IMPACTS OF THE THAI CANAL ON LINER SHIPPING CONTAINER NETWORK

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วิทยานิพนธ์ฉบับนี้นำเสนอแบบจำลองคณิตศาสตร์สำหรับการจำลองการขนส่งตู้คอนเทนเนอร์ในเครือข่ายเรือขนส่งคอนเทนเนอร์ โดยมุ่งเน้นในภูมิภาคอินโด-แปซิฟิก ซึ่งมีช่องแคบมะละกาตั้งอยู่ เพื่อประเมินผลกระทบของคลองไทยต่อเครือข่ายดังกล่าว แบบจำลองที่นำเสนอได้ถูกออกแบบโดยการนำเอาปัญหาต้นทุนการส่งผ่านที่น้อยที่สุดของสินค้าหลายชนิด (Multi-Commodity Network Flow Problem; MCNFP) มาประกอบกับปัญหาการจัดการกองเรือคอนเทนเนอร์ (Liner Shipping Fleet Deployment Problem; LSFDP) เพื่อจำลองปริมาณการค้าระหว่างประเทศ ควบคู่ไปกับการพิจารณาการติดขัดในท่าเรือในเวลาเดียวกัน ผู้วิจัยได้ทำการสอบเทียบแบบจำลองกำหนดการเชิงเส้นแบบผสมเลขจำนวนเต็ม (Mixed Integer Linear Programming; MILP) ที่นำเสนอกับข้อมูลเครือข่ายเรือขนส่งคอนเทนเนอร์ในปี ค.ศ.2015 โดยมีสมมติฐานหลักที่สำคัญ คือ สายการเดินเรือจะให้บริการโดยอ้างอิงจากค่าใช้จ่ายเป็นหลัก ผลการสอบเทียบระบุว่า ปริมาณการขนส่งของเรือคอนเทนเนอร์ที่ได้จากแบบจำลองมีความสอดคล้องกับข้อมูลที่นำมาสอบเทียบในระดับประเทศ หากแต่ยังขาดความแม่นยำในระดับท่าเรือ เนื่องจากสมมติฐานที่ได้ตั้งไว้ ภายหลังการสอบเทียบ ผู้วิจัยได้นำแบบจำลองดังกล่าวมาทดสอบกับเครือข่ายเรือขนส่งคอนเทนเนอร์ที่มีคลองไทยเป็นทางเลือกในการเดินเรือ โดยผู้วิจัยพบว่า คลองไทยสามารถดึงดูดเรือคอนเทนเนอร์ให้เปลี่ยนรูปแบบการเดินเรือจากช่องแคบมะละกาได้ ทั้งในกรณีที่คลองไทยสามารถลดเวลาเดินเรือได้ 2 วัน และในกรณีที่เวลาการเดินทางไม่เปลี่ยนแปลงเมื่อเทียบกับการเดินเรือผ่านช่องแคบมะละกา ซึ่งส่งผลให้ปริมาณเรือที่ผ่านท่า (Port Call) และปริมาณสินค้าถ่ายลำ (Transshipment) ของท่าเรือในช่องแคบมะละกาลดลงอย่างชัดเจน โดยเฉพาะท่าเรือสิงคโปร์

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Krittitee Yanpisitkul : IMPACTS OF THE THAI CANAL ON LINER SHIPPING CONTAINER NETWORK. Advisor: Assoc. Prof. PISIT JARUMANEEROJ, Ph.D.

This thesis proposes a mathematical model that imitates the flow of containers in the container liner shipping network — particularly, in the Indo-Pacific region, where the Strait of Malacca is located — in order to assess the potential impact of the proposed Thai Canal on such a network. This model is constructed based on a combination of two network problems, namely (*i*) the Multi-commodity Minimum Cost Network Flow Problem (MCNFP) and (*ii*) the Liner Shipping Fleet Deployment Problem (LSFDP), which allows a more realistic representation of international trade, while taking to account congestion at container ports at the same time. We validate the resulting mixed-integer linear programming model (MILP) using information of the container liner shipping network in 2015, assuming that liners provide their services based solely on the costs. Based on our computational results, the resulting container flows from the proposed model seem to well align with the actual data at the country level — but with some differences at the port level, due to the posed assumption. Once validated, the model is then applied to a network configuration where the Thai Canal serves as an alternative route to the Strait of Malacca. We explore two distinct scenarios: in the first, the Thai Canal reduces transit time by 2 days; in the second, we consider a scenario where the Thai Canal does not offer any transit time savings. Our experimental results indicate that, under both scenarios, the Thai Canal could instigate a substantial shift in traffic volume from the Strait of Malacca — leading to a significant decrease in port calls and transshipment operations of ports around the Strait of Malacca, particularly the port of Singapore.

Field of Study:	Industrial Engineering	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

Chapter 1 Introduction

1.1 Background

Maritime shipping

Maritime shipping, or seaborne transportation, is one of the world's oldest and most important industries, with a profound impact on the global economy spanning over 5,000 years. Sea transport has long been recognized for driving commerce and promoting economic development (Stopford, 2008). Notably, (Smith, 1776), in his most influential work '**The Wealth of Nations**', highlights the advantages of seaborne transportation for the transportation of goods. He argued that seaborne transportation is more efficient and cost-effective than other modes of transportation, such as land transportation. Two centuries after the publication, maritime transportation remains the most efficient method for transporting substantial volumes of goods at the most cost-effective unit rates (Rodrigue, 2020), despite the advancements in transportation modes such as rail and airplanes. As of 2017, seaborne freight transport carried around 80 percent of global trade by volume and over 70 percent by value (UNCTAD, 2018). Also, regarding global freight demand, around 75.6 out of the 107.7 trillion tonne-kilometers were transported by sea in 2015, representing a substantial 70 percent share. This number indicates the dominance of maritime transportation in facilitating the movement of goods across the globe (International Transport Forum [ITF], 2019).

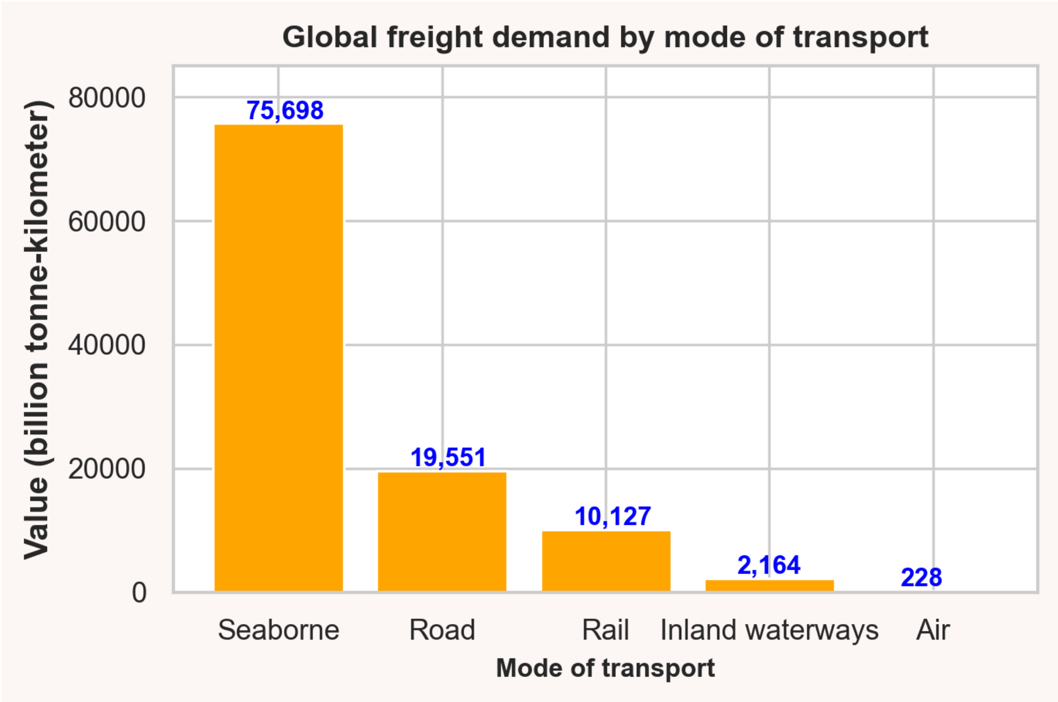


Figure 1.1 Component of transportation mode in global trade (ITF, 2019)

Maritime shipping is the backbone of the global economy and supply chains. It plays a crucial role in the movement of goods in international trade, as it is the most cost-effective and efficient means of transporting large quantities of goods over long distances (Rodrigue, 2020). It is an integral part of the global economy and encompasses a well-coordinated network comprising specialized vessels, ports, and transportation infrastructure that connect factories, terminals, distribution centers, and markets. Waterborne commerce is frequently unrivaled for a variety of commodities and trade routes as an essential complement and occasional alternative to other modes of freight transportation. Maritime transportation has played a pivotal role in globalization by facilitating global transportation services and connecting manufacturers with consumers worldwide. This has expanded the movement of goods and driven the growth of global trade, thereby contributing to the overall expansion of the global economy (Corbett and Winebrake, 2008). In this interconnected landscape, world seaborne trade is closely tied to the state of the global economy and world trade. Consequently, even as the growth rates of global economic output, international trade, and maritime trade shipments might fluctuate and diverge, these variables exhibit a positive correlation (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT [UNCTAD], 2017). Figure 1.2 support the argument and shows the upward trend in maritime trade volume growth with 5.8 % of Average annual growth rate (AAGR) from 2002 to 2018, corresponding with global trade volume (7.7 % AAGR) and the world GDP growth (3.1 % AAGR) in the same period (The World Bank, 2021b).

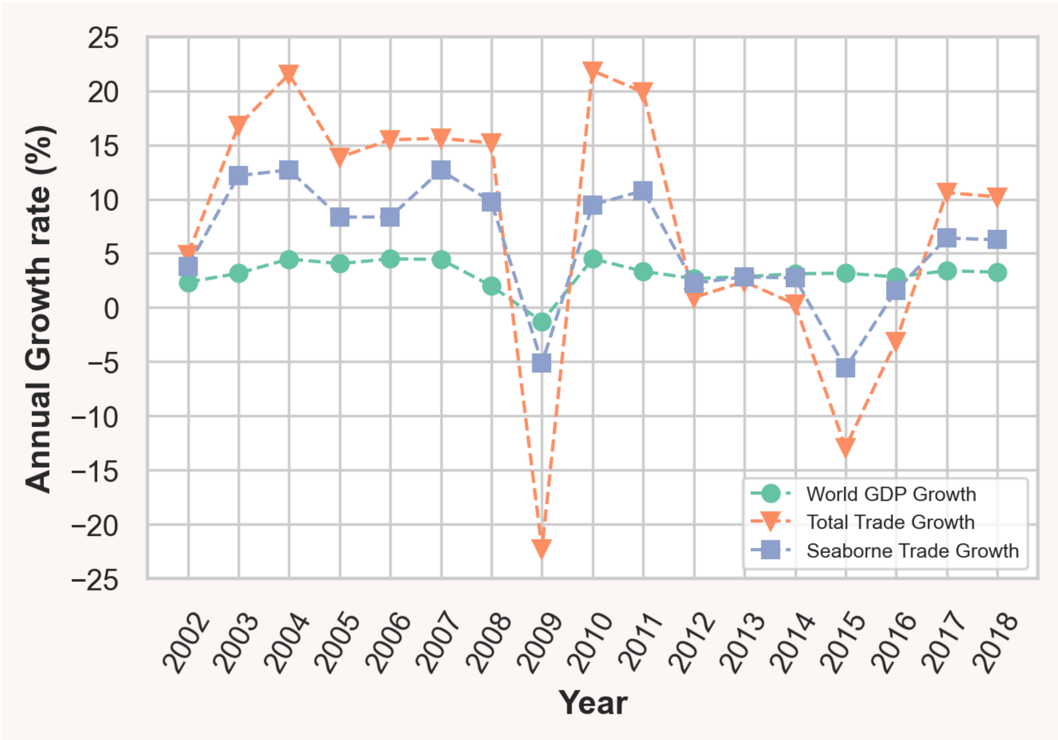
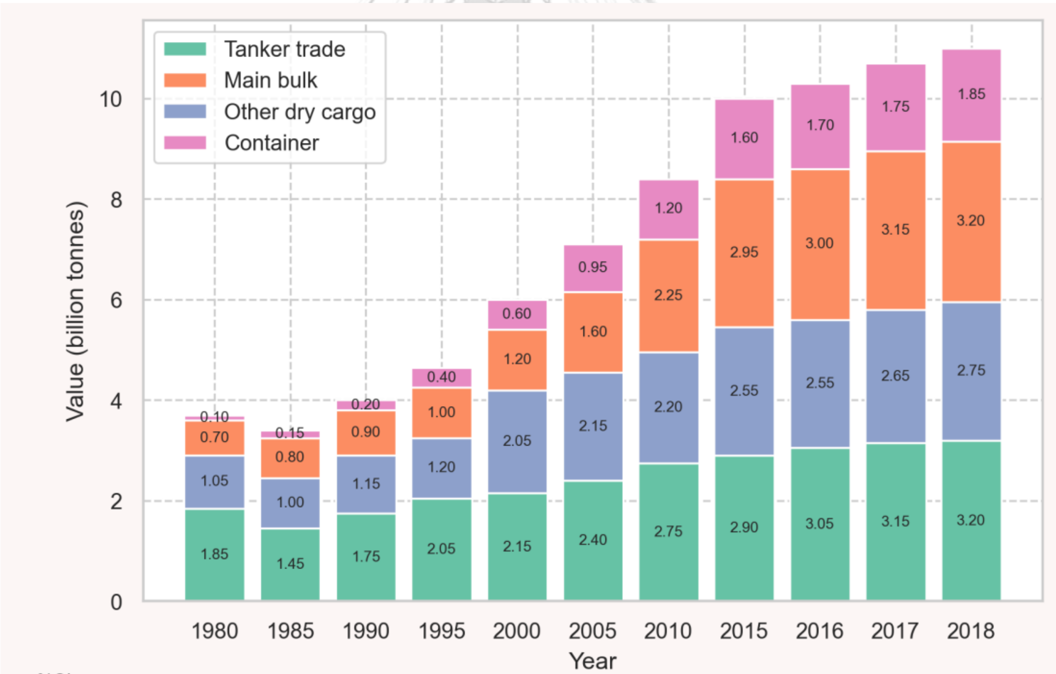


Figure 1.2 Annually growth of global Trade, World GDP, and Maritime Trade (The World Bank, 2021b)

Maritime transportation moves several categories of cargo, which can be classified in a variety of ways depending on the criteria used. Rodrigue (2020) identified maritime cargoes into two main categories: '**general cargo**' and '**bulk cargo.**' General cargo, carried in specific load units, is further categorized into **break bulk**, **neo bulk**, and **containerized cargo**. Break bulk refers to cargo that is transported in individual packages, such as drums, bags, pallets, or boxes. Neo bulk refers to cargo that is individually accounted for, such as lumber, paper, steel, and vehicles. Containerized cargo is transported in container load units. On the other hand, bulk cargo, which is carried loose, is divided into **liquid bulk** and **dry bulk**.

Liquid bulk, often transported in tankers, mainly comprises petroleum and the emerging segment of Liquefied Natural Gas (LNG). Dry bulk includes a range of materials such as coal, iron ore, and grains. Cargo types dictate the kind of vessel utilized for their transportation. General cargo and dry bulk are usually transported by ships referred to as ‘**dry cargo vessels,**’ which come in a variety of types to accommodate the different forms of cargo. On the other hand, liquid bulk cargo, which consists of liquids or gases, is commonly carried by ships designed specifically for this purpose, known as ‘**tankers.**’ The International seaborne trade volume of each cargo type is presented in Figure 1.3. Note that the breakdown by cargo type differs slightly between 1980–2005 and 2006 onwards. In the earlier period, ‘main bulks’ included iron ore, grain, coal, bauxite/alumina, and phosphate. However, starting in 2006, the main bulks only included iron ore, grain, and coal, with bauxite/alumina and phosphate data included under ‘other dry cargo.’



%Share

	1980	1985	1990	1995	2000	2005	2010	2015	2016	2017	2018
Tanker trade	50	43	44	44	36	34	33	29	30	29	29
Other dry cargo	28	29	29	26	34	30	26	26	25	25	25
Main bulk	19	24	22	22	20	23	27	30	29	29	29
Container	3	4	5	9	10	13	14	16	17	16	17

Figure 1.3 Volume of international seaborne trade from 1980 to 2018 by cargo type (UNCTAD, 2018).

As illustrated in Figure 1.3, bulk cargoes, including tankers trade and main bulk, had a dominant presence in maritime trade in terms of volume, accounting for around 60% of the total tonnage from 1980 to 2010. Although the volume of main bulks trade has continued to grow, its share in international seaborne trade has experienced a decline in comparison to previous decades. By 2015, this share had declined to 58%, a significant reduction from 65% in the 1990s. The share of bulk cargoes in international seaborne trade has leveled off since 2015, indicating a shift in maritime trade patterns. This change has allowed for an increased influence of other cargo types, particularly containerized cargo. Containerized cargo, despite its humble beginnings, has experienced consistent growth in recent years in terms of volume. Its volume increased from 0.10 billion tonnes in 1980 to an impressive 1.83 billion tonnes by 2017. This represents a growth of over 1,800 %, and the share of containerized cargo in total seaborne trade volume has increased from 2.7% in 1980 to 16.8% in 2018. Remarkably, its value share has surged even more, with containerized cargo accounting for 60% of total seaborne trade value by 2018 (UNCTAD, 2018).

Since the introduction of containerization in the 1950s by Malcolm McLean, the maritime industry was the first to pursue containerization. Before then, the industry was most restricted by the time required to load and discharge vessels. A typical cargo ship may spend the same amount of time in port as it does at sea. Cargoes were managed by workers who loaded, unloaded, and transported cargo between ships, piers, and warehouses without standard techniques or tools for handling cargo. Containerization enables the mechanization of the handling process since various cargoes have been packed into standard-sized boxes. Previously, loading or unloading a ship was a labor-intensive process that could take days, but now it takes only minutes. It took only a few decades to revolutionize maritime transportation with ease of operations, standard sizes, time, and cost efficiencies. It has been widely adopted in major ports and ship operators across the globe (Notteboom et al., 2022).

Acting as a catalyst for globalization, containerization has played a crucial role in facilitating international trade, aiding in reducing trade costs and allowing for an impressive diversity in the types of goods transported. With the ability to overcome distance barriers, containerization has expanded the scale and volume of global trade, while enabling economies to leverage their comparative advantages more efficiently. The composition of international trade goods carried in containers is vast and diverse. The 20 most important SITC (Standard International Trade Classification) categories accounted for 65% of the global containerized trade, underlining the versatility of containers in transporting a wide range of goods. Furthermore, consumer spending on retail goods accounts for over 75% of container freight flows, illustrating the substantial role of containerization in the global economy (Notteboom et al., 2022).

Moreover, containerized cargo could also be used in intermodal transportation; that is, containers could be used in different modes of transportation in their journey. Containers can be easily loaded onto ships, trucks, and trains, with their operational velocity, allowing for the seamless movement of goods between different modes of transportation. Along with their flexibility of usage, containers can transport a wide variety of goods ranging from raw materials, manufactured goods, and cars to frozen products. There are specialized containers for transporting liquids (oil and chemical products) and perishable food items in refrigerated containers. These advantages accelerate the growth of containers as a dominant means of trade, not just maritime transportation but the whole process of transportation, especially for non-bulk commodities, where the container accounts for more than 90% of all movements. (Rodrigue, 2020).

The use of containers for maritime transportation has increased significantly in recent decades. As illustrated in Figure 1.4, the annual average growth rate between 2002 and 2012 was 9.4%. This growth trend was only briefly interrupted by the global economic crisis of 2008-2009, which resulted in a contraction of container traffic by 8.5% in 2009. However, the overall trend of growth remained robust, and by 2012, the volume of world container traffic had more than doubled from 263 million TEUs (TEU refers to the twenty-foot equivalent unit, a standard measure in the shipping industry) in 2002, reaching 617 million TEUs. This growth has been driven by increasing demand for goods and services, particularly in emerging markets, and the globalization of production processes. However, between 2014 and 2018, the annual average growth of container traffic slowed down to 4.5%. Despite this deceleration, the trend remained positive (The World Bank, 2021a) .

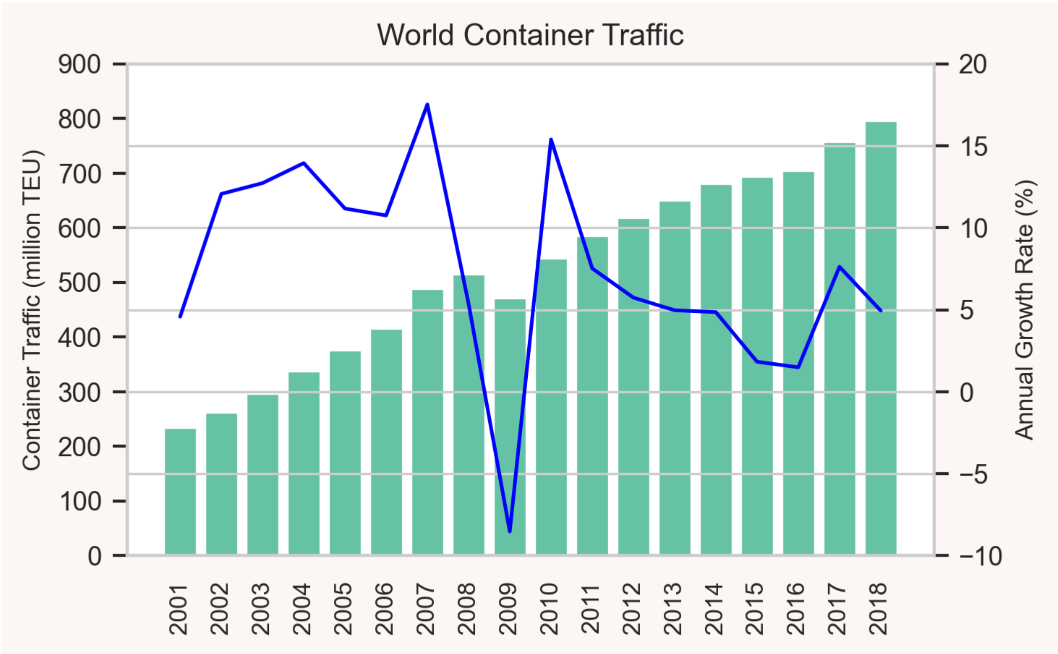


Figure 1.4 The global container traffic volume measured in TEUs and its annual growth rate from 2001 to 2018 (The World Bank, 2021a).

Liner services are a critical component of containerized cargo transportation and have been instrumental in driving its rapid growth in maritime transportation. In maritime shipping, liner shipping refers to the operation of vessels that follow a fixed schedule and route, providing regular services between specific ports along established itineraries, better known as ‘**maritime routes**.’ This operation provides fast, frequent, and reliable transport for a wide range of cargo to numerous foreign destinations, offering predictable charges. These services can encompass global service coverage, connecting ports across different continents, or regional coverage within a specific geographic area (Notteboom, 2006). The service providers of liner shipping, commonly referred to as ‘**carriers**’ or ‘**liners,**’ play a key role in establishing and maintaining a network of maritime routes that facilitate the seamless and reliable transportation of goods.

In terms of regional contribution, Asia plays a crucial role in the container trade volume, as it accounted for over 64% of world container port volume in 2017 (see Table 1.1), with some of the world's busiest container terminals and trade routes located in China, Singapore, South Korea, Japan, and Hong Kong (UNCTAD, 2018). The domination of Asia's container volume can be attributed to two factors: its manufacturing capabilities and transshipment operations. Asia has been a major world manufacturing base, dating back to the 1970s with Japan's industrial development. This was later followed by a wave of globalization, encouraging the outsourcing of manufacturing and services from developed Western countries to low-cost Asian developing countries. Asian economies have been growing rapidly and have become the world factory of finished goods, with China and South Korea leading the way. This chain of events significantly expanded Asia's manufacturing capacity, leading to a large volume of export containers (Su et al., 2011). Another aspect is the transshipment operation. Due to the increasing complexity as well as the scale of shipping networks, transshipment hubs have become increasingly important. These hubs allow shipping lines to consolidate cargo from multiple feeder ports and then transship it to its destination on larger mainline vessels (UNITED NATIONS ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC [UNESCAP], 2007). Due to the vast geography of Asia, this has resulted in the emergence of transshipment ports such as Singapore, Colombo, Hong Kong, Kaohsiung, Busan, and Port Klang. Moreover, Asia is experiencing a rise in industrial activities beyond China, particularly in Southeast Asia, further solidifying its role as a manufacturing powerhouse. This increase is not just supply-side driven but is also supported by the growing demand within Asia. Predictions suggest that by 2040, Asia will account for 39 percent of global consumption, a significant increase from 28 percent recorded in 2017, due to factors such as the growth of the working-age population and urbanization across the region (McKinsey Global Institute, 2019). Asia's contribution to container trade is expected to keep rising because of these changing trends.

Table 1.1 World container port throughput by region, 2016-2017 in TEU (UNCTAD, 2018).

Region	2016		2017	
	Volume	Share	Volume	Share
Asia	454,513,516	64%	484,176,997	64%
Africa	30,406,398	4%	32,078,811	4%
Europe	111,973,904	16%	119,384,254	16%
North America	54,796,654	8%	56,524,056	8%
Oceania	11,596,923	2%	11,659,835	2%
Developing America	46,405,001	7%	48,355,369	6%
World total	709,692,396	100%	752,179,322	100%

Chokepoints in maritime shipping

Seaborne transportation relies on maritime shipping lanes or routes that connect major ports and facilitate the transportation of cargo across vast distances worldwide, spanning from hundreds to thousands of miles. However, certain locations along these routes present challenges to the transportation system. As a result, vessels often navigate through straits, channels, and narrow waterways due to geographical features. These strategic locations, known as '**chokepoints,**' are areas where circulation is constrained and cannot be easily avoided, resulting in significant expenses and delays. Chokepoints play a crucial role in shaping maritime activities, impacting the national interests of countries. They have historical significance in both peaceful and hostile contexts, making them vital considerations in global trade and security (Rodrigue, 2004).

From the complex network of global maritime routes, chokepoints can be identified based on geography, geopolitics, and trade flows. Notteboom et al. (2022) differentiated between core maritime routes, which facilitate significant commercial shipping flows to main markets and secondary routes, primarily connecting smaller markets, but deliberately excluded chokepoints associated with major river systems. They further classify these strategic chokepoints into primary and secondary ones, as depicted in Figure 1.5. Primary chokepoints, such as the Suez Canal, Panama Canal, and Strait of Malacca, are integral to the core routes and provide limited cost-effective maritime alternatives. Secondary chokepoints, like the Magellan Passage and Dover Strait, are acknowledged as important for secondary routes, offering alternative pathways, but their disruption would require substantial detours. Furthermore, they stressed that changes in the technical and operational characteristics of chokepoints could have a significant impact on global trade patterns, highlighting their critical role in maintaining the continuous flow of global freight. They emphasized that four interoceanic passages—the Panama Canal, the Suez Canal, the Strait of Malacca, and the Strait of Hormuz—have a significant impact on global trade patterns due to their strategic location and efficient access to economic activities and resources. However, the Strait of Hormuz is unique in that it is the only chokepoint that provides access to a maritime dead-end, the Persian Gulf, yet critically significant due to its contribution to the global economy as a major oil production hub, accounting for 25-30% of the world's crude oil output. In contrast, the other three chokepoints are located on major maritime shipping routes, which makes them even more important for global trade beyond their direct contribution to resource access.

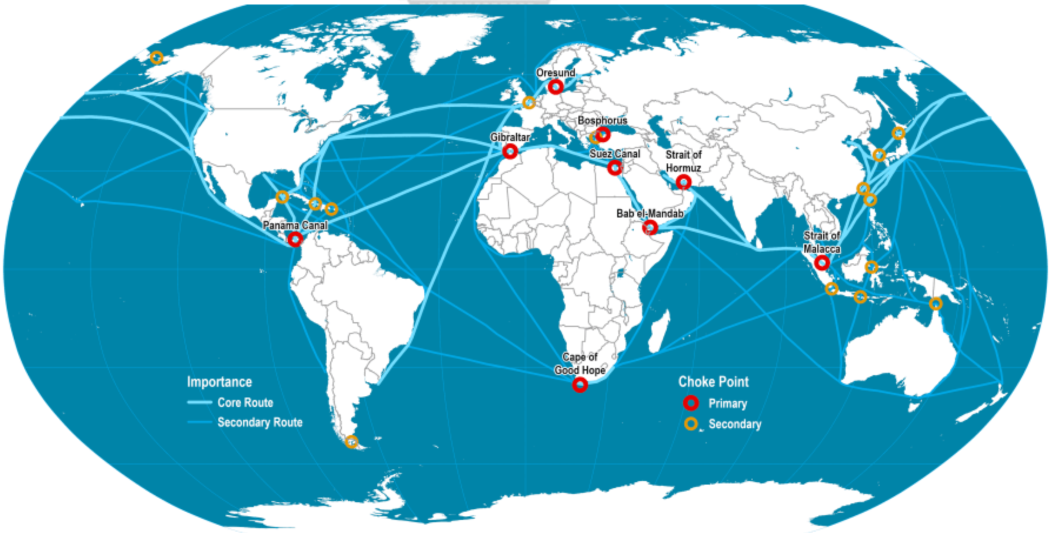


Figure 1.5 Main Maritime Shipping Routes and Chokepoints (Notteboom et al., 2022).

The Strait of Malacca is considered the world's most important bottleneck among these passages. It serves as the main shipping lane connecting the Pacific and Indian Oceans, linking the South China Sea in the Pacific Ocean to the Andaman Sea in the Indian Ocean. Most of the shipments from Europe and the Middle East to East Asia, and vice versa, typically passed through this strait. Some of the intra-Asia shipments also passed through the strait, as it is a major shipping route for goods between countries in the region. Furthermore, the straits also pose strategic importance in terms of oil trade flow, tying the oil-producing countries of the Persian Gulf with the burgeoning consumer countries of East Asia. International Energy Agency [IEA] (2017) estimated that nearly 80 percent of China's crude oil imports pass through the strait from the Middle East and Africa.

The Strait of Malacca is one of the busiest maritime transportation routes in the world. Table 1.2 compares the traffic volumes of the three canals in 2017. The table shows that the Strait of Malacca had the highest traffic volume, with 84,456 ships (with more than 300 gross tonnage) passing through (Maritime Electronic Highway [MEH], 2018). This translates to an average of 231 vessels per day, or nearly 10 vessels entering or leaving the straits every hour, equating to one vessel every six minutes. This figure surpasses the traffic volumes of the Suez Canal, which recorded 51,140 ships (Suez Canal Authority [SCA], 2018) , and the Panama Canal, which saw 44,070 ships (Panama Canal Authority [PCA], 2018), during the same year. The high volume of vessel transit through the Strait of Malacca underscores its vital role in facilitating global maritime trade, especially in intra-Asia and Asia-Middle East-Europe trade.

Table 1.2 Number of ships transit through major chokepoints (MEH 2018; SCA, 2018; PCA, 2018).

Type of Ships	Strait of Malacca	Suez Canal	Panama Canal
Container	24,446 29%	**5,569** **32%**	2,493 18%
Tanker (Liquid Bulk)	**27,340** **32%**	4,537 26%	1,959 14%
Bulk (Dry bulk)	15,411 18%	3,288 19%	**2,915** **22%**
Total	84,456	17,550	13,548

Regarding the distribution of vessel types transiting through the Strait of Malacca, tankers (27,340, 32%) hold the largest share, followed by container ships (24,446, 29%), as indicated in Table 1.2. Despite being the second-largest category in terms of share, container ships continue to hold a prominent position, with a narrow margin of just 3.3% behind. Compared to other key passages, the volume of container ships passing through the Strait of Malacca is considerably higher than the traffic volumes observed in the Suez Canal (5,569 ships) and the Panama Canal (2,493 ships) in the same year. It is worth noting that container ships consistently maintained the largest share of vessel transit through the Strait of Malacca from 2009 to 2016, with the numbers from the table revealing their dominance throughout those years (Hand, 2017). In terms of container volume, Notteboom et al. (2022) estimated the total container traffic nearby ports *with* 59.4 million TEU passing, which suggests that the actual number of ships passing through the strait may have been significantly higher than this figure. Moreover, in terms of liner routes services, the top 100 global container liner shipping companies accounted for 93% of global capacity, operated their container routes in 2015 had 23.13% of global shipping routes that passed through the Malacca Strait, and 32.83% of container ports had shipping route passing through Malacca Strait (Wu et al., 2019).

With the economic importance of the Strait of Malacca, any interruption, failure in critical infrastructure or extreme blockage could have a devastating impact on global trade. International Risk Governance Council [IRGC] (2011) presented a risk governance report on Maritime Global Critical Infrastructure focused on the Straits of Malacca and Singapore as a case study for the development of commonly recognized impacts on the domestic economies of affected littoral states: (Indonesia, Malaysia, and Singapore). The study assumes the loss of international shipping services from the littoral states due to damage to port facilities and the closure of the Straits. Based on a straightforward input-output analysis, the study estimated an economic loss of 18 billion USD in the littoral states alone if the closure lasts for a year as the strait of Malacca is navigationally challenging, with the presence of many navigational hazards, weather, water currents, haze, the high navigational traffic, and the cross-traffic shipping in the Straits of Malacca that could interfere with the navigation of vessels transiting through the strait (Rusli, 2020). The Strait of Malacca has a historical risk of piracy and armed robbery, with Southeast Asia, including the Straits of Malacca and Singapore, being one of the most affected regions globally. Recent efforts by Indonesia and Malaysia have significantly reduced piracy incidents, but vigilance and security measures remain essential for vessels navigating through these busy straits (Lott, 2022). In terms of global trade, the interruption of the Strait of Malacca would have severe repercussions on global trade and energy security, as it serves as a vital passageway for a significant portion of seaborne trade and crude oil transportation. The strait's strategic importance and the dependence of countries, particularly China, on its uninterrupted flow make cooperative efforts crucial in ensuring its security and stability in the global supply chain (Zhong, 2016).

Should any interruption occur in the Strait of Malacca, the Sunda and Lombok Straits offer alternative passages. Located between the Indonesian islands of Java and Sumatra and Bali and Lombok, respectively. However, they introduce certain detours to the maritime routes. Specifically, a container ship on a round trip between the Suez Canal and the Port of Busan in South Korea would have to cover an additional 1,086 nautical miles (2,011.272 kilometers) if using the Sunda Strait and 2,488 nautical miles (4,607.776 kilometers) if using the Lombok Strait. In terms of time, assuming a standard speed of 25.5 knots, this would mean an extra 43 hours via the Sunda Strait and roughly 98 hours via the Lombok Strait. To maintain the schedule, shipping companies might need to increase the ship's speed or introduce additional vessels to the route, both of which could lead to increased costs (Rimmer and Lee, 2007).

Figure 1.6 The strait of Malacca, Sunda Strait and Lombok Strait

(U.S. Energy Information Administration [EIA], 2017)

The Thai Canal Proposal

There has been an idea for an alternative route by constructing a canal through the Southern peninsula of Thailand that enables ships to bypass the Malacca Strait, similar to the Suez Canal and Panama Canal. It is known as '**Kra Canal**' according to the name of Kra Isthmus, the narrowest part of the Malay Peninsula. The idea of constructing a canal across the Isthmus of Kra has been around for centuries. It was first proposed in the 17th century, during the reign of King Narai of Ayutthaya. In the 18th century, during the colonial era, the British and the French saw the possibility of a canal. Both countries were granted permission to survey the area from the Siamese government, which was the former name of Thailand. However, the project was not pursued due to political problems between Thailand, Britain, and France, as well as the high cost of construction (Dobbs, 2016).

Following World War II, Thailand (still named Siam at the time) was expressly prohibited from constructing the Kra Canal under a peace treaty clause enacted by Britain in 1946. This restriction was codified in Article 7 of the treaty, which stated:

“The Siamese Government undertakes that no canal linking the Indian Ocean and the Gulf of Siam shall be cut across Siamese territory without the prior concurrence of the Government of the United Kingdom”. This restriction remained in force until it was lifted in 1954 (Jirawiwat, 2016). Since then, the idea of building a canal across the Malay Peninsula has been the subject of discussion in Thailand, with the potential to boost the country’s economy. There have been numerous attempts to revive the project, but implementation has not progressed beyond the pre-feasibility study stage.

Later, the canal was referred to as the ‘**Thai Canal**’ because of the many proposals to build it in different locations. The Thai Canal project has seen numerous proposals, with a total of 12 routes being considered (Keovimol, n.d.). According to the engineering pre-feasibility study conducted by Tippetts-Abbett-McCarthy-Stratton (TAMS) in 1973, their study is recognized as the earliest comprehensive examination of the Kra isthmus in Thailand, potentially remaining the most thorough analysis to date. The report proposed ten different models, with model 5A being identified as the most feasible option. Model 5A proposed the construction of a single 102-kilometer canal that would connect Satun in the Andaman Sea to Songkhla in the Gulf of Thailand, cutting through Songkhla Lake (Koontanakulvong, 1999). However, following the study conducted by the committee on the Kra Canal Project of the Thai senate assembly in 2005, the study favored model 9A over model 5A due to several reasons. Firstly, model 9A cut through a lower population density area which would result in lower costs for relocation. Additionally, it would have a lesser impact on the environment, as it did not cut through the Songkhla Lake area as model 5A did. Importantly, its location that model 5A is closer to the Malaysian border and too near to the Strait of Malacca. Thus, the canal would not significantly shorten sailing routes. Model 9A was proposed to have a length of approximately 120 km. The plan involved the construction of two parallel canals to facilitate two-way transportation. The canals were estimated to be around 300-350 meters wide, and the turning point had a width of 500 meters (The Senate Ad-hoc Committee on Kra Canal Project, 2005). Nevertheless, after the military coup in 2006, the project was put on hold once more.

Figure 1.7 The proposed model 2A, 5A, and 9A of the Thai Canal (Port Strategy, 2021)

Later in the 2010s, two developments sparked renewed interest in the Thai canal project. This was due to the weakening of Thailand's economy, which had been performing poorly since the 2014 coup. The World Bank estimates that Thailand's economic growth will be the weakest among developing Southeast Asian nations between 2017 and 2019, expanding by just 3.3%. In hoping that the canal could revive the Thai economy, some people argued that the canal would provide a shorter and more direct route between the Indian Ocean and the Gulf of Thailand, which would boost trade and tourism (Parpart, 2018, Mellor, 2017).

The first development was the announcement of plans to build a canal in Nicaragua. In 2012, the Nicaraguan government and a Chinese state-owned enterprise signed a memorandum of understanding to construct a new canal known as the Nicaragua Canal (see Figure 1.8). This ambitious project aims to rival the Panama

Canal and establish a new interoceanic waterway. The Nicaragua Canal, once operational, will provide an alternative route for vessels to pass between the Atlantic and Pacific oceans, challenging the monopoly held by the Panama Cana (Yip and Wong, 2015). The Nicaragua Canal work started in late 2015, expected to take five to seven years to be finished. However, by 2016 the project stalled, and limited information has been released since then concerning its status. In all appearances, it has been abandoned (Notteboom et al., 2022). The construction of the Nicaragua canal has renewed interest in the proposed Thai canal. However, the Thai canal would be much more expensive and technically challenging to build than the Nicaragua canal (Boonma, 2015).

Figure 1.8 The proposed Nicaragua Canal and the Panama Canal (Notteboom, 2018)

The second development that has raised interest in the Thai canal was the Belt and Road Initiative (BRI). In 2013, Chinese President Xi Jinping unveiled the proposal for the ‘Belt and Road Initiative’ or the ‘One Belt & One Road Initiative’ (OBOR), which included the establishment of the “Silk Road Economic Belt” and the “21st Century Maritime Silk Road”, see Figure 1.x. The BRI aims to promote regional economic development by enhancing connectivity and cooperation across Asia, Europe, and Africa. The Silk Road Economic Belt focuses on land routes, while the

21st Century Maritime Silk Road emphasizes maritime routes, with both components seeking to foster trade, infrastructure development, and cultural exchange among participating countries (Huang, 2016).

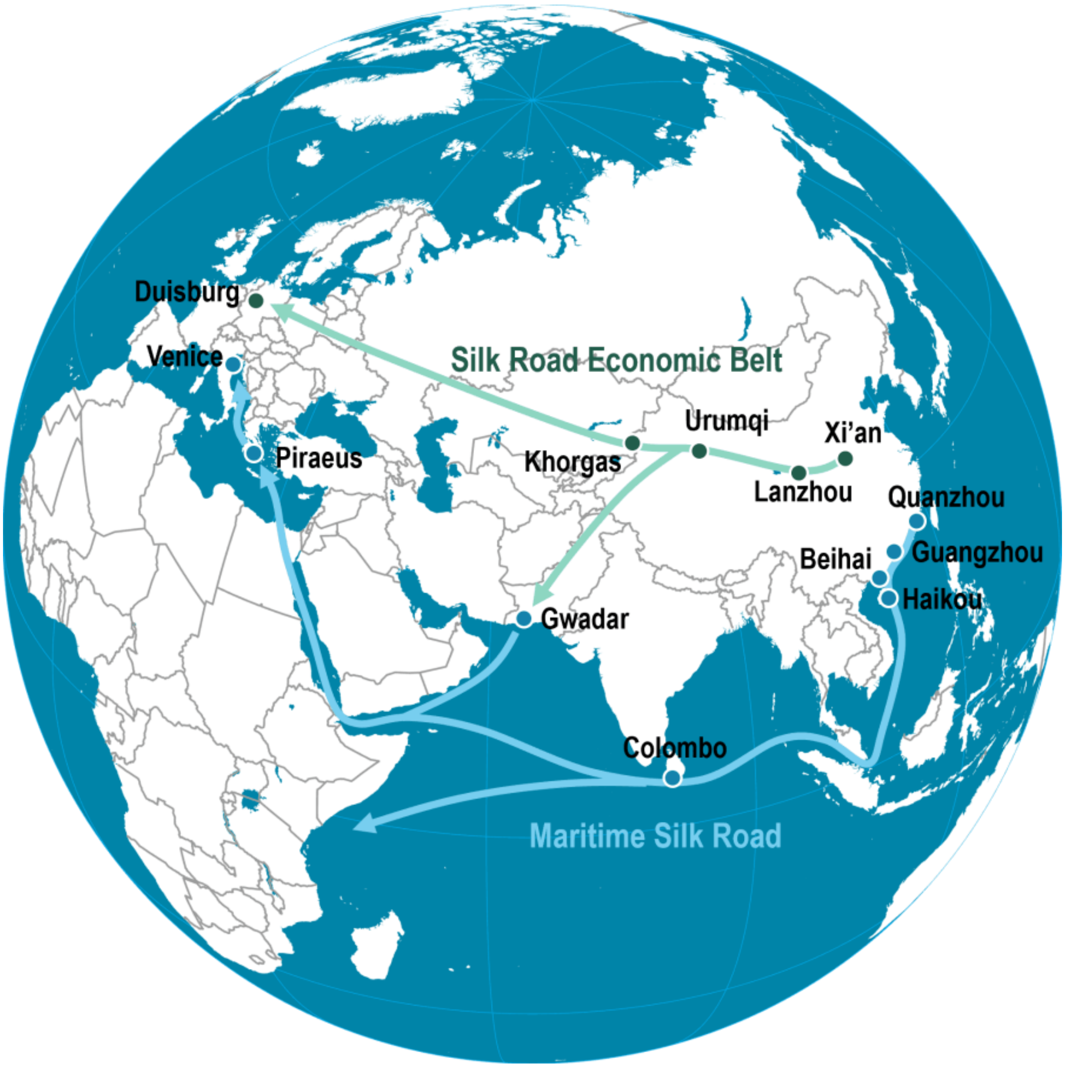


Figure 1.9 The Belt and Road Initiative (Notteboom et al., 2022).

The Maritime Silk Road encompasses routes that extend from China's coastal ports through the South China Sea, reaching the Indian Ocean and connecting to Africa and Europe. Despite the strategic importance of the Strait of Malacca in maritime trade, it should be noted that the Thai Canal is not part of the Belt and Road Initiative (Jariod and Osés, 2020).

In 2017, the construction of a canal across Thailand became the subject of renewed discussions, following the proposed Nicaragua Canal and the Belt and Road Initiative. This reignited the national policy debate on the topic. Advocates, including a Chinese consortium, put forth proposals for the canal, particularly highlighting model 9A as a potential option. This project caught the attention of various stakeholders, such as businessmen, retired military officers, engineers, retired politicians, and bureaucrats, who later formed the Thai Canal Association for Study and Development (TCASD). The TCASD actively organized conferences and conducted site visits to enhance public understanding of the project (Storey, 2019). Additionally, the association urged the Thai government to initiate a feasibility study on the construction of the Kra Canal (Thai Public Broadcasting Service [ThaiPBS], 2020).

In 2018, the Thai government stated that the proposed Kra Canal is not currently a priority project. A review is underway to evaluate its feasibility and potential environmental impact (Nanuam, 2018) Meanwhile, the government is considering the Southern Economic Corridor project, aimed at enhancing transportation connections in southern Thailand. This project includes the development of a port on the Andaman Sea in Ranong and a new railway connecting it to a port in the Gulf of Thailand. These initiatives contribute to the concept of a land bridge in the region (Sabpaitoon and Theparat, 2018).

In 2020, following the 2019 election in Thailand, Members of Parliament (MPs) from the house of representatives proposed a motion to set up a House committee to study the Thai Canal project. The house accepted the motion and set up a committee to study the plan, along with the proposed Southern Economic Corridor (Bangkok Post Editorial Board, 2020). After two years, the committee presented a comprehensive report based on extensive data collection from experts in the public, private, and government sectors. The report was then submitted to the house for a debate and vote, resulting in a majority voting against it. One MP argued that a more thorough study was needed, while another MP contended that the decision should be left to the government’s executive branch (Wipatayotin, 2022).

Although, there are also other ideas for an alternative way for Malacca Strait, such as a hinterland rail network, land bridge, the northern sea route, and pipeline (Peng Er, 2018). The Thai government also has considered a land bridge development plan that encompasses a deep-sea port, motorway, and double-track rail, connecting the Gulf of Thailand and the Andaman Sea on both sides of the peninsula. This option is being explored as it offers advantages such as reduced environmental impact and lower construction costs compared to a canal. The proposed project is still in the early planning stages, with a feasibility study underway to assess its viability (Takahashi, 2022, Muramatsu, 2021).

While the study was conducted by the house committee, in 2020, the Thai government took further action under the Prime Minister's order. The National Economic and Social Development Council (NESDC) was assigned to conduct public hearings and feasibility studies for the Thai Canal or 9A canal route and a double-track railway linking Chumphon and Ranong (Theparat, 2020a, THEPARAT, 2020b). The report was also submitted in 2022, delivering a comprehensive study that includes a review of strategies and studies, data collection on cargo flow, situational analysis of the Gulf of Thailand and Andaman Sea connection, assessment of transportation service demand, comparison of alternative development means, organization of seminars and meetings, and policy recommendations (Chula Unisearch and Office of the National Economic and Social Development Council [NESDC], 2022). However, as of 2023, no further actions have been taken yet.

The potential benefits of the Thai Canal depend on the distance saved and the resulting time savings. However, conflicting reports exist regarding these factors. The study by TAMS (1973, cited in Koontanakulvong, 1999) calculated the time savings that could be achieved by using the Kra Canal (model 5A) instead of the Strait of Malacca. The study found that vessels could save 1.5 days when transiting from the Middle East to Bangkok and 0.45 days when transiting from the Middle East to Yokohama. Nevertheless, the calculation was based on the assumptions of the maritime industry's conditions in the 1960s. Around three decades later, in the report from The Senate Ad-hoc Committee on Kra Canal Project (2005), Keovimol, an advisor of the committee, stated that "If the Thai Canal is completed, these ships will not have to pass the Malacca Strait saving 1,000 – 1,400 kilometers or 2-3 days of travel". There are several expert opinions about the time savings that align with Keovimol's statement. For instance, Chuchottaworn, chairman of the government's steering committee on the economy and former deputy minister of transportation, stated that "using the canal saves only two days of sailing [through the Malacca Straits], which is not attractive enough to draw shippers to change marine routes" (Theparat, 2020a). Furthermore, The Ad-hoc Committee on Considering the Study of Digging Thai Canal and Development of the Southern Economic Corridor (2022) concluded that the Thai Canal has the potential to reduce the distance by 1,200-1,400 km compared to the Strait of Malacca, resulting in a corresponding reduction in travel duration by approximately 1-2 days. Lastly, Notteboom et al. (2022) also argue that the canal is projected to be 102 km long, and it could potentially reduce shipping distance by 1,200 km. This reduction in distance corresponds to a time savings of approximately 2-3 days. Note that these figures do not account for the transit times through the canal itself. However, there are also counterarguments to the potential time savings offered by the Thai Canal. For example, Lane (2015), a consultant in maritime business, established that the distance saved from the canal compared to the Malacca Straits is about 357 nautical miles (661.164 kilometers). The canal would save about 0.7 days of sailing through the Strait of Malacca. This corresponds with the findings of Lohaviriyasiri, a logistics expert and advisor of the Bangkok Shipowners and Agents Association. He spoke at an academic seminar on "What to think about digging Thai canals?" on 6 November 2020. Lohaviriyasiri showed that the canal would save around 293 nautical miles (542.636 kilometers) in comparison to the Strait of Malacca, potentially reducing the travel time by less than one day depending on the sailing speeds in the sea and canal (Cherawattana, 2021).

While the saving distance may not be significant, it could relieve pressure on the strait in terms of maritime security and reduce transportation costs (Kinder, 2007). If the proposed canal were to be constructed, its implications would be far-reaching and multifaceted, spanning areas such as the environment, international politics, national security, and, crucially, maritime security (Cho and Topeongpong, 2015).

The proposed Thai canal has the potential to reshape international maritime trade. This could result in shifts in trade routes, countries' competitive positions, and the economic landscape of the Asia-Pacific region. Container shipping, as one of the major modes of maritime transport, is a complex, dynamic network system that drives global trade. The implications of the Thai canal on container shipping are still yet to be fully explored. As such, this study aims to investigate the impacts of the Thai Canal on container shipping network service routes by developing a model to assess the potential changes in container service routes, while comparing scenarios of different time savings achievable from the Thai Canal. By analyzing these scenarios, the study seeks to provide valuable insights into the potential benefits and effects of the Thai Canal on container shipping networks.

1.2 Objective

The objective of this study is to develop a Mixed-Integer Linear Programming (MILP) model of the maritime container shipping network that can assess the potential impacts of the Thai Canal on the network within ports in the Indian Ocean (excluding the Arab Sea), Southeast Asia, and the South China Sea. Specifically, the study will focus on the Malacca Strait and ports situated in its vicinity.

1.3 Scope

1. This study focused on the containerized maritime cargo networks, which only transport through dedicated container vessels which operated in liner services with cycle port calls.
2. The Thai Canal will only act as a passageway in the maritime network, not operate as a container port.
3. The Thai Canal in this model is assumed to accommodate container ships with a capacity of up to 20,000 TEUs, as well as vessels of smaller sizes.
4. The proposed model will concentrate on the area of interest, which includes major ports in the Indian Ocean (excluding the Arab Sea), Southeast Asia, and the South China Sea.

5. Use the model to compare 3 scenarios.
   a) Base Scenario: This scenario utilizes unaltered data from the real-world network.
   b) The scenario with the Thai canal is constructed, which saves 2-day sailing time compared to the Strait of Malacca, as it is the most claimed to be the savings achieved from the canal.
   c) The scenario with the Thai Canal is constructed, which has the same sailing time as the Strait of Malacca, to further considerations regarding its potential benefits and implications.
6. This study uses estimated and collected/retrieved data from container ports and container vessels only in 2015 to avoid the effect of the Panama Canal Expansion (opening in 2016) and the US-China trade war (2017-2020).
7. The main impact analysis of this study focuses on the port traffic within ports in the Strait of Malacca, examining the container shipping activities and vessel volumes passing through the strait and the Thai canal.

1.4 Benefits

- To explore the impacts of the Thai Canal on the container network.
- To enhance the understanding of the effects of infrastructural changes on the global flow of containerized cargoes.
- To provide a framework for future infrastructure development and policy decisions related to the container network.
- To help predict the economic feasibility of the proposed Thai Canal.

1.5 Outcomes

- The mathematical model for maritime container trade enables comprehensive analysis and prediction of the effects of infrastructural changes on the global flow of containerized cargoes.
- The preliminary result on the impacts of the Thai Canal on container shipping network.

Chapter 2 Literature Review

In this chapter, we provide an overview of maritime cargo transportation, and delve into related theories such as queueing theory, mathematical modeling, and optimization. Additionally, we offer background information on the Strait of Malacca and the ports situated there, context that is crucial for the subsequent comparative analysis of the impacts of the Thai Canal. We then proceed to review and summarize related research on decision-making in maritime transportation, specifically regarding container network, which underscores the objectives of this thesis and reinforces the importance of this research. Finally, to gain a more comprehensive understanding, we review academic literature to encompass both qualitative and quantitative implications of this significant maritime development."

2.1 Maritime Cargo Transportation

(Stopford, 2008, Rodrigue, 2020, Notteboom et al., 2022, Christiansen et al., 2004)

Maritime cargo transportation, maritime shipping, is a vital component of global trade as it facilitates the transportation of substantial freight quantities across extensive distances. In the absence of a comparably efficient substitute, its significance stems from the unparalleled capacity to transport sizable cargo volumes. The systematic expansion of maritime freight traffic finds its roots in a multitude of advantages, including geographical accessibility, operational efficiency, and economic benefits. Maritime transportation offers the advantage of unrestricted access to numerous destinations, including even the most distant regions and secluded islands. Maritime freight transport is also recognized for its capacity to accommodate large quantities of cargo within a single voyage, with an unparalleled efficacy of the revolutionary advent of containerization. Moreover, the cost-effectiveness intrinsic to maritime transportation, particularly for long-distance shipments, unequivocally engenders it as a preference for international commerce.

Maritime transportation involves various participants who play important roles. These players include shippers, port operators, customs authorities, carriers, and consignees. **Shippers** are entities or enterprising individuals responsible for the goods under transit. Among them are manufacturers, exporters, importers, logistics firms, etc. The duty of shippers encompasses packaging and priming the goods for their onward journey, ensuring adherence to pertinent regulations, and organizing their prompt delivery to the port of origin. **Port operators** are organizations that manage and operate ports. They provide infrastructure and services, such as secure berths for docking vessels, cargo-handling apparatus, commodious storage equipment, and logistical sustenance that perpetuate the smooth flow of maritime transportation. Meanwhile, **customs authorities** serve as the vanguards of governance, entrusted with the task of regulating and supervising the intricate movement of goods across international borders. **Carriers** traverse the vast expanse of oceans under various appellations, such as shipping companies or ocean carriers, being responsible for shepherding the maritime transport of goods. Finally, **consignees**, such as individuals, enterprises, or organizations, are the beneficiaries stationed at the destination port. These players work together to ensure the smooth functioning of maritime transportation. Their collaboration is crucial for the efficient movement of goods across international borders and the timely delivery of cargo to their destination.

The classification of maritime shipping vessels and the types of cargo they transport provides a comprehensive understanding of maritime operations. Maritime transportation encompasses various categories of cargo, each requiring specialized vessels for transportation. The main classifications include general cargo and bulk cargo (see Figure 2.1). General cargo consists of unitized shipments that are transported in specific load units, while bulk cargo refers to loose shipments that can be transported in any quantity.

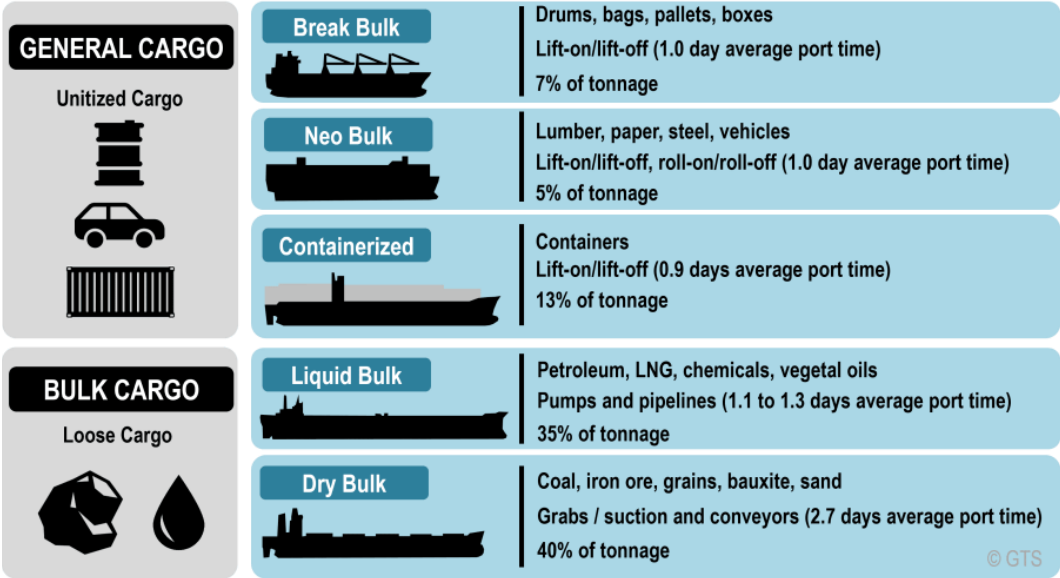


Figure 2.1 Type of maritime cargo (Rodrigue, 2020)

Within the classification of general cargo, three distinct categories can be identified: break bulk, neo bulk, and containerized. Break bulk involves the transportation of goods packaged in drums, pallets, bags, or boxes, using vessels equipped for such purposes. Neo bulk refers to the carriage of cargo in individually accountable pre-packaged units, such as lumber bundles, paper rolls, steel, and vehicles. Containerized cargo represents a classification that emerged with the rise of container shipping, where goods are transported in standardized container load units.

Bulk cargo can be further categorized into two fundamental types: liquid bulk and dry bulk. Liquid bulk shipments predominantly consist of petroleum and liquefied natural gas (LNG), making it a growing sector in the industry. Vessels specializing in the transportation of liquid bulk are commonly known as tankers. Dry bulk encompasses a wide range of materials, including bauxite, coal, iron ore, sand, and grains.

Moreover, for objectives like documentation, customs clearance, logistics planning, and trade analysis, the classification of cargo must be systematic and standardized. In this regard, two widely used classification systems are the Standard International Trade Classification (SITC) and the Harmonized System (HS). The SITC, developed by the United Nations, provides a uniform method of categorizing goods based on their economic attributes and utilization for international trade data purposes. It is predominantly employed for statistical analysis, employing codes that encompass different levels of classification. On the other hand, the HS Code, established by the World Customs Organization, is internationally recognized, and utilized by customs authorities worldwide for customs declarations and trade statistics. It offers a detailed classification of goods, considering their nature, composition, and intended application.

STIC Code	Category	Examples
0	Food & Live Animals	Meat (01), Fish (03), Wheat (041), Rice (042), Corn (044), Orange juice (0591), Sugar (0611), Coffee (071), Cocoa (072), Tea (0741)
1	Beverages & Tobacco	Wine (1121), Beer (1123), Tobacco (12)
2	Raw Materials	Rubber (23), Cotton (263), Iron ore (281)
3	Fuels & Lubricants	Coal (32), Crude oil (333), Kerosene (3342), Natural gas (343)
4	Animal & Vegetable Oils	Olive oil (4214), Corn oil (4216)
5	Chemicals	Salt (52332), Fertilizers (56), Plastics (57)
6	Manufactured Goods	Paper (64), Textiles (65), Cement (661), Iron & Steel (67), Copper (682)
7	Machinery & Transport Equipment	Computer equipment (752), Televisions (761), Cars (781)
8	Miscellaneous Manufactures	Furniture (82), Clothes (84), Footwear (85), Cameras (88111), Books (8921), Toys (894)
9	Others	Postal packets (91) © GTS

Figure 2.2 Standard International Trade Classification SITC (Rodrigue, 2020)

Furthermore, maritime shipping can be broadly classified by mode of operation into three general modes: industrial, tramp, and liner shipping. Industrial shipping is characterized by ownership of ships by the shipper, who aims to minimize overall costs, making it ideal for large corporations transporting large quantities of goods regularly. In contrast, tramp shipping doesn't operate on fixed routes or schedules, as specialized vessels are chartered by individual shippers for specific voyages. This mode is typically used for transporting goods irregularly or to remote destinations. Lastly, liner shipping operates on fixed sequences of ports of call and schedules, with itineraries announced in advance to attract customers. Predetermined routes, frequencies, port arrivals, and departures make liner shipping a suitable choice for shippers requiring regular transportation of goods to a variety of destinations.

Maritime Container Transportation

The advent of container transportation, which was pioneered by the innovative Malcolm McLean in 1956 has brought about a profound revolution in the shipping industry through the introduction of standardized containers for the movement of goods. It is worth noting that prior to the implementation of containerization, the handling of cargo was characterized by a sluggish and laborious process, fraught with risks of damage and delays. McLean's visionary concept of employing large, hermetically sealed containers has effectively streamlined the entire procedure, allowing for a seamless and integrated mode of transportation across different modes of transit. It was under McLean's guidance that the SS Ideal-X, the very first vessel to be fully containerized, embarked on its maiden voyage in 1956, thereby marking the birth of the modern era of container shipping. The resounding success achieved during this momentous journey served as the catalyst for the establishment of Sea-Land Service Inc., thus becoming the pioneering enterprise in the field of container shipping. Containerization performed an indispensable function during globalization by reducing transportation expenses and fostering the expansion of trade.

Container transportation assumes an important function in shaping the contemporary global economy, transforming the way finished goods are transported and distributed across the globe. The utilization of standardized containers has has led to significant improvements in the effectiveness of loading and unloading goods from ships, trucks, and trains, helping faster and more cost-effective logistical operations. A key advantage of containerization is its ability to speed up the delivery of finished goods. Generally, manufactured finished goods, such as electronics, apparel, and consumer wares, necessitate careful handling and safeguarding while in transit, maintaining their quality and guaranteeing punctual delivery to ultimate consumers. Standardized containers furnish a reliable and uniform mechanism for transporting these wares, affording them shelter against harm, pilferage, and inclement weather circumstances. The implementation of container shipping has empowered manufacturers, retailers, and exporters to optimize their supply networks and extend their market penetration.

Containers are standardized reusable units that play a pivotal role in transportation. They are designed to withstand the rigors of shipping. The most commonly used sizes are 20-foot and 40-foot containers. These dimensions have become industry standards. The 20-foot container size is used as the key measurement unit in container shipping, referred to as a TEU (Twenty-foot Equivalent Unit). A 40-foot container, also known as an FEU (Forty-Foot Equivalent Unit), is equivalent to two TEUs. The adoption and widespread use of these standard sizes has greatly simplified international trade. It ensures seamless compatibility across different transportation modes such as ships, trains, and trucks, thereby streamlining logistics.

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The introduction and widespread use of these standard unit sizes – TEU and FEU – has greatly simplified international trade by ensuring compatibility across various transportation modes such as ships, trains, and trucks, thereby streamlining the logistics process. For example, a shipment of goods that is 10 TEUs in size can be easily transported from a ship to a train to a truck, without the need to repack or remeasure the cargo.

Figure 2.3 20-foot and 40-foot containers and their technical characteristics (Haralambides, 2019).

Liner services constitute the fundamental framework of container trade, interconnecting prominent ports and expediting the transportation of goods in an organized fashion. These services are purposefully devised to accommodate the requirements of shipper, encompassing a multitude of trade routes and geographic areas. Liner services exhibit distinctive characteristics comprising fixed timetables, regular departures, and standardized operational protocols. These services provide an array of benefits to cargo consignors, such as dependable transit durations, access to multiple ports, competitive cargo fees, and streamlined logistical oversight. Moreover, liner services can be further classified according to their geographic reach, encompassing intra-regional, intercontinental, or global liner services.

2.2 Queueing Theory

(Hopp and Spearman, 2001, Shortle et al., 2018)

Queueing theory is a mathematical study of waiting lines or queues that form when there are limited resources for providing a service. The queues contain customers, which can be people, objects, or information. For instance, if a bank has only three teller registers, queues will form if more than three customers wish to make their transaction at the same time. The application of queueing theory have seen in telecommunication, traffic engineering, and particularly industrial engineering, which extends to the domain of manufacturing systems, facilitating a comprehensive examination of production line behavior.

A basic queuing system is composed of three principal components, namely the arrival process, the queue itself, and the service process. Figure 2.4 shows the graphical representation of these components and their interactions within the queuing system. The arrival process is depicted by arrows representing the arrival of customers or entities into the system. The queue component is represented by a box symbolizing the waiting area where customers are held until they can be served. The service process is represented by a box with servers inside, indicating the provision of service to the customers in the queue. The number of servers can be a single server or multiple servers, depending on the system design. These components collectively facilitate the flow of tasks within the system. In order to illustrate the fundamental principles of a queuing system, we will examine each of its components in detail as outlined in Figure 2.3 below.

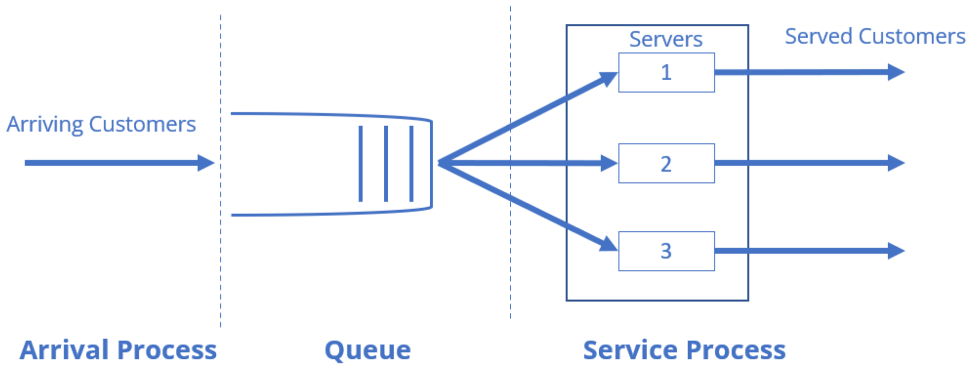

Figure 2.4 The graphical representation of components in queueing system

First, we demonstrate an in-depth understanding of the service process within the system. Consider a manufacturing system where a workstation, which is defined as a grouping of one or more machines or manual stations fulfilling identical functions, is assigned the task of executing a specific operation in accordance with its functionality for a given job. In order to evaluate the performance of the workstation or, several key factors must be considered, including throughput (TH), cycle time (CT), and work-in-process (WIP).

Throughput (TH) refers to the average rate at which the workstation completes jobs or produces output, reflecting its workload efficiency. The workstation is limited by its **Capacity** which is the upper limit or maximum throughput that it can handle effectively. **Work in process (WIP)** represents the inventory or unfinished work at any time within the workstation. **Cycle time (CT)** refers to the average time it takes for a specific job or task to complete its entire routing or process, from the beginning to the end. It represents the duration of the entire production cycle, including the time spent as WIP within the workstation.

By examining the interplay between throughput, process time, and WIP, a comprehensive assessment of the workstation's performance can be obtained, shedding light on its productivity, efficiency, and overall effectiveness in job processing. Fundamental relationship among WIP, CT, and TH. At every WIP level, WIP is equal to the product of throughput and cycle time. This relation is known as Little's law which is defined by the following equation.

$$WIP = TH \ x \ CT \tag{2.1}$$

The relationship has been proved that it holds for all production lines, not just those with zero variability, but also underlying stochastic processes (Little, 2011). Little's law is quite useful in that it can be applied to any system to which entities arrive and from which they depart. As long as the three quantities are measured in consistent units, the aforementioned relationship will hold over the long term. This attribute renders Little's law immensely applicable and relevant to a wide range of practical scenarios. Moreover, it should be noted that Little’s law can be applied to the queueing system.

Since there are no perfect system in practical. Systems usually have random variation as a consequence of events beyond our immediate control. Consequently, we should expect the performance at any workstation to fluctuate. In such cases, the concept of probability becomes essential for capturing and understanding the variability in system processes. For a service process characterized by variability, the **effective process time** of a job at a workstation, which encompasses all relevant factors affecting its progress, serves as a representative parameter for assessing the service process behavior. By focusing on the **mean** of the effective process time, we can establish a robust framework that accounts for the average behavior while acknowledging and managing the inherent randomness present in the system. In addition, **variance** plays a crucial role in quantifying and assessing the extent of variability within the system. However, variance is a measure of absolute variability, which may not always provide a complete understanding of the system's behavior. To analyze variability more comprehensively, the relative measure of variability, such as the **coefficient of variation (CV)**, is more reasonable to consider. The CV, calculated as the ratio of the standard deviation to the mean, considers the scale of the data and allows for meaningful comparison and assessment of variability across different systems or processes.

Second, the arrival process in a queuing system refers to how customers or entities arrive at the system. In the context of a manufacturing system, it involves the transfer of jobs to a specific workstation. Given the stochastic nature of the arrival process, it is necessary to consider the probability distribution that characterizes the times between successive customer arrivals, known as interarrival times. This distribution provides insights into the variability and patterns of customer arrivals or job transfers. There are important parameters that characterize the arrival process in a queuing system. First, we have the **arrival rate (r_a)**, which is measured in jobs or customers per unit time, represents the average rate at which arrivals occur. Note that, in order for the workstation to be able to keep up with arrivals, it is essential that capacity exceed the arrival rate, On the other hand, we have the **mean time between arrivals (t_a)**, which represents the average time duration separating consecutive arrivals. It is worth noting that the arrival rate and the mean time between arrivals are inversely related, meaning that they convey the same information but from different perspectives. Additionally, we have the **coefficient of variation of arrival time (C_a)**, which quantifies the relative variability of the interarrival times in relation to their mean, describing the probability distribution of arrival time. These parameters play a significant role in analyzing queuing systems, as will be discussed in more detail later.

The last principal component of a queuing system is the queue itself. The primary focus is on two essential features of the queue: queue discipline and capacity. Queue discipline refers to the rules or policies that govern the order in which customers or entities are served from the queue. A common in everyday life discipline is first-come-first-served (FCFS). Nevertheless, there exist numerous alternative queue disciplines beyond FCFS. Examples include the last-come-first-served" (LCFS), and the service-in-random-order (SIRO). Queue capacity, on the other hand, refers to the maximum number of customers that the queue can accommodate at any given time.

The components outlined above collectively define the fundamental characteristics of a queueing system. The characteristics of a queue system can be effectively described and analyzed using Kendall's notation (Kendall, 1953), which characterizes a queueing system through four parameters as $A/ B/ m/ b$, where A describes the distribution of interarrival times, B describes the distribution of process times, m is the number of servers at services process, and b, is the maximum number of customers that can be in the system. In many cases, queue capacity is not explicitly constrained (i.e., the buffer is considered very large). We indicate this case simply as $A/ B/ m$.

To provide further insights into the distribution parameters, typical values for A and B can be considered. For instance, the symbol "D" represents a constant or deterministic distribution. The symbol "M" denotes an exponential or Markovian distribution, characterized by memoryless property of a stochastic process. Lastly, the symbol "G" encompasses a completely general distribution, such as normal or uniform distributions, capable of representing a wide range of probability distributions.

The analysis of a queueing system generally focuses on two performance measures, that is the **average waiting time (CT_q)** and the **number of customers in the queue system (WIP_q)**. These metrics are determined by the underlying probability distribution for customers interarrival times and service. It is worth noting that if one of these parameters is known, the other can be calculated using Little's Law and the arrival rate (r_a).

$$WIP_q = r_a \, x \, CT_q \tag{2.2}$$

However, this study specifically concentrate on analyzing the average waiting time in a queueing system. For this purpose, we consider a queue system with general distributions for both interarrival and process times. Moreover, the system consists of multiple servers operating in parallel, which falls under the **G/G/m** queueing model. While the system has characteristics of each component as follows.

t_a is the mean time between arrivals of the arrival process.

r_a is the arrival rate which $r_a = \frac{1}{t_a}$.

C_a is the coefficient of variation of arrival time.

m is the number of servers in the services process.

t_e is the effective process time.

C_e is the coefficient of variation effective process time.

Before getting into the calculation of the average waiting time, it is essential to address a fundamental relation known as **utilization (u)**. Utilization refers to the fraction of time that the service process is busy over the long run, indicating the probability that the station is occupied. In the case of a service process consisting of m identical servers, utilization is formally defined as follows:

$$u = \frac{r_a t_e}{m} \quad (2.3)$$

The average waiting time can be computed by using the following equation.

$$Waiting\ Time = \left(\frac{{C_a}^2 + {C_e}^2}{2}\right)\left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}\right)t_e \quad (2.4)$$

2.3 Mathematical Modeling and Optimization

(Schichl, 2004, Winston and Goldberg, 2004, Bertsimas and Tsitsiklis, 1997, Bradley et al., 1977)

Modeling is the practice of constructing abstractions of systems, which are defined as the collection of entities that comprise the facility or process of interest (Menner, 2015). Modeling is fundamental to providing a framework for analysis in many domains, including science, engineering, and economics. It involves creating a simplified representation of a system, which enables the structured representation of knowledge about the original system and facilitates analysis of the resulting model. In other words, modeling breaks down complex systems into smaller, more manageable parts, allowing for a better understanding of the system as a whole by analyzing the behavior of its components. However, it's important to note that a model can only describe a specific system, and its usefulness is limited by its scope of application.

Mathematics has been a crucial tool for representing and formulating the model. As in science and engineering, mathematical modeling has become a formal framework for demonstrating complex systems. The mathematical model uses mathematical objects to represent systems in a formalized mathematical language, which enables the model to utilize the means to analyze systems precisely through mathematical theory and algorithms. The structure of mathematical models consists of mathematical concepts as follows.

- **Variables**: These represent *unknown* or changing parts of a model.
- **Relations**: These are *equations*, *inequalities*, or other mathematical relationships that define how different parts of a model are related.
- **Parameters**: These are symbolic representations for real-world data, which might vary for different problem instances

Models can be classified as either static or dynamic, depending on whether they represent a system at a particular point in time or how the system changes over time, respectively. Additionally, models can be stochastic or deterministic. A stochastic model includes at least one random variable, while a deterministic model does not. Stochastic models are used to represent systems that involve uncertainty or randomness, while deterministic models are used when all variables are known or assumed to be constant.

Optimization modeling is a widely used application of mathematical modeling that involves finding the best solution to a problem while satisfying a set of constraints and objectives. In this process, mathematical functions are used to represent system goals or objectives, which can be analyzed to explore system trade-offs and find solutions that optimize system objectives.

One common type of optimization model is linear programming, which involves finding the optimal solution to a problem that can be represented by linear equations and inequalities. Linear programming is used in a variety of applications, including production planning, resource allocation, and transportation logistics. By representing complex systems in a simplified way, linear programming can provide a powerful tool for decision-making and optimization in many different fields.

2.3.1 Linear Programming

A linear programming problem (LP) is an optimization problem for which we attempt to maximize or minimize a linear function of the decision variables. While the decision variables must satisfy a set of constraints, which must be a linear equation or linear inequality. In addition to the constraints, there are also sign restrictions associated with each variable. For any decision variable, the sign restriction specifies that the variable must be either non-negative or unrestricted in sign. The mathematical representation of a linear programming problem (LP) with n decision variables and m constraints as follows:

$$Minimize \quad c_1x_1 + c_2x_2 + \cdots + c_nx_n \tag{2.5}$$

$$\begin{aligned} subject\ to \quad a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,n}x_n &= b_1 \\ a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,n}x_n &= b_2 \\ &\dots \\ a_{m,1}x_1 + a_{m,2}x_2 + \cdots + a_{m,n}x_n &= b_m \\ x_1, x_2, \dots, x_n &\geq 0 \end{aligned}$$

where

$x_i \in [x_1, x_2, \dots, x_n]$	is a decision variable.
$a_{i,j} \in [a_{1,1}, \dots, a_{m,n}]$	is a constant of left-hand-side coefficients.
$b_i \in [b_1, b_2, \dots, b_m]$	is a constant of right-hand-side coefficients.
$c_i \in [c_1, c_2, \dots, c_n]$	is a cost coefficient of the variables.

We can rewrite this in Summation form as follows.

$$Minimize \sum_{i}^{N} c_i x_i \tag{2.6}$$

$$subject\ to \sum_{j}^{N} a_{i,j}x_j = b_i \quad \forall i$$

$$x_i \geq 0$$

We can also rewrite this in vector- matrix form as follows.

$$\begin{aligned} Minimize \quad & \boldsymbol{c'x} \\ subject\ to \quad & \boldsymbol{Ax = b} \\ & \boldsymbol{x} \geq 0 \end{aligned} \tag{2.7}$$

Where $\boldsymbol{x}$ is the n-dimensional vector of decision variables., $\boldsymbol{A}$ is the m x n matrix of LHS coefficients of the constraints, $\boldsymbol{b}$ is the m-dimensional vector of RHS coefficients, and $\boldsymbol{c}$ is the n-dimensional cost vector.

The form in (2.7) is the standard form of a linear programming (LP) problem. In standard form, the objective function is to minimize a linear function of the decision variables, subject to a set of linear equality constraints and non-negativity constraints on the decision variables. This form allows for the generalization of all LP problems, as any LP problem can be generalized by applying the following transformations:

- For the maximization problems, it can be consider as minimizing the linear cost function $-\boldsymbol{c}'\boldsymbol{x}$
- For the inequality constraints, we can transform it into equality constraints by adding a slack variable s_j,which is a non-negative variable that represents the surplus or slack in a constraint as expressed follows.

$$\sum_{i}^{n} a_{i,j}x_i + s_j = b_j \tag{2.8}$$

$$s_j \geq 0$$

- For the unrestricted variable, we can replace the unrestricted variable x_r with the difference of two new variables, $x_r = x^{+} - x^{-}$. Where x^{+} and x^{-} are non-negative variables, and we impose the sign constraints $x^{+} \geq 0$ and $x^{-} \geq 0$.
- The inequality constraint $a_{i,j}x_i \leq b_j$ can be equivalently expressed as the inequality constraint $-a_{i,j}x_i \geq b_j$

These transformations enable us to convert any LP problem into the standard form, allowing the use of standard LP algorithms to solve the problem while preserving the objective function and other constraints. As a result, LP techniques can be effectively employed across a broader range of optimization problems, enhancing their applicability and versatility.

Once an LP problem has been converted into the standard form, the next step is to find an LP solution. An LP solution refers to a feasible assignment of values to the decision variables in a linear programming problem that satisfies all the constraints. Two fundamental concepts come into play to find a solution for any linear programming (LP) problem: the **feasible region** and the **optimal solution**. These concepts revolve around the notion of a "**point**," which represents a specific value assigned to each decision variable. The feasible region of an LP problem is the set of all the points that satisfy the problem's constraints and sign restrictions. Within this region, an optimal solution is a point that minimizes the objective function in case of minimization problems or maximizes it for maximization problems Most LPs have either a unique optimal solution or an infinite number of solutions. However, it is also possible for some LPs to have no feasible solution or multiple optimal solutions. The presence of a unique optimal solution depends on the specific problem and its constraints. In cases where the feasible region is unbounded, the LP may have infinitely many optimal solutions. Conversely, if the feasible region is empty or there is a contradiction among the constraints, the LP will have no feasible solution. The feasible region and optimal solution play crucial roles in linear programming as they guide the search for the most favorable outcomes and assist in making informed decisions. To illustrate those concepts, let's consider the following example LP problem:

$$
\begin{aligned}
Minimize \quad & -x_1 - x_2 \\
subject\ to \quad & x_1 + 2x_2 \le 3 \\
& 2x_1 + x_2 \le 3 \\
& x_1, x_2 \ge 0
\end{aligned}
\tag{2.9}
$$

The feasible regions of this LP problem are represented by the shaded area in Figure 2.5 Within this region, the point $(x_1 = 0, x_2 = 1)$ is considered a feasible solution since it satisfies the constraints and sign restrictions. However, the point $(x_1 = 0, x_2 = 2)$ does not belong to the feasible region as it violates the constraint $2x_1 + x_2 \le 3$. Any point that lies outside an LP's feasible region is referred to as an infeasible point, indicating it is an infeasible solution.

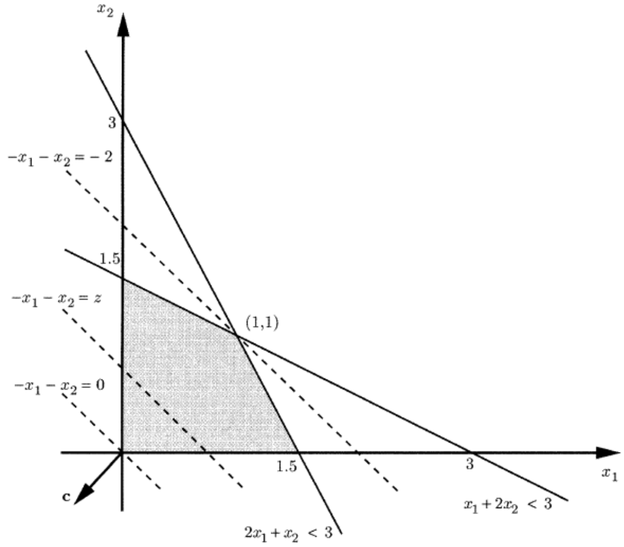

Figure 2.5 Feasible region (Bertsimas and Tsitsiklis, 1997).

To identify an optimal solution, we examine the set of points that yield the minimum objective value. In this problem, the optimal solution is ($x_1 = 1$, $x_2 = 1$), which is unique and offers an objective function value of -2. It's worth noting that this solution corresponds to a corner of the feasible set. This implies that the optimal solution for an LP problem often lies at one of the extreme points of the feasible region.

2.3.2 Integer Linear Programming

An integer programming problem (IP) is an extension of linear programming (LP) where some or all the variables are required to be non-negative integers. This is particularly useful in real-life scenarios that involve discrete value problems. For instance, in production planning, integer programming ensures that production quantities are represented as whole numbers, avoiding impractical fractional values. Another application is modeling specific states, such as on or off, where integer variables, often referred to as binary variables, are used to represent binary choices accurately. By utilizing integer programming, these real-life problems can be effectively formulated and solved, considering the discrete nature of the variables involved.

Integer variables in these formulations can generally take any integer value. Integers that should only take the values of 1 or 0 are known as binary (or Boolean) variables. Binary variables are also often referred to as Boolean variables because the Boolean values of true and false are analogous to 1 and 0. The IP problems that only contain binary variables are referred to as Binary Integer programming, "**BIP**".

Another formulation is Mixed Integer Programming (**MIP**). This approach extends the concept of integer programming (IP) by allowing a mixture of both integer and continuous variables within the problem. Not every variable is required to be an integer in MIP, which allows for greater flexibility in modeling complex situations. This makes MIP well-suited to real-world optimization problems, like supply chain management, where decisions might involve a mix of discrete and continuous variables. MIP problems with linear objectives are specifically termed as Mixed Integer Linear Programming (**MILP**) problems.

Solving Integer Linear Programs (ILPs) presents more complexity compared to Linear Programs (LPs). This arises from the fact that the optimal solution for an ILP does not necessarily correspond to the closest integers to the LP solution. Simply rounding the LP solution to the nearest integer values may yield a solution that is either not optimal or infeasible for the ILP. To illustrate this point, let us consider the following Integer Linear Programming (ILP) problem:

$$\begin{aligned} &Maximize \quad 21x_1 + 11x_2 \\ &subject\ to \quad 7x_1 + 4x_2 \leq 3 \\ &x_1, x_2 \geq 0;\ x_1, x_2\ integer \end{aligned} \tag{2.10}$$

The feasible regions of this MILP problem are represented by the shaded area in Figure 2.6. While consider this problem as LP, neglecting the integer constraints, the optimal solution would be $(x_1 = \frac{13}{7}, x_2 = 0)$, which gives the objective value of 39. However, when we round the LP optimal solution to $(x_1 = 2, x_2 = 0)$, this point is infeasible region. Furthermore, if we consider all points in feasible region, which x_1 and x_2 are integer, we found that the optimal solution of this problem is $(x_1 = 0, x_2 = 3)$.

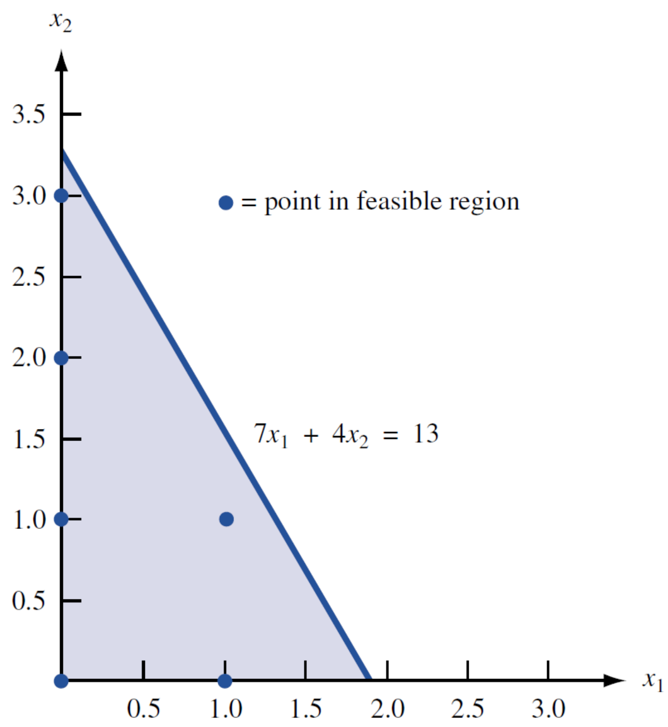

Figure 2.6 Feasible Region for Simple IP

The technique of transforming an Integer Programming (IP) problem into a Linear Programming (LP) problem is referred to as 'LP relaxation'. It is a crucial technique used to find solutions to Integer Programming (IP) problems. This approach involves the transformation of an IP problem into an LP problem by disregarding or 'relaxing' the integrality constraints. The significance of this method lies in its ability to simplify the original problem, creating a Linear Program with fewer constraints and, consequently, more solution flexibility. It's noteworthy that although the feasible region for an Integer Linear Program (ILP) is a subset of that for its LP relaxation, the IP is typically harder to solve.

The optimal cost from the LP relaxation is guaranteed to be less than or equal to that of the original problem. If the optimal solution of the LP relaxation also satisfies the integer conditions, it simultaneously provides the optimal solution to the original IP. However, if the solution isn't integer, one feasible (though not necessarily optimal) solution to the original problem can be obtained by rounding up each variable.

2.3.3 Network Model

Network representations are a valuable tool for analyzing optimization problems in Operations Research (OR) due to the wide range of decision problems that involve interconnected systems, particularly in the field of Logistics. One common scenario in industrial logistics is the distribution of a single homogeneous product from plants (origins) to consumer markets (destinations). This scenario presents a network-flow problem where the focus is on optimizing the flow of the product through the interconnected system.

Network models offer a structured approach to represent and optimize complex interactions within a system. By utilizing the special structure of network models, specialized algorithms have been developed to efficiently solve these problems. This has allowed researchers and practitioners to tackle large-scale network models that would otherwise be challenging to solve using traditional linear programming techniques.

A network, or graph, is a conceptual structure that can be described by two fundamental objects: **nodes**, also known as **vertices**, and **arcs**, also known as **edges**.

We can represent a graph as $G = (N, A)$ where N represents the set of nodes or vertices, and A represents the set of arcs or edges connecting these nodes.

The nodes in the graph can represent a wide range of objects or entities, such as locations, individuals, or data points, depending on the context of the network. The edges, on the other hand, describe the interactions, dependencies, or associations between the nodes. Nodes represent individual entities or points within the network, while arcs represent the connections or relationships between nodes. Arcs can be either directed or undirected, depending on the nature of the relationship they represent.

Figure 2.7 illustrates an example of a directed graph. The nodes are represented by numbered circles and the arcs by arrows. The arcs are assumed to be directed so that, for instance, material can be sent from node 1 to node 2, but not from node 2 to node 1. Generic arcs will be denoted by (i, j), so that $(2,3)$ means the arc from node 2 to node 3. The mathematical representation of this graph can be expressed as $G = (N, A)$ where $N = \{1, 2, 3, 4\}$ and $A = \{(1,2), (2,3), (3,4), (4,3), (4,1)\}$.

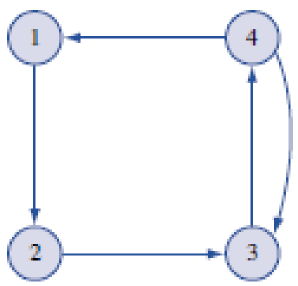

Figure 2.7 Example of a directed graph (Winston and Goldberg, 2004)

One concept about networks that is crucial to understand and further explore is the notion of a **path**. A path in a network refers to a sequential collection of arcs where the terminal node of each arc is identical to the initial node of the next arc. It is a connected sequence of arcs that allows traversal from one node to another, following the defined connections between them.

Maximum-Flow problems

Maximum-flow problems is one of occur when a network model represents various scenarios, with arcs symbolizing capacity-constrained connections through which a limited quantity of resource can be transported with no costs associated with flow. The primary objective of these problems is to determine the optimal flow, aiming to transport the maximum amount of the product from a designated starting point, referred to as the **source**, to a designated endpoint known as the **sink**. Hence, these problems are commonly referred to as maximum-flow problems. The focus lies on finding the most efficient flow distribution within the network, considering the capacities of the arcs, to achieve the highest possible volume of transportation from the source to the sink.

Let v denotes the amount of material sent from node s to node t and $x_{i,j}$ denotes the flow from node i to node j over arc (i,j) with the flow upper bound of $u_{i,j}$. The Maximum-flow problems can be formulated as follows:

$$Maximize \quad v \tag{2.11}$$

$$subject\ to \quad \sum_j x_{i,j} - \sum_k x_{k,j} = \begin{cases} s_i, & if\ i = source \\ -d_i, & if\ i = sink \\ 0, & otherwise \end{cases}$$

$$x_{i,j} \le u_{i,j}$$

$$x_{i,j} \ge 0$$

Minimum-Cost Network Flow Problems

Minimum-Cost Network Flow Problems (MCNFPs) are a class of optimization problems critical to a wide array of applications, notably in fields such as industrial logistics, manufacturing, and transportation systems. It is closely related to the maximum flow problem, in which each arc in the graph has a unit cost for transporting material across it. The problems involve devising a strategy to transport commodities from multiple supply nodes to various demand nodes along a network. The MCNFPs are considered the most fundamental of all network flow because most other such problems can be generalized as a minimum cost flow problem.

The objective is to find the minimum-cost flow pattern to fulfill demands from the source nodes. Such problems usually are referred to as minimum-cost flow or capacitated transshipment problems. To illustrate the problem, let a network $G = (N, A)$, where N is the set of nodes and A represents the set of arcs or connections between the nodes. The minimum-cost flow problems can be formulated as follows:

$$Minimize \sum_{all\ arcs} c_{i,j} x_{i,j} \tag{2.12}$$

$$\begin{aligned} subject\ to \sum_{j} x_{i,j} - \sum_{k} x_{k,i} &= b_i \quad \forall i \in E \\ L_{i,j} \leq x_{i,j} &\leq U_{i,j} \\ x_{i,j} &\geq 0 \end{aligned}$$

where

$x_{i,j}$ is the number of units of flow sent from node i to node j through arc (i, j).

b_i is the net supply (outflow - inflow) at node i

$c_{i,j}$ is the cost of transporting 1 unit of flow from node i to node j via arc (i, j)

$L_{i,j}$ is the lower bound on flow through arc (i, j)

$U_{i,j}$ is the upper bound on flow through arc (i, j)

As for the network flow problems mentioned above, it assumes that all material flows are homogeneous and can be treated as a single commodity. However, in practical applications, material flows often exhibit heterogeneity, leading to the emergence of multicommodity problems. This problem, known as the multicommodity flow problem, considers each traffic flow between origin-destination pairs as a distinct commodity. The multi-commodity minimum-cost flow problems can be formulated as follows:

$$\textit{Minimize} \sum_{(i,j)}^{A}\sum_{j}^{N} c_{i,j}x_{i,j}^{k} \tag{2.13}$$

$$\textit{subject to} \quad \sum_{j}^{N} x_{i,j} - \sum_{k}^{N} x_{i,j}^{k} = b$$

$$x_{i,j} \leq u_{i,j}$$

$$x_{i,j} \geq 0$$

2.3.4 Piecewise Linear function

(Croxton et al., 2003, Winston and Goldberg, 2004)

Piecewise linear functions are commonly encountered in optimization problems across various domains such as transportation, telecommunications, and production planning. The functions provide a framework for modeling functions that display non-linear behavior. By approximating non-linear functions into a series of straight-line segments, where the points that the slope changes are called the **break points**. This process of approximating is referred to as piecewise linear approximation. The resulting function, composed of a set of linear functions, is known as a piecewise linear function. Piecewise linear functions enable the application of LP techniques, allowing for precise analysis and optimization of the problem.

To illustrate the process of piecewise linear approximation, we'll reference Figure 2.8, where a non-linear function is depicted as a black curve. This function can be approximated using a piecewise linear function, which is made up of three segments, each represented by a different color.

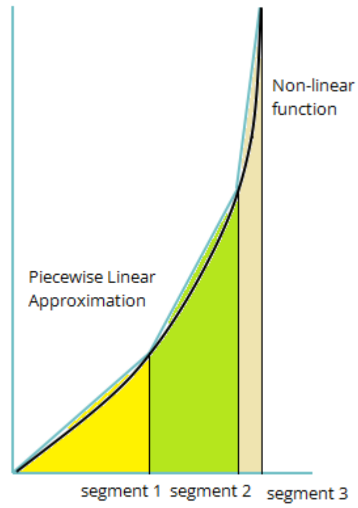

Figure 2.8 Piecewise linear approximation

Mixed-integer programming provides a robust methodology for the construction of a piecewise linear function. It enables the function to be broken down into distinct segments, each representing a different aspect of the function, thereby capturing the overall behavior of the non-linear function. Various methods for linearizing a non-linear function in a piecewise manner have been extensively discussed by Lin et al. (2013). Three well known valid Mixed Integer Programming (MIP) models have been identified: the Incremental Model, the Multiple-Choice Model, and the Convex Combination Model. As demonstrated by Croxton et al. (2003), the LP relaxations of these three models are equivalent, suggesting that they each provide a similar level of accuracy and efficiency in approximating piecewise linear functions.

Considering a single-variable nonlinear cost function $f(x)$, where x denotes the load. For the purpose to approximate this nonlinear function to the piecewise linear function $g(x)$. The notations and assumptions for this approximation process are outlined as follows. Firstly, we assume that $g(x) = 0$, through the translation of the cost function. Secondly, the function $g(x)$ is divided into linear segments $s \in [1,2,\ldots,S]$. Next, each segment possesses a variable cost, c^s (the slope), a fixed cost, f^s (the cost intercept), and upper and lower bounds, b^{s-1} and b^{s-1} (the breakpoints), on the load corresponding to that segment. Finally, we assume that $b^0 = 0$, meaning we only consider scenarios where the load is non-negative. A graphical representation of these notations can be found in Figure 2.9.

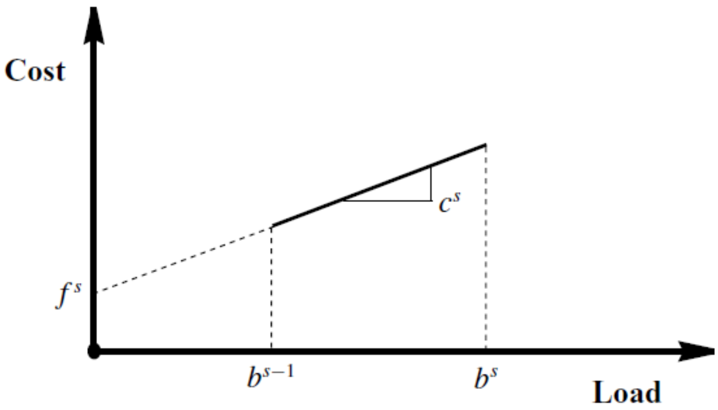

Figure 2.9 Graphical representation of load.

This study will exclusively focus on the implementation of the incremental model for piecewise linear approximation. Therefore, we will solely demonstrate the formulation of piecewise linear approximation using this model. The MIP formulation can be expressed as follows.

$$g(x) = \sum_{n}^{S} (c^n z^n + \hat{f}^n y^n) \tag{2.14}$$

$$x = \sum_{n}^{S} z^n$$

$$y^{n+1}(b^n - b^{n-1}) \leq z^n \leq y^n(b^n - b^{n-1}) \quad \forall n \in S$$

$$y_n \in \{0,1\} \ \forall n \in S$$

where

z^n is the load on the segment n.

y^n is the binary condition that segment n is not empty. Note that $y^{n+1} = 0$ for the rightmost piecewise linear segment.

$\hat{f}^n$ is the gap in the cost at the breakpoint between segment n-1 and n, which can be calculated by

$$\hat{f}^n = (f^n + c^n z^n) - (f^{n-1} + c^{n-1} z^{n-1}) \quad (2.15)$$

2.4 The Strait of Malacca

The Strait of Malacca is a narrow waterway that lies roughly on north-east/south-west orientation, it is situated between the Malay peninsula in the west and the island of Sumatra in the East. It connects the Andaman Sea in the Indian ocean and South China sea in the Pacific Ocean. According to the International Hydrographic Organization [IHO] (1953) define the limits of the Strait of Malacca as follows:

"*On the West*. A line joining Pedropunt, the Northernmost point of Sumatra (5°40′N 95°26′E), and Lem Voalan the Southern extremity of Goh Puket in Siam (7°45′N 98°18′E).

On the East. A line joining Tanjong Piai (Bulus), the Southern extremity of the Malay Peninsula (1°16′N 103°31′E) and The Brothers (1°11.5′N 103°21′E), and thence to Klein Karimoen (1°10′N 103°23.5′E).

On the North. The Southwestern coast of the Malay Peninsula.

On the South. The Northeastern coast of Sumatra as far to the eastward as Tanjong Kedabu (1°06′N 102°58′E) thence to Klein Karimoen."

Figure 2.10 The Strait of Malacca and Singapore Strait

Furthermore, the Strait of Singapore is also mentioned along the Strait of Malacca, as the two straits are essentially one continuous waterway. According to the International Hydrographic Organization [IHO] (1953) define the limits of the Strait of Malacca as follows:

"On the West. The Eastern limit of Malacca Strait

On the East. A line joining Tanjong Datok, the Southeast point of Johore (1°22′N 104°17′E) through Horsburgh Reef to Pulo Koka, the Northeastern extreme of Bintan Island (1°13.5′N 104°35′E).

On the North. The Southern shore of Singapore Island, Johore Shoal and the Southeastern coast of the Malay Peninsula.

On the South. A line joining Klein Karimoen to Pulo Pemping Besar (1°06.5′N 103°47.5′E) thence along the Northern coasts of Batam and Bintan Islands to Pulo Koka."

The Strait of Singapore is not technically part of the Strait of Malacca, but it is located at the southern end of the Strait of Malacca. The two straits are often referred to together as the Straits of Malacca and Singapore, but there are some important differences between them. The Strait of Malacca is wider and deeper than the Strait of Singapore, which means that it can accommodate larger ships. For the purpose of this study, while we focus on the Thai Canal as the alternative waterway, we denote both straits in other parts of this study as the Strait of Malacca. As vessels passing through the Strait of Malacca from the Indian Ocean and journeying beyond to the South China Sea must pass through both straits, and vice versa.

The straits are situated at the core of the Indo-Pacific region, the term used to capture the strategic importance of the Indian and Pacific Oceans as a single interconnected region, emerged from the Asia-Pacific as the Indian Ocean gained in importance. Carrying two-thirds of world oil shipments and a third of the world's bulk cargo, the Indian Ocean is now the globe's busiest and most strategically significant trade route. The Indo-Pacific region is home to some of the world's most important economies, including China, India, Japan, and the United States. These countries are increasingly interconnected through trade and investment. This interconnectedness makes the region strategically important, as it facilitates global trade. The security of the region's maritime trade routes is essential for the economic growth of these countries, and the global economy as a whole (Medcalf, 2013).

The Malacca Straits are bordered by four littoral States, namely Thailand, Indonesia, Malaysia and Singapore. However, the navigational channel passes through the territorial seas of Indonesia, Malaysia and Singapore. The Strait of Malacca is the longest strait in the world used for international navigation, Stretching approximately 900 kilometers in length. The strait varies in width, from the widest section to over 400 kilometers (about 220 nautical miles) at its gateway to the Andaman Sea, and gradually tapers to roughly 14 (around 8 nautical miles) at the south-east entrance. It joins the Straits of Singapore, which itself spans about 70 miles or approximately 60.8

nautical miles in length and has a width of about 15 kilometers (9 nautical miles). The depth of the water in the straits is inconsistent, ranging from 17 to 55 meters, with an average depth of approximately 25 meters. Figure 2.x presents the map The Straits of Malacca and Singapore

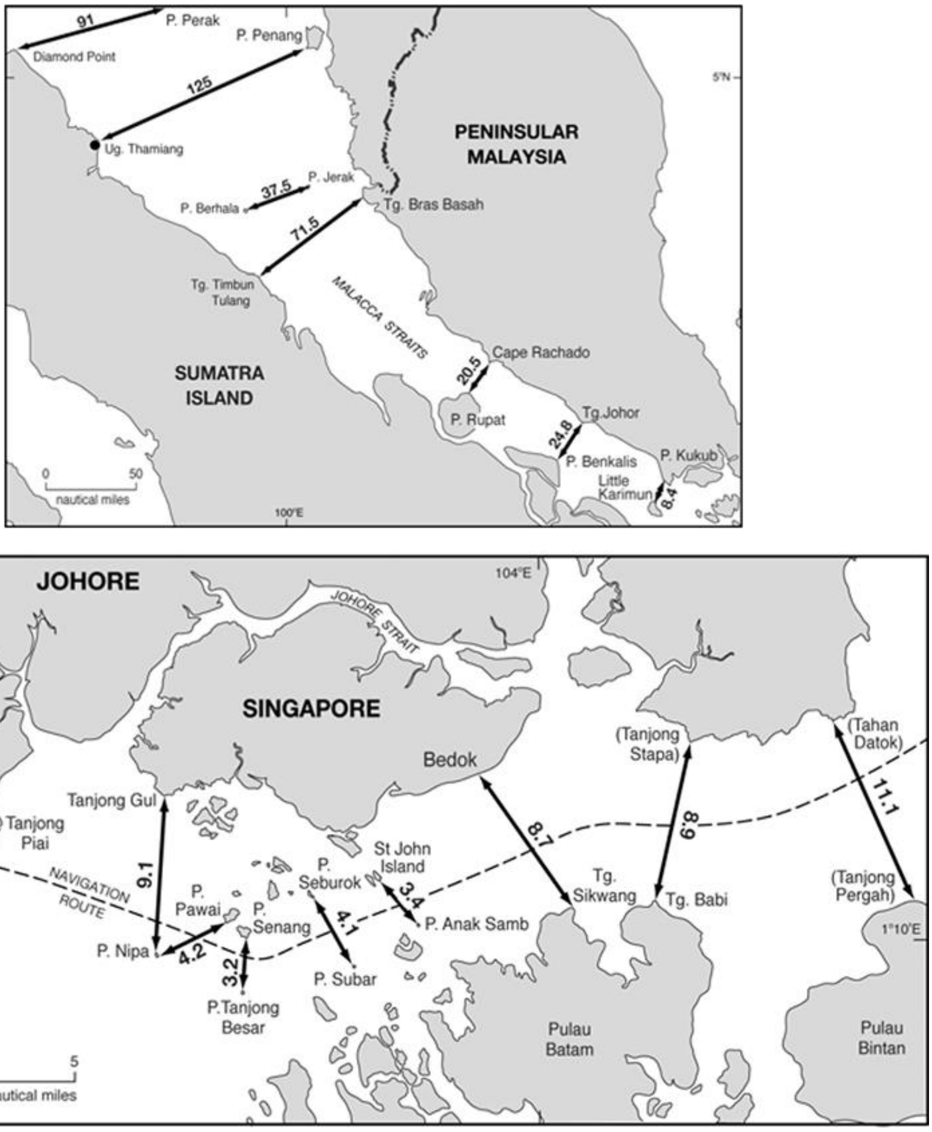

Figure 2.11 Geography of the Straits of Malacca and Singapore (Thia-Eng et al., 2000).

2.5 Related Research

2.5.1 Impact of changes in the Maritime route

Previous studies had been conducted to evaluate the impact of changes in the maritime route. Fan et al. (2009) studied impacts of the North American container import flow in rail and maritime networks from new route development such as new Canadian port in Pacific coast and the expansion of Panama Canal. They developed an optimization model that accounted for operation costs, including congestion cost and demand uncertainty. The result of the studies determined that the optimal route, ship size, port, and hinterland affected by change of new route development. Liu et al. (2016) analyzed the impacts of the Panama Canal expansion on the container shipping market. They used cooperative game theory to quantify and assess the cooperative competitive relationships and distribution of market power in transportation stakeholders. They concluded that the expansion would have a positive effect on the US East Coast player. However, should the grand coalition be formed, the total market profit would be maximized. Pham et al. (2018) studied route selection decision on the maritime trade route between Hong Kong and New York after the expansion of the Panama Canal, they developed a two-staged methodological framework, combine both qualitative and quantitative analysis to the competitiveness of the Panama canals, the Suez Canal, and US intermodal system. The result showed that the Panama Canal was preferred, they also indicated that transportation cost is the most important factor in decisions. Shibasaki et al. (2016) analyzes the significance of the Suez Canal (SC) in global maritime shipping, particularly in terms of competition with routes like the Panama Canal and Cape of Good Hope. It examines the changes in the SC's transit shares for different regional cargo origins and destinations between 2010 and 2013, highlighting its changing competitive environment. The paper develops an aggregated logit model that focuses on the supply side of the container shipping market, namely monetary shipping cost and time. The model's accuracy is validated by comparing its outputs to actual route shares. The model is further applied to simulate future scenarios, such as the potential impact of the Panama Canal expansion.

There is also research evaluating an alternative route on the existing route. Notteboom (2012), for instance, analyzed the competition between the Cape route and the Suez route using distance analysis, transit time analysis, and general cost analysis. They showed that the cape route has potential as an alternative for the Suez route in some trade lanes. This research discussed the impacts of another alternative trade route such as the North Arctic route and Euro-Asian rail transport corridor. Additionally, Tavasszy et al. (2011) also analyzed the impacts alternative trade routes using their presented strategic model to predict the global container movement on a yearly basis. This model accounted for over 400 container ports around the globe, over 800 liner services, based on trade information of each country.

2.5.2 Impact of the Thai Canal

Many studies have analyzed the impacts of the Thai canal. In 1999, Maritime Institute, Chulalongkorn University conduct the feasibility study on the Kra Canal. The study was divided into 3 aspects, Physical, Commercial, and environmental. The detail of these studies are as follows:

Koontanakulvong (1999) undertook a thorough review of the canal project proposals. The researcher meticulously gathered data, focusing on the physical attributes such as topography, climate, surface water hydrology, oceanography, geology, and infrastructure of the area surrounding the proposed canal project. The study concluded that Route 5A was the optimal choice, based on a previous study conducted by TAMS (1973). In addition, Koontanakulvong proposed the idea of integrated development in the canal vicinity, incorporating deep-sea ports and industrial estates. Notably, Koontanakulvong underscored the importance of assessing factors such as infrastructure, area development, maintenance, and environmental impact in further feasibility studies for the canal project.

Suthiwartnarueput and Menasveta (1999) conducted an analysis of the commercial aspects of a canal project, focusing especially on its feasibility. They assessed the economic conditions of Thailand and the dynamics of its international trade and estimated the potential volume of vessel traffic, which was limited by the canal's capacity to around 40 vessels per day. In addition, they performed a financial analysis of the canal project, underscoring that uncertainties and risks such as currency value fluctuations, construction timelines, and global political scenarios could render the investment of this project Uncompetitive. While under assumptions of low risk, their analysis projected a return-on-investment period of 56 years, a timeline they deemed as rather lengthy.

Menasvet et al. (1999) embarked on an environmental impact study. The research was comprised of a project description, an evaluation of the project area and conditions, field surveys and secondary data collection, and impact assessments on three main parameters: physical, biological, and resources. The researchers examined 32 distinct environmental attributes, each showing different levels of impact on both the Andaman Sea and the Gulf of Thailand. In their findings, they noted that the number of parameters indicating adverse impacts was slightly higher than those presenting beneficial impacts.

Qu and Meng (2012) proposed a decision tree model to estimate the loss to global economy on the hypothesis of an extreme scenario when blockade of the Malacca strait and Singapore occurred. Many articles also analyzed the impact of the canal to specific conditions. Abdul Rahman et al. (2016) assessed the implications of Thai canal decisions on maritime business in Malaysia using descriptive analysis and PESTLES analysis. They identified possible changes in Malaysian maritime business and determined positive and negative outcomes for the Malaysian maritime business.

Jeevan et al. Jeevan et al. (2018) employed an interview with experts to conduct the impact of the Thai Canal on Malaysian trade and infrastructure. They concluded that the Thai canal could affect the trade performance of northern Malaysian seaports.

There are studies that try to quantify the impact of the canal. Zeng et al. (2018) tried to identify the impacts of the Thai Canal as a potential new channel of China's Belt and Road initiative. They developed a modified gravity prediction model to calculate changes in transshipment traffic. Their result indicated that the opening of the canal would decrease market share from ports in Malacca Strait to other regions. Yang et al. (2011) presented an intermodal network optimization model to optimize freight routings from China to the Indian Ocean through the rail, road, vessel, and airplane. The model has utilized goal programming to emphasize conflicting objectives such as cost control, transit time, and transit time variability. The results provided insights of the transportation development in China and Indian Ocean area. For transportation development in other areas, Yuan et al. (2019) introduced a model that accounted for the potential impact of the Arctic Sea route and the Kra Canal on the Europe-Far East route. They used the fuzzy cognitive map to evaluate important factors that affected operational resilience. The model shows that the Kra Canal could improve operational resilience for the Europe-Far East route significantly more than the Arctic Sea route. For other cargo types than container cargo, Heng and Yip (2017) investigated the impacts of the Kra Canal on the tanker market. They forecasted the number of tankers transited through the Malacca strait and estimated the size distribution of tankers. They then analyzed Kra Canal's potential users based on distance-saving cooperation with the toll price policy. Their finding was interesting that the canal would become more profitable during an unfavorable market situation.

2.5.3 Liner ship fleet deployment

Several studies presented the outlook of container network model formulation, which has been known as liner shipping network problems or liner ship fleet deployment problems (LSFD). (Tran and Haasis, 2013) provided a review of network optimization in container liner shipping. reviewed over 120 pieces of literature regarding network optimization in container liner shipping. They classified those papers into three key categories: container routing, fleet management, and network design. Among these, container routing, which is considered tactical level network optimal decision, has the same definition as LSFD that is to find the optimal plan for container movement giving routes and fleet to satisfy demand under capacity constraints. They also reported that most network optimizations tried to obtain minimum total cost or maximum profit with the objective of the minimum total cost being more favorable.

Generally, The LSFD problems were formulated as a mixed-integer programming model. (Wang and Meng, 2011, Wang and Meng, 2012) proposed mixed-integer linear programming to investigate the LSFD problem with container transshipment operations by considering the total cost. They formulated their model as a mixed-integer non-linear programming model, then transformed the model into a mixed-integer linear programming model. Then, they experimented with the proposed model on the Asia-Europe-Oceania shipping network, showing that the model can be solved efficiently using CPLEX. (Brouer et al., 2013, Plum et al., 2014) presented the formulation of a model for the LSFD. They emphasized the route's ports call by introducing numbered arcs between a port and a service node. The mixed-integer programming model was formulated to maximize the profit of the generated network. This model could design liner shipping networks for a liner shipping service provider to operate efficiently and investigate possible scenarios of changed market conditions.

Shibasaki et al. (2017) introduced a network assignment model to optimize the distribution of containers across maritime and hinterland transportation methods, with a focus on Central America. By considering factors such as costs, transit times, and capacity limits, the model reduces empty container movements, minimizes transportation distances, and improves infrastructure utilization, leading to significant cost savings and efficiency improvements in the logistics network. The model was validated using real-world data and compared to existing transportation practices in the region.

Besides, Jula and Leachman (2011b) introduced models to solve the allocation ports and transportation channel problems, which similar to the LSFD problems, to predict containerized goods, imported flow from Asia to the USA. They introduced the Long-Run model using a mixed-integer non-linear programming to determine strategies for importers by terms of ports and routes.

Chapter 3 Methodology

This chapter provides an overview of the problem at hand, including its formulation, cost function, and mathematical representation. The problem is first described in detail, highlighting its key features and challenges. The formulation of the model is then outlined, providing a clear and concise overview of the mathematical concepts involved. The cost function is then stated, which captures the objective of the optimization problem. Finally, the proposed mathematical model is presented, which is a formal representation of the problem in mathematical terms.

3.1 Problem description and model setting

Examining the implications of the Thai Canal on the container shipping network requires a Wide-ranging analysis that considers several elements. These include liner shipping routes, route deployment decisions, and their subsequent implications for port services. Given this complexity, it is vital to construct a comprehensive model that can capture these elements. Therefore, this thesis aims to develop such a model of the maritime container shipping network that holistically considers these factors.

Building on this model, the main problem we need to address is evaluating the impacts of the Thai Canal on the container shipping network. The core of this issue is centered around the liner shipping routes, which include aspects of route design and fleet deployment of liners. The introduction of the Thai Canal would potentially alter existing shipping routes, it would influence the carriers' decisions regarding the liner services. However, it is important to note that changes in liner services also have implications for port service. When carriers modify their services, it directly affects the volume of container traffic for ports along those routes. Moreover, port capacity is a key limiting factor in accommodating increased container traffic.

Therefore, our proposed model is designed to analyze the potential impacts of the Thai Canal by incorporating considerations for both the decision-making process of carriers regarding route deployment and the resulting effects on port operations. This approach allows the model to account for these complexities and provide valuable insights into the potential consequences of the Thai Canal on the container shipping network.

In this study, we primarily focused on the evaluation of the impact of the proposed Thai Canal in the Indo-Pacific regions, where the effects on the liner shipping industry would be most observable. Should it be constructed, the Thai Canal would serve as a shortcut from the Strait of Malacca, offering an alternative passageway for vessels in the Southeast Asian and Indo-Pacific areas. Therefore, the scope of the impact evaluation is specifically directed towards assessing the consequences within this region, which encompasses South Asia, Southeast Asia, and East Asia.

In the construction of the model, we selected the framework of the multi-commodity minimum cost flow network problem (MCNFP) to analyze the container shipping network. The MCNF is particularly suitable for this task due to its goal of minimizing the total cost of the system. which aligns with the assumption that liners seek to minimize their operational costs while fulfilling the demands of their routes.

Furthermore, we adapted the network concept from Tavasszy et al. (2011) and Fan et al. (2009), which the network is comprised nodes and arcs. The nodes represent economies acting as the source and sink of the container flow, and ports serving as transshipment points. As for the arcs, there are two types: one connecting economies and ports to depict hinterland transport and flow distribution within an economy, and the other representing liner services or '**routes**' facilitating flow between ports (refer to Figure 3.1 for an illustration of the network).

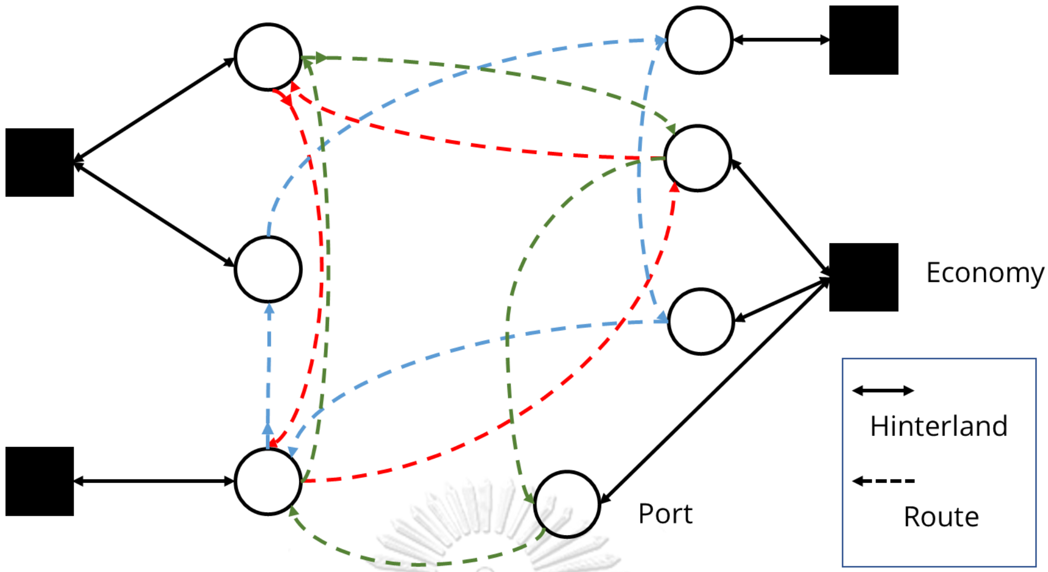

Figure 3.1 Network of container flow

We further refined the model by designating the origin of each container as a specific commodity, an idea adapted from Agarwal and Ergun (2008). This additional detail allows for a more realistic representation of international trade between countries, This, in turn, provided us with Thoughtful consideration into how the introduction of the Thai Canal might impact shipping routes and economies in the targeted region.

In our next step, we address route operation, particularly the deployment of vessels on various routes. Drawing from the frameworks of the Liner Ship Fleet Deployment (LSFD) problem as presented by (Wang and Meng, 2012), and the Liner Shipping Network Design Problem (LSNDP) as outlined by (Plum et al., 2014). We designed our model to integrate the deployment of different types of vessels to each route, ensuring a weekly frequency of service. This includes recognizing and incorporating the constraints of ports that limit the types of vessels they can accommodate. Accordingly, we aim to select the optimal vessel types for each route. Our goal is to determine the optimal number of each type of vessel to deploy on routes, thereby allowing the container flow, including transshipments, to satisfy the weekly demand in the shipping network.

Next, we incorporate the congestion model into our analysis to taking consideration of port capacity, drawing inspiration from studies such as Jula and Leachman (2011a) (Leachman and Jula, 2011)and Fan et al. (2012). This congestion shows the non-linear behavior; hence we used the piecewise linear approximation to linearize the congestion. We formulate the model as a Mixed Integer Linear Programming (MILP) problem, where the number of vessels deployed is treated as an integer variable. To reduce computational complexity, we relax the flow of containers into batches, which allows us to simplify the model.

While solving the model, it is important to note that obtaining the optimal solution may not always be feasible due to the complexity of the problem. However, even if the solution obtained is not optimal, it can still provide valuable insights into the optimal network configuration and operational decisions. These insights help us gain a better understanding of the system and guide us towards making informed decisions to improve network efficiency and mitigate congestion-related challenges.

After the completion of the Thai Canal, there arises uncertainty regarding which route of container liner shipping service will opt for. As the Thai Canal serves as a shortcut from the Strait of Malacca, leading to a reasonable assumption that some ships currently enroute to the Strait of Malacca may choose to utilize the Thai Canal. However, it is also possible that certain routes will continue using the Strait of Malacca.

To assess the traffic of the Thai Canal on shipping routes, we employ the model with the additional alternative virtual routes that passing through the Thai Canal instead of the strait of Malacca, then incorporate with available routes. Then we solve the new model to find out the effect of the Thai Canal on route choice.

We find that the Thai Canal will have a significant impact on shipping routes. Some ships that currently use the Strait of Malacca will switch to using the Thai Canal, while others will continue to use the Strait of Malacca. The exact number of ships that switch to using the Thai Canal will depend on several factors, including the cost of using the Thai Canal, the distance savings, and the security of the Thai Canal.

Finally, in order to assess the impact of the Thai Canal on shipping routes, we construct alternative virtual routes that the Thai Canal incorporate with existing options. By solving the model, we aim to determine the effect of the Thai Canal on route selection. Our findings indicate that the Thai Canal will indeed exert a substantial influence on shipping routes. Some ships currently navigating through the Strait of Malacca will transition to using the Thai Canal, while others will persist in utilizing the Strait. The specific number of ships transitioning to the Thai Canal will hinge upon various factors, such as the cost associated with using the Thai Canal, the distance savings it offers, and the overall security it provides.

3.2 Model Conceptualization

In this section, we will discuss the various concepts that come together in the process of formulating a model. Various definitions and assumptions would be stated in this section. Noting that all calculations are presented follows assuming a homogeneous commodity to simplify the notation, the summation over commodities will be implied. In the model calculations, the results will be aggregated to represent the cumulative effects of all commodities.

3.2.1 Timeframe

Given that container liner shipping is operated on a weekly frequency, it is sensible to define timeframe for the model to also be weekly. As a result, all solutions generated by the model are presented on a weekly basis. However, it should be acknowledged that while port calls are made on a weekly basis, the demand and container throughput may vary from one week to the next, due to seasonal and economic fluctuations. Therefore, it is essential to assume that demand and throughput are uniformly distributed across each week of the year.

3.2.2 Economics Zone and Interest Area

In this model, we defined the "**economic zone**" to act as a source where container demand and supply takes place. Each economic zone generates supply of containers to others and required number of containers from others for domestic consumption. The economic zones in this model can be seen as representing countries engaged in international trade. The supply and demand of containers from one economic zone to another can be thought of as the import and export of goods between countries.

In order to manage the complexity of the global container network, we have simplified our model by assuming that the impacts of the Thai canal on the container network will be localized in a nearby region, rather than being spread out evenly throughout the global container network. We will refer to this region as '**the interested area**', which includes South Asia, Southeast Asia, and East Asia together forming a substantial part of the Indo-Pacific Asia, recognized as '**Indo-Pacific**' region. Figure 3.2 shows the region in the shaded area. Note that we omitted landlocked economies from the interested area, as their container network are not directly affected by the Thai canal. Additionally, we also excluded economies that have a small contribution to global container trade (i.e., Brunei, North Korea).

Figure 3.2 The interested area

Furthermore, to incorporate global trade in our model, we have simplified the representation of economic zones outside the interested area by consolidating these economic zones into distinct maritime trade regions, which we will refer to as "**region**" for the further part of this study. Each region represents a specific group of economies, encompassing geographical areas such as the Middle East and Oceania.

This approach allows us to include these regions in our study without introducing unwarranted complexity. This way, we maintain the integrity of our model, acknowledging the interconnectedness of the global trade network while keeping our focus on the Indo-Pacific region. To shed light on the economic zone, interested area, and region, a graphical representation is provided in Figure 3.3.

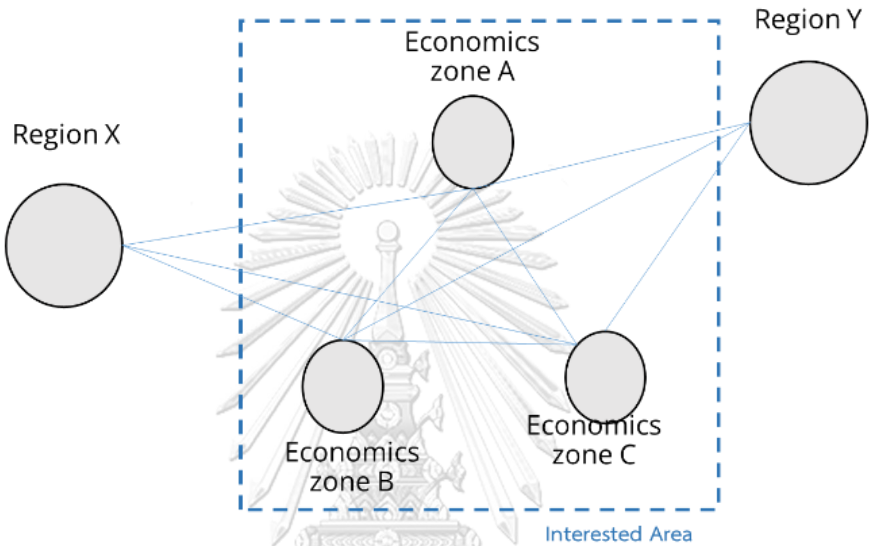

Figure 3.3 Graphical representation of economic zones interested area, and regions.

3.2.3 Demand

The model serves as a network flow problem for facilitating the flow of container demand between different economic zones. Each demand represents a predetermined weekly volume of containers that must be transported from a specific origin to a designated destination. A multi-commodity flow concept is utilized to identify the origin of each container flown in the network, ensuring that the demands from each economic zone are met.

In this model, demand is represented by origin-destination pairs, refer as OD pairs, indicating the locations where containers need to be transported. The container flow within this model occurs between economic nodes, utilizing ports and routes as transportation channels. However, it is important to note that the model primarily focuses on the Indo-Pacific region. As a result, constraints related to demands that fall outside of this region will be relaxed or given less emphasis within the model. For example, as shown in Figure 3.4, the demand between economic zone A and C occurs outside of the interested area, so the demand constraint of this trade will be relaxed. This means that the number of containers flowing from economy A to economy C may not need to be equal to the demand in economy C. Likewise, the number of containers flowing from economic zone C to economic zone A may not need to be equal to the demand in economic zone A.

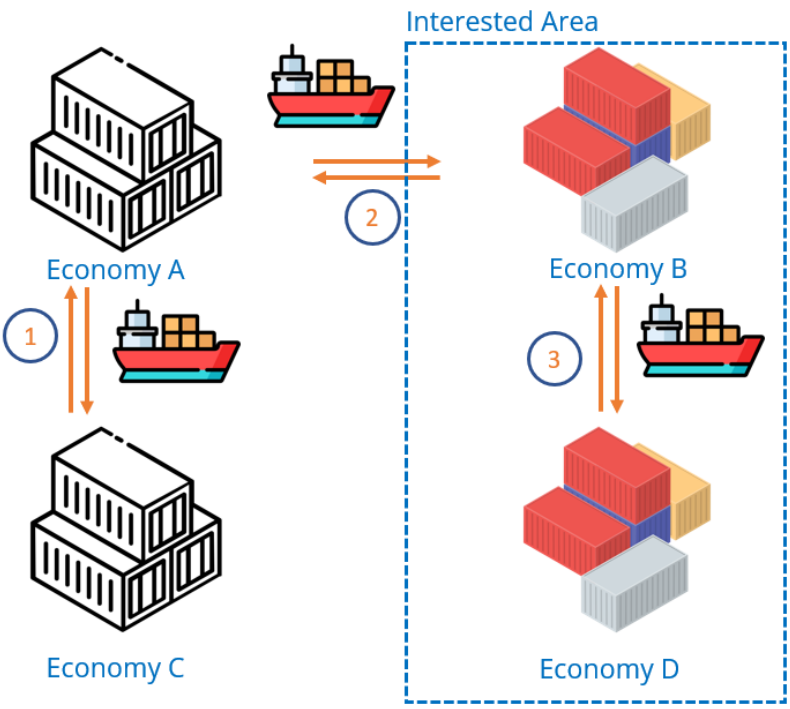

Figure 3.4 Demand Trade Flow in the model.

3.2.4 Vessel

In this model, container vessels are considered as limited resources that are allocated to each route to facilitate the flow capacity of each route. The number of weeks required for each route to complete a roundtrip of port calls is used as a basis to determine the number of vessels assigned to that route. This allocation is necessary to ensure that the route maintains its desired weekly frequency. For instance, if route A takes 7 weeks to complete the roundtrip, it is necessary to assign 7 vessels to route A, in order to maintain its weekly frequency.

We note that the number of vessels available is limited, as such, it is important to manage the allocation of these vessels to maximize their utilization and optimize the overall operation of the container shipping network. By considering the limited number of vessels and their efficient allocation, we can enhance the effectiveness and efficiency of container transportation.

Container vessels come in a range of sizes, and these varying sizes necessitate different port properties and facilities. Larger vessels often require ports with deeper drafts to accommodate their size and ensure safe navigation. Different vessel sizes require different port sizes. It is important to consider the specific characteristics of each vessel when choosing a port to berth in. We then classify vessels based on their specific characteristics to determine the suitable port for berthing. This helps us consider the different sizes and requirements of each vessel type, ensuring they are matched with ports that can accommodate them properly.

In this model, we classify vessels into different types and assign unique capacity, cost, quantity, and dimension requirements to each type (i.e., length and draft). This classification enables us to ensure that vessels are berthed at ports capable of meeting their requirements. Moreover, we allow vessels to berth at ports equipped with deep berths, as this may be the case in practical situations.

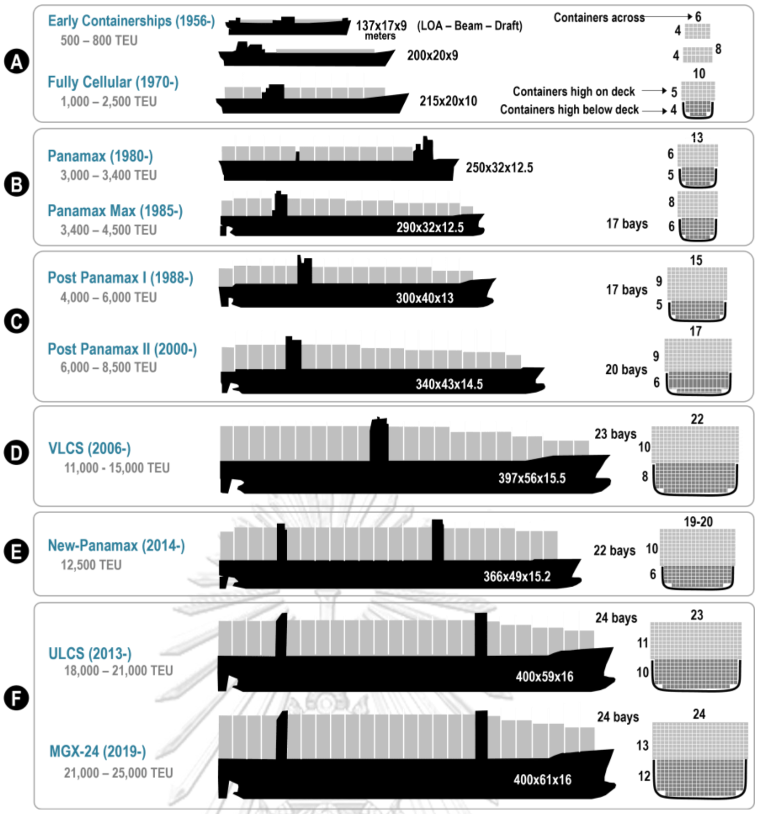

Figure 3.5 Different vessel types (Rodrigue, 2020)

The cost of vessel deployment is considered on a weekly basis in our model, as it has a weekly timeframe. According to Stopford (2008), the cost of deploying vessels is primarily influenced by fuel costs, which are proportional to the speed of navigation. However, because our model focuses on vessel deployment on a given route rather than setting the speed of sailing, we assume that vessels of the same type have the same cost over the week.

3.2.5 Port

Ports play a critical role in the container network as they serve as a transshipment point which receives and distributes the flow of containers from both the economic zone and the container route. Therefore, most of the container flow activity takes place there. The ports in the model will consist of important ports of each country in the interested area and dummy ports for region outside the interested area, one port per maritime trade region.

The activities of handling containers that happen in ports in this model are the import, export, load, unload, and transshipment as shown in Figure 3.5. Import is the activity when containers from various parts of the world arrive and enter the economy zone. Export is the activity when containers from the economy zone are shipped to other parts of the world. Loading is the activity of transferring containers from the port to a vessel, and unloading is the activity of transferring containers from a vessel to the port. Transshipment is the activity of moving containers from one vessel to another. Of all the activities of container flow, only transshipment happens inside the port itself.

Transshipment is a process that transfers containers from one vessel to another. This is often done when the original vessel is not going to the destination of the container, or when it is more efficient to transfer the container to a smaller vessel that can access a smaller port. The transshipped container can stay at the port for a considerable amount of time. Nevertheless, as the model is set up in weekly timeframe and the route provides the weekly frequency service, Consequently, any transshipment periods exceeding one week are not accounted for in the model.

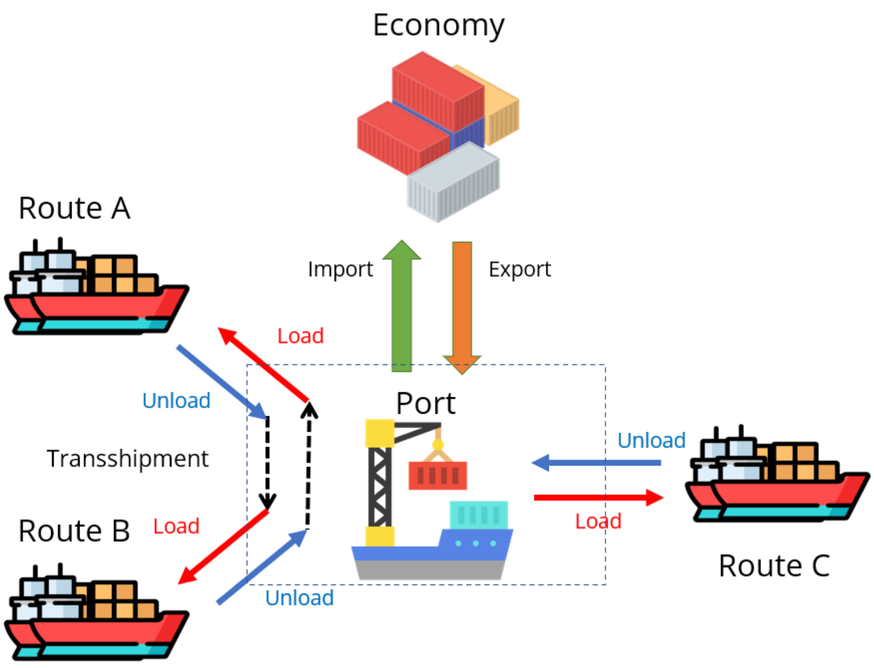

Figure 3.6 The flow of containers in port

In this model, we are assuming that there were no delays or backlogs of containers at the port during the timeframe. This assumption implies that the flow of containers through the port was balanced, with an equal number of containers entering and leaving the port each day. Maintaining flow balance is crucial to ensure the smooth and efficient operation of the port, as well as to meet the demands of the container network.

The concept of flow conservation in container ports can be understood as follows: For each port, the total number of containers entering the port must be equal to the total number of containers leaving the port. In other words, the inflow and outflow of containers at a particular port must be conserved. To illustrate this concept mathematically, at a particular port has the flow conservation relation as:

$$Export - Import = \sum_{vessel\ berth} Load - \sum_{vessel\ berth} Unload \tag{3.1}$$

where $Export$ is the number of container export from economy zone to port, $Import$ is the number of container import from port to economy zone, $Load$ is the number of containers load at a route. $Load$ is the number of containers load at a route, and $vessel\ berth$ is a set of vessel berth at the port.

In addition, ports impose restrictions on the type of vessels that can berth based on their draft limitations. Ports have different draft depths, and as a result, large vessels that require deeper drafts are unable to berth at ports with shallow drafts. Conversely, smaller vessels have more flexibility and can berth at any port regardless of draft limitations.

The capacity of a port is often indicated by the length of the berth available for each draft depth. As vessels berth at a port, the berth space is utilized to provide various services and facilities for cargo handling, loading, and unloading operations. The length of the berth determines the number of vessels that can be accommodated simultaneously and influences the port's overall capacity to handle cargo efficiently.

Lastly, for the sake of simplicity in the model, a uniform assumption is made regarding the time vessels spend at the port. Regardless of the vessel's size or the number of containers being loaded or unloaded, the model considers a standard one-day duration for vessel berthing. This simplification allows for a consistent time frame in the model's calculations and analysis, making it easier to analyze and compare different scenarios.

Port traffic

Port traffic is a vital element in port competition and serves as a measure of the effect of change within the container network. Essentially, port traffic is the movement of ships and containers into and out of a port. To gauge the performance of ports in our model, we use three primary types of port traffic in this study:

1. **Port call size**: This refers to the number of a vessel making a call at the port within a specific timeframe typically known as a 'port call'. In this study, we differentiated the port call size by type of vessel to better understand the impact of different vessel sizes on port operations. Port call at a particular port p can be calculated as follows:

$$PCall_{p,v} = \sum_{r}^{Route} \sum_{l}^{L_r} Rcall_{r,l,p} w_{r,v} \tag{3.2}$$

where

$Route$ is the set of routes in the model.

L_r is the number of leg (port call rotation) on route r.

$PCall_{p,v}$ is the number of port call at the port p with vessel type v.

$Rcall_{r,l,p}$ is the binary parameter indicating that whether route r at leg l is called at port p.

$w_{r,v}$ is the number of vessel type v deploy in the rotation of route r.

2. **Port throughput**: Port throughput is the amount of cargo that a port loads and unloads within a specific timeframe. By measuring port throughput, we gain insight into the volume of goods a port can efficiently manage. Port throughput at a particular port p can be calculated using the following equation:

$$PThp_p = \sum_{e}^{E} PLoad_{p,e} + \sum_{e}^{E} PUnload_{p,e} \tag{3.3}$$

where

E is the set of economics zones in this model.

$PThp_p$ is the port throughput of port p.

$PLoad_{p,e}$ is the total container from origin e load at port p, which can be obtained by:

$$PLoad_{p,e} = \sum_{r}^{Route} \sum_{l}^{L_r} Rcall_{r,l,p} Load_{r,l,e} \tag{3.4}$$

$Load_{r,l,e}$ is the number container from origin e load at leg l of route r

$PUnload_{r,l,e}$ is the number container from origin e unload at leg l of route r, which can be obtained by:

$$PUnload_{p,e} = \sum_{r}^{Route} \sum_{l}^{L_r} Rcall_{r,l,p} Unload_{r,le} \tag{3.5}$$

$Unload_{r,l,e}$ is the number container from origin e unload at leg l of route r

$Rcall_{r,l,p}$ is the binary parameter indication that port p is called at leg l of route r

3. **Port transshipment**: The number of transshipment containers at a particular port p equals the difference between the number of containers handled at the port and the sum number of containers import and export at this port, divided by 2. The number of containers transshipped at port p can be calculated by

$$Transshipment = \frac{(\sum Load + \sum Unload) - (Export + \ Import)}{2} \tag{3.6}$$

Moreover, the percentage of transshipment can be calculated by

$$\% \, Transshipment = 2 \frac{Transshipment}{Throughput} \tag{3.7}$$

Port cost

As ports provide services such as berthing vessels and handling containers, they charge for these services. In this model, we define the costs associated with ports into three categories:

- **Berthing fees**: These fees are charged for the use of a port's berths, which are the areas where vessels are moored. The amount of the fee is typically based on the size of the vessel and the length of time it is berthed. This model assumed that the berthing fees vary depending on the specific port and the size of the vessel. The fees can be calculated using a linear relationship with respect to the capacity $Vcap$ (TEU) of the container vessel. The berthing fees for any port can be calculated by

$$Pdue = Vcap(Pvar) + Pfix \tag{3.8}$$

  where $Pdue$ is the Berthing fees (USD), $Pvar$ is the rate at which the berthing fees increase per unit of vessel capacity (USD/TEU), and $Pfix$ is the fixed component of the berthing fee (USD).

- **Container handling fees**: These fees are charged for the loading and unloading of containers at a port. The amount of the fee is typically based on the number of containers handled and the weight of the cargo. In this model, we base only on the number of containers handled, we denote the fees as $Pthc_p$ for any port p.
- **Transshipment fees**: During the transshipment process, containers are unloaded from one ship and stored in port until they are loaded onto another ship. The port charges a fee for this storage space, which is called a transshipment process charge. The transshipment process charge is typically based on the size and weight of the container, as well as the length of time the container is stored in the port. However, in this model, we consider only the number of containers transshipped and we denote it as $Ptrc_p$ at any port p.

Note that for the dummy ports located outside the interested area region, we have omitted the inclusion of berthing and handling fees in our cost calculations. However, we have imposed high costs for transshipment fees at these dummy ports. This decision is made to impose the restriction that transshipment activities should not occur outside the interested area. Therefore, while berthing and handling fees are neglected, the high transshipment fees serve as a deterrent to prevent transshipment operations outside the defined region. The details of container flow will be provided in the container flow part later.

3.2.6 Route

In this model, we consider a route as a collection of arcs in the network, which connects a set of ports, we call these ports as '**port of call**' or '**port rotation**'. Routes enable the flow of containers the ways to transfer between ports. In the scope of this study, we consider all routes to be circular routes, meaning route will rotate along the ports of call and return to the first port of call. This creates a loop in the flow of containers. Next, we will introduce the following notation for routes, adapted from the work of Wang and Meng (2012) as follows.

A shipping route r which have number of port call N can be expressed by its port of call:

$$p_{r,1} \rightarrow p_{r,2} \rightarrow \cdots \rightarrow p_{r,N} \rightarrow p_{r,1} \tag{3.9}$$

where $p_{r,i}$ is the i^{th} port of call of route r , $i \in \{1,2, \ldots , N\}$.

The voyage from $p_{r,i}$ to $p_{r,i+1}$ is referred as a '**leg**'. The number of legs in each route is equal to the number of port call, which denote as $Rleg_r$.

A port can be called more than once in routes during it rotation. To indicate that port p is called on route r at leg l, we use the binary parameter $Rcall_{r,l,p}$, which is 1 if the port is called and 0 otherwise.

Defining $p_{r,N+1} := p_{r,1}$, shows the route characteristics of its circular rotation, which allows the flow of containers to continue without interruption along port calls.

For example, Figure 3.7 illustrates a loop shipping route that calls on port of Ningbo, Shanghai, Busan, and Kwangyang, before returning to Ningbo. This implies that the number of leg or port call, $Rleg_r = 4$. The loop of port calls enables the flow of containers from any port to any other port along the route.

Figure 3.7 Example of route: Ningbo – Shanghai – Busan – Kwangyang -Ningbo (COSCO Shipping, 2022)

Furthermore, let's consider a specific route illustrated in Figure 3.8 This route consists of the following ports of call: Yantian, Xiamen, Ningbo, Shanghai, Busan, Vancouver, Seattle, and Gwangyang, with the route ultimately returning to Yantian, has the number of port call of 8.

Figure 3.8 Example of route : Yantian - Xiamen - Ningbo - Shanghai – Busan - Vancouver - Seattle - Gwangyang – Yantian (CMA-CGM, 2022).

We observe that the ports of Vancouver and Seattle are located outside the scope of the interested area for this study. As previously mentioned, the model utilizes dummy ports to represent regions outside the interested area. For each region, a specific dummy port is designated. Which in this case, let both ports located in the North American region, denoted as 'NAM'. Therefore, the revised port rotation for this route would be: Yantian, Xiamen, Ningbo, Shanghai, Busan, NAM, Gwangyang, and Yantian, effectively reducing the number of port calls to 7.

One important aspect to note is that the port rotation can be described by using any port as the initial port. However, for the sake of standardization in this study, the first port of all routes has been selected as the westernmost port within the ports of call. This standardization ensures consistency across the routes, As demonstrated in the two routes provided in the example.

Generally, liners provide shipping services with routes that operate on a weekly frequency. This implies that if a route is called on port A, there will be one vessel berthing at the respective port around the same time every week, maintaining a consistent schedule. To ensure the reliability and continuity of these routes, liners organize port rotations in loops and deploy vessels based on the duration of a complete round-trip transit. As a result, most routes have transit times that are multiples of 7 days, aligning with the weekly operational cycle. This standardized approach helps to streamline operations and maintain the regularity of vessel services within the liner industry.

The parameter $Rweek_r$ indicates the number of weeks required to complete the rotation for route r. This parameter dictates the number of ships that are required to enable the service route r. For example, let's consider the route Ningbo – Shanghai – Busan – Kwangyang – Ningbo. If this route takes 2 weeks to complete its rotation, $Rweek_r = 2$, then 2 vessels are required to be deployed on this route in order to maintain weekly frequency. This ensures that the liner can adhere to the schedule and provide regular service to the ports along the route.

Additionally, liners aim for operational uniformity and consistent sailing speed by deploying the same type of vessel for each route. This approach helps to achieve operational efficiency, maintain service reliability, and streamline the management of the fleet (Wang and Meng, 2012).

In the context of flow operations in routes, we use the following notation to represent handling operations:

- **Loading**: The process of transferring containers from a port into a vessel.
- **Unloading**: The process of transferring containers from a vessel into a port.
- **Carried**: Containers that remain in a vessel and are carried to the next leg of the route.

At each leg of route, route always carried the loading is the operation that the container as present in Figure 3.9. The capacity of these operations in each leg is restricted by the capacity of vessels deploy in each route, the route capacity of any route r, $RCap_r$, can be calculated by

$$RCap_r = \sum_{v}^{V} Vcap_v w_{r,v} \tag{3.10}$$

where $Vcap_v$ is the capacity of vessel type v, and $w_{r,v}$ is a group of vessels type v deploy on route r that enabled weekly frequency. For example, if route A is required 3 vessels to enable weekly frequency, $w_{A,X}$ = 1 means there are 3 vessel of type X is deployed in this route.

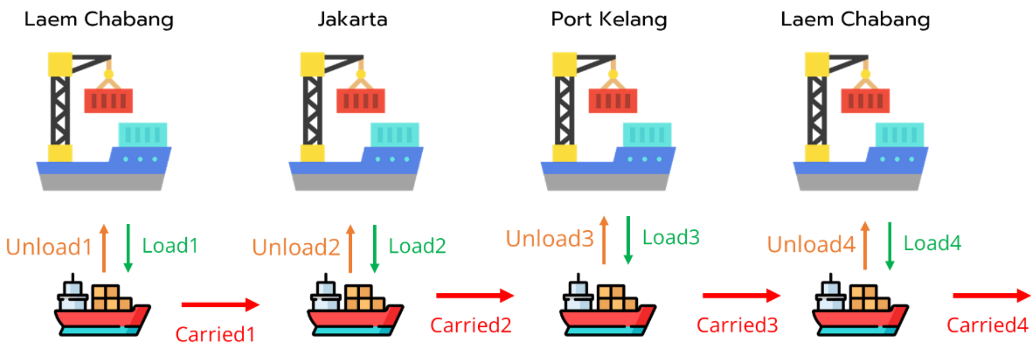

Figure 3.9 Container flow in a route.

3.2.7 Congestion

In this model, we consider the congestion that occurs at port and may influence carriers' port choice to deploy routes. For this purpose, we try to quantify the cost of a missed opportunity caused by congestion at port as did, Fan et al. (2012), Leachman and Jula (2011) and Jula and Leachman (2011a) proposed.

Consider ports as a system which provides a service to port call and transferring container from the vessel to port or conversely. Then, ports must experience variability in both flow of vessel berthing and berthing time of each call. Hence, the average waiting time at a port could be analyzed using queue theory. The general problem of the queueing system with parallel server (G/G/m) could be calculated by

$$Waiting\ Time = \left(\frac{{C_a}^2 + {C_e}^2}{2}\right)\left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)}\right)t_e \qquad (3.11)$$

where C_a is the coefficient of variation of inter-arrival time, C_e is the coefficient of variation of service time, u is the utilization of services process, m is the number of parallel server and $t_e$is the average services time.

The utilization of services process can be obtained by

$$u = \frac{r_a t_e}{m} \tag{3.12}$$

where r_a is the average inter-arrival time (Hopp and Spearman, 2001).

In this model, we represent the frequency of port calls over time as the inter-arrival rate, and we consider the time taken for a ship to berth as the process time. As we stated above, we assume that each vessel berthing at any port will be taking a berthing time, t_e, of 1 day. We also assume that both the inter-arrival rate (C_a) and the process time (C_e) follow exponential distributions, that is, both have a coefficient of variation equal to 1. Moreover, for the calculation of the waiting time, we used the unit of days instead of week as we use weeks in our simulation because of the variability in the inter-arrival times. Based on the above assumptions, we can calculate the arrival rate of any port r_a as follows:

$$r_a = \frac{7}{Port\ call} \tag{3.13}$$

where $Port\ call$ is the number of vessels that berth at a port in one week, the number seven divided by the port's capacity for vessels to berth per day. From equation (3.13), we can see that all parameters except the utilization are constant, and the utilization is a function of the arrival rate. Therefore, the average waiting time can be described as a function of port call. Figure 3.11 illustrates how the average waiting time varies with respect to the number of port calls, given a value of m = 12.

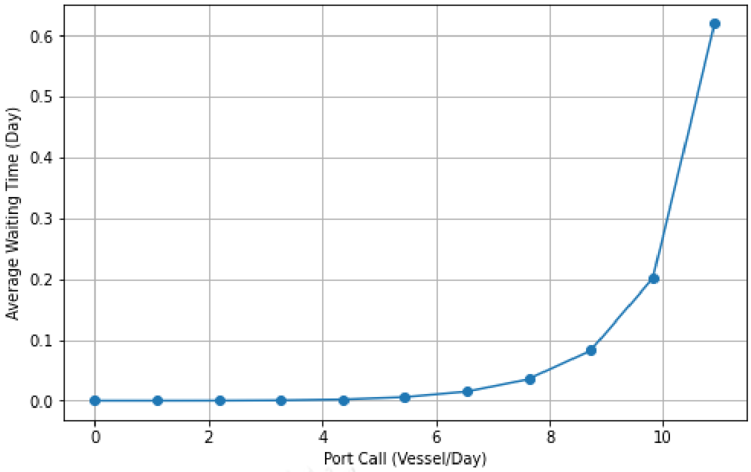

Figure 3.10 Average waiting time of a parallel server M/M/12

Based on the calculated waiting time, the total congestion cost of any port can be determined by multiplying the average waiting time, WT, by the number of port calls of each type of vessel, $Port\ call_v$, and further multiplying it by the vessel cost corresponding to each vessel type, $Vcost_v$, as follows:

$$Congestion\ Cost = \sum_v Vcost_v\ .\ Port\ call_v\ .WT\left(\sum_v Port\ call_v\right) \qquad (3.14)$$

From Figure 3.11 it is evident that the total congestion cost is not a linear function. To linearize the cost, we can employ the piecewise linear approximation technique. However, to approximate it for all vessel types, we would need to perform the piecewise linear approximation equal to the number of vessel types. For the simplicity of the model, we utilize the weighted average cost of all vessel types, $WVcost$,. By employing this approach, we can obtain the total congestion cost by

$$Congestion\ Cost = WVcost\ .\sum_v Port\ call_v\ .WT\left(\sum_v Port\ call_v\right) \qquad (3.15)$$

With the given relation, we can linearize the total congestion cost and represent it as a piecewise linear function. This function is composed of connected linear segments. The number of segments determines the level of approximation, where a higher number of segments leads to a better approximation. In this specific model, we choose to use a total of 3 segments for the piecewise linear function. This means there are 2 break points and 3 linear segments, each with a different slope. Figure 3.11 visually depicts the linearized representation of the total congestion cost for a port with 12 berths.

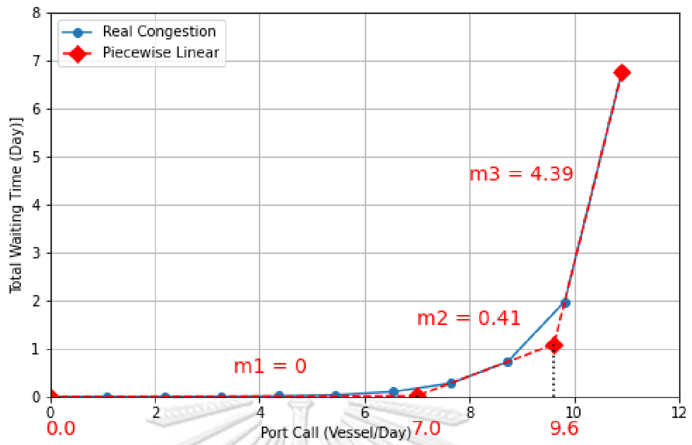

Figure 3.11 Total waiting time of a parallel server M/M/12 with piecewise linear approximation

3.2.8 The Thai canal

This study examined the Thai Canal to act as a pathway for vessels that cannot load or unload containers. Hence, the model denotes the canal as a port, the vessel passing through the canal is considered as vessel berthing at mockup port. The characteristics of the canal, such as capacity, travel time, and toll, were also considered. In this study, we investigated the following:

The capacity of the Thai Canal is concern about 2 aspect the **vessel capacity** and **berthing capacity**.

- Vessel capacity refers to the maximum size of vessel that can pass through the canal. This is determined by the width and depth of the canal. According to a physical survey conducted by the Thailand Council of Engineers, it is suggested that the proposed canal should have a depth of approximately 30 meters and a minimum width of 400 meters, covering a total distance of 129.65 kilometers (The Ad-hoc Committee on Considering the Study of Digging Thai Canal and Development of the Southern Economic Corridor, 2022). Compared to the Suez Canal, which is 24 meters deep and 205 meters wide, capable of accommodating the largest type of container vessels (The Suez Canal Authority, 2015), suggesting that the proposed canal should also be capable of handling all size of container vessels.

- Berthing capacity refers to the maximum number of vessels that can pass through at any given time. We interpolate from the Suez Canal that has a record of daily number of ships passing through of 87 vessels (THE MARITIME EXECUTIVE, 2021a), that is over 600 vessels passing through each week. As the Suez Canal is 193.30 kilometers long, while it does not allow for two-way traffic along the entire length of the canal, it does enable navigation in both directions simultaneously through the 72-kilometer-long Ballah Bypass (The Suez Canal Authority, 2015). Comparing to the 129.65 kilometers of the Thai canal, it is not explicitly mentioned whether the Thai canal can handle two-way traffic. Therefore, for the purpose of our assumption, we consider that the Thai canal berthing capacity is similarly to the Suez Canal, allowing for a maximum of 600 vessels per week.

The Thai canal would save the distance around 1,200 – 1,400 kilometers (The Ad-hoc Committee on Considering the Study of Digging Thai Canal and Development of the Southern Economic Corridor, 2022). However, the distance saved may not result in transit time saving, we analogous from vessels transiting through the Suez Canal are subject to speed restrictions (The Suez Canal Authority, 2018), which may prevent them from achieving their maximum operating speed. These speed limitations can result in increased transit times for vessels navigating the canal. Hence, this may be the case for the Thai canal, thus we set that the time saving from canal as a parameter vary in scenario in the model.

Figure 3.12 The new route from the Thai Canal (THE MARITIME EXECUTIVE, 2021b)

Regarding the toll for the Thai canal, for the simplicity within the model, we assume that the toll charged for utilizing the canal is equivalent to the berthing charge applicable at the port of Singapore. This assumption allows for a straightforward comparison and estimation of potential competition. However, it is important to acknowledge that in practice, the actual toll structure and pricing for the Thai canal would likely be subject to further analysis.

3.3 Cost

In this study, a cost minimization objective function is utilized to develop a mathematical model for a liner container network. The total cost comprises six factors, including vessel deployment cost, berthing cost, container handling cost, transshipment cost, congestion cost, and route saving cost. Detailed descriptions of each of these cost components are provided below.

3.3.1 Vessel deployments Cost

Vessel deployment cost refers to the expenses associated with deploying vessels on routes. In this study, we built the model on a weekly basis, so all the costs associated with vessel deployment are calculated directly from the number of vessels deployed on each route. As mentioned before, vessels in this model are classified into types, and each type has a different cost to deploy based on its size. Thus, the total cost of vessel deployment for any route is equal to the sum of the costs for each type of vessel deployed over that route. The following equation shows the total cost of vessel deployment for any route.

$$Vessel\ Deployment\ Cost_{\ r} = Vcost_v \sum_{Vessel\ Type} VDeploy_{r,v}\, w_{r,v} \qquad (3.16)$$

where

$Vcost_v$ is the vessel deployment cost of vessel type v ($)

$Rweek_r$ is the number of weeks for a route r that would complete roundtrip sailed (week)

$w_{r,v}$ is the number of identical vessels type v deploy at route r for one rotation (vessel/week)

3.3.2 Berthing cost

The berthing cost is charged when route calling at a port, often call as port dues. This cost vary on two factor tonnage of vessel and time stay at the port. As we classified vessel into types, we would assume each type has different charge with linear relationshi. We also assume that the time stay at the port is 1 day for all port calling, hence the difference of charge will depend only on type of vessel. Berthing cost for each port can be calculated by

$$Berthing\ Cost_{\ p} = \sum\nolimits_{Vessel\ Type} PCall_{p,v}\ x\ \ Pdue_{p,v} \tag{3.17}$$

where

$PCall_{p,v}$ is the number of containers transshiped at port p(TEU)

$Pdue_{p,v}$ is transshipment cost per TEU at port p ($)

3.3.3 Container Handling cost

The cargo handling cost refers to the charges imposed by ports for all activities involved in loading and unloading containers. This cost is categorized as a variable expense, as it depends on the number of containers being loaded and unloaded. In this model, the cargo handling cost for each port can be determined by multiplying the container throughput at that specific port by the port's handling rate as follows:

$$Cargo\ Handling\ Cost_{\ p} = PThp_p\ x\ \ Pthc_p \tag{3.18}$$

where

$PThp_p$ is the containers throughput of port p (TEU)

$Pthc_p$ is container handling cost per TEU at port p ($/TEU)

3.3.4 Transshipment Cost

The cost of transshipping cargo is determined by the number of containers that are transshipped at the port in a single week. However, in practice, some cargoes may remain at the port for longer periods of time before being transshipped to another vessel. In the model, each container is assumed to be transshipped within one week, as each route must call at the port once per week. The transshipment cost for each port can be calculated as follows:

$$Transshipment\ Cost_p = \ PTran_p\ x\ \ Ptrc_p \tag{3.19}$$

where

$Ptran_p$ is the number of containers transshipped at port p (TEU).

$Ptrc_p$ is transshipment cost per TEU at port p ($/TEU).

3.3.5 Congestion cost

Congestion cost is representing cost of a missed opportunity due to congestion at ports, as number of vessels berthing at port is closing to capacity, the longer waiting time. As discussed in the previous section, this model uses piecewise linear approximation to approximate the total waiting time in port. We also aggregated the cost of the vessel by using the weighted average cost of deployment to reduce the complexity. The congestion cost at any port can be calculated as follows:

$$Congestion\ Cost_p = \frac{1}{7} WVCost\ x\ \ WTime_p \tag{3.20}$$

where

$WVCost$ is the weighted average cost for deploying vessel ($/week-vessels)

$WTime_p$ is the total waiting time in port p (vessels- day

3.3.6 Route saving cost

In this model, the virtual Thai canal will reduce the transit time of passing route, as the transit time is reducing the vessels need to deploy decrease also, even from the less time need to chart the route, the less fuel to drive the vessel, and less operational cost such as labor etc. The cost saving will represent the cost saved by using the canal. The route saving cost per each route $(Rsave_r)$ can be obtained as follows.

$$Route\ Saving_r = RSave_r \sum_{V}^{Vessel\ Type} VDeploy_{r,v}\ x\ VCost_v \qquad (3.21)$$

where

$VDeploy_{r,v}$ is the number of vessel type v deploy on route r (vessels)

$VCost_v$ is the cost for deploying vessel type v (\$/week-vessels)

$RSave_r$ is the time saving from using route r (week)

3.4 Mathematical Model

Based on the model conceptualization presented in section 3.2 and the cost model described in section 3.3, we have developed a mathematical model to analyze the container liner flows. The mathematical model is formulated as follows:

3.4.1 Indices and Sets

The sets used in the model are shown as follows :

R : Set of routes operated in the model.

RA : Set of virtual routes operated in the model, while $RA \subseteq R \; and \; RA \cap RV = \emptyset$

RV : Set of virtual routes operated in the model, while $RV \subseteq R \; and \; RV \cap RA = \emptyset$

L_r: Set of number of Leg in route r

E : Set of all economic nodes in the model

EI : Set of the economic nodes inside the interested area, while $EI \subseteq E, EI \cap EO = \emptyset$

EO : Set of the economic nodes outside the interested area, while $EO \subseteq E, EO \cap EI = \emptyset$

P : Set of all ports in the model

PI : Set of ports in the interested area, while $PI \subseteq P, PI \cap PO = \emptyset$

PO : Set of dummy-ports for economics outside the interested area, while $PI \subseteq E, EO \cap EI = \emptyset$

V : Set of vessel types in small to large order.

N : Set of segments of vessel calling

3.4.2 Parameters

The parameters used in the model are shown as follows. However, the specific parameters used may vary depending on the instance of network used.

Limitation parameters

$Rvesmax$ Maximum number of vessels operate in one route per one rotation.

Demand parameters

$Dem_{f,t}$ Container demand from economy f to economy t (TEU).

Vessel parameters

$Vcost_v$ Cost for operating the vessel type v over timeframe ($).

$Vquan_v$ Total number of vessels type v available (vessel).

$Vcap_v$ Container capacity of a vessel type v (TEU).

$Vlen_v$ Berth length of a vessel type v (m).

WV The weight average of cost for operating the vessel ($).

Port parameters

$Pberth_{p,v}$ Berth length of port p that can accommodate vessel type v smaller type (m).

$Pthc_p$ Handling cost per load or unload per TEU at port p ($/TEU).

$Ptrc_p$ Transshipment cost per TEU at port p ($/TEU).

$Pdue_{p,v}$ Berthing cost for vessel type v at port p ($).

$Plink_{p,c}$ Binary parameter indicating that port p is in economic c (e.g., $Plink_{THLCH,THA} = 1$).

$S_{p,n}$ Slope of waiting time piecewise linear in section n at port p.

$F_{p,n}$ Offset of waiting time piecewise linear in section n at port p.

Route parameters

$Rleg_r$ Number of legs in route r.

$Rcall_{r,l,p}$ Binary parameter indicating whether port p is called in leg l of route r.

$Rweek_r$ Number of weeks for route r to circle around (week).

$Rsave_r$ Time saving from using route r (week).

3.4.4 Intermediate Variable

We define intermediate variables to represent the performance indicator from the network model. These variables are also used as constraints in the model, as shown below.

Port Call

$$PCall_{p,v} = \sum_{r}^{R} \sum_{l}^{L_r} Rcall_{r,l,p} w_{r,v} \quad \forall p \in EI, \ \forall v \in V \tag{3.22}$$

Port Load

$$PLoad_p = \sum_{r}^{R} \sum_{l}^{L_r} \sum_{f}^{E} Rcall_{r,l,p} x_{r,l,f} \quad \forall p \in EI \tag{3.23}$$

Port Unload

$$PUnload_p = \sum_{r}^{R}\sum_{l}^{L_r}\sum_{f}^{E} Rcall_{r,l,p}\, y_{r,l,f} \quad \forall p \in EI \tag{3.24}$$

Port Transshipment

$$PTran_p = \frac{1}{2}\left(\sum_{r}^{R}\sum_{l}^{L_r}\sum_{f}^{E} Rcall_{r,l,p}(x_{r,l,f} + y_{r,l,f}) - \sum_{f}^{E} e_{p,f} - \sum_{f}^{E} m_{p,f}\right)$$
$$\forall p \in EI \tag{3.25}$$

Port Throughput

$$PThp_p = PLoad_p + PUnload_p \quad \forall p \in EI \tag{3.26}$$

Route Capacity

$$RCap_r = \sum_{v}^{V} Vcap_v w_{r,v} \quad \forall r \in R \tag{3.27}$$

Port Congestion

$$PCong_p = \sum_{n}^{N}\left(S_{p,n} z_{p,n} + F_{p,n} l_{p,n}\right) \quad \forall p \in EI \tag{3.28}$$

3.4.5 Objective Function

$$minimize\ TC = \sum_{v}^{V}\sum_{r}^{Rs}(Vcost_r Rweek_r w_{r,v}) \tag{3.29}$$

$$+ \sum_{p}^{P}\left(Pdue_{p,v}PCall_{p,v}\right)$$

$$+ \sum_{p}^{P}\left(Pthc_p PThp_p\right)$$

$$+ \sum_{p}^{P}\left(Ptrc_p PTran_p\right)$$

$$+ \sum_{p}^{P} WV.PCong\ _p$$

$$- \sum_{v}^{V}\sum_{r}^{RV}(Rsave_r Vcost_r w_{r,v})$$

The objective function seeks to construct a container network with a minimum total cost, satisfying demands for all interested economics pairs. The cost consists of 6 terms. The first term represents the vessel deployment cost (including fixed and operating costs over time). The second term captures berth occupancy costs of ports in selected routes. The third term depicts every port's total container handling cost. The fourth term calculates the total transshipment cost at all ports. The penultimate term computes the congestion cost at every port in the interested area of the model. Finally, the last term represents the cost saving from using the route that pass through the Thai canal.

3.4.6 Constraints

Constraints in this model can be classified into 6 groups as follows:

The economic zone demand-supply constraints

$$\sum_{p}^{P} Plink_{p,f} e_{p,f} = \sum_{t}^{E} Dem_{f,t}$$

$$\forall f \in C \qquad (3.30)$$

$$\sum_{p}^{P} Plink_{p,t} m_{p,f} = Dem_{f,t}$$

$$\forall f \in E, \qquad \forall t \in C \qquad (3.31)$$

Constraint (3.30) dictates the flow of export containers from an economic zone inside the interested area to all ports in that economy equates to its supply of container trade. while constraint (3.31) dictates the flow of import containers originated from other economies from all ports in an economic zone inside the interested area equals to the trade demand.

$$\sum_{p}^{P} Plink_{p,f} e_{p,f} \leq \sum_{t}^{E} Dem_{f,t}$$

$$\forall f \in E - C \qquad (3.32)$$

$$\sum_{p}^{P} Plink_{p,t} m_{p,f} \leq Dem_{f,t}$$

$$\forall f \in E - C, \qquad \forall t \in C \qquad (3.33)$$

On the other hand, constraint, (3.32) relaxes the flow of export containers for regions outside the interested area. Conversely, constraint (3.33) relaxes the flow of import containers from economic node outside the interested area.

$$m_{p,f} \leq \sum_{e}^{E} Dem_{e,f} \left(1 - Plink_{p,f}\right)$$
$$\forall p \in P, \quad \forall f \in E \quad (3.34)$$

$$e_{p,f} \leq \sum_{t}^{E} Dem_{f,e}\, Plink_{p,f}$$
$$\forall p \in P, \quad \forall f \in E \quad (3.35)$$

Constraint (3.34) ensures that the import flow of containers is only flow inward from the economic zone to ports, while constraint (3.35) ensures the export flow of containers is only flow outward from ports to the economic zone, respectively.

The port container flow constraints

$$\sum_{r}^{R}\sum_{l}^{L_r} Rcall_{r,l,p}\left(x_{r,l,f} - y_{r,l,f}\right) - e_{p,f} + m_{p,f} = 0$$
$$\forall p \in P, \forall f \in E \quad (3.36)$$

Constraint (3.36) balances the flow of containers at each port by stating that the total number of containers entering a port must equal the total number of containers leaving the port. The first term represents total container load/unload from routes that call on ports. The second and third terms represent the exported and imported container flow from economic zone to port, respectively.

$$y_{r,l,f} \leq M_{unload} Rcall_{r,l,p} Plink_{p,f}$$
$$\forall r \in R, \ \forall l \in L_r, \ \forall p \in P, \ \forall f \in E \quad (3.37)$$

Constraint (3.37) ensures that containers cannot be unloaded at ports located in the economic zone where they originated.

The route container flow constraints

$$c_{r,l,f} + x_{r,l,f} - y_{r,l,f} - c_{r,l+1,f} = 0$$
$$\forall r \in R, \forall l \in L_r, \forall f \in E \quad (3.38)$$

Constraint (3.38) balances the flow of containers at each leg on each route for every container originated from each economy.

$$\sum_{f}^{E} x_{r,l,f} \leq RCap_r$$
$$\forall r \in R, \forall l \in L_r \quad (3.39)$$

$$\sum_{f}^{E} y_{r,l,f} \leq RCap_r$$
$$\forall r \in R, \forall l \in L_r + 1 \quad (3.40)$$

$$\sum_{f}^{E} c_{r,l,f} \leq RCap_r$$
$$\forall r \in R, \forall l \in L_r + 1 \quad (3.41)$$

Constraints (3.39), (3.40), and (3.41) limit the flow of containers in route handling operations, including loading (3.39), unloading (3.40), and carried (3.41), for each leg of any route.

$$\sum_{l}^{L_r} x_{r,l,f} - \sum_{l}^{L_r} y_{r,l,f} = 0$$
$$\forall r \in R, \forall f \in E \quad (3.42)$$

Constraint (3.42) ensures that containers loaded onto a route must be unloaded along the route.

$$x_{r,1,f} - x_{r,Rleg_r+1,f} = 0$$
$$\forall r \in R, \forall f \in E \qquad (3.43)$$

$$y_{r,1,f} - y_{rRleg_r+1,f} = 0$$
$$\forall r \in R, \forall f \in E \qquad (3.44)$$

$$c_{r,1,f} - c_{r,Rleg_r+1,f} = 0$$
$$\forall r \in R, \forall f \in E \qquad (3.45)$$

Constraints (3.43), (3.44), and (3.45) impose the circulation loop of each route by requiring that the number of containers loaded (3.43), unloaded (3.44), and carried (3.45) after the last leg of the route must be equal to the total number of containers loaded, unloaded, and carried in the first leg.

The vessel assignment constraints

$$\sum_{v}^{V} w_{r,v} \leq Rvesmax \quad \forall r \in R \qquad (3.46)$$

Constraint (3.46) restricts the number of group vessels that enable weekly frequency on a route that can be deployed on each route.

$$\sum_{r}^{R} Rweek_r w_{r,v} \leq Vquan_v \quad \forall v \in V \qquad (3.47)$$

Constraint (3.47) ensures that the number of vessels deployed in the model does not exceed available vessels for all types.

$$\sum_{r}^{R}\sum_{l}^{L} Rcall_{r,l,p} Vlen_v w_{r,v} \leq \sum_{v'=v}^{V} 7Pberth_{p,v'}$$
$$\forall v \in V, \quad \forall p \in P \qquad (3.48)$$

Constraint (3.48) ensures that berth occupancy of each port over a week is less than berthing capacity while the smaller vessel can board on a berth for a larger size vessel.

The congestion constraints

$$\sum_{v}^{V} PCall_{p,v} = \sum_{n}^{N} z_{p,n} \qquad \forall p \in PI \tag{3.49}$$

Constraint (3.49) assigns the load of port calls to each segment, considering the congestion cost for each port.

$$l_{p,n+1}\left(b_{p,n} - b_{n-1}\right) \leq z_{p,n} \leq l_{p,n}\left(b_{p,n} - b_{n-1}\right) \quad \forall p \in PI, \ \forall n \in N \tag{3.50}$$

Constraint (3.50) assigns a binary variable, which represents the load of port calls to each segment, factoring in the congestion cost associated with each port.

Chapter 4 Experimental Setting

This chapter provides a detailed overview of the data, environment, and settings used in the model.

4.1 Input Data

The input data for the model was obtained from real-world data from 2015. This was done to avoid the effects of the Panama Canal Expansion, which opened in 2016, and the US-China trade war, which lasted from 2017 to 2020.

4.1.1 Economic zones

The economic zones we used in this instance are classified into 2 types, the economics zone in the interest area and the region outside interested area. included the Asian economies in Indo-pacific area stretch from Pakistan to Japan. However, we neglect small economies likes Brunei, Macao, Timor-Leste, and North Korea. We based on economy in the UNCTADstat Data Center (UNCTAD, 2021), which refers to a country or any other type of territorial unit. Table 4.1 shows the economic zone in the interest area, also their abbreviation, and major ports in each economic zone are also listed.

Table 4.1 The economic zones in the interest area

Economic Zone	Abbreviation	Major port
Japan	JPN	Tokyo, Yokohama
Sri Lanka	LKA	Colombo
Hong Kong	HKG	Hong Kong
China (mainland)	CHN	Shanghai, Ningbo
Singapore	SGP	Singapore
Malaysia	MYS	Port Klang, Tanjung Pelapas
South Korea	KOR	Busan
India	IND	Nhava Sheva, Chennai
Taiwan	OAS	Kaohsiung
Pakistan	PAK	Karachi
Indonesia	IDN	Jarkata
Philippines	PHL	Manilla
Bangladesh	BGD	Chattogram

Table 4.1 (cont.) The economic zones in the interest area

Economic Zone	Abbreviation	Major port
Thailand	THA	Laem Chabang
Vietnam	VNM	Ho Chi Minh
Cambodia	KHM	Kampong Saom
Myanmar	MMR	Yangoon

Next, we designated the regions outside the interested area, aggregating the economies in these regions into distinct maritime trade regions. Table 4.2 presents the regions in this instance, its abbreviation, and economies included in the region.

Table 4.2 Regions in this instance

Region	Abbreviation	Economies Included
Africa	AFR	Tanzania, Kenya, South Africa
Europe	EUR	Greece, France, the Netherland
East Latin America	ELT	Brazil, Argentina, Cuba
West Latin America	WLT	Chile, Panama, Colombia
Middle East	MDE	Egypt, UAE, Saudi Arabia
North America	NAM	Canada, USA, Mexico

4.1.2 Demand

The demand for container transportation between economic zones, for each origin and destination pair, is derived from various factors based on available data. These data include:

- **Trade value between economies by product**: We use the data of trade value between economies by product based on Standard International Trade Classification (SITC) as the classification system provided by The World Integrated Trade Solution (WITS), a software which provide access to international trade data (The World Bank, 2021c). Note that we only used the export data as its report in FOB terms, as it presents the trade value which the exporter bears from the point of loading the goods up to the point of loading them onto the ship at the port of origin, excluding freight charges, insurance premiums, and other costs. The example of the trade value between economies by product is represented in Table 4.3.

- **Cargo Value per container unit**: The model relies on volume-based demand, but to convert trade value to trade volume, it is necessary to determine the cargo value per container unit. However, it is important to note that the value per container unit can vary across different types of cargo, even within the same product category. We assume that the average cargo value per container unit, as provided by Rodrigue (2020) and illustrated in Figure 4.1, can be used to represent the value of all cargo within a product category. Furthermore, different economies may have different average values for each product, leading to variations in values across different regions. To address this issue, we use the average cargo value per container unit for each region to further calibrate our derived demand. This prevents outliers in cargo value from skewing the results.
- **Rate of containerization**: This indicates the degree to which goods are transported in containers compared to all other transportation methods. Different product categories have different levels of containerization. For instance, manufacturing goods often have a high rate of containerization, while fuels, which are commonly transported by tankers, may have a lower rate. Rodrigue (2020) provide the rate of containerization (Figure 4.2) which helps determine the derived demand for container units for each product type. In the case of certain product types where data is not available, their containerization rate is estimated from the product in the same type of categories in the Standard International Trade Classification (SITC).
- **Total container throughput in each economy**: We used the reported number by (The World Bank, 2021a). This measure represents the total amount of container traffic handled by each economy. It can be used as a key indicator to estimate the demand for container trade between the economies. The total throughput for each economics zone in the interested area is shown in Table 4.4.

- **Rate of transshipment at each economy**: The rate of transshipment is the percentage of containers that are transshipped at that port. This measure is used to deduct the containers that are not the result of trade between the economy and other economies. However, the rate of transshipment is usually published by port authorities, not by whole countries. To obtain the rate of transshipment for an economy, we aggregate the weight-average transshipment rates of all the ports in the economy which are provided in the work of (Shibasaki et al., 2016). The calculated rate of transshipment for each economics zone in the interested area is shown in Table 4.4.

Table 4.3 Sample of trade value between economies by product, 2015 (The World Bank, 2021c)

Origin	Destination	Product	Value (Thousand USD)
Japan	Singapore	Wood	53,175.58
South Korea	Hong Kong	Metals	559,320.4
Vietnam	Europe	Footwear	4,388,774
Hong Kong	North America	Plastic or Rubber	850,706.7
China	India	Chemicals	11,432,800

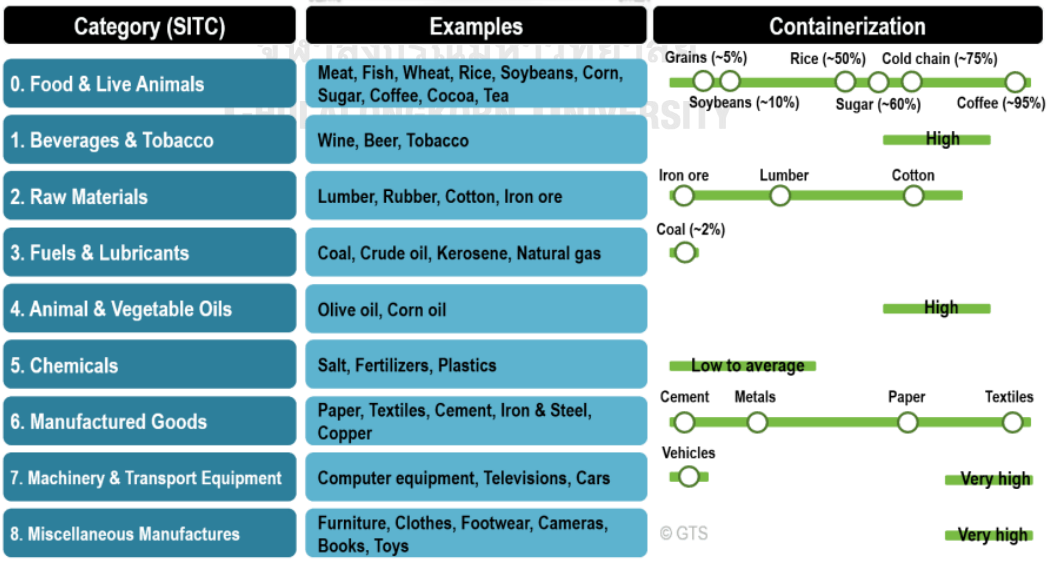

Figure 4.1 Commodity Group and Containerization Level (Rodrigue, 2020)

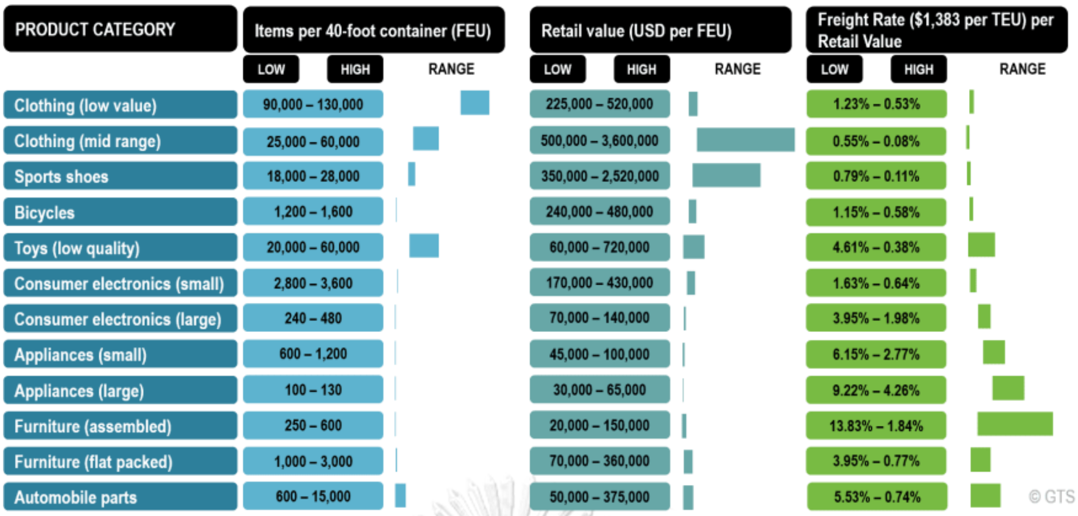

Figure 4.2 Container Shipping Costs and Cargo Value (Rodrigue, 2020).

Table 4.4 Total throughput and rate of transshipment for economic zone in the interested area.

Economic Zone	Abbreviation	Total Throughput (Million TEU)	Calculated rate of transshipment (%)
Japan	JPN	21.09	12
Sri Lanka	LKA	5.19	75
Hong Kong	HKG	20.11	42
China (mainland)	CHN	199.84	9
Singapore	SGP	30.92	85
Malaysia	MYS	24.01	65
South Korea	KOR	25.48	52
India	IND	12.32	1
Taiwan	OAS	14.49	45
Pakistan	PAK	2.71	0
Indonesia	IDN	9.58	3
Philippines	PHL	7.07	0
Bangladesh	BGD	2.07	1
Thailand	THA	8.88	1
Vietnam	VNM	10.17	1
Cambodia	KHM	0.39	0
Myanmar	MMR	0.83	0

Then, we derived the origin-destination demand using the collected data by solving following optimization:

$$minimize \quad minimize \sum_{e}^{E} (ET_e - CT_e)^2 \qquad (4.1)$$

$$subject\ to \quad FTT_{o,d} = \sum_{p}^{P} (Price_{o,p}\ TVal_{o,d,p}\ PctCont_p) \qquad \forall o, d \in E$$

$$CT_e = \sum_{o}^{E} FTT_{o,e} + \sum_{d}^{E} FTT_{e,d} \qquad \forall e \in E$$

$$ET_e = (1 - RT_e) TCT_e \qquad \forall e \in E$$

$$FTT_{e,e} = 0 \qquad \forall e \in E$$

$$CT_e \leq ET_e \qquad \forall e \in E$$

$$Price_{e,p} \leq 0.8 \qquad \forall e \in E, \forall p \in P$$

$$FTT_{o,d}, CT_e, Price_{o,p} \in R^+$$

where

E is the set of economics zone.

P is the set of SITC products.

RT_e is the rate of transshipment at economic zone e.

$TCT_e$is the total container throughput at economic zone e.

ET_e is the estimated total trade demand at economic zone e, which is the throughput after excluding the transshipped containers.

CT_e is the calculated total trade throughput at economic zone e.

$FTT_{o,d}$ is the total flow of container trade from economic zone o to economic zone d.

$Price_{o,p}$ is the cargo value of product type p from economic zone o.

$TVal_{o,d,p}$ is the trade value of product p from economic zone o to economic zone d.

$PctCont_p$ is the rate of containerization of product p.

After solving the problem (4.1), we would get origin-destination (O-D) demand between economics zone as in $FTT_{o,d}$. It should be noted that we iterate the process of optimization to control the cargo value per product type at each economic zone, dictate that it falls within the reasonable range compared to the average value of this product.

The calculated origin-destination (o-d) demand is presented in Table 4.5. Additionally, to provide more meaningful representation, we have converted the demand into a weekly value. This conversion assumes that a year consists of 52 weeks.

Table 4.5 Sample of Origin-Destination container demand

Origin	Destination	Annual Demand (TEU)	Weekly Value (TEU)
Europe	Middle East	1,373,527	26,414
China	North America	28,539,867	548,844
China	South Korea	14,703,503	282,760
Indonesia	Japan	910,614	17,512
India	Singapore	109,755	2,111
Vietnam	Malaysia	123,040	2,366

4.1.3 Vessels

We collected data on container vessels from multiple reliable sources, including carriers, and AIS data providers as shown in Table 4.6. The data was filtered to focus on operational vessels that made at least one berthing in ports within the Indo-Pacific Area in the year 2015.

Table 4.6 Data source for collecting vessel data.

Data Source	Type of Data Source
Fleetmon	AIS Data Provider
Myshiptracking	AIS Data Provider
Vesselfinder	AIS Data Provider.
Balticshipping	Online Ships database
Marine Traffic	AIS Data Provider.
MAERSK	Container Carriers
CMA CGM	Container Carriers
EVERGREEN	Container Carriers
YANG MING	Container Carriers
HMM	Container Carriers
COSCO	Container Carriers
ONE	Container Carriers
HAPAG Lloyd	Container Carriers
MSC	Container Carriers

These collect vessels were then processed by removing duplicated, filtering out vessels that were built after 2015, and then classified into four types based on their carrying capacity in TEU, as seen in the histogram shown in Figure 4.3.

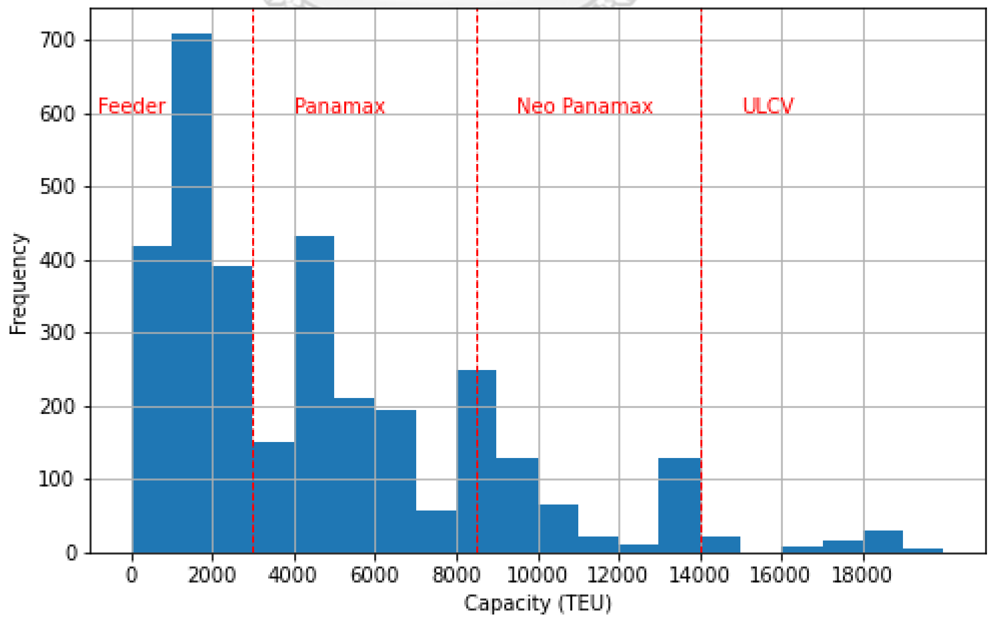

Figure 4.3 Histogram of Vessel Carrying Capacities of collected vessel data.

The classification of these vessel types aligns with the size limits for ships traveling through the Panama Canal (Panama Canal Authority, 2018) with feeder vessels falling within the smaller size range, Panamax vessels conforming to the maximum size limits of the original Panama Canal, neo-Panamax vessels adhering to the expanded size limits of the Panama Canal after its expansion project, and ULCVs representing the largest container vessels that exceed the Panama Canal's size limits. The descriptive statistics of the collected vessel data by type are shown in Table 4.7 and Table 4.8.

Table 4.7 Attributes of collected vessel data by types (capacity and quantity).

Type	Capacity (TEU)				Quantity
	Max	Average	Median	Min	
Feeder	2,992	1,511	1,368	142	1,550
Panamax	8,498	5,334	4,896	3,028	1,150
Neo Panamax	13,994	10,474	9,614	8,500	460
ULCV	19,870	17,178	17,816	14,108	60

Table 4.8 Attributes of collected vessel data by types (length and draft).

Type	Length (m)				Draft (m)			
	Max	Average	Median	Min	Max	Average	Median	Min
Feeder	247	168	168	78	12.4	8	8	2.65
Panamax	366	278	276	175	14.5	11.3	11.3	6.7
Neo Panamax	397	340	337	298	16	12.5	12.5	6.5
ULCV	400	392	399	366	17	13.9	14	6.5

Based on the collected data, we characterized the attributes of each vessel type. We rounded up the median value for each attribute and used it as a specification for each type, except for the capacity. For the capacity attribute, we used the maximum value as the specification for each vessel type in the model.

Additionally, we utilized the rounded-up median value to calculate the vessel deployment cost. Table 4.9 represents the characteristics of each type of vessel.

Table 4.9 The characteristics of each type of vessel.

Type Name	Median Capacity (TEU)	Length (m)	Draft (m)	Maximum Capacity (TEU)	Available Quantity
Feeder	1,500	170	8	3,000	1,550
Panamax	5,000	275	11	8,500	1,150
Neo Panamax	10,000	335	13	14,000	460
ULCV	18,000	400	14	20,000	60

The main consideration regarding the assignment of vessels to routes is the cost incurred. In this study, we have adopted the vessel cost calculation method presented by Shibasaki et al. (2017) as our reference. For any container vessel with the capacity $Vcap$ (TEU). The vessel cost deployment per day, VC, (USD) can be calculated by

$$VC = FC + CC \ + OC \tag{4.2}$$

where FC is the fuel cost, CC is the capital cost, and OC is the operation cost. These costs are measured on a per-day basis.

The fuel cost, FC, is defined as

$$FC = BP\ (6.49x10^{-6}).DWT^{\frac{2}{3}}.v^3 \tag{4.3}$$

where BP is the bunker (ship fuel) price (USD/ton), DWT is the dead weight tonnage of the vessel (tonnage), and v is the vessel speed (knot). Both the dead weight tonnage, DWT, and the vessel speed, v, can be related with ship size as

$$DWT = 11.89\,Vcap + \ 4414 \tag{4.4}$$

$$v = (4.0x10^{-5})Vcap + \ 20.8 \tag{4.5}$$

The capital cost, CC, is defined as

$$CC = VP \frac{ir}{(1-(1+ir)^{-PP}} \frac{1}{365\ x\ ODR} \quad (4.6)$$

where VP is the vessel price (USD); ir is the interest rate (we set ir = 0.02), PP is the project period which vessel would be operating (year; we set PP = 15), and ODR is the operation day rate per year (we set ODR = 0.9, that mean 329 days in operation a year). The ship price, VP, is estimated as follows:

$$VP = (9.9x10^3)Vcap + (8.0x10^6) \quad (4.7)$$

The operation cost, OC, is defined as

$$OC = (4.0x10^{-5})Vcap + 20.8 \quad (4.8)$$

To determine the cost for vessel deployment using median size of vessel capacity applied on the calculation presented in the last chapter, using the average bunker price in 2015 of 468.45 USD/ton (BunkerIndex, 2016). The calculated vessel deployment cost for each type of vessel is shown in Table 4.10.

Table 4.10 Vessel deployment cost (Thousand USD/Week).

Type Name	Median Capacity (TEU)	Capital Cost	Bunker Cost	Operation Cost	Total Cost (Rounded)
Feeder	1500	47	145	46	240
Panamax	5000	114	277	77	470
Neo Panamax	10000	182	380	107	670
ULCV	18000	256	482	140	880
Weighted Average	-	-	-	-	400

4.1.4 Ports

We utilized port data sourced from the Sailing Directions publication published by the National Geospatial-Intelligence Agency [NGA] (2018). This publication offered comprehensive information on various ports, including details such as berth length, depth, maximum vessel size, and the intended purpose of berths. Table 4.11 provides an example of the data extracted from this publication. Although it is worth mentioning that the publication has undergone updates since 2015, leading to the data we present not being from that specific year, we conducted cross-referencing with port authorities and news to ensure the accuracy and reliability of the information utilized in our study.

Table 4.11 Example of Ports Data from Sailing Directions publication (NGA, 2018)

Laem Chabang—Berth Information				
Berth No.	Length (m)	Depth (m)	Maximum Vessel Size (dwt)	Remarks
Terminal A				
A0	590	11.6	1,000	Coastal and multi-purpose. Two berths available
A1	365	11.6	70,000	Passenger and ro-ro.
A2	400	14.0	50,000	Multipurpose.
A3	350	14.0	83,000	Multipurpose.
A4	520	11.6	40,000	Agri-bulk.
A5	450	14.0	70,000	Vehicles.
Terminal B				
B1	300	14.0	50,000	Containers.
B2	300	14.0	50,000	Containers.
B3	300	14.0	50,000	Containers.
B4	300	14.0	50,000	Containers.
B5	400	14.0	50,000	Containers.
Terminal C				
C0	500	16.0	80,000	Passengers.
C1	500	16.0	80,000	Containers.
C2	500	16.0	80,000	Containers.
C3	500	16.0	80,000	Containers.

Table 4.11 (Cont) Example of Ports Data from Sailing Directions publication (NGA, 2018)

Laem Chabang—Berth Information				
Berth No.	Length (m)	Depth (m)	Maximum Vessel Size (dwt)	Remarks
Terminal D (Under construction 2016)				
D1	700	16.0	80,000	Containers.
D2	500	16.0	80,000	Containers.
D3	500	16.0	80,000	Containers.
Unithai Shipyard and Engineering				
Floating Dock No.1	47	8.0	—	Drydock.
Floating Dock No.2	34	7.0	—	Drydock.

Next, we process the extracted data to utilized in our model, by selected a berth that only handled container cargoes and aggregated the berth length available for each type of vessel we used in this model and rounded up into the multiplier of vessel length of each type, based on the draft of each berth facility.

For example, the Port of Laem Chabang only includes berths B1-B5 and C1-C3 in its berth length calculation. The depth of berths B1-B5 is 14.0 meters, which means that the largest vessel type that can be accommodated at these berths is the Neo Panamax. Berths C1-C3 have a depth of 16.0 meters, which means that they can accommodate the ULCV. Therefore, the port can accommodate all vessel types. The aggregate berth length would be 1,600 meters for Neo Panamax, and 1,500 meters for ULCV, we round up the berth length into the multiple of vessel length, hence the berth length of port of Laem Chabang would be 1,675 (5 of 335 meters) for Neo Panamax and 1,600 (4 of 400 meters).

Additionally, we have determined the vessel capacity, which represents the minimum number of berthing vessels that a port can handle simultaneously. This capacity is crucial for calculating the port's congestion level. In our calculations, we take into account port efficiency and assume that ports cannot operate all their berths simultaneously due to various operational factors. We consider an efficiency rate of 90%, meaning that the actual number of berths in operation at any given time is reduced by this percentage. This adjustment allows for a more realistic assessment of port congestion levels. Table 4.12 presents information on all ports located in the interested area in this model, including the port's name, economy, designated UNLOCODE (United Nations Economic Commission for Europe [UNECE], 2022), and port berthing properties for all ports located in the interested area in this instance.

Table 4.12 Ports berthing properties.

Port Name	Economy	UNLOCODE	Port Berthing Properties				
			Draft <10.5 m (m)	Draft <= 10.5 m (m)	Draft <= 14 m (m)	Draft > 14 m (m)	Vessel Capacity (vessel)
CHATTOGRAM	BGD	BDCGP	3,060	-	-	-	16
DA CHAN BAY	CHN	CNDCB	-	-	-	2,340	6
DALIAN	CHN	CNDAL	-	825	1,005	2,730	11
Fuzhou	CHN	CNFOC	340	1,650	-	1,950	11
LIANYUNGANG	CHN	CNLYG	510	-	670	1,560	8
NINGBO	CHN	CNNBG	-	-	-	9,360	21
NANSHA	CHN	CNNSA	4,930	1,925	670	5,460	46
QINGDAO	CHN	CNQDG	680	550	335	8,580	26
QINZHOU	CHN	CNQZH	-	-	-	1,560	4
SHANGHAI	CHN	CNSHG	3,570	2,750	2,010	7,800	51
SHEKOU	CHN	CNSHK	-	1,100	1,675	3,900	17
TIANJIN XINGANG PT	CHN	CNTXG	1,020	2,750	1,005	3,510	25
XIAMEN PT	CHN	CNXMG	510	275	2,345	5,460	22
YANTAI PT	CHN	CNYTG	170	-	1,340	2,730	10
YANTIAN PT	CHN	CNYTN	-	-	1,340	6,240	18
HONG KONG	HKG	HKHKG	3,060	-	1,005	5,070	30
JAKARTA, JAVA	IDN	IDJKT	2,380	2,750	670	2,730	29
SEMARANG	IDN	IDSRG	680	-	-	-	4
SURABAYA	IDN	IDSUB	3,570	-	-	-	18
KOLKATA (CALCUTTA)	IND	INCCU	1,700	-	-	-	9
COCHIN	IND	INCOK	510	-	335	780	6
KRISHNAPATNAM	IND	INKRI	-	-	-	780	2
HAZIRA PORT/SURAT	IND	INHZA	-	-	670	-	2
CHENNAI	IND	INMAA	-	-	1,005	780	5
MUNDRA	IND	INMUN	-	-	-	3,510	8

Table 4.12 (cont.) Ports berthing properties.

Port Name	Economy	UNLOCODE	Port Berthing Properties				
			Draft <10.5 m (m)	Draft <= 10.5 m (m)	Draft <= 14 m (m)	Draft > 14 m (m)	Vessel Capacity (vessel)
JAWAHARLAL NEHRU (NHAVA SHEVA)	IND	INNSA	1,190	-	-	3,510	14
PIPAVAV (VICTOR) PORT	IND	INPAV	-	-	335	390	2
TUTICORIN	IND	INTUT	340	275	-	390	4
VISAKHAPATNAM	IND	INVTZ	-	-	-	780	2
HAKATA/FUKUOKA	JPN	JPHKT	2,550	550	670	390	18
MOJI/KITAKYUSHU	JPN	JPMOJ	1,190	-	-	1,170	9
NAGOYA, AICHI	JPN	JPNGO	680	825	1,005	1,560	12
OSAKA	JPN	JPOSA	-	-	2,010	1,170	8
SHIMIZU	JPN	JPSMZ	680	825	-	780	8
TOKYO	JPN	JPTYO	680	-	2,010	2,340	14
KOBE	JPN	JPUKB	-	-	1,340	3,510	11
YOKKAICHI	JPN	JPYKK	-	-	1,005	-	3
YOKOHAMA	JPN	JPYOK	-	-	1,005	4,290	12
KAMPONG SAOM	KHM	KHKOS	680	-	-	-	4
INCHEON	KOR	KRINC	850	1,375	1,675	1,560	17
GWANGYANG	KOR	KRKAN	-	550	-	4,290	11
BUSAN	KOR	KRPUS	2,380	-	1,340	10,530	40
ULSAN	KOR	KRUSN	-	1,925	335	-	7
COLOMBO	LKA	LKCMB	1,360	275	335	3,120	16
YANGON	MMR	MMRGN	4,760	-	-	-	25
BINTULU, SARAWAK	MYS	MYBTU	510	-	335	-	4
JOHOR BAHRU	MYS	MYJHB	-	825	-	-	3
PENANG	MYS	MYPEN	1,190	550	-	-	8
PORT KLANG	MYS	MYPKG	170	1,100	2,345	1,560	14
TANJUNG PELEPAS	MYS	MYTPP	-	-	-	5,070	11
BATANGAS/LUZON	PHL	PHBTG	-	-	670	-	2
CEBU	PHL	PHCEB	510	-	-	-	3
DAVAO, MINDANAO	PHL	PHDVO	-	825	-	390	4
MANILA	PHL	PHMNL	850	1,100	1,675	-	12
SUBIC BAY	PHL	PHSFS	-	-	670	-	2
MUHAMMAD BIN QASIM	PAK	PKBQM	-	-	670	780	4
KARACHI	PAK	PKKHI	-	-	1,675	1,560	8
SINGAPORE	SGP	SGSIN	1,700	1,375	-	17,160	53
BANGKOK	THA	THBKK	2,890	-	-	-	15

Table 4.12 (cont.) Ports berthing properties.

Port Name	Economy	UNLOCODE	Port Berthing Properties				
			Draft <10.5 m (m)	Draft <= 10.5 m (m)	Draft <= 14 m (m)	Draft > 14 m (m)	Vessel Capacity (vessel)
LAEM CHABANG	THA	THLCH	-	-	1,675	1,600	7
SONGKHLA	THA	THSGK	510	-	-	-	3
KEELUNG	OAS	TWKEL	3,400	550	335	390	21
KAOHSIUNG	OAS	TWKHH	1,190	-	3,015	2,730	20
TAIPEI	OAS	TWTPE	-	-	-	1,560	4
TAICHUNG	OAS	TWTXG	-	275	1,340	390	6
HAIPHONG	VNM	VNHPH	7,140	550	-	780	41
HO CHI MINH CITY	VNM	VNSGN	5,780	1,100	1,340	-	37

Regarding the cost related to port we use the data present in the LINER-LIB 2012, presented by Brouer et al. (2013). The berthing costs, port dues, are calculated for each type of vessel and presented along the handling Cost and the transshipment Cost show in Table 4.13.

Table 4.13 Ports cost.

UNLOCODE	Port dues Draft <10.5 (1,000 USD/Call)	Port dues Draft < 12 (1,000 USD/Call)	Port dues Draft < 14 (1,000 USD/Call)	Port dues Draft > 16 (1,000 USD/Call)	Handling Cost (1,000 USD/TEU)	Tranship Cost (1,000 USD/TEU)
BDCGP	36.38	104.63	202.13	358.13	0.052	2
CNDCB	15.797	24.547	37.047	57.047	0.0895	0.062
CNFOC	5.428	15.928	30.928	54.928	0.0795	0.062
CNLYG	14.712	30.462	52.962	88.962	0.058	0.06
CNNBG	10.275	17.275	27.275	43.275	0.059	0.036
CNNSA	8.823	21.073	38.573	66.573	0.0675	0.091
CNQDG	10.563	19.313	31.813	51.813	0.062	0.025
CNQZH	8.823	21.073	38.573	66.573	0.0675	0.091
CNSHG	10.997	21.497	36.497	60.497	0.075	0.062
CNSHK	15.693	26.193	41.193	65.193	0.1065	0.079
CNTXG	8.922	15.922	25.922	41.922	0.086	0.049
CNXMG	8.267	15.267	25.267	41.267	0.054	0.057
CNYTG	8.922	15.922	25.922	41.922	0.086	0.049
CNYTN	10.22	17.22	27.22	43.22	0.0885	0.078

Table 4.13 (cont.) Ports cost.

UNLOCODE	Port dues Draft <10.5 (1,000 USD/Call)	Port dues Draft < 12 (1,000 USD/Call)	Port dues Draft < 14 (1,000 USD/Call)	Port dues Draft > 16 (1,000 USD/Call)	Handling Cost (1,000 USD/TEU)	Transship Cost (1,000 USD/TEU)
HKHKG	8.309	11.809	16.809	24.809	0.1285	0.093
IDJKT	8.249	20.499	37.999	65.999	0.0675	0.062
IDSRG	10.426	27.926	52.926	92.926	0.067	0.081
IDSUB	4.634	13.384	25.884	45.884	0.0925	0.003
INCCU	35.296	101.796	196.796	348.796	0.0105	0.058
INCOK	9.633	14.883	22.383	34.383	0.083	0.056
INHZA	7.372	14.372	24.372	40.372	0.104	0.009
INKRI	35.296	101.796	196.796	348.796	0.0105	0.058
INMAA	7.57	23.32	45.82	81.82	0.0745	0.16
INMUN	36.013	102.513	197.513	349.513	0.0935	0.076
INNSA	19.587	49.337	91.837	159.837	0.1	0.186
INPAV	7.372	14.372	24.372	40.372	0.104	0.009
INTUT	7.57	23.32	45.82	81.82	0.0745	0.16
INVTZ	7.57	23.32	45.82	81.82	0.0745	0.16
JPHKT	10.9	19.65	32.15	52.15	0.0915	0.085
JPMOJ	10.9	19.65	32.15	52.15	0.0915	0.085
JPNGO	23.11	35.36	52.86	80.86	0.067	0.063
JPOSA	24.566	52.566	92.566	156.566	0.08	0.086
JPSMZ	26.41	45.66	73.16	117.16	0.0985	0.082
JPTYO	9.617	25.367	47.867	83.867	0.1375	0.087
JPUKB	16.695	23.695	33.695	49.695	0.0535	0.063
JPYKK	23.11	35.36	52.86	80.86	0.067	0.063
JPYOK	17.65	19.4	21.9	25.9	0.0525	0.068
KHKOS	10.656	28.156	53.156	93.156	0.0425	0.063
KRINC	7.087	15.837	28.337	48.337	0.04	0.064
KRKAN	3.203	4.953	7.453	11.453	0.0385	0.048
KRPUS	6.592	15.342	27.842	47.842	0.0385	0.048
KRUSN	6.592	15.342	27.842	47.842	0.0385	0.048
LKCMB	5.568	12.568	22.568	38.568	0.136	0.073
MMRGN	36.38	104.63	202.13	358.13	0.052	0.002
MYBTU	9.963	25.713	48.213	84.213	0.067	0.06
MYJHB	9.963	25.713	48.213	84.213	0.067	0.06
MYPEN	9.963	25.713	48.213	84.213	0.067	0.06
MYPKG	4.799	10.049	17.549	29.549	0.025	0.034
MYTPP	4.242	9.492	16.992	28.992	0.0575	0.059

Table 4.13 (cont.) Ports cost.

UNLOCODE	Port dues Draft <10.5 (1,000 USD/Call)	Port dues Draft < 12 (1,000 USD/Call)	Port dues Draft < 14 (1,000 USD/Call)	Port dues Draft > 16 (1,000 USD/Call)	Handling Cost (1,000 USD/TEU)	Transship Cost (1,000 USD/TEU)
PHBTG	8.375	20.625	38.125	66.125	0.0755	0.001
PHCEB	8.432	20.682	38.182	66.182	0.0135	0.085
PHDVO	8.432	20.682	38.182	66.182	0.0135	0.085
PHMNL	8.375	20.625	38.125	66.125	0.0755	0.001
PHSFS	8.375	20.625	38.125	66.125	0.0755	0.001
PKBQM	24.831	65.081	122.581	214.581	0.051	0.06
PKKHI	46.012	131.762	254.262	450.262	0.1285	0
SGSIN	4.018	5.768	8.268	12.268	0.065	0.085
THBKK	5.399	15.899	30.899	54.899	0.0475	0.001
THLCH	5.399	15.899	30.899	54.899	0.0475	0.001
THSGK	10.793	28.293	53.293	93.293	0.0415	0.065
TWKEL	9.963	25.713	48.213	84.213	0.0635	0.083
TWKHH	4.481	9.731	17.231	29.231	0.009	0.025
TWTPE	9.963	25.713	48.213	84.213	0.0635	0.083
TWTXG	9.963	25.713	48.213	84.213	0.0635	0.083
VNHPH	9.112	23.112	43.112	75.112	0.038	0.002
VNSGN	9.317	21.567	39.067	67.067	0.0455	0.066

4.1.5 Routes

The route data used in this model were obtained from open access data provided by carriers, as shown in Table 4.14. After retrieving the data, we removed any duplicated entries and filtered out routes that did not pass through the interested area. As a result, a total of 431 routes were included in our instance. Of which 263 routes were passing through the strait of Malacca. From the routes roundtrip travel time and the number port called on route, we can classify routes into 4 types including Short Feeder, Long Feeder, Region to Region, Multi Region. The graphical representation of the classification is presented in Figure 4.4. The characteristics of each route type are shown in Table 4.15.

Table 4.14 Data sources for collecting routes data.

Liners	URL/Publication
MAERSK	https://www.maersk.com/local-information/
MSC	MSC pamphlet EAST-WEST Service 2020
CMA CGM	https://www.cma-cgm.com/products-services/line-services
COSCO	https://lines.coscoshipping.com/home/Services/route/16
HAPAG-LLOYD	https://www.hapag-lloyd.com/en/online-business/schedule/schedule-download-solution.html
EVERGREEN	https://www.evergreen-line.com/serviceroutes/jsp/RUT_ServiceRoutes.jsp
ONE	https://www.one-line.com/en/routes/current-services
HMM	https://www.hmm21.com/e-service/general/schedule/serviceNetwork/serviceNetwork.do
YANG MING	https://www.yangming.com/e-service/schedule/LongTermSchedule.aspx

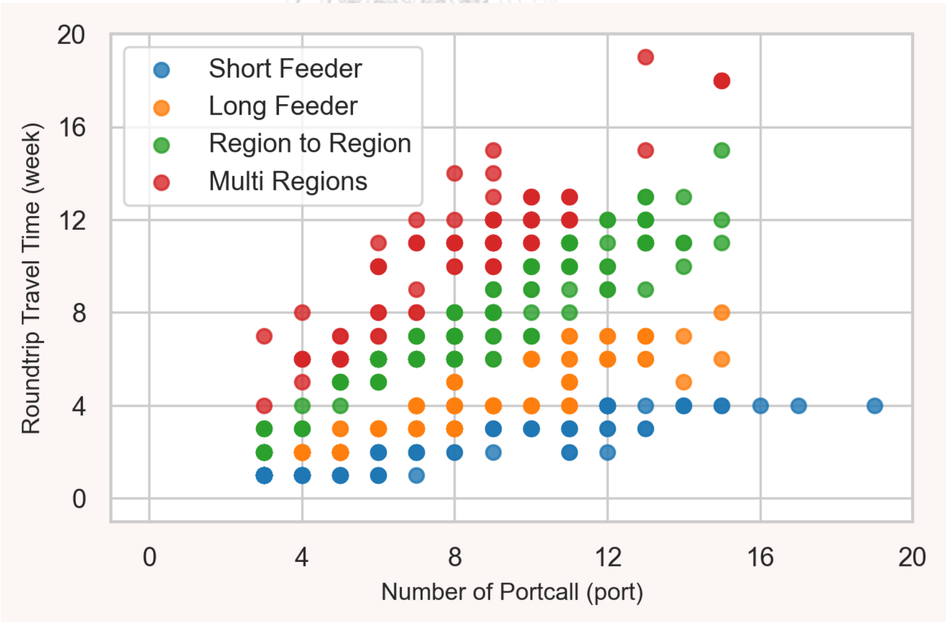

Figure 4.4 The classification of route types.

Table 4.15 Characteristics of each type of route.

Route Types	Ports of Call (Port)		Roundtrip Travel Time (week)		Number of routes this type	Routes passing through the strait of Malacca
	Mean	Median	Mean	Median		
Short Feeder	8.19	6	2.07	2	96	47
Long Feeder	8.43	8	3.88	4	115	76
Region to Region	7.5	8	7.41	7	128	75
Multi Regions	8.25	9	10.63	11	92	65
Overall	8.13	8	5.96	5	431	263

Table 4.16 provides examples for each type of route discussed. The examples provided in the table highlight the specific ports visited, the number of port calls made, and the travel time associated with each route type. The graphical representations of the example routes are illustrated in Figure 4.5 – 4.8.

Table 4.16 Examples of each type of route.

Route Types	Port call	Ports of call (port)	Travel Time (week)
Short Feeder	THBKK, THLCH, VNHPH, CNNSA, CNSHK, THLCH, THBKK	6	2
Long Feeder	IDJKT, IDSUB, VNSGN, CNSHG, KRPUS, KRKAN, CNSHG, IDJKT	7	4
Region to region	MDE, MYPKG, CNQDG, CNSHG, CNNBG, CNNSA, SGSIN, MDE	7	7
Multi Regions	EUR, CNSHG, CNTXG, CNDLC, CNQDG, CNSHG, CNNBG, SGSIN, EUR	8	11

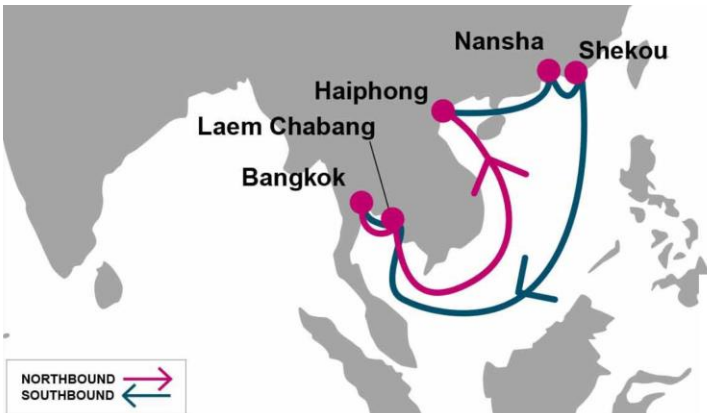

Figure 4.5 An example of Short Feeder route (ONE, 2023).

Figure 4.6 An example of Long Feeder route (EVERGREEN, 2023).

Figure 4.7 An example of region-to-region route (CMA-CGM, 2023a).

Figure 4.8 An example of multi region route (CMA-CGM, 2023b).

4.1.6 Virtual Routes

For 263 routes that were passing the Strait of Malacca, we filtered out all routes that only pass through the Strait of Malacca, but do not go beyond the ports in the Strait of Malacca. The remaining 138 routes are used to construct new virtual routes. The characteristics of new virtual routes by its type are shown in Table 4.17. Note that the number port of call also counts the Thai canal on both eastbound and westbound, and travel time did not taken account of saving from the canal (travel time is the same as real route). Table 4.16 provides examples for each type of virtual route.

Table 4.17 Characteristics of each type of virtual route,

Route Types	Ports of Call (Port)		Travel Time (week)		Number of routes this type
	Mean	Median	Mean	Median	
Short Feeder	6	6	3	3	1
Long Feeder	9.32	9	6.12	6	25
Region to region	9.78	10	9.67	10	51
Multi Regions	8.57	8	12.35	12	52
Overall	9.17	9	10.0	11	138

Table 4.18 Examples of each type of route.

Route Types	Port call	Ports of call (port)	Travel Time (week)
Short Feeder	THBKK, THLCH, KHKOS, THCAN, MMRGN, THCAN, THBKK	6	3
Long Feeder	CNSHG, CNNBG, CNXMG, CNSHK, THCAN, LKCMB, PKKHI, INMUN, THCAN, CNSHG,	9	6
Region to region	MDE, THCAN, CNQDG, CNSHG, CNNBG, CNSHK, THCAN, MDE	7	7
Multi Regions	EUR, CNSHG, CNTXG, CNDLC, CNQDG, CNSHG, CNNBG, THCAN, EUR,	8	12

4.2 Scenario setting

In this study, we undertake a comparative analysis of three scenarios. The first scenario explores the base scenario of the container network which is the original state of the network. While the second scenario investigates the canal's construction with a timesaving of two days, the most claimed time saving of the Canal (Keovimol, n.d., THEPARAT, 2020b, Takahashi, 2022, Notteboom et al., 2022, The Ad-hoc Committee on Considering the Study of Digging Thai Canal and Development of the Southern Economic Corridor, 2022). Lastly, we examine the scenario in which the Thai canal does not save any transit time, which represents the most unfavorable scenario for the Thai canal. Even in this scenario, the canal would still be a viable option for shipping, but it would be less attractive. It should be noted that, the scenario that the Thai Canal shows no saving time, could be used in equivalent of the case where the fee of passing Thai Canal is cancelled out the benefit. Moreover, the routes passing through the Thai Canal in this case, while gain no benefit in sailing time, it would bypass ports in the Strait of Malacca, avoiding berthing fee, and congestion in ports. Finally, the parameters used in different scenarios are presented in Table 4.19.

Table 4.19 The parameters used in each Scenarios.

Scenario	Parameters		
	The Thai Canal available	Thai Canal Saving $TCSave$ (days)	Routes available
Base	N/A	N/A	Actual Route
Canal with 2 day saving transit time	Available	2	Actual Route + Virtual Route
Canal with no saving transit time	Available	0	Actual Route + Virtual Route

In subsequent discussions, the scenario featuring a canal with a 2-day saving in transit time can be referred to as the '**2-day saving**' scenario. Conversely, the scenario where the canal does not provide any timesaving in transit can be referred to as the '**0-day saving**' scenario.

4.3 Solving's environment

The optimization model was solved using IBM® CPLEX-20.1, with the Python interface of IBM® Decision Optimization Modeling for Python (DOcplex). The solver was run on a computer was operated on Windows 10 with an AMD Ryzen 5 3600 6-Core 12-Thread Processor and equipped with 64 GB of RAM.

Chapter 5 Experimental Results and Discussion

This chapter details the experimental results derived from the model, using the instance discussed in the previous chapter. The presentation of these results is twofold: initially, we validated the base scenario solution using real-world data; subsequently, we carried out a comparative analysis of different Thai canal scenarios.

5.1 Validation of base scenario solutions

The model utilizes the unaltered data of the container network to determine the solution for the base scenario, representing the network's original state and serving as a reference point for comparison in this study. However, it is crucial to consider that the model is subject to certain assumptions, which may introduce disparities between the solution and the actual data. Therefore, the base scenario solutions must be validated to ensure the model's alignment with actual data and to guarantee the model feasibility to determine the impacts on infrastructure change container network.

Through the validation process, any disparities between the model's assumptions and the real-world observations can be identified. This evaluation can shed light on aspects in the proposed model that do not comply with the real-world network. If the identified non-compliance has a minimal impact on the overall results, it may indicate the feasibility of the model for further analysis. Conversely, if the non-compliance significantly affects the overall results, it underscores the necessity for refining and adjusting the model to enhance its reliability and accuracy.

In this study, we validated the base solution by comparing it to real-world data in the same year (2015) across four key aspects: the throughput of economies in the interested area, the throughput of the busiest ports, the number of vessels passing through the Malacca Strait, and the port traffic for ports in the strait of Malacca, including measures such as port throughput, port calls, and port transshipment activities. This validation process was essential to assess the feasibility of the model and its alignment with the actual container network. The validation results provide assurance that the model captures the essential characteristics of the container network and can be relied upon for reliable insights.

5.1.1 Throughput of economies in the interested area

In the first aspect of validation process, we conducted a comparison between total port throughput of economies in the interested area with container port traffic for each economy reported in 2015 (The World Bank, 2021a) Furthermore, we also compare the total port throughput of economies with the given demand data (including both export and import) to observe the transshipment that occurs along the port network in each economy. Note that the model results and the given demand are weekly. We converted them on an annual basis by assuming 52 weeks per year. Table 5.1 presents a comparison of the annual throughput of economies in the interested area.

Table 5.1 The comparison of annual throughput of economies in the interested area.

Economy	Actual Throughput	Model Throughput	% deviation	Trade demand	Transshipment	% transshipment
China	199.8	183.7	-8%	183.3	0.2	0%
Singapore	30.9	33	7%	5	14	85%
South Korea	25.5	17.5	**-32%**	12.7	2.4	27%
Malaysia	24	21.5	-10%	8.7	6.4	59%
Japan	21.1	21.5	2%	18.4	1.55	14%
Hong Kong	20.1	14.3	-29%	14.2	0.05	1%
Taiwan	14.5	20.1	38%	8.3	5.9	59%
India	12.3	12.4	1%	12.2	0.1	2%
Vietnam	10.2	13.7	34%	11.4	1.15	17%
Indonesia	9.6	12.1	26%	12.1	0	0%
Thailand	8.9	12.6	41%	9.7	1.45	22%
Philippines	7.1	7.5	6%	7.5	0	1%
Sri Lanka	5.2	4.1	-22%	1.3	1.4	67%
Pakistan	2.7	2.9	8%	2.9	0	2%
Bangladesh	2.1	2.1	0%	2.1	0	0%
Myanmar	0.8	0.9	7%	0.9	0	0%
Cambodia	0.4	0.5	23%	0.5	0	0%

Note. All unit is in Million TEU

The key findings, in terms of deviation, reveal that the model's precision varies across different economies. For some economies, such as South Korea (-32%), Hong Kong (-29%), and Sri Lanka (-22%) the model tends to underestimate the throughput, suggesting a potential oversight of factors like transshipment operations, port efficiencies, and local trade policies. Conversely, the model overestimates the throughput for economies including Thailand (41%), Taiwan (38%), Vietnam (34%), Indonesia (26%), and Cambodia (23%) indicating a potential overvaluation of elements like trade demand or a neglect of constraints such as logistical issues or trade barriers.

Interestingly, the model's throughput estimates for the economies of Malaysia and Singapore, both have major ports situated along the Strait of Malacca, show deviations of -10% and 7% respectively from the actual data. While these aren't perfect matches, the deviations are not extreme, especially when compared with other economies. This suggests that the model's parameters and assumptions manage to capture, to a fair degree, the dynamics of port operations in the Strait of Malacca.

Next, for a holistic perspective on the validation results, we draw on (Shibasaki et al., 2017) approach by charting a scatter plot that compares the model's estimates directly with the actual data. This technique, displayed in Figure 5.1, effectively demonstrates the extent of deviation and underscores where the model either accurately mirrors or diverges from the actual throughput for all economic zones. In addition, to quantify the accuracy of our model's estimates, we calculated the coefficient of determination, R^2, which stands at 0.987. This statistical measure, along with the scatter plot visualization, indicates that our results seem to well match the actual data, displaying an average error of just 6%.

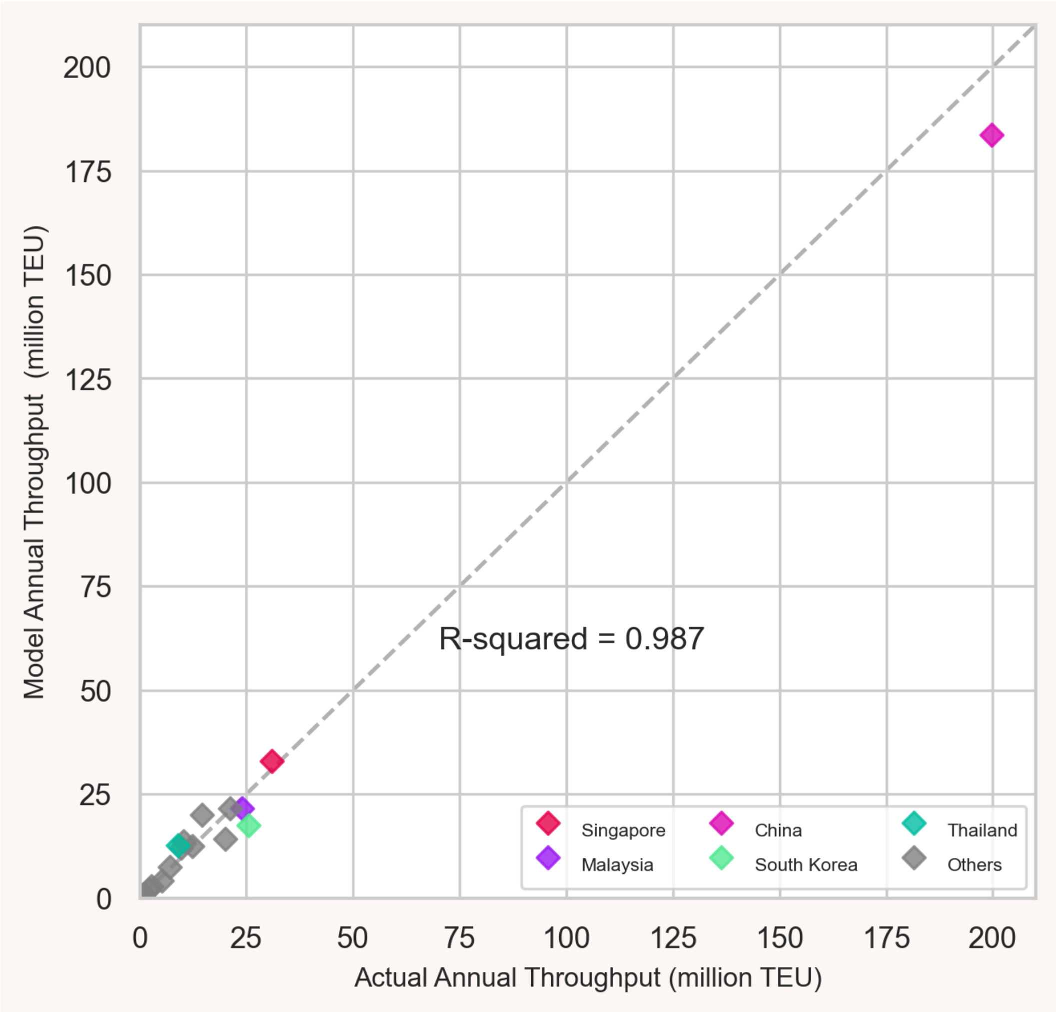

Figure 5.1 The comparison between the actual data and the model's results of throughput for all economic zones in the interested area.

Furthermore, when examining the transshipment operation, we discover that Singapore, Taiwan, and Malaysia are notable players in transshipment, with annual volumes of 14, 5.9, and 6.4 million TEUs, respectively. This corresponds to 85%, 59%, and 59% of their model estimated throughput, respectively. Sri Lanka is also an interesting case, with a relatively low absolute volume of transshipments at 1.4 million TEUs. However, this accounts for 67% of its model's estimated throughput.

5.1.2 Throughput of the busiest ports

We conducted a comparison between the port throughput data reported in 2015 (World Shipping Council, 2016) and the results obtained from our model using the as-is data of the container network. To focus our analysis on the interested area, we selected the top 20 ports in the interest area, However, there are variations in the port designations between the real-world reported data and ports used in our model. To address this, we made necessary adjustments to align the results with the real-world data's port designation. Furthermore, the throughput results obtained from our model were in weekly units. To provide a more meaningful comparison, we converted these results to an annual basis by assuming 52 weeks per year. Table 5.1 presents the ranked list of ports and their corresponding annual throughput values.

Table 5.2 The comparison of top 20 ports by throughput between the actual data and the base Scenario solutions.

Port	Economy	Ports in model	Actual Data (2015)			Base Scenario solutions		
			Throughput (Million TEU)	Rank	Global Rank	Throughput (Million TEU)	Model Rank	% deviation
Shanghai	China	CNSHG	36.54	1	1	15.31	7	-58%
Singapore	Singapore	SGSIN	30.92	2	2	33.03	3	7%
Shenzhen	China	CNDCB, CNSHK, CNYTN	24.2	3	3	22.45	4	-7%
Ningbo-Zhoushan	China	CNNBG	20.63	4	4	70.51	1	242%
Hong Kong	Hong Kong	HKHKG	20.07	5	5	14.32	9	-29%
Busan	South Korea	KRPUS	19.45	6	6	17.00	6	-13%
Qingdao	China	CNQDG	17.47	7	7	7.66	15	-56%
Guangzhou	China	CNNSA	17.22	8	8	9.52	13	-45%
Tianjin	China	CNTXG	14.11	9	10	0.00	-	-100%
Port Klang	Malaysia	MYPKG	11.89	10	12	14.87	8	25%
Kaohsiung	Taiwan	TWKHH	10.26	11	13	20.05	5	95%
Dalian	China	CNDLC	9.45	12	15	1.62	19	-83%
Xiamen	China	CNXMG	9.18	13	16	52.72	2	474%

Table 5.2 (cont.) The comparison of top 20 ports by throughput between the actual data and the base Scenario solutions.

Port	Economy	Ports in model	Actual Data (2015)			Base Scenario solutions		
			Throughput (Million TEU)	Rank	Global Rank	Throughput (Million TEU)	Model Rank	% deviation
Tanjung Pelepas	Malaysia	MYTPP	9.1	14	17	3.85	17	-58%
Keihin Ports*	Japan	JPTYO, JPYOK	7.52	15	20	13.94	10	85%
Laem Chabang	Thailand	THLCH	6.82	16	22	11.65	11	71%
Ho Chi Minh	Vietnam	VNSGN	5.31	17	26	8.88	14	67%
Jakarta	Indonesia	IDJKT	5.2	18	27	9.77	12	88%
Colombo	Sri Lanka	LKCMB	5.19	19	28	4.06	16	-22%
Lianyungang	China	CNLYG	5.01	20	30	3.20	18	-36%

The comparison presented in Table 5.1 reveals that the top 20 busiest ports in the actual data align with the top 20 busiest ports in the model results, with only minor variations in their ranking order. Notably, the port of Tianjin is the exception, as it does not appear in the model's top 20 list.

The comparison between the actual data and the model's results of throughput for all ports in this model is illustrated in Figure 5.2. The figure highlighted the deviations of Ningbo-Zhoushan, Xiamen, Shanghai, and Tianjin. Notably, the port of Shenzhen and Singapore exhibit relatively minimal deviation, indicating a close alignment between the actual data and the model's predictions for these ports.

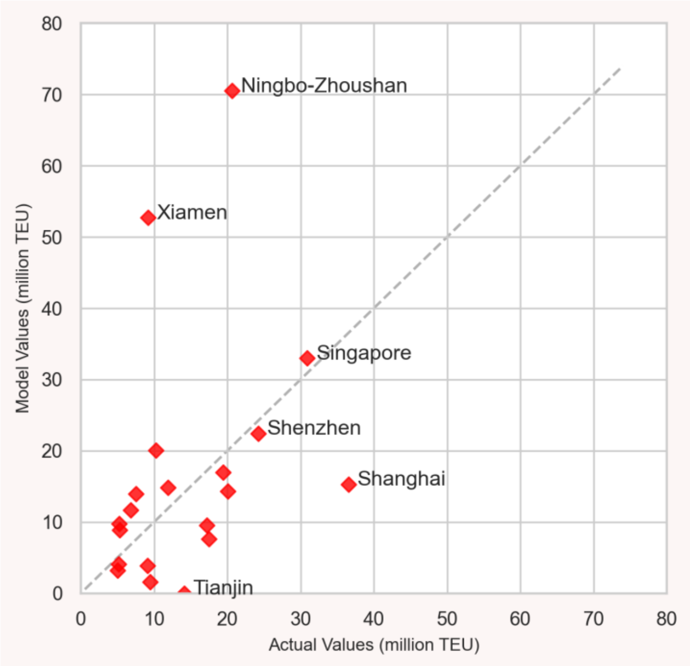

Figure 5.2 The comparison between the actual data and the model's results of throughput for all ports in this model

The ports of Ningbo-Zhoushan, Xiamen, and Tianjin exhibit substantial deviations exceeding 100% in their throughput rankings. Among them, Ningbo-Zhoushan demonstrates the most significant variation with a positive deviation of 242%. Despite being ranked fourth based on the actual data, it ranks first according to the model. Similarly, Xiamen displays a notable positive deviation of 474%, ranking second in the model's results despite being ranked 13th based on the actual data. In contrast, Tianjin experiences a considerable negative deviation of -100%. Although ranked ninth based on the actual data, it does not have a recorded throughput value in the model's results.

From the result we noticed a trend in the result that container throughput in each economic zone tends to concentrate in 1-2 major ports within an economy. This concentration pattern can be seen in the case of the ports of Ningbo and Xiamen in China, Busan in South Korea, Port Klang in Malaysia, Yokohama in Japan, Kaohsiung in Taiwan, Laem Chabang in Thailand, Ho Chi Minh in Vietnam and Jakarta in Indonesia. Table 5.3 further illustrates this finding by offering a comparison of throughput and share of major ports within each economic zone between actual values and the model estimated value. It specifically highlights ports that, collectively, account for a 60% share of their respective economy's throughput. It's important to note that this comparison only applies to those economic zones where the top 20 busiest ports are located.

Table 5.3 Port throughput share in economic zones.

Economy	Rank	Actual			Estimated		
		Port(s)	Annual Throughput	% Share	Port(s)	Annual Throughput	% Share
China	Total		**193.7**			**183.7**	
	1	CNSHG	36.54	19%	CNNBG	70.5	38%
	2	CNSHK, CNYTN, CNDCB	24.2	12%	CNXMG	52.7	29%
	3	CNNBG	20.63	11%	CNSHK, CNYTN, CNDCB	22.5	12%
	4	CNQDG	17.47	9%	CNSHG	15.3	8%
	5	CNNSA	17.22	9%	CNNSA	9.5	5%
South Korea			**25.5**			**17.46**	
	1	KRPUS	18.85	74%	KRPUS	17.0	97%
Malaysia			**24.0**			**21.51**	
	1	MYPKG	11.89	50%	MYPKG	14.9	69%
	2	MYTPP	9.1	38%	MYBTU	3.8	18%
Taiwan			**14.5**			**20.1**	
	1	TWKHH	9.78	67%	TWKHH	20.1	100%
Vietnam			**11.1**			**13.7**	
	1	VNSGN	5.31	48%	VNSGN	8.9	65%
	2	VNHPH	3.87	35%	VNHPH	4.8	35%
Japan			**20.1**			**21.5**	
	1	JPTYO, JPYOK	7.52	37%	JPYOK	13.9	65%
	2	JPOSA, JPUKB	4.93	24%	JPUKB	6.7	31%
Thailand			**9.5**			**12.6**	
	1	THLCH	6.82	72%	THLCH	11.6	93%

It is noteworthy that China, with its vast size of economy and extensive coastal geography, has a high demand and supply of containers and a prolific number of ports. China's major ports are strategically located along diverse coastal regions (see Figure 5.2). For example, in the north, near the Yellow Sea, there are ports like Qingdao and Tianjin. In the south, ports like Shenzhen and Guangzhou can be found. The busiest port, Shanghai, had the share of the total throughput, approximately 19%. Meanwhile, the ports ranking from second to fourth each contribute their own substantial shares, each within the range of 8-12% (see Table 5.3).

Figure 5.3 Top container ports in China (SHIPHUB, 2022)

However, as our model considers each economy as a single node of container source and sink, it does not take regions within a country separately. Consequently, the results from the model show that the throughput of the economy is concentrated in ports such as Ningbo-Zhoushan and Xiamen, these contributions account for over 67% of the total. This contrasts with the actual data, where it took the fifth-ranked ports to account for 60% of the total throughput. this concentration of container flow in major Chinese ports leads to reduced throughput for other ports within the country.

Furthermore, in terms of major from the result, the top 5 busiest ports in China are located in the middle and southern parts, with a combined share of over

90%. This means that the northern part of China would have a share of throughput of less than 10%. In contrast to the actual data, ports in northern China, such as Qingdao and Tianjin, have an annual throughput of over 30 million TEUs, accounting for over 14% of China's total throughput. This evidence suggests that the model overlooks the realistic distribution of hinterland flow within economic zones.

The prominent role of China in container traffic, coupled with the concentration of throughput in its ports, results in these major ports gaining an increased share. Conversely, the remaining ports within the same economy experience a decrease in throughput. This has resulted in a deviation of the busiest port rank in the list of the 20 busiest ports in the area of interest.

Despite the variations in throughput and concentration effects observed in major ports, the model consistently identifies key ports contributing to the container traffic in the Indo-Pacific region. Ports like Shanghai, Singapore, and Shenzhen maintain their top rankings consistently in both the actual data and the model's results, reflecting the model's ability to accurately capture the high levels of throughput associated with these ports. This alignment reaffirms the significance of these ports in the region's container traffic and underscores the model's effectiveness in representing the major ports of the Indo-Pacific area.

It is important to note that while the throughput variations in individual ports have been identified, they do not significantly impact the overall flow of containers along the Strait of Malacca. Therefore, the observed deviations may not affect the feasibility of the model in assessing the potential impact of the Thai Canal on container traffic. Nonetheless, by delving into the concentration effect and addressing associated factors, the model's accuracy and reliability can be further enhanced, providing valuable insights for decision-making processes related to port operations and infrastructure planning.

5.1.3 Vessel passing the strait of Malacca.

Another aspect of the base solution we validate is the number of container vessels passing through the strait of Malacca. We compare the base scenario solutions with actual data in the same year reported by STRAITREP, the ship reporting system for the Straits of Malacca and Singapore (Maritime Electronic Highway [MEH], 2018). However, the statistics only report the number of container vessels of all sizes on an annual basis. It does not provide information on the specific classification of vessels size or the routes they take through the Strait of Malacca.

To provide a more meaningful comparison, we converted these results to an annual basis by assuming 52 weeks, to compare the result from the model. The comparison is presented in Table 5.4.

Table 5.4 The caparison of number of vessels passing through the Strait of Malacca

Actual		Base scenario solutions		
Annually (vessel/year)	Weekly Average. (vessel/week)	Mean (vessel/week)	% Comparison	SD (vessel/week)
25,389	488.25	421	-13.77 %	2.70

Comparing the weekly average of actual data to the mean value from the base scenario solutions, we find that the base scenario solutions is lower by 13.77%. This difference suggests that the result from the model agrees with the actual data, suggesting that it is a feasible model for predicting container traffic in passing through the strait of Malacca. Moreover, it's important to note that the standard deviation of 2.70 indicates a relatively low level of variability. This implies that the model provides consistent and stable predictions for container traffic.

5.1.4 Port traffic in the Strait Ports

In this section, we will compare the base scenario solutions with the actual data in terms of port traffic, specifically focusing on ports located on the Strait of Malacca, such as the port of Singapore, Port Klang, and the port of Tanjung Pelapas. We will assess various aspects, including port calls, port throughput, and port transshipment, to evaluate how accurately the model captures the traffic dynamics in these ports. It is crucial for the model to provide reliable estimations and predictions for the traffic in these ports, as they serve as major gateways for container trade in the Strait of Malacca.

The actual data used to compare is collected from the port statistics provided by the port authorities of these port (Port Klang Authority, 2023, Maritime and Port Authority of Singapore [MPA], 2023, Johor Port Authority, 2023)

Port calls

Table 5.5 presents a comparison of number of port calls for port of Singapore, Port Klang, and the port of Tanjung Pelapas. All actual data was reported on an annual basis. We convert the value into weekly basis assuming 52 weeks.

Table 5.5 Comparison of actual and model results for port calls in the ports of the Strait of Malacca in the base scenario

Port Name	Actual		Model		
	Annually (vessel/year)	Weekly Average (vessel/week)	Mean (vessel/week)	% Comparison	SD (vessel/week)
Singapore	17,722	340.81	342.4	0.47%	3.13
Port Klang	11,944	229.7	97.8	-57.42%	0.45
Tanjung Pelapas	4,696	90.3	61.6	-31.78 %	1.82

From Table 5.5, it can be observed that the port call result from the model for the Singapore port is relatively close to their corresponding actual values. The estimated percentage difference for Singapore stands at 0.47%, indicating a high level of accuracy. However, there is a notable difference between the estimated and actual result for Port Klang and Tanjung Pelapas, with the base solution deviate by 57.42% and 31.78% respectively, suggesting a potential bias or missing assumption in the model that leads to the underestimation of port calls in these ports.

Upon further investigation, it was discovered that in maritime operations, shipping liners often designate specific ports as their regional operational hubs. With the Port of Tanjung Pelapas serves as the Southeast Asia hub for Maersk (Hand, 2016) while Port Klang is the port of choice for CMA CGM (Schoer, 2013) As a result, liners tend to favor these ports in their services, resulting in higher port call frequencies in these ports as expected. The model's underestimation of port calls in Port Klang and Tanjung Pelapas could be attributed to the omission of this specific liner preference and allocation pattern.

Port throughput

Table 5.6 presents the comparison of throughput between the base scenario and Scenario A for three ports: Singapore, Port Klang, and Tanjung Pelepas. The actual data was also converted into weekly basis using the same assumptions of 52 weeks a year.

Table 5.6 Comparison of actual and model results for port throughput in the ports of the Strait of Malacca in the base scenario

Port Name	Actual		Model		
	Annually (1,000 TEU/year)	Weekly Average (1,000 TEU/week)	Mean (1,000 TEU/week)	% Comparison	SD (1,000 TEU/week)
Singapore	30,922.3	594.6	635.25	6.8%	0.24
Port Klang	11,886	228.6	286.04	25.1%	0.49
Tanjung Pelepas	9,117	175.3	74.02	-57.8%	0.35

Table 5.6 compares container throughput values between the actual and base scenario solutions. For the port of Singapore, the model estimated a throughput of 635.25 thousand TEUs/week, while the actual data has a weekly average of 594.6 thousand TEUs/week. This result is closely aligned with the actual data, with a relatively small deviation of 6.80%.

However, as discussed previously, Port Klang and Tanjung Pelepas are subject to the effects of container concentration at major ports in the economy. This results in the container flow in the Malaysian economy tending to concentrate at Port Klang. This concentration leads to an increase in the throughput of Port Klang, resulting in a deviation of 25.1% from the model's predicted throughput compared to the actual data. Conversely, Tanjung Pelepas experiences a decrease in throughput due to diversifying container flows to Port Klang, leading to a deviation of -57.8% from the actual data. Moreover, it is important to note that Tanjung Pelepas serves as Maersk's operational hub in the Asia Pacific region (Hand, 2016). As Maersk held the largest share in terms of container liner shipping in 2015 and partners with MSC in the same year, the second-largest container liner shipping (Alphaliner, 2015, Gronholt-pedersen, 2023), it is expected that Tanjung Pelepas would experience a higher number of container throughputs. This could explain the higher actual data throughput compared to the model's estimation for Tanjung Pelepas, which resulted in a deviation of -57.8%.

Transshipment

Table 5.7 presents a comparison between the actual and model results for the number of transshipments container for ports located in the strait of Malacca: Singapore, Port Klang, and Tanjung Pelepas, it also presented the percentage of transshipment compared to throughput. The actual data was also converted to a weekly basis using the same assumptions of 52 weeks a year. Note that we found no report on a specific number of containers transshipped at the port of Singapore; the number was estimated using the number of %transshipment reports by Shibasaki et al. (2017). Moreover, there are differences in the counting of the number of containers transshipped; in this study, we use the number of transshipments to count the number of containers when they are transferred from one vessel to another at a port. While Port authorities may count transshipments as both loaded and unloaded containers, resulting in a number that is twice as high as the number reported by the model.

Table 5.7 Comparison of actual and model results for transshipment in the ports of the Strait of Malacca in the base scenario

Port Name	Actual			Model		
	Annually (1,000 TEU/year)	Weekly Average (1,000 TEU/week)	% Transship	Mean (1,000 TEU/week)	% Comparison	% Transship
Singapore	26,284	252.7	85%	270.01	6.9%	85%
Port Klang	7,932	76.3	67%	100.48	31.7%	70%
Tanjung Pelepas	8,643	83.1	95%	22.32	-73%	60%

The comparison of the number of transshipment containers between the model estimation and the actual data reveals a relatively close alignment for Singapore, with a slight difference of 6.9% in the number transshipment container compared to the actual data. However, there are significant deviations observed for Port Klang, with a deviation of 31.8% compared to the actual data, and Tanjung Pelepas, which exhibits a substantial deviation of -73% compared to the actual data.

As mentioned earlier, Tanjung Pelepas serves as a major transshipment hub in the region for various liners. However, the model's estimation significantly underestimates the number of transshipment containers for Tanjung Pelepas, due to the model did not incorporating additional factors as mentioned. This discrepancy can be attributed to the model's limitations in incorporating additional factors that are relevant to transshipment activities, as discussed previously.

Still, the model demonstrates a relatively accurate estimation in terms of the percentage of container transshipment compared to total throughput for both the port of Singapore and Port Klang, with deviations of less than 3%. This indicates that the model captures the relative importance of transshipment activities in the container traffic for ports in the Malacca Strait. However, it is important to acknowledge that the model exhibits limitations in accurately estimating the absolute number of transshipment containers, particularly in the case of Tanjung Pelepas, as discussed earlier.

5.1.5 Model feasibility

From the validation process, which involves comparing the model's results of the base scenario with the actual data. In the aspect of throughput in each economic zone, the model’s estimation exhibits a fair degree of accuracy in estimating total throughput in economic zones in the interested area. Moreover, holistically, the model's results seem to well match with the actual data.

Although the model's estimates of throughput in each economic zone align well with actual data, the throughput appears to be primarily concentrated around one or two major ports within each economy. This concentration effect might be attributed to intra-economic port competition, and the hinterland flow, factors that our current model doesn't account for.

However, one notable aspect of the model's estimation is its accuracy in predicting port traffic for the port of Singapore. The model's estimation for port calls shows a deviation of less than 1% compared to the actual data. While the estimation of other port traffic demonstrates a deviation within 10% from the actual data.

Overall, the model demonstrates feasibility in assessing the impact of the Thai Canal on the container network. Despite some limitations and deviations in the aspect of intra-economic port competition and liner hub of operation. The model still captures the relative importance of major ports, transshipment activities, and overall container traffic patterns. The model provides a preliminary basis for assessing the potential effects and implications of the Thai Canal on the container network. However, it is important to continually refine and enhance the model by incorporating additional factors and considering specific port characteristics to improve its accuracy and reliability for future assessments.

5.2 Comparative analysis

In this section, we perform a comparative analysis between the base scenario and the Thai canal scenarios. The primary focus is on examining the number of vessels transiting through both the Malacca Strait and the Thai canal, as well as evaluating the impact on port traffic in the strait of Malacca. By comparing the solutions of each scenario, our objective is to assess the potential effects and implications of the Thai canal on the container network in the region.

Additionally, we provide a comparison of the objective value of costs in the model to assess the overall network performance. This analysis allows us to understand the potential benefits and opportunities that the Thai canal can offer in terms of optimizing the container network and attracting shipping companies to utilize this alternative route.

5.2.1 Objective value

The model's objective values and their respective components, along with the percentage share of each scenario, and percentage of change from the Base scenario are presented in Table 5.8.

Table 5.8 Comparison of objective value on different scenarios by cost components.

Objective Value component	Scenarios							
	Base scenario		Canal with 2 day saving transit time			Canal with no saving transit time		
	Mean	%share	Mean	%share	%change	Mean	%share	%change
Total cost	1,791,312	-	1,596,964	-	-	1,631,915	-	-
Vessels deploy cost	1,263,756	70.5%	1,245,756	78.0%	-1.4%	1,238,324	78.0%	-2.0%
Port Call cost	43,335	2.4%	39,905	2.5%	-7.9%	39,852	2.5%	-8.0%
Handling cost	434,938	24.3%	404,481	25.3%	-7.0%	403,270	25.3%	-7.3%
Transshipment cost	38,172	2.1%	26,921	1.7%	-29.5%	27,187	1.7%	-28.8%
Congestion cost	11,112	0.6%	8082	0.5%	-27.3%	8,392	0.5%	-24.5%
Route Saving	-	-	-128,180	8.0%	-	-85,108	8.0%	-
Net vessel deployment cost	1,263,756	70.5%	1,117,576	70.0%	-11.6%	1,153,216	70.0%	-8.7%

Units: Thousand USD/Week

The results show that all cost components decrease in the canal scenarios compared to the base scenario. The scenario with no saving time has a smaller percentage of change than the scenario with 2 day saving time in most cost components.

Considering the share of the total cost, the vessel deployment cost and the handling cost constitute the two major components. These two cost components, with their significant shares, reflect their critical role in the container network's cost structure and operational efficiency. While other cost components have relatively smaller shares, they still contribute to the overall cost.

The vessel deployment cost represents the largest proportion of the total cost in all scenarios, encompassing the expenses related to deploying vessels for container transportation. This highlights the significant role of vessel deployment in the overall cost structure of the container network. Despite an increase in the vessel deployment cost observed in the canal scenarios, it is counterbalanced by the route saving cost, leading to a consistent share of the net vessel deployment cost across all scenarios.

The handling cost also plays a significant role in the total cost of the container network and maintains a relatively stable share across all scenarios. In the canal scenarios, there is a slight decrease in handling cost compared to the base scenario. This suggests potential operational efficiencies that can be attributed to the utilization of the Thai canal. These operational efficiencies also include reduced waiting times, as the notable decrease in congestion cost implies that the Thai canal plays a crucial role in alleviating congestion at ports.

Furthermore, consider the change the substantial decrease in transshipment cost in the scenario with the Thai canal highlights a significant reduction in transshipment activities.

In conclusion, the model's objective values provide valuable insights of the container network in different scenarios. It is important to note that the accuracy and reliability of the cost distribution analysis heavily depend on the quality and accuracy of the input data. Therefore, obtaining reliable and comprehensive data on cost structure is crucial to gain more accurate insights and enhance the reliability of the analysis. By improving the data quality, we can gain deeper insights into the cost distribution and make more informed decisions to optimize the cost performance of the container network.

5.2.2 The comparison of vessel traffic between the Strait of Malacca and the Thai Canal

The comparison of vessel traffic between the Strait of Malacca and the Thai Canal is presented in Table 5.9, showcasing the distribution of vessel types and the volume of carrying containers passing through both passages.

Table 5.9 Comparison Vessel traffic in the Strait of Malacca and the Thai Canal in different scenarios.

Vessel traffic	Scenarios				
	Base	2 days saving		0 day saving	
	Mean	Mean	% Change (from base)	Mean	% Change (from base)
The strait of Malacca					
Vessel passing Though (vessels/week)	420.6	339	-19%	344	-18%
Feeder	176	187.6	7%	182.4	4%
Panamax	158.4	101.6	-36%	110	-31%
Neo Panamax	76.6	45.2	-41%	46	-40%
ULCV	10	4.6	-54%	5.6	-44%
Carrying Containers (1,000 TEU/week)	1,869.7	1,661.2	-11%	1,687.8	-10%
The Thai canal					
Vessel passing Though (vessels/week)	-	154.2	-	144.4	-
Feeder	-	63	-	57.4	-
Panamax	-	56.8	-	55.2	-
Neo Panamax	-	31	-	29.4	-
ULCV	-	3.4	-	2.4	-
Carrying Containers (1,000 TEU/week)	-	309.8	-	285.9	-

Units: vessel/week

Table 5.9 presents a comparison of vessel traffic between the Strait of Malacca and the Thai Canal in different scenarios. In the base scenario, the Strait of Malacca witnesses a vessel passing through 420.6 vessel/week, with the Feeder vessels playing a prominent role, accounting for 176 vessels/week, followed closely by Panamax vessels with a contribution of 158.4 vessels/week. However, With the implementation of the Thai Canal, there are changes in vessel traffic in both the 2-day saving and 0-day saving scenarios. The vessel passing through decreases to 339 vessels/week representing a decrease of 19% in the 2-day saving scenario. Similarly, in the 0-day saving scenario, the vessel passing through further decreases to 344 vessels/week, reflecting an 18% decrease. These changes indicate a decrease in overall vessel traffic through the Strait of Malacca. In contrast to the overall decreasing trend, feeder vessels experience slight increases of 7% (187.6 vessels/week) and 4% (182.4 vessels/week) in the 2-day saving scenario, while Panamax vessels witness notable decreases of 36% (101.6 vessels/week) and 31% (110 vessels/week) in both scenarios. Neo panamax vessels and ULCV also experience significant decreases of over 40% in all canal scenarios.

For the Thai Canal scenarios, the implementation of the canal would result in a minimum of 144 vessels passing through every week, as estimated from the model in the 0-day saving scenario. In the 2-day saving scenario, this number would increase to 154.2 vessels/week. Feeder vessels hold the largest share among the different types of vessels, with 63 vessels/week in the 2-day saving scenario and 57.4 vessels/week in the 0-day saving scenario. They are followed by Panamax vessels, accounting for 56.8 vessels/week in both scenarios. Comparing these results to the traffic in the Strait of Malacca, the Thai Canal scenarios indicate a notable shift in vessel traffic patterns. This suggests that the implementation of the Thai Canal has the potential to alter the vessel traffic in the region.

We also observe significant changes in the carrying capacity of containers passing through both the Strait of Malacca and the Thai Canal. In the scenarios with the Thai Canal, the carrying capacity of containers in the Strait of Malacca decreases by 11% (1.66 million TEU/week) and 10% (1.69 million TEU/week) compared to the base scenario. This decline indicates a decrease in container traffic through the Strait of Malacca.

On the other hand, the carrying capacity of containers passing through the Thai Canal is estimated as 309.77 thousand TEU/week in the scenario with a 2-day saving time. This translates to an annual throughput of approximately 16.1 million TEU, which is comparable to the annual throughput of the port of Guangzhou in 2015, with 17.22 million TEU. In the scenario with no saving time on the canal, the carrying capacity is estimated as 285.9 thousand TEU/week, resulting in an annual throughput of approximately 14.8 million TEU, which is slightly higher than the annual throughput of the port of Tianjin (14.11 million TEU). These numbers demonstrate the significant impact of the Thai Canal on container traffic and highlight the canal's role in reshaping regional trade and logistics patterns.

5.2.3 The comparison of route deployed in the Strait of Malacca and the Thai Canal

In this section, we offer a comparison of the number of routes deployed in the Strait of Malacca with those in the Thai Canal. Table 5.10 shows the number of routes in different scenarios and the type of route.

Table 5.10 Comparison of number of routes passing through the Strait of Malacca and the Thai Canal on different scenarios.

Types of routes	Scenarios				
	Base	2 days saving		0 day saving	
	The strait of Malacca	The strait of Malacca	The Thai canal	The strait of Malacca	The Thai canal
Total Route	103	63	49.2	68.2	45.8
Short Feeder	19.6	17.4	1	17.8	0
Long Feeder	18.8	19.8	9.2	21.2	8
Region to Region	39.6	17.8	25	19.8	24.2
Multi Region	25	8	14.2	9.4	13.6

Units: routes/week

From Table 5.10, in base scenario, it's observed that the Strait of Malacca has a total of 103 routes, with the region-to-region routes taking a significant portion at 39.6. The rest of the routes are distributed among short feeders (19.6), long feeders (18.8), and multi-region routes (25).

In the scenario where the Thai Canal provide 2-day sailing advantage, the total number of routes decreases to 63 for the Strait of Malacca, while shifting noticeably towards the Thai Canal, amounting to 49.2 routes. The Strait of Malacca sees a significant decline in region-to-region (39.6 to 17.8) and multi-region (25 to 8) routes. Notably, the Thai Canal primarily accommodates routes in the region-to-region category in this scenario (25 of 49.2).

Furthermore, in the scenario where the Thai Canal provides no sailing advantage, similar trends persist. The Strait of Malacca, compared to the base scenario, experiences decrease in region-to-region (39.6 to 19.8) and multi-region (25 to 9.4) routes, representing a slight increase in both categories compared to the scenario with time savings.

From these findings, it can be inferred that the Thai Canal attracts long-range routes even when the time savings might be marginal. Thus, the canal's potential influence extends beyond mere time efficiency. Simultaneously, the data suggests a shift in route dynamics in the Strait of Malacca with a decrease in total routes, specifically region-to-region and multi-region routes, when savings are introduced through the Thai Canal.

5.2.4 Port traffic for strait ports

In this section, the comparison of port traffic for major ports in the Strait of Malacca is presented to analyze the impact of the Thai canal. Despite the validation process indicating certain limitations, these findings offer insights into the potential changes and implications for port traffic resulting from the implementation of the Thai canal. We also analyze the distribution of port calls by vessel type at each port and examine port throughput for both load and unload activities.

Port of Singapore

Table 5.11 compares the port traffic for the Port of Singapore estimated by a model on different scenarios. The percentage change in port traffic from the baseline scenario is also provided in the table.

Table 5.11 Comparison of port of Singapore's traffic for estimated by model on different scenarios.

Port Traffic	Scenarios				
	Base	2s days saving		0 day saving	
	Mean	Mean	% Change (from base)	Mean	% Change (from base)
Port Call (call/week)	342.4	150.4	-56%	162.6	-53%
Feeder	157.4	97.6	-38%	100.6	-36%
Panamax	119.4	36.8	-69%	43.8	-63%
Neo Panamax	59.4	14.6	-75%	17.2	-71%
ULCV	6.2	1.4	-77%	1	-84%
Throughput (Thousand TEU/Week)	635.2	482.9	-24%	493.8	-22%
Load	283.4	207.3	-27%	212.7	-25%
%Load	45%	43%	-	43%	-
Unload	351.8	275.6	-22%	281.1	-20%
%Unload	55%	57%	-	57%	-
Transshipment (Thousand TEU/Week)	270.0	193.8	-28%	199.3	-26%
%Transshipment	85%	80%	-	81%	-

The port traffic for the port of Singapore shows significant changes in different scenarios with the Thai canal. The port calls show a substantial decrease of 56% in the scenario with a 2-day saving transit time and a 53% decrease in the scenario with no saving transit time. Among the different types of vessels analyzed, the feeder vessels exhibit a relatively smaller decrease compared to the other vessel types. Specifically, when comparing the two canal scenarios to the base scenario, feeder vessel traffic experiences a notable decrease of 38% and 36% respectively. In contrast, the remaining vessel types, excluding the feeder, encounter substantial decreases ranging from 63% to 84%. This finding suggests that the impact of the canal resulting the higher share of feeder vessels calling at the port of Singapore.

The slight changes in the percentages of load and unload activities in the port of Singapore suggest a consistent pattern of port operations across different scenarios. Despite the overall throughput having decreased by approximately 22% in the canal scenarios, the relative proportions of load and unload activities remain relatively stable. This indicates that the fundamental nature of cargo handling and distribution at the port is not significantly affected by the implementation of the Thai canal.

Despite a decrease in transshipment volume of 28% and 26% in the Thai canal scenarios, the port of Singapore continues to maintain its position as a transshipment port. The percentage of transshipment activities remains significant, accounting for approximately 80% of the overall port operations in both the canal scenarios. It is noteworthy that transshipment accounted for 85% in the base scenario, highlighting the enduring significance of transshipment activities in the port of Singapore.

Port Klang

Table 5.12 compares the port traffic for Port Klang estimated by a model on different scenarios. The percentage of change in port traffic from the base scenario is also provided in the table.

Table 5.12 Comparison of Port Klang's traffic estimated by model on different scenarios.

Port Traffic	Scenarios				
	Base	2s days saving		0 day saving	
	Mean	Mean	% Change (from base)	Mean	% Change (from base)
Port Call (call/week)	97.8	76.2	-22%	82.6	-16%
Feeder	31.6	51	61%	52	65%
Panamax	38.2	19.2	-50%	23.2	-39%
Neo Panamax	26.2	5.6	-79%	6.6	-75%
ULCV	1.8	0.4	-78%	0.8	-56%
Throughput (Thousand TEU/Week)	286	331.5	16%	372	30%
Load	155.9	155.3	0%	172.8	11%
%Load	55%	47%	-	46%	-
Unload	130.1	176.2	35%	199.2	53%
%Unload	45%	53%	-	54%	-
Transshipment (Thousand TEU/Week)	100.5	97.2	-3%	114.9	14%
%Transshipment	70%	59%	-	62%	-

From the validation process, it is evident that there are factors that affect the model's ability to accurately estimate the traffic on this port. However, it could provide insights into the trends and potential impacts from the construction of the Thai Canal.

In the case of Port Klang, the port call experiences a decrease of 22% in the scenario with a 2-day saving and a decrease of 16% in the scenario with a 0-day saving. On the other hand, the feeder vessel traffic shows a significant increase of 61% and 65% in the respective canal scenarios. While other vessel types exhibit notable decreases in their traffic volumes, ranging from 40% to 80%, in both canal scenarios. This indicates that the implementation of the Thai canal has a notable impact on the traffic patterns, leading to a higher share of feeder vessels calling at Port Klang. This trend aligns with the findings observed in the port of Singapore.

The overall throughput of Port Klang increases by 16% in 2-day saving scenario compared to the base scenario. This increase in throughput is accompanied by a shift in the distribution of activities, with a greater emphasis on unloading compared to loading. Specifically, the unloading activity shows a significant increase of 35% in the same scenario while the loading activity remains relatively stable with a negligible change of 0%. Resulting in the percentage of unloading activities also experiences a notable increase from 45% in the base scenario to 53% in the 2-day saving scenario. In the 0-day saving canal scenario, the overall throughput of Port Klang exhibits a more significant increase of 30% compared to the base scenario, surpassing the growth observed in the 2-day saving scenario. This substantial increase in throughput is primarily attributed to a remarkable 53% growth in unloading activity, indicating a higher volume of goods being unloaded at the port. Additionally, the loading activity also demonstrates a notable increase of 11%. Consequently, the percentage of unloading activities remains consistent with the 2-day saving scenario, reflecting the sustained importance of unloading operations at Port Klang.

The transshipment volume at Port Klang experiences a slight decrease of 3% compared to the base scenario in the 2-day saving scenario, However, in the 0-day saving scenario, there is a notable increase of 14% in transshipment volume. Despite these changes, the percentage of transshipment activities shows a decline from 70% in the base scenario to 59% and 62% in the 2-day and 0-day saving scenarios, respectively. This shift is primarily driven by the significant increase in overall throughput, reflecting the port's capacity to handle a higher volume of direct cargo without the need for transshipment.

These findings indicate that the implementation of the Thai canal has resulted in increasing port traffic for the Port of Klang, by redirect potential economic imports toward the port. The observed increase in feeder vessel traffic and overall throughput indicates the impact of the canal.

However, it is important to consider the effect of port concentration on these results, as the redirection of traffic to Port Klang may be influenced by factors such as the concentration of container flows in major ports. Moreover, the preferences of liners and other relevant factors should also be taken into account. These considerations will provide a more comprehensive understanding of port traffic in Port Klang.

Tanjung Pelapas

Table 5.13 compares the port traffic for Port Tanjung Pelapas estimated by a model on different scenarios. The percentage change in port traffic relative to the base scenario is also provided in the table.

Table 5.13 Comparison of Port of Tanjung Pelapas's traffic estimated by model on different scenarios.

Port Traffic	Scenarios				
	Base	2s days saving		0 day saving	
	Mean	Mean	% Change (from base)	Mean	% Change (from base)
Port Call (call/week)	61.6	40.8	-34%	40	-35%
Feeder	24.4	19.8	-19%	17	-30%
Panamax	22.2	11.8	-47%	11.8	-47%
Neo Panamax	9.4	8	-15%	8	-15%
ULCV	5.6	1.2	-79%	3.2	-43%
Throughput (Thousand TEU/Week)	74	54.3	-27%	41	-45%
Load	27.6	17.7	-36%	13.7	-50%
%Load	37%	33%	-	34%	-
Unload	46.4	36.7	-21%	27.3	-41%
%Unload	63%	68%	-	66%	-
Transshipment (Thousand TEU/Week)	22.3	15.1	-32%	10.9	-51%
%Transshipment	60%	56%	-	53%	-

As discussed previously, Tanjong Pelepas reveals certain limitations in accurately estimating its traffic using the model. The base scenario results do not align closely with the actual traffic observed at the port. Despite this discrepancy, the analysis provides insights into the trends and potential impacts of the Thai canal on port traffic.

The Port of Tanjung Pelapas experiences a significant decrease of approximately 34% in port calls in both the 2-day and 0-day saving scenarios. However, it is interesting to note that Neo Panamax vessels show a relatively smaller decrease compared to other types, with a consistent port call volume in both canal scenarios and a change of -15% from the base scenario. Similarly, Panamax vessels also exhibit the same port call volume in both scenarios, but with a larger decrease. In contrast, feeder vessels experience a notable decrease of 19% and 30% in port calls for the respective scenarios, second only to Panamax vessels. These findings suggest a potential shift in vessel preferences and traffic patterns at Tanjung Pelepas, with a noticeable trend of Neo Panamax vessels being preferred over feeder vessels.

The overall throughput of Tanjung Pelepas also experiences a significant decrease of approximately 27% and 45% in the 2-day and 0-day saving scenarios, respectively. This decrease in throughput is accompanied by notable decreases in both loading and unloading activities, with decreases ranging from 36% to 50% and 21% to 41%, respectively. These changes indicate a shift in the distribution of cargo handling activities at the port, with a relatively higher decrease in unloading compared to loading. The percentage shares of loading and unloading activities also exhibit slight variations, with the percentage of loading activities decreasing from 37% in the base scenario to 33% in the 2-day saving scenario, and the percentage of unloading activities decreasing from 63% to 68% in the same scenarios. The port of Tanjung Pelepas continues to maintain a higher emphasis on unloading activities compared to loading activities, even with the decrease in overall throughput.

Furthermore, the transshipment volume at Tanjung Pelepas exhibits a substantial decrease of approximately 32% and 51% in the 2-day and 0-day saving scenarios, respectively. Despite the decrease in transshipment volume, the percentage of transshipment activities shows a relatively minor decline, with only slight changes from 60% in the base scenario to 56% and 53%, observed in the respective canal scenarios. These findings highlight a reduction in transshipment volume at Tanjung Pelepas as a result of the implementation of the Thai canal, while the overall proportion of transshipment activities remains relatively stable.

Overall, the analysis suggests that the Thai canal has the potential to influence traffic patterns and cargo distribution at the Port of Tanjung Pelepas. The decreases in port call, transshipment volume, and overall throughput indicate changes in vessel preferences and potential shifts in cargo flows. However, it is important to note that these findings are based on model estimations and may not precisely reflect the actual traffic at the port. Further refinement and validation are necessary to improve the accuracy and reliability of the model's predictions for Tanjung Pelepas. Additionally, the role of Tanjung Pelepas as an operational hub for liners and its significance in facilitating trade may influence the observed changes in traffic patterns.

5.3 Graphical representation

Based on the model's results, we generate a visualization of the container liner shipping network. This involves plotting the navigational direction of the routes in use and highlighting each port according to its throughput. We categorize both the waterways and the ports into four levels, using the quartiles of their distribution. The marker size corresponds to the port throughput: the larger the throughput, the larger the marker size. Similarly, the line width in our visualization represents the waterway's density: a higher density corresponds to a wider line. Subsequently, we incorporate this plotting into a map of the interested area. The visualization corresponding to each scenario is presented below.

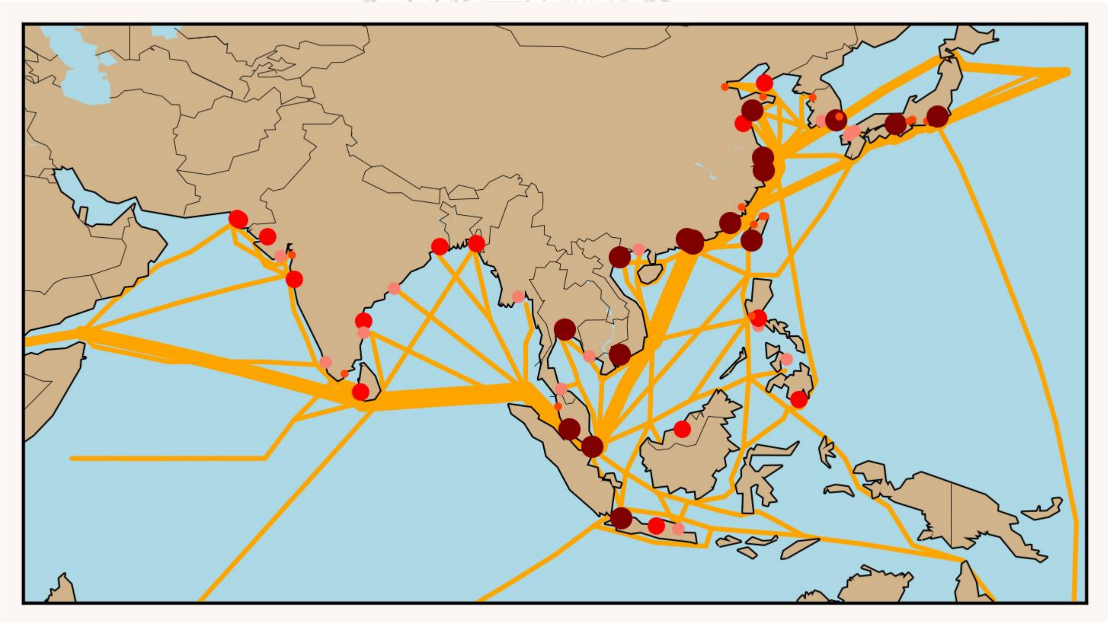

Figure 5.4 Graphical representation of container liner network from the base scenario results.

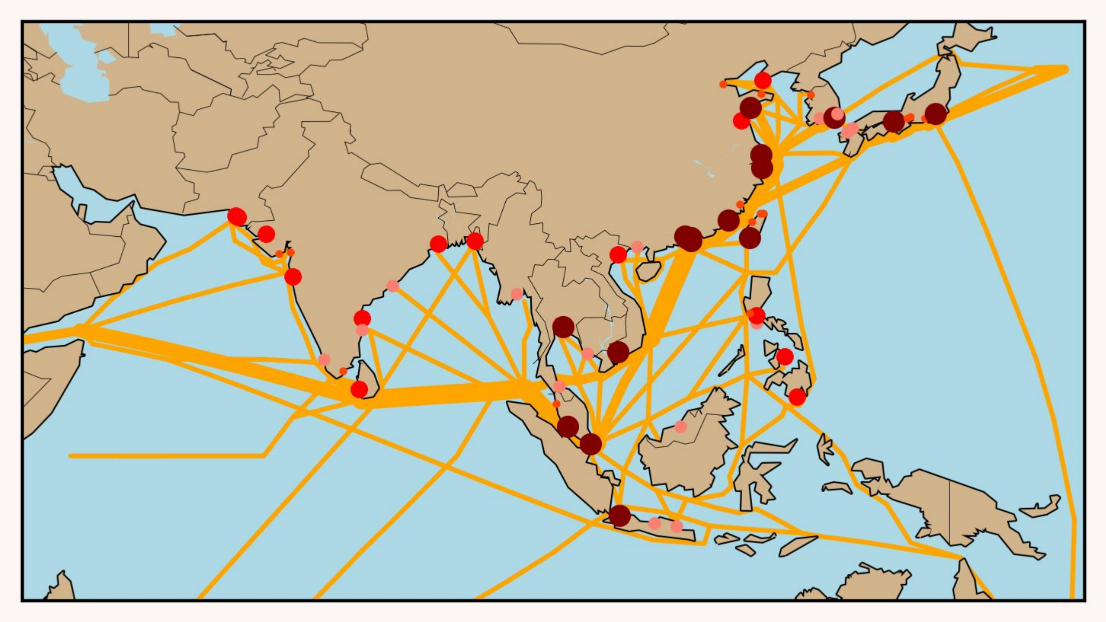

Figure 5.5 Graphical representation of container liner network from the Thai Canal with 2 days sailing saving scenario.

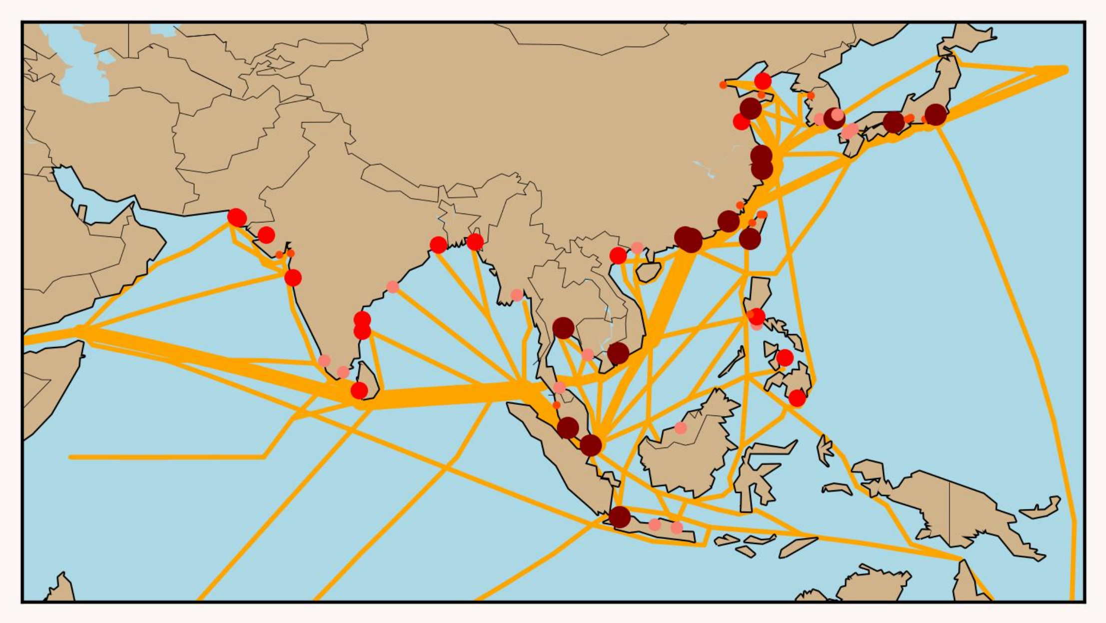

Figure 5.6 Graphical representation of container liner network from the Thai Canal with no sailing saving scenario.

Chapter 6 Conclusion

This study focused on assessing the potential impact of the proposed Thai Canal on the container network in the Indo-Pacific region, with a specific emphasis on the Strait of Malacca. A framework was developed using a multi-commodity Minimum Cost Network Flow Problem (MCNFP) approach, which incorporated the liner shipping fleet deployment problem (LSFDP) and accounted for congestion at container ports. The model, formulated as a mixed-integer linear programming model (MILP), aimed to minimize network costs considering liner services and their associated operational costs. Then the model was applied using a sample instance derived from the 2015 network and the LINER-LIB 2012 dataset. The model was solved on three scenarios, namely the base scenario where canal is not constructed, the scenario with the canal constructed with 2 days transit time saving, and the scenario of canal constructed with no transit time saving. These scenarios allowed for the assessment of the impact of the Thai Canal on vessel traffic and port operations under different transit time conditions.

First, the validation process is conducted in this study to examine the feasibility of the proposed model. Result indicates that there are factors that affect the model's ability to accurately estimate the traffic on specific ports. However, despite these limitations, the model provides valuable insights into the trends and potential impacts resulting from the implementation of the Thai Canal.

Next, we execute the comparative analysis of vessel traffic between the Strait of Malacca and the Thai Canal highlights the influence of the canal in attracting feeder vessels and potentially altering the composition of vessel traffic in the region. Feeder vessels show an increasing trend in the Thai Canal scenarios, indicating the canal's ability to accommodate and attract these types of vessels.

The comparative analysis of port traffic at specific ports located in the Strait of Malacca, including Port of Singapore, Port Klang, and Port of Tanjung Pelapas. demonstrates the impact of the Thai Canal on port operations. Changes in port calls, vessel traffic, throughput, and transshipment volumes indicate a notable shift in traffic patterns and port preferences. The findings suggest potential benefits for ports such as Port Klang, which may experience increased traffic and economic benefits due to the redirection of imports.

Overall, the study highlights the potential impact of the Thai Canal on regional trade and logistics. The changes in vessel traffic, carrying capacity of containers, and port operations demonstrate the significance of the canal in reshaping the trade landscape. However, it is important to consider factors such as port concentration and liner preferences when interpreting the results and assessing the long-term implications of the Thai Canal implementation.

However, it's important to acknowledge that our model is constructed on specific assumptions and input data, both of which have the potential to significantly influence the results. One major limitation of our study is the absence of recent and reliable data, which restricts the precision of our model's outcomes. For future research, it is essential to conduct a thorough review and update of both the assumptions and data used to apply with the model. Consulting with experts in the field can provide an additional layer of validation, allowing us to test our assumptions and enhance our understanding of the subject matter. Such a collaborative and systematic approach will undoubtedly lead to more accurate and reliable forecasts.

Moreover, the potential implications of economic growth and industrial development should also be integrated into future models. By examining the Thai Canal's impact within the broader context of economic development and industrialization, researchers can achieve a more comprehensive understanding of its effects. Ultimately, it is our hope that these recommendations will contribute to the continuous refinement of predictive models, thus helping stakeholders to make well-informed decisions regarding the Thai Canal.

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