Figure 17: The relationship between number of ports in ship's voyage and cost elements.
Source: the author

Moreover, from these functions, we can also forecast that the variation of number of port calls seems to go in the same direction with ship capacity which coincides with computational results about optimal number of ports in ship's voyage presented in the prior section.

Total cost (TC) = cost group (1) + cost group (2) + cost group (3)

Cost group (1) = $-a1 * Ln(x) + b1$

Cost group (2) = $a2 * Ln(x) + b2$

Cost group (1) = $a3 * x + b3$ (a1, a2, a3, b1, b2, b3 > 0)

We estimate TC through 3 regression functions of (1), (2) and (3)

TC = $(-a1 * Ln(x) + b1) + (a2 * Ln(x) + b2) + (a3 * x + b3)$

Derivative of TC: $TC' = \frac{-a1}{x} + \frac{a2}{x} + a3$

TC get minimum when its derivative equal with 0 $\Rightarrow x = \frac{a1 - a2}{a3}$

Figures in the regression table shows that when a ship is larger, the value of **a1-a2**, the numerator, increases whereas that of **a3**, the denominator, decreases. It means that, with a larger vessel, **x**, a *theoretical* optimal visited port number, seems to go up.

With the tendency of the deployment bigger and bigger vessels, many ideas have supported the use of the hub and spoke system, in which ship operates in a few transhipment ports. (Wijnost et al, 2000; Ashar, 2002a, 2002b; Baird 2002, 2005; Francesetti & Foschi, 2002). However, calculations and estimations in our model realize that with bigger vessels, the port call number is not actually smaller but tends to be higher. Without physical constraints, it is still more economical when using the multi port system. This thing is suitable to the practical ship operation. When Maersk Line first deployed a 6,600 TEU vessel, many people thought that the ship would only visit one or maximum two hubs in Europe; may be three in the Far East, but she still visited all EU major ports, including Goteborg (Sweden), sometimes Arhus (Denmark). Today, Emma Maersk and her sister ships also act in the same way. [15] By studying Maersk Line's route between Europe and Far East, we can notice that bigger vessels tend to visit more ports and operate for a longer duration.

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[15] The information results from a discussion with Mr Ton van Hoorn, APM terminal, Rotterdam.

Table 22: Route configuration

Route	Average ship size	Port calls	Duration
AE8	6,881 TEU	10	49 days
AE7	8,007 TEU	13	56 days
AE1*	8.125 TEU	15	64 days

Source: Combined from the Containerisation International Yearbook, 2007.

* In AE1, there are two ships with a capacity of 11,000 TEU: Emma Maersk and Estelle Maersk.

Savings of smaller ship cost, inventory cost or port tariff when shortening the routine sometimes can not make up for considerable increase of inland/feeder cost, which constitutes a high percentage in total cost (nearly 40%). Operation in fewer ports is only beneficial when we can control inland/feeder process, especially inland transport. In our study, inland cost plays more than 95% in cargo transport cost between ports and origins/destinations of shipments. Jansson and Shneerson (1987), Wijnolst et al (2000) evaluated that hub and spoke system is only competitive when a substantial percentage of cargo are not feedered to other ports but generated in the hubs. We clarify that it is only feasible when modest volumes of cargo come from the *captive hinterlands* of transhipment ports. Hinterland accessibility can be considered as an important element which influence significantly to port attractiveness. Notteboom et al (1997) emphasized inland connection as an advantage for upstream ports to compete with downstream ports who has better conveniences about draughts, ship accessibilities, and closeness to mainline. Malchow (2001) found that the inland distances between a shipment's position and a port is one of the most influential factors in the assignment of a shipment to a particular port. Studies of Lirn et al (2004), Song and Yeo (2004) also confirmed the importance of inland transportation to port selection.

As we are concerned above, the optimal number of ports depends on the trade-off between inland/feeder cost and others. The alteration of any components will influence the optimal state. For example, savings of inland/feeder cost, the increase of port tariff or ship cost (route with longer distance, higher bunker price), transportation of higher value container can also lead to decline visited ports in ship's route. In the later part, we make two simulations to demonstrate the change of number of port calls when some factors vary.

In the first one, we increase sailing distance two times (in correspondence with Transpacific route), then three times (Far East – Europe route).[16] In this simulation, only ship cost and inventory cost during sailing times are changed. In the second simulation, impacts of decreasing inland/feeder cost to optimal number of port calls will be taken into consideration. In figures 18 and 19, we can observe clearly the tendencies to reduce the number of port calls when there are increases of sailing distance or decrease of inland/feeder cost. Although, in these simulations, there are the declines of ports in ship's voyage, a ship still operates in several ports (minimum 5 ports) which asserts again the advantages of the multi port system in liner service.

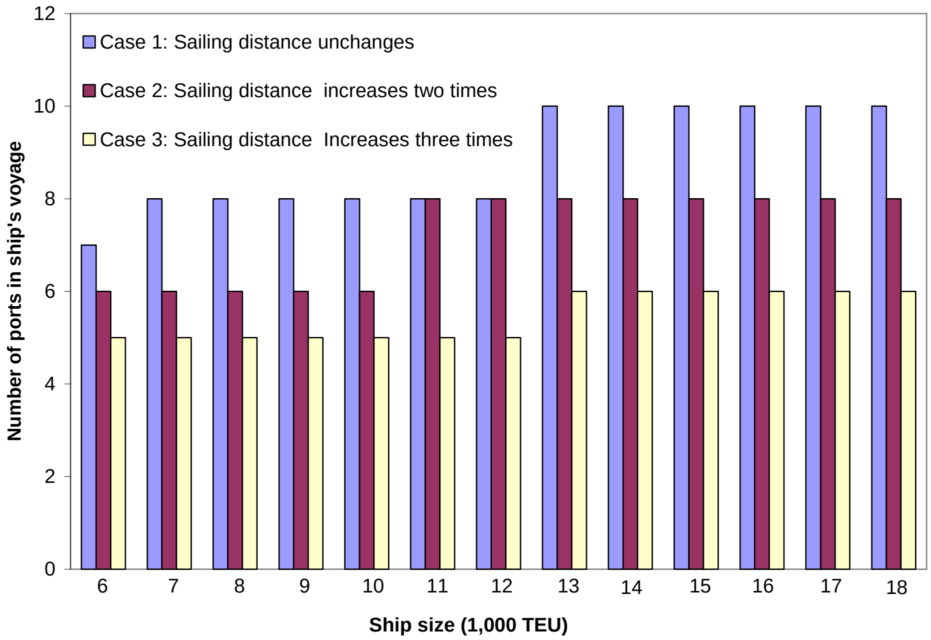

Figure 18: The impact of sailing distance to optimal number of port calls
Source: The author

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[16] Sea distances between Rotterdam and New York: 3,314 miles; Rotterdam and Hong Kong; 9,668; Hong Kong and Long Beach: 6,335. From these figures, we assume sailing distances in TransPacific route two times higher, Far East-Europe three times higher than TransAtlantic route (our case).

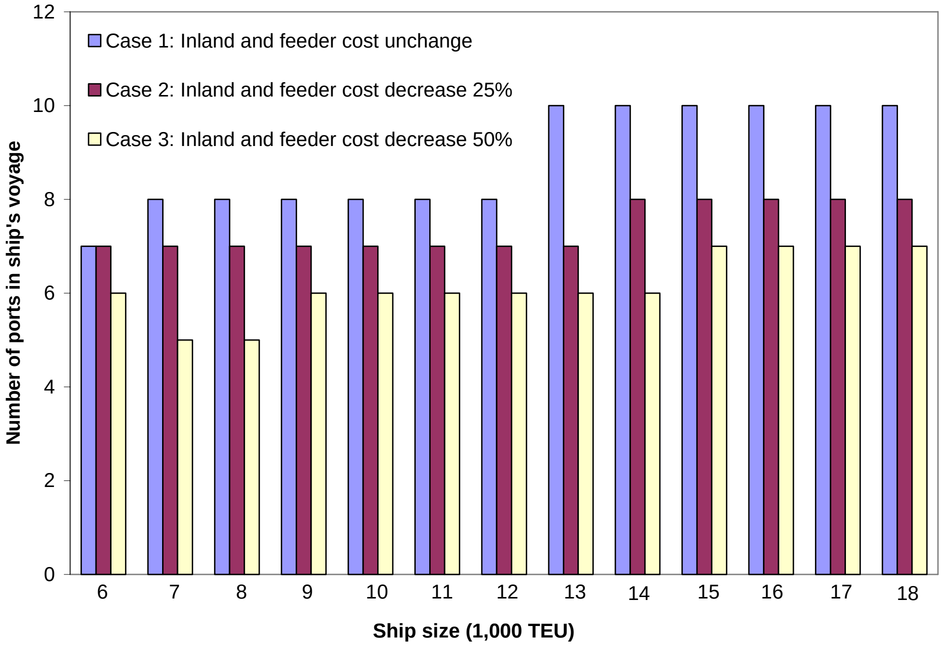

Figure 19: The impact of inland and feeder cost to optimal number of port calls
Source: The author

Efficiency of ship size:

Economies of ship size have been proved in many studies. Unit *ship cost* will decrease when we deploy a bigger vessel. However, shipping is only a part of a game. Its savings do not automatically lead to a general benefit of the transport system. The most important thing we consider is how to minimize total cost rather than cost of an individual process. In a whole system, the change of any aspect is likely to have negative effects on the cost of both total cost and other aspects. (Ma, 2002). Economies of ship size are only fully understood when we put it in the correlation with other components. In our case, ship cost often plays just around 18% in total cost. The benefit of operating large container vessels is only marginal. From 6,000 TEU to 11,000 TEU, total cost per TEU reduces only 26 USD (1.56 %). For ships of more than 11,000 TEU, its deployment becomes scale diseconomies which cause higher total cost. The reason explaining the inefficiency of mega vessels in our problem may come from the short voyage distance (Transatlantic) which can not fully exploit the the ship cost advantage of these ships. To overcome this matter, we made a simulation concerning sea distance as the previous part to survey their efficiency. In longer distances, it appears to be more beneficial when using large vessels. In the case of double sailing distance (Transpacific route), minimum total cost gains at 16,000 TEU size, then comes to 18,000 TEU with triple sailing distance simulation (Far East – Europe route). Nevertheless, cost saving is still limited, even with the latter simulation. In this simulation, from 6,000 TEU to 10,000 TEU, total cost per TEU declines 68 USD (2.6%), from 10,000 TEU to 14,000 TEU, this figure is 39 USD (1.5%) and from 14,000 TEU to 18,000 TEU, the saving is only 21 USD (0.8%).

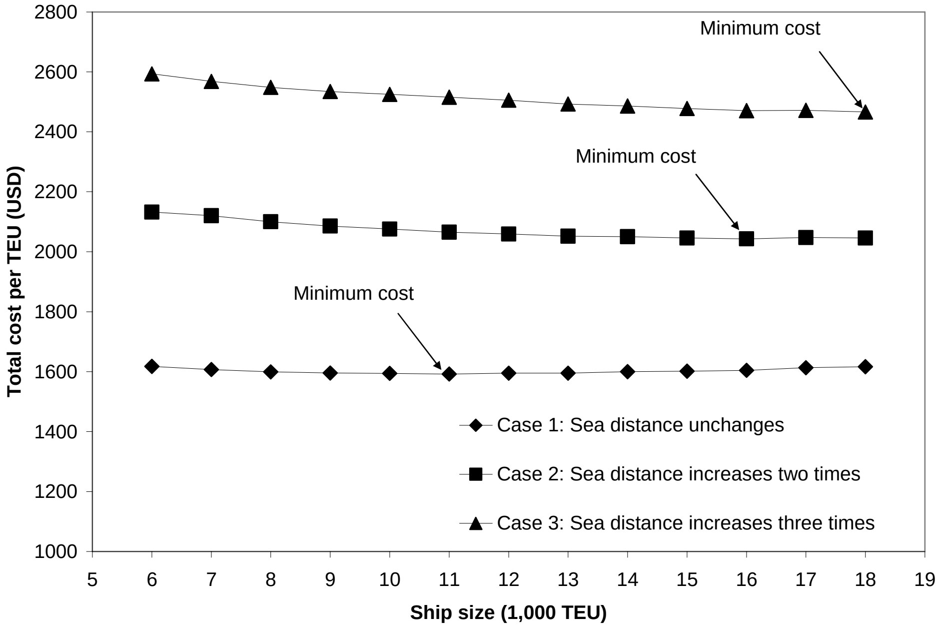

Figure 20: Average total cost per TEU in different simulations
Source: the author

We will assess the impact of ship size to total cost by concentrating on three cost groups. The first are transport and inventory cost during inland and feeder process (inland/feeder cost). The second includes ship cost and inventory cost during sailing time (cost at sea). The third are port-concerned costs: ship cost, inventory cost during time in port and port tariff (cost in port). Logarithm regressions are also taken to consider the correlations between these groups and ship size.

Correlation between inland/feeder cost (y) and ship size (x):

$y = -43.5 \cdot \mathrm{Ln}(x) + 1035$ $R^2 = 0.8085$

Correlation between sea cost (y) and ship size (x):

$y = -89.8 \cdot \mathrm{Ln}(x) + 1310.3$ $R^2 = 0.993$

Correlation between port cost (y) and ship size (x):

$y = 134.1 \cdot \mathrm{Ln}(x) - 750.7$ $R^2 = 0.9579$

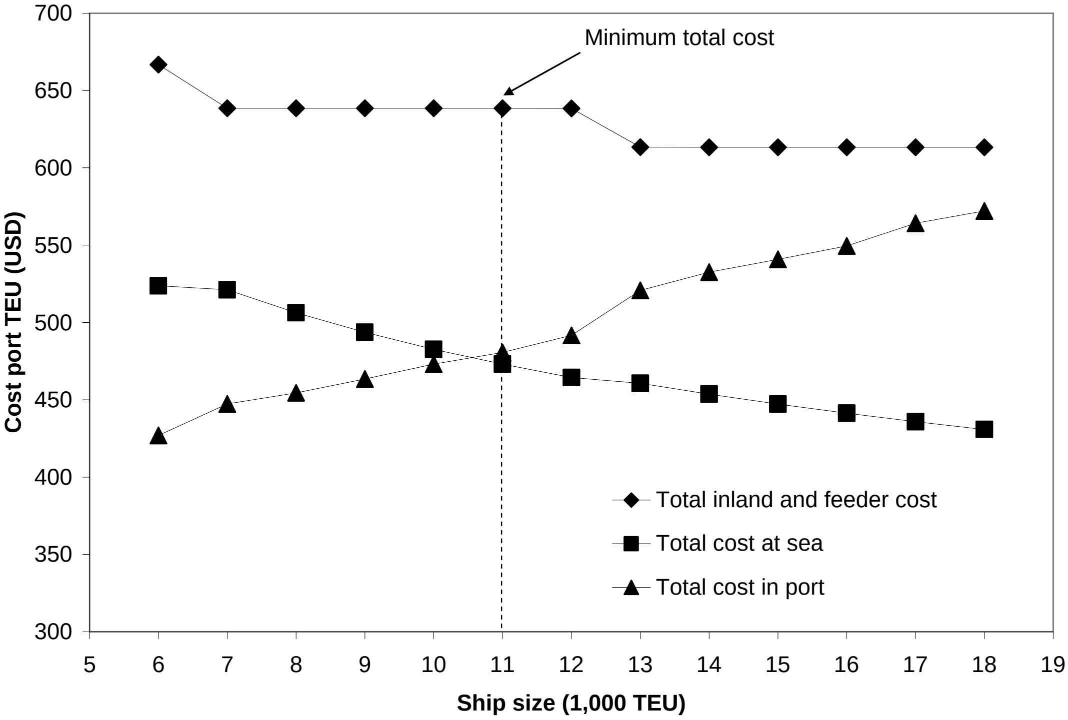

Figure 21: The relationship between ship size and cost elements.
Source: the author

With larger vessels, the inland/feeder cost tends to decline. It can relate to the increase of optimal number of ports mentioned in previous parts which provides denser port coverage. It helps reduce the transport cost between loading/unloading ports and hinterland points. Economies of ship size are also expressed very clearly in the part of sea cost with strict relationship between sea cost and ship size (R-square quite close to 1). Unlike two first groups, the last, cost in port, increases together with ship size. It can origin from more ports in ship's voyage which leads to higher port tariff. As a matter of fact, port tariff is only a minor reason for this increase although port tariff represents from 43% to 57% of the costs arising in ports. The average increase rate is only 0.05% with each 1,000 TEU capacity. The main reason stays on the side of ship cost and inventory cost during time in port. With higher volumes of cargo, large ships must spend more time in ports for loading and discharging. On average, increasing ship capacity each 1,000 TEU will make two costs 2% higher. For ships from 6,000 TEU to 10,000 TEU, ship turnaround time increases 40%; from 10,000 TEU to 14,000 TEU, 37% ; from 14,000 TEU to 18,000 TEU, 20%. In the studies of Baird (2001) and Francesetti & Foschi (2002), the authors also recognized the negative impact of time in port to the efficiency of ship size. However, in their model, they are not concerned with inventory cost of cargo which can not realize further impact of port time. In our case, during time in ports, inventory cost is often two times higher than ship cost.

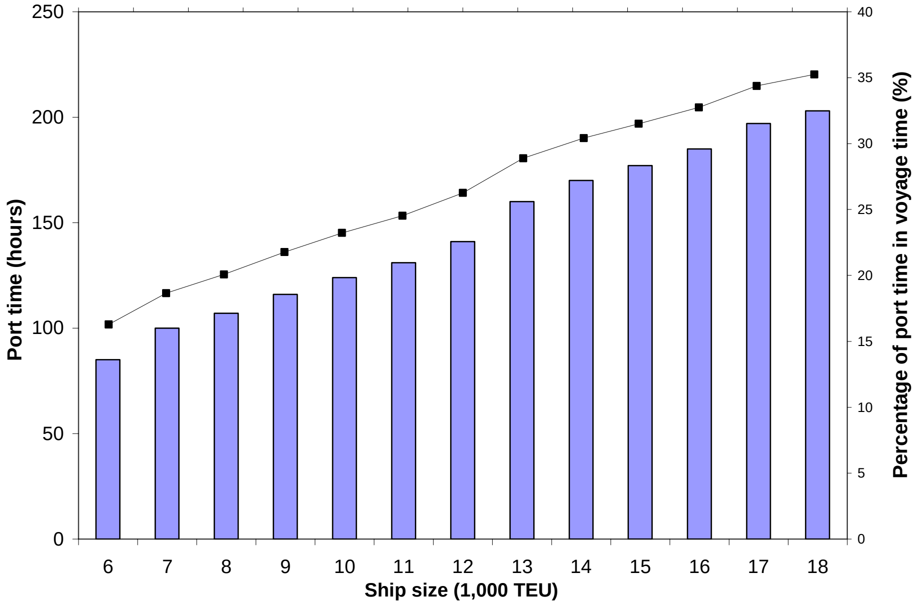

Figure 22:Ship size and time in port
Source: the author

Once again, we must be subjected to the dilemma in defining optimal ship size. Jansson and Shneerson (1987) argued that economies of ship size are enjoyed at sea while diseconomies are suffered in ports. The lower cost at sea can lead to higher cost in ports. We need a balance between them. Port operations can be the main obstacle to gain full advantage of mega vessels. Reducing laytime in port is a key to succeed in deploying them. In most papers studying mega ships, authors put priority concerns on solutions to enhance the efficiency of port operations, especially, cargo handling facilities. (McLellan, 1997; Ashar 2002b; Payer, 2002; Imai, 2007 and Dragovic et al, 2007). Impacts of the handling operation on the efficiency of larger ship have been simulated in our study. In the simulation, only time in port modifies which influences ship cost and inventory cost (cost during time in port), others remain the same state. Firstly, we increase handling productivity by 50% from 198 TEU to 297 TEU per hour, optimal ship size moves from 11,000 TEU to 13,000 TEU. Later, handling capacity is doubled, the minimum cost gains at a size of 18,000 TEU. These results have verified again the importance of improving port operations to mega ship efficiency.

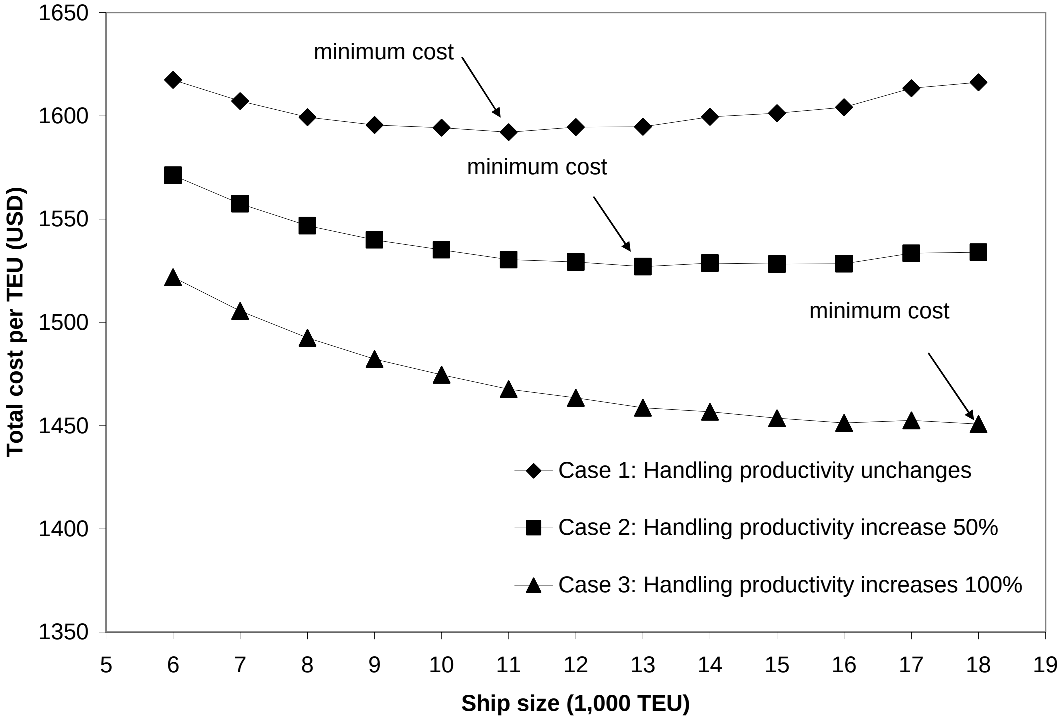

Figure 23: The impact of handling capacity to optimal ship size
Source: the author

4.4 Conclusion

In this chapter, the port selection model has been applied in a real case, container transportation between the USA and Europe, and solved by computational programs. The most priority concern in the application is the quality of input data. The primary data from Piers includes all basic profiles about export/import shipments between two regions. The detailed information helps us to get a quite accurate estimation in many elements which are often barriers in liner network problems: inland connection (by origin/destination of cargo), inventory of cargo (by precise value), handling operation (by number of boxes). Secondary data are retrieved from reliable sources: sea distance from Veson Nautical Distance, inland distance and time from ViaMichellin, cost models from Wijnolst et al (2000), Baird (2001), operational information from APM terminal, Rotterdam.

Results from computational programs and sensitive analyses have proved the appropriateness of our model. On the other hand, they provide us with some in-depth views about liner network matters.

Firstly, shipping is only an element in the whole transport network. The optimal network does not depend only on shipping but also other elements. Ship cost or port tariff plays only a part in the total cost of cargo transportation. In our calculations with different ship sizes, they are even smaller than inventory cost or inland transportation cost. The missing of other elements can deviate the optimality. The lack of inventory cost can dim the negative effect of mega vessels. Without inland transport, we can not fully understand the benefit of the direct call pattern on liner services.

Secondly, the deployment of larger vessels does not mean that the number of port calls will be reduced, on the contrary, they tends to increase. The decrease in port calls can give the advantage of lower ship cost, inventory cost and port tariff, but we must pay a higher inland/feeder transport cost. The extra inland/feeder transport cost is an obstacle to reduce ports in ship’s voyage as well as the use of hub and spoke system as well.

Lastly, when put in an entire network, mega vessels are not as beneficial as desired. Their benefit is only marginal. The main bottleneck is in the port which causes a longer time the ship and cargo are spending in port, consequently, a higher ship cost and inventory cost.

Chapter 5 Conclusion

Port selection can be considered as one of the most sophisticated matters in liner shipping involving many operational factors. It is a key leading to the success or failure of any shipping line. To study this problem, we have concentrated on three main research questions.

In research question 1, we elaborate previous studies concerned with port selection matters. They come from many perspectives with different approaches. Most of these focus only on the sea leg. Evidently, with the development of logistics, a port has become one element in the logistics chain. It is necessary to put ports in the relationship with other elements. Our problem is not new; many authors have tried to deal with it. The only difference is we approach it from a logistics perspective. We consider the optimality of the entire logistics network, not only the shipping network.

In research question 2, we select a non-linear programming model to deal with the routing problem. We are concerned with four main factors in the model: ship cost, inventory cost of cargo, port tariff (port due and handling cost) & inland transport cost. The objective is to minimize the total cost of these components. The model tries to answer three questions:

- Which port should be selected among candidate ports?
- What is the sequence of port calls in a ship’s voyage?
- For each shipment, what are the loading and unloading ports?

With a non-linear programming model, it is quite complicated to find a solution. We propose 4 algorithms to deal with this in the programming language Turbo Pascal 7.0. The model has been applied to solve the cargo flow between the USA and Northern Europe (Transatlantic route) using different sizes of ship. The results of the application have emphasized that the optimal of the entire network does not depend on the efficiency of the sea side alone but it is the combination between seaside and landside. A voyage with a shorter sea distance can reduce ship cost, on the other hand, it can increase considerably inland transport cost.

Regarding research question 3, some sensitive analyses have been made. The number of port calls has much impact on the total cost. This figure is determined by the trade-off analysis between transportation cost (between origin/destination of shipments) and ship cost, inventory cost in voyage time and port tariff. In opposition to some ideas that the number of port calls will be reduced when ship size increases, the results in our case clarify the opposite results. This figure goes in the same direction with ship size.

Cost comparison indicates that the benefit of mega vessels is rather small. It seems to be more efficient when deploying mega vessels on a long route in which the advantage of lower ship cost is upheld. The main barriers of deployment of mega ships stays in ports with the increase of ship turnaround time causing higher ship cost and inventory cost of cargo. Increasing port operations is the key in taking full advantage of these ships.

In summary, the main results of this study are:

- Propose a port selection model from a logistics perspective, a port in the correlation with both sea side and land side operation.
- Insist on the impact of inland/feeder transportation cost (especially inland transportation cost) and inventory cost in optimizing liner routes.

- By studying the number of port calls, affirm advantages of the multi port system compared with the hub & spoke system. The main obstacle for the hub & spoke pattern is higher transportation cost between the shipments's position and hubs.
- Evaluate the viability of mega vessels, realize the marginal benefit as well as some constraints of their deployment.
- By taking simulations, quantify the impact of operational factors such as sea distance, inland/feeder transport or handling operation on the optimal number of port on the ship's voyage as well as the efficiency of mega vessels.

Limitation

The main data are retrieved from Piers. Nevertheless, with some others, we still need to estimate from secondary sources (ship cost, port tariff) or take some assumptions (dwell time, manoeuvring time, inland transport). Although with these secondary data, we have taken some discussions with experts in the maritime field to reduce the error or check the suitability, it can not avoid some gaps compared to the practical operation.

Only a few ports are selected as feeder ports. In fact, many ports can be used to take this function. With inland transport between port and origin/destination of shipments, due to the lack of information, we assume that cargo is carried only by rail or road, yet it is also still used by inland waterway.

The model is applied to the TransAtlantic route, sea distance of which is not so long. Therefore, we can not understand the full effect of mega containers which seem to be more suitable for long distance.

The model is mainly concerned with the economic view, does not deal with technical problems which can get more constraints from ports. Draught restrictions can prevent some large ships visiting a port. Serving a large number of containers in a short time can impact on transfer, yard operations, receipt/delivery (especially in the case of a few transhipment ports). With inland connection, we assume that there is no limitation, actually, when using a large number of vehicles, it can cause a congestion which influences cargo flow.

The greedy algorithm for solving problem is mainly based on the brute force method. This algorithm is not so effective, requires a huge number of calculations expressed by a long running time. With bigger input data, it is not easy to get a solution in a short time.

Future research

With some data able to be retrieved from primary sources, we can update the application to increase the accuracy of input data (for e.g. port tariff, manoeuvring time). The application can expand to other geographical scopes (Far East – Europe or Transpacific) to take the overall effect of mega vessels or transhipment patterns.

Inland transportation should be extended also to inland waterways which are used widely in European ports. Port technical constraints should be considered to get more accurate and reasonable results. In later research, port operations and inland operations which are not mentioned in this paper, should be elaborated on.

Some effective algorithms can be developed to solve the model problems which can expand to more variables, reducing running time, e.g. the approach by the Genetic Algorithm (GA).

References

AXS-Alphaliner (2007). *Liner shipping report*. Retrieved April 14 2007 from the World Wide Web: http://www1.axsliner.com/WWW/research_files/liner_studies/no32/BRS-rep-0701.pdf

AXS-Alphaliner (2007). *The containership market in 2006*. Retrieved April 14 2007 from the World Wide Web: http://www1.axsliner.com/WWW/research_files/liner_studies/misc/container-a.pdf

Ashar, A. (2002a). The fourth revolution. In *Proceedings of The IFPCD 6th regular conference*, Antwerp. Belgium.

Ashar, A. (2002b). The liner shipping of 2020: Equatorial Round-the-world services and Pure Transshipment ports. In *Proceedings of The IFPCD 6th regular conference*, Antwerp. Belgium.

Aversa, R. Botter, R.C. Haralambides, H.E and Yoshizaki, H.T.Y. (2005). A mixed integer programming model on the location of a hub port in the East Coast of South America. *Maritime Economics & Logistics, 7,* 1-18.

Baird, A.J. (1996). Containerization and the decline of the upstream urban port in Europe. *Maritime Policy & Management*, *23*, 145-156.

Baird, A.J (2001). A new economic evaluation of the Hubport versus Multiport strategy. In *Proceedings of IAME Conference*, The Hongkong Polytechnic University, Hongkong.

Baird, A. J. (2002). The economics of transhipment. In Grammenos, C (ed). *The handbook of Maritime Economics and Business.* London and Hongkong: Lloyd of London press, Chapter 36, pp 832-859.

Baird, A.J. (2003). Global Strategy in the Maritime Sector: Perspectives for the Shipping and Ports Industry. *Paper Presented at the Third Meeting of the Inter-American Committee on Ports (CIP).*

Baird, A. J. (2005). Optimising the container transhipment hub location in Northern Europe. *Journal of Transport Geography.*

Cariou, P. (2001). Vertical integration within the logistic chain: does "regulation" play rational? The case for dedicated container terminals. *Transporti Europei, 17,37-41*.

Cariou, P. (2004). Social cost-benefit analysis of Dedicated container terminals. *Proceedings of IAME annual conference*, Dokuz Eylul University, Turkey.

Cho, S.C and Perakis, A.N. (1996). Optimal liner fleet routeing strategies. *Maritime Policy & Management, 23,* 249-259.

Containerisation International Monthly (CI): various issues.

Containerisation International.(2007) *Containerisation International Yearbook.* Informa Group Plc: London.

Coulter, D.Y. (2002). Globalisation of Maritime Commerce: The rise of hub ports. Retrieved April 14 2007 from the World Wide Web: http://www.ndu.edu/inss/books/books_2002/Globalization_and_Maritime_Power_Dec_02/08_ch07.htm

Cullinane, K and Khanna, M. (1998). Economies of scale in large container ships. *Journal of Transport Economics and Policy. 33.* 185-208.

Dragovic, B. Ryoo, D.K. Park, N.K and Radmilovic, Z (2007). Container ship development: a review of state-of-the-art. *Proceedings of IAME annual conference*, Athens. Greece.

Fagerholt, K. (2000). Evaluating the trade-off between the level of customer service and transportation costs in a ship scheduling problem. *Maritime policy & Management, 27,* 145-153.

Fagerholt, K. (2004). Designing optimal routes in a liner shipping problem. *Maritime policy & Management, 31,* 259-268.

Fleming, D.K and Hayut, Y. (1994). Spatial characteristics of transportation hubs: centrality and intermediacy. *Journal of Transport Geography, 2,* 3-18.

Francesetty, D.C and Foschi, A.D. (2002). The impact of hub and spoke networks in the Mediterranean perculiarity. In *Proceedings of IAME Conference* , Panama.

Frankel, E.G (2004). The future of containerization. In *Proceedings of IAME Conference*, Dokuz Eylul University, Turkey.

Fremont, A and Soppe, M. (2004). The evolution of North-European shipping networks: from inter-continential links to a global system, 1990-2000. In *Proceedings of World Conference of transport research.* Instanbul. Turkey.

Fremont, A. (2006). Shipping lines and logistics? In *Proceedings of IAME Conference.* Melbourne, Australia.

Genco, P and Pitto, A. (2000). Transhipment and liner network restructuring: opportunities and threats for Mediterranean ports. In *Proceedings of IAME Conference,* Naples. Italy.

Gilma, S. (1999). The size economies and Network efficiency of Large containerships. *In Journal of Maritime Economies, 1, 39-59.*

Guy, E and Urli, B. (2006). Port selection and multicriteria analysis: An Application to the Montreal-New York alternative. *Maritime Economics & Logistics, 8,* 169-186.

Haralambides, H.E. Cariou, P. Benacchio, M. (2002). Costs, Benefits and Pricing of Dedicated container terminals. *International Journal of Maritime Economics, 4,* 21-34.

Hayut, Y. (1981). Containerization and the Load center concept. *Economic Geography, 57.* 160-176.

Heaver, T. (2002). Supply chain and logistics management: Implications for liner shipping. In Grammenos, C (ed). *The handbook of Maritime Economics and Business.* London and Hongkong: Lloyd of London press, Chapter 17, pp 375-396.

Heaver, T. Meersman, H. Voorde, E.V.D. (2001). Co-operation and competition in international container transport: strategies for ports. *Maritime Policy & Management, 28,293-305.*

Hong, E and Menachof, D. (2004). System dynamics model for port selection. In *Proceedings of IAME Conference,* Dokuz Eylul University, Turkey.

Hsu, C.I and Hsieh, Y.P. (2005). Direct versus hub-and-spoke routing on a maritime container network. *Journal of Marine science and technology, 13,* 209-219.

Hsu, C.I and Hsieh, Y.P. (2007). Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. *Mathematical and Computer Modelling, 45,* 899-916.

Imai, A and Mioajia, L. (2004). A model and solution algorithm for optimal routing problem in competitive circumstances. In *Proceedings of IAME Conference*, Dokuz Eylul University, Turkey.

Imai, A and Papadimitriou, S. (1997). A containerized liner routing in Eastern Asia. *Infrastructure Planning Review, 14,* 843-850.

Imai, A and Rivera, F. (2001). Strategic fleet size planning for maritime refrigerated containers. *Maritime policy & Management, 28,* 361-374.

Imai, A. Nishimura, E. Papadimitriou, S and Liu, M. (2006). The economic viability of container mega-ships. *Transportation Research Part E, 42,* 21-41.

Imai, A. (2007). *Container Shipping Strategies in the Mega-ship era.* Unpublished lecture handout, World Maritime University, Malmo, Sweden.

Ircha, M. C. (2001). Serving tomorrow’s mega-size containerships: The Canadian Solution. *Maritime Economics & Logistics, 3,* 318-332.

ISL (2006). *Market analysis 2006.*

Jansson, J.O and Shneerson, D. (1987). *Liner shipping economics*. London and New York: Chapman and Hall.

Jaramillo, D.I and Perakis, A.N. (1991) . Fleet deployment optimization for liner shipping. Part 2. Implementation and results. *Maritime Policy & Management, 18,* 235-262.

Junior, G.A.D.S. Beresford, A.K and Pettit, S.J (2003). Liner shipping companies and terminal operators: Internationalisation or Globalisation. *Maritime Economics & Logistics, 5,* 393-412.

Kelly, M.E and Miller, H.J. (1994). The hub network design problem. *Journal of Transport Geography, 2,* 31-40.

Lane, D.E. Heaver, T.D and Uyenno, D. (1987). Planning and scheduling for efficiency in liner shipping. *Maritime policy & Management, 14,109*-125

Lee, H.L. Chew, E.K and Lee, L.S. (2006). Multicommodity network flow model for Asia's container ports. *Maritime policy & Management, 33,* 387-402.

Lim, S.M (1994). Economies of container ship size: a new evaluation. *Maritime Policy & Management, 21,*149-159.

Lim, S.M (1996). Round the world service: The rise of Evergreen and the fall of U.S. Lines. *Maritime Policy & Management, 23,119-144.*

Lim, S.M (1998). Economies of scale in container shipping. *Maritime Policy & Management, 25,361-373.*

Lirn, T.C. Thanopoulou, H. Beynon, M.J and Beresford, A.K.C. (2004) An Application of AHP on Transhipment port selection: a global perspective. *Maritime Economics & Logistics, 6,* 70-91.

Ma, S. (2002). *An introduction to Logistics and SCM*. Unpublished lecture handout, World Maritime University, Malmo, Sweden.

Ma, S. (2006). *Maritime Economics*. Unpublished lecture handout, World Maritime University, Malmo, Sweden.

Maersk Line . (2007). *Supply and demand.* Unpublished lecture handout, World Maritime University, Malmo, Sweden.

Malchow, M.B and Kanafani, A. (2001). A disaggregate analysis of factors influencing port selection. *Maritime Policy & Management, 28*, 265-277.

Malchow, M.B. (2001). *An analysis of port selection.* Umpublished Phd's thesis, University of California, Berkeley, USA.

McCalla, R. Slack, B and Comtois, C. (2004). The geographical hierarchy of container shipping networks in the Caribbean basin and Mediterranean sea. In *Proceedings of World Conference of transport research.* Instanbul. Turkey.

McLellan, R.G. (1997). Bigger vessels: How big is too big? *Maritime Policy & Management, 24*,193-211.

McLellan, R. (2006). Liner shipping development trends. *Maritime policy and management, 33*, 519-525.

MDS Transmodal (2006): Can container barges capture a competitive niche in the UK. Retrieved April 14 2007 from the World Wide Web: http://www.mdst.co.uk/homepage.htm

Midoro, R. Musso, E. Parola, F. (2005). Maritime liner shipping and the stevedoring industry: market structure and competition strategies. *Maritime Policy & Management, 32,89-106.*

Mourao, M.C. Pato, M.V and Paixao. A.C. (2001). Ship assignment with hub and spoke constraints. *Maritime policy & Management, 29,* 135-150.

Ng, K.Y (Adolf). (2006). Assessing the attractiveness of Ports in the North European container transshipment market: An agenda for future research in port competition. *Maritime Economics & Logistics, 8,* 2346-250.

Notteboom, T.E. Coeck, C. Verbeke, A and Winkelmans, W. (1997). Containerization and the competitive potential of upstream urban ports in Europe. *Maritime Policy & Management, 24,* 285-289.

Notteboom, T.E. (1997). Concentration and load centre development in the European container port system. *Journal of Transport Geography, 5,* 99-115.

Notteboom, T.E. (2000). The peripheral port challenge in container port systems. In *Proceedings of IAME Conference,* Naples, Italy.

Notteboom, T.E. (2002). The interdependence between liner shipping networks and intermodal networks. In *Proceedings of IAME Conference.* Panama city, Panama.

Notteboom, T.E. (2004). A carrier's perspective on container network configuration at sea and on land. *Journal of international logistics and trade, 1,* 73-100.

Notteboom, T,E. (2006). The time factor in liner shipping services. *Maritime Economics & Logistics, 8,* 19-39.

Oliver, D. (2005). Private entry and emerging partnerships in Container terminal operations: Evidence from Asia. *Maritime Economics & Logistics, 7,* 87-115.

Oliver, D. Parola, F. Slack, B. Wang, J.J (2007). The time scale of Internationalisation: The case of container port industry. (2007) *Maritime Economics & Logistics, 9,* 1-34.

Parola, F. Lee, S.W. Ferrari, C. (2006). Economic integration and logistics restructuring: Rising opportunities for shipping lines in East Asia. In *Proceedings of IAME Conference.* Melbourne, Australia.

Payer, H.G. (2002). Economic and Technical Aspects of Mega-container carriers. In *Proceedings of IAME Conference*, Panama.

Perakis, A.N and Jaramillo, D.I (1991). Fleet deployment optimization for liner shipping. Part 1: Background, problem formulation and solution approaches. *Maritime Policy & Management, 18*, 183-200.

Powell, B.J and Perakis, A.N. (1997). Fleet deployment optimization for liner shipping: an integer programming model. *Maritime policy & Management, 24,* 183-192

Robinson, R. (1998). Asian hub/feeder nets: the dynamics of restructuring. *Maritime Policy & Management, 25,* 21-40.

Rodrique, J.P and Notteboom, T. E (2007). The future of containerization. Box logistics in Light of Global Supply Chains. In *Proceedings of IAME Conference,* Athens, Greece.

Sartini, N. (1999). Transhipment versus Direct ports. In *Proceedings of The Terminal operations Conference & Exhibition.* Genova. Italy.

Shintani, K. Imai, A. Nishimura, E and Papadimitriou, S. (2005). The container shipping network design problem with empty container repositioning. *Transportation Research Part E.*

Slack, B and Fremont, A. (2005). Transformation of port terminal operations: from the Local to the Global. *Transport review, 25,117-130.*

Song, D. Zhang, J. Carter, J. Field, T. Marshall, J. Polak, J. Schumacher, K. Ray, P.S and Woods, J. (2005). On cost-efficiency of the global container shipping network. *Maritime policy & Management, 32,* 15-30.

Song, D.W and Yeo, K.T. (2004). A competitive analysis of Chinese container ports using the Analytic hierarchy process. *Maritime Economics & Logistics, 6,* 34-52.

Stopford, M. (1997) *Maritime Economics.* London: Unwin Hyman Ltd.

Stopford M. (2002). *Is the drive for ever bigger containership irrestible?* Paper presented at Lloyds List Shipping Forecasting Conference 26th April 2002.

Talley, W.K (1990). Optimal containership size. *Maritime Policy & Management, 17,*165-175.

Ting, S.C and Tzeng G.H. (2003) . Ship scheduling and cost analysis for route planning in liner shipping. *Maritime economics and Logistics, 5,* 378-392.

Ting, S.C and Tzeng, G.H. (2004). An optimal containership slot allocation for liner shipping revenue manegement. *Maritime Policy & Management, 31,* 199-211.

Tiwari, P. Itoh, H and Doi, M. (2003). Shippers' port and Carrier selection behaviour in China. A discrete choice analysis. *Maritime economics and Logistics, 5,* 23-39.

Tzong, J. (2001). Key success factors for transhipment hubs: the case of the port of Singapore. In *Proceedings of IAME Conference,* Hongkong.

Ugboma, C. Ugboma, O and Ogwude, I.C. (2006). An analytic hierarchy process (AHP) approach to port selection decisions – Empirical evidence from Nigerian ports. *Maritime Economics & Logistics, 8,* 251-266.

United Nations (1998). Concentration in liner shipping. Retrieved April 14 2007 from the World Wide Web: http://www.eclac.org/publicaciones/xml/5/5175/LC_G.2027.pdf

United Nations Conference on Trade and Development (1990). The establishment of tran-shipment facilities in developing countries

United Nations Conference on Trade and Development (2006). *Review of Maritime Transport 2006.* New York and Geneva: United Nations.

Veldman, S and Buckman, E.H. (2003). A model on Container port Competition: An Application for the Wet European Container Hub-ports. *Maritime Economics & Logistics, 5,* 3-22.

Veldman, S. Buckman, E.H and Saitua, R.N. (2005). River depth and container port market shares: The impact of Deepening the Scheldt river on the West European Hub-port market shares. *Maritime Economics & Logistics, 7,* 336-355.

Wang, J.J. (1998). A container load center with a developing hinterland: A case study of Hongkong. *Journal of Transport Geography, 6,*187-201.

Wedley, W.C. Choo, E.U and Schoner, B. (2001). *Magnitude adjustment for AHP benefit/cost ratios. European journal of operational research, 133,* 342-351.

Wijnolst, N. Waals, F. Bello, F. Gendroneau, Y and Kempen, D.V. (2000). *Malacca-max [2] Container shipping network economy*. Delft: DUP.

Yang, C.H. (2004). The impact of bigger vessels on shipping & ports. Retrieved April 14 2007 from the World Wide Web: http://www.kmi.re.kr/english/data/publication/k2004_02.pdf

Zeng, Z and Yang, Z. (2002). Dynamic programming of port position and scale in the hierachized container ports network. *Maritime policy & Management, 29,* 163-177.

Zijian, G and Hong, H. (2001). An optimization model of international container transport system in China. In *Proceedings of 9th World Conference on Transport research* , Seoul, Korea.

Electronic sources and databases:

Bunkerworld:
http://www.bunkerworld.com/markets/prices/nl/rtm/

Eurostat:
http://www.eurunion.org/profile/facts.htm

Europa:
http://epp.eurostat.ec.europa.eu

Nonlinear Programming Frequently Asked Questions:
http://www-unix.mcs.anl.gov/otc/Guide/faq/nonlinear-programming-faq.html#Q2

Optimization method:
http://www.vias.org/tmdatanaleng/cc_optim_meth_brutefrc.html

Solver Technology – Smooth Nonlinear Optimization:
http://www.solver.com/technology4.htm

Via Michelin – Driving direction:
http://www.viamichelin.com/viamichelin/gbr/dyn/controller/Driving_directions#

US Bureau of Transportation Statistics (BTS):
http://www.bts.gov/

Veson Nautical Distance 2004: database through the access of WMU.

PIERS - the Port Import Export Reporting Service: sea freight cargo profiles between the USA and Europe.

Appendix 1 Sample of cargo flow

(Source: the Port Import Export Reporting Service).

From US to Europe

Ultimate city	COUNTRY	DISCHARGE PORT	LOAD PORT	Original city	Original state	Container size	Container quantity	ESIMATED VALUE IN US$	TEUS
AARHUS	DENMARK	ANTWERP	BALTIMORE		MD	40	1	31062	2.00
AARHUS	DENMARK	ANTWERP	BALTIMORE		MD	40	1	18060	2.00
DUNKIRK	FRANCE	ROTTERDAM	HOUSTON	MONROE	LA	40	2	13090	4.00
LE HAVRE	FRANCE	LE HAVRE	HOUSTON	ST MARTINVILE	LA	20	1	19322	1.00
LILLEBONNE	FRANCE	LE HAVRE	HOUSTON	PT ALLEN	LA	40	1	52227	2.00
LILLEBONNE	FRANCE	LE HAVRE	HOUSTON	PT ALLEN	LA	40	1	62907	2.00
LILLEBONNE	FRANCE	LE HAVRE	HOUSTON	PT ALLEN	LA	40	2	117190	4.00
ST JUST	FRANCE	ANTWERP	HOUSTON	LULING	LA	40	1	18097	2.00
ST JUST	FRANCE	ANTWERP	HOUSTON	LULING	LA	20	2	182728	2.00
ST JUST	FRANCE	ANTWERP	HOUSTON	LULING	LA	20	1	91364	1.00
ST JUST	FRANCE	ANTWERP	HOUSTON	LULING	LA	20	1	91364	1.00
BREMERHAVEN	GERMANY	BREMERHAVEN	HOUSTON	DENVER	CO	20	1	79171	1.00
BREMERHAVEN	GERMANY	BREMERHAVEN	HOUSTON	DENVER	CO	20	1	28479	1.00
BREMERHAVEN	GERMANY	BREMERHAVEN	HOUSTON	W MONROE	LA	40	13	85221	26.00
CELLE	GERMANY	BREMERHAVEN	HOUSTON	DE RIDDER	LA	40	1	41241	2.00
CELLE	GERMANY	BREMERHAVEN	HOUSTON	DE RIDDER	LA	40	1	41011	2.00
HAMBURG	GERMANY	BREMERHAVEN	HOUSTON	SCOTT	LA	40	2	79224	4.00
KIRCHHEIM	GERMANY	BREMERHAVEN	HOUSTON	DE RIDDER	LA	40	1	41011	2.00
KIRCHHEIM	GERMANY	BREMERHAVEN	HOUSTON	DE RIDDER	LA	40	1	37600	2.00
KIRCHHEIM	GERMANY	BREMERHAVEN	HOUSTON	DE RIDDER	LA	40	1	40545	2.00
FELIXSTOWE	U KING	FELIXSTOWE	HOUSTON	DENVER	CO	20	1	541	1.00
FELIXSTOWE	U KING	FELIXSTOWE	HOUSTON	DENVER	CO	40	1	15611	2.00
FELIXSTOWE	U KING	FELIXSTOWE	HOUSTON	DENVER	CO	20	1	358	1.00

From Europe to US

Original city	COUNTRY	Loading port	Unloading port	Ultimate city	Ultimate state	Container size	Container quantity	ESTIMATED VALUE IN US$	TEUS
AARSCHOT	BELGIUM	ROTTERDAM	NEW YORK		NY	20	1	8117	1.00
AARSCHOT	BELGIUM	ROTTERDAM	NEW YORK		NY	20	1	8117	1.00
AARSCHOT	BELGIUM	ROTTERDAM	NEW YORK		NY	20	1	8117	1.00
ANTWERP	BELGIUM	ROTTERDAM	NEW YORK		NY	20	1	207541	1.00
AALBORG	DENMARK	BREMERHAVEN	SAVANNAH		GA	40	1	84736	2.00
AARHUS	DENMARK	BREMERHAVEN	NORFOLK		VA	40	1	25270	2.00
AARHUS	DENMARK	BREMERHAVEN	SAVANNAH	JACKSONVILLE	FL	40	1	57242	2.00
COPENHAGEN	DENMARK	BREMERHAVEN	NORFOLK		VA	20	3	461985	3.00
BREMERHAVEN	GERMANY	BREMERHAVEN	SAVANNAH		GA	40	3	267112	6.00
ENSCHEDE	NETHLDS	ANTWERP	BALTIMORE		MD	40	10	158125	20.00
HELMOND	NETHLDS	ROTTERDAM	SAVANNAH		GA	40	1	81040	2.00
ROTTERDAM	NETHLDS	ANTWERP	BALTIMORE		MD	20	2	301091	2.00
ROTTERDAM	NETHLDS	ANTWERP	BALTIMORE		MD	40	1	18031	2.00
VENLO	NETHLDS	ROTTERDAM	SAVANNAH		GA	20	3	49474	3.00
HALDEN	NORWAY	BREMERHAVEN	NEW YORK		NY	20	5	70503	5.00
HALDEN	NORWAY	BREMERHAVEN	NEW YORK		NY	20	8	126022	8.00
OSLO	NORWAY	BREMERHAVEN	NEW YORK		NY	40	1	42175	2.00
OSLO	NORWAY	HAMBURG	NORFOLK		VA	40	1	30763	2.00
FELTHAM	U KING	FELIXSTOWE	NORFOLK	CINCINNATI	OH	20	1	204171	1.00
GLASGOW	U KING	FELIXSTOWE	NORFOLK		VA	20	1	23857	1.00
IPSWICH	U KING	FELIXSTOWE	NORFOLK		VA	40	2	203788	4.00
KINGS LYNN	U KING	FELIXSTOWE	NORFOLK		VA	ZZ	3	407466	3.00

Appendix 2 Sea distance

(unit:miles)

	LH	AT	RT	BR	HA	FL	NY	CL	HT	NF	SA	BA
LH	0	231	259	441	509	174	3119	3587	4807	3296	3651	3418
AT	231	0	93	283	351	116	3286	3754	4975	3463	3818	3585
RT	259	93	0	235	303	125	3314	3782	5003	3491	3846	3613
BR	441	283	235	0	90	290	3419	3887	5128	3596	3951	3718
HA	509	351	303	90	0	358	3471	3939	5180	3648	4003	3770
FL	174	116	125	290	358	0	3229	3647	4918	3406	3761	3528
NY	3119	3286	3314	3419	3471	3229	0	618	1895	289	682	411
CH	3587	3754	3782	3887	3939	3647	618	0	1357	415	72	532
HO	4807	4975	5003	5128	5180	4918	1895	1357	0	1693	1316	1810
NF	3296	3463	3491	3596	3648	3406	289	415	1693	0	480	151
SA	3651	3818	3846	3951	4003	3761	682	72	1316	480	0	597
BA	3418	3585	3613	3718	3770	3528	411	532	1810	151	597	0

	FL	Arhus	Oslo	Gothenburg
LH	174	635	746	683
AT	116	477	598	533
RT	125	429	550	485
BR	290	216	403	314
HA	358	226	442	324
FL	0	594	581	520

LH: Le Havre
AT: Antwerp
RT: Rotterdam
BR: Bremerhaven
HA: Hamburg
FL: Felixstowe
NY: New York
CH: Charleston
HO: Houston
NF: Norfolk
SA: Savannah
BA: Baltimore

Appendix 3 Optimal voyage records

Ship size: 6,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	340	371	476	489	499	522	529	537	545	557	574
Sailing time (hours)	285	310	409	416	420	437	438	440	442	448	459
Port time (hours)	55	61	67	73	79	85	91	97	103	109	115
Voyage distance (miles)	7056	7672	10122	10295	10381	10797	10842	10873	10936	11078	11346
Ship cost (sailing time) (USD/TEU)	163.05	177.28	233.89	237.89	239.88	249.49	250.53	251.25	252.7	255.99	262.18
Ship cost (port time) (USD/TEU)	31.6	35.04	38.47	41.9	45.33	48.76	52.19	55.62	59.05	62.48	65.91
Inland transportation cost (USD/TEU)	1068.93	854.61	641.89	661.91	622.15	627.94	614.63	602.24	598.51	584.48	563.61
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.23	51.23	20.2	20.19	20.19	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	192.57	204.29	255.74	259.87	262.56	274.24	275.28	276.46	278.23	282.15	289.69
Inventory cost (port time) (USD/TEU)	138.66	133.96	134.55	130.18	132.16	133.15	135.2	137.51	140.99	143.75	147.42
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	14.04	13.28	8.97	8.95	8.83	8.75	8.62	8.25
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	24.72	24.72	9.61	9.6	9.6	6.38	6.48	6.48
Port due (USD/TEU)	12.88	19.31	25.75	32.19	38.63	45.07	51.5	57.94	64.38	70.82	77.26
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2016.42	1830	1732.78	1653.93	1629.94	1617.43	1618.07	1619.64	1621.95	1627.77	1633.8

Ship size: 7,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	341	372	474	487	506	528	536	544	542	554	570
Sailing time (hours)	277	302	398	405	418	434	436	438	430	436	446
Port time (hours)	64	70	76	82	88	94	100	106	112	118	124
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	10936	11078	11346
Ship cost (sailing time) (USD/TEU)	156.38	170.03	224.33	228.16	235.36	244.58	245.58	246.98	242.37	245.51	251.45
Ship cost (port time) (USD/TEU)	35.98	39.36	42.74	46.12	49.5	52.88	56.26	59.64	63.02	66.4	69.78
Inland transportation cost (USD/TEU)	1068.93	854.61	641.86	662.36	608.05	613.36	600.04	596.31	598.49	584.45	563.57
Feeder cost (USD/TEU)	126.16	126.16	126.16	50.94	50.94	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	187.46	198.86	248.96	253	263.21	274.56	275.58	277.29	270.84	274.68	282.02
Inventory cost (port time) (USD/TEU)	150.27	143.94	144.09	138.17	140.59	141.02	142.8	146.23	147.61	150.21	153.79
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	14.05	13.07	8.73	8.72	8.66	8.75	8.62	8.25
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	24.52	24.52	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	12.1	18.14	24.19	30.24	36.29	42.33	48.38	54.43	60.48	66.53	72.57
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2019.85	1830.45	1728.66	1647.56	1621.53	1607.29	1607.17	1608.88	1610.9	1615.88	1620.91

Ship size: 8,000 TEU

Number of ports in ship's voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	342	372	472	485	503	525	533	542	540	551	567
Sailing time (hours)	271	295	389	396	408	424	426	429	421	426	436
Port time (hours)	71	77	83	89	95	101	107	113	119	125	131
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	10936	11078	11346
Ship cost (sailing time) (USD/TEU)	150.93	164.1	216.51	220.21	227.16	236.06	237.02	238.37	233.92	236.95	242.69
Ship cost (port time) (USD/TEU)	39.68	43.02	46.36	49.7	53.04	56.38	59.72	63.06	66.4	69.74	73.08
Inland transportation cost (USD/TEU)	1068.93	854.6	641.85	662.35	608.01	613.31	600	596.27	598.46	584.42	563.4
Feeder cost (USD/TEU)	126.16	126.16	126.16	50.94	50.94	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	183.14	194.29	243.23	247.18	257.18	268.28	269.27	270.95	264.6	268.35	275.6
Inventory cost (port time) (USD/TEU)	160.31	152.58	152.34	145.04	147.19	147.2	148.74	152.14	153.36	155.78	159.34
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	14.05	13.07	8.73	8.72	8.66	8.75	8.62	8.24
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	24.52	24.52	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	11.51	17.27	23.02	28.78	34.53	40.29	46.04	51.8	57.55	63.31	69.06
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2023.23	1831.37	1725.8	1642.77	1615.64	1600.08	1599.32	1600.59	1602.38	1606.65	1610.89

Ship size: 9,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	345	375	473	485	504	525	533	541	548	560	567
Sailing time (hours)	265	289	381	387	400	415	417	419	420	426	427
Port time (hours)	80	86	92	98	104	110	116	122	128	134	140
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	146.35	159.13	209.94	213.53	220.27	228.9	229.83	231.14	231.78	234.73	235.33
Ship cost (port time) (USD/TEU)	43.93	47.24	50.54	53.85	57.15	60.46	63.76	67.07	70.37	73.68	76.99
Inland transportation cost (USD/TEU)	1068.93	854.6	641.7	662.21	607.98	613.28	599.96	596.23	585.82	571.78	563.36
Feeder cost (USD/TEU)	126.16	126.16	126.16	50.93	50.93	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	179.41	190.33	238.44	242.3	251.97	262.84	263.81	265.45	265.9	269.57	270.01
Inventory cost (port time) (USD/TEU)	171.71	162.38	161.75	152.89	154.7	154.21	155.47	158.83	160.62	162.85	165.59
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	14.05	13.07	8.73	8.72	8.66	8.58	8.44	8.24
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	24.51	24.51	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	11.06	16.58	22.11	27.64	33.17	38.69	44.22	49.75	55.28	60.8	66.33
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2030.12	1835.77	1726.97	1641.91	1613.75	1596.94	1595.58	1596.47	1597.69	1601.33	1605.33

Ship size: 10,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	349	378	475	487	505	526	534	542	549	561	568
Sailing time (hours)	261	284	375	381	393	408	410	412	413	419	420
Port time (hours)	88	94	100	106	112	118	124	130	136	142	148
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	142.43	154.86	204.31	207.81	214.37	222.76	223.67	224.94	225.57	228.44	229.02
Ship cost (port time) (USD/TEU)	48.28	51.55	54.83	58.11	61.38	64.66	67.93	71.21	74.49	77.76	81.04
Inland transportation cost (USD/TEU)	1068.93	854.6	641.69	662.21	607.98	613.28	599.96	596.23	585.59	571.54	563.14
Feeder cost (USD/TEU)	126.16	126.16	126.16	50.93	50.93	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	176.14	186.87	234.1	237.89	247.38	258.05	259	260.62	261.16	264.76	265.18
Inventory cost (port time) (USD/TEU)	183.41	172.43	171.35	160.88	162.37	161.39	162.37	165.68	167.46	169.53	172.08
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	14.05	13.07	8.73	8.72	8.66	8.57	8.44	8.23
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	24.51	24.51	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	10.69	16.04	21.38	26.73	32.07	37.42	42.76	48.11	53.45	58.8	64.15
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2038.61	1841.86	1730.15	1643.12	1614.06	1596.12	1594.22	1594.79	1595.63	1598.75	1602.32

Ship size: 11,000 TEU

Number of ports in ship's voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	352	380	475	488	505	527	534	542	550	561	568
Sailing time (hours)	257	279	368	375	386	402	403	405	407	412	413
Port time (hours)	95	101	107	113	119	125	131	137	143	149	155
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	139.01	151.15	199.41	202.82	209.23	217.42	218.31	219.55	220.16	222.96	223.53
Ship cost (port time) (USD/TEU)	51.65	54.9	58.16	61.41	64.66	67.91	71.16	74.41	77.67	80.92	84.17
Inland transportation cost (USD/TEU)	1068.93	854.57	641.69	660.13	605.9	613.27	599.95	596.22	585.56	571.51	563.12
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.61	51.61	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	173.23	183.81	230.24	234.04	243.36	253.79	254.73	256.32	256.86	260.41	260.82
Inventory cost (port time) (USD/TEU)	192.74	180.47	179	167.66	168.91	167.14	167.87	171.15	172.82	174.73	177.19
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	13.99	13.01	8.73	8.72	8.66	8.57	8.43	8.23
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.52	25.52	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	10.39	15.59	20.79	25.98	31.18	36.38	41.57	46.77	51.96	57.16	62.36
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2044.68	1846	1731.78	1643.16	1613.38	1594.47	1592.12	1592.42	1592.94	1595.6	1598.9

Ship size: 12,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	357	385	479	491	509	530	537	546	553	564	571
Sailing time (hours)	252	274	362	368	380	395	396	399	400	405	406
Port time (hours)	105	111	117	123	129	135	141	147	153	159	165
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	136	147.87	195.09	198.42	204.69	212.71	213.57	214.79	215.38	218.12	218.68
Ship cost (port time) (USD/TEU)	56.35	59.58	62.81	66.04	69.27	72.5	75.73	78.96	82.19	85.42	88.65
Inland transportation cost (USD/TEU)	1068.93	854.57	641.68	660.12	605.9	613.27	599.95	596.21	585.56	571.5	563.06
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.61	51.61	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	170.62	181.04	226.77	230.51	239.69	249.97	250.9	252.46	252.99	256.48	256.93
Inventory cost (port time) (USD/TEU)	205.4	191.34	189.37	176.33	177.24	174.89	175.3	178.54	180.05	181.77	184.16
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.28	13.99	13.01	8.73	8.71	8.66	8.57	8.43	8.23
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.52	25.52	9.63	9.62	6.38	6.38	6.48	6.48
Port due (USD/TEU)	10.14	15.22	20.29	25.36	30.43	35.51	40.58	45.65	50.72	55.8	60.87
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2056.17	1855.13	1738.5	1647.9	1617.36	1597.41	1594.55	1594.61	1594.8	1597	1600.06

Ship size: 13,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	361	389	481	493	511	531	539	547	554	565	572
Sailing time (hours)	249	271	357	363	375	389	391	393	394	399	400
Port time (hours)	112	118	124	130	136	142	148	154	160	166	172
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	133.31	144.94	191.23	194.5	200.64	208.5	209.35	210.54	211.12	213.81	214.36
Ship cost (port time) (USD/TEU)	59.78	62.99	66.2	69.41	72.62	75.83	79.04	82.25	85.46	88.67	91.88
Inland transportation cost (USD/TEU)	1068.93	854.56	641.47	659.91	605.88	613.25	599.93	596.2	585.5	571.43	562.99
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.61	51.61	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	168.25	178.54	223.83	227.52	236.38	246.51	247.43	248.97	249.51	252.97	253.41
Inventory cost (port time) (USD/TEU)	214.89	199.52	197.27	182.95	183.52	180.74	180.92	184.13	185.57	187.18	189.48
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.27	13.98	13.01	8.73	8.71	8.66	8.57	8.43	8.23
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.52	25.52	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.93	14.9	19.87	24.84	29.8	34.77	39.74	44.7	49.67	54.64	59.61
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2063.82	1860.96	1742.35	1650.24	1618.98	1598.16	1594.93	1594.79	1594.74	1596.6	1599.43

Ship size: 14,000 TEU

Number of ports in ship's voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	368	395	487	499	516	537	544	552	559	570	577
Sailing time (hours)	246	267	353	359	370	385	386	388	389	394	395
Port time (hours)	122	128	134	140	146	152	158	164	170	176	182
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	130.88	142.31	187.76	190.97	196.99	204.71	205.55	206.71	207.29	209.92	210.46
Ship cost (port time) (USD/TEU)	64.85	68.04	71.23	74.43	77.62	80.81	84.01	87.2	90.39	93.58	96.78
Inland transportation cost (USD/TEU)	1068.93	854.55	641.45	659.89	605.87	613.24	599.92	596.19	585.48	571.42	562.97
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.61	51.61	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	166.09	176.26	220.97	224.62	233.36	243.37	244.27	245.79	246.33	249.74	250.18
Inventory cost (port time) (USD/TEU)	228.58	211.3	208.52	192.36	192.55	189.12	188.99	192.14	193.41	194.82	196.98
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.27	13.97	13	8.72	8.71	8.65	8.56	8.43	8.22
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.52	25.52	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.75	14.63	19.51	24.39	29.26	34.14	39.02	43.89	48.77	53.65	58.53
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2077.81	1872.6	1751.92	1657.76	1625.78	1603.94	1600.28	1599.91	1599.57	1601.03	1603.59

Ship size: 15,000 TEU

Number of ports in ship's voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	372	399	490	502	519	539	547	555	562	573	580
Sailing time (hours)	243	264	349	355	366	380	382	384	385	390	391
Port time (hours)	129	135	141	147	153	159	165	171	177	183	189
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	128.69	139.92	184.6	187.76	193.69	201.27	202.09	203.24	203.81	206.4	206.93
Ship cost (port time) (USD/TEU)	68.33	71.51	74.68	77.86	81.04	84.22	87.39	90.57	93.75	96.93	100.1
Inland transportation cost (USD/TEU)	1068.93	854.54	641.45	659.93	605.88	613.2	599.88	596.15	585.44	571.38	562.93
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.57	51.57	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	164.1	174.15	218.33	221.93	230.6	240.49	241.38	242.89	243.42	246.79	247.22
Inventory cost (port time) (USD/TEU)	238.27	219.64	216.48	199.02	198.99	195.15	194.78	197.9	199.06	200.3	202.37
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.27	13.99	13.01	8.72	8.7	8.65	8.55	8.42	8.21
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.5	25.5	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.6	14.4	19.2	24	28.79	33.59	38.39	43.19	47.99	52.79	57.59
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2086.65	1879.67	1757.22	1661.56	1629.07	1606.47	1602.42	1601.93	1601.36	1602.48	1604.82

Ship size: 16,000 TEU

Number of ports in ship's voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	377	404	493	505	522	542	550	558	565	576	583
Sailing time (hours)	240	261	344	350	361	375	377	379	380	385	386
Port time (hours)	137	143	149	155	161	167	173	179	185	191	197
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	126.68	137.74	181.72	184.83	190.66	198.13	198.94	200.07	200.63	203.18	203.7
Ship cost (port time) (USD/TEU)	72	75.16	78.32	81.49	84.65	87.81	90.98	94.14	97.3	100.47	103.63
Inland transportation cost (USD/TEU)	1068.93	854.54	641.4	659.88	605.88	613.2	599.88	596.15	585.44	571.38	562.93
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.57	51.57	20.2	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	162.26	172.2	215.93	219.49	228.02	237.8	238.68	240.17	240.69	244.02	244.45
Inventory cost (port time) (USD/TEU)	248.44	228.39	224.87	206.05	205.72	201.42	200.79	203.88	204.91	205.97	207.94
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.27	13.98	13.01	8.72	8.7	8.65	8.55	8.42	8.21
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.5	25.5	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.46	14.19	18.92	23.65	28.39	33.12	37.85	42.58	47.31	52.04	56.77
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2096.5	1887.73	1763.64	1666.44	1633.4	1610.03	1605.63	1604.98	1604.17	1604.95	1607.1

Ship size: 17,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	386	413	502	513	530	550	558	566	573	584	591
Sailing time (hours)	237	258	341	346	357	371	373	375	376	381	382
Port time (hours)	149	155	161	167	173	179	185	191	197	203	209
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	124.83	135.73	179.07	182.13	187.88	195.24	196.04	197.15	197.7	200.21	200.73
Ship cost (port time) (USD/TEU)	78.04	81.19	84.34	87.49	90.64	93.79	96.94	100.09	103.24	106.39	109.54
Inland transportation cost (USD/TEU)	1068.93	854.54	641.39	659.87	605.88	613.18	599.87	596.14	585.44	571.37	562.92
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.57	51.57	20.21	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	160.55	170.39	213.66	217.18	225.62	235.3	236.17	237.64	238.16	241.47	241.89
Inventory cost (port time) (USD/TEU)	264.73	242.4	238.28	217.26	216.47	211.38	210.39	213.41	214.25	215.12	216.93
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.26	13.98	13.01	8.71	8.7	8.65	8.55	8.42	8.21
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.5	25.5	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.34	14.01	18.68	23.35	28.02	32.69	37.36	42.04	46.71	51.38	56.05
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2115.15	1903.77	1777.89	1678.33	1644.59	1620.13	1615.28	1614.46	1613.39	1613.83	1615.74

Ship size: 18,000 TEU

Number of ports in ship’s voyage	2	3	4	5	6	7	8	9	10	11	12
Voyage time (hours)	391	417	505	517	534	554	561	569	576	587	594
Sailing time (hours)	236	256	338	344	355	369	370	372	373	378	379
Port time (hours)	155	161	167	173	179	185	191	197	203	209	215
Voyage distance (miles)	7056	7672	10122	10295	10620	11036	11081	11144	11175	11317	11346
Ship cost (sailing time) (USD/TEU)	123.13	133.87	176.63	179.65	185.32	192.58	193.36	194.46	195	197.48	197.98
Ship cost (port time) (USD/TEU)	81.29	84.43	87.57	90.71	93.85	96.98	100.12	103.26	106.4	109.54	112.68
Inland transportation cost (USD/TEU)	1068.93	854.54	641.38	659.86	605.85	613.14	599.83	596.1	585.39	571.33	562.88
Feeder cost (USD/TEU)	126.16	126.16	126.16	51.57	51.57	20.21	20.19	12.96	12.96	13	13
Inventory cost (sailing time) (USD/TEU)	158.96	168.7	211.54	215.03	223.39	232.98	233.85	235.3	235.82	239.08	239.5
Inventory cost (port time) (USD/TEU)	273.9	250.28	245.8	223.55	222.53	217.09	215.88	218.87	219.59	220.26	221.99
Inventory cost (inland transport time) (USD/TEU)	23.52	20.3	17.26	13.98	13.01	8.71	8.7	8.65	8.55	8.42	8.21
Inventory cost (feeder time) (USD/TEU)	59.05	59.05	59.05	25.5	25.5	9.63	9.62	6.38	6.38	6.47	6.47
Port due (USD/TEU)	9.23	13.85	18.47	23.09	27.7	32.32	36.94	41.55	46.17	50.79	55.4
Handling cost (USD/TEU)	200	200	200	200	200	200	200	200	200	200	200
Total cost (USD/TEU)	2124.17	1911.18	1783.86	1682.94	1648.72	1623.64	1618.49	1617.53	1616.26	1616.37	1618.11