Integrative and sustainable port hinterland intermodal development with green concerns

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**INTEGRATIVE AND SUSTAINABLE PORT
HINTERLAND INTERMODAL DEVELOPMENT
WITH GREEN CONCERNS**

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School of Civil and Environmental Engineering

2014

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Abstract

Owing to a surge in international trade volume, greenhouse gas emissions are rapidly increasing. The challenge countries and societies face today is how to reduce the associated greenhouse gas emissions while the demand for transportation volume is growing. Sustainable development in the transportation domain deserves our utmost attention. An additional challenge comes from ever-increasing customer expectations and requirements, for example, door-to-door delivery and fast delivery at minimum cost. Through conducting an in-depth review of the literature concerning the container network optimisation domain and the environmental issues in transportation planning, it is found that very few efforts have been made to the issue of intermodal container flows considering both empty and laden containers with green concerns using bi-objective optimisation. This is a research gap which will be filled by this research. Considering all of the above, port hinterland intermodal development that addresses environmental concerns has become a crucial domain for exploration, which is the main objective of this research.

Both qualitative and quantitative research methods are applied in this research. A qualitative research on comparing the potentials and challenges in terms of intermodal development in China and India is undertaken. Such a comparative analysis is useful for China and India while carrying out their port hinterland intermodal development. Other countries can also benefit from this research.

Two original optimisation models are developed in this research as two quantitative research methods. The first model is a tactical model with green concerns incorporated as a constraint. The second model is an operational model that takes three environmental regulatory frameworks into consideration. This operational model adds to the literature by including in its investigation three environmental regulatory frameworks, namely: (1) carbon tax, (2) carbon emission trading scheme and (3) direct restriction on carbon emission.

The tactical model is an integer linear programming optimisation model. Normally,

for small scale problems, they can be solved by using CPLEX solver (IBM ILOG CPLEX Optimisation Studio). However, for large-scale problems, no ready solutions are available. We thus have developed a metaheuristic algorithm to tackle the large-scale problems. We have given this algorithm the name of “the enhanced NSGA-II” algorithm. It is also worth mentioning that the three-stage supply-demand matrix-based chromosome presentation embedded in the enhanced NSGA-II algorithm is unique. The model is applied to a case study of intermodal container flows in China which is a medium-scale problem, and the enhanced NSGA-II’s results are compared with CPLEX’s results to test the enhanced NSGA-II’s performance. It is shown that the enhanced NSGA-II is able to obtain near-optimal solutions while CPLEX cannot solve large-scale problem instances. Insightful policy implications are provided in inland intermodal infrastructure development through analysing the results of the tactical model.

The operational model is a mixed integer non-linear programming optimisation model. CPLEX cannot be used to solve this non-linear problem directly. Therefore, a special linearisation technique is used to transform its non-linear part to a linear relationship. After this transformation, the operational model can adapt CPLEX in solving relatively large-scale problems. A case study on a Trans-Pacific container intermodal chain is conducted to illustrate the operational model’s applicability and significance. Through analysing the results of the operational level model, it is found that carbon emission trading would be the most preferable choice among the three frameworks from both the company’s and the government’s perspectives. A medium-cap level is found to be the most preferable because it can offer more flexibility with regard to the decision-making processes of companies in the carbon emission trading market.

Overall, research on sustainable development in intermodal transport and port-related topics has obtained increasing attention from scholars and industry professionals. This thesis contributes to this emerging research direction. It not only provides insights into the existing knowledge but makes practical contributions to the maritime and land transport industries and government policies.

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Table of contents

Abstract.....	I
Acknowledgements	III
Table of contents.....	V
List of tables.....	IX
List of figures.....	X
Chapter 1 Introduction.....	1
1.1 Research background	2
1.2 Research objectives.....	4
1.3 Research scope.....	6
1.4 Research significance.....	8
1.4.1 Academic significance	8
1.4.2 Practical significance	9
1.5 Organisation of the thesis.....	10
Chapter 2 Literature review	12
2.1 Introduction.....	13
2.2 Ports' spatial hierarchy evolution with transportation function	13
2.2.1 Ports' spatial hierarchy evolution to regionalisation stage.....	14
2.2.2 Diversified inland ports springing-up in port regionalisation stage.....	16
2.2.3 Further discussion and critique	19
2.3 Regionalisation drives ports to supply chain integration.....	21
2.3.1 Port performance evaluation model updated with new element.....	21
2.3.2 Information technology support and organisation reformation in port integration into supply chains	23
2.3.3 Barriers in integration	24
2.3.4 Port regionalisation links port spatial integration to supply chain functional integration	25

2.3.5 Different players' interests in the integration.....	27
2.3.6 Further discussion and critique	28
2.4 Intermodality and empty container repositioning with green concerns.....	29
2.4.1 Containerisation and intermodality in port development.....	29
2.4.2 Empty container repositioning.....	35
2.5 A specific review on intermodal container flow optimisation	36
2.5.1 Review methodology	36
2.5.2 Analysis for identifying research trends and gaps and directions for research	38
2.5.3 Research gaps and directions in this study	58
Chapter 3 Research methodology.....	61
3.1 Research design	62
3.2 Field studies	63
3.3 Research methods	65
3.3.1 Qualitative approach: Comparative research	65
3.3.2 Quantitative approach	65
3.4 Chapter summary	69
Chapter 4 Comparative analysis on intermodal development in China and India	70
4.1 Introduction.....	71
4.2 Opportunities and challenges of sustainable port intermodal development in China	72
4.2.1 Opportunities and challenges co-existing in Chinese port development	72
4.2.2 Intermodal development in China.....	76
4.3 Opportunities and challenges of sustainable port intermodal development in India	79
4.3.1 Opportunities and challenges in Indian port development	80
4.3.2 Intermodal development in India	83
4.4 Comparison between China and India in terms of port intermodal development and recommendations.....	86
4.5 Chapter summary	98

Chapter 5 A bi-objective tactical level intermodal optimisation model under environmental constraints	99
5.1 Problem description and model development.....	101
5.1.1 The sea-and-land intermodal container transport problem	101
5.1.2 A bi-objective tactical level optimisation model.....	102
5.2 Solution method: The bi-objective three-stage enhanced NSGA-II	106
5.2.1 Representation of chromosome.....	107
5.2.2 Population chromosome initialisation for each stage	111
5.2.3 Elitist non-dominated sorting genetic algorithm (NSGA-II)	112
5.2.4 Crossover operation	114
5.2.5 Mutation operation.....	116
5.2.6 Pareto solutions	118
5.2.7 Overall procedure of the enhanced NSGA-II	118
5.3 Model application to the Chinese intermodal network	120
5.3.1 Case description	120
5.3.2 Experimental results and scenario analysis.....	122
5.3.3 Policy implications.....	128
5.4 Chapter summary	131
 Chapter 6 A bi-objective intermodal operational level optimisation model under three different environmental regulatory frameworks	 132
6.1 Background to the problem.....	133
6.2 A novel bi-objective operational-level optimisation model	136
6.2.1. Main assumptions	138
6.2.2. Model presentation.....	139
6.3 Case study	151
6.3.1 Case description	151
6.3.2 Main results.....	153
6.3.3 Managerial and Policy implications.....	168
6.4 Chapter summary	172
 Chapter 7 Conclusions and recommendations for future research.....	 173
7.1 Summary of main findings.....	174

7.2 Main research contributions.....	177
7.3 Limitations and recommendations for future research	179
7.3.1 Research limitations.....	179
7.3.2 Recommendations.....	179
References	182

List of tables

Table 2.1 A comparison of the characteristics of different transportation mode	32
Table 2.2 Summary and classification of literature on intermodal container transportation....	40
Table 2.3 Classification according to journal domains.....	44
Table 2.4 Classification according to research problem categories	47
Table 2.5 Classification according to mathematical models.....	49
Table 2.6 Classification according to algorithms	52
Table 2.7 Classification according to case study areas	54
Table 4.1 * Quantitative Characterisation Comparison between China and India in terms of Intermodal Development	94
Table 4.2 * Policy and Regulatory Regime Comparison between China and India in terms of Intermodal Development	95
Table 4.3 * Potentials and Challenges' Comparison between China and India in terms of Intermodal Development	96
Table 5.1 Set description in the tactical model	103
Table 5.2 Decision variable description in the tactical model	103
Table 5.3 Parameter description in the tactical model	104
Table 5.4 Given supply-demand in both import/export directions.....	121
Table 5.5 Main variable parameters for cost, time and carbon emission's calculations.....	122
Table 5.6 Scenario 1: Results comparison between CPLEX and the enhanced NSGA-II (K=590)	123
Table 5.7 Scenario 2: Results comparison between CPLEX and the enhanced NSGA-II (K=560)	123
Table 5.8 Average Container Distribution by Transportation Modes (Inland Modal Split)	127
Table 6.1 Set description in the operational model	139
Table 6.2 Decision variable description in the operational model	140
Table 6.3 Parameter description in the operational model	141
Table 6.4 Main parameters of different ship types	153
Table 6.5 Findings on inland modal splits in the Basic Model	156
Table 6.6 Different sailing speeds on each segment in Shipping Route 1 in each node.....	157
Table 6.7 Findings on Average inland modal split situations for OD-Pairs under Scenario 4 and Scenario 5.....	167
Table 6.8 Merit comparison for three environmental regulatory frameworks	171

List of figures

Figure 2.1 The relationships of a seaport and a dry port in three different distances	19
Figure 2.2 The key factors influencing the global freight intermodal distribution	33
Figure 3.1 The overall research process.....	62
Figure 4.1 Container port traffic in China and India.....	88
Figure 4.2 Freight split of China	90
Figure 4.3 Freight split of India and gap with China in total freight volume.....	90
Figure 5.1 Port hinterland intermodal container transport network	101
Figure 5.2 “Stage One” in Chromosome.....	108
Figure 5.3 “Stage Two” in Chromosome.....	109
Figure 5.4 “Stage Three” in Chromosome.....	110
Figure 5.5 Mutation Operator Illustration	117
Figure 5.6 Pareto Front when K=590 (Scenario 1)	124
Figure 5.7 Pareto Front when K=560 (Scenario 2)	125
Figure 5.8 Combined Scenario 1 and Scenario 2 in a single figure	126
Figure 6.1 A Trans-Pacific case to illustrate the global intermodal network.....	137
Figure 6.2 Basic Pareto Frontier between unit cost per TEU and average time per TEU.....	154
Figure 6.3 Optimal Pareto Frontier under carbon tax rate = \$0.03 per kg	159
Figure 6.4 Optimal Pareto Frontier under a carbon emission trading price = \$0.2 per kg and cap value = 1200 kg	161
Figure 6.5 Optimal Pareto Frontier under a carbon emission trading price = 0.2 per kg and cap value = 1909.3 kg	162
Figure 6.6 Optimal Pareto Frontier under a carbon emission trading price = 0.2 per kg and cap value = 2500 kg	163
Figure 6.7 Optimal Pareto Frontiers under two different carbon emission restrictions	166

Chapter 1 Introduction

Owing to a surge in international trade volume, greenhouse gas emissions are rapidly increasing. The challenge countries and societies face today is how to reduce the associated greenhouse gas emissions while the demand for transportation volume is growing. Sustainable development in the transportation domain deserves our utmost attention. An additional challenge comes from ever-increasing customer expectations and requirements, for example, door-to-door delivery and fast delivery at minimum cost. These challenges present research opportunities which deserve more attention. Considering all of the above, port hinterland intermodal development that addresses environmental concerns has become a crucial domain for exploration, which is the main objective of this research.

1.1 Research background

As operations in ports increase in their complexities and extensiveness, the role of ports has developed into one that is powerful enough to influence the performance of supply chains. This fact has been recognised and thus has resulted in an increasing number of studies that analyse supply chain competitiveness in relation to ports. The hinterland is a key component of the supply chain, and there is also a close connection between hinterland connectivity and port performance. Some studies have shown a positive relationship between these two elements (Marlow and Paixao, 2003; Paixao and Marlow, 2003; Bichou and Gray, 2004; Rodrigue and Notteboom, 2009). As they represent significant nodes in the international intermodal chain, ports must provide sustainable values to the chain in order to survive and thrive (Yap et al., 2006). Ports that offer efficient inland transportation integration result in a higher competitive advantage for the supply chain. It is through collaborative efforts within the supply chain that ports are able to deliver optimal performance and value to their customers. Thus the integration of ports into supply chains has become a fundamental requirement by shippers, and some inland shippers express a need for inland port services, and treat as their facilities (Harrington, 1991; Walter and Poist, 2003; Walter and Poist, 2004; Roso and Lumsden, 2010). It has been illustrated by some studies that the concepts of supply chain, when incorporated into port planning and management, can enhance port performance (Carbone and Martino, 2003; Almotairi and Lumsden, 2009; Lam and Yap, 2011). Relationships and types of collaboration between ports and supply chain nodes, including inland transport connections, have also been examined extensively in recent studies (Lee and Song, 2008; Notteboom and Rodrigue, 2008; Fremont and Géographie, 2009).

The closer link between ports and supply chains has prompted a growing research area — port hinterland intermodal development — which is the focus of this study. Notteboom and Rodrigue (2005) revised the port spatial model by adding a new phase, “regionalisation”. The main characteristic of the port regionalisation phase is port function integration and even joint development with hinterland logistics

platforms in order to shape a regional transportation network to meet the demands of global supply chains. Intermodality with inland terminals and associated transport corridors which are recognised as cornerstones in port regionalisation provides the incentive for gateway ports (maritime load centres) to maximise their hinterland reach in order to provide a seamless, synchronised and highly efficient integration between ocean shipping and inland transportation (Notteboom and Rodrigue, 2008; Rodrigue and Notteboom, 2009; Iannone and Thore, 2010). There is no consensus on the definition of intermodal freight transport (Bontekoning et al., 2004). Intermodal container transportation is a major component of intermodal freight transportation (Dewitt and Clinger, 2003) and can be defined as container transportation in multimodal chains which link the original nodes of consignors to the destination nodes of consignees in order to offer door-to-door service to customers (Barnhart and Laporte, 2007). The container was invented in the mid-1900s for purposes of standardisation and addressing concerns about the safety of freight, including the risk of loss and damage. Since then, the container has become a powerful vector of intermodal integration, enabling maritime and land transportation modes to interconnect more effectively (Thill and Lim, 2010). Containerisation contributes to the world economy by greatly facilitating globalisation and world trade. Today, the “Box” carries more than 90 percent of all non-bulk freights in world trade (Containerisation International Yearbooks, 2012). A variety of container types have developed gradually over time. Almost every type of non-bulk freight can be carried in the “Box”.

Therefore, intermodal development which can address integration and efficiency in facilitating cargo flow is fundamental. In addition to the economic perspective, intermodality that takes environmental concerns into consideration will contribute to sustainable development and is the approach that is increasingly preferred by stakeholders, including shippers (Eng-Larsson and Kohn, 2012). Seaports linked with inland ports by railway services, especially those with double-stack trains, inland barge connections, employing foldable containers to tackle empty container repositioning issues and using the shortest possible initial and final journeys by truck in intermodal container networks are being categorised into green profiles for sustainable development (Hayutha, 1991; Choong et al., 2002; Rahimi et al., 2008;

Liao et al., 2009; Shintani et al., 2010).

China is a suitable case for studying port hinterland intermodal development. Since its implementation of the “reform and opening-up policy” from 1978 and its entrance into the WTO (World Trade Organisation) in 2001, there has been a tremendous increase both in foreign trade volume and value (China Foreign Trade and Economic Yearbook, 2010). In this post-WTO era, the global economy is influenced greatly by the “China Effect” and the development of Chinese ports is remarkable. In 2012, among the world's busiest container ports, seven Chinese ports ranked in the top ten in terms of container throughput, namely Shanghai (1st), Hong Kong (3rd), Shenzhen (4th), Ningbo (6th), Guangzhou (7th), Qingdao (8th) and Tianjin (10th) (Containerisation International Yearbooks, 2012). This phenomenal trend renders conducting an in-depth study on Chinese ports significant. Chinese ports face plenty of opportunities and challenges, among which is sustainable port intermodal development, such as Chinese ports’ spatial hierarchy evolution.

1.2 Research objectives

Based on the above research background, the primary objective of this research is to address port hinterland intermodal sustainable development that takes into consideration environmental concerns, especially for the fastest-growing economies with a large hinterland, such as China and India. This research not only can meet the requirements of the developing intermodal transportation industry, but also can assist governments in making decisions regarding their long-term planning in intermodal development.

As such, the following research questions are formulated and should be answered in this research:

- (1) What is the present situation of the port hinterland intermodal sustainable development issue?
- (2) Both China and India have the fastest economic growth, largest populations

and large hinterland areas. What are the potentials and challenges in terms of port hinterland intermodal sustainable development in China and India, two fast-developing new economies in Asia?

- (3) What kinds of optimisation model can be developed to assist planning in a port hinterland intermodal network? How to incorporate environmental concerns into these optimisation models? How to solve these optimisation models in a case study?

This research will address and answer the above questions. To be more specific, the detailed objectives of this research may be summarised as follows:

- (1) To investigate China's and India's port hinterland intermodal development with a focus on sustainability. The study aims to conduct a qualitative comparative analysis to identify the present situation, potentials and challenges in terms of port hinterland intermodal sustainable development in China and India.
- (2) To develop a tactical model for port hinterland intermodal network optimisation with sustainable development and to analyse the effect of different carbon emission restrictions on transport planning using China as a case study.
- (3) To develop an operational model for sea-and-land intermodal optimisation subject to the three main different environmental regulatory frameworks, namely carbon tax, carbon emission trading scheme and direct restriction using a Trans-Pacific container intermodal chain as a case study.
- (4) To develop solving techniques to solve large-problem instances as illustrated by the tactical optimisation model in (2) above. The study will suggest and enhance the elitist non-dominated sorting genetic algorithm (NSGA-II) method.

1.3 Research scope

The scope of this study is centred on those countries suitable for applying port hinterland intermodal development. It is well recognised that China and India are two Asian countries with vast hinterlands and fast-developing economies. Their conditions match the requirements of the study topic and hence these two developing countries are chosen as ideal cases for our research. A comparative analysis is conducted on China and India in Chapter 4. The study will provide suggestions that the countries may use in their intermodal infrastructure planning and policy making.

Usually, a decision making process can typically be classified into three levels: strategic, tactical and operational. The combined decisions on these inter-related levels are often too complex to be solved at once. A possible and alternative approach is to divide the total decision making process into several sub-problems, which can be solved step by step. In a logistics network, the strategic level is concerned with the number, location and size of particular network nodes and these strategic decisions are defined as long-term decisions, usually involving a number of years. On the tactical level, the decision maker has to decide on the design of i) the network topology, i.e. how the established nodes should be connected, and ii) the detailed layout of the particular nodes, i.e. the location of resources and cargoes at one facility. These tactical decisions are defined as medium-term, involving a couple of months. The operational level is regarded as a short-term decision which involves days or weeks. Routing and scheduling the cargoes through the established network are typical problems in this level (Schmidt and Wilhelm, 2000; Hendriks, 2009).

The research objective of this research is to investigate an integrative and sustainable port hinterland intermodal development. The problem is divided into two levels: tactical and operational. The tactical optimization model is described in Chapter 5 and the operational optimization model is built-up in Chapter 6. The tactical model can provide information and insights to the decision makers from the tactical level, i.e. the inland modal split situation under different trade-off portfolios

between cost minimization and time minimization in different carbon emission restriction levels, or the capacity of certain node/link should be increased or decreased under these three factors (cost, time and emission). Policy implications can be drawn for governments and freight/ logistics integrators from this tactical model, such as more inland dry ports or inland barge ports should be built up, trucking mode should be discouraged. The operational model can help the decision makers (the freight/ logistics operators) to optimize their weekly-based operations also concerning these three factors (cost, time and emission) from the operational level, i.e. routing/re-routing, sailing speed optimization.

The core of this research is to optimise the port hinterland container intermodal network with environmental concerns. According to this given research scope, two mathematical models are proposed in Chapter 5 and Chapter 6. One model is a tactical-level model (in Chapter 5) while the other is an operational-level model (in Chapter 6). The tactical-level model is an integer linear programming model and the operational-level model is a mixed integer non-linear programming model. These two models are suitable for seaports with large hinterlands, such as Chinese seaports, Indian seaports, and seaports in the USA and Europe. Seaports which act as a hub linking all three main modes of transport (road, rail and waterway) or any two of these are the preferred and most suitable options for applying these models because the three main kinds of inland transportation mode are already considered in these mathematical models.

In this research, one case study of China using the tactical-level model and another case study on a Trans-Pacific (between China and the United States, door-to-door) container intermodal chain using the operational-level model are proposed. The reason for this is not only the remarkable progress of China's economy and the rapid development of Chinese seaports and supply chains in China, but also because Chinese seaports have a vast hinterland accessible by means of three different inland transportation modes. Such seaports are the preferred option for applying these proposed models in Chapter 5 and Chapter 6. Beyond China, countries and regions with a large hinterland could also be suitable for case study, such as India, Europe and the USA. Hence, a country or area with small-scale inland hinterland

infrastructure and access such as Singapore would not be suitable for case study within the scope of this research. These two models do not take into consideration of countries that mainly rely on road transportation, because the nature of these two models is to analyse and provide alternative choices between three different inland transportation modes namely, train, barge and truck. There are some assumptions that have been made according to China's circumstance before model application. Minor adjustments to these models may be required if these models should be applied in a case study on another country.

1.4 Research significance

The topic of this research is significant as it addresses key issues in both academic research and industry practice.

1.4.1 Academic significance

Environmental consciousness is a global consensus. Research concerning environmental impacts for intermodal transport and maritime shipping is progressively increasing but inadequate. There is an urgent need for addressing the intermodal network and sustainable development with green concerns. Providing cost-minimisation solutions alone in the optimisation problem is insufficient. Bi- or multi-objective optimisation should be carried out to address these complex problems. This research uses a bi-objective approach in tackling sustainability in port hinterland intermodal development in an effort to answer these two challenges. Two original optimisation models are developed in this research. The first model is a tactical model with green concerns incorporated as a constraint. Our second model is an operational model that takes three environmental regulatory frameworks into consideration for the first time. This operational-model adds to the literature by including in its investigation three environmental regulatory frameworks, namely: (1) carbon tax, (2) carbon emission trading scheme and (3) direct restriction.

The tactical model is an integer linear programming mathematical optimisation model. Normally, for small scale problems, they can be solved by using CPLEX

solver (IBM ILOG CPLEX Optimisation Studio). However, for large-scale problems, no ready solutions are available. We thus have developed a metaheuristic algorithm to tackle the large-scale problems. We have given this algorithm the name of “the enhanced NSGA-II” algorithm. It is also worth mentioning that the three-stage supply-demand matrix-based chromosome presentation embedded in the enhanced NSGA-II algorithm is unique.

The operational model is a mixed integer non-linear programming mathematical optimisation model. CPLEX cannot be used to solve this non-linear problem directly. Therefore, a special linearisation technique is used to transform its non-linear part to a linear relationship. After this transformation, the operational model can adapt CPLEX in solving relatively large-scale problems.

1.4.2 Practical significance

Referring to practical significance, this research is beneficial to the integrators from the industry side, such as shipping lines and the supply chain integrator. These two optimisation models can become a decision-aiding tool for the integrator to design and plan its global network. They can help the integrator to handle more practical situations, such as getting the trade-off portfolio between cost minimum and time minimum, because these two models are bi-objective optimisation models. From Chapter 5, it can be seen that when cost minimization is the only objective, barge transport is the most favourable mode. When transit time minimization is the only objective, trucking is the preferred transportation mode. When we consider both cost and transit time objectives, there is a trade-off for the choice of transportation modes. It is one of the first few attempts to incorporate environmental concerns into transportation network planning. Such a green attempt can help the integrator build a good reputation and become a benchmark in industry circles.

Besides the benefits to the industry side, this research can also provide insightful policy implications with regard to a government’s decision making. Such implications can help shape a systematic policy framework to ensure the development of global intermodal networks. It also can help governments to

establish a set of policy guidelines to realise environmental protection targets.

1.5 Organisation of the thesis

This thesis consists of seven chapters. This chapter (**Chapter 1**) describes the background information of this research. It delivers the research elements in terms of research objectives and research scope. The research significance is highlighted after these two elements. The outline of this thesis is as follows.

Chapter 2 provides a comprehensive literature review of earlier academic research papers in a growing and contemporary subject area in order to identify the research gap on intermodal container transport optimisation, especially using the bi- or multi-objective optimisation with environmental concerns which will be fulfilled in this research. This literature review helps to channel future research direction in the relevant academic areas.

Chapter 3 presents detailed explanations of the research methodologies adopted in this research, including research process design. This chapter can help to provide a better understanding of the whole research process.

Chapter 4 uses a comparative research method to compare the intermodal development between two fast-developing Asian economies, China and India, in terms of intermodal transport from the sustainability perspective.

Chapter 5 develops a bi-objective port hinterland intermodal container flow optimisation model with green concerns at the tactical level based on the research gap uncovered in Chapter 2. This tactical model is an integer linear programming model. It also proposes a genetic algorithm (the enhanced NSGA-II) to solve large-problem instances. Model application is illustrated through a case study of intermodal container transport in China.

Chapter 6 develops a bi-objective door-to-door intermodal container flow optimisation model subject to three different environmental regulatory frameworks

at the operational level. This operational-level problem is formulated as a mixed integer non-linear programming model. A linearisation technique is applied to transform the model from a non-linear to a linear model. After this linearisation transformation, the state-of-the-art commercial solver, CPLEX, is applied to solve the operational-level model. A case study on a Trans-Pacific (between China and the United States) container intermodal chain is conducted to elaborate its applicability and significance.

Chapter 7 concludes the research findings based on previous chapters. The research contributions and implications are highlighted and research limitations are explained in this chapter. Recommendations for future research are also provided.

Chapter 2 Literature review¹

As mentioned in Chapter 1, port hinterland intermodal development with consideration of environmental concerns is the aim of this research. In order to understand clearly the research gaps in this domain, this literature review chapter focuses on related researches in order to identify specific research gaps. A summary table of the literature with mathematical models in the relevant domains (the scope is confined to those with intermodal connection) and the sub-tables are employed to identify the research trends and gaps, and to suggest research directions in this thesis. The literature review shows that there is substantial need for research addressing greening the intermodal network and sustainable development. Based on the research gaps discovered in the literature and subsequently discussed in this chapter (Chapter 2), the following chapters (Chapter 4, Chapter 5 and Chapter 6) will demonstrate how each of these research gaps is filled, respectively.

¹ The following publication from the author is based on part of this chapter:

Lam, J. S. L. and Gu, Y. (2013), "Port Hinterland Intermodal Container Flow Optimisation with Green Concerns: A Literature Review and Research Agenda", *International Journal of Shipping and Transport Logistics*, Vol. 5, No. 3, pp. 257-281.

2.1 Introduction

In the first half of this chapter (Sections 2.2 to 2.4), a descriptive and extensive review is delivered about recent development trends in the port industry (port regionalisation), the integration between port development and supply chain development, and the relationship between port development and sustainable development. The close link between ports and supply chains leads to a growing research area — port hinterland intermodal development. This growing research area is the focus of this research. It is necessary to identify the specific research gaps in this growing research area.

Based on the background provided in the first half of this chapter, the focus of the second half of this chapter is to summarise and compare the relevant literature that includes mathematical models. The scope is confined to those with intermodal connection. A summary table and the sub-tables are drawn out accordingly. The purpose is to categorise and analyse earlier research contributions on intermodal container flow optimisation in order to identify the research trends and gaps and, in the second half of this chapter (Section 2.5), to suggest research directions.

2.2 Ports' spatial hierarchy evolution with transportation function

Nowadays, there are a substantial number of varied inland transportation nodes emerging which conduct many kinds of transportation functions. These include inland dry ports, inland barge terminals, warehouses and distribution centres. With long-term development around the main gateway seaports and inland transportation nodes, there are many corridors taking shape which can provide strong linkages between the sea sector of transportation and the land sector. The port regionalisation concept has been proposed as a result of this background and tendency. This section reviews and provides comment on the related literature and concepts.

2.2.1 Ports' spatial hierarchy evolution to regionalisation stage

The “Any Port” model developed by Bird (1971) is one of the popularly acknowledged conceptual models in port development, with the three steps in port development identified as: setting, expansion and specialisation. Another kind of widely accepted model is about port spatial evolution of port locations derived and elaborated from Taaffe et al. (1963), which is earlier than “Any Port”. In this paper of the year 1963, the sequence of port development is as follows: (1) scattered ports (2) penetration lines and port concentration (3) feeders and lateral interconnections and (4) high-priority linkage. On the basis of Taaffe et al.'s paper in 1963, Rimmer (1967) modifies the port development conceptual model to three phases: (1) scattered ports (2) penetration lines and port piracy, and (3) interconnection and concentration. With rapid development in container transportation technology and industry, Hayuth (1988) proposes the “centralisation” phase as reinforced stage of “concentration” followed by the “deconcentration and decentralisation” phase. After many years, Notteboom and Rodrigue (2005) revise the port spatial model, adding the sixth phase “regionalisation”.

On another track, Notteboom and Rodrigue (2005) also revise Bird (1971)'s “Any Port” model with an additional “regionalisation” stage. The “Any Port” model proposed by Bird (1971) cannot explain the emergence of inland ports driven by inland demand from a hinterland perspective and some island ports with limited hinterland for expansion like Singapore which is a world famous transshipment hub from a foreland perspective.

The main characteristic of the port regionalisation phase is port functional integration and even joint development with hinterland logistics platforms in order to shape a “regional transportation network” to meet the demands of global freight distribution channels and chains. Paradoxically, ever-increasing port traffic places pressure on ports with huge stresses of jamming and blocking. On the other hand, environmental concerns and local residents' opposing voices would have a significant impact on port expansion in its nearby territory and this imposes restrictions on port expansion and development. Inland ports and other logistics

platforms together with gate seaports would shape a regional network to mitigate these kinds of acute problems and achieve an alternative smart pattern of port expansion and externalisation. The development of inland ports could be considered as a port regionalisation process involving integration between maritime and inland freight transportation (Notteboom and Rodrigue, 2005).

Gateways are the node points through which intercontinental containers are transhipped onto continental axes, and the gateways could become hub port cities via continuous development later on (Fleming and Hayuthb, 1994). Starr and Slack (1995) recognise that many ports acting as gateways expand the hinterland as much as they can and thus intensify port competition in a hinterland context. Some hinterlands are serviced by several intensively competing ports thereby preventing only a few ports having the monopoly or the oligopoly. Many ports endeavour to explore faraway discontinuous hinterlands beyond the periphery of the immediate hinterland with a competitive nature. Intermodality with inland terminals and associated transport corridors which are recognised as cornerstones in port regionalisation give the incentive for gateway ports (maritime load centres) to maximise their hinterland reach. The inland terminals can be treated as extended gateways of these gateway seaports. In the extended gateway concept, port operations can be moved to an inland location and more space becomes available for dock-related activities in the gateway seaport. Extended gateways can further stimulate the development of intermodal transport.

Port regionalisation strategy implementation would achieve cost and service advantages vis-à-vis other rivals with lower inland cost and quicker response to customers. Port A could win over the customers from neighbouring port B who are located in port B's continuous hinterland (Notteboom and Rodrigue, 2005).

However, there are also some arguments and critiques on this "Regionalisation phase" concept. For instance, Rimmer and Comtois (2009) argue that over-emphasis on "Regionalisation phase" concept would lead us to be preoccupied by the land-based network and neglect the development of maritime space, similar to putting the cart before the horse. They also ask what are the real differences between the

“Regionalisation phase” and the “Decentralisation phase”. In their opinion, the additional elements of the “Regionalisation phase” can all be accommodated in the “Decentralisation phase”.

2.2.2 Diversified inland ports springing-up in port regionalisation stage

Due to ever-increasing international trade volume, port congestion is a prevalent phenomenon. Ships have to queue up outside the port area and wait for an available time slot so they can load or offload. Ports only have limited resources, such as a limited amount of dockage and cranes. High traffic volume causes port congestion. The port congestion situation is very severe in some ports, such as the port of Los Angeles and the port of Long Beach on the west coast of the USA, the port of Rotterdam and the port of Antwerp in Europe, Shenzhen port, Shanghai port and Qingdao Port in China (Simões and Marques, 2010; Leachman and Jula, 2011). Port congestion almost becomes a worldwide problem. Port congestion is caused by a number of different factors, i.e. a period of bad weather, an unexpected accident, and strikes in other ports nearby. Among these various factors, the extraordinary growth in international trade may be the primary cause. In 1999, Slack (1999) proposed the concept of a “satellite port” which would provide a solution to port congestion. A satellite port is close to the seaport and the two are connected by a road or highway depending on the type of truck transportation.

Some more recent papers propose a new notion of “dry port” which is an inland intermodal terminal directly connected to a seaport with high capacity transport mean(s), preferably rail connection, where customers can leave/pick up their standardised units (containers) as if directly to a seaport, which is initiated by Leveque and Roso (2002) and highlighted in Roso and Lumsden (2010)’s paper. Seven years later after 2002, Roso et al. (2009) have given a more specific definition of the “dry port” concept which is an inland intermodal terminal directly connected to a gateway seaport by railroad available with double-stack trains. In another paper by Rodrigue et al. (2010), the “dry port” definition is an inland

terminal connected with a seaport but excludes the barge terminal. This means it would be connected by truck, rail or both, but excludes the inland water connection. In these dry ports, containers would be treated in the same way as in a seaport, even with a customs clearance function. Roso and Lumsden try to unify the dry port concept in their paper in 2010 (Roso and Lumsden, 2010). They propose that some extra functions are identified as necessary, such as customs clearance and storage, while some services are not considered as essential, such as the forwarding function. The results of Jaržemskis and Vasiliauskas (2007)'s investigation into a dry port project being implemented in the Baltic sea region show that it could be demonstrated that the dry port concept implementation would have positive impacts on not only the seaport development but also the region's economic development. This investigation result could be side evidence of the port regionalisation phenomenon. Roso and Lumsden (2010), in their review paper, find that many governments of developing countries have realised the importance of dry ports and that is promising. In 2011, Do et al. (2011) revisit the dry ports' development in the Indochina area (including Vietnam, Laos and Cambodia — all three countries are developing countries) and make the point that the dry port's existence would make import and export easier and increase trade both in volume and value terms. They also point out that government resources are not sufficient to meet the requirements of developing an efficient intermodal transportation system, and some private partnerships are welcomed to assist and speed up this development.

In Roso et al. (2009)'s paper, they compare a conventional port-hinterland transport system with a “dry port” link in three models for different distances, which are the dry port to the seaport in far, midrange and close distances. In Figure 2.1 that follows, there are three sub-figures (a, b and c) to express these three different scenarios. In Scenario (a), a dry port is located in the far city area and is linked to a seaport by railway. In this Scenario (a), some land-locked shippers (3,4,5,6,7) which are near to the dry port would prefer to use the dry port, but the shippers which are not so close to the inland dry port would also use the seaport with direct truck access as before, e.g. Shipper 8 in Scenario (a). There is a dry port between the seaport and inland city in Scenario (b) and it links two sub-hubs (conventional

intermodal terminal) with railway access. In Scenario (b), apart from Shipper 1 and Shipper 10, all shippers use the dry port directly or indirectly. In Scenario (c), there is a dry port in close proximity to the seaport. There are railway links between the seaport and the dry port, and also between the dry port and the inland conventional intermodal terminal. In this Scenario (c), all the shippers (from Shipper 1 to Shipper 10) pass their cargos via the dry port. The dry port in Scenario (c) is just like a backyard of the seaport and it can take on a buffer function to reduce any congestion in the seaport.

(a) A seaport with a far dry port.

(b) A seaport with a midrange dry port.

(c) A seaport with a close dry port

Figure 2.1 The relationships of a seaport and a dry port in three different distances

Source : (Roso et al., 2009)

Another inland transport mode, barge transportation, also plays an important role in the seaport-hinterland intermodal transportation system. In Notteboom (2007)'s paper, he finds that the seaports of Rotterdam and Antwerp have fully developed the inland waterway transport systems by building barge terminals from an infancy phase to a fully-fledged phase during the past twenty-five years. In other European seaports, the barge option is attracting more and more interest because of its low cost and low carbon footprint attributes. It is acknowledged that the barge transportation system is too dependent on and restricted by geographical conditions. Some regions and some seaports are not able to develop inland barge terminals and inland waterway systems because of geographical limitations. The barge option would be a good choice when there are favourable inland water tributaries, because it is an economical and environmental choice. For these reasons, inland waterway links and barge terminals are considered in this research.

2.2.3 Further discussion and critique

No matter whether the ports are satellite ports (connected by truck), dry ports (connected by railway), barge terminals or other logistics nodes, they could be considered as secondary ports or inferior hierarchy ports in a seaport's spatial hierarchy system and would be linked together to connect with gateway seaports, thereby forming an intricate and dynamic transportation framework. In Klink and Berg (1998)'s article, Rotterdam and Northern Italy's creative provision of a shuttle

rail service is presented as a successful case that shows us the Rotterdam port regionalisation strategy representatively even though Italy has three of its own port clusters. Rail services can offer faster transportation than shipping and generate less pollution than truck transportation. The cost of using rail is acceptable as it is priced in between these other two transport modes. These kinds of shuttle service provision can be considered as corridors or axes to access inland ports or other logistics nodes, on the whole, inland distribution systems. A port's potential hinterland is dynamic. Some ports have hinterlands with growing markets while others have shrinking hinterland markets due to neighbouring ports' market invasion. Those inland locations which can be served by a particular port cheaper and/or more efficiently than other ports belong to the port's hinterland. In practice and reality, monetary cost is not the only reason to determine port competitiveness. Risk, time and environmental factors also need to be taken into account according to different shippers' and commodities' particular requirements. However, while the shuttle rail operations between Rotterdam and Northern Italy appear to be successful, they are not without problems. The imbalance in this bi-direction transportation is serious, with often loaded import freight flows from Rotterdam to Italy and badly loaded backhauls from Italy to Rotterdam. In most cases, there are challenges in gaining sufficient cargo to make the backhaul cost effective and the frequency of the backhauling train service is very low.

This framework, organised by gateway seaports with their secondary ports and even inferior hierarchy ports, would assist the gateway seaports to enhance their market competitiveness in the global freight distribution network. Ports with an efficient, cost-effective and seamless hinterland connection network and well-developed inland port hierarchy infrastructure would encourage and attract more shipping lines' calls in order to capture higher market share and keep ports' customer loyalty. This also helps some inland-locked shippers to access the global distribution network effortlessly at a bargain price. The port regionalisation concept and network analysis perspective should be embraced in order to increase a port's competitive power. And the assumption should not be made that a port is merely a loading and unloading point or a break of bulk point as past research studies have

done.

Admittedly, in the emerging, dynamic and somewhat uncertain port regionalisation tendency, maintaining a cautious attitude is crucial so that the success of the port's competitiveness and expansion may be secured. It is not advisable to have an over-optimistic view when developing inland distribution systems as this can lead to overcapacity and cutthroat competition between existing competitors and newcomers. Another concern is that to build and complete a regional distribution system is time consuming with years of painstaking efforts by port and transport authorities, infrastructure developers and market operators under the dynamic and ever-changing market environment. Hence port regionalisation strategies should be adjusted and modified simultaneously and properly. Port regionalisation should be considered a cost-effective alternative which is a stronger driving force than incentives from port authorities per se. It is an ideal situation, but in most practical cases the basic infrastructures need huge investment and rely on government support. Port regionalisation is often influenced more by political motives than purely by the "invisible hand" of an efficient market. Apart from the aforementioned concerns, how to balance and arrange benefit distribution among the market players that are involved is a challenge and a conundrum in the implementation of port regionalisation.

2.3 Regionalisation drives ports to supply chain integration

Many shippers in landlocked areas prefer to use the transportation resource nearby. How to provide them with a seamless integration service is a challenge for the players in the global distribution supply chain network. A port, as a single node in this big map, has to be involved in supply chain integration without exception.

2.3.1 Port performance evaluation model updated with new element

Robinson (2002) finds that the role of ports and port authorities must be embedded as elements in value chain constellations in the new paradigm. In the old paradigm, seaports only functioned as minor roles in some major shipping lines' network

mapping and were only considered as the places to exchange cargos with loading and unloading between ship and shore. In the new paradigm, seaports deliver value to their main customers (shipping lines), finally to shippers, and accessorially to other third-party service providers.

Marlow and Paixao (2003), Paixao and Marlow (2003), Bichou and Gray (2004) and Levinson (2009) all have witnessed that ports are increasingly integrated in supply chains and the port performance evaluation framework should be built from the supply chain perspective. These port performance evaluation models include information technology adoption, value-added services, connection with inland transportation modes, and relationships with shipping lines, relationships with inland transportation operators, and channel integration practices and performance. In the last years of the twentieth century, containerisation and door-to-door service were required and accordingly gave rise to a new form of business organisation: “The global supply chain”. In the past, port authorities played the role of facilitators, just focusing on the port performance and efficiency within ports. With contemporary maritime transportation development it is not enough that ports must place themselves as a member of the global supply chains which involve both sea and inland transportation. In 2010, Zondag et al. (2010) present a model called port competition model consisting of maritime transportation (sea leg), port, and hinterland transportation (land leg) characteristics, which would be used in forecasting and policy analysis to support governments and port authorities with strategy development and decision making. This port competition modelling framework has more functionality than “fixed market share” models without detailed OD flows. This framework originally combines the trade model and transportation network together. It is very useful to test and help understanding port competition deeply. One significant finding is that the port volumes appear particularly sensitive to port efficiency and the effectiveness of its hinterland connections. Another test result of this framework also illustrates the importance of understanding each port’s geographical characteristics. Under various socio-economic scenarios, different ports should have different hinterland development strategies.

2.3.2 Information technology support and organisation reformation in port integration into supply chains

Frankel (1999) concludes that information technology would assist in controlling and coordinating the whole network flow of the global supply chain. Therefore, information technology is important for ports in order to synchronise and integrate into the supply chains with other participants. Aligning overall organisational strategy with supply chain strategy is also crucial for ports' integration into supply chains. Thus Lee and Song (2008) use a lean system in supply chains as a new direction for port organisation changes. The lean system has some main features as follows: (1) waste removal, (2) quick response, and (3) continuous improvement. It is envisaged that there would be reform and restructuring in port authorities' and terminal operators' internal organisations to a lean system that would help ports to seamlessly integrate into supply chains according to different port hierarchies.

The springing up of global supply chains over the last two decades contributes to a reshaping of competitive relationships among transportation carriers, among terminal operators, among port authorities and among other participants. Shipping lines' alliances are notable particularly those which are horizontal integrations, and vertically, shipping lines, as ocean carriers, also integrate with inland carriers, for example rail and truck service providers, and terminal operators. However, terminal operators who are the main and direct beneficiaries of port development expand themselves to strengthen their bargaining powers versus shipping lines through horizontal integration. For example, PSA, which is a terminal operator owned by the Singapore government investment corporation, and HPH (Hutchison Port Holdings) which is a private terminal operator based in Hong Kong, are both expanding their operations in many ports all over the world to establish port operator alliances to counteract the shipping lines' alliances. Moreover, not all the ports have sufficient water depth to handle the larger ships; therefore the ports with natural deep-water resources would have the competitive advantage in the global supply chains (Levinson, 2009).

Nowadays, competition between ports is actually a competition between supply chains. When two different supply chains are passing through the same seaport, the port authority could use a benchmarking approach to identify the proper management model for the specific port and could utilise this benchmarking approach to make decisions about infrastructure investments and related hinterland connections (Carbone and Martino, 2003). Benchmarking is the process of comparing one's business processes and performance metrics to the best firms in this industry or best practices from other industries where similar processes exist (Adebanjo et al., 2010). Here, using a benchmarking approach means that a port authority should learn from the best practices in other ports or similar industries.

2.3.3 Barriers in integration

As a matter of fact, more and more inland ports not only function as consolidation and deconsolidation hubs to the seaports but also as value-adding centres to the whole supply chain.

Inland port locations and inland transportation networks have attracted shipping line and seaport operators' attention and action. Endeavours between seaports and inland ports via co-operation and synchronisation are made. However, there are barriers to integrating seaports with inland ports as follows: (Podevins, 2007; Notteboom, 2008)

- (1) Connection complexity and high costs correspondingly;
- (2) Lack of reliability (delay and damage) and low operational efficiency;
- (3) Many actors involved, each with different individual objectives;
- (4) Need for a better data interchange system in the whole supply chain and organisation mechanism.

Even though the barriers still exist, the increasing trade volumes, customers' demand requirements (door-to-door delivery), severe seaport congestion, technology availability and deregulation by governments are key drivers and there is a strong tendency to launch and develop inland port networks in different forms.

Some may have storage function only while others include value-added logistics activities. Some also include customs clearance and registration functions (dry ports). These changes help to reshape the shipping markets from the traditional shipping market to a dynamic integrative shipping market.

2.3.4 Port regionalisation links port spatial integration to supply chain functional integration

Notteboom and Rodrigue (2005) propose a multi-layer model approach to analyse port dynamics. In their model, there are four inter-related layers evolving from a spatial to a functional perspective which are location layer, infrastructure layer, transport layer and logistics layer. The port regionalisation concept is proposed to link port spatial hierarchy development to port strategic positioning in supply chain integration functionality.

Corresponding to this four-layer model, port regionalisation links the lower three layers to the higher logistics layer which is more dynamic than the other three layers, ultimately shaping a regional distribution network or logistics pole.

In the port regionalisation phase, shipping lines, port authorities and other relevant participants and stakeholders all aim to reduce the inland transportation cost which accounts for a large proportion of the total supply chain cost and which could be reduced largely via seamless integration and by improving the corresponding efficiencies of every party and the whole supply chain. Regionalisation provides answers to the strategic integrating maritime distribution segment and inland distribution segment of the global supply chain in terms of cost reduction, efficiency improvement and other logistics feature enhancement. The target of supply chain integration is providing a “one-stop shop” by a single party from consignors to consignees. However, in this situation, monopoly would appear as a potential risk which is not the consignors’ expectation. It is a paradox that on the one hand consignors need “one-stop shop” services and on the other hand they are afraid of monopoly which would result in the loss of their bargaining power.

Notteboom and Rodrigue (2008) have found that many neighbourhood ports in the same region functioned as gateways to serve global supply chains. These could be considered as a port cluster that would result in new port hierarchies. This new port cluster proposition is also contained in port regionalisation development strategies. The interface of maritime and inland would be expanded in landscape orientation under a port cluster strategy that is included in the wider scope of the port regionalisation strategy. The function of gateways is not changed. However, it can bring about geographical space expansion and higher efficiency.

In 2010, Rodrigue and Notteboom develop the port regionalisation concept, adding the foreland-based regionalisation which differentiates from the hinterland-based regionalisation they proposed in 2005 (Rodrigue and Notteboom, 2010). They find three foreland-based regionalisation circles in Pacific Asia which are Busan, Kaohsiung and Singapore circles and two hinterland-based regionalisation circles which are Shanghai and Hong Kong circles. The emergence of this paradigm shift is mainly influenced by the global manufacturing and distribution network re-location which would be further confirmed in Lee and Rodrigue (2006)'s paper. Busan, Kaohsiung and Singapore play a role more like transshipment hubs in this re-location tide while Shanghai and Hong Kong function as gateway ports in mainland China.

Rodrigue and Notteboom (2009) first of all put forward a "supply chain terminalisation" concept. In their paper, inland terminals including dry ports, barge terminals, satellite ports and distribution centres in various forms, could be seen as "extended gates" and "extended distribution centres" with a buffer function in port regionalisation strategies. The buffer function integration is just one example of port functionally integration into supply chains. Regionalisation links port spatial integration to supply chain functional integration through value creation, enhancement and capture. Regionalisation is an inevitable product with the development of the global distribution network and it would become the driving force to push ports into this global integration tide.

2.3.5 Different players' interests in the integration

The interest of consignors (shippers) is usually to get the lowest transportation cost at a given service level (surely, the higher service level the better under the same transportation cost) in inland transportation and it would be the shipper's concern to arrange land-leg transportation, additional logistics services (customs clearance, storage, consolidation, etc.), using an environmentally friendly transportation mode (reducing the truck haulage) by themselves in the past. Shippers have an interest in benefitting from inland intermodal transportation services, but they have no intention to organise this integration since this is not their main business activity. Therefore shippers would not be interested in becoming an integrator, especially when the shipper has limited cargo volumes to be transported.

Both shipping lines and freight integrators are interested in integrating inland transportation. Shipping lines provide sea carrier haulage and freight forwarders use merchant haulage. Among the various players, shipping lines are the most interested in taking on the role of integrators. This integration could help them to provide door-to-door solutions to customers. It would also aim to reduce transportation costs of the inland leg and this could enable the shipping line to become more competitive than its competitors. In order to realise this integration, both shipping lines and freight forwarders could purchase the slots from inland transportation service providers in the contract which in turn would help to reduce commercial and operational risks.

Seaport terminal operators, inland terminal operators and inland transportation service providers have much interest in becoming integrators in order to extend their activities. This integration of sea leg and inland leg would help the containers to complete a smooth inland journey and return back to their shipping lines under more control and care. Nevertheless, they do not have enough power to act as integrators in most cases, because in normal circumstances these three types of player have no direct contact with shippers.

Finally, when other players demonstrate inadequate power to become conscious integrators, port authorities would take the responsibility of becoming an integrator. Particularly in the initial stage, a port authority would facilitate such integrations in order not to lose the benefits of hinterland preservation under competition in the same region from other competitors (Frémont et al., 2009).

2.3.6 Further discussion and critique

Although a port is just a node in the whole supply chain, it plays a crucial and indispensable role which links the sea-leg and land-leg transportation networks with a seamless interface, acting as the catalyst to boost the whole supply chain. The phenomenon of many industry supply chains passing through the same ports gives the ports and their surrounding inland areas opportunities and motivating forces to develop miscellaneous logistics nodes nearby which work together with ports as port clusters to attract more industry supply chains using the ports. In such a situation, the port can attract many shippers and consignees nearby who are the customers of shipping lines. At the same time, shipping lines are the main customers of the port. Consequently, the port with excellent regionalisation development strategies would possess more competitive power than others. Nowadays, many ports in the world are reaching the regionalisation stage with varying degrees of formal linkage between the port and its hinterland nodes in the regional distribution networks. This affects global supply chains and even the value chains from a business globalisation perspective. Ports have to deliver value to shippers (consignors), consignees, some relevant participants and stakeholders while they capture value for themselves. The best practices of other ports have been investigated by many forerunners through benchmarking studies. However, quantification of their specific contribution made by ports to supply chains remains as a puzzle and a conundrum both in maritime academic terms and the industry. However, the business environment under economic globalisation is dynamic and ever changing and this would have a strong impact on value chains and supply chains. Ports, as embedded nodes in these chains, must adjust themselves to serve these chains accordingly. How to use different regionalisation strategies to define a port's hinterland is subject to the business environment. Today, if a port is without a

chain vision and business sense, it is tough for its survival and prosperity in the long term.

2.4 Intermodality and empty container repositioning with green concerns

When considering intermodal transportation, how to rationally arrange inland container transportation in order to get cost minimum, time minimum and carbon footprint minimum is a big topic for us to study and research. How to deal with the empty containers that result from the imbalance of global trade also deserves our efforts.

2.4.1 Containerisation and intermodality in port development

The “intermodal freight transport” concept was introduced thirty years ago in the 1980s and, after reviewing many previous researchers’ papers, Bontekoning et al. (2004) conclude that there is no consensus about intermodal freight transport definition and which one should be advocated. Different definitions come from different aspects of intermodal transport, such as physical characteristics, modal choice and organisations’ relationships. A popularly accepted definition proposed by the European Conference of Ministers of Transport in 1997 from the physical characteristics aspect to give a clear definition about the intermodal freight transport is “Intermodal freight transport is the movement of goods in one and the same loading unit or vehicle by successive modes of transport without handling of the goods themselves when changing modes”. In Barnhart and Laporte (2007) intermodal freight transportation refers to container transportation in multimodal chains which link the original nodes of consignors to the destination nodes of consignees in order to offer door-to-door service to the customers. In fact, intermodal freight transportation is not only about container transportation in multimodal chains, but very important to note that many bulk and semi-bulk commodities are also moving intermodally and are non-containerised, such as grain and fertilisers. But container transportation is a major component of intermodal

freight transportation (Dewitt and Clinger, 2003). This research only considers intermodal container-based transportation as in Barnhart and Laporte (2007)'s definition and focuses on the box (container) flow in intermodal freight transportation. In intermodal container freight, goods would remain in the same container throughout the entire trip without a change of container for the goods, with most of the trip travelled by an ocean-going vessel, inland waterway barge or rail, and with the shortest possible initial and final journeys by truck (Macharis and Bontekoning, 2004). The goal of intermodal transfer is to provide door-to-door intermodal freight transportation which is coordinated, seamless, flexible and continuous on two or more transportation modes under just a single freight bill (Muller, 1999). While the definition of intermodal transportation and its associated processes may be complicated and would not be uniform, it would become easier to define when it comes to the practical issues.

The container was invented for standardisation purposes and to address safety concerns (to avoid loss and damage of freight) about fifty years ago in the mid-1900s. Containers are large metal boxes which are made in standard dimensions (among all container dimensions, 20-foot and 40-foot are the two most popular container dimensions in practical use) and measured in 20-foot equivalent units in container throughput computing. In terms of the major advantages in following the development largely in maritime transportation, container utilisation can reduce ship turn-around time for loading/unloading cargo and offer standard interchange processes in intermodal transportation with door-to-door service provision, also accompanied by economies of scale at lower cost.

Containerisation has propelled the development of intermodal transportation. But the container industry is approaching a maturity phase with relatively marginal hardware technology advancement. For example, in sea transportation, more container liner ships are larger than before in order to achieve economies of scale, and meanwhile the ships in inland barge system are also larger and more trains are double stack. In the long run, smart management of a container logistics system is crucial for successful and sustainable development, using systematic support

(software) to offset the limitations in equipment (hardware) (Notteboom and Rodrigue, 2008).

Primarily due to China's spectacular economic growth in the past twenty years, the whole shipping industry has witnessed the prosperity of the container shipping industry. Containerisation has been a powerful vector of intermodal integration, enabling maritime and land transportation modes to more effectively interconnect. It is the container invented fifty years ago which has a tremendous impact on global freight distribution, initially applied only in maritime transportation and eventually applied to inland intermodal transportation. The containerised box can offer the inland distribution system the possibility of operating in a seamless and synchronised environment (Notteboom and Rodrigue, 2008).

There are three main mode choices in hinterlands as an intermodal container transport choice: truck, train and barge (with the limitations of geography and infrastructure), and some seaports might only provide one or two mode choices. In the next few years, the emergence and development of hinterland intermodal networks represents a strong interest. The strategies, which are about to invest in seaport infrastructure, road, rail and water infrastructure and logistics sites and dry ports in order to establish the seaport-hinterland network and to optimise the transportation flow to achieve the global optimisation objective, are studied and researched by more practitioners and academics. An agent-based model approach can be proposed for hinterland intermodal transportation because there are various participants involved with their own individual objectives. An agent-based model approach can be introduced to allow negotiations between different participants to achieve a global objective. Agent-based modelling tools can be used to test how individual behaviour changes would affect the system's holistic behaviour and realise complex multi-objective optimisation. Team-building of autonomous agents to share information and solutions via the same memory to solve the combined optimisation problems is the mechanism of a multi-agent system (Kazemi et al., 2009). The following table (Table 2.1) illustrates a comparison of the characteristics among different transportation modes, namely truck, rail, air and water (Stock and

Lambert, 2001).

Table 2.1 A comparison of the characteristics of different transportation mode

Characteristics of different transportation mode				
Characteristics	Truck	Rail	Air	Water(sea and barge)
Cost	Moderate	Low	High	Low
Service	Point-to-point	Terminal-to-terminal	Terminal-to-terminal	Terminal-to-terminal
Average haul length	515	617	885	376(barge) 1367(ocean)
Capacity(tons)	10-25	50-12000	5-125	1000-60000
Speed	Moderate	Slow	Fast	Slow
Flexibility	High	Moderate	Moderate	Low
Reliability(arrive in time)	High	Moderate	High	Low
Damage	Low	Moderate -high	Low	Moderate-low

Source: (Stock and Lambert, 2001)

According to these transportation modes' different characteristics and sea-hinterland intermodal freight transportation's requirements and features, in this research only sea-truck (to/from satellite port), sea-train (to/from dry port), and sea-barge (to/from barge terminal) and from these inland terminals to shippers or from shippers to these inland terminals using truck (pre- and end- haulage) are focused on. Inland terminals are assumed to be present in the inland intermodal development framework and could link a region to global supply chains (Rodrigue et al., 2010). The following figure (Figure 2.2) is a list of key factors which would significantly influence global freight intermodal distribution when facing mode-choice decision problems (Min, 1991).

Figure 2.2 The key factors influencing the global freight intermodal distribution

Source: Modified based on (Min, 1991)

Muller (1999) concludes that there are three driving forces of intermodalism's emergence, and they are: (1) Globalisation, which often brings about shifts in trading patterns, (2) New and emerging technologies, and (3) Deregulation and perhaps some reregulation of transportation. He also summarises the three impacts of intermodalism. The three impacts are: (1) transportation service including transportation, warehousing and communication, (2) the cost for providing that service, and (3) the price the customer is willing to pay for that service.

Yap et al. (2006) have found that there is more attention and awareness being paid to environmental and sustainable issues in East Asian port competition. It is the Green Groups dedicating themselves to being alert and waking up society to protect our planet and environment, and they also play a very important role in ensuring that the relevant decision-making parties maintain a cautious attitude to investing in and developing new port projects with green concerns. In other words, ports with green and sustainable ideas would give themselves a competitive advantage when facing rivals' competitive pressure. They also highlight that future inter-port competition in East Asia would depend on the ports' ability to harness and

coordinate the resources and support of Green Groups. Increasingly, seaport authorities and terminal operators realise that seaports have to implement inland expansion strategy with second or third hierarchy in various forms (satellite ports, dry ports, barge terminals, inland distribution centres and so on), especially the dry ports linked by trains and barge terminals linked by barges, because these two modes (railway and barge) are considered greener than the truck mode with less energy consumption, less carbon footprint and lower unit price caused by economies of scale which would bring about sustainable development for seaports in the long run. In addition, regarding cost concerns, the rising oil price also helps to shift from trucks being dominant to railway and inland waterway.

Port authorities and port operators try to enhance and improve intermodal capacity because port regionalisation heavily relies on the infrastructure of inland logistics nodes or other nodes in the regional distribution systems and transportation service capacity accordingly. However, most inland logistics nodes and inland transportation services are within inland market players' grasp whereas they are often out of the maritime community's hands. In the evolution and development of port regionalisation, how to coordinate the sea-leg and land-leg's seamless integration and how to balance the benefits of every participant in order to achieve a win-win result are tough and challenging problems for port authorities and port operators to figure out. In some hinterlands, seaports want to build secondary-level ports by themselves with some infrastructure investments, but in other hinterlands, seaports just prefer to use various kinds of cooperation with inland operators to acquire market share without investing themselves. Where to build secondary-level ports with shuttle service provision and when just to cooperate with inland operators is the port authorities' strategic decision which is inevitably associated with risk. If intermodalism is happening in the region which is between the seaport and its secondary ports connected with shuttle services, this kind of intermodal connection is under the control of the seaport with less cost, less delay risk, less loss and damage risk, less pollution to the environment and more reliability, more value delivery to shipping lines with a footloose nature and inland-locked shippers facing geographic limitation. If the railway or barge services between the seaports and the

secondary seaports are not shuttle services, many relevant players have to participate: railway players and barge players are pushed to carry out effective market policies for attracting the inland shippers and ocean carriers to shift to the intermodal solution, while the port authority should pose as “facilitator” of the whole chain to enhance the aggregation of the demand through the dry port or barge terminal options. Of course, the extra benefits should be shared by all players (Parola and Sciomachen, 2009; Fu et al., 2010).

2.4.2 Empty container repositioning

With the imbalance of global trade, both maritime and inland transportation are facing the empty container repositioning problem. Many shipping lines are reluctant to let their containers go far inland mainly because of inappropriate inland empty container repositioning situations. In most cases, the containers shipped from the coast to inland areas come back empty to seaports and this yields a huge resource waste for shipping lines and also incurs great loss in terms of revenue. The movement of inland containers is often and easily out of the shipping lines’ control and supervision. But shippers’ demands pull these containers from the sea leg to the inland leg in order to let shippers enjoy being able to offer door-to-door services. On the other hand, in some export-oriented countries like China, the large volume of export requires a large number of empty containers. Some empty containers which could be utilised better are put aside and empty containers from foreign countries far away are imported. This consumes more time, money and resources. In some import-intensive countries like the United States, containers are destined to linger around and there is an over-supply of empty containers waiting to be repositioned. These empty containers should be consolidated in some ports and transported to other markets where they are in demand. If this empty container repositioning problem could be coped with and handled very well, it is possible to substantially reduce empty container transport volume from foreign countries to meet the local market’s requirements which would bring about green effects in environmental protection and sustainable development.

Generally, there are four main reasons for the complexity in empty container

repositioning: (1) trade imbalances, (2) empty container repositioning cost, (3) container manufacturing and leasing costs, and (4) the usage preferences of customers (Notteboom and Rodrigue, 2005). Inland empty container repositioning is more complicated than sea-leg repositioning because inland repositioning has to add intermodal transportation's complexity to empty container repositioning.

2.5 A specific review on intermodal container flow optimisation

Through quantifiable means, issues about container flow optimisation were examined by a number of earlier published contributions with increasing interest so far. Key concepts include "Globalisation", "Port regionalisation", "Intermodality", "Sustainable development" and "Empty container repositioning" among others. After a thorough literature review, we uncover that there are an unexpectedly low number of research articles tackling intermodal container flow optimisation issues that also have a sustainable development concern. An earlier review by Macharis and Bontekoning (2004) did not include the environmental aspect and sea transportation or connection to ports. Hence it is timely and valuable to conduct a review on container flow optimisation research to cover a wider perspective and the latest developments.

2.5.1 Review methodology

In the following subsections, the focus is on the literature relating to container flow optimisation with mathematical approaches. The scope is confined to those with an intermodal connection. Those studies purely on shipping network design, routing and scheduling are excluded since they are outside the study focus of port hinterland intermodal development. The merit of this focus is to advance our understanding on the methodological aspect of the research topic. The study will also be able to provide a consistent and in-depth comparison among the research papers. Thus, those studies only with qualitative analysis are not covered in the comparison. Within this scope of intermodal container optimisation with green

concerns which will provide policy implications for integrative port hinterland development, some related keywords and strings are identified, such as: "container network optimisation", "intermodal container flow optimisation", and "green supply chain". A search was conducted by specifying these keywords and strings which appear in both the abstract and the paper's main body using library databases (e.g. Web of Science, Science Direct, SciVerse Scopus and IEEE Xplore). This search method allows us to cover the major established international journals and conference papers in logistics and transportation, as well as management science and operations management, including *Operations Research*, *European Journal of Operational Research*, *Annals of Operations Research*, *OR Spectrum*, *Transportation Research* (Parts A,B,D,E), *Transportation Science*, *Journal of Transport Geography*, *Maritime Policy & Management*, *Maritime Economics & Logistics*, *Decision Support Systems*, and other relevant journals. From these comprehensive sources, forty-nine most relevant journal articles and one conference paper about intermodal container flow optimisation problems have been selected and thoroughly examined. These span forty years in chronological order from 1972 to 2012.

After reviewing the fifty research contributions, these papers were differentiated and categorised in a summary table (Table 2.2) based on eleven different elements, namely "Empty Container", "Laden Container", "Sea Leg in Sea-Land Intermodal (SI)", "Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)", "Green Concern", "Geographical Area of Case Study", "Model", "Model Classification (stochastic/dynamic (A) or deterministic/static (B))", "Objective", "Algorithm" and "Algorithm Classification". Explanations of these classification labels are as follows: (1) "Empty Container" and "Laden Container" classify these fifty papers into groups, only with empty container optimisation, only with laden container optimisation, or concerning both; (2) Same as above, "Sea Leg in Sea-Land Intermodal (SI)" and "Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)" classify them into groups from the perspective of intermodal transport. Due to the scope of this review, all papers selected should be intermodal in nature. It can be determined whether sea- or land-based intermodal transport is

more researched; (3) “Green Concern” highlights the papers with environmental efforts to reduce carbon footprint generated by container transport; (4) “Geographical Area of Case Study” illustrates the territories of case study, from which one can be informed as to which areas have received more attention; (5) “Model”, “Model Classification (stochastic/dynamic(A) or deterministic/static(B))”, “Objective”, “Algorithm” and “Algorithm Classification” classify these papers clearly according to mathematical model used, model classification, objective in the optimisation model, algorithm to solve the model and the algorithm’s classification, respectively.

These eleven classification elements are selected in order to illustrate the content and methodology of the articles comprehensively. The fifty papers followed the same structure with three components: "Problem Definition", "Problem Solving" and "Numerical Example". Each component can be categorised by certain classification elements. "Problem Definition" can be classified by the elements of “Empty Container”, “Laden Container”, “Sea Leg in Sea-Land Intermodal (SI)”, “Land Leg in Sea-Land Intermodal (LI) or only Land Leg and Port Related (LP)”, and “Green Concern”. The "Problem Solving" component can be sorted by the elements: “Model”, “Model Classification (stochastic/dynamic (A) or deterministic/static (B))”, “Objective”, “Algorithm” and “Algorithm Classification”. "Numerical Example" uses different regions for case studies and hence it is labelled with “Geographical Area of Case Study”.

2.5.2 Analysis for identifying research trends and gaps and directions for research

This subsection presents a comprehensive table (Table 2.2), in which the selected fifty research contributions are summarised and classified. The papers are listed in chronological order, indicating the evolution of intermodal container flow optimisation research over time. Each paper is documented in detail in this review which serves as an informative guide for researchers and practitioners interested in this area. Afterwards, five sub-tables (Table 2.3 to Table 2.7) are formulated to

assist in analysing Table 2.2 thoroughly in terms of different perspectives.

Table 2.2 Summary and classification of literature on intermodal container transportation

Paper	Empty Container	Laden Container	Sea Leg in Sea-Land Intermodal (SI)	Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)	Green Concern	Geographical Area of Case Study	Model	Model Classification (stochastic/dynamic(A) or deterministic/static(B))	Objective	Algorithm	Algorithm Classification
1,(White, 1972)	Yes	No	SI	LI	No	Not specified	Linear programming (single commodity)	A	Min cost	Inductive "Out-of-Kilter" algorithm	Exact algorithm
2,(Min, 1991)	No	Yes	SI	LI	No	Not specified	Chance-Constrained goal programming model	A	Min cost+ Max on-time service	Not specified	*
3,(Crainic et al., 1993)	Yes	No	No	LP	No	Not specified	Linear programming (1)deterministic single commodity model (2)deterministic multicommodity model (3)two stage stochastic single commodity model	A	Min cost	Not specified	*
4,(Crainic et al., 1993)	Yes	Yes	No	LP	No	Not specified	Mixed integer linear programming (multicommodity)	B	Min cost	Tabu Search	Metaheuristics
5,(Lai et al., 1995)	Yes	Yes	SI	LI	No	Ship routes from Europe to Far East	Simulation model	A	Min cost with safety stocks	Heuristic search	Classical heuristics
6,(Shen and Khoong, 1995)	Yes	No	No	LP	No	Not specified	Simulation model	A	Min cost	Constraint relaxation	Classical heuristics
7,(Miller et al., 1996)	No	Yes	No	LP	No	North America	Mixed integer linear programming	B	Min cost	Not specified	*
8,(Newman and Yano, 2000)	No	Yes	No	LP	No	Not specified	Integer linear programming	B	Min cost	decomposition procedure	Classical heuristics
9,(Cullina ne et al., 2002)	No	Yes	No	LP	No	Mainland China	Linear programming	B	Min cost + Min time	Pareto optimal	Exact algorithm
10,(Choo ng et al., 2002)	Yes	No	No	LP	Yes	Mississippi River basin (USA)	Integer linear programming	B	Min cost	Not specified	*
11,(Janse n et al., 2004)	Yes	Yes	No	LP	No	Netherlands	Simulation model	A	Min cost	Not specified	*
12,(Kari mi et al., 2005)	Yes	Yes	SI	LI	Yes	Not specified (tank container)	Linear programming	B	Min-cost	Two step, Event-Based, Demand-Driven, Deterministic methodology	Exact algorithm

Chapter 2 Literature Review

Paper	Empty Container	Laden Container	Sea Leg in Sea-Land Intermodal (SI)	Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)	Green Concern	Geographical Area of Case Study	Model	Model Classification (stochastic/dynamic(A) or deterministic/static(B))	Objective	Algorithm	Algorithm Classification
13,(Parola and Sciomachen, 2005)	No	Yes	No	LP	No	Italy	Simulation model	A	Scenario capacity comparison analysis	Not specified	*
14,(Erera et al., 2005)	Yes	Yes	SI	LI	Yes	Not specified (tank container)	Integer linear programming + Time-Discredited	B	Min cost	Not specified	*
15,(Olivo et al., 2005)	Yes	No	No	LP	No	Mediterranean basin	Integer linear programming	A	Min cost	linearisation technique	*
16,(Cheang and Lim, 2005)	Yes	No	No	LP	No	Singapore	Simulation model	A	Min cost	Not specified	*
17,(Jula et al., 2005)	No	Yes	No	LP	No	Not specified	Linear programming	B	Min cost	(1)two phase dynamic programming(DP) (2)hybrid the DP with GA (3)heuristic	Exact algorithm+ Metaheuristics + Classical heuristic
18,(Coslovich et al., 2006)	Yes	Yes	No	LP	No	Italy	Integer linear programming	A	Min cost	Lagrangian relaxation+ Decomposition method	Classical heuristics
19,(Jula et al., 2006)	Yes	No	No	LP	Yes	USA	Integer linear programming	A	Min cost	Two dynamic optimisation strategies	Exact algorithm
20,(Imai et al., 2007)	No	Yes	No	LP	No	Not specified	Linear programming	B	Min cost	Lagrangian relaxation	Classical heuristics
21,(Wang and Wang, 2007)	Yes	No	SI	LI	No	Not specified	Integer linear programming	B	Min cost	Not specified	*
22,(Deidda et al., 2008)	Yes	Yes	No	LP	Yes	Not specified	Integer linear programming	B	Min cost	Not specified	*
23,(Rahimi et al., 2008)	No	Yes	No	LP	Yes	USA	Truck VMT(vehicle-miles travelled) model to reduce the truck miles	B	Min truck distance+ Min cost	Pure calculation	Exact algorithm
24,(Feng and Chang, 2008)	Yes	Yes	SI	LI	No	Intra-Asian (Taiwan shipping company)	First stage (safety stock)+ Second stage(linear programming)	B	Min cost	Not specified	*

Chapter 2 Literature Review

Paper	Empty Container	Laden Container	Sea Leg in Sea-Land Intermodal (SI)	Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)	Green Concern	Geographical Area of Case Study	Model	Model Classification (stochastic/dynamic(A) or deterministic/static(B))	Objective	Algorithm	Algorithm Classification
25,(Chang et al., 2008)	Yes	No	No	LP	No	USA	Mixed Integer linear programming+ Container substitution (multicommodity)	B	Min cost	Decomposing problem into independent and dependent(heuristic and branch-and-bound are used separately)	Classical heuristics+ Exact algorithm
26,(Kim et al., 2008)	No	Yes	SI	LI	No	Korea	Integer linear programming	B	Min cost	Not specified	*
27,(Leachman, 2008)	No	Yes	SI	LI	No	From Asia to USA	Special model concerning the safety stock	B	Min cost	Pure calculation	*
28,(Caris and Janssens, 2009)	No	Yes	No	LP	No	Not specified	Mixed Integer linear programming	B	Min cost	Two phase local search in three neighbourhoods	Metaheuristics
29,(Sun et al., 2009) (conference paper)	Yes	No	No	LP	No	Mainland China	Mixed Integer linear programming + Price with Quantity-Discount inventory model	B	Min cost	Dynamic programming	Exact algorithm
30,(Bandeira et al., 2009)	Yes	Yes	No	LP	No	Not specified	Mixed integer linear programming	A	Min cost	Decomposing problem into static model and dynamic model	Simulation based on heuristics
31,(Imai et al., 2009)	Yes	Yes	SI	LI	No	Asia-Europe and Asia-North America lanes	Mixed integer linear programming	B	Min cost	Comparing Multi-Port and Hub-and-Spoke with Genetic Algorithm	Metaheuristics
32,(Liao et al., 2009)	No	Yes	SI	LI	Yes	Taiwan	Linear programming	B	Min CO2 emission	Simple calculation comparison	Exact algorithm
33,(Francesco et al., 2009)	Yes	No	Yes	LP	No	Mediterranean region	Integer linear programming	B+A	Min cost	Multi-Scenario policies+ Stochastic Simulation	Simulation
34,(Infante et al., 2009)	No	Yes	SI	LI	No	Not specified	Linear programming	B	Min cost	Three phase heuristic algorithm	Classical heuristics
35,(Chen and Yang, 2010)	No	Yes	No	LP	No	Mainland China	Non-linear programming	B	Min cost	Genetic Algorithms	Metaheuristics
36,(Fan et al., 2010)	No	Yes	SI	LI	No	Europe	Linear programming	B	Min cost	Not specified	*
37,(Lannone and Thore, 2010)	Yes	Yes	No	LP	No	Southern Italy	Deterministic linear programming (multicommodity)	B	Min cost	Not specified	*

Chapter 2 Literature Review

Paper	Empty Container	Laden Container	Sea Leg in Sea-Land Intermodal (SI)	Land Leg in Sea-Land Intermodal (LI) or Land Leg and Port Related (LP)	Green Concern	Geographical Area of Case Study	Model	Model Classification (stochastic/dynamic(A) or deterministic/static(B))	Objective	Algorithm	Algorithm Classification
38,(Thill and Lim, 2010)	No	Yes	No	LP	No	USA	GIS-Based mapping	B	Min cost	Accessibility analysis	*
39,(Fan et al., 2010)	No	Yes	SI	LI	No	USA	Linear programming	B	Min cost	Not specified	*
40,(Zhang et al., 2010)	Yes	Yes	No	LP	No	Not specified	Linear programming	B	Min time	Window-Partition Based(WPB)method(heuristic) is better than Tabu Search (Metaheuristics)	Classic heuristics + Metaheuristics
41,(Shintani et al., 2010)	Yes	No	No	LP	Yes	Europe (foldable container)	Integer linear programming	B	Min cost	Not specified	*
42,(Jula and Leachman, 2011)	No	Yes	SI	LI	No	From Asia to USA	Mixed integer non-linear programming(long run); mixed integer non-linear programming model+Queuing model(short run)	B	Min cost	Heuristics	Classical heuristics
43,(Jula and Leachman, 2011)	No	Yes	SI	LI	No	From Asia to USA	Mixed integer non-linear programming	B	Min cost	Comparing heuristics to commercial solver and heuristics is better.	Classical heuristics
44,(Meng and Wang, 2011)	No	Yes	SI	LI	No	Mainland China	Mixed integer non-linear programming	B	Min cost	Hybrid Genetic Algorithm	Metaheuristics
45,(Wang and Yun, 2011)	Yes	Yes	No	LP	No	Not specified	Mixed integer linear programming	B	Min cost	A Hybrid Tabu Search	Metaheuristics
46,(Yang et al., 2011)	No	Yes	SI	LI	No	From Mainland China to India	Mixed integer linear programming (goal programming)	B	Min cost+Min transit time+Min transit time variability	Not specified	*
47,(Zhang et al., 2011)	Yes	Yes	No	LP	No	Not specified	Mixed integer linear programming	B	Min time	Tabu Search	Metaheuristics
48,(Davidson and Leachman, 2012)	No	Yes	SI	LI	No	From Asia to USA	Mixed integer non-linear programming	B	Min cost	Heuristics	Classical heuristics
49,(Iannone, 2012)	Yes	Yes	No	LP	No	Southern Italy	Deterministic linear programming (multicommodity)	B	Min cost	Not specified	*
50,(Dang et al., 2012)	Yes	No	SI	LI	No	Not specified	Simulation model	B	Min cost	Simulation-based Genetic Algorithms	Metaheuristics

Source: compiled by the author (Notes: “*” denotes no algorithm classification)

2.5.2.1 Overview of selected papers according to journal domains

By using "Logistics and Transportation", "Operations Research/Management" and "Maritime" to classify domains of these selected forty-nine journal papers as shown in Table 2.3, it can be found that the domain of "Logistics and Transportation" has the largest share of 42.9% (21 papers), which indicates that container flow optimisation issues are in accordance with the editorial objectives of journals in the logistics and transportation domain. Such research is also widely accepted by "Operations Research/Management" and other journals. This study area is contemporary and popular, receiving considerable attention from the international research community. However, there are only nine papers published in the two major maritime journals, which are *Maritime Policy & Management* and *Maritime Economics & Logistics*. The trend is rising, which can imply that more and more intermodal networks' optimisation is involving a maritime factor. The importance of integrative port hinterland intermodal development in maritime industries should map into the academic field with sufficient research findings. Hopefully, in the future, these two mainstream maritime journals will accept more articles on this issue.

Table 2.3 Classification according to journal domains

Journal Domain Classification	Journals (totally 49 journal papers)	Number (%)
Logistics and Transportation	Transportation Research Part A (1), Transportation Research Part B (1), Transportation Research Part D (1), Transportation Research Part E (12), Location Science (1), Transportation Science (1), International Journal of Transport Economics (2), Journal of Transport Geography (2).	21 (42.9%)
Operations Research/Management	Networks (1), Operations Research (1), Annals of Operations Research (1), Journal of the Operational Research Society (1), European Journal of Operational Research (3), International Journal of Production Economics (3), OR Spectrum (1), Computers & Operations Research(1).	12 (24.5%)
Maritime	Maritime Policy & Management (4), Maritime Economics & Logistics (5).	9 (18.4%)
Other Journals	Decision Support Systems (2), AIChE Journal (1), International Journal of Computer Applications in Technology (1), Journal of Transportation Systems Engineering and Information Technology(1), Journal of Marketing Channels(1), Computers &Industrial Engineering(1).	7 (14.3%)

Source: Compiled by the author

2.5.2.2 Discussion according to research problem categories

Table 2.4 is derived to help us explore the research gaps through categorising research problems and analysis perspectives. Row (1) combines "SI" and "LI" in Table 2.2, labelling as intermodal container transportation to differentiate such sea-land intermodal papers from the others. Likewise, Row (2) selects "LP" only in Table 2.2, identifying those studies on land transport related to seaports to distinguish such papers from sea-land intermodal container transportation. Row (3) integrates "Empty Container" and "Laden Container" columns in Table 2.2 to show which papers deal with the more complicated and realistic situation in optimising the flows of both laden containers and empty container repositioning. Row (4) is based on the "Green Concern" column in Table 2.2 to discover the insufficiency of environmental protection concern in container flow optimisation research. Based on the "Objective" column in Table 2.2, Row (5) summarises such papers with two or more objectives as "bi/multi-objective optimisation" scope. Finally, Row (6) joins the above five rows together to devise a research niche accordingly.

In general terms, Rows (1) to (5) in Table 2.4 classify the selected research studies from five different analysis perspectives on the research issues and Row (6) integrates these five perspectives to narrow down the research issue to "Intermodal container flow considering both empty and laden containers with green concern using bi/multi-objective optimisation" as a research gap. No previous paper is found under this classification. Hence it can be concluded that this research area is under-represented with insufficient study, which would be attributed to the problem's higher level of complexity.

Although intermodal container transportation is increasingly important in practice as discussed in the "Introduction" section, most previous papers have examined only sea-leg container transportation or only land-leg container transportation optimisation thus far. Research involving a larger span of the supply chain with both sea and land transportation optimisation is quite limited with only twenty (40%) papers among the fifty papers. The seaport, as an essential interface, links these two separate networks together to shape an international/regional intermodal container

network. In the traditional concept, a port is a node in a seaborne network while a voyage between two nodes carried out by ships is called an arc in such a network (Imai and Rivera, 2001). Under this background, academic researchers focus on container network optimisation issues in sailing voyages. Next, a brief review is conducted on a series of representative research articles related to liner shipping. As early as 1988, Rana and Vickson formulated a model for a single ship route design which can help to decide whether a container ship should be chartered or not (Rana and Vickson, 1988). Three years later, they extended their model to the multiple-ship route design problem which is closer and more relative to industry (Rana and Vickson, 1991). Later on, with increasing empty containers, the empty container repositioning problem attracted a lot of scholars' attention. Many scholars advanced the design of ship networks with empty container repositioning, e.g. (Shintani et al., 2007; Francesco et al., 2009; Meng and Wang, 2011). Ship network design is usually treated as tactical-level planning. However, shipping lines require not only tactical planning, but also operational planning, for example container routing. Actual operational planning is their daily work and such planning is also very important. Hence, some papers propose models that combine these two levels together in their planning (Agarwal and Ergun, 2008; Wang and Meng, 2012). Some papers focus on strategic planning, such as fleet deployment (Dong and Song, 2009; Wang and Meng, 2012). Bunker consumption of a ship is normally proportional to the third power of its sailing speed, thus research on ship sailing speed optimisation is important (Fagerholt et al., 2010). Such sailing speed optimisation can greatly help reduce the total cost of shipping lines as well as total GHG emissions in maritime transport (Fagerholt et al., 2010; Wang and Meng, 2012). However, maritime transport is usually only one of the legs in the global intermodal network. Very little effort has been made to study the global intermodal network as a whole. Meanwhile, a port is obliged to enter the new stage of regionalisation which is driven by market demand. Integrative intermodal transportation and port regionalisation development conform to market demand, thus more effort should be made to tackle such sea-land intermodal optimisation issues.

In recent years, previous research articles which concern environmental protection are still relatively limited, although progressively increasing. There are only eight

papers (16%) classified into the "With green concern" category with the aim to cut down carbon footprint. Research involves using greener modes of transportation like inland barge connections and innovative solutions such as double-stack trains and utilisation of foldable containers. Future research about intermodal container flow optimisation issues should be embedded with green concern to keep pace with the times and regulatory requirements to protect our planet. Noting this imminent trend, those ports and transport providers which can be both commercially viable and environmentally responsible would gain a competitive edge.

Table 2.4 Classification according to research problem categories

Research problem categories	Papers (totally selected 50 papers)	Number (%)
(1) Concerning intermodal freight transportation (both sea leg(SI) and land leg(LI))	1,(White, 1972), 2,(Min, 1991), 5,(Lai et al., 1995), 12,(Karimi et al., 2005), 14,(Erera et al., 2005), 21,(Wang and Wang, 2007), 24,(Feng and Chang, 2008), 26,(Kim et al., 2008), 27,(Leachman, 2008), 31,(Imai et al., 2009), 32,(Liao et al., 2009), 34,(Infante et al., 2009), 36,(Fan et al., 2010), 39,(Fan et al., 2010), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 44,(Meng and Wang, 2011), 46,(Yang et al., 2011), 48,(Davidson and Leachman, 2012), 50,(Dang et al., 2012)	20(40%)
(2) Concerning land leg and port related(LP)	3,(Crainic et al., 1993), 4,(Crainic et al., 1993), 6,(Shen and Khoong, 1995), 7,(Miller et al., 1996), 8,(Newman and Yano, 2000), 9,(Cullinane et al., 2002), 10,(Choong et al., 2002), 11,(Jansen et al., 2004), 13,(Parola and Sciomachen, 2005), 15,(Olivo et al., 2005), 16,(Cheang and Lim, 2005), 17,(Jula et al., 2005), 18,(Coslovich et al., 2006), 19,(Jula et al., 2006), 20,(Imai et al., 2007), 22,(Deidda et al., 2008), 23,(Rahimi et al., 2008), 25,(Chang et al., 2008), 28,(Caris and Janssens, 2009), 29,(Sun et al., 2009) (conference paper), 30,(Bandeira et al., 2009), 33,(Francesco et al., 2009), 35,(Chen and Yang, 2010), 37,(Iannone and Thore, 2010), 38,(Thill and Lim, 2010), 40,(Zhang et al., 2010), 41,(Shintani et al., 2010), 45,(Wang and Yun, 2011), 47,(Zhang et al., 2011), 49,(Iannone, 2012)	30(60%)
(3) Concerning both empty and laden container transportation	4,(Crainic et al., 1993), 5,(Lai et al., 1995), 11,(Jansen et al., 2004), 12,(Karimi et al., 2005), 14,(Erera et al., 2005), 18,(Coslovich et al., 2006), 22,(Deidda et al., 2008), 24,(Feng and Chang, 2008), 30,(Bandeira et al., 2009), 31,(Imai et al., 2009), 37,(Iannone and Thore, 2010), 40,(Zhang et al., 2010), 45,(Wang and Yun, 2011), 47,(Zhang et al., 2011), 49,(Iannone, 2012)	15(30%)
(4) With green concern	10,(Choong et al., 2002), 12,(Karimi et al., 2005), 14,(Erera et al., 2005), 19,(Jula et al., 2006), 22,(Deidda et al., 2008), 23,(Rahimi et al., 2008), 32,(Liao et al., 2009), 41,(Shintani et al., 2010)	8(16%)
(5) Bi/Multi-objective optimisation	2,(Min, 1991), 9,(Cullinane et al., 2002), 23,(Rahimi et al., 2008), 46,(Yang et al., 2011)	4(8%)
(6) Intermodal container flow considering both empty and laden containers with green concern using bi/multi-objective optimisation	None.	0(0%)

Source: Compiled by the author

Most previous research papers focus only on single-objective optimisation. The share of papers with bi/multi-objective optimisation is 8% (4 papers). It is observed

that most selected papers concern cost optimisation only. However, to deal with practical problems, attention should also be paid to time consumption, carbon footprint and time variation. Hence multi-objective optimisation would have wider application in upcoming optimisation models to consider trade-offs among multiple objectives. In the diversified markets of today, including merely the cost objective in the optimisation model is insufficient since some customers require a fast and on-time delivery service with less carbon footprint such as those adopting environmental policies as part of their business strategy and shippers transporting products with higher value and demand uncertainty like computers (Eng-Larsson and Kohn, 2012).

2.5.2.3 Analysis according to mathematical models

Turning to research methodology, Table 2.5 illustrates that there are three main classifications regarding the type of mathematical models in this domain, which are: linear model (35 papers or 70%), non-linear model (5 papers or 10%) and simulation model (6 papers or 12%). Under the classification of "Linear model", there are three subdivisions: linear programming (14 papers), integer linear programming (11 papers) and mixed integer linear programming (10 papers). Among them, linear programming is more popular with higher frequency of occurrence. Linear programming (LP) is a mathematical method for determining a way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model for some requirements represented as linear relationships. More formally, LP is a technique for the optimisation of a linear objective function, subject to linear equality and linear inequality constraints. If the unknown variables are all required to be integers, then the problem is called integer linear programming (ILP). If only some of the unknown variables are required to be integers, then the problem is called a mixed integer linear programming (MILP) problem. The decision to use linear programming, integer linear programming or mixed integer linear programming may depend on the scale of the problem and the authors' preferences. Generally speaking, if the variable which represents the quantity of containers has a high order, such as 1000,000, there is no significant difference between 1000,000 and 1000,000.5. Hence the decision variables about container

numbers in a large-scale problem could be fractional values. However, the nature of container quantity should be an integer value. Different authors have different preferences and designs regarding their model selection. For example, Iannone (2012) applies a linear programming model in his paper, while Shintani et al. (2010) design an integer linear programming model to fix their problem, even if the problem scales are very similar. If some papers use binary variables (0 or 1) or some papers involve both vehicle quantity (integer value) and container quantity (fractional value) in their models, mixed integer linear programming models are employed. Besides the linear model, the non-linear model and simulation model are also created to present some cases which do not have a linear relationship or have a more dynamic relationship. Which model would be applied depends on the actual problems to be solved and the authors' preferences. Together with Table 2.2, this review provides a technical reference for researchers in considering the applicability of various models.

According to another classification of the mathematical model, among the selected 50 papers, 13 papers are included in A (dynamic/stochastic) while 37 papers are counted in B (deterministic/static). The dynamic/stochastic math model is more suitable for the container flow optimisation problem because of its dynamic nature. However, dynamic/stochastic math models are often difficult to solve. This explains why a much lower percentage (26%) of studies attempted the stochastic approach.

Table 2.5 Classification according to mathematical models

Model Classification I (linear, non-linear or simulation)	Papers (totally selected 50 papers)	Number (%)
(1) Linear programming model (LP)		35(70%)
Linear programming (LP)	1,(White, 1972), 3,(Crainic et al., 1993), 9,(Cullinane et al., 2002), 12,(Karimi et al., 2005), 17,(Jula et al., 2005), 20,(Imai et al., 2007), 24,(Feng and Chang, 2008), 32,(Liao et al., 2009), 34,(Infante et al., 2009), 36,(Fan et al., 2010), 37,(Iannone and Thore, 2010), 39,(Fan et al., 2010), 40,(Zhang et al., 2010), 49,(Iannone, 2012)	14/35
Integer linear programming (ILP)	8,(Newman and Yano, 2000), 10,(Choong et al., 2002), 14,(Erera et al., 2005), 15,(Olivo et al., 2005), 18,(Coslovich et al., 2006), 19,(Jula et al., 2006), 21,(Wang and Wang, 2007), 22,(Deidda et al., 2008), 26,(Kim et al., 2008), 33,(Francesco et al., 2009), 41,(Shintani et al., 2010)	11/35

Model Classification I (linear, non-linear or simulation)	Papers (totally selected 50 papers)	Number (%)
Mixed integer linear programming (MILP)	4,(Crainic et al., 1993), 7,(Miller et al., 1996), 25,(Chang et al., 2008), 28,(Caris and Janssens, 2009), 29,(Sun et al., 2009)(conference paper), 30,(Bandeira et al., 2009), 31,(Imai et al., 2009), 45,(Wang and Yun, 2011), 46,(Yang et al., 2011), 47,(Zhang et al., 2011)	10/35
(2) Non-linear programming model (NLP)	35,(Chen and Yang, 2010), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 44,(Meng and Wang, 2011), 48,(Davidson and Leachman, 2012)	5(10%)
(3) Simulation model	5,(Lai et al., 1995), 6,(Shen and Khoong, 1995), 11,(Jansen et al., 2004), 13,(Parola and Sciomachen, 2005), 16,(Cheang and Lim, 2005), 50,(Dang et al., 2012)	6(12%)
(4) Other models	2,(Min, 1991), 23,(Rahimi et al., 2008), 27,(Leachman, 2008), 38,(Thill and Lim, 2010)	4(8%)
Model Classification II (dynamic/stochastic or deterministic/static)	Papers (totally selected 50 papers)	Number (%)
dynamic/stochastic(A) model	1,(White, 1972), 2,(Min, 1991), 3,(Crainic et al., 1993), 5,(Lai et al., 1995), 6,(Shen and Khoong, 1995), 11,(Jansen et al., 2004), 13,(Parola and Sciomachen, 2005), 15,(Olivo et al., 2005), 16,(Cheang and Lim, 2005), 18,(Coslovich et al., 2006), 19,(Jula et al., 2006), 30,(Bandeira et al., 2009), 33,(Francesco et al., 2009)	13(26%)
deterministic/static(B) model	4,(Crainic et al., 1993), 7,(Miller et al., 1996), 8,(Newman and Yano, 2000), 9,(Cullinane et al., 2002), 10,(Choong et al., 2002), 12,(Karimi et al., 2005), 14,(Erera et al., 2005), 17,(Jula et al., 2005), 20,(Imai et al., 2007), 21,(Wang and Wang, 2007), 22,(Deidda et al., 2008), 23,(Rahimi et al., 2008), 24,(Feng and Chang, 2008), 25,(Chang et al., 2008), 26,(Kim et al., 2008), 27,(Leachman, 2008), 28,(Caris and Janssens, 2009), 29,(Sun et al., 2009)(conference paper), 31,(Imai et al., 2009), 32,(Liao et al., 2009), 33,(Francesco et al., 2009), 34,(Infante et al., 2009), 35,(Chen and Yang, 2010), 36,(Fan et al., 2010), 37,(Iannone and Thore, 2010), 38,(Thill and Lim, 2010), 39,(Fan et al., 2010), 40,(Zhang et al., 2010), 41,(Shintani et al., 2010), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 44,(Meng and Wang, 2011), 45,(Wang and Yun, 2011), 46,(Yang et al., 2011), 47,(Zhang et al., 2011), 48,(Davidson and Leachman, 2012), 49,(Iannone, 2012), 50,(Dang et al., 2012)	37(74%)

Source: Compiled by the author

2.5.2.4 Analysis according to algorithms

After analysing the type of mathematical models, which algorithm would be proposed and used to solve the model is addressed in Table 2.6. Exact algorithms are usually proposed to solve instances involving limited variables and power degree (vertices). But in some real cases, when the size of vertices exceeds the limitation, heuristics algorithms would be the preferred algorithms to be utilised especially with Metaheuristics' recent powerful and speedy development. The simulation method is used in such cases as a last resort when an exact algorithm or heuristic algorithm is not applicable to get the optimal solution or near-optimal solutions especially in some stochastic problems. But the simulation method cannot

find an optimal solution and is not inherently an optimisation tool. It is often the only means to approach complex systems analysis.

Here, the difference between “Classical Heuristics” and “Metaheuristics” may be highlighted. “Classical Heuristics” does not have any mechanisms to allow the objective function changing from one iteration to the next iteration while “Metaheuristics”, on the contrary, offers these mechanisms. The Metaheuristic algorithm is a heuristic method to solve computation problems using black-box procedures in a more efficient way. Metaheuristic algorithms are used for combinatorial optimisation in which an optimal solution or a near-optimal solution is sought over a discrete search-space. Popular and common Metaheuristic algorithms for combinatorial optimisation problems include Simulated Annealing, Tabu Search, Genetic Algorithms and Ant Colony Optimisation (Caserta and Voß, 2010).

From the algorithm classifications in Table 2.6, there is no conclusion suggesting which algorithm is more prevalent than others. Which algorithm would be approached depends on the scale and difficulty level of the given math model. If the scale of the given math model is not so large, it can be solved through designing an exact algorithm to get the optimal solution. Although an exact algorithm can only solve some relatively small-scale instances, many papers prefer to create some sophisticated exact algorithms to increase the difficulties and contributions of their research articles. From their standpoint, an exact algorithm is more highly challenging in a mathematical sense. When the scale of the given math model is large and it is difficult or impossible to use an exact algorithm, then a heuristics algorithm would be suitable to search the near-optimal solution instead. Recently, Metaheuristics has a rapid practical development and attracts more attention than classical heuristics because of its computational effectiveness and general applicability. In other words, unlike classical heuristics, Metaheuristics requires much less work than developing a specialised heuristic for a specific problem. Metaheuristics has its standard mechanisms to guide the search from an initial solution set to near-optimal solutions. Many problems can implement

Metaheuristics via using general-purpose software. But it also means that the user must understand and specify its complicated mechanisms.

Three papers (6%) use more than two classes of algorithms in their papers to solve or compare the solutions. Researchers can consider this approach if the problem is complex and achieving optimal results is their primary aim. Adopting a hybrid approach has become more popular in recent years and is a rising trend since multi-objective optimisation and tackling larger-scale practical problems as discussed above would increase the level of complexity.

Twenty-one (42%) papers do not specify algorithms which is the most common approach. They use commercial software, for example, CPLEX and LINGO revealing such softwares' good performance in linear optimisation. Problem-solving methods benefit from the development of computer technology. Much optimisation software is updated and embedded with some common algorithms becoming powerful optimisation platforms. This is not a bad phenomenon. Such optimisation platforms can assist scholars using their models to optimise practical problem instances easily and efficiently.

Table 2.6 Classification according to algorithms

Algorithm Classification	Papers (totally selected 50 papers)	Number (%)
Exact algorithm	1,(White, 1972), 9,(Cullinane et al., 2002), 12,(Karimi et al., 2005), 19,(Jula et al., 2006), 23,(Rahimi et al., 2008), 29,(Sun et al., 2009) (conference paper), 32,(Liao et al., 2009)	7(14%)
Classical heuristics	5,(Lai et al., 1995), 6,(Shen and Khoong, 1995), 8,(Newman and Yano, 2000), 18,(Coslovich et al., 2006), 20,(Imai et al., 2007), 34,(Infante et al., 2009), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 48,(Davidson and Leachman, 2012)	9(18%)
Metaheuristics	4,(Crainic et al., 1993), 28,(Caris and Janssens, 2009), 31,(Imai et al., 2009), 35,(Chen and Yang, 2010), 44,(Meng and Wang, 2011), 45,(Wang and Yun, 2011), 47,(Zhang et al., 2011), 50,(Dang et al., 2012)	8(16%)
Simulation	30,(Bandeira et al., 2009), 33,(Francesco et al., 2009)	2(4%)
No specified algorithm just using commercial software	2,(Min, 1991), 3,(Crainic et al., 1993), 7,(Miller et al., 1996), 10,(Choong et al., 2002), 11,(Jansen et al., 2004), 13,(Parola and Sciomachen, 2005), 14,(Erera et al., 2005), 15,(Olivo et al., 2005), 16,(Cheang and Lim, 2005), 21,(Wang and Wang, 2007), 22,(Deidda et al., 2008), 24,(Feng and Chang, 2008), 26,(Kim et al., 2008), 27,(Leachman, 2008), 36,(Fan et al., 2010), 37,(Iannone and Thore, 2010), 38,(Thill and Lim, 2010), 39,(Fan et al., 2010), 41,(Shintani et al., 2010), 46,(Yang et al., 2011), 49,(Iannone, 2012)	21(42%)

Algorithm Classification	Papers (totally selected 50 papers)	Number (%)
With more than two algorithm classes	17,(Jula et al., 2005), 25,(Chang et al., 2008), 40,(Zhang et al., 2010)	3(6%)

Source: Compiled by the author

2.5.2.5 Discussion according to case study areas

Table 2.7 is formulated to analyse the geographical locations of case studies in the selected papers. It is found that case studies centred around three major areas, namely Asia, the USA and Europe. Major ports and maritime countries are located in these areas. It implies that research interest is driven by the demand for practical application.

To conduct a more thorough analysis, each area is classified into countries and sub-regions. Although Mainland China and Taiwan are considered parts of one China, they are differentiated in this literature review because they have their own administrative independencies. Among the Asian countries and sub-regions, Mainland China might be a relatively popular sub-region in such optimisation issues, with five publications. It is not surprising that the world economy is affected by the “China effect”. Many foreign corporations have relocated their production and distribution networks to Mainland China. The volume of intermodal freight movement in Mainland China has increased dramatically in recent years and would maintain a high growth rate in the following years. There is great potential in China's distribution and logistics development (Frankel, 1998; Jiang and Prater, 2002; Lam and Yap, 2011). However, among these fifty selected papers, there are only five research contributions using Mainland China as a case study area to test the container flow optimisation model and algorithm. There is also a pressing need for more research to be conducted for another fast growing country — India. An integrated intermodal transportation network which translates to high quality management of cargo flows with low inventory costs, more reliable delivery time and distribution will enhance Indian merchandises’ competitiveness within the global market (Ng and Gujar, 2009). Only one container flow optimisation study

has been done in India's case, thus presenting great potential for future research.

Concerning North America, the USA is the most researched country (ten papers out of twelve papers in total). The USA is a major trading nation with a long coastline and extensive land-bridge transportation infrastructure. Corresponding research for the USA would continue to grow with higher sophistication. It would be interesting to model the port hinterland intermodal network in consideration of the Panama Canal's upgrading work in future studies.

With respect to Europe, Italy might be the country with more case studies conducted (four papers out of eleven) into such optimisation issues. There are many countries, each with only a small territory, in the European continent. Six out of the eleven papers conducted case studies on container network optimisation relating to a large range of the European area, not to an individual country owing to the territory limitation. Since the European ports' hinterland involves more than one country in most cases, researching intermodal networks with multiple countries aligns with such a practical situation. This approach is also recommended for other regions with active or growing cross-border intermodal transport, for example, between China and the Southeast Asian peninsula including countries like Vietnam and Thailand.

Table 2.7 Classification according to case study areas

Case Study Area	Papers (totally selected 50 papers)	Number (%)
(1) Asia		16(32%)
Mainland China	9,(Cullinane et al., 2002), 29,(Sun et al., 2009)(conference paper), 35,(Chen and Yang, 2010), 44,(Meng and Wang, 2011), 46,(Yang et al., 2011)	5/16
Taiwan	32,(Liao et al., 2009)	1/16
India	46,(Yang et al., 2011)	1/16
Singapore	16,(Cheang and Lim, 2005)	1/16
Korea	26,(Kim et al., 2008)	1/16

Case Study Area	Papers (totally selected 50 papers)	Number (%)
No specified country or sub-region just Asian area	5,(Lai et al., 1995), 24,(Feng and Chang, 2008), 27,(Leachman, 2008), 31,(Imai et al., 2009), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 48,(Davidson and Leachman, 2012)	7/16
(2) North America		12(24%)
USA	10,(Choong et al., 2002), 19,(Jula et al., 2006), 23,(Rahimi et al., 2008), 25,(Chang et al., 2008), 27,(Leachman, 2008), 38,(Thill and Lim, 2010), 39,(Fan et al., 2010), 42,(Jula and Leachman, 2011), 43,(Jula and Leachman, 2011), 48,(Davidson and Leachman, 2012)	10/12
No specified country just North America area	7,(Miller et al., 1996), 31,(Imai et al., 2009)	2/12
(3) Europe		11(22%)
Netherlands	11,(Jansen et al., 2004)	1/11
Italy	13,(Parola and Sciomachen, 2005), 18,(Coslovich et al., 2006), 37,(Iannone and Thore, 2010), 49,(Iannone, 2012)	4/11
No specified country just European area	5,(Lai et al., 1995), 15,(Olivo et al., 2005), 31,(Imai et al., 2009), 33,(Francesco et al., 2009), 36,(Fan et al., 2010), 41,(Shintani et al., 2010)	6/11
(4) No specified area	1,(White, 1972), 2,(Min, 1991), 3,(Crainic et al., 1993), 4,(Crainic et al., 1993), 6,(Shen and Khoong, 1995), 8,(Newman and Yano, 2000), 12,(Karimi et al., 2005), 14,(Erera et al., 2005), 17,(Jula et al., 2005), 20,(Imai et al., 2007), 21,(Wang and Wang, 2007), 22,(Deidda et al., 2008), 28,(Caris and Janssens, 2009), 30,(Bandeira et al., 2009), 34,(Infante et al., 2009), 40,(Zhang et al., 2010), 45,(Wang and Yun, 2011), 47,(Zhang et al., 2011), 50,(Dang et al., 2012)	19(38%)

Source: Compiled by the author

2.5.2.6 Further discussion on green concerns

When Tables 2.4 and Table 2.7 are analysed together, among the scant literature (eight papers) with environmental concerns, three studied the case of the USA, one studied Europe and one was about Taiwan. The other three did not specify any region. There is no study into the two fast-growing economic giants – China and India. As discussed above, more research should be devoted to studying intermodal development in these two countries. China and India's speedy economic growth, huge potential demands for consumption and ever-rising pressure from global production and distribution have all granted strong support for the development of their transportation and logistics industries, including port intermodal development due to their wide hinterland ranges. Nevertheless, pollution would also be increased with such rapid growth in economic development and transport volume. Intermodal

development offers great potential to improve sustainability, because railway and inland barge transport incurs much lower carbon emissions than trucking which is at present dominant in inland transport (Rahimi et al., 2008; Liao et al., 2009; Shintani et al., 2010).

In addition to the suggestions in the previous subsections, more scientific research is recommended to be conducted on sustainable port hinterland intermodal development in order to fulfil industry needs. In particular, the identified research gap "Intermodal container flow considering both empty and laden containers with green concern using multi-objective optimisation" can be explored for China, India and other countries especially those with a large hinterland area. For example, given the closer scrutiny on the environmental performance of the transport sector, the optimisation model can be developed to consider the various carbon footprint restriction scenarios for the planning of intermodal container flows. Such a model can achieve optimal cost and transit time given a certain level of carbon emission requirement suggesting the most desirable modal split. Sensitivity analysis can be done to find out the effect on cost and time with tighter carbon emission control. To plan intermodal development and monitor its environmental impact, the change in carbon emission generated by the transport network can also be modelled in relation to infrastructure expansion and cargo volume growth. There is no research effort that has been made in these topics so far according to the published research papers. It would be meaningful and beneficial if future studies can fill this research gap to address the challenges for various countries' port hinterland development.

Nowadays there exist three key approaches taken by governments around the world to reduce carbon emissions: carbon tax, carbon emission trading and direct restriction (ABC News in Australia, 2011). Let us briefly review the existing literature about these three schemes. There is much discussion about whether carbon tax or carbon emission trading is the best way to cut down carbon emissions, and whether the public will accept an additional price on carbon emission. Ekins and Barker (2001) have conducted a comprehensive survey of the literature which was available at that time as early as 2001, and they conclude that more and more countries would introduce carbon tax and a carbon emission trading scheme due to

increasing environmental concerns. Bristow et al. (2010) designed another survey using the stated preference method to test public acceptability for the two schemes: carbon tax and carbon emission trading. Their results show that there is no unique preference for carbon emission trading relative to carbon tax since it will depend upon the features of the scheme. A key result of their research is that both carbon emission trading and carbon tax can be politically acceptable. Wadud (2011) holds a different opinion in that a carbon emission trading scheme is potentially more acceptable to the public than carbon tax as the former can allow more flexibility, and therefore be potentially more cost efficient. However, Wadud (2011) also recognises that one significant drawback of carbon emission trading is the initial administration and monitoring cost which will adversely affect its cost-efficiency advantage. Wadud (2011) uses a comprehensive method to evaluate the carbon emission trading scheme with respect to cost efficiency, effectiveness, equity and few other criteria and compare it with other policies (e.g. carbon tax). It is worth mentioning that cost efficiency is the competency in performance to accomplish with a minimum cost, while cost effectiveness means how well the goal (cost reduction) gets done. In other words, cost efficiency refers to the quantity of cost reduction, while cost effectiveness refers to the quality of cost reduction. In another paper, Vespermann and Wald (2011) aimed to quantitatively analyse the economic and ecological impacts on the aviation industry in Europe by inclusion of a carbon emission trading scheme. They conclude that while the whole system will reveal both its economic and ecological effects in the long term, the current situation is not ideal. The current system design will not evoke a substantial reduction of carbon emissions in the aviation industry, and carbon emission reduction can only be reached by a more restrictive system design. The first two schemes use economic instruments to limit carbon emission, then the third scheme uses political means to impose direct restrictions on carbon emission. Under a direct restriction scheme, if a company's carbon emissions exceed the government's restriction, the government reserves the right to shut down the company. The third scheme, "direct restriction", has rarely been discussed in academic circles when compared to the first two schemes. However, there is no scientific literature on transport planning or transportation optimisation which concerns these three schemes together until now.

This represents another research gap.

2.5.3 Research gaps and directions in this study

In this original and specific literature review, a total of fifty earlier research articles on intermodal container flow optimisation issues which were published between 1972 and 2012 with a forty-year time span are selected and examined. The contributions are twofold: firstly, an overall summary table (Table 2.2) is built on and relevant sub-tables (from Table 2.3 to Table 2.7) provide a structured and classified review and insightful analysis on the growing and contemporary subject of container transport optimisation; secondly, through such tables and detailed analyses from various perspectives, the trends and gaps in this research area are identified and future research directions are suggested accordingly, thereby assisting scientific and practical efforts in port hinterland intermodal development.

Future research should focus on global intermodal container flow optimisation, involving both laden containers and empty containers, taking green issues into account and addressing the approaches of port integration into such a global intermodal chain. Research concerning environmental impacts is progressively increasing but inadequate. There is substantial need for research addressing greening the intermodal network and sustainable development. The three key environmental protection schemes (carbon tax, carbon emission trading and direct restriction) should be taken into consideration in future transport planning studies. It can be discovered that providing cost-effective solutions alone in the optimisation problem is rather traditional and one-sided. In practice nowadays, those market players possessing commercially viable capabilities and also environmental responsibilities would gain a competitive advantage in the future dynamic business environment. Bi- or multi-objective optimisation would be more suited to actual situations. The findings and suggestions would guide intermodal transport operators and integrators in their network design.

Relating to case study areas, the identified research gaps in this research would be explored for China, India and regions with an intermodal network involving

multiple countries. It would be beneficial if future studies can address the pressing demand for the emerging countries' port hinterland development. It would also be interesting to analyse the effects brought about by upcoming changes such as the upgrading of the Panama Canal. Optimisation and simulation models not only aid tactical and operational planning, but also intermodal infrastructure development and policy making. Through quantifying commercial and environmental impacts, more optimal intermodal transport networks can be planned and built according to the desirable economic objectives and environmental performance. Correspondingly, intermodal development will affect the industry and market players due to, for example, the number of concessions granted by the government to truckers, rail operators, barge operators and dry port operators. Such strategic decisions should be supported by analytical tools rather than by intuition only. In this literature review, observations in research methodology and algorithm classifications have also been drawn. In short, adopting a hybrid approach in combining two algorithms in one problem could be an increasing tendency since multi-objective optimisation and tackling larger-scale practical problems as discussed above would increase the level of complexity. Therefore, this literature review serves as a practical guide assisting future efforts in developing analytical tools.

As a whole, this literature review has provided a comprehensive review of earlier research contributions to a growing and contemporary subject. The insightful analyses about these sub-tables help channel future research efforts along the identified paths to be both practical and forward-looking. While endeavours were made to be all-inclusive and holistic the same as other literature review studies, some research activities and efforts might have been unconsciously neglected. However, this literature review should be a comprehensive representation of the body of research on intermodal container transport optimisation published in international outlets during the specified timespan.

Before closing this subsection, the on-going opportunity for the development of global intermodal container network approaches and related studies, including

supply chain and policy perspectives in the future, is highlighted. Issues such as the surge of port-hinterland container transportation flows in major exporting/importing countries, the shortage of corresponding infrastructure capacity and environmental concerns about the emission of greenhouse gas are up and coming. If the potential arose for someone to be the leader in supply chain integration between sea and land transportation, then the seaport could endeavour to play the leading role due to its unique status. Seaports have natural features that make them a suitable interface between the sea and the land. The port regionalisation concept gives seaports opportunities to realise the complex and dynamic integration especially focusing on container transportation flows. This integration's objective should be versatile in coping with supply chain dynamics. Multiple factors along the supply chain including economic, social and environmental aspects are very important to be considered. Trying to find and deal with the trade-offs among these multi-objectives would be paramount and can be achieved by utilising the reviewed mathematical models in future research.

Based on this specific literature review, the following chapters will be presented to fill the research gaps discovered.

Chapter 3 Research methodology

As discussed in Chapter 1, this research aims to investigate port hinterland intermodal development that addresses environmental concerns. In this chapter (Chapter 3), the methodology for systematically solving the proposed research issue will be presented. The methodology design framework is illustrated in the research flowchart in Section 3.1. Detailed explanations regarding particular components of the research flowchart are provided in this chapter. The research methodology design in Chapter 3 is based on an understanding of the research gaps in previous studies, as discussed in Chapter 2. This chapter focuses on the whole framework of the research methodology design. Hence it can be regarded as a guide to the following chapters (Chapter 4, Chapter 5 and Chapter 6).

3.1 Research design

A research design is a detailed outline of how the overall research is conducted. Figure 3.1 illustrates the major components in this thesis, which include “Introduction”, “Literature Review”, “Research Methodology”, “Qualitative Research”, “Quantitative Research” and “Conclusion”. The “Field Studies” component helps to validate the applicability of our research to a real situation.

Figure 3.1 The overall research process

In the following sections, there will be detailed explanations regarding particular components of the overall research process. Section 3.2 explains about the “Field Studies” component, while Section 3.3 explicates “Qualitative Research” and “Quantitative Research”.

3.2 Field studies

Two kinds of field studies are adopted for this research in order to link the research with a practical situation (Schatzman and Strauss, 1973). One kind of field study is interviewing industry people (Burgess, 1995), and the other kind of field study is site visit (port visit)²(Lawrenz et al., 2003). These two kinds of field studies can help to link this research with a practical situation, which will in turn facilitate the understanding of Chapter 1, Chapter 4, Chapter 5 and Chapter 6. It will do this by such means as examining research questions, collecting data and validating the models. The purpose of adopting these field studies is to make this research more practical and reliable in revealing the demands and current status of both the industry side and the government side. With the help of model verification, research validity is also enhanced.

Three in-depth interviews have been conducted in this research. We selected three

² In order to gain deeper understanding of the function and importance of port hinterland intermodal development, there is no better way than to compare ports that have little, intermediate and heavy intermodal reliance. The Port of Singapore, Port of Marseille-Fos Port (France) and Port of Guangzhou (China) each fit into our above study criteria, respectively. The author had thus made site visits to these three ports at different times for close study. They are listed as follows:

(1) 29 March 2011, Port of Singapore (Pasir Panjang Terminal, Singapore);

(2) 6 July 2013, Port of Marseille-Fos in France;

(3) 7–8 June 2013, Port of Guangzhou in southern China.

Through these visits, the author not only has gained great experiences but also collected very useful first-hand data and a better understanding of port operations. These efforts strongly assist the author in analysing the relationship between ports and hinterland in intermodal development. The author has found that intermodal development is most important for the Chinese case, because it inherits a vast hinterland and enjoys high trade volume. In comparison, although Singapore and Marseille each possess their own outstanding merits in terms of port facilities and operations, their reliance on intermodal transport is of smaller scale.

Chinese officials from different parts of China, namely: (1) the Bohai Bay region in northern China, (2) the Yangtze River Delta in the middle part of China, and (3) the Pearl River Delta in southern China. The three interviewees were selected based on their designations which are all at the director level, a minimum of 20 years' experience in their respective organisation and their involvement in port development at their respective organisation. These interviews help us to know more about China's maritime and port development strategy at both regional and national levels, such as the challenges and opportunities present. They also help to add face validity to this research.

The first interview was conducted on 10 March 2011 with Mr Wang Junguo who is from Tangshan Port in Bohai Bay. He is the Director of the Tangshan Caofeidian Industrial Zone Management Committee, and in charge of the planning of Caofeidian Port which is a subordinate unit of the bigger Tangshan Port. Mr Wang particularly pointed out that developing hinterland intermodal transport infrastructure, such as dry ports or railway links, is crucial in realising the vision of increasing the competitiveness of Chinese ports in Northeast Asia against foreign competitors.

The second interview was conducted on 22 January 2012 with Mr Wang Xiongchang. Mr Wang is the Director of the Planning Board for the "free trade zone" of Ningbo, Zhejiang Province, China. He is not only very familiar with the port industry of the Yangtze River Delta, but also the policies and long-term planning of the Chinese government. He particularly stressed that intermodal development is most important to Ningbo-Zhoushan Port because, despite its water depth advantage over Shanghai Port, more still needs to be done to overcome shortcomings in its intermodal foundations, such as improving its railway system and increasing its number of dry ports.

The third interview was carried out on 7 June 2013 with Mr Yuan Huahui, the Deputy Director of Guangzhou Port Authority. He pointed out that there is now fervent competition between Guangzhou Port, Shenzhen Port and Hong Kong Port at the Pearl River Delta. He is of the opinion that whoever possesses outstanding

intermodal advantages will come out as the winner.

3.3 Research methods

In order to achieve the objectives mentioned in Chapter 1, the research methods employed in this research include both qualitative and quantitative approaches.

3.3.1 Qualitative approach: Comparative research

Comparative research is a research methodology in the social sciences that aims to make comparisons across different countries or cultures. Comparative research is a fundamental tool of systematic analysis. It will sharpen our power of description to identify similarities and contrasts among cases (Collier, 1993). Comparisons can be applied to explore whether shared phenomena can be explained by the same causes. In this research, the comparative research method is employed in Chapter 4 to compare and address potentials and challenges in terms of intermodal development in China and India, the two fastest developing new economies in Asia, and to bridge the gap of comparing port hinterland intermodal development between these two countries for the first time.

3.3.2 Quantitative approach

In this subsection, detailed explanations are given with regard to the mathematical models and the algorithm, respectively, both of which have been applied in this research.

3.3.2.1 Linear and non-linear programming techniques

Linear programming (LP) is a mathematical method for determining a way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model for some requirements represented as linear relationships. More formally, LP is a technique for the optimisation of a linear objective function, subject to linear equality and linear inequality constraints. If the unknown variables

are all required to be integers, then the problem is called integer linear programming (ILP). In contrast to LP, which can be solved efficiently in the worst case, ILP problems are NP-hard in many practical situations such as those with bounded variables (Sierksma, 2002; Rader, 2010; Schrijver, 1986). If only some of the unknown variables are required to be integers, then the problem is called a mixed integer linear programming (MILP) problem. These are generally also NP-hard (Lodi, 2010). If some of the constraints or the objective functions are non-linear, then the problem is called non-linear programming (NLP). Many NLP problems are proved as NP-complete problems, which means the time required to solve even moderate-size problems can easily require a huge computing time (Drexl et al., 2009). The most notable characteristic of NP-complete problems is that no fast solution to them is known. NP-complete problems are often addressed by using heuristic methods and approximation algorithms. For example, some convex NLP problems can be solved through some approximation linearisation techniques (Murty and Kabadi, 1987).

In this research, an integer linear programming mathematical optimisation model is developed as the tactical level model and a mixed integer non-linear programming mathematical optimisation model is developed as the operational level model. A metaheuristics algorithm, the enhanced NSGA-II (an elitist non-dominant sorting genetic algorithm is termed as NSGA-II), is developed to solve the tactical level model. In the operational level model, the non-linear part is about sea-leg sailing speed optimisation. The approximate relationship between bunker consumption and sailing speed is the third power (convex). A linearisation technique is used to transform this part from a non-linear relationship to a linear relationship. After this linearisation transformation, the state-of-the-art commercial solver, CPLEX, is applied to solve the operational level model. Unlike the tactical level model, there is no specific algorithm developed in the operational level model. In this operational model, the decision variables about vehicle numbers should be integer values and the decision variables about container numbers could be fractional values. There is no significant difference between 1,000,000 and 1,000,000.5, because the quantity of containers has a high order, such as 1,000,000. Hence the decision variables about container numbers could be fractional values. But the number of vehicles

must be integer because of the nature of small quantity order. This operational model can be solved by CPLEX at a relatively large scale as well, since some variables can be relaxed to fractional values.

3.3.2.2 The enhanced NSGA-II algorithm

Generally speaking, there are two classifications of optimisation algorithms. One is exact algorithm classification which can get a global optimal solution of the specific problem no matter the time consumption in the computation. Another one is heuristic algorithm classification which can find the near optimal solution with less time. Heuristic algorithm is a technique designed to find a solution of a problem no matter whether this solution is global optimal or not in limited time. Heuristics are intended to gain good computation performance and conceptual simplicity, even potentially at the expense of accuracy or precision of the solutions. Both exact algorithms and heuristic algorithms have their pros and cons. Exact algorithms can guarantee that their solutions are global optimal, but when the size of the problem (the number of variables) is large and the computation time is large, particularly in some integer linear programming models (NP-hard) exact algorithms are not feasible. Although heuristic algorithms may be considered less-time-consuming methods, there is no guarantee that they can find the optimal solution each time (Caserta and Voß, 2010).

In recent years, a branch of heuristic algorithms known as metaheuristic algorithm was highlighted and emerged. Metaheuristic algorithm is a heuristic method to solve computation problems using black-box procedures in a more efficient way, usually using black-box concept heuristics for the algorithm itself. Popular and common metaheuristic algorithms for combinatorial optimisation problems include Simulated Annealing, Tabu Search, Ant Colony Optimisation and Genetic Algorithms (termed as GA) (Yang, 2008; Caserta and Voß, 2010). Compared to the other three metaheuristic algorithms, GA can deal with sets of solutions all at the same time, using the string of values pattern, while the other three metaheuristic algorithms can only get one optimal solution at a time (Zäpfel, 2010).

GA mimics the biological process of natural evolution. GA belongs to the larger class of evolutionary algorithms (termed as EA), which generate solutions to optimisation problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. This approach was first proposed by Holland in 1975 and based on the Darwinian principle of survival of the fittest. It has been implemented to solve many difficult problems with quick searching in large feasible regions (Holland, 1975). GA randomly generates an initial set named population. Each solution would be evaluated according to a fitness function which is related to the objective function. From this population, a parent solution is just the subset of the population and the parent solution selection can be random or be dependent on the fitness function. By using the crossover operation to combine the two parent subsets to generate the offspring set, the next generation solution can be found in it. This offspring set may bring diversity into the population. This process is repeated until the termination condition is met. GA identifies individuals with the optimising fitness values, and those with lower fitness values will be discarded from the population eventually. Thanks to its ability to deal with sets of solutions, GA turns into the most powerful approach to solving the most difficult discrete optimisation problems (integer linear programming or mixed integer linear programming) and multi-objective optimisation problems (Vose, 1999; Gen and Cheng, 2000; Buseti, 2001; Caserta and Voß, 2010). Therefore, GA is selected in this study as the method of metaheuristic algorithm in solving large-size problems.

GA has become increasingly popular in optimisation problems, and multi-objective optimisation is one of the fastest growing fields of operational research in recent years. Multi-objective optimisation problems are crucial because of the multi-objective nature of most real-world decisions. An elitist non-dominant sorting GA (termed as NSGA-II) is deployed to solve the bi-objective optimisation problem in this research. Developed by Deb et al. in 2002 (Deb et al., 2002), NSGA-II can help avoid the conventional problems of evolutionary algorithms such as premature convergence. It is widely accepted as the most popular evolutionary algorithm to solve optimisation problems having two or more objective functions (KanGAL, 2013). An enhanced NSGA-II is developed in Chapter 5 to solve the tactical level model, in order to accelerate its convergent speed.

3.4 Chapter summary

This chapter draws the outline of the research and presents the research design in the form of a flowchart. There are six main components in this thesis, namely “Introduction”, “Literature Review”, “Research Methodology”, “Qualitative Research”, “Quantitative Research” and “Conclusion”. In this chapter, the author has provided detailed explanations regarding three components of the research methodology, namely “Field Studies”, “Qualitative Research” and “Quantitative Research”. Field studies can link our research to real cases. Three face-to-face interviews and three on-site port visits were carried out. The details can be found in the “Field studies” section (Section 3.2). In the “Research methods” section (Section 3.3), the research methods can be classified into qualitative and quantitative approaches to achieve the research objectives stated in Chapter 1. For the qualitative analysis, a comparative research method is used to compare China and India from the aspect of intermodal development. For the quantitative approach, detailed explanations about the linear and non-linear programming techniques and the enhanced NSGA-II algorithm are given. The linear and non-linear programming techniques are adapted to build the mathematical models on tactical and operational levels. The enhanced NSGA-II algorithm is applicable to solving the tactical model in large-scale cases. These respective research findings will be presented in the following chapters (Chapter 4, Chapter 5 and Chapter 6).

Chapter 4 Comparative analysis on intermodal development in China and India

This chapter (Chapter 4) compares port hinterland intermodal development between China and India, the two fastest developing new economies. To fill the research gap found in Chapter 2, it addresses both opportunities and challenges in terms of intermodal development in these two countries. This chapter also analyses the anticipated future direction of these two new economic poles, China and India, in terms of intermodal transport and provides recommendations from the sustainability perspective.

Both China and India have opportunities and yet face challenges in terms of intermodal development. The problem faced by China is that its inland port development is still in its infancy stage. Thus it is unable to catch up with the pace of rapid economic growth in China. As compared to China, India focuses more on the social aspect in order to protect the welfare of its residents, which in turn jeopardises India's intermodal development in an economic sense. The biggest challenge for India is its social institution which would take a long time to change.

4.1 Introduction

Based on the findings in Chapter 2, it is evident that intermodal development with port regionalisation, supply chain integration and green concerns playing a crucial role in the sustainability of a seaport as well as economic development of the entire region is an emerging point of interest. Inland ports that link seaports via rail or barge corridors would bring a lot of benefits to intermodal development, such as economies of scale, decongestion of seaports, environmental protection and stable hinterland markets that utilise the ports by shifting flows from road to rail or barge, thereby offering more sustainable inland access. Never, in recent history at least, has there been such rapid expansion of economies like China and India with their large populations. A number of studies about China and India converge on comparing bases of economic growth, political structures, institutional reform processes and trade. Postigo (2008) conducts a comparative analysis on China's and India's transport infrastructure development as a whole from the macro level. Pucher et al. (2007) make such comparison from the transport policy perspective. Another two papers, written by Kroeze et al. (2004) and Shalizi (2007), highlight that the greenhouse gas emission problem will worsen with the rise of the two countries' rapid economic development and call for an array of protective action. Only a recent paper by Hanaoka and Regmi (2011) keeps an eye on the comparison of intermodal issues about Asia, including China and India. However, after revisiting and examining the existing literature carefully, studies about China's and India's port hinterland intermodal development, especially from the sustainability perspective and their comparison, are limited and largely unexplored. This chapter thus intends to bridge this research gap and make contributions to the ongoing comparative analyses about these two economies in terms of sustainable port hinterland intermodal development.

4.2 Opportunities and challenges of sustainable port intermodal development in China

The global economy is influenced greatly by the “China effect” and the development of Chinese ports is remarkable. In 2012, among the world's busiest container ports, seven Chinese ports ranked within the top ten in terms of container throughput, namely Shanghai (1st), Hong Kong (3rd), Shenzhen (4th), Ningbo (6th), Guangzhou (7th), Qingdao (8th) and Tianjin (10th) (Containerisation International Yearbooks, 2012). Hence, conducting an in-depth study into Chinese ports is valuable when one considers such a phenomenal trend. Chinese ports face plenty of opportunities and challenges, among which is sustainable port intermodal development. This section (Section 4.2) will elaborate on these in detail.

4.2.1 Opportunities and challenges co-existing in Chinese port development

This study has identified the following major opportunities in current Chinese port development: (1) rapid economic growth and trade growth due to globalisation; (2) central government’s planning and support and local governments’ active participation; (3) deregulation and privatisation within the transport sector. However, the major challenges co-exist as follows: (1) cut-throat competition among Chinese ports, especially in the same region; (2) absence of integrative institutional and regulatory framework from central government to local governments; (3) underdeveloped information management; (4) absence of a national green and sustainable port development strategy. Detailed and illustrative examples of the opportunities and challenges of Chinese port development are as follows.

4.2.1.1 Three opportunities

Referring to the first opportunity, from the beginning of China’s “reform and opening up” in the late 1970s and early 1980s, economic development became the

target of the whole nation. Especially in the last decade (2003-2012), China kept a remarkable double-digit average GDP growth rate of 10% (World Bank, 2012). Even after the impact of the global financial crisis of 2008, the economic development of China is still vigorous. In accordance with its economic prosperity, China's trade growth is remarkable as well, especially after entering the WTO in 2001. More and more international companies are relocating their manufacturing sites to China in the recent globalisation trend. Gradually, China is developing into an export-oriented economy. About 90% of its foreign trade is sea-bound, so Chinese port development is crucial for China's economic development (China Foreign Trade and Economic Yearbook, 2010).

With regard to the second opportunity, China's governments at various levels have realised the importance of Chinese seaport development. In November 2006, China's Ministry of Transport released the "Coastal Port Layout of China" to formally divide China's coastal ports into five port clusters which are: the Bohai Bay region in the north, the Yangtze River Delta in the middle, the South-Eastern Coast, the Pearl River Delta in the south, and the South-Western Coast. Among these, the South-Eastern Coast and the South-Western Coast have been newly added based on the conventional three-cluster division and China's new strategy development requirement. The planned layout was to develop Dalian Port, Tianjin Port, Qingdao Port, Shanghai Port, Ningbo Port, Xiamen Port, Shenzhen Port and Guangzhou Port as coastal container-hub seaports to form the hub-and-spoke container transport system in China. It also strategically designed China's specialised seaports' development, such as coal, oil, iron ore, grain and Ro-Ro seaports (MOT, 2012). In the meantime, local governments in the coastal areas have witnessed the positive influence of seaport development on the local economy. Hence they have shown great enthusiasm for seaport construction and expansion. As early as 1985, the Chinese central government proposed a vision for "Shanghai International Shipping Centre". After many years of endeavour, in 2010, Shanghai Port's container throughput surpassed that of Singapore and it became the top container port in the world.

The third opportunity, which should not be neglected, is the phenomenon of

deregulation and privatisation in China which began from the start of “reform and opening up” thirty years ago. After the 1970s, the tide of deregulation and privatisation appeared worldwide, especially in the transport industry. Under such domestic and international background, private capital has increasingly participated in China’s seaport industry. Domestic private capital mostly chooses small-sized or middle-sized seaports and inland barge ports as targets for investment. However, foreign private capital mainly shows great interest in investing in the large seaports of China. In spite of this successive growth of the privatisation process, the amount of private capital invested in China’s seaport industry is still limited due to China’s institutional setting. There is still a great deal of potential for its seaport deregulation and privatisation (Cullinane et al., 2005). Shanghai International Port (Group), founded in 2003, is a good example that demonstrates this new privatisation tendency in Chinese ports.

4.2.1.2 Four challenges

The first and greatest challenge might be cut-throat competition among Chinese ports especially in the same region, and competition may also exist between any Chinese ports or sometimes between Chinese ports and the ports in neighbouring countries. The over-capacity problem due to Chinese ports’ over-building in the last decade, the shipping market slump due to the latest global financial crisis, and the rapid maritime industry development in the neighbouring countries should be the three main factors that explain such fierce competition in Chinese ports. For instance, the competition between Shanghai Port and Ningbo Port, between Shenzhen Port and Hong Kong Port, between Chinese ports in the Bohai Bay region and seaports in Japan and Korea, have already been thoroughly researched by many academic articles (Cullinane et al., 2004; Cullinane et al., 2005; Lee and Rodrigue, 2006; Yap and Lam, 2006; Yap et al., 2006). Hence more and more Chinese coastal seaports are shifting their competition from sea bound to hinterland. The hinterland connectivity and its inland economic development are the main concerns in a port’s hinterland development strategy (Zhang et al., 2009; Zondag et al., 2010). On the other hand, port cooperation may mitigate such excessive competition, especially with regard to seaport cooperation in the same region. Like Shanghai Port and

Ningbo Port, the port authorities must reach a consensus that they should diversify and differentiate their portfolio and service packages to avoid vicious competition in the same region, in order to achieve a win-win situation (Cullinane et al., 2005; Comtois and Dong, 2007).

The second challenge of China is institutional in nature. Although the process of deregulation and privatisation has spread across China gradually, China's institutional setting still needs improvement. There is an absence of a unified top-level institutional coordination body in China. Many ministries within China work independently and with insufficient communication and coordination. The lack of a uniform set of policy guidelines in China may cause many legal challenges as well. Usually, the central government modifies relevant institutional settings based on the existing regulatory framework, but local governments may interpret the intention of the central government with flexibility according to local needs (Beresford et al., 2012). Institutional reform in China is imperative. The third plenary session of the 18th central committee of the Chinese Communist Party has recently ended (in November 2013) and China's institutional reform is anticipated.

The third challenge that shows up for China is its underdeveloped information management. By merely improving hardware such as infrastructure construction, the seaport transportation system cannot be enhanced. The development of information technology is also crucial. The Chinese government has realised this issue and input a great amount of funding to develop the Intelligent Transportation System (ITS) from the national level. Information flow is an essential factor in supply chain integration. According to some researchers, the information management level is counted as a port performance measurement factor. However, China's information management level is underdeveloped and there is still a long way to go compared to the developed countries (Li and Miao, 2003; Bichou and Gray, 2004; Carbon Tax Centre, 2013). From the statistical data provided by the World Bank in 2012 about the overall logistics performance index (1=low to 5=high), China scores 3.52 and is ranked 24th (see Table 4.1 below), which means that there exists a obvious gap compared with other developed countries in terms of information system development (World Bank, 2012).

The fourth challenge appears in the absence of a national green and sustainable port development strategy. The notion of “Green Port” is popularly proposed in recent years and is associated with a sustainable supply chain strategy (Notteboom, 2010; Lam and Notteboom, 2014). The greening of ports is not only a challenge for China, but it is also a challenge for seaports worldwide. As with other world-famous seaports, the good practice of “Green Port” in China is on the rise. For example, Shanghai Port has established an index system to evaluate the “Green Port” (Lin, 2010). Seaports’ intermodal linkage will help seaports to get closer to the goal of “Green Port”. However, a national strategy of green and sustainable port development is missing in China.

4.2.2 Intermodal development in China

Intermodal development in China can be reviewed from the perspective of four major opportunities and two major challenges. The four opportunities are: (1) Chinese seaport competition evolves into hinterland capture competition and various forms of inland ports spring up in inland mainland China; (2) great potential to increase the containerised cargo ratio of China; (3) China’s Western Development Strategy; (4) the capacity of inland river transport in China is considerable. The two major challenges of intermodal development in China are: (1) freight rail of China faces capacity shortage; (2) a systematic policy framework, to ensure intermodal development, is missing. Next these opportunities and challenges will be discussed in detail.

4.2.2.1 Four opportunities

For the first opportunity, as mentioned in Subsection 4.2.1, Chinese seaport competition is cut-throat nowadays. Many researchers have observed that seaport competition has shifted to a hinterland capture campaign (Starr and Slack, 1995; Carbone and Martino, 2003; Yap et al., 2006; Zondag et al., 2010). A seaport is a node which connects the shipping network and inland transportation network. An increasing number of inland-locked shippers want to enjoy door-to-door services and a nearby seaport service in the same manner as using seaports that are far away.

Hence many shipping lines aim to provide an intermodal service to the shippers, and various forms of inland ports are emerging, such as barge ports or dry ports, some of which have customs clearance functions just like seaports. Along the Yangtze River, many barge ports are newly built and expanded (Zhang et al., 2009). In the meantime, many Chinese container seaports build dry ports in their hinterland which usually have customs clearance functions and such actions are warmly welcomed by local governments. On the other hand, local governments develop dry ports on their own and such dry ports generally are far away from seaports and more like logistics parks (Beresford et al., 2012). The emergence and development of all of these inland ports may be seen as a milestone in significantly promoting China's intermodal development.

The second opportunity comes in China's great potential to improve the containerised cargo ratio. Currently only less than 20% of cargoes in volume (16.7% in 2009) are containerised in China (China Ports Year Book, 2010) which is far lower than those in developed countries (e.g. 28.8% of USA in 2009) (Bureau of Transportation Statistics of the USA, 2009). Containerisation plays an essential role in intermodal transportation and the containerised box can make the intermodal process more efficient and safe and therefore its use has become widespread since its invention. There is a great deal of potential to improve the containerised cargo ratio of China. If the ratio of the containerised cargo of China catches up with other developed countries, intermodal development in China will be at a new level.

The third opportunity is found in China's Western Development Strategy. This strategy was proposed in 1999 by former president Jiang Zemin, aiming to reorient the vigorous growth towards the western region. Neither the economy nor technological development is synchronised between the eastern and western parts of China. The development of transport links between populated and developed eastern coastal regions and the undeveloped western reaches is crucial for the carrying out of this national strategy. All levels of government have invested massive manpower, physical resources and financial resources on this great project. It offers a good opportunity to develop China's intermodality which can in turn boost the western region's economy through domestic trade and international trade

(Lu and Neilson, 2004). The presently unbalanced regional development will be gradually improved after the Western Development Strategy is promoted by the Chinese central government. The Western Development Strategy therefore opens up a great opportunity for China's intermodal development.

The fourth opportunity of China appears in its considerable capacity with regard to inland river transport. In China, inland waterway-barge transportation has the biggest market share (see Figure 4.2 below) because of abundant inland waterway tributaries, especially the Yangtze River (Frankel, 1998; Rimmer and Comtois, 2009). Barge is a good choice for China. Currently, inland barges are mainly used to transport low-value bulk commodities constrained by waterway depth and seasonal water level change. Notteboom (2007) compares the gateway ports in the Yangtze River and the Rhine River according to their inland barge system and highlights that Shanghai Port has huge potential to develop its inland barge system along the Yangtze River from upstream to downstream. If more containerised cargoes can be shipped efficiently and seamlessly by China's inland waterways in the future, China's intermodal development will be greatly improved.

4.2.2.2 Two challenges

For the first challenge, the absence of good rail links in China, which are the bases of freight intermodal transportation, would affect China's intermodal development substantially (Rimmer and Comtois, 2005). Unlike other developed countries, the railway system in China is owned by the state and has little involvement from private investors. China has a large population size. A large portion of railway capacity is used for passenger transport, and thus limited capacity can be deployed for freight transport. According to the statistical data of China in 2011, it can be noticed that the growth of rail freight capacity cannot meet the requirements of its fast economic development (China Statistical Yearbook, 2011). The Chinese government has never stopped the expansion of the railway network of China since China's independence in 1949. In recent years, the Chinese government has made many efforts to build its High Speed Rail system to relieve the pressure of passenger transport and release more rail capacity to its freight transport, according

to the Chinese Ministry of Railways (Guo, 2010). According to China's actual situation and referring to foreign experience, China's railway network needs a multi-layer hub-and-spoke pattern and double-stack capability. The railway infrastructure in China needs more time and more resources to construct and modify, because China is a big country with a vast geographical area and complex terrains from east to west, from south to north. To overcome the capacity constraint of the railways, the Chinese government may consider partial privatisation of its railway system in order to speed up the pace of its railway development, just like privatisation in its seaport system. For example, the Chinese government should allow more private capital to enter into the construction of shuttle railways with a dedicated link that connects the inland dry ports with seaports.

The second challenge is that a systematic policy framework to ensure intermodal development is missing. The institutional problems in China have been elaborated on in Subsection 4.2.1 above. The same challenge will also exist in relation to intermodal development in China. For example, some researchers have realised that there is no standard and clear definition of "Dry Port" in China, with related problems in management and operation (Beresford et al., 2012). How to improve the existing institutional and regulatory framework in order to get closer and proactive cooperation among different government departments is a critical question in contemporary China. The Chinese government could learn from the successful experience of other developed countries and provide more detailed policy support to inland intermodal infrastructure development (Wang, 2009; Yang, 2009).

4.3 Opportunities and challenges of sustainable port intermodal development in India

Compared to China's port development, India is still far behind. There is only one Indian port (Jawaharlal Nehru Port located in Mumbai) ranking in the top 50 (ranked 33rd) in terms of container throughput in 2012 (World Bank, 2012). However, India's achievement in economic development should not be disregarded. India was the ninth economy in terms of GDP in 2012 (World Bank, 2012).

Although the transport sector of India has great potential due to its rising trade volume, its disadvantages should be studied seriously and not be disregarded either. There are also more social problems in India due to its regulatory framework and this would impede its economic development.

4.3.1 Opportunities and challenges in Indian port development

Similarly to above, the opportunities and challenges of Indian port development are enumerated in this Subsection 4.3.1. Two opportunities are: (1) GDP and trade's quick growth and great potential; (2) inherent geographical advantages. The four challenges are listed as: (1) India's social institution; (2) current status of port development is not ideal; (3) its import-led economy; (4) serious power shortage. Detailed and illustrative examples regarding the opportunities and challenges of Indian port development are as follows.

4.3.1.1 Two opportunities

For the first opportunity, India's economic development is remarkable, as it is for China. Both China and India, the two developing countries, have become global economic drivers with amazing recent economic growth rates. In line with India's fast economic development, its trade growth is also significant. India's foreign trade (import and export) accounted for 56% share of GDP in 2012. But in 1991 the share was only 17%. During the past two decades, this share reached its peak in 2008 (53%) and then went down slightly after the global financial crisis of 2008. From 2011, this share has risen again to 56% in 2012 (World Bank, 2012). Such a phenomenon implies the increasing contribution of trade to economic development. A good port system development brings a growing trade volume which in turn leads to better economic development. In a good economic situation, there will be more money to develop and expand India's port system. Accelerated economic growth and increasing the foreign trade of India will result in good opportunities for India's port development.

Concerning the second opportunity of India, in addition to its economic advantages

above, it also inherits geographical advantages in the maritime industry. India is a pivot maritime country from early ancient times. India is endowed with a 7000km coastline, along which are twelve major seaports out of one hundred and eighty minor seaports. Among these twelve major seaports, Mumbai and Chennai are the two biggest and most modernised seaports in India. Moreover, India has a big hinterland with coasts on three sides which implicates great geographical advantages in its maritime industry.

4.3.1.2 Four challenges

The first challenge for India shows up in its social institution problem. Many research papers about India have noticed the disadvantages presented by the infrastructure of its ports and national transportation network. But after comprehensively reviewing this literature, it is not surprising to perceive that the most challenges might come from its social institution (Muller, 2006). India's development strategy started with a rational approach to maintaining a balance between economic growth and distribution. But in mid-course it put a great emphasis on the redistribution of wealth rather than economic growth which is led by its social institution (Kim and Nangia, 2008). The Indian government has pursued economic liberalisation since the late 1970s. Under this background, various economic sectors such as transportation have opened their doors to private investors, whether they are domestic or foreign. The port of JNPT (Jawaharlal Nehru Port Trust) represents an initial trial of privatisation in India's seaport system, established by the Indian government in 1993 (Bennett, 1995; Monie, 1995). Despite India's economic liberalisation reform, not many private investors would like to invest a large amount of money in Indian seaports due to India's huge social safety net concern. Employment implies not only responsibility for the employee's whole life, but also with a package normally including housing, health and education for his or her whole family. It might be a big challenge for the Indian government to achieve a harmonic consensus between the private sectors and its social institution. It would be unwise to postpone the privatisation process in Indian ports but cautious steps are required. It might be possible to negotiate with the labour sector in India and introduce them to some new commercial orientations.

Moreover, the Major Ports Trust Act (MPTA) has been criticised as the main stumbling block to the introduction of successful privatisation in India (Haralambides and Behrens, 2000). Legislation and institutional change should be more important than physical infrastructural improvement in the Indian context, and will take a considerable time to achieve. As a matter of fact, various international organisations and foreign countries have provided vast technical assistance in Indian ports, but the results are disappointing because of the deep-rooted social institution of India (Monie, 1995; De and Ghosh, 2003; Ng and Gujar, 2009).

For the second challenge, the undesirable current status of India's port development is a disadvantage as well. Ghosh and De (2001) have found that the inequality among major ports had hindered India's port development. Geographically, the ports on the east coast have stagnated, while the ports on the west coast and south coast have done better. De and Ghosh (2003) have attempted to find out the causal relationship between port performance and port traffic by using Indian statistical data. They uncover that a better port performance (higher efficiency with better facilities) will lead to higher traffic in Indian ports. However, most Indian ports have a poor performance. Generally, the capacities of both major and minor ports in India need to be increased to cater for increasing trade volume, and also there is a strong need to form a global hub port or at least a regional hub port for the whole country, like Singapore or Shanghai (Gujar, 2006).

For the third challenge, India's import trade still holds a dominant position relative to its export trade, and the gaps are even wider in the last decade (World Bank, 2012). An export-oriented economy would bring more fortune to a country and a positive impact on its economic development (Kim and Nangia, 2008). India's import-oriented economy will inhibit its port development due to less trade volume than an export-oriented economy (Ghosh and De, 2001). Its import-oriented economy will be another disadvantage in Indian port development.

For the fourth challenge, India's biggest infrastructural deficiency shows up in its shortage of power which would not only influence port development, but also the economic development of the whole country (Gujar, 2006). Almost a decade ago,

the Indian government set an ambitious goal to provide enough electric energy for the whole country before March 2012. However, in 2012, this goal was only 64% complete. In India, in 2012, almost 300 million people did not yet have access to electricity and there is a serious electricity shortage (Yep, 2012).

4.3.2 Intermodal development in India

Similar to the analysis on China, India's intermodal development is also investigated from the perspective of opportunities and challenges. There are two major opportunities as follows: (1) numerous dry ports have been built up already; (2) intermodal transport will inevitably be needed because major manufacturing sites are far away from seaports. Three challenges come with: (1) restricted inland waterway transport; (2) its insufficient infrastructure in intermodal development; (3) its social institution problem and ineffective government policy guidance. These opportunities and challenges for India's intermodality are illustrated in detail as follows.

4.3.2.1 Two opportunities

For the first opportunity, a number of dry ports have been built in India's large hinterland. Dry port development could accelerate India's intermodal development. There are two kinds of inland dry ports in India, ICD (inland container depot) and CFS (container freight station). Generally speaking, ICDs are normally located near port areas while CFSs are usually near inland customers and may have more functions than ICDs. A port will become a hub only when its spokes are connected with ICDs or CFSs (Gujar, 2006). Founded in 1989, the intermodal branch of Indian Railways, CONCOR ("Container Corporation of India Ltd") currently operates the largest network of 61 ICDs/CFSs in India (Thorby, 2004; Dayal, 2007; Yep, 2012). It has complete monopoly over the control of rail movement of containers, but it also outsources its road transportation activity, as a multi-modal logistics operator. Collaboration with some global liners and container terminal operators to develop intermodal services is one of CONCOR's cornerstones (Dayal, 2007). India's dry port development is relatively mature, compared with other inland infrastructure

development. By 2010, a total of 61 large-scale inland dry ports had already been established (see Table 4.1 below).

For the second opportunity, there is a large demand for intermodal transport services because many manufacturing sites are far away from seaports in India. In India, major manufacturing activities take place in the north-western states, notably Delhi, Punjab and Uttar Pradesh where textiles are produced and automotive components are both produced and assembled. In contrast, international trade is conducted through the gateway ports far away along the southern and western coasts, such as JNPT, Mumbai and Mundra ports which are visited by the mainline vessels. JNPT, Mumbai and Mundra ports handle almost 80% of the Indian containerised cargoes which almost entirely originated from north-western states (Lall et al., 2004; Indian Port Association, 2012). Hence many ICDs and CFSs are built near to such manufacturing plants which are linked with gateway ports by rail using intermodal transport in India.

4.3.2.2 Three challenges

For the first challenge, restricted inland waterway transport is a disadvantage for India's intermodality. Although India has 14500km of inland waterways, vessels hardly can use them due to insufficient draught depth. Furthermore, these rivers are mainly used for irrigation and electricity generation. The Government of India (GOI) established the Inland Waterways Authority of India (IWAI) as a statutory body in 1986 with the responsibility to develop, maintain and regulate the national waterways in India. However, the effect is not obvious. Only very few restricted rivers can be utilised. The capacity of India's inland waterway transport can almost be ignored (IWAI, 2012). As this is the case, India would not be able to capture the advantages of inland waterway transport, including the least impact on the environment, the lowest cost for domestic and international transport, enormous capacity reserves and the least energy consumption. This disadvantage of India's waterway transport can impact its intermodal development significantly.

Referring to the second challenge, insufficient inland intermodal infrastructure in

India is a drawback. Nowadays about 40% of containers are transported by railway in India (Carbon Tax Centre, 2013). The rail haulage is conducted by Indian Railways, being a monopoly. There are two kinds of gauges of the railway route, 1.00 metre and 1.67 metre, which may cause some discontinuities to impede the Indian railway connectivity. Another shortcoming of the Indian railway system is that the length of electrified railway routes is insufficient (Gujar, 2006). Although the Indian roadway system carries over 57% of the total container traffic in India, its road infrastructure is unsatisfactory. For example, India's road conditions are poor and many roads are unpaved. India has less than 0.07 kilometres of highways per 1000 people, as of 2010, while the USA has a value that is over 15 times as much as India (NHAI, 2012). Wu and Lin (2008)'s result is consistent with Chandrasekaran and Kumar (2004)'s finding that most Indian ports and its inland transportation network are inefficient, and the Indian government should upgrade the infrastructure and facilities of its ports, rails and roads, and make this a national intermodal development strategy. The necessary construction of intermodal infrastructure in India is seriously lagging behind.

For the third challenge, India's social institution problem has hampered its intermodal development. Effective government policy guidance is missing. The dry port performance has an increasingly significant impact on the whole transportation network in India (Cezar-Gabriel, 2010). The Indian government calls for foreign private investors to participate in its inland dry port development, but as mentioned before under the Indian rooted social institution tradition, the government has to protect its local operators' interests. Hence in order to resolve this contradictory issue, the Indian government is trying for dualistic policies on "land pricing and distribution" and "dry port operation" between foreign investors and the state-owned corporation, which may provide an insightful solution for other countries, especially for developing countries needing foreign investment badly (Ng and Gujar, 2009). Recently, excessive investments have been thrown into the roadway system at the expense of the railway system, and this trend needs to be changed (Sriraman, 2009). The Indian government should guide such investment in the railway system and integrate its now available dry ports in order to achieve efficient and sustainable intermodal development. Intermodal services in India should target

high-value and finished goods which need high-frequency, reliable and fast services. Railway is the unique choice in the Indian context (Shinghal and Fowkes, 2002). The Indian government needs to provide more guidelines and support for this strategic target's realisation.

4.4 Comparison between China and India in terms of port intermodal development and recommendations

Sections 4.2 and 4.3 above have analysed the major opportunities and challenges for China and India, respectively, in terms of their port and intermodal development. In this section, a comparative analysis is conducted with regard to these two countries. It is expected that this comparison would not only give direction to future development in these two countries, but also set an example for other countries. All the detailed information in Section 4.2, Section 4.3 and Section 4.4 is concluded and listed in Table 4.1, Table 4.2 and Table 4.3, respectively, for reference. Table 4.1 is about a quantitative characterisation comparison between China and India in terms of intermodal development. The focus of Table 4.2 is policy and regulatory regime comparison between China and India in terms of intermodal development. Table 4.3 lists the potential and challenges' comparison between China and India in terms of intermodal development.

From Table 4.1's quantitative characterisation comparison (see below), it can be deduced that both China and India have great potential for their intermodal development. Both China and India have large populations covering huge geographical areas with the most extreme rapid-growth economies in the world. Asia has become the centre of production for the whole world since the 1970s. This globalisation has strengthened Asian economic development. Both China and India are experiencing urbanisation and globalisation processes which would imply huge potential demand for not only domestic trade but also international trade in terms of value and volume, especially China. This phenomenon can be verified from Figure 4.1, that China's container port traffic has experienced a dramatic and continuous growth since China entered the WTO in 2001. In 2011 (ten years after entering

WTO), the Chinese port of Shanghai was ranked first in the world, based on its container port traffic. Both China and India have gradually become the world's largest manufacturing centres for the world. Owing to their abundant natural resources, relatively low labour costs, sufficiently skilled worker supplies, increasing open economic policies and so forth, many international manufacturers have relocated their production sites to China or India. This trend would increase the pressure of global distribution, especially for China and India's transport systems. As they are under the pressure of global distribution, China and India are in urgent need of their intermodal development.

Due to the export-orientation economy of China, it has more potential than India in economic development, in terms of GDP growth rate and seaport traffic (see Figure 4.1 below). The degree of a country's busy port traffic could mirror the status of its economic development somehow. The sharp increase of container cargoes exported from China to North America and Europe bears witness to China's success. China has performed well in its export-led economy. It is suggested that India should transform its current import-oriented development strategy to an export-oriented economy, the same as China. India should make more effort with regard to this transition.

Along with China and India's rapid economic growth, environmental issues such as CO₂ emission and water pollution become more severe than before. Intermodal transport and various inland terminals are all included in the "Green Port" strategy of Europe's successful experiences (Notteboom, 2010). However, few studies have focused on intermodal development in Asia. Hanaoka and Regmi (2011) analyse five dry port projects in five Asian developing inland-locked countries, respectively, including China and India. These projects reach the conclusion that railway connection to dry ports can greatly reduce carbon footprint. Hence intermodal transport can be suggested as a national development strategy from both economic and environmental perspectives. Both the Chinese government and the Indian government have paid attention to environmental protection issues already. In China's 11th Five-Year plan (2006–2010), intermodal development was firstly proposed as a national strategy. The Indian government has also realised the

significance of environmental protection in the transport sector, but a national sustainable intermodal strategy is missing.

Figure 4.1 Container port traffic in China and India

Source: Drawn by the author based on the data of World Bank (2012)

In the following paragraphs, detailed analyses will be given about intermodal infrastructure development in China and India, such as links and nodes in different transport modes. Presently India mainly uses the roadway to carry containers (see Figure 4.3 below). Although China's biggest share of container traffic is barge mode, its road traffic for containers holds the second largest proportion and this proportion is increasing every year (see Figure 4.2 below). While China has focused on the development of highways and expressways, India has concentrated its investment in low-level district and rural roads. It is suggested that a middle-way approach could be more appropriate for these two countries to rethink their different strategies in road transport development. In the near future, India should put more effort into its modern highway network construction, and these main highways could help connect major seaports, state capitals and large industrial centres in India. However, China should pay more attention to its paved rural roads' construction, which can help China improve its whole road network's connectivity and door-to-door services.

Both China and India's rail freight modal shares are insufficient in terms of good

intermodal development strategies. An improved situation for both China and India should be a modal shift from road to rail. These two countries both have huge hinterland ranges, and their industrial sites are far away from their seaports. Hence dry ports with long-distance intermodal rail corridors as load centres are suggested. Geographically, China aspires to these long-distance intermodal rail corridors more than India, because its central and western parts are land-locked while India has more favourable maritime access than in China. Hence the Chinese government has made great efforts in rail line construction, 24% growth in 2012 compared to 1991 (see Table 4.1 below). In terms of rail line length, India has seen almost no improvement, stagnating at its initial stage of colonial times. Although China has built up a lot of new rail lines, its railway capacity is also insufficient. The capacity shortage of Indian railway transport is even worse. In order to solve the railway capacity shortage, the Chinese government is developing its high-speed railway network, which can attract huge passenger traffic and release more capacity to its freight traffic. While the high-speed railway network has reached a certain scale in China, high-speed rail has even not started in India. The number of large-scale dry ports in India was greater than in China in 2010, but India's inadequate railway infrastructure holds back its overall development of the intermodal. Although the number of Indian dry ports is larger than that of China, the development speed of Chinese dry ports is very fast. Chinese dry ports, in various forms, have sprung up. As a result of double-stack development in the railway system, India has done well enough, ranked third in the world, after the USA and Canada. China has only just begun this double-stack journey but has seen rapid development. In 2007, Chinese Railways operated 680 double-stack trains that carried 53,161 TEU, compared to 2005, when it operated 454 trains that carried 39,437 TEU (UNESCAP, 2009; Hanaoka and Regmi, 2011). Overall, the development of China and India in terms of intermodal rail mode can be improved greatly, such as developing dry ports and railway links. Good performances of both dry ports and railway links are essential for the overall performance of the whole rail mode system.

Figure 4.2 Freight split of China

Source: Compiled by the author based on Carbon Tax Centre (2013)

Figure 4.3 Freight split of India and gap with China in total freight volume

Sources: Compiled by the author based on Carbon Tax Centre (2013) and World Bank (2012)

From Figure 4.2 above, inland waterway always accounts for a large proportion among inland transport modes in China. With strong development of the Yangtze River strategy by the central government of China, driven by the Shanghai international shipping centre, the barge intermodal along the Yangtze River from upstream Chongqing to downstream Shanghai has attracted a lot of attention. Many satellite barge terminals have been established along the Yangtze River. However, more maintenance works need to be done, such as dredging, widening and deepening the waterway channels accordingly. Unfortunately inland waterway is almost unavailable in India as mentioned above in the last section (Section 4.3). The

great potential of inland barge transport in China can give China more confidence in its intermodal development, compared with India.

India's port industry is a little lagging behind that of China, and there is still a long way to go in India. It is essential to promote India's port industry in order to speed up its economic development. China has achieved its tremendous progress owing to its fast transport infrastructure development. China follows other developed countries' successful experience in that transport infrastructure development should be in advance of economic development (Pillania, 2007; Wu and Lin, 2008). Construction of port facilities should be put in first place, because ports can help link the domestic economy with the global economy. Compared with other developed countries, the proportion of transport infrastructure investment in the GDP of China was 5.64% in 2009, still very low, while the same proportion in the USA in the same year was 9.90% (Yu et al., 2012). China has already tasted the success of transport infrastructure development, especially infrastructure development in seaports. Better port facilities could bring about higher liner shipping connectivity. China's liner shipping connectivity index is ranked first in 2012. India has a poor performance in terms of the ranking of liner shipping connectivity index. Hence it is suggested that India should put more money into its transport infrastructure improvement, especially in its port industry, in order to promote steady and fast economic growth in India.

In addition to the differences between China and India in terms of intermodal infrastructure stated above, their different social institutional settings will result in a developmental gap as well. Figure 4.3 above shows that there exists a huge gap in terms of total freight volume between China and India in these years, although they have a very similar background, such as similar population and land area. China and India began economic liberalisation almost at the same time, in the late 1970s and early 1980s, and at that time India's transportation structure was actually better than that of China in terms of railway and roadway. However, after 20 years of development, India's original advantage has gradually disappeared due to its deep-rooted social institution. Under India's specific social institution, the Indian government focuses on redistributing its wealth and welfare rather than economic

growth, though at the beginning of its economic liberalisation, the Indian government applied a rational approach to keep the balance between its economic growth and distribution (Kim and Nangia, 2008). India's social institution discourages many foreign investors who would otherwise be interested. In China, the picture of the social institution is different. China's social institution is a centralised and autocratic political system. Unlike India, the Chinese government intends to reduce its poverty by its rapid economic growth. The Chinese central government can easily concentrate all the national resources to focus on its big national projects. Intermodal development in China is treated as a big national project (see Table 4.2 below). An array of national policies is being issued to guarantee its implementation. However, like India, China should attach more importance to its wealth distribution to maintain its social equity and justice.

Both China and India have made great efforts to create favourable policies and mechanisms to attract investments in their intermodal development, including domestic and foreign investments. There has been a total of 48,168 billion US\$ private investment in the transport sector of China, versus 28,659 million US\$ in India during the last two decades (Table 4.1, see below). Although the difference between China and India in terms of private investment in the transportation domain cannot reflect the whole situation, it can mirror that China is more attractive than India to private investors. The Chinese government has explored and adopted many efficient, flexible and sustainable mechanisms and policy frameworks to encourage various investments involving the transport sector of China, achieving the right balance both between international and domestic capital and between private and public financing (Kim and Nangia, 2008; Postigo, 2008). India's privatisation process is not as fast and in-depth as that of China, which may be caused by India's social institution problem as well. However, both countries have still much to do in making and modifying more policies and regulations to facilitate the involvement of private investors.

In addition to the above comparisons between China and India in terms of their general background information, environmental policies and intermodal strategies,

intermodal infrastructure development, social institution settings and private investment situations, a comparison in terms of other aspects in the following tables is conducted in this paragraph. From Table 4.3, it can be concluded that both China and India have the following challenges in terms of intermodal development: (1) their regional economic development is unbalanced; (2) the systematic regulation and policy framework is missing; (3) their overall logistics management levels are low; (4) the degree of containerisation is low. Seaport congestion due to the rapid growth of port traffic and increasingly fierce seaport competition could be classified into the potential category. These two potentials give the interested parties, such as port operators and shipping lines, more incentives to implement their intermodal strategies. India faces two more challenges: (1) unbalanced seaport development and (2) insufficient electricity resource. According to these two points, China has a better situation. The Chinese central government has set its long-term strategic layout for its port development. Hence Chinese port cluster development is relatively balanced. While India is troubled about its power shortage, China has relatively abundant power resources. From the start, the Chinese government has focused on the development of electric power, in various forms of power generation modes such as hydropower, thermal power and nuclear power.

The potentials and challenges of China and India's intermodal development are all listed in Table 4.1, Table 4.2 and Table 4.3 (see below for details). The Chinese government has made great efforts with regard to its inland intermodal infrastructure development, but Chinese dry port development is still in the infancy stage, which is the biggest challenge for China's intermodal development. India's social distribution institution is the largest challenge which is a stumbling block for its intermodal development. After taking all factors into consideration, it is concluded that China's intermodal development is better-performed than that of India.

Table 4.1* Quantitative Characterisation Comparison between China and India in terms of Intermodal Development

Comparison Factors	China	India
Total Area (millions of square kilometre)	9.6 (ranked 3rd)	3.3 (ranked 7th)
Population in 2012 (billions)	1.36 (ranked 1st)	1.24 (ranked 2nd)
GDP in 2012 (US\$ millions)	8,221,015 (ranked 2nd)	1,841,717(ranked 9th)
GDP per capita in 2012 (US\$)	6071(ranked 87th)	1501(ranked 138th)
GDP annual growth rate in 2012	7.8%	3.2%
GDP per capita annual growth rate in 2012	7.3%	1.9%
Economic liberalisation dates from	Late 1970s and early 1980s	Late 1970s and early 1980s
Entering WTO dates from	Year 2001	Year 1995
Private investment sum in transport in last two decades (1991-2009)(US\$ millions)	48168	28659
Container port traffic in 2011 (millions of TEUs)	139.74 (ranked 1st)	9.98(ranked 14th)
Container port traffic growth rate compared to Year 2000	241% (41 million in 2000)	307% (2.45 million in 2000)
Coastline length(km)	14500	7000
Railway length (1000 km)	66.24(53.42 in 1991)	63.97(62.46 in 1991)
Paved roadway length(1000 km)	1447	2411
Waterway length (1000 km)	123	14.5 (not available as inland waterway transport mode)
Number of large scale inland dry ports in 2010	18	61
Liner shipping connectivity index(LSCI) ³ in 2012 by UNCTAD	156.19(ranked 1st)	41.29(ranked 32th)
Logistics performance index(LPI) ⁴ in 2012 by World Bank	3.52 (ranked 24th)	3.08 (ranked 45th)

3 Liner shipping connectivity index(LSCI) is computed based on five components: (1) number of ships (2)their container-carrying capacity(3) maximum vessel size (4)number of services (5)number of relevant companies

4 Logistics performance index(LPI) is weighted on six key dimensions: (1)efficiency of the clearance process(2)trade quality and transport related infrastructure(3)ease of arranging priced shipments(4)quality of logistics services (5)ability to track consignments (6)expected delivery time

Table 4.2* Policy and Regulatory Regime Comparison between China and India in terms of Intermodal Development

Comparison Factors	China	India
Political system	<p>China is a centralised and autocratic political system:</p> <ol style="list-style-type: none"> (1) Central government uses the Five-Year Plans to develop economy. (2) Central planning can help China easily make national decisions. (3) Privatisation in China is primarily the joint venture which will retain government's control. (4) Intermodal development strategy has been added to China's national agenda as a means of environmental protection. 	<p>India is a democratic political system:</p> <ol style="list-style-type: none"> (1) Social distribution institution gets first priority in national decisions. (2) Usually, government needs a long time for making a big decision. (3) Privatisation in India is not popular due to its social institution settings. (4) A national intermodal strategy in India is missing.
Major relevant policies	<ol style="list-style-type: none"> (1) "Environmental Protection Law" enacted in 1989 is out of date and its amendment is on the way. (2) "Develop-the-West" strategy which will shift investment attention to inland intermodal transportation. (3) "Social Harmony" policy promotes the high-speed railway development which leads to railway freight capacity's increase. (4) 11th Five-Year plan (2006-2010) puts forward logistics and intermodal development as a national issue for the first time. 	<ol style="list-style-type: none"> (1) "Environment Protection Act of 1986" has helped India to protect its environment effectively. (2) India's national urban transport policy (NUTP) of 2006 highlights the need to reduce transportation emission. (3) "Dualistic policies" proposed by government balance the conflict between foreign investment and social distribution institution on dry port development. (4) "Major Ports Trust Act (MPTA)" has been criticised as the main stumbling block to the introduction of successful privatisation in India which may lag India's intermodal development.

Table 4.3* Potentials and Challenges' Comparison between China and India in terms of Intermodal Development

Factors affecting intermodal development	China		India	
	Potentials	Challenges	Potentials	Challenges
Rapid economic growth	✓		✓	
Unbalanced regional economic development		✓		✓
Political system	✓			✓
Systematic regulation and policy framework's missing in terms of intermodal development		✓		✓
Government' efforts on intermodal development	✓		✓	
Large land area	✓		✓	
Industrial sites far away from seaports	✓		✓	
Large population	✓		✓	
Geographical conditions for intermodal development	✓		✓	
Trade type (China is export oriented while India is import oriented)	✓			✓
Rapid urbanisation	✓		✓	
WTO membership	✓		✓	
The level of logistics management		✓		✓
Low degree of containerisation		✓		✓
Roadway links		✓		✓
Current railway freight capacity		✓		✓
High-speed railway links	✓			✓

Factors affecting intermodal development	China		India	
	Potentials	Challenges	Potentials	Challenges
Double stack railway system		✓	✓	
Inland waterway links	✓			✓ (almost not available)
Rapid growth of seaport traffic	✓	✓	✓	✓
Fierce seaport competition	✓		✓	
Unbalanced seaport development	Better situation in China			✓
Seaport infrastructure development	✓			✓
Inland dry port infrastructure development	✓			✓
The number of inland dry port		✓	✓	
Private investment on intermodal development	✓			✓
The degree of privatisation in the entire transport sector	✓			✓
Insufficient electricity resource	Better situation in China			✓

*Main sources for the above three tables (Table 4.1, Table 4.2 and Table 4.3): compiled by the author based on (1)(World Bank, 2012); (2)(International Monetary Fund, 2012); (3)(Carbon Tax Centre, 2013); (4)(FHWA, 2007); (5)(OECD, 2012); (6)(CONCOR, 2012);(7)(Central Intelligence Agency (CIA), 2012); (8)(China Ports Year Book, 2010);(9) (Sustainable Urban Transport Programme, 2011); (10) (Haralambides and Behrens, 2000); (11)(Pucher et al., 2007); (12)(Postigo, 2008);(13) (Kim and Nangia, 2008); (14) (Ng and Gujar, 2009)

4.5 Chapter summary

This chapter attempts to compare the potentials and challenges of port hinterland intermodal development between China and India, the two fastest-growing economies in Asia. Both countries possess immense potential in terms of port hinterland intermodal development. Their high prospects for future development are not difficult to foresee, because of their fast speeds of economic development, vast hinterlands, and huge populations. However, they also encounter common problems in terms of insufficient infrastructure, absence of favourable regulation and legal support, and a low degree of privatisation and deregulation. Although they share a lot of common characteristics, they also have many different individual problems to solve. In India, its unique social institution problem gives rise to a bigger challenge compared to its shortcomings in intermodal infrastructure. Such a problem is not present in China. India leads China in having number of inland dry ports. However, China is fast catching up. In 2006, the Chinese central government put intermodal development as its national strategy, while a similar strategy is missing in India.

Chapter 5 A bi-objective tactical level intermodal optimisation model under environmental constraints⁵

This chapter (Chapter 5) aims to develop a bi-objective optimisation model for the tactical planning of sea-and-land intermodal container flows that takes into consideration environmental concerns to fill the existing research gap which had been discovered and was then described in Chapter 2. This tactical model has two objectives: the minimisation of both transportation cost and transit time. This reflects the need for a diversified market as some customers demand the lowest freight rates while some others would rather pay more for a faster delivery. Carbon footprint restriction is incorporated in the model as a constraint to represent the environmental protection requirement. The modelling work is relevant to shipping businesses and one-stop logistics service providers.

An enhanced NSGA-II method (elitist non-dominated sorting genetic algorithm) is proposed in order to solve this model, because this model is an integer linear type of programming which is an NP-hard problem. When the variable size of an NP-hard problem increases, even for a moderate scale instance, the NP-hard problem needs a huge computing time (i.e. many years) by using exact algorithms to search the optimal results (Chvátal and Hammer, 1977; Schrijver, 1986; Toth, 2000; Sierksma,

⁵ The following publications from the author are based on this chapter:

Gu, Y., Lam, J. S. L. and Zhang, A. (2012), "Bi-objective Optimisation for Sea-and-land Intermodal Container Flows with Environmental Concerns", Proceedings of International Association of Maritime Economists Conference, Taipei, Taiwan.

Gu, Y. and Lam, J. S. L.(2013), "Port Hinterland Intermodal Network Optimisation for Sustainable Development: A Case Study of China", Proceedings of International Forum on Shipping, Ports and Airports Conference, Hong Kong, China.

2002; Rader, 2010). Hence a heuristic method should be invented to solve this problem. The NSGA-II method is widely accepted as the most popular evolutionary algorithm to solve multi-objective optimisation problems and its selection mechanism (retaining mechanism) is enhanced to efficiently accelerate its convergent speed in this research. This specific retaining mechanism is an improvement over the standard NSGA-II, and hence we refer to it as an enhanced NSGA-II. It can guarantee a higher chance of achieving good solutions to the next generation. The model is applied to a case study of intermodal container flows in China which is a medium-scale problem, and the enhanced NSGA-II's results are compared with CPLEX's results to test the enhanced NSGA-II's performance. It is shown that the enhanced NSGA-II is able to obtain near-optimal solutions while CPLEX cannot solve large-scale problem instances. This model can achieve efficient bi-objective optimisation along with the consideration of different carbon footprint restriction scenarios for the planning of intermodal container flows. Analysis based on the results and implications for policy are given accordingly.

5.1 Problem description and model development

5.1.1 The sea-and-land intermodal container transport problem

As mentioned in previous chapters, a growing number of logistics and transport operators act as freight integrators. These include shipping lines that now provide door-to-door services to their landlocked end-customers. Different transport operators have different business operation modes. Some transport operators operate their own inland transport network, while some others prefer outsourcing part of their transport operations. In both cases, transport operators need to understand how to optimise transport planning based on customer requirements and infrastructure settings. Usually the operators' first concern is to minimise their transportation cost. However, under the market-driven business environment, they also need to meet the transit time requirements of customers. At the same time, they have to comply with carbon footprint restrictions.

Figure 5.1 Port hinterland intermodal container transport network

Source: Drawn by the author

This modelling work is for the tactical planning of port hinterland intermodal container flows. The detailed network is illustrated in Figure 5.1. For imports, containerised freights are shipped from many foreign seaports to many domestic seaports. After containers are discharged at domestic seaports, customs clearance is required before they can be routed through an inland transport network to end-customers' distribution centres in domestic inland cities. There are three available inland transportation modes from which a choice may be made: truck, railway and barge. Where there are available rail linkages or barge ports nearby, line-haul may be carried out by rail or barge before last-mile delivery by truck. Where such facilities do not exist, the transportation of containers from domestic seaports to end-customers may be conducted entirely by truck. With the same reasoning, export container flows start from inland cities and progress through the inland transport network and domestic seaports before their arrival at foreign seaports.

5.1.2 A bi-objective tactical level optimisation model

This model has two objectives: transportation cost minimisation and transit time minimisation. Bi-objective optimisation is more reasonable and practical than single-objective optimisation. In real-world situations, decision makers often need to deal with conflicting objectives. Cost and transit time are the two most common considerations in transport planning problems. This model is formulated in a setting where a major shipping line, also operating as a freight integrator, is the decision maker. It is assumed that there is no capacity constraint for container transport in the sea leg for this tactical level model. On the tactical level, the liner shipping network optimisation problems in the sea leg have been well-studied and are not our focus in this research. Our main concern is put on the inland container routing optimisation and its modal split situation which can reveal tactical policy implications and serve as references for decision makers. Hence a relaxed assumption is set on the capacity constraint of the sea leg. This assumption is also practical due to over-supply of ships in the market in recent years. Transit times are assumed to be deterministic for all transportation modes. To analyse the effect of different carbon emission requirements on transport planning, carbon emission

restrictions set by the government for transport operations are considered as a model constraint.

This model is formulated with reference to the container transport network optimisation literature, including the works of Altiparmak et al. (2006), Kim et al. (2008), and Jawahar and Balaji (2009). After defining model parameters and decision variables, the model formulation and its associated explanation are presented as follows.

Model Formulation

Table 5.1 Set description in the tactical model

Set	Description
N	A set of nodes, let $N = F \cup C \cup D \cup B \cup I$, while F stands for foreign seaports, C stands for domestic seaports, D stands for dry ports, B stands for barge ports, I stands for inland cities.
A	A set of arcs, let $A = A_{FC} \cup A_{CF} \cup A_{CD} \cup A_{DC} \cup A_{CB} \cup A_{BC} \cup A_{CI} \cup A_{IC} \cup A_{DI} \cup A_{ID} \cup A_{BI} \cup A_{IB}$, For each $(i, j) \in A_{XY}$, (i, j) denotes the arc from $i \in X$ and $j \in Y$, and $X, Y \in \{F, C, D, B, I\}$.

Table 5.2 Decision variable description in the tactical model

Decision Variable	Description
TCM_{ij}	Total container transport quantity from node n_i to n_j in TEUs, $(i, j) \in A$
ECM_{ij}	Empty container transport quantity from node n_i to n_j in TEUs, $(i, j) \in A_{FC} \cup A_{CF}$
LCM_{ij}	Laden container transport quantity from node n_i to n_j in TEUs, $(i, j) \in A_{FC} \cup A_{CF}$
$VNUM_{ij}$	Number of deployed vehicles from node n_i to n_j , $(i, j) \in A$ while $n_i, n_j \notin F$

Table 5.3 Parameter description in the tactical model

Parameter	Description
K	Average carbon footprint limitation of this network per TEU in kg
$cIMCS$	Customs clearance cost for import laden container per TEU
$cEXCS$	Customs clearance cost for export laden container per TEU
$cIMO$	Other miscellaneous cost for import container per TEU
$cEXO$	Other miscellaneous cost for export container per TEU
$amountX_{ij}$	Container quantity per vehicle on the arc $(i, j) \in A$
$fixX_{ij}$	Fixed cost per vehicle on the arc $(i, j) \in A$
spM_i	Container supply quantity of node n_i in TEUs, $n_i \in F \cup I$
dmM_i	Container demand quantity of node n_i in TEUs, $n_i \in F \cup I$
$spEM_i$	Empty container supply quantity of node n_i in TEUs, $n_i \in F$
$dmEM_i$	Empty container demand quantity of node n_i in TEUs, $n_i \in F$
cap_i	Container throughput capacity of node n_i in TEUs, $n_i \in C \cup D \cup B$
cHC_i	Container handling cost in node n_i per TEU, $n_i \in C \cup D \cup B$
tHT_i	Container handling time in node n_i per TEU, $n_i \in C \cup D \cup B$
cST_i	Container storage cost in node n_i per hour per TEU, $n_i \in C \cup D \cup B$
tST_i	Container storage time in node n_i per TEU, $n_i \in C \cup D \cup B$
cTP_{ij}	Transportation cost from node n_i to n_j in US\$ per TEU, $(i, j) \in A$
tTP_{ij}	Transportation time from node n_i to n_j in hours, $(i, j) \in A$
gTP_{ij}	Transportation carbon footprint from node n_i to n_j in kg per TEU, $(i, j) \in A$

Parameter	Description
$avNUM_{ij}$	Available vehicle number from node n_i to n_j , $(i, j) \in A$ while $n_i, n_j \notin F$

Two Objective functions:

Minimise Cost= (

$$\begin{aligned}
& \sum_{(i,j) \in A} cTP_{ij} \times TCM_{ij} + \sum_{(i,j) \in A} 2 \times (cHC_i) \times TCM_{ij} + \sum_{(i,j) \in A, n_i \notin F \cup I} (cST_i \times tST_i) \times TCM_{ij} + \\
& \sum_{(i,j) \in A_{FC}} (cIMCS + cIMO) \times LCM_{ij} + \sum_{(i,j) \in A_{CF}} (cEXCS + cEXO) \times LCM_{ij} \\
& + \sum_{(i,j) \in A_{FC}} cIMO \times ECM_{ij} + \sum_{(i,j) \in A_{CF}} cEXO \times ECM_{ij} + \sum_{(i,j) \in A, n_i \notin F, n_j \notin F} fixX_{ij} \times VNUM_{ij} \\
&) \div \sum_{i \in F} (spM_i + dmM_i)
\end{aligned} \tag{1}$$

Minimise Time= (

$$\begin{aligned}
& \sum_{(i,j) \in A} tTP_{ij} \times TCM_{ij} + \sum_{(i,j) \in A} 2 \times (tHT_i) \times TCM_{ij} + \sum_{(i,j) \in A, n_i \notin F \cup I} tST_i \times TCM_{ij} \\
&) \div \sum_{i \in F} ((spM_i + dmM_i) \times 24)
\end{aligned} \tag{2}$$

Constraints:

$$\sum_{(i,j) \in A} (gTP_{ij} \times TCM_{ij}) \div \sum_{i \in F} (spM_i + dmM_i) \leq K \tag{3}$$

$$\sum_{(k,i) \in A} TCM_{ki} = \sum_{(i,j) \in A} TCM_{ij}, \forall n_i \in C \cup D \cup B \tag{4}$$

$$\sum_{(i,j) \in A} TCM_{ij} = spM_i, \forall n_i \in F \cup I \tag{5}$$

$$\sum_{(i,j) \in A} TCM_{ij} = dmM_j, \forall n_j \in F \cup I \tag{6}$$

$$\sum_{(i,j) \in A_{FC}} ECM_{ij} = spEM_i, \forall n_i \in F \tag{7}$$

$$\sum_{(i,j) \in A_{CF}} ECM_{ij} = dmEM_j, \forall n_j \in F \tag{8}$$

$$VNUM_{ij} \leq avNUM_{ij}, \forall (i, j) \in A, n_i \notin F, n_j \notin F \tag{9}$$

$$TCM_{ij} \leq amountX_{ij} \times VNUM_{ij}, \forall (i, j) \in A, n_i \notin F, n_j \notin F \quad (10)$$

$$\sum_{(i,j) \in A} TCM_{ij} \leq cap_i, \forall n_i \in C \cup D \cup B \quad (11)$$

$$TCM_{ij} = ECM_{ij} + LCM_{ij}, (i, j) \in A_{FC} \cup A_{CF} \quad (12)$$

$$TCM_{ij} \in \mathbb{Z}^+, \forall (i, j) \in A \quad (13)$$

$$ECM_{ij} \in \mathbb{Z}^+, \forall (i, j) \in A_{FC} \cup A_{CF} \quad (14)$$

$$LCM_{ij} \in \mathbb{Z}^+, \forall (i, j) \in A_{FC} \cup A_{CF} \quad (15)$$

$$VNUM_{ij} \in \mathbb{Z}^+, \forall (i, j) \in A, n_i, n_j \notin F \quad (16)$$

The objective function (1) minimises total average costs of laden and empty containers flowing through the transport network. They include transportation cost, terminal handling cost, storage cost, customs clearance cost and fixed cost of using inland vehicles (trucks, trains and barges). The objective function (2) minimises total average transit times per day (needs to divide by 24) of laden and empty containers flowing through the transport network. They include transportation time, terminal handling time and storage time. Constraint (3) represents the carbon footprint restrictions set by the government or international convention. Constraint (4) balances container in-flows and out-flows at transport nodes. Constraints (5) and (6) are supply and demand constraints of total containers. Constraints (7) and (8) are supply and demand constraints of empty containers. Constraint (9) sets the number of available vehicles in each inland arc. Constraint (10) defines the relationship between container transport quantity and the number of available vehicles in each inland arc. Constraint (11) is a capacity constraint of transport nodes. Constraint (12) defines the relationship of total container transport quantity, laden container transport quantity and empty container transport quantity in transport arcs. Constraints (13) - (16) define the characteristics of decision variables.

5.2 Solution method: The bi-objective three-stage enhanced NSGA-II

For this bi-objective model presented above, the Pareto Optimal method is used to find the trade-offs on the Pareto frontier (Nakayama and Sawaragi, 1984). It should

be noted that the model is non-deterministic polynomial-time hard (NP-hard) due to the existence of integer variables (Lodi, 2010). Small- and medium-problem instances can be solved through commercial solver CPLEX 12.4. The interface named “YALMIP” is used (Löfberg, 2004) between the CPLEX and MATLAB platforms to call and run the CPLEX solver. For large-problem instances, an enhanced NSGA-II (elitist non-dominated sorting genetic algorithm) is proposed to obtain near-optimal solutions. This enhanced NSGA-II is also coded in the MATLAB platform.

As noted in Chapter 3, Genetic Algorithm (GA) has become increasingly popular in optimisation problems, and multi-objective optimisation becomes one of the fastest growing areas of operational research in recent years. Multi-objective optimisation problems are crucial because of the multi-objective nature of most real-world decisions. NSGA-II can help avoid the conventional problems of evolutionary algorithms such as premature convergence. It is widely accepted as the most popular evolutionary algorithm to solve optimisation problems having two or more objectives (KanGAL, 2013).

5.2.1 Representation of chromosome

Matrix-based notation is widely applied in linear programming (LP) problems. The transportation problem can be treated as a special case of LP which deals with the problems of searching the optimal allocation schedule to minimise the total shipping cost between O origins and D destinations under some resource constraints. Vignaux and Michalewicz (1991) is the first paper to use GA for solving the linear transportation problem where matrix-based representation has been used. The transportation LP problem can be conveyed as follows:

$$\text{Minimize} \sum_{i=1}^O \sum_{j=1}^D c_{ij} \times x_{ij} \quad (17)$$

Subject to:

$$\sum_{i=1}^O x_{ij} \geq a_j, \quad \forall j \in D \quad (18)$$

$$\sum_{j=1}^D x_{ij} \leq b_i, \quad \forall i \in O \quad (19)$$

$$x_{ij} \geq 0, \quad \forall i \in O, j \in D \quad (20)$$

Where x_{ij} represents the amount transported from origin i to destination j , c_{ij} represents the cost per unit from origin i to destination j , a_j represents the demand of destination j , and b_i represents the supply of origin i (Ramadan and Ramadan, 2012).

Based on the basic matrix-based notation approach above, the enhanced NSGA-II algorithm process can be divided into three stages (each stage is a matrix-based presentation), taking the import flows from foreign seaports to inland cities $F \rightarrow I$ as an example to illustrate:

(1) “**Stage One**” presents the relationship between F and C (import direction).

Figure 5.2 “Stage One” in Chromosome

Source: Drawn by the author

- (2) “**Stage Two**” presents the relationship between C and D; C and B (import direction).

Figure 5.3 “Stage Two” in Chromosome

Source: Drawn by the author

- (3) “**Stage Three**” presents the relationship between C, D, B and I (import direction).

Figure 5.4 “Stage Three” in Chromosome

Source: Drawn by the author

Now the model can be analysed from “Stage Three” to “Stage one”. The demand of “I” should be fulfilled by “C”, “D” or “B”. The corresponding chromosome segment of the “Stage Three” can generate the supply of “C”, “D” and “B”. In “Stage Two”, the supply of “D” and “B” of “Stage Three” becomes the demand, and the chromosome segment of “Stage Two” can help to get the supply of “C”. The total supply of “C” in “Stage Three” and “Stage Two” can transfer into demand of “Stage One”. The problem could become a simple problem from supply “F” to demand “C”. The chromosome segment of “Stage One” could provide this solution. In this three-stage supply-demand matrix-based chromosome presentation, the row sums of “F” in “Stage One” as supply requirements and the column sums of “I” in “Stage Three” as demand requirements are given and need to be fulfilled finally.

5.2.2 Population chromosome initialisation for each stage

Based on the above illustration about the three-stage chromosome presentation and the supply-demand relationships between “Stage One” and “Stage Two”, and between “Stage Two” and “Stage Three”, a three-dimension three-stage chromosome initialisation is applied (Gen and Cheng, 2000; Gen et al., 2006; Jawahar and Balaji, 2009). The third dimension is the population’s chromosome number of size N . It deserves to be highlighted that the row sums of “F” in “Stage One” as total supply and the column sums of “I” in “Stage Three” as total demand should finally be fulfilled. For each chromosome, the initialisation process of each stage is illustrated as follows:

$$[X_p] = \begin{bmatrix} x_{11}x_{12}\dots x_{1d} \\ x_{21}x_{22}\dots x_{2d} \\ \vdots \\ x_{o1}x_{o2}\dots x_{od} \end{bmatrix}$$

Begin

$$\pi \leftarrow \{1, 2, \dots, od\};$$

Repeat

Random select k from π ;

Calculate its row number i and column number j ;

$$i \leftarrow \lfloor (k-1)/d + 1 \rfloor;$$
$$j \leftarrow (k-1) \bmod d+1;$$

Give x_{ij} assignment as much as possible;

$$x_{ij} \leftarrow \min \{a_i, b_j\}; \text{ // } a_i \text{ and } b_j \text{ present the column sums and row sums which present}$$

the supply and demand requirements in each stage

Update data;

$$a_i \leftarrow a_i - x_{ij};$$
$$b_i \leftarrow b_i - x_{ij};$$
$$\pi \leftarrow \pi \setminus \{k\};$$

Until π is empty

End

5.2.3 Elitist non-dominated sorting genetic algorithm (NSGA-II)

Based on the standard NSGA-II, the enhanced NSGA-II's procedure is designed in order to accelerate its convergent speed and this is illustrated in Subsection 5.2.7.

The main parts of the standard NSGA-II's selection (elitist) module are illustrated, respectively, in the following (Deb et al., 2002):

5.2.3.1 Non-Dominated Sorting Process:

fast-non-dominated-sort (P)

```

for each  $p \in P$ 
   $S_p = \emptyset$ 
   $n_p = 0$ 
  for each  $q \in P$ 
    if  $(p < q)$  then // If  $p$  dominates  $q$ 
       $S_p = S_p \cup \{q\}$  //Add  $q$  to the set of solutions dominated by  $p$ 
    else if  $(q < p)$  then
       $n_p = n_p + 1$  //Increment the domination counter of  $p$ 
  if  $n_p = 0$  then //  $p$  belongs to the first front
     $p_{rank} = 1$ 
     $F_1 = F_1 \cup \{p\}$ 
     $i=1$  //Initialise the front counter
  while  $F_i \neq \emptyset$ 
     $Q = \emptyset$  //Used to store the member of the next front
    for each  $p \in F_i$ 
      for each  $q \in S_p$ 
         $n_q = n_q - 1$ 
        if  $n_q = 0$  then // $q$  belongs to the next front
           $q_{rank} = i + 1$ 
           $Q = Q \cup \{q\}$ 
     $i = i + 1$ 
     $F_i = Q$ 

```

5.2.3.2 Crowding Distance Assignment Procedure:

Step1: Let us calculate the number of solutions in F as $l = |F|$. For each i in the set, first assign $d_i = 0$.

Step2: For each objective function $m = 1, 2, \dots, M$, find the $f_m^{\max}$ and $f_m^{\min}$

Step3: For $m = 1, 2, \dots, M$, assign a large distance to the two boundary solutions ($d_{l1}^m = d_{ll}^m = \infty$), and other solutions from $j = 2$ to $(l - 1)$, assign:

$$d_j^m = d_j^m + \frac{f_m^{j+1} - f_m^{j-1}}{f_m^{\max} - f_m^{\min}}$$

5.2.3.3 Crowded Tournament Selection Operator:

A solution i wins a tournament with another solution j if any of the following conditions are true:

If solution i has a better rank, that is $r_i < r_j$ (the smaller the better).

If they have the same rank but solution i has a better crowding distance than solution j , that is $r_i = r_j$ and $d_i > d_j$ (the bigger the better).

5.2.3.4 The standard NSGA-II

The detailed algorithm of standard NSGA-II is illustrated in the following steps (Deb et al., 2002):

Step1: A random population P_0 of size N is generated.

Step2: The population is sorted into different non-dominated levels (The detailed process has been described in Subsection 5.2.3.1). Each solution is assigned a fitness equal to its non-dominated level (1 is the best level, then 2, 3...).

Step3: Crowded tournament selection (The detailed process has been described in Subsection 5.2.3.3), crossover and mutation operators are used to create an offspring population Q_0 of size N .

Step4: Combine parent and offspring population to get $R_t = P_t \cup Q_t$ of size $2N$. Perform a non-dominated sorting to R_t and identify different fronts: $F_i, i = 1, 2, \dots$

Step5: Set the next generation new population $P_{t+1} = \emptyset$. Set a counter $i = 1$. Until $|P_{t+1}| + |F_i| < N$, perform $P_{t+1} = P_{t+1} \cup F_i$ and $i = i + 1$. Perform the crowding-sort procedure and add the most widely spread ($N - |P_{t+1}|$) solutions by using the crowding distance values in the sorted F_i into P_{t+1} gradually, till the number of selected solutions in P_{t+1} is N . In the same front, the population is arranged in descending order of the crowding distance values (The crowding distance

calculation process has been described in Subsection 5.2.3.2).

Step6: Create offspring population Q_{t+1} from P_{t+1} by using the crowded tournament selection, crossover and mutation operators.

It is essential to highlight here that non-dominated sorting in Step4 and filling up population P_{t+1} can be performed together. That is to say every time a non-dominated front is found, its size can be checked to decide whether it can be filled into the new population entirely. If it can be filled entirely, no more sorting is needed which can save running time.

5.2.4 Crossover operation

The crossover is used to explore a new part of the solution space. The selection module in Subsection 5.2.3 cannot create any new chromosomes to the population. The creation of new chromosomes is accomplished in the crossover and mutation module. For each chromosome, a random number r_c is generated from the range $[0, 1]$. If $r_c < p_c$ (Given p_c) then this chromosome will have a crossover operation. In this research work, an original Three-Stage Chromosome Crossover Operator is designed by the author. The requirement of a crossover operation is that the two matrixes should have the same supply row sums and demand column sums. Some preparation work is needed before the crossover operation, because it cannot guarantee achieving two chromosomes as parents with the same supply-demand matrixes in each stage. For example, if two chromosomes are chosen as parents, it can be found that the row sums and column sums in each stage are not the same, although the final row sums of “F” and the final column sums of “I” are the same. The three-stage chromosome presentation is different from a simple one-stage chromosome presentation. A three-stage chromosome is selected initially as “Parent_X1” for the crossover operation. The row sums and column sums are calculated for each stage of the operation, and these sums are used to generate a new matrix for each stage, then a new chromosome is obtained with same row sums and column sums in each stage as “Parent_X2” for the crossover operation. The detailed process of the “Three-Stage Chromosome Crossover Operator” as designed by the author is illustrated as follows:

- (1) If probability $< P_c$, the crossover operation is deployed in each stage between these two elite parent chromosomes: Parent_X1 and Parent_X2.

Step1: Crossover operation happens between StageThree_matrix_Parent_X1 and StageThree_matrix_Parent_X2 to generate StageThree_matrix_Child_X1 and StageThree_matrix_Child_X2.

Step2: Crossover operation happens between StageTwo_matrix_Parent_X1 and StageTwo_matrix_Parent_X2 to generate StageTwo_matrix_Child_X1 and StageTwo_matrix_Child_X2.

Step3: Crossover operation happens between StageOne_matrix_Parent_X1 and StageOne_matrix_Parent_X2 to generate StageOne_matrix_Child_X1 and StageOne_matrix_Child_X2.

- (2) Till now, the Three-Stage Chromosome crossover operation is finished. After crossover operation, the three stage matrixes can be combined to get Child_X1 and Child_X2, respectively.

Child_X1: StageOne_matrix_Child_X1 + StageTwo_matrix_Child_X1 + StageThree_matrix_Child_X1

Child_X2: StageOne_matrix_Child_X2 + StageTwo_matrix_Child_X2 + StageThree_matrix_Child_X2

In the above “Three-Stage Chromosome Crossover Operator”, in each stage, the crossover operation between two parent matrixes is illustrated as follows (Gen and Cheng, 2000):

- (1) At beginning, two matrixes in each stage of parents are selected: $X^1 = (x_{ij}^1)$ and $X^2 = (x_{ij}^2)$.

- (2) There are three steps:

Step1: Build two temporary matrixes, $D = (d_{ij})$ and $R = (r_{ij})$,

$$d_{ij} = \lfloor (x_{ij}^1 + x_{ij}^2) / 2 \rfloor, r_{ij} = (x_{ij}^1 + x_{ij}^2) \bmod 2$$

Step2: Divide R into two matrixes, $R^1 = (r_{ij}^1)$ and $R^2 = (r_{ij}^2)$

$$R = R^1 + R^2$$

$$\sum_{j=1}^n r_{ij}^1 = \sum_{j=1}^n r_{ij}^2 = (1/2) \times \sum_{j=1}^n r_{ij}, \quad i = 1, 2, \dots, m$$

$$\sum_{i=1}^m r_{ij}^1 = \sum_{i=1}^m r_{ij}^2 = (1/2) \times \sum_{i=1}^m r_{ij}, \quad j = 1, 2, \dots, n$$

Step3: Generate two offspring: X'_1 and X'_2

$$X'_1 = D + R^1$$

$$X'_2 = D + R^2$$

Notes: If the row sums and column sums in each stage of these two offspring meet the requirements of supply and demand as their parents, the crossover operation is successful in this stage; if not, keep the same in this stage as parents.

5.2.5 Mutation operation

Similarly to crossover, mutation is also used to avoid premature convergence and to maintain diversity. However, unlike crossover, the mutation operator is usually a modified gene within a chromosome (Altıparmak et al., 2006).

The detailed mutation process designed by the author is illustrated as follows:

Step1: For each stage in each chromosome, a random number r_m is generated from the range $[0, 1]$. If $r_m < p_m$ (Given p_m) then mutation operation will happen independently.

Step2: In the next step, a random integer number r_x will be generated from the range $[1, \text{max row number}]$ as the mutation point.

Step3: The old chromosome matrix segment is replaced with a new matrix with row number $(\text{max row number} - r_x)$. The new chromosome segment should have the same row sums and column sums as the replaced old segment.

Chromosome Mutation Operator

If mutation happens, an example to show the process for each chromosome in each stage

Figure 5.5 Mutation Operator Illustration

Source: Designed and Drawn by the author

5.2.6 Pareto solutions

The Pareto Optimal method is used to find the trade-offs on the Pareto frontier in the bi-objective optimisation problem (Nakayama and Sawaragi, 1984). The Pareto solutions can be achieved by the following process:

Let E be the Pareto solutions at current iteration t , i_max be the max number of iteration given in advance, and the procedure is given as follows:

Step1: Set iteration $k=1$, and $E(t) = \{\emptyset\}$.

Step2: If $k > i_max$, then stop. Otherwise, go to step3.

Step3: Evaluate chromosome T_k and get solution vector $z_k = [z_1(T_k) z_2(T_k) \dots z_Q(T_k)]$

Step4: Compare it with all Pareto solutions in E .

If it is dominated by one Pareto solution, go to step5.

If it dominates some Pareto solutions, add it into E and delete solutions dominated by it.

If it is a new Pareto solution and dominates none of existing ones, simply add it into E .

Step5: Set $k=k+1$ and go back to step 2.

5.2.7 Overall procedure of the enhanced NSGA-II

Based on the standard NSGA-II with original additions in crossover and mutation as explained above, the enhanced NSGA-II is developed. From the procedure detailed below, it can be found that the $3*N$ population can be collected for the next generation from three modules, respectively: the Tournament Selection Module, the Crossover Module and the Mutation Module. This specific retaining mechanism can guarantee a higher chance of good solutions to the next generation. Hence it can help to speed up the convergence process. Once a good solution is generated, the probability of its being kept in the population is higher, and this can help avoid being knocked out from the current population. The overall procedure of the enhanced NSGA-II designed by the author is illustrated in steps as follows:

Step1: Set current generation $i = 0$ initially.

Step2: A random population P_i is initialised with population size of $2*N$ with three stage chromosomes.

Step3: Perform non-dominated sorting over the population P_i to assign the rank level and crowding distance value to each chromosome.

Step4: If the current generation $i \leq \text{Generation}_{\max}$, perform tournament selection on the population P_i to generate mating pool M_i with population size of $1*N$. If the current generation $i > \text{Generation}_{\max}$, go to **Step 13**.

Step5: A random crossover fraction number N_{rc} between $[0, 1]$ is generated. P_c is set as the crossover probability. If $N_{rc} \leq P_c$, perform crossover operation on mating pool M_i to generate offspring pool $O1_i$ with population size of $1*N$. If $N_{rc} > P_c$, crossover operation will not happen, then set $O1_i == M_i$.

Step6: A random mutation fraction number N_{rm} between $[0, 1]$ is generated. P_m is set as the mutation probability. If $N_{rm} \leq P_m$, perform mutation operation on offspring pool $O1_i$ to generate offspring pool $O2_i$ with population size of $1*N$. If $N_{rm} > P_m$, mutation operation will not happen, then set $O2_i == O1_i$.

Step7: Combine M_i , $O1_i$ and $O2_i$ to get an intermediate population pool IT_i with population size of $3*N$.

Step8: Perform non-dominated sorting over the intermediate population pool IT_i to assign the rank level and crowding distance value to each chromosome.

Step9: Perform tournament selection on the intermediate population pool IT_i to get an elite population pool E_i with population size of $1*N$.

Step10: Initialise a new population N_i with population size of $1*N$.

Step11: Combine E_i and N_i to get the population pool P_{i+1} with population size of $2*N$.

Step12: Let $i=i+1$ and go back to Step 3.

Step13: Exit the iteration.

5.3 Model application to the Chinese intermodal network

5.3.1 Case description

After explaining the solution method above, this section (Section 5.3) applies the model to a case study of intermodal container transport in China. China is a large economy undergoing rapid development and is a country with a vast continental area. China's continued economic rise has had a significant impact on the global economy in terms of trade patterns and orientation. The rapid economic growth of China has brought about the prosperity of its maritime industry, and in turn its maritime industry development speeds up and promotes its global competitiveness. In particular, the hinterland area of the Yangtze River in Central China is selected as our focus. The Yangtze River is the longest river in China and is one of the main arteries of waterway container traffic. Shanghai Port sits at the mouth of the Yangtze River. Not far away from Shanghai Port, Ningbo-Zhoushan Port is a new rising port. Shanghai Port and Ningbo-Zhoushan Port are chosen as the two domestic seaports in the case study. Both ports have achieved extraordinary container traffic growth in the past ten years. Since 2010, Shanghai Port has been the world's top busiest container port in terms of throughput volume. Ningbo-Zhoushan Port has maintained its ranking as the 6th top container port since 2010 (Marine Department, 2012).

Twenty-five foreign seaports are included in this case study. These 25 foreign seaports are heavily involved in Mainland China's international trade. They are Los Angeles, Long Beach, Seattle, Oakland, New York, Boston, Miami, Rotterdam, Antwerp, Hamburg, Le Havre, Kobe, Tokyo, Yokohama, Osaka, Tanjung Pelepas, Port Klang, Singapore, Hong Kong, Busan, Inchon, Gwangyang, Kaohsiung, Keelung and Taichung. Regarding the hinterland setting, three main inland transport modes are included which are truck, rail and barge. Since this tactical model is applied to the Yangtze River and its hinterland, hence barge transport is available under this background. The selected hinterland area of Shanghai and Ningbo-Zhoushan ports includes Shanghai Municipality, Jiangsu Province, Zhejiang

Province, Anhui Province, Jiangxi Province, Hubei Province and Hunan Province. Five big cities are chosen as inland city nodes from for each province. In total, there are 30 selected inland cities. Based on the current infrastructures situation in Mainland China, five railway-linked dry ports in Suzhou, Hangzhou, Nanjing, Wuhan and Changsha and three barge ports in Suzhou, Nanjing and Wuhan are considered.

The case study assumes that there are 80% and 20% empty containers for import and export, respectively, in Mainland China (Rodrigue, 2007). It is assumed that the total supplies are equal to the total demand at the two ends. Detailed supply and demand requirements are given in the following table (Table 5.4):

Table 5.4 Given supply-demand in both import/export directions

Supply-demand in import network to China(in TEUs) in one planning period (1 month) (F: Foreign Seaports / I: Inland Cities)	Supply-demand export network from China(in TEUs) in one planning period (1 month) (F: Foreign Seaports / I: Inland Cities)
F_supply=[600 600 600 600 600 600 600 600 600 600 600 1800 1800 1800 1800 3120 3120 3120 3120 3120 3120 3120 3120 3120 3120 3120]	F_demand=[600 600 600 600 600 600 600 600 600 600 600 1800 1800 1800 1800 3120 3120 3120 3120 3120 3120 3120 3120 3120 3120 3120]
I_demand=[1500 1500]	I_supply=[1500 1500]
The ratio of empty container to laden container in import direction is 4:1 as stated above	The ratio of empty container to laden container in export direction is 1:4 as stated above

Source: Compiled by the author

The customs clearance costs per TEU are \$120 and \$100, respectively, for import- and export-laden containers. The port handling costs per TEU amount to \$165 and \$85, respectively, for import and export containers. It is supposed that one road truck carries two TEUs, one rail truck can carry 100 TEUs, and one barge can carry 500 TEUs per trip. Other main variable parameters are given in Table 5.5.

Table 5.5 Main variable parameters for cost, time and carbon emission's calculations

	Ship	Rail	Barge	Truck
Variable transportation cost (\$/km)	0.19	0.5	0.17	2
Average speed (km/hour)	40	70	30	70
Carbon footprint (Kg/km)	0.084	0.205	0.084	0.472

Source: Compiled by the author

Data sources: Compiled from the technical report (TEMS, 2008), “BLM-Shipping” professional software, the website of Ministry of transport of China, and (Maersk Line, 2012).

5.3.2 Experimental results and scenario analysis

In this Subsection 5.3.2, the preliminary results are presented to assess the bi-objective three-stage enhanced NSGA-II algorithm. This case can be solved by using CPLEX 12.4 (25 foreign seaports, 30 Chinese inland cities, 2 Chinese domestic seaports, 3 Chinese barge ports, and 5 Chinese dry ports) because this case study is a medium-scale instance. Here the Pareto Frontiers of CPLEX are obtained by plotting some dots which represent different trade-offs between costs and transit times. Some transit times are selected from within the feasible solution space, and they are then set as a model constraint to obtain optimal results of costs. Hence the results of the enhanced NSGA-II can be compared with the results of CPLEX for the medium-scale instance to assess the performance of the enhanced NSGA-II. Here the carbon emission constraint K value is set above the extreme value of 530kg, as 590kg per TEU (Scenario 1) and 560kg per TEU (Scenario 2), respectively. If the K value is set as 530kg per TEU, no optimal result will be achieved by either method. In the following parts, Table 5.6 and Table 5.7 are used to compare the results of CPLEX and the enhanced NSGA-II (100th generation) where K=590 and K=560. Although there exists a randomness mechanism in the NSGA-II algorithm, after a long evolutionary process of enough generations, its near-optimal solutions converge to the global exact optimal solutions with a low-standard deviation. This case is tested and run about 20 times (different population sizes, maximum generation settings, crossover rates and mutation rates) by using this enhanced NSGA-II algorithm and it is found that, after the evolution of many generations, the convergence rate is very similar. More generation evolutions will be closer to exact optimal solutions but need more CPU time consumption. The time values of optimal nodes on the Pareto Front of the enhanced NSGA-II are used

as input values into CPLEX to find the exact optimal results of cost values. Then a comparison between the enhanced NSGA-II and CPLEX cost values is conducted accordingly. The scale of the problem is increased (using some random virtual data of distances between two linked nodes), e.g. 50 foreign seaports, 100 Chinese inland cities, 8 Chinese domestic seaports, 8 Chinese barge ports, and 20 Chinese dry ports. CPLEX cannot solve such a large-scale case, but it can be handled by the enhanced NSGA-II.

Table 5.6 Scenario 1: Results comparison between CPLEX and the enhanced NSGA-II (K=590)

CPLEX 12.4 Solver		The enhanced NSGA-II 100th generation (population size=50,max generation=100,crossover rate=0.8,mutation rate=0.3)		Gap(%) = Cost(the enhanced NSGA-II)-Cost(CPLEX) / Cost(CPLEX)*100%
Average Time per TEU	Unit Cost per TEU	Average Time per TEU	Unit Cost per TEU	
17.7273	1998.2575	17.7273	2055.6410	2.87
18.1893	1977.3835	18.1893	2024.7187	2.39
17.8458	1992.9109	17.8458	2051.1011	2.92
17.9856	1986.5990	17.9856	2032.5570	2.31
18.1882	1977.4310	18.1882	2026.3489	2.47
17.8405	1993.1560	17.8405	2052.4192	2.97
17.7355	1997.9091	17.7355	2054.8351	2.85
17.9849	1986.6304	17.9849	2032.6631	2.32
18.1884	1977.4212	18.1884	2026.2892	2.47
17.8447	1992.9741	17.8447	2051.5010	2.94
17.7275	1998.2512	17.7275	2055.6172	2.87
18.5403	1966.5163	18.5403	2006.0360	2.00
Standard Deviation of GAPS=0.32%				Average Gap=2.62%

Source: Compiled by the author

Table 5.7 Scenario 2: Results comparison between CPLEX and the enhanced NSGA-II (K=560)

CPLEX 12.4 Solver		The enhanced NSGA-II 100th generation (population size=50,max generation=100,crossover rate=0.8,mutation rate=0.3)		Gap(%) = Cost(the enhanced NSGA-II)-Cost(CPLEX) / Cost(CPLEX)*100%
Average Time per TEU	Unit Cost per TEU	Average Time per TEU	Unit Cost per TEU	
18.5158	1967.1691	18.5158	2017.3882	2.55
18.2141	1976.2603	18.2141	2030.8802	2.76
18.2353	1975.3105	18.2353	2024.2106	2.48
18.7045	1962.2334	18.7045	2003.7420	2.12
18.2164	1976.1599	18.2164	2030.1852	2.73
18.2284	1975.6033	18.2284	2024.3797	2.47
Standard Deviation of GAPS=0.24%				Average Gap=2.52%

Source: Compiled by the author

Figure 5.6 Pareto Front when K=590 (Scenario 1)

(CPLEX results in above figure, the enhanced NSGA-II results in below figure)

Source: Drawn by the author

Figure 5.7 Pareto Front when K=560 (Scenario 2)

(CPLEX results in above figure, the enhanced NSGA-II results in below figure)

Source: Drawn by the author

As it can be observed from Table 5.6 and Table 5.7, the enhanced NSGA-II can find solutions that are really close to the exact optimal solution solved by CPLEX when the case scale is one that is medium and can be solved by CPLEX. The average gap is 2.62% (from 2% to 2.97%) in Scenario 1, and the average gap is 2.52% (from 2.12% to 2.76%) in Scenario 2. Both are within an acceptable range (smaller than 5%) (Coello and Lamont, 2004). Moreover, the standard deviations are 0.32% and 0.24% which means that until the 100th generation the convergence rate is high and stable. In both scenarios (Scenario 1 and Scenario 2), the Pareto Front curve range of the enhanced NSGA-II is shorter than CPLEX. This may be due to the

randomness mechanism of NSGA-II, which may not guarantee achievement of the boundary values as shown in CPLEX. The optimal solutions of Scenario 1 and Scenario 2 are combined in a single figure to get a clearer idea (CPLEX and the enhanced NSGA-II, respectively). The combined scenario figure of CPLEX (on the above of Figure 5.8) and the enhanced NSGA-II (on the below of Figure 5.8) are as follows:

Figure 5.8 Combined Scenario 1 and Scenario 2 in a single figure

(combined scenario figure of CPLEX in above figure; combined scenario figure of the enhanced NSGA-II in below figure)

(curve in black asterisk denotes K=590; curve in green circle denotes K=560)

Source: Drawn by the author

From the above combined scenario figure (Figure 5.8) of CPLEX and the enhanced NSGA-II, it can be discovered easily that a looser carbon emission constraint ($K=590$) will have a wider Pareto Frontier range than a tighter carbon emission constraint ($K=560$) no matter whether applying CPLEX or the enhanced NSGA-II. The Pareto Frontier of a tighter carbon emission constraint is part of the Pareto Frontier of a looser carbon emission constraint. It should also be noticed that a small change in K value will have a significant impact on the Pareto Frontier range. This is because the highest generator of carbon emissions is from sea-leg transport. Its transport distance represents a major share of the total intermodal chain's mileage. Nevertheless, this does not imply that it is not beneficial to address environmental concerns for inland transport planning.

Table 5.8 Average Container Distribution by Transportation Modes (Inland Modal Split)

	Scenario 1 ($K=590$ kg per TEU)	Scenario 2 ($K=560$ kg per TEU)
	Truck Mode Usage: 45%	Truck Mode Usage: 42%
CPLEX Solver	Rail Mode Usage: 36%	Rail Mode Usage: 38%
	Barge Mode Usage: 19%	Barge Mode Usage: 20%
	Truck Mode Usage: 44%	Truck Mode Usage: 41%
The Enhanced NSGA-II	Rail Mode Usage: 37%	Rail Mode Usage: 39%
	Barge Mode Usage: 19%	Barge Mode Usage: 20%

Source: Compiled by the author

From Table 5.8 about average inland container modal split ratios, it can be found that from Scenario 1 to Scenario 2 in both CPLEX and the enhanced NSGA-II, the usage rate of truck mode decreases while the usage rates of barge mode and rail mode increase. This finding is in line with the common understanding that, of the three transportation modes, barge is the most environmentally friendly and truck is the opposite. Through careful observation, it is found that in both Scenario 1 and Scenario 2, the usage rate of truck mode is dominant while the usage rate of barge mode is low. This is because, in this specific case study about China's Yangtze River basin, many inland cities do not have barge links or railway links to seaports. About 67% of inland cities have road links (truck) to seaports, while the rate of inland waterway links (barge) is 20% and the rate of railway links is 28%. These results relating to the modal split are due to the specific infrastructure situation in this case study.

5.3.3 Policy implications

Policy implications for sustainable development can be drawn from the findings in the previous Subsection 5.3.2. Reducing the dependence on trucking for inland transport is not only good for the environment, but also saves cost because it is more economical to transport cargoes over a long distance by railway or waterway. To reap the benefits, however, there must be substantial improvement in intermodal transport infrastructures, including not only inland railways and waterways, but also dry ports and barge ports. Thus, practical solutions can be generated addressing the important concerns of economic viability and environmental consequence simultaneously. With regards to macro impact, the results imply that the government has a responsibility to promote the use of inland railways and waterways where the geographical conditions allow for sustainable economic development. This will help to reduce the ratio of last-mile trucking mileage to the total intermodal chain's mileage.

The Pareto Frontier curves, in both Scenario 1 and Scenario 2, in both CPLEX and the enhanced NSGA-II (Figure 5.6 and Figure 5.7), can help us to find the different trade-offs regarding the choice of transportation mode. It can provide a portfolio choice to the customers, decision makers and service providers. This research work also suggests several policy implications. First, as long as inland waterways are available, barge is the most preferred transportation mode to lower cost and carbon emissions. Second, where natural waterways are not available, governments need to consider the development of the railway links and dry ports as a priority. Third, trucking has the shortest transit time, but incurs the highest cost and carbon emissions. Unless transit time is a major concern, trucking should not be encouraged for long-distance transport. Fourth, barge or railway intermodal transport provides opportunities to reduce the ratio of last-mile trucking mileage to the total transport mileage. This not only brings about economic benefits, but also better preserves the environment. Last but not least, tighter environmental regulations on carbon emissions favour barge and rail transport. However, more environmentally friendly transport modes require the development of supporting infrastructure including inland waterways, barge ports, railways and dry ports.

For the case of Mainland China, the Yangtze River is a natural corridor linking Western China and Eastern China. It can provide huge potential for reducing pollution in the transport sector in Mainland China if the Chinese government can focus on, utilise and explore the issues from a sustainable development perspective and purpose. The Chinese government has been promoting the development of Western and Central China by offering various investment incentives. In fact, the Chinese government has realised that inadequate transport infrastructure is a bottleneck to its economic development. Yu et al. (2012) discover that since 1994 the transport infrastructure growth of Mainland China has surpassed its GDP growth and this gap has been growing bigger since that time. Barge intermodal transport along the Yangtze River from upstream Chongqing to downstream Shanghai is deserving more attention. The central and local governments of China should coordinate their efforts in developing the inland Yangtze River barge system by, for example, dredging the Yangtze River, building new and upgrading existing barge terminals, introducing preferential policies and attracting more private inland barge shipping companies. Such a series of measures can change customers' previous impressions that the inland Yangtze River barge system's transport capacity and efficiency is low. This would lead to an increase in inland customers choosing the Yangtze River barge system as it would offer a low price but better quality service. In comparison with railways and highways, the development of the Yangtze River waterways would require less time and capital investment. Such a development would also bring about substantial economic benefits for export-oriented manufacturers in the hinterland because it is most cost effective to barge containers from inland provinces to coastal seaports. In Europe, the Rhine River has greatly benefited the transport and economic development of the Rhine-Scheldt Delta region. Similarly, the development of the Yangtze River waterways and barge ports could play a strategic role in stimulating the economic growth of Western and Central China (FHWA, 2007) while addressing ecological concerns.

The railway system in Mainland China is owned by the state and there is little involvement of private investment. Although many years ago some scholars recommended introducing private investment in Chinese Railways in order to

strengthen competition (Rong and Bouf, 2005), the Chinese Railway still maintains its own operation pattern today. A large portion of Chinese railway capacity is used for passenger transport due to the large population size, and thus limited capacity can be deployed for its freight transport. Fortunately, the Chinese government has recognised this problem, and has put much effort into its “High Speed Rail” system which can help release more capacity into its freight transport (Guo, 2010). Further reforms of the railway system in Mainland China are on the way. After the upcoming two sessions in Mainland China, its Ministry of Railways will be incorporated into its Ministry of Transportation. This reform of its organisation will promote a substantial development of China’s railway system. Although this development of its railway system is controlled by the Chinese central government, it presents an opportunity for dry port development in Mainland China. Many local governments have expressed a desire to build dry ports themselves by attracting private investment. In order to avoid over-development, local governments in Mainland China should adhere to good-practice planning for the development of its dry ports.

Currently, transport users have not paid all costs associated with their transport activities, especially the costs they impose on the environment. Usually, a transport user should pay the external costs, mainly in terms of congestion, air pollution, noise, and accident. Internalisation of the external cost is an instrument based on a comprehensive consideration of the fairness and efficiency of the transport market (Gibbons and Mahony, 2002). The external costs of road transport are generally larger than the external costs of barge and rail modes (Wang and Li, 2006). However, if full internalisation of the external costs of road transport happens, it may restrict the development of the road transport industry. In order not to affect the competitiveness of the road transport, governments should design the internalisation level of each transport mode based on its competitiveness in the integrated transport network. Liu (2005) conducts a research about the road transport between Chengdu and Chongqing in the southwest part of China. On the one hand, he finds that road transport in this area is competitive. On the other hand, this shows the degree of internalisation of external costs in terms of road transport in Chengdu-Chongqing area is insufficient. This is to say appropriately increasing the degree of

internalisation of external costs in this area will not affect the development of its road industry. Our research findings complement the above literature in assisting policy makers to choose various internalisation instruments on the external costs in the transport sector.

5.4 Chapter summary

In this chapter, a novel bi-objective integer linear programming mathematical model is designed to deal with tactical planning of intermodal container transport. As some major shipping lines venture into land transport to offer door-to-door solutions, there is an increasing need for simultaneous optimisation of container flows in both sea and land legs. Some shippers demand the lowest cost while some others look for fast delivery. In addition to the above two problems, shipping lines also need to address carbon footprint requirements. In answer to these challenges, we develop a bi-objective optimisation model to minimise cost and transit time for intermodal container transport in both sea and land legs, taking carbon footprint restriction into consideration.

Because CPLEX cannot handle large-scale integer problems, an enhanced NSGA-II algorithm is suggested and used in this tactical model to tackle large-scale instances. Its enhanced selection mechanism efficiently accelerates its convergent speed. Better solutions have higher possibilities of being retained as the next generations. A case study of intermodal container flows in China with a medium-sized case for both methods was carried out. Result comparison shows that the deviation of the enhanced NSGA-II from CPLEX is only 2%–3%. Hence, we can confidently use the enhanced NSGA-II to solve large-scale cases of this tactical model. Analysis based on the results and its implications for policy are given in this chapter.

In the next chapter, another mathematical model is developed and explored from an operational level to fill the research gap uncovered in Chapter 2 from another perspective.

Chapter 6 A bi-objective intermodal operational level optimisation model under three different environmental regulatory frameworks⁶

This chapter (Chapter 6) addresses the problem of optimising a trade-off between the minimum cost and minimum time in the operational-level planning of sea-and-land intermodal transport flows subject to the three main different environmental regulatory frameworks which are carbon tax, carbon emission trading scheme and direct restriction. This problem is formulated as a mixed-integer non-linear programming model. A case study on a Trans-Pacific container intermodal chain is conducted to illustrate the operational model's applicability and significance. The operational-level model in this chapter and the tactical-level model in Chapter 5 together formulate optimisation models at different levels in order to achieve the overall research objective of integrative and sustainable port hinterland intermodal development.

⁶ The following publication from the author is based on part of this chapter:

Gu, Y. and Lam, J. S. L.(2013), "Operational Level Sea-and-Land Intermodal Bi-objective Optimisation under Environmental Regulation Framework", Proceedings of International Association of Maritime Economists Conference, Marseille, France.

6.1 Background to the problem

The world would be very different if it were not for the existence of the container which was invented in the 1950s/1960s. Containerisation contributes to the world economy by greatly facilitating globalisation and world trade. In this regard, operational research on container routing is becoming more and more crucial. Every container in the transport network has its origin node and destination node. Usually the origin and destination of containers are located in two inland areas that are a great distance apart. The global intermodal network has the responsibility of carrying these inland-laden containers from the origin in one continent to the destination in another continent. For such long-distance and wide-ranging routes, an integrator is needed to ensure safe and efficient operations in the global intermodal network. Many major shipping lines have the capability and incentive to expand their services from a traditional shipping network to the one that is larger and includes the hinterland network pertaining to both the origin and the destination.

While transportation can improve people's daily life via passenger transport and freight transport, it is also a significant source of greenhouse gas (GHG) emissions. The transport sector accounts for approximately 15% of overall global GHG emissions and it has a high growth rate in terms of volume. From 1990 to 2007, this GHG emission growth rate was 45% (OECD, 2010). CO₂ (carbon dioxide) emission is a dominant source of GHG. The road transport sector is a dominant source in terms of GHG volume, while shipping is dominant in terms of GHG growth rate. It is estimated that from 2007 to 2030, the GHG emission growth rate will be 40% (OECD, 2010). There is a conflict between the growing demand for transport volume and urgent targets for reducing GHG emissions. Integration and optimisation of the global intermodal network can offer great potential for sustainable development to address this conflict. Environmental issues have been extensively researched, but quantitative models about environmental issues in transportation planning are relatively few (Rahimi et al., 2008; Shintani et al., 2010; Lam and Gu, 2013).

As stated in the previous chapters, there are three common inland transport modes: road, rail and inland waterway. Road transport is a dominant mode which is convenient for inland customers without too much installation cost. It can provide not only flexible and convenient first-mile and last-mile distribution in the door-to-door service networks, but also long-haul transportation. Although the road sector is indispensable in the global intermodal container door-to-door network, it cannot generate the economies of scale which can help reduce unit cost and unit carbon footprint. Hence a shortening of the total mileage in this network is needed. For inland long-haul mileage, rail, train and barge are preferred due to their cost-efficient and environmentally friendly characteristics. As traffic volume increases, the inland rail and waterway sectors will be even more essential in protecting supply chains from congestion due to inordinate delay in the inland road system.

Many efforts have been made by peer researchers to study pure maritime network design. However, very few efforts have been made to study the global intermodal network. It was suggested by one literature review article that a focus for future research could be the whole intermodal network that has extended from the traditional maritime supply chain (Christiansen et al., 2004). Another recent literature review paper (Lam and Gu, 2013) also presents a similar point of view, that rarely have papers considered both sea and land legs together in intermodal transport network optimisation. This research gap is also deduced in depth in Chapter 2.

There is growing interest in sustainable development and sustainable transportation (Litman and Burwell, 2006). On the whole, there exist three key approaches by which governments around the world are taking action to lower carbon emissions: carbon tax, carbon emission trading and direct restriction (ABC News in Australia, 2011). Moreover, in Lee et al. (2013)' paper, they have given a more comprehensive and updated summary. They summarise that till 2013, the International Maritime Organization (IMO) has studied the policy options for maritime carbon emission reduction, mainly including emissions standards, environmental indexing, voluntary agreements, carbon tax and carbon emission trading scheme. Among these policy options, the former three (i.e. emissions standards, environmental indexing and

voluntary agreements) follow the idea of a mandatory or voluntary approach, while the latter two (i.e. carbon tax and carbon emission trading scheme) are market-based approaches. Because the scope of this research is not only maritime shipping but also inland transportation, “direct restriction” can be treated as a typical representative among the former three policy options. Hence in this research, we conduct a comparison among carbon tax, carbon emission trading and direct restriction approaches.

Although carbon tax and carbon emission trading scheme both are market-based instruments, they have distinct operation mechanisms. In the carbon tax scheme, government imposes a tax on each unit of carbon emission. As such, the quantity of pollution reduced depends on the chosen level of the tax, which means that choosing the right tax level is the key point (Metcalf and Weisbach, 2009; Lee et al., 2013). About the carbon emission trading scheme, a central authority sets a maximum level of pollution, a cap, and distributes the cap among companies in the form of carbon emissions permits (Lohmann, 2006). The companies must have enough permits to cover their pollution. They can obtain their carbon emissions permits either through an initial allocation or auction, or through trading with other companies at a later date. To sum up, the carbon tax approach is a price intervention, while the carbon emission trading scheme is within the scope of quantity intervention. With regard to a direct restriction on carbon emission scheme, the government will impose a carbon emission restriction on each company in order to decrease the total carbon emission of the whole society. Unlike carbon tax and carbon emission trading schemes, direction restriction is not a market-based approach. However, all of these three regulatory frameworks can help to achieve the purpose of environmental protection, and the first two (carbon tax and carbon emission trading) are through cost-reduction incentives. Under the first two schemes, companies will reduce their carbon emissions consciously in order to achieve their cost-reduction targets.

6.2 A novel bi-objective operational-level optimisation model

The aim of this chapter is to develop a mathematical model for a global shipping line or integrator to design and plan its network, including both sea-leg and sub-hinterland network, from an operational level. There are two objectives in this model: cost minimisation and transit time minimisation. A comparative analysis among carbon tax, carbon emission trading scheme and direct restriction on carbon emission is also conducted.

From Figure 6.1 below, it can be seen that the seaborne distance is long, and this accounts for a large proportion of the whole intermodal chain. Port-to-port service is essential to link two separate and faraway hinterlands together. Port-to-port service can provide a lower cost than aviation service mainly due to its economy of scale. Hence for long-haul distance and large-scale transportation, maritime shipping is a dominant solution. Although the inland distance takes up less proportion than the seaborne distance, it also deserves our attention in order to improve the door-to-door service's efficiency and quality. When the laden containers arrive at specific seaports, waiting for import to land customer sites, or when inland customers decide to export their containers to another hinterland via some specific seaports, a decision should then be made as to which inland route should be used to meet different customers' requirements.

Figure 6.1 A Trans-Pacific case to illustrate the global intermodal network

Source: Drawn by the author

Assume that there is a global shipping line whose container transport system comprises the sub-hinterland network (truck, rail and barge) and the sub-maritime network. This shipping line not only needs to optimise its pure maritime network, but also needs to design its sub-hinterland network for a better global intermodal door-to-door service. Shipping lanes often involve seaports from many countries in order to attract more containers in practical operation. However, the research scope is chosen to be the Trans-Pacific trade between Mainland China and the United States. Two continents (Hinterland 1 and Hinterland 2 as shown in Figure 6.1) and their major seaports are considered in the research work in this chapter. Hence these shipping lanes only include such given seaports.

Before elaborating on the model, the main assumptions and all the symbols used in this model will be explained as follows:

6.2.1. Main assumptions

- (1) This study only considers this specific intermodal network for a specific shipping line/integrator. Hence it is supposed that this shipping line/integrator has enough ships for this network, without concerning charter in and out ships for this network. This assumption is reasonable because this shipping line/integrator can coordinate the whole of its resources among its networks. For example, it can deploy ships from its other networks to this network in order to achieve balance.
- (2) Suppose that each ship route is deployed with a given type of ship. It makes it easier for the liner shipping company to maintain a stable service frequency by achieving the same speed and capacity for each ship route. The service frequency is crucial for liner shipping (Wang and Meng, 2012).
- (3) Suppose that only inland D (standing for inland dry port) or B (standing for inland barge port) nodes have surplus empty containers to be transported to the I (standing for inland city) node which is deficient in empty containers in the sub-hinterland transport network. Empty containers should also be transported from ports with surplus empty containers to ports deficient of empty containers in the sea voyage.
- (4) Suppose that, in this network, the carbon emission is mainly generated from transport operation routing. No carbon emission is generated from the container loading and discharging operations. This assumption is also realistic because the main carbon emission comes from vehicles' fossil fuel consumption.

6.2.2. Model presentation

Table 6.1 Set description in the operational model

Set	Description
$N, N^o, N^d, I^o, D^o, B^o, P^o, I^d, D^d, B^d, P^d$	A set of inland nodes, let $N^o = I^o \cup D^o \cup B^o \cup P^o$, and $N^d = I^d \cup D^d \cup B^d \cup P^d$, then $N = N^o \cup N^d$. The superscript “o” means the nodes in origin inland, while the superscript “d” means the nodes in destination inland. N^o stands for inland nodes in origin inland, where N^d stands for inland nodes in destination inland. Where I stands for inland cities, D stands for inland dry ports, B stands for inland barge ports, P stands for seaports with export/import function in this network design.
D_{od}	A set of demand O-D pairs, from a specific inland city $o \in I^o$ to another inland city $d \in I^d$.
NSI, NSI^o, NSI^d	A set of inland nodes with surplus empty containers. Where NSI^o stands for inland nodes with surplus empty containers in origin inland, NSI^d stands for inland nodes with surplus empty containers in destination inland.
NFI, NFI^o, NFI^d	A set of inland nodes with deficit empty containers. Where NFI^o stands for inland nodes with deficit empty containers in origin inland, NFI^d stands for inland nodes with deficit empty containers in destination inland.
HA, HA^o, HA^d	A set of inland arcs, let $HA^o = HA^o_{I^o P^o} \cup HA^o_{I^o D^o} \cup HA^o_{I^o B^o} \cup HA^o_{D^o P^o} \cup HA^o_{B^o P^o}$, and $HA^d = HA^d_{P^d I^d} \cup HA^d_{D^d I^d} \cup HA^d_{B^d I^d} \cup HA^d_{P^d D^d} \cup HA^d_{P^d B^d}$, then $HA = HA^o \cup HA^d$.
P	A set of sea ports, let $P = P^o \cup P^d$.
R	A set of ship routes.
I_r	A set of port indices of ship route $r \in R$.
NSP, NSP^o, NSP^d	A set of seaports with surplus empty containers. Where NSP^o stands for seaports with surplus empty containers in origin inland, NSP^d stands for seaports with surplus empty containers in destination inland.
NFP, NFP^o, NFP^d	A set of seaports with deficit empty containers. Where NFP^o stands for seaports with deficit empty containers in origin inland, NFP^d stands for seaports with deficit empty containers in destination inland.

Table 6.2 Decision variable description in the operational model

Decision Variable	Description
b_{ri}	bunker consumption per nautical mile at the sailing speed ss_{ri} on segment i in ship route $r \in R$.
v_{ij^o}	number of vehicles used on the inland arcs, $(i, j) \in HA^o$.
v_{ij^d}	number of vehicles used on the inland arcs, $(i, j) \in HA^d$.
$x_{ij^o}^{od}$	number of laden containers transported on the inland arcs, $(i, j) \in HA^o$ for the specific $od \in D_{od}$.
$x_{ij^d}^{od}$	number of laden containers transported on the inland arcs, $(i, j) \in HA^d$ for the specific $od \in D_{od}$.
y_{ij^o}	number of empty containers transported on the inland arcs, $(i, j) \in HA^o$.
y_{ij^d}	number of empty containers transported on the inland arcs, $(i, j) \in HA^d$.
ef_{ri}	number of empty containers transported on the i th segment in the route $r \in R$.
lf_{ri}	number of laden containers transported on the i th segment in the route $r \in R$.
$e\tilde{w}_p$	number of loading empty containers at port $p \in P$ for all ship routes $r \in R$.
$e\hat{w}_p$	number of discharging empty containers at port $p \in P$ for all ship routes $r \in R$.
$e\tilde{\bar{w}}_p$	number of transshipment empty containers at port $p \in P$ for all ship routes $r \in R$.
$h\tilde{w}_p$	number of loading laden containers at port $p \in P$ for all ship routes $r \in R$.
$h\hat{w}_p$	number of discharging laden containers at port $p \in P$ for all ship routes $r \in R$.
$h\tilde{\bar{w}}_p$	number of transshipment laden containers at port $p \in P$ for all ship routes $r \in R$.
$e\tilde{w}_{ri}$	number of loading empty containers for the route $r \in R$ in the i th port of call.
$e\hat{w}_{ri}$	number of discharging empty containers for the route $r \in R$ in the i th port of call.
$h\tilde{w}_{ri}$	number of loading laden containers for the route $r \in R$ in the i th port of call.
$h\hat{w}_{ri}$	number of discharging laden containers for the route $r \in R$ in the i th port of call.
pod_{od}	number of laden containers from port $o \in P$ to port $d \in P$
w_{ri}	sailing speed on segment i in ship route $r \in R$
u_{ri}	$u_{ri} = 1 / w_{ri}$

Table 6.3 Parameter description in the operational model

Parameter	Description
N_{od}	weekly number of laden containers transported from a specific inland city $o \in I^o$ to another inland city $d \in I^d$.(TEUs/week)
AV_{ij}	available number of vehicles on arc $(i, j) \in HA$.
BP	bunker price (USD/ton)
CH_{i^o}	storage cost (USD/TEU*hour) of laden/empty containers in inland node in origin $i \in D^o \cup B^o \cup P^o$.
CH_{i^d}	storage cost (USD/TEU*hour) of laden/empty containers in inland node in destination $i \in D^d \cup B^d \cup P^d$.
CI_{ij^o}	transport cost (USD/TEU) of laden/empty containers transported on the inland arcs in origin including the loading and discharging cost on two ends, $(i, j) \in HA^o$.
CI_{ij^d}	transport cost (USD/TEU) of laden/empty containers transported on the inland arcs in destination including the loading and discharging cost on two ends, $(i, j) \in HA^d$.
CV_{ij^o}	fixed cost (USD/one vehicle) for deploying inland vehicles on the inland arcs in origin, $(i, j) \in HA^o$.
CV_{ij^d}	fixed cost (USD/one vehicle) for deploying inland vehicles on the inland arcs in destination, $(i, j) \in HA^d$.
CEX_o	cost for export laden container (USD/TEU) from origin inland, including customs clearance fee and other cost related to export.
CIM_d	cost for import laden container (USD/TEU) to destination inland, including customs clearance fee and other cost related to import.
$CPSI_{i^o}$	penalty cost (USD/TEU) for not repositioning inland empty container from surplus node in origin $i \in NSI^o$.
$CPSI_{i^d}$	penalty cost (USD/TEU) for not repositioning inland empty container from surplus node in destination $i \in NSI^d$.
$CPFI_{i^o}$	penalty cost (USD/TEU) for not repositioning inland empty container to deficit node in origin $i \in NFI^o$.
$CPFI_{i^d}$	penalty cost (USD/TEU) for not repositioning inland empty container to deficit node in destination $i \in NFI^d$.
CAP_{i^o}	capacity of inland nodes in origin $i \in D^o \cup B^o \cup P^o$.
CAP_{i^d}	capacity of inland nodes in destination $i \in D^d \cup B^d \cup P^d$.
C_r^{opr}	operation cost for deploying shipping route $r \in R$,including the whole route transportation cost and port visiting cost (port dues) in the whole route.
C_r^{fix}	Fixed cost for deploying shipping route $r \in R$ (each route uses a specific ship type), including the costs of crew, insurance, administration, opportunity cost, depreciation cost of assets.
CP_p^{load}	loading cost (USD/TEU) of one empty/laden container in port $p \in P$.
CP_p^{disc}	discharging cost (USD/TEU) of one empty/laden container in port $p \in P$.
CP_p^{tran}	transshipment cost (USD/TEU) of one empty/laden container in port $p \in P$, $CP_p^{tran} < CP_p^{load} + CP_p^{disc}$.Usually many ports want to attract transshipment operation, and they will lower the transshipment cost.
$CPSP_{p^o}$	penalty cost (USD/TEU) for not repositioning sea-leg empty container from surplus port in origin $p^o \in NSP^o$.
$CPSP_{p^d}$	penalty cost (USD/TEU) for not repositioning sea-leg empty container from surplus port in destination $p^d \in NSP^d$.
$CPFP_{p^o}$	penalty cost (USD/TEU) for not repositioning sea-leg empty container to deficit port in origin $p^o \in NFP^o$.
$CPFP_{p^d}$	penalty cost (USD/TEU) for not repositioning sea-leg empty container to deficit port in destination $p^d \in NFP^d$.
CAP_r	container capacity (TEUs) of a ship deployed on ship route $r \in R$.
CTX	carbon tax on consumption amount of bunker fuels (USD/kg)
D_{ri}	the distance of sea segment i in ship route $r \in R$.
E_{ij^o}	number of containers(TEUs) transported per vehicle on arc in origin $(i, j) \in HA^o$.
E_{ij^d}	number of containers(TEUs) transported per vehicle on arc in destination $(i, j) \in HA^d$.
FI_{i^o}	number of deficit empty containers in inland nodes in origin $i \in NFI^o$.
FI_{i^d}	number of deficit empty containers in inland nodes in destination $i \in NFI^d$.
FP_{p^o}	number of deficit empty containers in port in origin $p^o \in NFP^o$.

Parameter	Description
FP_{p^d}	number of deficit empty containers in port in destination $p^d \in NFP^d$.
GI_{ij^o}	carbon footprint (kg/TEU) of laden/empty containers transported on the inland arc in origin $(i, j) \in HA^o$.
GI_{ij^d}	carbon footprint (kg/TEU) of laden/empty containers transported on the inland arc in destination $(i, j) \in HA^d$.
G_r^{opr}	operation carbon emission for deploying shipping route $r \in R$, including transportation carbon emission in the whole route.
K	carbon footprint constraint value for this whole network.
SI_{i^o}	number of surplus empty containers in inland nodes in origin $i \in NSI^o$.
SI_{i^d}	number of surplus empty containers in inland nodes in destination $i \in NSI^d$.
SP_{p^o}	number of surplus empty containers in port in origin $p^o \in NSP^o$.
SP_{p^d}	number of surplus empty containers in port in destination $p^d \in NSP^d$.
TH_{i^o}	average storage time (hours) of laden/empty containers in inland node in origin $i \in D^o \cup B^o \cup P^o$.
TH_{i^d}	average storage time (hours) of laden/empty containers in inland node in destination $i \in D^d \cup B^d \cup P^d$.
TI_{ij^o}	transport time (hours/TEU) of laden/empty containers transported on the inland arcs in origin including the loading and discharging time on two ends, $(i, j) \in HA^o$.
TI_{ij^d}	transport time (hours/TEU) of laden/empty containers transported on the inland arcs in destination including the loading and discharging time on two ends, $(i, j) \in HA^d$.
T_r^{opr}	operation time for deploying shipping route $r \in R$, including the whole route transportation time and port visiting time in the whole route.
TP_p^{load}	loading time (USD/TEU) of one empty container in port $p \in P$.
TP_p^{disc}	discharging time (USD/TEU) of one empty container in port $p \in P$.
ε	tolerance error in sailing speed optimisation (non-linear part)
$PCEP$	price of carbon emissions permits under the carbon emission trading scheme market (USD/kg)
PC	purchasing carbon permit amount in kg
SC	selling carbon permit amount in kg
CAP	carbon emission quota in kg
A_{ri}	the coefficients to represent each segment's relationship between sailing speed and bunker consumption
E	carbon emissions (in tons) per ton of bunker fuel consumption

Two Objective Functions:

$$\begin{aligned}
Min \text{ Cost} = & \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o od}^{od} + y_{ij^o} \right) \times CI_{ij^o} + \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d od}^{od} + y_{ij^d} \right) \times CI_{ij^d} + \left(\sum_{od \in D_{od}} N_{od} \right) \times (CEX_o + CIM_d) + \sum_{ij^o \in HA^o} v_{ij^o} \times CV_{ij^o} + \\
& \sum_{ij^d \in HA^d} v_{ij^d} \times CV_{ij^d} + \sum_{n_i \in D^o \cup B^o \cup P^o} \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o od}^{od} + y_{ij^o} \right) \times TH_{i^o} \times CH_{i^o} + \sum_{n_i \in D^d \cup B^d \cup P^d} \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d od}^{od} + y_{ij^d} \right) \times TH_{i^d} \times CH_{i^d} + \\
& \sum_{i \in NSI^o} (SI_{i^o} - \sum_{ij^o \in HA^o} y_{ij^o} + \sum_{ji^o \in HA^o} y_{ji^o}) \times CPSI_{i^o} + \sum_{i \in NSI^d} (SI_{i^d} - \sum_{ij^d \in HA^d} y_{ij^d} + \sum_{ji^d \in HA^d} y_{ji^d}) \times CPSI_{i^d} + \\
& \sum_{i \in NFP^o} (FI_{i^o} - \sum_{ji^o \in HA^o} y_{ji^o} + \sum_{ij^o \in HA^o} y_{ij^o}) \times CPFI_{i^o} + \sum_{i \in NFP^d} (FI_{i^d} - \sum_{ji^d \in HA^d} y_{ji^d} + \sum_{ij^d \in HA^d} y_{ij^d}) \times CPFI_{i^d} + \sum_{r \in R} C_r^{opr} + \sum_{r \in R} C_r^{fix} + \\
& \sum_{p \in P} ((e\tilde{w}_p - e\tilde{w}_p) \times CP_p^{load} + (e\tilde{w}_p - e\tilde{w}_p) \times CP_p^{disc} + e\tilde{w}_p \times CP_p^{iran}) + \sum_{p \in P} l\tilde{w}_p \times CP_p^{iran} + \\
& \sum_{p \in P} ((\sum_{d \in P} pod_{pd}) \times CP_p^{load} + (\sum_{o \in P} pod_{op}) \times CP_p^{disc}) + \sum_{p^o \in NSP^o} (SP_{p^o} - (\sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^o} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^o} e\tilde{w}_{ri})) \times CPSP_{p^o} + \\
& \sum_{p^d \in NSP^d} (SP_{p^d} - (\sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^d} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^d} e\tilde{w}_{ri})) \times CPSP_{p^d} + \sum_{p^o \in NFP^o} (FP_{p^o} - (\sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^o} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^o} e\tilde{w}_{ri})) \times CPFP_{p^o} + \\
& \sum_{p^d \in NFP^d} (FP_{p^d} - (\sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^d} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_{ri}=p^d} e\tilde{w}_{ri})) \times CPFP_{p^d}. \tag{21}
\end{aligned}$$

$$\begin{aligned}
 \text{Min Time} = & \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o}^{od} + y_{ij^o} \right) \times TI_{ij^o} + \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d}^{od} + y_{ij^d} \right) \times TI_{ij^d} + \sum_{n_i \in D^o \cup B^o \cup P^o} \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o}^{od} + y_{ij^o} \right) \times TH_{i^o} + \\
 & \sum_{n_i \in D^d \cup B^d \cup P^d} \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d}^{od} + y_{ij^d} \right) \times TH_{i^d} + \sum_{r \in R} T_r^{opr} + \sum_{p \in P} ((e\tilde{w}_p + l\tilde{w}_p) \times TP_p^{load} + (e\tilde{w}_p + l\tilde{w}_p) \times TP_p^{disc})
 \end{aligned} \quad (22)$$

Definition of presentation:

$$\text{Carbon emission} = \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o}^{od} + y_{ij^o} \right) \times GI_{ij^o} + \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d}^{od} + y_{ij^d} \right) \times GI_{ij^d} + \sum_{r \in R} G_r^{opr} \quad (23)$$

Constraints:

$$\sum_{k^o \in HA^o} x_{k^o}^{od} = \sum_{ij^o \in HA^o} x_{ij^o}^{od}, \forall n_i \in D^o \cup B^o, \forall od \in D_{od} \quad (24)$$

$$\sum_{k^d \in HA^d} x_{k^d}^{od} = \sum_{ij^d \in HA^d} x_{ij^d}^{od}, \forall n_i \in D^d \cup B^d, \forall od \in D_{od} \quad (25)$$

$$\sum_{ij^o \in HA^o} x_{ij^o}^{od} = N_{od}, \forall n_i \in I^o, \forall od \in D_{od} \quad (26)$$

$$\sum_{ij^d \in HA^d} x_{ij^d}^{od} = N_{od}, \forall n_i \in I^d, \forall od \in D_{od} \quad (27)$$

$$\sum_{od \in D_{od}} x_{ij^o}^{od} + y_{ij^o} \leq v_{ij^o} \times E_{ij^o}, \forall (i, j) \in HA^o \quad (28)$$

$$\sum_{od \in D_{od}} x_{ij^d}^{od} + y_{ij^d} \leq v_{ij^d} \times E_{ij^d}, \forall (i, j) \in HA^d \quad (29)$$

$$v_{ij^o} \leq AV_{ij^o}, \forall (i, j) \in HA^o \quad (30)$$

$$v_{ij^d} \leq AV_{ij^d}, \forall (i, j) \in HA^d \quad (31)$$

$$\sum_{k^o \in HA^o} \sum_{od \in D_{od}} x_{k^o}^{od} + \sum_{ik^o \in HA^o} \sum_{od \in D_{od}} x_{ik^o}^{od} + \sum_{ji^o \in HA^o} y_{ji^o} + \sum_{ij^o \in HA^o} y_{ij^o} \leq CAP_{i^o}, \forall n_i \in D^o \cup B^o \cup P^o \quad (32)$$

$$\sum_{k^d \in HA^d} \sum_{od \in D_{od}} x_{k^d}^{od} + \sum_{ik^d \in HA^d} \sum_{od \in D_{od}} x_{ik^d}^{od} + \sum_{ji^d \in HA^d} y_{ji^d} + \sum_{ij^d \in HA^d} y_{ij^d} \leq CAP_{i^d}, \forall n_i \in D^d \cup B^d \cup P^d \quad (33)$$

$$0 \leq \sum_{ij^o \in HA^o} y_{ij^o} - \sum_{ji^o \in HA^o} y_{ji^o} \leq SI_{i^o}, \forall n_i \in NSI^o \quad (34)$$

$$0 \leq \sum_{ij^d \in HA^d} y_{ij^d} - \sum_{ji^d \in HA^d} y_{ji^d} \leq SI_{i^d}, \forall n_i \in NSI^d \quad (35)$$

$$0 \leq \sum_{ji^o \in HA^o} y_{ji^o} - \sum_{ij^o \in HA^o} y_{ij^o} \leq FI_{i^o}, \forall n_i \in NFI^o \quad (36)$$

$$0 \leq \sum_{ji^d \in HA^d} y_{ji^d} - \sum_{ij^d \in HA^d} y_{ij^d} \leq FI_{i^d}, \forall n_i \in NFI^d \quad (37)$$

$$0 \leq \sum_{r \in R} \sum_{i \in I_r, p_r = p^o} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_r = p^o} e\tilde{w}_{ri} \leq SP_{p^o}, \forall p^o \in NSP^o \quad (38)$$

$$0 \leq \sum_{r \in R} \sum_{i \in I_r, p_i = p^d} e\hat{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_i = p^d} e\tilde{w}_{ri} \leq SP_{p^d}, \forall p^d \in NSP^d \quad (39)$$

$$0 \leq \sum_{r \in R} \sum_{i \in I_r, p_i = p^o} e\hat{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_i = p^o} e\tilde{w}_{ri} \leq FP_{p^o}, \forall p^o \in NFP^o \quad (40)$$

$$0 \leq \sum_{r \in R} \sum_{i \in I_r, p_i = p^d} e\tilde{w}_{ri} - \sum_{r \in R} \sum_{i \in I_r, p_i = p^d} e\hat{w}_{ri} \leq FP_{p^d}, \forall p^d \in NFP^d \quad (41)$$

$$e\hat{w}_p = \sum_{r \in R} \sum_{i \in I_r, p_i = p} e\hat{w}_{ri}, \forall p \in P \quad (42)$$

$$e\tilde{w}_p = \sum_{r \in R} \sum_{i \in I_r, p_i = p} e\tilde{w}_{ri}, \forall p \in P \quad (43)$$

$$e\tilde{w}_p = \min\{e\hat{w}_p, e\tilde{w}_p\}, \forall p \in P \quad (44)$$

$$e\hat{w}_{ri} + ef_{r(i-1)} = e\tilde{w}_{ri} + ef_{ri}, \forall r \in R, \forall i \in I_r \quad (45)$$

$$l\hat{w}_p = \sum_{r \in R} \sum_{i \in I_r, p_i = p} l\hat{w}_{ri}, \forall p \in P \quad (46)$$

$$l\tilde{w}_p = \sum_{r \in R} \sum_{i \in I_r, p_i = p} l\tilde{w}_{ri}, \forall p \in P \quad (47)$$

$$l\hat{w}_p = ((l\hat{w}_p - \sum_{d \in P} pod_{pd}) + (l\tilde{w}_p - \sum_{o \in P} pod_{op})) / 2, \forall p \in P \quad (48)$$

$$\sum_{d \in P} pod_{pd} = \sum_{ij^o \in HA^o} x_{ij^o}^{od}, \forall p \in P, \forall n_j = n_p \quad (49)$$

$$\sum_{o \in P} pod_{op} = \sum_{ij^d \in HA^d} x_{ij^d}^{od}, \forall p \in P, \forall n_i = n_p \quad (50)$$

$$l\hat{w}_{ri} + lf_{r(i-1)} = l\tilde{w}_{ri} + lf_{ri}, \forall r \in R, \forall i \in I_r \quad (51)$$

$$lf_{ri} + ef_{ri} \leq CAP_r, \forall r \in R, \forall i \in I_r \quad (52)$$

$$ef_{ri}, lf_{ri} \in \mathbb{R}^+, \forall r \in R \quad (53)$$

$$v_{ij^o} \in \mathbb{Z}^+, \forall (i, j) \in HA^o \quad (54)$$

$$v_{ij^d} \in \mathbb{Z}^+, \forall (i, j) \in HA^d \quad (55)$$

$$e\hat{w}_p, e\tilde{w}_p, e\tilde{w}_p \in \mathbb{R}^+, \forall p \in P \quad (56)$$

$$l\hat{w}_p, l\tilde{w}_p, l\tilde{w}_p \in \mathbb{R}^+, \forall p \in P \quad (57)$$

$$e\hat{w}_{ri}, e\tilde{w}_{ri} \in \mathbb{R}^+, \forall r \in R \quad (58)$$

$$l\hat{w}_{ri}, l\tilde{w}_{ri} \in \mathbb{R}^+, \forall r \in R \quad (59)$$

$$x_{ij^o}^{od} \in \mathbb{R}^+, \forall (i, j) \in HA^o \quad (60)$$

$$x_{ij}^{od} \in \mathbb{R}^+, \forall (i, j) \in HA^d \quad (61)$$

$$y_{ij} \in \mathbb{R}^+, \forall (i, j) \in HA^o \quad (62)$$

$$y_{ij} \in \mathbb{R}^+, \forall (i, j) \in HA^d \quad (63)$$

Objective (21) represents the total cost in this intermodal network. As in Figure 6.1, laden containers with specific origin and destination nodes (abbreviation for OD-Pair onwards) will go through the whole network. Its journey begins from inland origin then maritime network, finally to inland cities in destination. Empty containers are repositioned from inland surplus nodes to inland deficit nodes or from sea-leg surplus nodes to sea-leg deficit nodes. If there are some empty containers which are not repositioned, there would be penalty cost incurred. This total cost includes transportation cost on each link, terminal handling cost (loading and discharging operations), storage cost, customs clearance cost, fixed cost of using inland vehicles (trucks, trains and barges), and penalty cost for non-repositioning.

Objective (22) represents the total transit time in this intermodal network. This total transit time includes transportation time on each link, terminal handling time (loading and discharging operations), and storage time.

Definition (23) represents the total carbon emission in this whole network, which is generated in the transportation link in both inland and sea legs.

Constraints (24)-(25) represent that in each inland intermodal node (D or B), for each OD-Pair, its total inflow to intermodal node equals to its total outflow from intermodal node.

Constraints (26)-(27) represent that all the outflows from each inland city (I) or all the inflows to each inland city (I) equals to the OD-Pair related to it.

Constraints (28)-(29) represent the inland vehicle capacity constraints.

Constraints (30)-(31) represent the available vehicle number constraints in each link in the sub- hinterland network.

Constraints (32)-(33) represent the inland intermodal node capacity constraints.

Constraints (34)-(37) represent the inland available empty repositioning number constraints.

Constraints (38)-(41) represent the sea-leg available empty repositioning number constraints.

Constraints (42)-(44) represent the relationship between the loading and discharging empty container number in each port and loading and discharging empty container number in each segment in different routes.

Constraint (45) represents the relationship between the empty container number in segment (i-1) and the empty container number in segment i.

Constraints (46)-(50) represent the relationship between the loading and discharging laden container number in each port and loading and discharging laden container number in each segment in different routes.

Constraint (51) represents the relationship between the laden container number in segment (i-1) and the laden container number in segment i.

Constraint (52) represents the ship capacity constraint.

Constraints (53)-(63) define the non-negative characteristics of decision variables.

The mixed-integer non-linear programming model presentation is provided as above. The decision variables about the vehicle numbers should be positive integer values, other decision variables could be positive fractional values. We suppose the decision variables about container numbers could be fractional values, because the quantity of container has a high order, such as 1000,000. There is no significant difference between 1000,000 and 1000,000.5. Hence the decision variables about container numbers in a large-scale problem could be fractional values.

From now on, it is called the “Basic Model”. In the following sections, some explanation will be given about the non-linear part of the sea leg (operation cost for deploying a shipping route, C_r^{opr} ; the other terms are linear relationships (Kim et al., 2008; Meng et al., 2012)) of this whole model and some extensions of this basic model under different environmental regulatory frameworks.

In order to take advantage of CPLEX, which is one of the state-of-the-art mixed-integer linear-programming solvers, the “Basic Model” needs to be linearised with regard to its non-linear part. The non-linear part (C_r^{opr}) is convex and non-negative, therefore a piecewise outer-approximation algorithm is employed. As a result, the approximation error can be controlled within an acceptable tolerance level (proof to

be found below in Subsection 6.2.2.1). After this linearisation transformation, this basic model can be solved by solvers such as CPLEX. The detailed linearisation technique will be described in Subsection 6.2.2.1. In Subsection 6.2.2.2, three extensions of the “Basic Model” under three different environmental regulatory frameworks will be developed and explanations are given accordingly.

6.2.2.1 Explanations about the non-linear sailing speed optimisation in the sea-leg part

The shipping bunker cost is included in the operation cost for the deploying shipping route (C_r^{opr}). Hence, the bunker consumption cost (bcc) can be calculated by

$$bcc = \min \sum_{r \in R} \sum_{i \in I_r} BP \times D_{ri} \times b_{ri}(w_{ri}) \quad [P1]$$

where BP represents bunker price in US dollars per ton, D_{ri} represents the distance (in nautical miles) of sea segment i on ship route r , $b_{ri}(w_{ri})$ denotes the bunker consumption per nautical mile at the sailing speed w_{ri} on segment i on ship route r .

Concerning the non-linear part in sea-leg sailing speed optimisation in this model, reference is made to Wang and Meng (2012)’s paper. In their paper, they used empirical data from the shipping industry to examine the relationship between bunker consumption and sailing speed, and reached the conclusion that the third power relationship is indeed a good approximation. This conclusion is in line with Ronen (1982)’s findings.

Thus, for each sea segment i in shipping route $r \in R$,

$$b_{ri}(w_{ri}) = A_{ri} \times \frac{(w_{ri})^3}{24 \times w_{ri}} = A_{ri} \times \frac{(w_{ri})^2}{24},$$

where A_{ri} is the coefficients to represent each sea segment’s relationship between sailing speed and bunker consumption.

This above function is convex and non-negative, therefore a piecewise outer-approximation algorithm is proposed to get a near optimal solution under a total tolerance error ε (Fourer, 1992; Wang and Meng, 2012). A total tolerance error ε of

all sea segments is set and the tolerance error for each segment is $\bar{\varepsilon}$. $\bar{\varepsilon}$ (tons per nautical mile) is in proportion to its sea segment distance, thus

$$\bar{\varepsilon} = \frac{\varepsilon}{BP} \times \frac{1}{\sum_{r \in R} \sum_{i \in I_r} D_{ri}}$$

Now new decision variables are defined as follows:

$$u_{ri} = \frac{1}{w_{ri}}, \text{ thus } z_{ri}(u_{ri}) = b_{ri} \left(\frac{1}{u_{ri}} \right) = \frac{A_{ri} \times \left(\frac{1}{u_{ri}} \right)^2}{24} = \frac{A_{ri}}{24 \times (u_{ri})^2}.$$

According to Wang and Meng (2012)'s result, [P1] can be transformed to [P2] which can help to get a lower bound for [P1]:

$$LB = \min \sum_{r \in R} \sum_{i \in I_r} BP \times D_{ri} \times z_{ri}(u_{ri}) \quad [P2]$$

Subject to $z_{ri} \geq \text{slope}_{rik} \times u_{ri} + z - \text{intercept}_{rik}, \forall r \in R, \forall i \in I_r, \forall k = 1, 2, \dots, K_{ri}$, where K_{ri} is the current value of k , k is the selected tangent line number.

Let the optimal objective value to the original [P1] be OptVal, and the optimal objective value of [P2] is a lower bound for OptVal, denoted by LB. The optimal solution u_{ri}^* to [P2] is also a feasible solution to [P1]. Hence, an upper bound for OptVal can be set by

$$UB = \min \sum_{r \in R} \sum_{i \in I_r} BP \times D_{ri} \times b_{ri} \left(\frac{1}{u_{ri}^*} \right)$$

Based on the piecewise outer-approximation scheme, it can be obtained that

$$LB \leq \text{OptVal} \leq UB \leq LB + \varepsilon$$

It should be noted that bcc is included in the operation cost for deploying shipping route (C_r^{opr}), which means that [P2]'s objective is only part of the total cost in the cost objective function in the “Basic Model”. Similarly, [P2] is also subject to other constraints in the “Basic Model”.

6.2.2.2 Carbon tax, carbon emission trading scheme or direct restriction?

“Climate change”, “Environmental protection”, “Carbon tax”, “Carbon emission trading scheme” — these are terms that we hear so much today. There is a growing

debate between these two economic policy instruments for climate change: carbon tax and carbon emission trading scheme. However, there is no simple answer as to which one is better. Alternatively, direct restriction is another choice. The government can put a direct carbon emission restriction on each company based on its historical data and the average level in the same industry.

From the total carbon emission definition (23) in the “Basic Model” as follows:

Carbon emission

$$= \sum_{ij^o \in HA^o} \left(\sum_{od \in D_{od}} x_{ij^o}^{od} + y_{ij^o} \right) \times GI_{ij^o} \\ + \sum_{ij^d \in HA^d} \left(\sum_{od \in D_{od}} x_{ij^d}^{od} + y_{ij^d} \right) \times GI_{ij^d} + \sum_{r \in R} G_r^{opr}$$

$\sum_{r \in R} G_r^{opr} = \sum_{r \in R} \sum_{i \in I_r} 1000 \times E \times D_{ri} \times b_{ri}(w_{ri})$, where $\sum_{r \in R} G_r^{opr}$ represents the carbon emission in the sea segment (in kg) and E presents the carbon emissions (in tons) per ton of bunker fuel consumption. “1000” is used here to convert the unit from ton to kg.

(1) Carbon tax: [P3]

A carbon tax is simply and directly levied by government, based on the carbon emission quantity of fuels. It is easy to implement. However, how to choose the correct tax level is difficult and crucial for government to decide. Under a carbon tax, a price for unit pollution is set, but the total emission quantity is uncertain. For instance, some industries will accept carbon taxes and pass this cost on to their consumers. Thus the final consumers need to pay more for a product due to carbon tax. In this case, the carbon emission itself is not cut down (Metcalf and Weisbach, 2009).

Under a carbon tax scheme, the carbon tax cost (ctc) is part of the total cost and can be calculated by

$$ctc = CTX \times \text{Carbon emission} \quad [P3]$$

where CTX represents carbon tax on carbon emission (USD/kg),

Carbon emission represents the total carbon emission amount of the whole network in kgs.

It should be noted that c_{tc} is included in the total cost for the carbon tax calculation, which means that [P3]'s objective is only part of the total cost in the cost objective function in the “Basic Model”. Similarly, [P3] is also subject to other constraints in the “Basic Model”.

(2) Carbon emission trading scheme: [P4]

Under a carbon emission trading scheme, the quantity of carbon emission is fixed (usually called “cap”). The cap represents the total maximum level of carbon emission and is set by the central authority. The carbon emissions permits or quotas are allocated to the participants through free allocation, auction or sale. The participants will obtain the permits or quotas greater than or equal to their actual carbon emission level. The permits or quotas are tradable. Some participants can reduce their carbon emissions through technological innovation and insightful management, thus they will have surplus permits to sell in the market and gain profits. Some heavily polluting participants can buy the permits from the market. This scheme is appealing and welcomed in private industry. It also has the advantage that the environmental outcome is fixed which can guarantee the environmental protection effect. However, these carbon emission trading systems are highly complicated and technical to operate (Lohmann, 2006).

Under a carbon emission trading scheme, the carbon emission trading cost or profit c_{etc} can be formulated as follows (when positive (+) means cost, negative (-) means profit):

$$c_{etc} = PCEP \times (PC - SC) \quad [P4]$$

Subject to Carbon emission = CAP + PC – SC

where PCEP represents the price of carbon emissions permits under the carbon emission trading scheme market (USD/kg), PC represents the purchasing carbon permit amount in kgs, SC represents the selling carbon permit amount in kgs, CAP represents the carbon emission quota in kgs, Carbon emission represents the

total carbon emission amount of the whole network in kgs.

It should be noted that $cetc$ is included in the total cost for the carbon emission trading calculation (when its value is positive, it means cost; otherwise it means profit), which means that [P4]’s objective is only part of the total cost in the cost objective function in the “Basic Model”. Similarly, [P4] is also subject to other constraints in the “Basic Model”.

(3) Direct restriction: [P5]

The government can put a direct carbon emission restriction on each company based on its historical data and the average level of the same industry. For this intermodal network, K is the carbon emission restriction value. Hence under this direct restriction scheme, only one more constraint needs to be simply added in the “Basic Model”,

Subject to $\text{Carbon emission} \leq K$ [P5]

where Carbon emission represents the total carbon emission amount of the whole network, K represents the carbon footprint constraint value for this whole network.

It should be noted that in [P5], the objective functions are kept the same as the “Basic Model”. Based on the constraints in the “Basic Model”, one more constraint is added as shown above.

6.3 Case study

6.3.1 Case description

A case study on China-US’s Trans-Pacific container intermodal chain will be conducted. The eastern half of China’s hinterland and major seaports on China’s east coast only are considered, including Dalian Port, Qingdao Port, Tianjin Port, Shanghai Port and Ningbo-Zhoushan Port. For the United States, the western hinterland of the United States and seaports on its west coast only are considered, including Seattle Port, Portland Port, Los Angeles Port and Long Beach Port. For

inland waterway, the Yangtze River for China's case is considered. The Yangtze River helps to transport containers between the western hinterland and the eastern seaports for export and import. The Mississippi River mainly flows through the eastern part of the United States from north to south, thus the inland barge transportation system of the US is not considered in this case study. Concerning the hinterland scope in Mainland China, Liaoning Province, Shandong Province, Shanxi Province, Hebei Province, Henan Province, Anhui Province, Jiangxi Province, Hubei Province, Hunan Province, Jiangsu Province, Zhejiang Province, Beijing Municipality, Shanghai Municipality, Tianjin Municipality and Chongqing Municipality as China's hinterland area are chosen in this case study (11 provinces plus 4 municipalities). Similarly, states are chosen as US's hinterland scope in this research work: Washington (WA), Oregon (OR), California (CA), Nevada (NV), Idaho (ID), Utah (UT), Arizona (AZ), Montana (MT), Wyoming (WY), and Colorado (CO). These ten chosen states are in the western part of the United States.

For the hinterland setting in Mainland China, three big cities are chosen from each of the selected provinces as the inland city location, and hence in total thirty-seven inland city nodes (33 cities plus 4 municipalities) are selected. According to the recent infrastructure situation in Mainland China, it can be supposed that every province has its dry port in its capital. Fifteen inland dry ports in Mainland China (11 in province capitals plus 4 in the municipalities) are selected in total. Along the Yangtze River from upstream to downstream, five barge terminals are selected: Chongqing barge terminal, Wuhan barge terminal, Nanjing barge terminal, Suzhou barge terminal and Shanghai barge terminal. Similarly, with regard to the hinterland setting in the United States, twenty-two inland cities are selected from these ten chosen states. Six dry port locations are set in Spokane, San Diego, San Francisco, Las Vegas, Phoenix and Denver.

In this case study, it can be supposed that there are 79 OD-Pairs (origin-destination pair, 11532 TEUs) with an origin from Mainland China inland cities (Hinterland 1) to the United States inland cities (Hinterland 2), and 75 OD-Pairs (11016 TEUs) with an origin from the United States inland cities (Hinterland 2) to Mainland China

inland cities (Hinterland 1) in one planning period (usually every 2–4 weeks). These containers with decided OD-Pairs mean laden containers. In this case study empty containers are considered as well. Empty containers do not have specified origin-destination information. If the empty containers are not repositioned, penalty costs will be charged. These kinds of penalty costs can help drive more empty containers to be repositioned.

Four maritime shipping routes are considered in this case study, as follows:

(1) Shipping Route1:

Shanghai>Tianjin>Seattle>Long Beach>Shanghai

(2) Shipping Route2:

Ningbo>Shanghai>Qingdao>Dalian>Seattle>Portland>LosAngeles>LongBeach>Ningbo

(3) Shipping Route3:

Tianjin>Dalian>Portland>Los Angeles>Ningbo>Shanghai>Qingdao>Tianjin

(4) Shipping Route4:

Seattle>Portland>Long Beach>Shanghai>Tianjin>Dalian>Seattle

There are three types of ships used in these four shipping routes (Type I: 4000 TEU; Type II: 5000 TEU; Type III: 8000 TEU). Type I is applied in Shipping Route1; Type II is used in Shipping Route 4; Type III is for Shipping Route 2 and Shipping Route 3. The main parameters of different ship types set for the case study are listed in the following Table 6.4.

Table 6.4 Main parameters of different ship types

Ship Type	Capacity	Minimum Speed	Maximum Speed
Type I	4000 TEUs	12 knots	20 knots
Type II	5000 TEUs	12 knots	20 knots
Type III	8000 TEUs	15 knots	25 knots

6.3.2 Main results

In each figure that follows (Figure 6.2 to Figure 6.8), Pareto Frontier is obtained by

plotting several dots representing different trade-offs between unit costs and average transit times. Unit cost and average transit time can deliver more clear information about these trade-offs compared to the total cost and total transit time of all containers. For example, the average transit time per TEU (21 days) and the total transit time sum for all containers (157,500 days for 7,500 TEUs) are two different approaches. Both are found to deliver the same result. However, one will find that the former (average time) approach gives us more easily perceivable information. The fixed time dots are used to optimise cost objective. For example, following a uniform distribution, several transit times are selected within the feasible solution space, and they are then set as a model constraint to obtain cost optimal results.

Without considering the carbon emission factor, the Pareto Frontier in the Basic Model is as shown in Figure 6.2 below. The trade-off nodes on the Pareto Frontier can help the companies (shipping lines or freight integrators) to make decisions in their daily operation. Each trade-off node provides a different plan in intermodal container network optimisation, including those such as the different inland modal split schemes, and the different optimal sailing speeds of ships in each segment in each shipping route.

Figure 6.2 Basic Pareto Frontier between unit cost per TEU and average time per TEU

Source: Drawn by the author

The leftmost node (Node A) has the minimum average time consumption of 15.66 days (in \$3707 unit cost and 2302 kg unit carbon emission). The rightmost node (Node B) has the minimum unit cost of \$2537 (in 24.20 days average time consumption and 1662 kg unit carbon emission). The middle node (Node C) has values in between: unit cost \$2695, average time 20.00 days and unit carbon emission 1770 kg.

There are a total of 19 trade-off nodes on the Pareto Frontier curve of the Basic Model. If we calculate all the change rates between two adjacent nodes in terms of unit cost and average time, the change pattern can be found as follows.

We set Ratio 1 as cost/time performance which is equal to the unit cost change rate divided by the average time change rate, and Ratio 2 is set as time/cost performance which is equal to the average time change rate divided by the unit cost change rate. Both Ratio 1 and Ratio 2 are arrays with 18 elements, respectively, because there are 18 intervals between 19 trade-off nodes.

Ratio 1(cost/time performance) = [9.11, 4.46, 3.55, 2.88, 1.96, 1.60, 1.35, 1.09, 1.05, 0.86, 0.77, 0.73, 0.59, 0.49, 0.38, 0.31, 0.19, 0.10];

Ratio 2(time/cost performance) = [0.11, 0.22, 0.28, 0.35, 0.51, 0.63, 0.74, 0.92, 0.96, 1.16, 1.29, 1.36, 1.69, 2.03, 2.65, 3.24, 5.03, 10.16].

It can be found that the numbers in Ratio 1 are decreasing while the numbers in Ratio 2 are increasing. Now let us use some examples to explain the meaning of these figures. The first number, 9.11, in the array of Ratio 1 means that the change rate of unit cost is 9.11 times as much as the change rate of average time between the second node and the first node (the leftmost node) from left to right on the Pareto Frontier curve. In other words, a small increase in average time will bring about a significant reduction in unit cost between the first node and the second node. The last number, 10.16, in the array of Ratio 2 means that the change rate of average time is 10.16 times as much as the change rate of unit cost between the

second last node and the last node (the rightmost node) from left to right on the Pareto Frontier curve. In other words, a small increase in unit cost will bring about a significant reduction in average time between the last node and the second last node.

From the above sensitivity analyses, some suggestions are given as follows. It can be found that the five trade-off nodes on the leftmost side and the five trade-off nodes on the rightmost side of the Pareto Frontier curve can be treated as two clusters. The five nodes in the leftmost cluster have the closer average time values while the five nodes in the rightmost cluster have the closer unit cost values. In the leftmost cluster, a small increase in average time brings about a significant reduction in unit cost. And in the rightmost cluster, a small increase in unit cost brings about a significant reduction in average time. Hence the fifth node in the leftmost cluster is the best choice among these five nodes, while the last fifth node in the rightmost cluster is the best choice among those five nodes.

A similar change pattern can also be found in the following Pareto Frontier curves, respectively, under carbon tax, carbon emission trading and direct restriction frameworks.

The below Table 6.5 shows the different modal split situations in the two hinterlands about Node A, Node B and Node C in the Basic Model.

Table 6.5 Findings on inland modal splits in the Basic Model

Modal Split	Node A		Node B		Node C	
	Unit Cost:\$3707		Unit Cost:\$2537		Unit Cost:\$2695	
	Average Time: 15.66 days		Average Time: 24.20 days		Average Time: 20.00 days	
	Unit Carbon Emission: 2302 kg		Unit Carbon Emission: 1662 kg		Unit Carbon Emission: 1770kg	
	Hinterland 1	Hinterland 2	Hinterland 1	Hinterland 2	Hinterland 1	Hinterland 2
Using inland dry port and railway link to seaport	34.5%	44.8%	43.9%	67.2%	42.3%	62.3%
Using inland barge port and waterway link to seaport	11.9%	Not Applicable	35.5%	Not Applicable	26.3%	Not Applicable
Directly using truck-link to seaport	53.6%	55.2%	20.6%	32.8%	31.4%	37.7%

Node A has the highest truck share and lowest rail and barge shares among these three nodes, while Node A incurs the highest unit cost and unit carbon emission and

lowest average transit time. Node B has an opposite characteristic to Node A. Node B owns the highest rail and barge shares and lowest truck share among the three, while it incurs the highest average transit time and lowest unit cost and unit carbon emission. The shares of Node C are in between the shares of Node A and Node B in terms of these three inland transport modes.

The above information reveals to us that barge and rail modes are the two preferred transportation modes with lower unit cost and unit carbon emissions than truck. Truck is the transport mode with the lowest average transit time but highest unit cost and unit carbon emission. Unless transit time is a major concern, trucking should not be encouraged for long-distance transport.

As for sea transportation, the sailing speeds in each segment of Shipping Route 1 are used as an example to illustrate the sailing speed changes on different trade-off nodes on the Pareto Frontier. As stated above, there are a total of 4 segments in Shipping Route 1:

- Segment 1: Shanghai(SH)>Tianjin(TJ);
- Segment 2: Tianjin(TJ)>Seattle(ST);
- Segment 3: Seattle(ST)>Long Beach(LB);
- Segment 4: Long Beach(LB)>Shanghai(SH).

Table 6.6 Different sailing speeds on each segment in Shipping Route 1 in each node

Segments in Shipping Route 1 (Using Ship Type I)	Node A (sailing speed in knots)	Node B (sailing speed in knots)	Node C (sailing speed in knots)
Segment 1(SH>TJ)	20 knots	12 knots	14.5 knots
Segment 2(TJ>ST)	20 knots	12 knots	16.9 knots
Segment 3(ST>LB)	20 knots	12 knots	13.9 knots
Segment 4(LB>SH)	20 knots	12 knots	16.2 knots

The sailing speeds of each segment in other shipping routes can be calculated similarly by using this operational model. Shipping lines and other freight integrators can apply this operational model to assist their daily operations.

The range of carbon emission per TEU in Figure 6.2 is between 1662 kg and 2302

kg. Hence 1662 kg is the lower bound of carbon emission in the Basic Model, while 2302 kg is the upper bound of carbon emission in the Basic Model.

6.3.2.1 Under a carbon tax scheme

Finland is the first country to have carbon taxation, and this has been in place since 1990. The carbon tax of Finland was \$24 per ton in 2008 (Sumner et al., 2009). Some countries, such as the United States and China, worry that carbon tax implementation may bring about a rise in unemployment rate (Metz et al., 2007; Kreutzer and Loris, 2013). British Columbia's carbon tax, inaugurated in 2008 in Canada, is an example of good practice that should ease this concern. British Columbia ratifies North America's first carbon tax. Elgie and McClay (2013) finds that, in the four years since 2008, British Columbia's fuel consumption has declined by 19% compared to the rest of Canada. At the same time, its economy has kept pace with the rest of Canada. The carbon tax in British Columbia reached \$30 per ton in 2012 (Carbon Tax Centre, 2013).

In this case study, the carbon tax rate is set at \$0.03 per kg (equal to \$30 per ton), the same as British Columbia's carbon tax rate stated above. The Pareto optimal results under a carbon tax scheme are in Figure 6.3 below.

Figure 6.3 Optimal Pareto Frontier under carbon tax rate = \$0.03 per kg

Source: Drawn by the author

In the above Figure 6.3, the “*” line denotes the Pareto optimal results of the Basic Model, while the “o” line denotes the Pareto optimal results of the model under a carbon tax rate of \$0.03 per kg. It can be noticed that all the trade-off nodes in the “o” line have the same values on the X-axis compared with the trade-off nodes in the “*” line. However, these “o” nodes’ values on the Y-axis are greater than the “*” nodes’ values on the Y-axis. This can imply that, under the carbon tax scheme, a higher unit cost is needed for each trade-off and the unit cost gap to basic result is due to the tax-rate setting. However, the increase in unit cost is at an acceptable level. In Figure 6.3, for Node A, the unit cost increases from \$3707 to \$3778 (1.92% increase), while for Node B, the unit cost increases from \$2537 to \$2587 (1.97% increase). Both rates of increase in unit cost are lower than 2%, which means this carbon tax rate should be acceptable for companies.

6.3.2.2 Under a carbon emission trading scheme (Scenario 1 to Scenario 3)

Under a carbon emission trading scheme, how much cap should be allocated to a company is crucial because the value of the cap can decide the company’s total cost.

When the cap is loose (with a high value) for a company, which means this company will own extra carbon emissions permits, the company can sell these permits in the market which can help the company to achieve savings on the total cost. On the other hand, when the cap is tighter (with a low value), this company needs to buy permits from the carbon emission trading market to cover its carbon emission and the total cost to this company will increase accordingly.

From the Pareto optimal results in the Basic Model in Figure 6.2, it is shown that the scope of carbon emission in this case study is between 1662 kg and 2302 kg. By referring to a technical report of London (2008), the price of CO₂ emission per kg is set to \$0.2 in this case study. Here, three scenarios are compared under three different cap values as follows. (Cap in Scenario 1 is tight; cap in Scenario 2 is medium; cap in Scenario 3 is loose.)

(1) Scenario 1 (a tight cap): Cap set = 1200 kg (smaller than the lower bound (1662 kg) in the Basic Model)

Figure 6.4 Optimal Pareto Frontier under a carbon emission trading price = \$0.2 per kg and
cap value = 1200 kg

Source: Drawn by the author

(2) Scenario 2 (a medium cap): Cap set = 1909.3 kg (between the lower bound (1662 kg) and the upper bound (2302 kg) in the Basic Model)

Figure 6.5 Optimal Pareto Frontier under a carbon emission trading price = 0.2 per kg and
cap value = 1909.3 kg

Source: Drawn by the author

(3) Scenario 3 (a loose cap): Cap set = 2500 kg (larger than the upper bound (2302 kg) in the Basic Model)

Figure 6.6 Optimal Pareto Frontier under a carbon emission trading price = 0.2 per kg and cap value = 2500 kg

Source: Drawn by the author

From the results of three scenarios above, under a carbon emission trading scheme some findings can be obtained as follows:

- (1) **In Scenario 1 (a tight cap):** The cap (1200 kg) in Scenario 1 (Figure 6.4) is set smaller than the lower bound (1662 kg) in the Basic Model. The cap setting in Scenario 1 is tighter than in the other scenarios (Scenario 2 and Scenario 3). In Figure 6.4, it can be found that under this tight cap in Scenario 1, all the trade-off nodes in the optimal Pareto Frontier have higher unit cost values compared with the trade-off nodes in the Basic Model. This means that if a tight cap is set, the company's total cost will increase at any trade-off point in Figure 6.4,

because every trade-off node's carbon emission is above the cap (1200 kg) setting here. In Figure 6.4, for Node A, the unit cost increases from \$3707 to \$3922 (5.80% increase), while for Node B, the unit cost increases from \$2537 to \$2629 (3.63% increase). The increase rate of Node A is higher than the increase rate of Node B, due to Node A's higher carbon emission. Node A needs more money to buy carbon emission permits from the carbon trading market to cover its carbon emission gap to the cap. It is worth mentioning that the unit cost increase rate for Node A is a little high (more than 5%), which means this tight cap (1200 kg) would not be welcomed by companies.

(2) **In Scenario 2 (a medium cap):** In Scenario 2 (Figure 6.5), the cap is set between the lower bound (1662 kg) and the upper bound (2302 kg) in the Basic Model as 1909.3 kg. The cap 1909.3 kg is the carbon emission value of one trade-off node in between the lower bound and the upper bound. The cap in Scenario 2 is moderate among these three scenarios (Scenario 1, Scenario 2 and Scenario 3). It can be found that some trade-off nodes' unit costs increase, while some nodes' unit costs decrease. The cut-off point is the trade-off node with 1909.3 kg (the cap value) carbon emission. The trade-off nodes below this cut-off point can make money by selling their extra carbon emission permits while the trade-off nodes above this cut-off point will lose money through having to buy carbon emissions permits from the trading market. In Figure 6.5, for Node A, the unit cost increases from \$3707 to \$3785 (+2.1% increase), while for Node B, the unit cost decreases from \$2537 to \$2487 (-2.0% decrease). Because we choose the middle trade-off node's carbon emission value as the cap in Scenario 2, it can be noticed that the absolute values of the change rates in the two extreme nodes are similar: +2.1% in Node A and -2.0% in Node B.

(3) **In Scenario 3 (a loose cap):** The cap (2500 kg) in Scenario 3 (Figure 6.6) is set greater than the upper bound (2302 kg) in the Basic Model. The cap setting in Scenario 3 is looser than that in the other scenarios (Scenario 1 and Scenario 2). In Figure 6.6, it can be found that under this loose cap in Scenario 3, all the trade-off nodes in the optimal Pareto Frontier have lower unit cost values compared with the trade-off nodes in the Basic Model. This means that if a

loose cap is set, the company's total cost will decrease at any trade-off point in Figure 6.6, because every trade-off node's carbon emission is below the cap (2500 kg) setting here. In Figure 6.6, for Node A, the unit cost decreases from \$3707 to \$3665 (-1.13% decrease), while for Node B, the unit cost decreases from \$2537 to \$2369 (-6.62% decrease). The decrease rate (absolute value) of Node B is higher than the decrease rate (absolute value) of Node A, due to Node B's lower carbon emission. Node B has more extra carbon emission permits for sale, which can earn more money to offset its cost. In practice, if the carbon cap is set too loose, although it can help companies save their costs, the effect of environmental protection will be weakened.

6.3.2.3 Under direct restriction (Scenario 4 to Scenario 5)

Under the 'Direct restriction' scheme, governments can intervene in business operations directly with some strict restrictions, e.g. closing high-emission factories, subsidies for low-emissions products, setting some emission standards for each industry or enterprise. These emission standards could be fine-tuned afterwards. The trade-off results under two extreme carbon emission standards will be illustrated as follows.

- (4) **Scenario 4:** When the unit carbon emission restriction is set as 2302 kg (a loose restriction emission standard, denoted in "*" line below)
- (5) **Scenario 5:** When the unit carbon emission restriction is set as 1900 kg (a tight restriction emission standard, denoted in "o" line below)

Figure 6.7 Optimal Pareto Frontiers under two different carbon emission restrictions
Scenario 4: 2302 kg (loose) / Scenario 5: 1900 kg (tight) combined together

Source: Drawn by the author

After careful observation of Figure 6.7, it can be found that the “o” line curve is a part segment of the “*” line curve. The “*” line curve shows that all the trade-offs could be obtained when the carbon footprint restriction is looser (Scenario 4). The “o” line curve represents that barge mode is dominant under a tighter carbon emission restriction which would require more average transit time but less unit cost and carbon emission (Scenario 5). When the unit carbon emission restriction is less than 1662 kg, there is no feasible solution. This restriction, 1662 kg, is the lower bound of unit carbon emission in the Basic Model. When the unit carbon emission restriction is greater than 2302 kg, there is no change regarding the feasible solution scope, which means all the trade-off nodes in the Pareto Frontier in the Basic Model can be achieved. This restriction, 2302 kg, is the upper bound of unit carbon emission in the Basic Model. In Figure 6.7, the percentage change (-17.5%) of unit carbon emission restriction from 2302 kg to 1900 kg will bring about a great impact on the Pareto Frontier range. The upper bound of unit cost is reduced from \$3707 to \$2950, -20.5% change, while the lower bound of average transit time increases from 15.66 days to 18.00 days, +14.9% change. From Table 6.7 below, it can be

implied that the change of inland modal split situation will generate a great impact on unit cost, average time and unit carbon emission. It is beneficial to address environmental concerns in inland transport planning for optimisation of the whole intermodal network.

Table 6.7 Findings on Average inland modal split situations for OD-Pairs under Scenario 4 and Scenario 5

Inland modal split for OD-Pairs	Scenario 4 Set 2302 kg as unit carbon emission restriction (looser)		Scenario 5 Set 1900 kg as unit carbon emission restriction (tighter)	
	Hinterland 1	Hinterland 2	Hinterland 1	Hinterland 2
Using inland dry port and railway link to seaport (average)	39.0%	53.1%	42.1%	61.1%
Using inland barge port and waterway link to seaport (average)	21.2%	Not Applicable	25.1%	Not Applicable
Directly using truck-link to seaport(average)	39.8%	46.9%	32.8%	38.9%

From Table 6.7 above, for Hinterland 1 (China), comparing Scenario 4 and Scenario 5, it can be found that under a tighter carbon emission constraint (Scenario 5), there are more containers (from 39.0% to 42.1%) handled by the inland railway to dry port system and more containers (from 21.2% to 25.1%) handled by the inland barge system than under a looser carbon emission constraint (Scenario 4). The change pattern of modal split in truck is opposite to that of rail and barge. There is a lesser modal split rate (from 39.8% to 32.8%) in truck under Scenario 5 compared with Scenario 4.

For Hinterland 2 (the United States), the situation is very similar. Under a tighter carbon emission restriction (Scenario 5), more containers (from 53.1% to 61.1%) shift to the inland railway to dry port system, because the barge system is not applicable in the United States (Hinterland 2) in this case study. Only the western hinterland of the United States and seaports on its west coast are considered in this

case study. The Mississippi River mainly flows through the eastern part of the United States from north to south, thus the inland barge transportation system of the US is not considered in this case study.

Although the modal split rates reported in Table 6.7 are the average modal split values under Scenario 4 and Scenario 5, these numbers can still assist us in finding some phenomena. Under a tighter carbon emission restriction (Scenario 5), more containers will shift their inland routes to the modal choice with less carbon emission, in order to meet the emission restriction. Among the three inland modal choices (truck, rail and barge), barge is the most preferred transportation mode to lower cost and carbon emissions. However, as we know, the barge transportation system is too restricted by geographical conditions. Some hinterlands do not have access to inland waterways. Where barge choice is not available, rail is considered the second preferred choice. Rail does not have the same geographical restriction as compared with barge. Under Scenario 5, for Hinterland 1, for inland routes the preference for moving containers is the inland barge system and inland railway to dry port system, while for Hinterland 2, more containers are moved by inland railway to dry port system, because barge is not applicable in Hinterland 2.

6.3.3 Managerial and Policy implications

The proposed model in this chapter can assist the shipping lines or freight integrators of the global supply chain at the operational-planning level. This model provides the optimal routing of containers in a holistic way for the whole global intermodal network. It can help companies to make operational decisions for their daily operation, such as obtaining the optimal routing of containers and the optimal sailing speed on each segment in each shipping route. Due to its bi-objective characteristic (cost minimisation and time minimisation), trade-off nodes on Pareto Frontier can be calculated and drawn accordingly. Each trade-off node represents a container routing plan in the global intermodal network in different cost-time trade-off.

Three environmental regulatory schemes are considered in this model, respectively:

carbon tax, carbon emission trading and direct restriction. The above subsections 6.3.2.1 to 6.3.2.3 have clearly illustrated these three environmental regulatory schemes and their optimal results. The figures within these subsections have differentiated the results of each environmental regulatory scheme from the results of the Basic Model. These figures help to provide visualisation about these optimal results.

Managerial implications about these three different environmental regulatory frameworks are given as follows. From Figure 6.3, under a carbon tax scheme (the first scheme), it can be noticed that all the trade-off nodes' costs are higher than the costs in the Basic Model. However, under a low carbon tax rate (\$0.03/kg), the cost gap is not large. Carbon tax rates are usually determined by governments. The greatest shortcoming associated with a carbon tax scheme is that companies may not have enough incentive to reduce their unit cost and unit carbon emission. Because no matter which trade-off node they choose as their operational plan, a carbon tax will be imposed (Lee et al., 2013). Hence carbon emission reduction cannot be guaranteed under a carbon tax scheme.

Under a carbon emission trading scheme (the second scheme), three different cap levels are set to analyse this scheme (Scenario 1: tight cap; Scenario 2: medium cap; Scenario 3: loose cap). The tight cap means the cap value is smaller than the lower bound of the Basic Model; the medium cap means the cap value is between the lower bound and upper bound of the Basic Model; the loose cap means the cap value is higher than the upper bound of the Basic Model. Figure 6.4 to Figure 6.6 illustrate these three scenarios. From Figure 6.4 under the tight cap, every trade-off node has a higher cost than in the Basic Model. From Figure 6.6 under the loose cap, every trade-off node has a lower cost than in the Basic Model. The disadvantage of the tight cap is similar to the shortcoming of "carbon tax" stated above. The loose cap can help companies to reduce their costs. However, the total carbon emission will increase under the loose cap. Under the medium cap, companies have more flexibility in making their decisions. For example, if transit time is a major concern in their planning at this time, they can choose the plan with

much higher carbon emission and they can purchase insufficient emission permits from the market. If, in their next planning, transit time is not a major concern, they can choose the plan with less carbon emission and they can sell extra emission permits to the market to offset their cost of last time. As a whole, they have not spent more money on their carbon emissions. From a government's point of view, the total carbon emission of all companies has been effectively controlled and reduced. It can be derived that the medium cap in Scenario 2 is better than the tight cap in Scenario 1 or the loose cap in Scenario 3. The medium cap under a carbon trading scheme would be welcomed by both companies and governments.

In this research, the third environmental regulatory scheme is called "direct restriction" on carbon emission. Under this scheme, a government can take direct action to cut down carbon emission. In Figure 6.7, if the unit carbon emission restriction is set as 1900 kg, it can be noticed that its new Pareto Frontier curve is part of the Pareto Frontier curve of the Basic Model. The trade-off nodes with unit carbon emission higher than 1900 kg are infeasible. In Figure 6.7, the left side nodes on the curve of the Basic Model mean infeasible nodes under a unit carbon restriction of 1900 kg. Hence a final carbon emission reduction can be guaranteed. Unlike carbon tax and a carbon emission trading scheme which affect mainly the cost of the intermodal network for the same Pareto frontier (i.e. the same set of feasible solutions), direct carbon restriction limits the choice of inland transport modes and ship speed within the boundary of the carbon emission level. Therefore, intermodal transport planning and operations are directly restricted. From the government's point of view, the scheme of direct carbon restriction is easier to execute than imposing a carbon tax or a carbon emission trading scheme. If the company's carbon emissions exceed the government's emission restriction, the government reserves the right to punish or shut down the company. For these reasons, many companies would not welcome this scheme. They treat this scheme as a simple and crude approach. Unlike the previous two schemes, a government cannot get any revenue under the third scheme. From an economic perspective, governments also prefer the previous two schemes and should prepare well for their implementation.

A table (Table 6.8) is provided hereunder as a simple summary of the above discussions.

Table 6.8 Merit comparison for three environmental regulatory frameworks

Three Environmental Regulatory Frameworks	Revenue for Government	Ease in Action for Government	Operational Flexibility for Company	Guarantee of Carbon Emission Reduction
Carbon Tax	Yes	Medium	Medium	No
Carbon Emission Trading	Yes	High	High	Yes
Direct Restriction	No	Low	Low	Yes

Source: Compiled by the author

From the above comparative analyses of these three environmental regulatory frameworks, it can be concluded that the second scheme (carbon emission trading scheme) is welcomed by both companies and governments. In the implementation process of an emission trading scheme, the setting of cap value is important. The optimisation model developed in this chapter contributes by analysing the differences in various cap levels. The medium-cap level is found to be the preferable choice compared to the loose-cap and tight-cap levels, because it can offer more flexibility with regard to the decision-making processes of companies in the carbon emission trading market. However, implementation of a carbon emission scheme also requires a mature emission trading market mechanism. The supervision and guidance functions of the government also become particularly important under this scheme.

As a whole, depending on their individual constraints, each government should choose the environmental regulatory framework which suits it best. Great importance must be attached to environmental protection in order to achieve sustainable development.

6.4 Chapter summary

This chapter deals with global intermodal container network optimisation at an operational level by using a mixed-integer non-linear programming model. To reduce carbon emission, there are three different environmental regulatory frameworks considered and incorporated in this research, namely: (1) carbon tax, (2) carbon emission trading, and (3) direct restriction. Until now, there has been no scientific literature that deals with these three schemes together in transport planning or transportation optimisation areas.

Similar to the tactical-level model in the last chapter, this operational-level model also considers cost minimisation and transit-time minimisation as two objectives in optimising the intermodal container network in both sea and land legs under the above three different environmental regulatory frameworks. In this operational-level model, its non-linear part deals with sea-leg sailing speed optimisation. Bunker consumption and sailing speed maintain a third power relationship approximately. A piecewise outer-approximation algorithm is used to approximate its non-linear part. After this linearisation transformation, the state-of-the art commercial solver, CPLEX, is brought in to solve the operational-level model. A case study on the Trans-Pacific container intermodal chain helps to illustrate the applicability and significance of this operational model. Shipping lines and other freight integrators can refer to the results of this operational model in their daily operations, such as getting the optimal routing of containers and the optimal sailing speed on each segment in each shipping route. Through comparative analyses of these three environmental regulatory frameworks, a carbon emission trading scheme would be preferred by both companies (shipping lines or freight integrators) and governments and a medium-cap setting is suggested under this scheme.

Chapter 7 Conclusions and recommendations for future research

This chapter is the last chapter of this thesis. All the research objectives were laid down in Chapter 1 and successfully fulfilled through carrying out the research process in Chapter 2 through Chapter 6 step by step. This chapter summarises the main research findings and contributions achieved in this research. The research limitations and recommendations for future research are also provided here.

Through conducting an in-depth review of the literature concerning the container network optimisation domain, it is found that very few efforts have been made to study container intermodal network optimisation that includes both sea and inland components. Moreover, quantitative models about environmental issues in transportation planning are relatively scarce. These are two gaps which this research aims to close. The combination of these two gaps is an issue of intermodal container flow considering both empty and laden containers with green concerns using bi-objective optimisation. This research gap was suggested in Chapter 2 through a specific literature review. Two optimisation models from tactical-level and operational-level perspectives were developed in Chapter 5 and Chapter 6, respectively, in order to address this issue. During the process of solving the tactical-level model, an enhanced NSGA-II algorithm was developed. Three environmental regulatory frameworks, namely carbon tax, carbon emission trading and direct restriction, are incorporated into the operational-level model. The analyses of the optimal results from this operational model can offer managerial insights into and policy implications about these three environmental regulatory frameworks. Last but not least, in addition to these quantitative models, qualitative research on comparing the potentials and challenges in terms of intermodal development in China and India was undertaken in Chapter 4. Such research can be useful for China and India while carrying out their port hinterland intermodal development.

Overall, the entirety of this research devoted great effort to investigating the port hinterland intermodal development issue with environmental concerns, in order to achieve sustainability. It not only provides insights into the existing knowledge but makes practical contributions to the maritime and land transport industries and government policies.

7.1 Summary of main findings

In Barnhart and Laporte (2007)'s definition, intermodal freight transportation refers to container transportation in multimodal chains which link the original nodes of consignors to the destination nodes of consignees in order to offer door-to-door service to the customers. Intermodal networks can boost economic globalisation considerably, because it can provide door-to-door services. Ports that are more closely and tightly incorporated into the global intermodal networks can gain more competitive power than others. Economic globalisation has brought about a surging international trade volume in recent years. Owing to this surge in international trade volume, carbon emissions are also rapidly increasing. How to achieve sustainable development in the transportation domain deserves our utmost attention. An intermodal network has three kinds of links in the land leg: truck, train and barge. These three modes incur different costs, transit times and carbon emissions. How to manage the trade-offs among these three factors is a challenge because their corresponding management objectives conflict with each other. Considering all of the above, the port hinterland intermodal development with environmental concern has been investigated in a comprehensive manner in this study. The major findings are summarised as follows.

- (1) The first research objective was to investigate China's and India's port hinterland intermodal development with a focus on sustainability by conducting a qualitative comparative analysis. This objective was met by researching the potentials and challenges in terms of intermodal development in China and India. Chapter 4 has provided a detailed comparison between these two fast-developing economies. As a whole, the study discussed that both China and

India present tremendous opportunities for intermodal development, mainly due to their rapid trade growth. Our analysis uncovered that China's inland port development is still in its infancy stage. It is unable to catch up with its rapid economic growth. As compared to China, India focuses more on the social aspect to protect the welfare of its residents, which in turn jeopardises India's intermodal development in an economic sense. The biggest challenge for India is its social institution which would take a long time to change.

- (2) Our second and fourth research objectives are closely related. The second objective is to build a model and the fourth objective is to develop a mathematical algorithm to solve the model. Both of these two objectives were achieved in Chapter 5.

Our second objective, to develop a tactical model for port hinterland intermodal network optimisation with sustainable development and to analyse the effect of different carbon emission restrictions on transport planning using China as a case study, was met in Chapter 5. This tactical-level model is a bi-objective integer linear programming optimisation model. Cost and transit time are considered as two minimisation objectives simultaneously. Carbon emission is incorporated in the model as a constraint to represent the environmental protection requirement. This tactical model can be solved by using the state-of-the-art solver “CPLEX”, providing the problem scale is not large. To solve a large-scale problem our fourth objective, an enhanced NSGA-II algorithm, was designed in Chapter 5.

Several findings were uncovered. Firstly, it is found that a looser carbon emission constraint will have a wider Pareto Frontier range than a tighter carbon emission no matter whether CPLEX or the enhanced NSGA-II is used. Secondly, it should also be noticed that a small change in K value will have significant impact on the Pareto Frontier range. This is because the majority of carbon emission is generated by sea-leg transport which comprises the major share of the total intermodal chain's mileage. However, it is also crucial to

address environmental concerns for inland transport planning. Thirdly, as long as inland waterways are available, barge is the most preferred transportation mode to lower cost and carbon emissions. Fourthly, trucking has the shortest transit time, but incurs the highest cost and carbon emissions. Unless transit time is a major concern, trucking should not be encouraged for long-distance transport. Fifthly, barge or railway intermodal transport provides opportunities to reduce the ratio of pre- or last-mile trucking mileage to the total transport mileage. This not only brings about economic benefits, but also better preserves the environment. Last but not least, tighter environmental regulations on carbon emissions favour barge and rail transport. However, more environmentally friendly transport modes require the development of supporting infrastructures including inland waterways, barge ports, railways and dry ports.

- (3) The third research objective was achieved in Chapter 6. It developed an operational model for sea-and-land intermodal optimisation subject to the three different environmental regulatory frameworks by using a Trans-Pacific container intermodal chain as a case study.

In Chapter 6, an operational-level mixed-integer non-linear programming model is formulated. This operational-level model also has two objectives (minimum cost and minimum transit time) similar to the model in Chapter 5. This operational-level model is subject to three main different environmental regulatory frameworks: carbon tax, carbon emission trading scheme and direct restriction. The study tackled these three schemes together and related them to transport planning or transportation optimisation. Through analyses and calculation, it was found the second choice (carbon emission trading) would be the most preferable choice among the three frameworks from both the company and the government perspectives. Companies would have more flexibility with regard to their operational network planning. Meanwhile, from the government's point of view, the total carbon emission of all companies can be effectively controlled and reduced. Under this choice, there are three alternatives of cap level, namely loose-cap, medium-cap and tight-cap. The

medium-cap level is found to be the most preferable because it can offer more flexibility with regard to the decision-making processes of companies in the carbon emission trading market.

7.2 Main research contributions

As discussed above, the research objectives that had been set for the study were achieved. The study's contributions are multi-faceted and are summarised as follows:

- (1) The contributions of Chapter 2 are twofold. Firstly, it conducts a descriptive literature review to demonstrate the relationship between seaports and supply chains, the development trends (such as sustainable development) and current situations in these industries. Secondly, it uses a summary table and several sub-tables to classify and structure the existing literature about the subject of container transport optimisation. Insightful analyses are provided accordingly. Through such analyses, new research gaps in this area are identified and future research directions are suggested.
- (2) There are two contributions in Chapter 4. Firstly, it is the first attempt to address and compare the potentials and challenges in terms of port and intermodal development of China and India, two fast-developing new economies in Asia. It bridges the second research gap uncovered in Chapter 2. The findings are of significant value. Secondly, its in-depth comparative analyses not only give future directions for intermodal development in China and India, but also set an example for the rest of the world.
- (3) Chapter 5 makes several contributions. Firstly, the tactical-level model is innovative. It not only simultaneously optimises intermodal container flows in both sea and land legs, but also measures transportation cost and transit time. More importantly, it is one of the few attempts that take carbon footprint constraints on transport planning into consideration. Secondly, this research finds that the gaps between the enhanced NSGA-II results and CPLEX's results

are within an acceptable range. Hence the enhanced NSGA-II method is proposed to solve large-scale instances efficiently, something that is beyond the ability of CPLEX. Thirdly, the model's application offers managerial insights and policy implications. As revealed by the case study of China's intermodal network, the Chinese central and local governments should coordinate their efforts to develop the inland barge system, because barge is the most preferred transportation mode to lower cost and reduce carbon emissions. In the hinterland area, where natural waterways are not available, governments need to consider the development of the railway links and dry ports as a priority. Governments should try to develop the infrastructure of their inland barge systems and railway to dry port systems as this can help to reduce the amount of last-mile trucking mileage to the total transport mileage.

- (4) The major contributions of Chapter 6 are as follows. Firstly, this operational-level model is original. It is able to optimise the intermodal container network at an operational level to measure cost and time simultaneously. Secondly, it is a new endeavour in the transportation sustainable research area. It innovatively illustrates the "Basic Model" under three different environmental regulatory frameworks: carbon tax, carbon emission trading and direct restriction. Thirdly, it has also provided an in-depth analysis about the premises and consequences should these three environmental regulatory frameworks been implemented. A carbon emission trading framework would be the most preferable scheme to be used by companies (such as shipping lines and other freight integrators) and governments. A medium-cap setting is suggested under this scheme.

As a whole, the two optimisation models at the tactical and operational levels provide both research and practical contributions. They can assist governments and enterprises, especially freight integrators such as major shipping lines and logistics service providers, when making decisions on tactical and operational levels. The common characteristics of these two models are: (1) both are bi-objective optimisation models which can get a portfolio of trade-offs between two conflict objectives, which means they can help handle more practical situations, and (2) both

models include environmental concerns. However, some differences between them must be pointed out: (1) the tactical model is a linear model while the operational model is a non-linear model, and (2) the tactical model is solved by an enhanced NSGA-II algorithm, while the operational model is solved only by the solver CPLEX. Last but not least, several significant and insightful policy implications are derived from the numerical results of these optimisation models.

7.3 Limitations and recommendations for future research

7.3.1 Research limitations

This research in its entirety has explored the issue of sustainable port hinterland intermodal development with environmental concerns. Much research has its own limitations, and this research is no exception. It only considers container intermodal transportation, without taking into account other kinds of intermodal transportation. For example, dry bulk, liquid cargo and Ro-Ro transportation supply chains are not covered in this research. This is because container intermodal transportation could be more readily quantified and calculated than other cargos due to the advantage of its standardisation. Moreover, these two models in Chapter 5 and Chapter 6 are both deterministic models, not stochastic models. Hence in one planning period, the demands and supplies and other configurations of the network are known and invariant. However, demand and supply uncertainties are not the main focus of the current study. The demand or supply changes in one planning period are accumulated and considered in the next planning period. All the demands and supplies are assumed to be determinate throughout one planning period. The research objectives focusing on sustainable port hinterland intermodal development can still be achieved, particularly for planning and policy purposes, without addressing precise short-term market fluctuations.

7.3.2 Recommendations

Based on Chapters 4, 5 and 6, and the research limitations stated above, the

following recommendations and suggestions are made for future research as they relate to each chapter.

- (1) Chapter 4 could be extended for further research. For example, comparisons made between China, the USA and Europe, three main world economies, in terms of intermodal development would be interesting. Future quantitative works should be carried out to measure the benefits of inland port application and intermodal optimisation in terms of cost and time minimisation as well as carbon footprint reduction. In Chapter 5 and Chapter 6, the two deterministic models have been applied to fill the gap. However, there is still room to extend further study along these lines. Studies using stochastic models can also become the subject of future research.
- (2) In Chapter 5, we have developed a novel bi-objective integer linear programming mathematical model to deal with tactical planning of intermodal container transport. Several extensions are proposed for this tactical research. Firstly, the tactical model could be extended to consider sailing speed and bunker consumption in the sea leg. Secondly, transit times are not always definite in reality. It is therefore necessary to incorporate stochastic features in the model if uncertainties are a major concern in transport planning. Thirdly, it is also beneficial to run more experiments in different problem scales to help further test the enhanced NSGA-II's performance. Last but not least, other metaheuristic algorithms could be developed to compare with the enhanced NSGA-II in Chapter 5, like other research papers (Fink and Voß, 2003; Ramezani et al., 2012).
- (3) An operational-level optimisation model is formulated in Chapter 6. This mixed-integer non-linear model could also be used to optimise cost and transit time simultaneously. Furthermore, it also incorporates three different environmental regulation frameworks (carbon tax, carbon emission trading scheme and direct restriction) in its considerations. The limitations and recommendations of Chapter 6 are as follows. Firstly, in a real-life situation, shipping lines are involved in partnerships or strategic alliances in ship

deployment. This research has not considered such an option for ship deployment, so future research may include partnerships or strategic alliances in liner operations. Secondly, only one single type of container has been considered in this chapter and future models could consider including multi-types. Thirdly, this operational model can be extended to consider different sailing speeds and their impacts on the sea leg, because sailing speed within the scope of maritime operations would have a significant impact on the total cost and total transit time. Last but not least, for operational-level transport planning (daily operation), uncertainties are usually a major concern, thus stochastic features should be taken into consideration.

In summary, research on sustainable development in intermodal transport and port-related topics has obtained increasing attention from scholars and industry professionals. This thesis has contributed to this emerging research direction. Topics on sustainable development are still relatively new and present ample room for future research efforts.

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