PORT HINTERLAND ESTIMATION AND OPTIMIZATION FOR INTERMODAL FREIGHT TRANSPORTATION NETWORKS

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SUMMARY

Ports are considered as critical transfer terminals in switching containers between maritime and inland transportation modes. Port hinterland is a key performance indicator reflecting the competitiveness of a port. From the point of view of port operators, there is a need to estimate and optimize port hinterland, so as to facilitate their knowledge of current port market areas and to make well-informed changes to maximize their port market shares. Though practically necessitated, unfortunately, these two issues have not been fully addressed in the past relevant studies. This work is focused primarily on developing a modeling approach for port hinterland estimation and optimization.

To achieve this goal, a new definition of probabilistic port hinterland is proposed. Two mathematical models are developed to formulate the attribute- and utility-based probabilistic hinterland of a particular port based on the behavior assumption of intermodal operators in route choice, respectively. Monte Carlo based algorithms are designed to solve these two models, respectively. Illustrative examples are given to assess the applicability of the proposed models and algorithms.

After having the port hinterland estimated, a port hinterland optimization problem is subsequently concerned. To serve to tackle the port hinterland optimization problem, this work also aims to solve a novel intermodal hub-and-spoke network design (IHSND) problem.

The IHSND problem is complicated by involving mode changes, multiple stakeholders and multi-type containers. A mathematical program with equilibrium constraints (MPEC) model is first developed to formulate the IHSND problem with uni-type containers. The model utilizes a transportation cost function having a U-shaped unit

cost function to describe the cost structure of carriers and a utility function integrating actual transportation rates and congestion impact to describe the preference of intermodal operators. Two fixed-points formulations are incorporated into the MPEC model to reflect the stochastic user equilibrium based behavior assumption of intermodal operators in route choice. A branch-and-bound algorithm embedded with a cost averaging (CA) algorithm is proposed to solve the model.

Another MPEC model is developed to formulate the IHSND problem with multi-type containers. In the model, a joint cost function of multi-type containers that can describe the multi-type container transportation cost structure is utilized for carriers. A utility function integrating actual transportation charges and congestion impact is proposed for intermodal operators. The model incorporates a variational inequality (VI) to represent the user equilibrium based route choice behavior of intermodal operators. Due to the non-convexity and complexity of the model, a hybrid genetic algorithm (HGA) is designed to solve the model. The proposed model and algorithm are assessed by numerical examples.

Based on the investigation of the port hinterland estimation and IHSND problems, a port market share optimization (PMSO) problem with respect a concerned study area is proposed to address the port hinterland optimization problem. The PMSO problem is formulated as an MPEC model and then solved by using a branch-and-bound algorithm. The optimal market share of the port of Shenzhen and the corresponding market shares of selected Asian ports are computed by using the proposed model and algorithm.

This work is believed to contribute new theories and methodologies to current literature of port competitiveness and intermodal network design studies.

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LIST OF ABBREVIATIONS

AAPA	American Association of Port Authorities
AHP	Analytical Hierarchical Process
ASEAN	Association of Southeast Asian Nations
CA	Cost Averaging
CMSA	China and Mainland Southeast Asia
EEA	Exhaustive Enumeration Algorithm
FEU	Forty-foot Equivalent Unit
GA	Genetic Algorithm
HGA	Hybrid Genetic Algorithm
HSND	Hub-and-Spoke Network Design
IHSND	Intermodal Hub-and-Spoke Network Design
IIA	Independence of Irrelevant Alternatives
MPA	Myanmar Port Authority
MPEC	Mathematical Programs with Equilibrium Constraints
MRC	Ministry of Railways of China
NBSC	National Bureau of Statistics of China
O/D	Origin/Destination
PMSO	Port Market Share Optimization
SGA	Simple Genetic Algorithm
SO	System Optimum
SUE	Stochastic User Equilibrium
TEU	Twenty-foot Equivalent Unit

TRB	Transportation Research Board
OOCL	Orient Overseas Container Line Limited
UE	User Equilibrium
UNCTD	United Nations Conference on Trade and Development
UNECE	United Nations Economic Commission for Europe
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
USCC	U.S. Chamber of Commerce
VI	Variational Inequality

GLOSSARY OF NOTATIONS

a	a physical link $a \in \mathcal{A}$
$\bar{a}$	an operational link $\bar{a} \in A$
$\mathcal{A}$	the set of all physical links
$\mathcal{A}_0$	the set of spoke links
$\mathcal{A}_1$	the set of existing non-spoke links
$\mathcal{A}_2$	the set of candidate physical links
A	the set of all carrier links
A_a	the set of carrier links derived from physical link a
A_n^1	the set of carrier links pointing at node n
A_n^2	the set of carrier links pointing out node n
b	a transshipment line $b \in \mathcal{B}$
$\mathcal{B}$	the set of transshipment lines
$\mathcal{B}_1$	the set of existing transshipment lines
$\mathcal{B}_2$	the set of transshipment lines
$\mathcal{B}_h$	the set of transshipment lines at transfer terminal h
$\mathcal{B}_h^1$	the set of existing transshipment lines at transfer terminal h
$\mathcal{B}_h^2$	the set of potential transshipment lines at transfer terminal h
B	the budget limit
$c_{\bar{a}}\left(v_{\bar{a}}\right)$	the uni-type container transportation cost function of on $\bar{a}$

$c_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right)$	the multi-type container transportation cost function on $\bar{a}$
$c_b\left(v_b\right)$	the uni-type container transportation cost function on b
$c_b\left(\mathbf{v}_b\right)$	the multi-type container transportation cost function on b
c_a	the expected value of C_a
c_h	the expected value of C_h
C_a	the random transportation cost on a
C_h	the random transfer cost at h
d	a destination $d \in \mathcal{D}$
$\mathcal{D}$	the set of all destinations, $\mathcal{D} \subseteq \mathcal{N}$
e	a carrier $e \in \mathcal{E}$
$e_{\bar{a}}$	the carrier over $\bar{a}$
$\mathcal{E}$	the set of carriers
$\mathcal{E}_a$	the set of carriers on a
$f_{od\bar{r}}^{p}$	the container flow of type p loaded on the route $\bar{r} \in R_{od}$
$\mathcal{G}$	the physical network $\mathcal{G} = \left(\mathcal{N}, \mathcal{A}\right)$
G	the operational network $G = \left(N, A, T\right)$
$G_{\bar{a}}$	the random utility of $\bar{a}$
$G_{\bar{l}}$	the random utility of $\bar{a}$
$g_{\bar{a}}$	the expected value of utility of $\bar{a}$
$g_{\bar{l}}$	the expected value of utility of $\bar{l}$

$\mathbf{g}$	$=\left(g_{\bar{a}}, g_{\bar{l}}, \bar{a} \in A, \bar{l} \in T\right)$
h	a transfer terminal $h \in \mathcal{H}$
$\tilde{h}_a$	the head of physical link a
$\tilde{h}_{\bar{a}}$	the head of carrier link $\bar{a}$
$\mathcal{H}$	the set of all transfer terminals
I_{od}	the cardinality of set $\mathcal{R}_{od}$
$\bar{I}_{od}$	the cardinality of set R_{od}
$\bar{l}$	a transfer $\bar{l} \in T$
m	a mode $m \in \mathcal{M}$
m_a	the mode physical link a
$m_{\bar{a}}$	the model of carrier link $\bar{a}$
$\mathcal{M}$	the set of all modes of transport
n	a node $n \in N$
$\mathcal{N}$	the set of all nodes in $\mathcal{G}$
N	the set of all nodes in G, $N \supseteq \mathcal{N}$
N_h^1	the set of virtual nodes with respect to A_h^1
N_h^2	the set of virtual nodes with respect to A_h^2,
N_h	the set of all virtual nodes at h
o	an origin $o \in O$
O	the set of all origins $O \subseteq \mathcal{N}$
p	a container type $p \in P$

$\mathcal{P}$	the set of all products
P	a particular port P
r	an intermodal route $r \in \mathcal{R}_{od}$
$\overline{r}$	an operational intermodal route $\overline{r} \in R_{od}$
$r_{\overline{a}}$	the actual rate for uni-type container transportation on $\overline{a}$
$r_{\overline{a}}^{p}$	the actual rate for transporting per container of p on $\overline{a}$
$r_{\overline{l}}$	the actual rate for uni-type container transportation on $\overline{l}$
$r_{\overline{l}}^{p}$	the fixed rate for handling per container of p on $\overline{l}$
$\mathcal{R}_{od}$	the set of intermodal routes between $(o \in O, d \in \mathcal{D})$
R_{od}	the set of operational intermodal routes between $(o \in O, d \in \mathcal{D})$
$\mathbf{s}$	the vector decision variable $\mathbf{s} = (\mathbf{x}, \mathbf{y}, \mathbf{z})$
t_a	the expected value of T_a
t_h	the expected value of T_h
$\tilde{t}_a$	the tail of h physical link a
$\tilde{t}_{\overline{a}}$	the tail of h carrier link $\overline{a}$
$t_{\overline{a}}$	the uni-type container transportation time function on $\overline{a}$
$t_{\overline{a}}^{0}$	the free-flow unit-type container transportation time on $\overline{a}$
$t_{\overline{a}}^{p}$	the transportation time function for per container of type p on $\overline{a}$
$t_{\overline{a}}^{p0}$	the free-flow transportation time for per container of type p on $\overline{a}$
$t_{\overline{l}}$	the uni-type container transfer time function on $\overline{l}$

$t_{\bar{l}}^{0}$	the free-flow unit-type container transfer time on $\bar{l}$
$t_{\bar{l}}^{p}$	the transportation time function for per container of type p on $\bar{l}$
$t_{\bar{l}}^{p0}$	the free-flow transfer time for per container of type p on $\bar{l}$
T	the set of all transfers in G
T_b	the set of transfers on b
T_h	the set of transfers at h
T_h^b	the set of transfers on $b \in T_h$
T_a	the random transportation time on a
$\tilde{T}_h$	the random transfer time at h
T_{od}	the transport demand between $(o \in O, d \in \mathcal{D})$
T_{od}^{p}	the transport demand of container type p $(o \in O, d \in \mathcal{D})$
$u_{od}^{\bar{r}}$	the expected value of $U_{od}^{\bar{r}}$
$U_{od}^{\bar{r}}$	the random utility of route $\bar{r} \in R_{od}$
$\mathbf{u}_{od}$	$=\left(u_{od}^{\bar{r}}, \bar{r} \in R_{od}\right), \forall o \in O, d \in \mathcal{D}$
v_a	the standard vehicle volume loaded on a
$v_{\bar{a}}$	the uni-type container flow loaded on $\bar{a}$
$v_{\bar{a}}^{o}$	the uni-type container flow loaded on $\bar{a}$ with origin o
$v_{\bar{a}}^{p}$	the container flow of type p loaded on $\bar{a}$
v_b	the standard container flow loaded on b
v_b^{p}	the container flow of type p loaded on b

$v_{\bar{l}}$	the uni-type container flow loaded on $\bar{l}$
$v_{\bar{l}}^{o}$	the uni-type container flow loaded on $\bar{l}$ with origin o
$v_{\bar{l}}^{p}$	the container flow of type p loaded on $\bar{l}$
$\mathbf{v}_{\bar{a}}$	$=\left(v_{\bar{a}}^{p}, p \in \mathcal{P}\right)$
$\mathbf{v}_{b}$	$=\left(v_{b}^{p}, p \in \mathcal{P}\right)$
$\mathbf{v}_{\bar{l}}$	$=\left(v_{\bar{l}}^{p}, p \in \mathcal{P}\right)$
$\mathbf{v}$	the vector network flow
x_a	the decision variable equivalent to one if traffic capacity of physical link $a \in \mathcal{A}_1$ is expanded; zero otherwise
$x_{\hat{a}}$	the decision variable equivalent to one if physical link $\hat{a} \in \mathcal{A}_2$ is established; zero otherwise
$\mathbf{x}$	$=\left(x_a, a \in \mathcal{A}\right)$
y_b	the decision variable equivalent to one if capacity of transshipment line $b \in \mathcal{B}_1$ is expanded; zero otherwise
$y_{\hat{b}}$	the decision variable equivalent to one if transshipment line $\hat{b} \in \mathcal{B}_2$ is established; zero otherwise
$\mathbf{y}$	$=\left(y_b, b \in \mathcal{B}\right)$
z_h	the decision variable equivalent to one if hub $h \in \mathcal{N}_2$ is selected; zero otherwise
$\mathbf{z}$	$=\left(z_n, n \in \mathcal{N}\right)$

δ_{od}^{ra} one if $r \in \mathcal{R}_{od}$ traverses carrier link a; zero otherwise

δ_{od}^{rn} one if $r \in \mathcal{R}_{od}$ traverses n; zero otherwise

$\delta_{od}^{\bar{r}\bar{a}}$ one if $\bar{r} \in R_{od}$ traverses carrier link $\bar{a}$; zero otherwise

$\delta_{od}^{\bar{r}\bar{l}}$ one if $\bar{r} \in R_{od}$ traverses transfer $\bar{l}$; zero otherwise

$\delta_{od\bar{r}}^{\bar{a}p}$ one is $\bar{r} \in R_{od}$ delivering p traverses $\bar{a}$; zero otherwise

$\delta_{od\bar{r}}^{\bar{l}p}$ one if route $\bar{r} \in R_{od}$ traverses transfer $\bar{l}$; zero otherwise

CHAPTER 1

INTRODUCTION

1.1 Intermodal Freight Transportation Operations

Intermodal freight transport has been defined as the movement of goods in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes (UNECE, 2009). Intermodal freight transportation involving multiple modes of transport provides an economical solution for international/transcontinental cargo delivery. Facilitated by the fast growing international merchandise trade and economic exchanges, intermodal freight transportation has developed into a significant sector of the transport industry in its own right (Bontekoning et al., 2004). The fundamental rationale behind making use of intermodal transportation is to take advantage of scale economies by consolidating transport units on large-size vehicles for cost-effectiveness long-haul transportation (e.g., rail or maritime transportation), while employing efficient short-haul transportation such as door-to-door truck services to accomplish local deliveries.

The intermodal transport units can be containers, swap bodies, or semi-trailers. Containerized cargo constitutes the main form of the goods shipped by intermodal transportation, and the fact that containers are best suited to intermodal transportation can be explained by the early established standards on container dimensions. The standardization leads to reduced handling cost and time in container transshipments at terminals by using standardized operational facilities. In this study we focus on container based intermodal freight transportation. Intermodal freight transportation may involve multi-type containers. The containers that serve for various specific purposes, possess different functions or sizes, and require different handling techniques, costs or time are regarded as containers of different kinds. Examples of multi-type containers include twenty-foot equivalent units (TEUs), forty-foot equivalent units (FEUs), refrigerated TEUs and tank containers.

Intermodal transportation seamlessly integrates short-haul services (e.g., drayage) and long-haul services to deliver containerized cargo using a sequence of interacting terminals such as rail-truck terminals, ports and border crossing terminals between adjacent countries. A typical intermodal containerized cargo delivery from a specific origin to a specific destination can be realized in the following steps. First, containers are collected from the origin to a nearby interacting terminal by short-haul truck services. At the terminal, the containers are transshipped to long-haul services and subsequently delivered to a final interacting terminal located around the destination. The long-haul transportation may transverse one or several such interacting terminals when changing modes. At the final interacting terminal, these containers are transshipped to a local short-haul service leading to the destination.

1.2 Intermodal Freight Transportation Networks

Intermodal freight transportation operations are accomplished through intermodal freight transportation networks, which provide basic infrastructure facilities such as railways, roadways and vehicles for transportation operations and interacting terminals for transshipment operations.

1.2.1 Network Elements

The infrastructure facilities in an intermodal freight transportation network can be represented by various network elements. The points or locations from which containers are originated are referred to as origins, and those to which containers are destined are referred to as destinations. A pair of origin and destination is termed as an origin-destination pair or O/D pair for short. Containerized cargo delivery is characterized by sequential transfers of the containers at interacting terminals. The interacting terminals at which containers are consolidated, sorted and switched between various modes are defined as transfer terminals. The handling of containers is generally ineluctable at transfer terminals due to mode change. Regular nodes are another type of interacting points which may exist in intermodal freight transportation networks. Regular nodes are referred to as the points where rail or road sections merge together without handling of containers, such as interaction of two roadways or railways. Generally, containers will be handled due to mode changes in transshipment, and as a consequence, additional transshipment cost and time will be accordingly incurred at transfer terminals, while no cost or time will be incurred at a regular node. All these origins, destinations, transfer terminals and regular nodes can be referred to as nodes.

Intermodal freight transportation comprises multiple modes of transport. A mode indicates one means of transportation with its own characteristics, such as vehicle type and capacity, and it may also represent a kind of specific infrastructures such as rail, road, and maritime. A connection between a pair of nodes, which is specified by a particular mode and provides the mode-based infrastructures for vehicles, is defined as a link. As mentioned above, intermodal transportation delivers containers from a specific origin to a specific destination by traversing through a sequence of nodes, links and transfer processes at transfer terminals. These sequential network elements constitute an intermodal route connecting the specific origin and destination. An intermodal route is defined as a sequence of physical network elements such as links, regular nodes and transfer terminals, which can be employed to accomplish a delivery task between a given O/D pair.

1.2.2 Mode Changes

Transfer terminals have been playing a vital role in transferring containers among different modes. Containers are consolidated, handled, and then transferred to next links at transfer terminals in order to realize higher efficiency and economies of scale. Coupled with the transfers, mode changes may occur at the same time. Mode change is one of the prominent characteristics of an intermodal transportation system and the process is accomplished by using transshipment lines at hubs. A transshipment line represents a collection of infrastructure facilities, such as trailers, straddle carriers and cranes, necessitated to transfer containers from one particular mode to another.

As for a particular container, it will be handled at a transfer terminal if the container needs to be transshipped to a different mode in the transfer terminal, and cost and time will be correspondingly incurred in the handling process. It must be noted that container handling procedure may be involved even if transport mode does not change. For instance, containers are usually unloaded, inspected and reloaded for customs clearance at a border crossing terminal without change of transport mode. Such a process is also regarded as one type of mode changes. It should be pointed out that the basic units of arrival to a transfer terminal are individual containers, opposed to vehicles such as ships and trains, and containers arrive at transfer terminals in batches according to the capacity of vehicles.

1.2.3 Multiple Stakeholders

Various behaviorally distinct decision makers or stakeholders are involved in intermodal freight transportation operations. Containers are intended to be transported from product manufacturers to consumers who demand products but are spatially separated from producers by some distance. The manufacturers are referred to as shippers, who desire to transport containers to specific consumers. The whole transportation process is governed and coordinated by intermodal operators on behalf of shippers, and an intermodal operator may represent a shipper himself, a third-party logistics company or an intermediary broker. Intermodal operators are considered as route choice decision makers for container transportation through the whole intermodal network (Macharis and Bontekoning, 2004). In general, intermodal operators will hire carriers possessing transportation facilities to accomplish the transportation task. Carriers are identified as decision-making entities operating carrying vehicles or vessels and providing transportation services on links or those having container handling facilities and providing transfer services at transfer terminals. A carrier may represent an inland transportation company, liner shipping company or a transfer terminal operator and can be considered as a direct user of intermodal infrastructure facilities. Port operators are a particular type of carriers who own port handling facilities such as berths, quay cranes and yard cranes and provide container transfer services at ports.

In addition, the infrastructure facilities in intermodal freight transportation networks are generally planned and established by strategic-level decision makers, who are responsible to enhance network efficiencies and accessibilities in order to promote the development of local or global economics. These strategic-level decision makers are called planners. A planner may represent a government authority or an association of several government authorities.

1.3 Port Hinterland and Market Share

A port is considered to be a critical gateway or intermodal transfer terminal, which provides transfer facilities for intermodal container movements between maritime and inland modes. Due to the drastically developing container shipping and port industries, mega ports such as Singapore, Hong Kong and Shanghai ports have become key infrastructures in determining the economic well-being of the areas served by them, as seaborne trade accounts for a major proportion of world trade (UNCTD, 2007). The area served by a particular port, over which shippers desire to transport their goods to a given destination via one or several intermodal routes traversing through the port, is referred to as the port's hinterland (also known as port market area) with respect to the given destination. It is worthwhile to notice that "hinterland" is specifically used for representing the market area of a port, and the market area is more suited to all kinds of transfer terminals. Port hinterland is a performance indicator to gauge the competitiveness of a port in competing with others, since it can graphically show the size and extent of the port market area in which container flows tend to traverse through the port. Dedicated port hinterlands are deemed to facilitate smooth intermodal movements of goods and to ensure goods reach their final destinations quicker and more cheaply and are considered as one way of value-adding to port facilities (UNESCAP, 2005).

The market share of a port is generally estimated associated with a study area, which is probably the hinterland of the port. Given a concerned study area, the market share of a particular port is defined as the proportion of the container traffic volume handled by the port to the total traffic demand generated in the study area. The port market share can be considered as another appropriate performance indicator that reflects the competitiveness of the port, since it quantitatively measures the scale of container traffic it attracts when vying with other ports. The competition between different ports which are serving the same region can be envisioned by comparing their market shares with respect to the region. Port market share actually provides a different perspective to investigate the port competitiveness from port hinterland.

It can be seen that both port hinterland and port market share are strongly related to container flow distribution in the whole intermodal freight transportation network, which is further determined by the decisions of the multiple stakeholders. Put simply, the area where a port's market share is greater than a given proportion is the hinterland of the port.

1.4 Issues and Motivations

1.4.1 Port Hinterland Estimation

Port hinterland estimation is widely concerned by various sectors involved. For local a government authority who has a port as the main engine of economic development, the extent and size of port hinterland would affect the economic viability, opportunity and propensity of the local area. By port hinterland analysis, they can obtain the knowledge of how to structure an intermodal hinterland network to invigorate local economies. As for port operators, estimating port hinterland can assist them in analyzing key impact factors of port hinterlands, so as to adjust competition policies to expand their hinterlands.

Estimating port hinterland enables shippers to easily select appropriate ports to transport their containers.

Although practically necessitated, however, the port hinterland estimation has not been fully investigated in the context of intermodal freight transportation operations. Past relevant studies are only restricted to estimating the market share of a transfer terminal, trade center or selling market by taking into account several competing transportation routes in a certain circumstance. Instead, the problem should be examined from the whole intermodal network level and should involve uncertainties existing in intermodal freight transportation such as fluctuating average price in transportation market and varying port handling cost and time. There is thus a research need to develop a probability-based port hinterland estimation approach in the context of intermodal operations.

1.4.2 Port Hinterland Optimization

After port hinterland estimation, a conceivable concern of a port operator or local government authority would be optimizing the port hinterland in terms of port market share, in order to attract more intermodal operators or containers flows to traverse through the port and to prevail in competing with other ports.

As indicated by port competitiveness studies (Yeo et al., 2008), the efficiency and cost effectiveness of hinterland connections of a port are crucial factors influencing its market area. The port market share can thus be expanded by organizing an efficient and economical hinterland network that serves the port and connects the port with the inland origins and destinations of container flows. The designed hinterland network would assist the port operator in expanding the port market share by leading containers to the port in a fast and cheap way. Besides, a highly efficient and cost-effectiveness hinterland network would provide carriers and intermodal operators with more economical transportation solutions. The port market share optimization using hinterland network design problem is of importance for port operators or local government authorities, carriers and intermodal operators. However, this issue has so far attracted limited attention of researchers. Thus a modeling approach to optimizing port market share using hinterland network design needs to be developed to provide an analytical tool for port operators and local government authorities.

1.4.3 Intermodal Hub-and-Spoke Network Design

Both port hinterland estimation and optimization problems are proposed from an intermodal network's point of view. Intermodal networks provide a basis for exploring these two problems. Especially in the port hinterland optimization problem, the hinterland network of a specific port needs to be optimally designed to expand its market share.

A port's hinterland network is essentially an intermodal freight transportation network involving multiple modes of transport and transfer terminals switching containers amongst various modes. As emphasized by Crainic and Kim (2007), an intermodal freight transportation system can be fundamentally organized as a hub-and-spoke network, where transfer terminals serve as hubs and non-transfer-terminals are spoke nodes. Thus, the intermodal hub-and-spoke network design (IHSND) problem needs to be investigated to pave the way for solving the port hinterland optimization problem from the points of view of port operators and local government authorities.

Although the conventional hub-and-spoke network design (HSND) problem has been extensively studied in the context of airline transportation and mail delivery operations, the IHSND problem with multiple stakeholders, multi-type containers, and mode changes has received limited attention perhaps due to the inherent complexities involved in intermodal freight transportation operations. A research need therefore arises to develop a modeling approach to solving the IHSND problem.

Investigating the IHSND problem is, of course, not only restricted to providing support for the port hinterland optimization problem; it could also provide a useful tool for a network planner to organize an optimal intermodal freight transportation network for network users.

1.5 Objectives and Scope of the Work

The primary objectives of this study are: (i) to develop a modeling approach to estimating the hinterland of a particular port by taking into account the uncertainties involved in intermodal freight transportation operations from a network level, (ii) to develop a mathematical model and solution algorithm for solving the IHSND problem incorporating multiple stakeholders, multi-type containers and mode changes, and (iii) to address the port hinterland optimization problem based on the realizations of the first two objectives.

To achieve these goals, seven main research topics addressing port hinterland estimation, freight transportation cost function, intermodal route choice of intermodal operators, IHSND design and port hinterland optimization are examined and comprised in the scope of this study. The scope of this study can be described in detail as follows:

(i) To develop an attribute-based probabilistic port hinterland estimation approach in terms of transportation cost and time for a hypothetical intermodal freight transportation network, surrounding each point of which it is assumed that there always exist shippers desiring to transport containers to a given destination.

(ii) To develop a utility-based probabilistic port hinterland estimation approach to identify the hinterland of a given port for a realistic intermodal freight transportation network, while taking into account batch-arrival containers at transfer terminals.

(iii) To investigate the available existing freight transportation cost functions which are capable of reflecting economies of scale in transport of containers, and assess their suitability in describing the cost structure of carriers and intermodal operators in intermodal freight transportation operations.

(iv) To propose an intermodal route choice model for intermodal operators based on the Wordropian user equilibrium (UE) or stochastic user equilibrium (SUE) principle.

(v) To formulate the IHSND problem with multiple stakeholders and uni-type containers as a mathematical model and design a solution algorithm for the model

(vi) To propose a mathematical model for the IHSND problem simultaneously incorporating multiple stakeholders and multi-type containers and develop an effective algorithm to solve the problem.

(vii) To address the port hinterland optimization problem by using hinterland network design.

1.6 Organization of the Thesis

This remainder of the thesis is organized as follows.

Chapter 2 reviews the past relevant studies on port selection criteria, qualitative and quantitative port hinterland estimation approaches, conventional hub-and-spoke network design, intermodal hub-and-spoke network design, bi-level and mathematical program with equilibrium constraints (MPEC) programming methods for freight transportation network design, and freight transportation cost functions.

Chapter 3 develops a mathematical model and algorithm for attribute-based probabilistic port hinterland estimation in an intermodal freight transportation network by assuming that there always exist shippers at each point of the network desiring to transport containers to a given destination. First, the transportation costs or time along all the available intermodal routes from an origin to a destination are assumed to be multivariate normally distributed. The probabilistic port hinterland is then mathematically formulated. To estimate the port hinterland, a Monte Carlo simulation based method that includes an interesting boundary curve fitting procedure and a cluster analysis method is proposed. A lower bound for the sample size required in the Monte Carlo simulation is also derived. Finally, two illustrative examples are presented to evaluate the effectiveness and application of the proposed methodology.

Chapter 4 proposes a utility-based probabilistic port hinterland estimation approach for the point of view of a realistic intermodal network. To develop the approach, this chapter first defines the random utility of an intermodal route as a summation of transportation cost and transport time multiplied by the value of time (VOT) perceived by intermodal operators. The random transfer time per container incurred at a transfer terminal on an intermodal route is then derived by modeling the transshipment process as an $M^{[X]}/G/1$ queue due to containers arriving in batches. According to the utility-maximization principle for intermodal operators faced with route choice, a mathematical expression of the utility-based probabilistic port hinterland is presented. A Monte Carlo simulation based algorithm is hence proposed to find the probabilistic port hinterland. Finally, an interesting case study is performed to estimate the probabilistic hinterland of Shanghai port and analyze impacts of the handling capacity of Shanghai port and VOT on the port hinterland.

Chapter 5 develops an MPEC model for the IHSND problem with multiple stakeholders - the network planner, intermodal operators and carriers - and uni-type containers. The model incorporates two fixed-point formulations that reflect the stochastic user equilibrium (SUE) behavior of intermodal operators in route choice for any given network design solution made by the planner. The model also uses a cost function that is capable of reflecting transition from scale economies to scale diseconomies in distinct flow regimes for carriers and a utility function integrating actual transportation charge and congestion impact for intermodal operators. To solve this non-convex and non-differential MPEC model, a branch-and-bound algorithm is designed with an embedded cost averaging algorithm for solving the SUE network flows on the basis of the linearization of the original model. Finally, two numerical examples are employed to assess the developed model and solution algorithm.

Chapter 6 formulates the IHSND problem with multiple stakeholders and multi-type containers as an MPEC model. The model incorporates a parametric variational inequality (VI) that formulates the user equilibrium (UE) behavior of intermodal operators in route choice for any given network design decision of the network planner. To solve the MPEC model, a hybrid genetic algorithm (HGA) embedded with a diagonalization method for solving the parametric VI is proposed. Finally, the comparative analysis of the proposed HGA, simple GA and exhaustive enumeration algorithm indicates a good performance of the HGA in terms of computational time and solution quality, and the HGA is also applied to solve a large-scale problem to show the applicability of the proposed model and algorithm.

Chapter 7 addresses the port hinterland optimization problem by solving the port market share optimization (PMSO) problem using hinterland network design based on the port hinterland estimation approach proposed in Chapter 4 and the IHSND design method proposed in Chapter 5. An MPEC model is proposed to formulate the PMSO problem and a branch-and-bound algorithm is proposed to solve the non-convex and non-differential model. A numerical example is finally given to indicate the applicability and importance of the proposed model and algorithm in solving the PMSO problem.

Chapter 8 draws conclusions and recommends future research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Port Hinterland Estimation Problem

The state of the art of port hinterland estimation studies can be envisioned by investigating port selection criteria which reflect the preferences of intermodal operators faced with port selection, qualitative and quantitative port hinterland analysis methods.

2.1.1 Port Selection Criteria

Spatial properties of hinterland of a port deeply relies on port selection criteria which are mainly emphasized in port competitiveness studies and straightly reflect preferences of port selectors, such as intermodal operators, confronted with port selection. There are abundant publications which have investigated a broad range of determinants related to port selection.

Mayer (1957) suggested that port competition could be analyzed by investigating rail transport cost between ports and their hinterlands. As stated by Bird (1963), development of port space is dependent on its hinterland and characteristics of inland transportation system. Apart from transportation networks, Kenyon (1970) extended to include other factors such as labor costs, productivities of ports, rail connection, port access, and land availability to delve port competition.

Studies carried out in the 1980s and 1990s almost covered all effective determinants conceived by port selectors. Pearson (1988) identified confidence in port schedules, frequency of calling vessels, variety of shipping routes, and accessibility of ports as important components determining port selection. Slack (1985) reviewed the factors considered by exporters and freight forwarders by concentrating on containerized cargo transportation between North America, Middle East and Western Europe. He suggested that decision makers are more concerned with price and service of land and ocean carriers than perceived differences in the ports. A series of studies conducted by Murphy and his group (Murphy et al., 1992) synthesized a very detailed directory of port selection criteria related to internal factors of ports such as specification of loading and unload facilities, ability to handle large-volume shipments, ability to provide low-frequency loss and damage, equipment availability, convenience of pickup and delivery time and so on. Geographical location of ports, inland transportation networks, availability and efficiency of transportation routes were highlighted together to be significant determinants by UNCTD (1992), McCalla (1994), and Starr (1994). Port costs and tariffs were suggested to be important factors influencing selector's decision of port choice by Brooks (1984 and 1985).

Entering the twenty-first century, diverse analysis approaches are proposed and applied to analyze port competitiveness. Malchow and Kanafani (2001 and 2004) analyzed commodity flow in US ports using discrete choice model and claimed the most significant characteristic of a port to be its location. Oceanic and inland transportation distances are also considered to be key determinants for port competitiveness. Haezendonck and Notteboom (2002) showed that hinterland accessibility, productivity, quality, cargo generating effect, reputation and reliability are crucial in enhancing competitiveness of a port. Ha (2003) identified important service quality factors amongst container ports and compared qualities of services in 15 major ports in the world by using Duncan's test. Song and Yeo (2004) employed AHP (analytical hierarchical process) to comparatively analyze container ports of China, and five most important criteria for the port competitiveness were advised - cargo volume, port facilities, port location, service level and port expense. Based on a complete literature review, Yeo et al. (2008) selected 38 determinants of port selection as to further analyze competition between ports in Korea and China. Chang et al. (2008) discerned the factors affecting port choice in perspective of shipping companies consisting of trunk liners and feeder service providers. Six relatively important factors such as local cargo volume, terminal handling charge, berth availability, port location, transshipment volume, and feeder network were identified.

Among these many important factors, some are closely related to port performance, such as productivity, availability, handling cost, and convenience of a port, and the performance of port hinterland network, such as network connectivity to shippers, transportation cost, time and accessibility. The review result thus indicates that the accessibility, efficiency and cost-effectiveness of hinterland network are important factors influencing port selection of port selectors as well as the extent of port hinterland. This explains the importance of port hinterland estimation and optimization in this study to both practical applications and current literature of port studies. Of course, there are also other important factors that may affect port selection such as reliability and reputation of a port; however, this study focuses attention on port and hinterland performance related factors.

In addition, it is implied by the review that transportation cost and time are two primary factors impacting the attraction of a port to port selectors. Thus, port hinterland should be estimated and optimized by taking into account these two factors.

2.1.2 Qualitative Analysis Methods

The qualitative analyses of port hinterland are focused mainly on forming a definition for hinterland of a port or transfer terminal of any other kind, identifying the significance of port hinterland to local economic development and port industry, and discussing the relation between port hinterland and transportation operations.

Van Cleef (1941) was the first scholar to define the hinterland of a trade center as follows: "*the area adjacent to a trade center with which economic and some culture activities are focused largely on the primary center*". This hinterland concept can be applied to define the hinterland of a port by treating the port as a trade center. Since this seminal paper, numerous transport geography researchers have qualitatively investigated various port hinterland related issues, such as the growth and coverage of a port, the function of a port in regionalization and globalization, and port-city relations and industrial changes (Lee et al., 2008). They have also noticed the impact of intermodal freight transportation services on port hinterland. Hoare (1986) thus argued that the above-mentioned port hinterland concept should be revisited and adapted for the changes in the context of intermodalism. Van Klink and Van den Berg (1998) therefore defined port hinterland as "*the continental area of origin and destination of freight traffic flows through a port by taking intermodal freight transportation operations into account*". To further examine the spatial and functional nexus that port hinterland has become, Notteboom and Rodrigue (2007) proposed the physical seaport hinterland that considers the extent of transportation supply from both uni-modal and intermodal perspectives.

It seems to us that the definition of port hinterland suggested by Van Klink and Van den Berg (1998) does not only highlight the spatial focus of port hinterland, but also reflects the significance of transportation in shaping the hinterland, that is, the hinterland of a port could be estimated by examining the origins and destinations of traffic flows transshipped via the port. This definition forms a basis for our probability-based port hinterland estimation and optimization.

Although the above studies can assist us in recognizing the significance of port hinterland to local economic development and port itself, however, these studies have not introduced available analysis methodologies that can quantitatively identify or estimate the hinterland of a port.

2.1.3 Quantitative Analysis Methods

As defined in Section 1.3, port hinterland is also known as port market area. The former is specifically used for ports and the term of market area is more suited to all kinds of transfer terminals. The following review is made to comprise quantitative analysis methods for port hinterland and port market area.

2.1.3.1 Deterministic Estimation Methods

Since ports are one type of major transfer terminals in intermodal freight transport, any methodology used for estimating the market area of a terminal or center of any kind would be enlightening. One type of studies related to market area estimation is deterministic market area estimation for a terminal/center. In the deterministic market area the terminal's market share is 100%, as customers will certainly choose to visit the terminal.

Fetter (1924), an economist, proposed a quantitative method to estimate the deterministic market area of a selling market by taking into account the access cost to the center as well as the market price of the center. His pioneering work established the first principle about the shape and extent of market area. In his study, freight rate per unit distance is hypothesized to hold same value in the area concerned, and with this assumption, the boundary line between two competing markets for homogenous goods is a hyperbolic curve, on which each point represents a fact that *the difference between freights from two markets are equal to the difference between the market prices*. Clearly, the assumption of same freight rate oversimplifies the computation of transportation costs and inevitably underplays the impact of different transport modes on market area. Hyson and Hyson (1950) generalized Fetter's law using mathematically derived *hypercircle* theory. This theory considers different freight rates for the goods originating from two separate markets and involves the extreme condition that hyperbola curves will evolve to a circle if transportation costs from two selling markets are measurably same. On the other hand, the authors seem to still take a simplified way to estimate transportation cost i.e. transportation cost is increasing proportionally to delivery distance. Niérat (1997) utilized a similar method to estimate the market area of a rail-road terminal, in which rail-road mode is mostly favored by freight forwarders. In fact, Niérat initiated a different issue from the traditional market area problem in economics. In the new problem, one of two selling markets is replaced by an intermodal transfer terminal, and the other one becomes the destination of transported goods. The concern of the study of market area switches form looking into attractive regions of selling markets to investigating the size of the market area of a rail-road terminal, in which the multimodal mode is more attractive than road transport.

The above-mentioned studies provide a valuable indication that market area estimation is directly related to freight forwarders' decision behaviors in route selection, and the estimation should be made on the basis of traffic distribution over available routes. However, in the deterministic market area estimation, transportation cost and terminal cost are considered as constants, which is sometimes unrealistic in intermodal freight transportation.

2.1.3.2 Probabilistic Estimation Methods

Quantitative analysis methods to directly estimate the port hinterland in a probabilistic context have so far received rare attention. In a border field, those to estimate the market share of a transfer terminal have been attracting attention of many researchers. Port hinterland and port market share are two performance indicators to reflect the competitiveness of a particular port from different perspectives. The estimation of port hinterland and that of port market share have the same foundation – container flow distribution in the whole intermodal freight transportation network; in other words, solving one of them would provide inspirations for solving the other one

To capture the uncertainties in market area estimation, which may source from transportation cost, time and other attributes concerned by analysts, discrete choice models such as logit- and probit-based models have been widely used. Martín and Román (2004) calculated the market share of an interested airline between a given city pair by using multinomial logit model. In the model, the utility of the airline was specified as a function of the average transport fare of the airline service, the service frequency and consumer's preference for non-stop service. Wei and Hansen (2005) applied the same multinomial logit model to calculate the market share of a given airline as well as the travel demand. Malchow and Kanafani, (2004) and Garcia-Alonso and Sanchez-Soriano

(2009) also utilized a standard multinomial logit model to compute the probability of carriers selecting a specific port, and the probability indicates the traffic share of the port.

Logit model is a broadly used approach due to its closed-form expression; however under its principles, the correlation between candidate alternatives is assumed not to exist. In addition, it should be pointed out that logit-based discrete choice model is sometimes unfit for identifying market share due to its independence of irrelevant alternatives (IIA).

To overcome such limitations, Wang et al. (2009) developed analytical expressions of probability-based port market area in the context of landbridge transport operations using probit-based discrete choice model. The study simply involved two correlated intermodal routes to estimate the probabilistic market area of a port. However this study only estimated probabilistic port market area for individual O/D pairs instead of a whole intermodal network.

2.1.4 Summary Remarks

It is learnt from the port selection criteria literature that the efficiency, cost effectiveness, connectivity and accessibility of hinterland network are key to a port to expand its hinterland (market area). This indicates the importance of our study on port hinterland optimization in terms of market share using hinterland network design. Transportation cost and time are two key factors influencing the extent of port hinterland and should be taken into account in port hinterland estimation. Qualitative analysis methods provide stringent definitions for port hinterland or market area of any other kind of transfer terminals, and inspire us that port hinterland estimation and optimization should be investigated by exploring the flow distribution over the intermodal freight transportation network resulting from the intermodal route choice of route selectors, i.e., intermodal operators in this study. Quantitative analysis methods use discrete choice analysis models to reflect the behavior of port selectors confronted with port selection in a probabilistic transportation circumstance, which paves the way for probabilistic port hinterland estimation from a network level.

2.2 Hub-and-Spoke Network Design Problem

An intermodal freight transportation system has the characteristics of hub-and-spoke transportation operations. The intermodal system involving mode changes and multi-type containers can be naturally organized as an intermodal hub-and-spoke network, where transfer terminals behave as hubs. The conventional and generalized hub-and-spoke network design models are reviewed.

2.2.1 Conventional HSND Models

As defined by O'Kelly (1987), "*hubs are a special type of central facilities in networks which are designed to act as switching, sorting and consolidating points for internodal flows*". Traditionally, the hub-and-spoke network design problem aims to locate hubs from a set of candidate hubs in a network, to allocate spoke nodes to hubs and to route cargo flows from origins to destinations. The problem is also referred to as hub location problem in some publications. Hub-and-spoke network design problem is a discrete network design problem which is different from the continuous network design problem locating hubs in a continuous plan (O'Kelly, 1986; Aykin, 1988; Campbell, 1990; O'Kelly and Miller, 1991; Aykin and Brown, 1992).

Since O'Kelly (1987) formulated the first quadratic integer programming model to locate interacting facilities, numerous literatures have been published to address the problem as well as its variants. Detailed review and classification to this problem can be obtained in Alumur and Kara (2008), which lists over 100 publications addressing this issue in the past three decades. Our review only confines on categorizing these studies into different groups according to their modeling approaches.

The hub-and-spoke network design problem was later referred to as a *p*-hub median problem by Campbell (1994). The *p*-hub median problem aims to select *p* hub facilities from a set of available candidates, to allocate spoke nodes to hubs and to simultaneously route freight flows. The HSND problem has been attracting numerous researchers and formulated as various mathematical modes, including path-based mixed-integer linear programming models with 4-dimensional variables (Campbell, 1996; Skorin-Kapov et al. 1996; Klincewicz, 1998; Pondar et al., 2002) and origin-based mixed-integer linear programming models with 3-dimensional variables (Ernst and Krishnamoorthy, 1998; Ebery et al., 2000; Boland et al., 2004).

Most of these models are developed under the following four basic assumptions: (i) no direct links are allowed to connect spoke nodes, (ii) hubs are fully interconnected, (iii) scale economies are exhibited in transportation between hub pairs, and (iv) each path traverses at most two hubs to connect each origin-destination (O/D) pair. The above-mentioned assumptions, however, are sometimes unrealistic for intermodal transportation network design. For example, intermodal transportation is a widely used service for international or transcontinental container delivery across different countries. Some hubs located in a country may only be connected to those situated in the same country, which does not comply with assumption (ii). As opposed to assumption (iv), an intermodal route may traverse more than two hubs with mode changes. Scale economies should not be stipulated to exist between hub pairs. Whether the transport of cargo exhibits scale economies are dependent on the cost structure of the transportation process.

2.2.2 Generalized HSND Models

Some studies have been conducted to relax these assumptions (Klincewicz, 1998; Nickel et al., 2001). Campbell et al. (2005*a* and 2005*b*) proposed a hub arc location model which does not impose restrictions on hub connections by incorporating bridge arcs. Yoon and Current (2008) developed a mixed integer programming model embedding a multi-commodity flow model to solve the hub location problem with no restrictions on network topology. They also considered direct links between spoke nodes. Alumur et al. (2009) provided a unified modeling method for single-allocation hub location problems with incomplete hub networks. Contreras et al. (2010) addressed a tree of hubs location problem with the particularity that all hubs are connected by means of a non-directed tree, which has the potential applications where the cost of establishing hub-hub links is significantly high.

These studies provide inspirations on formulating a more generalized hub location problem; however, they do not deal with locating transshipment lines, which are indispensable infrastructure facilities for intermodal transportation networks. Meanwhile, these generalized HSND studies do not involve the interactive decision process among different stakeholders, which is regarded as another important characteristic of intermodal freight transportation.

2.2.3 Summary Remarks

The conventional and generalized HSND studies provide us the idea for formulating the IHSND problem which may not comply with the four above-mentioned assumptions.

They are unfit for formulating the IHSND problem due to the inclusion of one of the following: (i) failing to consider multiple stakeholders, (ii) excluding cargo transfer processes, (iii) arbitrarily assuming economies of scale in the transport of cargo between hub pairs, and (iv) not considering multi-type container transportation.

2.3 Unit Cost Function for Freight Transportation

Three typical types of unit transportation cost functions have been widely used in the past HSND studies – functions with discount factors, decreasing piecewise-linear functions and nonlinear functions - in order to reflect scale economies. The discussion, nature and measurement of economies of scale have been delved and studied since the writings of Adam Smith (1776), who identified the labor and specialization as two key factors to achieve scale economies. The brief that larger-scale production can cause cost advantages is not only accepted as a casual opinion of the general public but widely discussed in publications of economists. The term economies of scale is employed by economists to refer to the phenomenon that production at a larger scale (more output) can be achieved at a lower average cost (i.e. with economies or savings) i.e., cost per unit falls with increase of output. More strictly, economies of scale is defined to be present when a k-fold proportionate increase in every input quantity yields a k'-fold increase in output with $k'>k>1$ (Menger, 1954).

The existence of economies of scale in transportation between hub pairs is considered as one of incentives of locating hubs in a network by O’Kelly (1986 and 1987). In order to express scale economies, the author discounted the transportation costs on inter-hub links by a constant factor less than one. Most subsequent studies adopted the same idea and further employed discount factors to the spoke-hub links (Campbell, 1994;

Ernst and Krishnamoorthy, 1998; Campbell and Krishnamoorthy, 2005*a* and 2005*b*; Rodríguez et al., 2007).

Balakrishnan and Graves (1989) suggested a piecewise-linear decreasing cost function with respect to freight flow for network design problems. O'Kelly and Bryan (1998) and Horner and O'Kelly (2001) proposed a nonlinear decreasing function for computing the unit transportation cost between hub pairs. Racunica and Wynter (2005) applied the nonlinear function as well to hub-spoke connections in a rail-road hub location problem.

However, this decreasing property is not constantly true in freight transportation. As pointed out by Norman (1979), the unit transportation cost has an increasing trend when the freight flow exceeds a threshold, since the labor, material and machinery costs will sharply increase to cater with the additional transportation demand beyond the safe operating capacity. Friesz and Holguín-Veras (2005) further emphasized that the unit cost function for freight transportation should have a "U" shape that can reflect transition from economies of scale to diseconomies of scale in different flow regimes.

Additionally, past cost functions were proposed for charactering the cost structure in transport of uni-type commodities and unable to reflect scope economies that reflect cost savings resulting from simultaneously transporting multi-type containers. Hence, we have to seek for a more realistic transportation cost function which can depict the cost structure of multi-type container transportation for the IHSND problem. Hence, we have to seek for a U-shaped unit transportation cost function which can depict the cost structure of container transportation for the IHSND problem.

2.4 Intermodal Freight Transportation Network Design Problem

The hub-and-spoke network design methods developed specifically for intermodal freight transportation are reviewed as follows. In addition, due to the existence of multiple stakeholders, bi-level or MPEC network design models which are able to reflect the interactive decision of multiple stakeholders are also overviewed.

2.4.1 Intermodal Hub-and-Spoke Network Models

As compared to the traditional HSND problem, the IHSND problem has received limited attention, presumably because intermodal freight transportation is a recently emerging research field and has not been so far explored in detail (Bontekoning et al., 2004). A few studies have been carried out for addressing the problem. Arnold et al. (2004) formulated an integer programming model for the rail-road hub location problem. Racunica and Wynter (2005) gave an optimal hub location model aiming to increase the market share of rail mode in a hub-and-spoke network. Limbourg and Jourquin (2007) located the best potential rail-road hubs in an intermodal network according to the traffic flow distribution and its geographical dispersion over the network.

Although these models extend the conventional HSND problem to involve partial characteristics of intermodal transportation operations, they neglect the interactions among different stakeholders and cargo transfers between multiple modes besides rail and road. Moreover, these models are inadequate to formulate multi-type container transportation problem, which is widely seen in practical intermodal freight operations.

2.4.2 Bi-level and MPEC Programming Methods

The MPEC or bi-level programming models have been employed by some researchers to deal with freight transportation network design problems. However, due to the non-convex and non-differential properties of the MPEC network design model, there is a challenge in designing an effective solution algorithm to solve the model. Following review comprises both model formulation and solution algorithm for network design problems.

2.4.2.1 Heuristic approaches

Some heuristic approaches have also been developed to solve freight transportation network design problems. Loureiro and Ralston (1996) proposed a bilevel multi-commodity network design model for determining investment policies for intercity freight transportation networks by assuming that the behavior of intermodal operators in route choice follows the logit-based SUE principle. A two-step heuristic algorithm based on column generation was designed to solve the model. Yamada et al. (2009) established a bi-level programming model for freight transportation network design, in which the lower-level problem is a multimodal multi-class user equilibrium traffic assignment problem. A series of heuristic approaches including genetic algorithm and tabu search based procedures were tested in realistic networks.

Each of these two models is a straightforward extension of the discrete network design problem with user equilibrium constraints for urban road networks (Yang and Bell, 1998; Meng et al., 2001). They are only concerned with network link design without hub locations and transshipment line establishments, which are imperative for IHSND problem. In general, heuristic algorithms are discouraged due to the lack of theoretical basis and low efficiencies. In addition, the unit transportation cost functions used in the two models are unable to reflect scale economies or to describe the cost structure of multi-type container transportation.

2.4.2.2 Exact and Approximation Algorithms

LeBlanc (1975) applied a branch-and-bound algorithm to solve a bi-level nonlinear integer model for urban transportation network design, in which the upper-level model minimizes the total network time and the lower-bound problem is formulated as a UE traffic assignment problem. Apivatanagul and Regan (2009) developed a similar branch-and-bound algorithm to solve a bi-level long-haul freight network design model embedding a shipper-carrier flow prediction model. In these two models, the convex BPR-form function is used as the unit transportation time (cost) function of carriers or travelers. By using the cost function, the lower bound can be obtained through solving a system optimum (SO) problem using the Frank-Wolf algorithm (LeBlanc et al., 1975) after assigning all pending binary integer variables value of one.

However, the above two algorithms are unfit for solving the IHSND problem with stochastic equilibrium flows and a U-shaped (non-convex) unit cost function. LeBlanc and Boyce (1986) proposed an exact algorithm for the network design problem with user equilibrium flows. The network design problem was first formulated as a linear bi-level programming model by assuming that total and unit transportation cost functions are piece-wise linear functions. Then the model was solved by using Bard's algorithm (1983), which iteratively solves a reformulated mixed-integer programming model with an objective function defined as the convex combination of the upper and lower objective functions. In this algorithm, the linearization of unit transportation cost function is enlightening, but it only works for the network design problem which uses an explicit Backman's formulation to obtain UE network flows and is not workable for solving the IHSND problem with a U-shaped unit transportation cost function.

2.4.3 Summary Remarks

Current IHSND studies extended the conventional HSND studies to take into account the cargo transfer processes at hubs (transfer terminals). They are, however, unsuitable for formulating the IHSND problem concerned in this study, which is more complex by involving multiple stakeholders and multi-type containers. The bi-level or MPEC modeling approaches provides an enlightening idea for reflecting the interactive decision among multiple stakeholders. As these modeling approaches were not developed specifically for solving the IHSND problem, a new mathematical model is needed to formulate the IHSND problem and an effective solution algorithm should be correspondingly proposed to solve the problem.

2.5 Contributions of the Study

Table 2.1 The contributions of the study

Research Topics		Comments on Existing Work	Contributions of the Study
Port hinterland estimation problem	Port selection criteria	Literature implies that cost and time are two key factors impacting port selection	We estimate and optimize port hinterland by taking into account these two factors into utilities.
	Qualitative analysis methods	Various definitions of port hinterland are proposed. However, these studies have not introduced available quantitative analysis approaches.	We propose a novel definition of probabilistic port hinterland by involving uncertainties in transportation cost and time.
	Deterministic quantitative estimation methods	Transportation cost and time are considered as constants, which is sometimes unrealistic in intermodal freight transportation	We propose a probabilistic port hinterland estimation model to involve the random transportation cost and time.
	Probabilistic quantitative estimation methods	Logit-based models are widely used to estimate port market share by neglecting the correlation between	We develop an attribute-based and utility-based model to estimate port hinterland by taking into

		routes or presuming a covariance structure of them. In addition, these models are developed by only considering a few routes instead of the whole intermodal network.	account (i) randomly distributed transportation cost, time and utility, (ii) freely correlated routes in terms of cost, time and utility, (iii) the whole intermodal network, (iv) queueing system at a transfer terminal. In addition, we propose a Monte Carlo simulation based algorithm to solve the models.
IHSND Problem	Model Formulation and solution algorithms.	The conventional and generalized HSND studies are unfit for formulating the IHSND problem due to the inclusion of one of the following: (i) failing to consider multiple stakeholders, (ii) excluding cargo transfer processes, (iii) arbitrarily assuming economies of scale in the transport of cargo between hub pairs, and (iv) not considering multi-type container transportation.	We formulate the IHSND problem as an MPEC model by incorporating multiple stakeholders, multi-type containers, cargo transfer process at transfer terminals, and randomly distributed route utilities. In addition, a branch-and-bound based algorithm and heuristic are proposed to solve the IHSND problem with uni-type containers and multi-type containers, respectively.
	Unit cost function	Three typical types of unit transportation cost functions have been widely used in the past HSND studies: (i) functions with discount factors, (ii) decreasing piecewise-linear functions, and (iii) nonlinear functions to reflect scale economies. The decreasing property is not true for freight transportation.	We adopt a U-shaped unit transportation cost function to reflect the transition from scale economies to scale diseconomies in distinct flow regimes, which is more realistic for freight transportation.

CHAPTER 3

ATTRIBUTE-BASED PROBABILISTIC PORT HINTERLAND ESTIMATION

3.1 Introduction

The recent changes in the world economy due to the globalization of markets have triggered a substantial increase in demand for international seaborne trade and intermodal freight transportation services involving multiple modes of transport. A port is considered to be a critical gateway or transshipment hub, which provides transfer facilities for intermodal good movements between maritime and land (Crainic and Kim, 2007). The area served by a particular port, over which shippers desire to transport their containers to a given destination via one or several intermodal routes traversing through the port, is referred to as the port's hinterland with respect to the given destination. Port hinterland is a key performance indicator reflecting the competitiveness of a port, since it can geographically represent the port's market area, from which containers originating trend to visit the port.

To identity the hinterland of a particular port, in addition to the level of service provided by the port itself, available logistics services, such as road, maritime and rail transportation, should also be taken into account. Given a delivery destination, a shipper desiring containers to be delivered to the destination will hire an intermodal operator to coordinate the whole transportation process. The intermodal operator will select intermodal routes to accomplish the delivery. As for the intermodal operator, there are usually several intermodal routes available to connect the shipper's location (origin) and the given destination. Some of these intermodal routes may traverse through the particular port and others may not. Only the containers transported along an intermodal route traversing through the port can be regarded as the market quota of the port, and accordingly, the origin of the intermodal route is considered to be located in the port's hinterland. Hence, the route choice of intermodal operators directly determines the size and extent of port hinterland.

As indicated by literature review of port selection criteria, many attributes of intermodal routes such as transportation time, cost and reliability are crucial in driving an intermodal operator's route choice. The values of these attributes along a given intermodal route vary based on carriers such as liner shipping companies and land transport companies. Therefore, they can be rationally formulated as random variables. As a reasonable decision behavior, we assume that an intermodal operator would choose the route with the best value in terms of a concerned attribute from a set of available intermodal routes to transport containers from a shipper's location (origin) to a given destination. In fact, this assumption coincides with the utility-maximization behavioral principle proposed in discrete choice analysis (Ben-Akiva and Lerman, 1985).

Under the aforementioned assumption, intermodal operators will choose a port by chance instead of certainly selecting it. We can define the attribute-based probabilistic hinterland of a particular port as the basis as follows: an area surrounding the port, over which intermodal operators will select the particular port to transport containers from the locations of shippers to a given destination with a certain probability falling within $[\alpha, 1]$, where $\alpha \in [0, 1]$, based on the attribute values of intermodal routes. The objective of this chapter is to develop a mathematical model and solution algorithm that can be used to estimate the attribute-based probabilistic hinterland of a port in the context of intermodal freight transportation operations. The methodology used to estimate the probabilistic port hinterland in terms of one attribute such as transportation cost could also be applied to estimate that in terms of any other attribute such as transportation time, reliability and safety. For the sake of presentation, we only use transportation cost to illustrate the attribute-based probabilistic port hinterland estimation in the subsequent sections.

3.2 Notation, Assumptions and Problem Statement

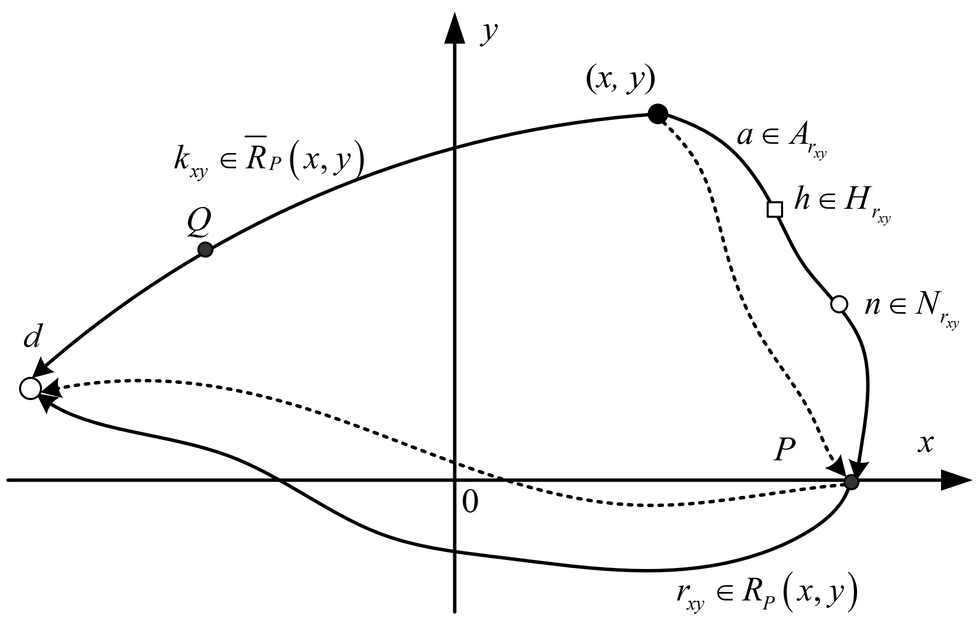


Fig. 3.1 An *x-y* coordinate system involving intermodal routes

To represent the hinterland of an interested port P, we use an x-y plane coordinate system as shown in Fig. 3.1, where P is located on the x-axis. Given an origin (x, y) surrounding P in the x-y plane, it is assumed that there always exist shippers around (x, y) who have identical characteristics and desire containers to be transported from the origin to a given destination d, and the shippers will hire a common intermodal operator to coordinate the container transportation process. The intermodal operator will route the containers through available intermodal freight transportation routes. All these available intermodal routes are denoted by set $R(x, y)$ and are classified into two exclusive subsets such that one set $R_P(x, y)$ consists of the routes traversing through P and the other $\bar{R}_P(x, y)$ exclusive of P, hence,

$$R(x, y) = R_P(x, y) \cup \bar{R}_P(x, y) \tag{3.1}$$

$\bar{R}_P(x, y)$ does not include the routes traversing P. But, it may contain a route passing by anther port other than P, such as Q as shown in Fig. 3.1.

The transport of containerized cargo addressed in this chapter is long-haul intermodal freight transportation traversing through several cities/countries or even continents. The number of all possible intermodal freight transportation routes is thus manageable and can be enumerated in practice.

Let r_{xy} denote an intermodal route from origin (x, y) to destination d, i.e. $r_{xy} \in R(x, y)$. It consists of a sequence of nodes (i.e., points) in the x-y plane and links connecting two consecutive nodes. A node on the intermodal route can represent a transfer terminal or a regular node. Let $H_{r_{xy}}$ and $N_{r_{xy}}$ be the sets of all transfer terminals and regular nodes on route r_{xy}, respectively. Without loss of generality, it is assumed that each link on route r_{xy} possesses only one transportation mode such as road, rail and maritime. If more than one mode exists between two consecutive nodes on the route, each mode should be represented by one individual link. All the links on route r_{xy} are denoted by set $A_{r_{xy}}$. As an instance, Fig. 3.1 depicts three intermodal routes from a given point (x, y) to destination d with the notations defined above.

For each link $a \in A_{r_{xy}}$, let C_a represent the cost for transporting one TEU on the link, which is assumed to be a normally distributed random variable. For each transfer terminal $h \in H_{r_{xy}}$, let C_h represent the transshipment cost for handling one TEU at the terminal, which is assumed to be a normal random variable. The above randomness assumptions are reasonable as transportation cost of a link or transfer terminal varies based on intermodal carriers and transportation market conditions. The distribution type followed by the random variables is, of course, not necessarily normal and depends on data verification process. However, since normal distribution can be used to describe, at least approximately, any variable that trends to cluster around its mean value, it has been extensively employed in practical applications. Without loss of generality, we assume that C_a and C_h are normally distributed. Mathematically, these two types of random variables can be rewritten as follows:

$$C_a(x,y) = \eta_a(x,y) + \xi_a(x,y), \forall a \in A_{r_{xy}} \tag{3.2}$$

$$C_h(x,y) = \lambda_h(x,y) + \omega_h(x,y), h \in H_{r_{xy}} \tag{3.3}$$

where $\eta_a(x,y)$ and $\lambda_h(x,y)$ are expected values of $C_a(x,y)$ and $C_h(x,y)$, and $\xi_a(x,y)$ and $\omega_h(x,y)$ are two random error terms with zero means, which reflect the variations in the costs incurred on link *a* and at transfer terminal *h*. Transportation cost along route $r_{xy} \in R(x,y)$ is thus normally distributed, and can be expressed by,

$$C_{r_{xy}} = \sum_{a \in A_{r_{xy}}} C_a(x,y) + \sum_{h \in H_{r_{xy}}} C_h(x,y) \tag{3.4}$$

Without loss of generality, it is supposed that all the random variables involved in the right-hand side of Eqn. (3.4) are statistically independent.

The attribute-based probabilistic port hinterland estimation problem aims to identify an area surrounding port *P*, over which intermodal operators will be employed to transport containers from shippers' locations to a given destination via port *P* with a certain probability exceeding $\alpha \in [0,1]$ based on the values of a concerned attribute of intermodal routes.

3.3 Attribute-based Probabilistic Port Hinterland Modeling

In this section, we first investigate the transportation cost function of intermodal routes possessing piecewise-linear characteristics. The covariance between any two routes in terms of transportation cost is subsequently derived to formulate the probabilistic port hinterland estimation problem.

3.3.1 Piecewise-Linear Characteristics of Intermodal Routes

The expected value $c_{r_{xy}}$ and variance $\delta_{r_{xy}}$ of any route $r_{xy} \in R(x,y)$ in terms of transportation cost is given as follows.

$$c_{r_{xy}} = E\left(C_{r_{xy}}\right) = \sum\nolimits_{a \in A_{r_{xy}}} \eta_a(x,y) + \sum\nolimits_{h \in H_{r_{xy}}} \lambda_h(x,y) \tag{3.5}$$

$$\delta_{r_{xy}} = \operatorname{var}\left(C_{r_{xy}}\right) = \sum\nolimits_{a \in A_{r_{xy}}} \operatorname{var}\left(\xi_a(x,y)\right) + \sum\nolimits_{h \in H_{r_{xy}}} \operatorname{var}\left(\omega_h(x,y)\right) \tag{3.6}$$

Eqns. (3.5) and (3.6) indicate that the expected value and variance of an intermodal route are equal to summation of those of the links and transfer terminals on the route. For freight transportation operations, the expected value of transportation cost on a link can be considered as a linear function with respect to travel distance, and that of transshipment cost at a transfer terminal can be represented by a constant value.

As shown in Fig. 3.2, the expected values of transportation costs from origin (x, y) to transfer terminal *h* and from *h* to destination *d* are linear functions of travel distance. The expected value of transshipment cost at h is a constant value, and there is no transshipment cost at regular node $n \in N_{r_{xy}}$. c_1 and (c_3-c_2) are the expected values of transportation costs incurred over two links from (x, y) to h, and from h to d, respectively. (c_2-c_1) is regarded as the expected value of transshipment cost expended at h. The considered piecewise-linear function reflects the unique characteristic of intermodal freight transportation consisting of cargo handing processes at transfer terminals. The shape of this function has a significant impact on the port hinterland estimation.

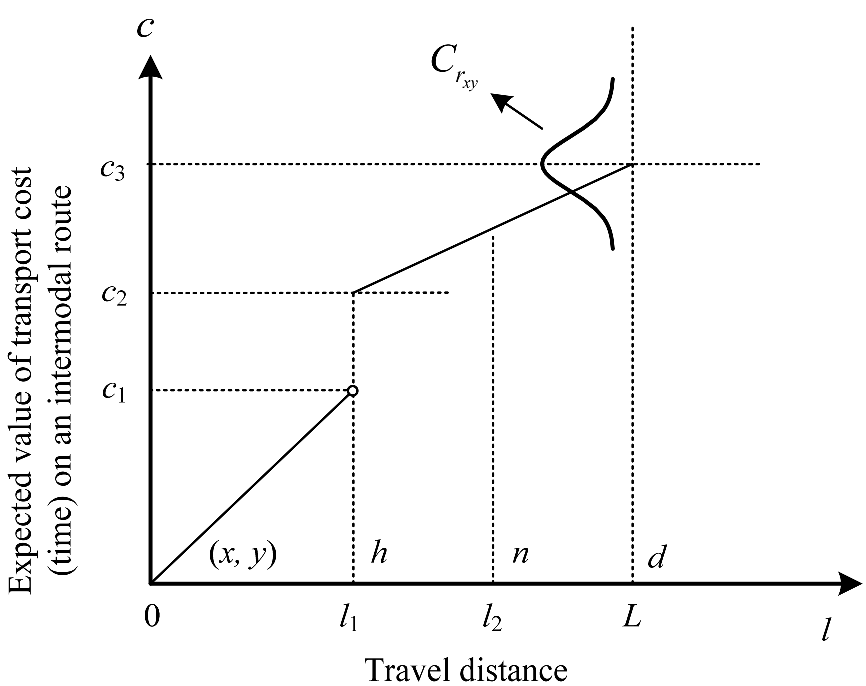


Fig. 3.2 The piecewise-linear function of an intermodal route

3.3.2 Covariance Matrix

Based on the above assumptions, the covariance between any two routes $r_{xy}, k_{xy} \in R(x, y)$ in terms of transportation cost is given by Eqn. (3.7).

$$\mathrm{cov}\left(C_{r_{xy}}, C_{k_{xy}}\right) = \sum_{a \in \left(A_{r_{xy}} \cap A_{k_{xy}}\right)} \mathrm{var}\left[\xi_a(x, y)\right] + \sum_{h \in \left(H_{r_{xy}} \cap H_{k_{xy}}\right)} \mathrm{var}\left[\omega_h(x, y)\right] \quad (3.7)$$

Eqn. (3.7) implies the covariance of two intermodal routes depends on the variances of common links and transfer terminals shared by them. Thus, the covariance matrix for all the routes in set $R(x,y)$ can be expressed by

$$\Sigma_{xy} = \left[\operatorname{cov}\left(C_{r_{xy}}, C_{k_{xy}}\right)\right]_{r_{xy}, k_{xy} \in R(x,y)} \tag{3.8}$$

3.3.3 Probabilistic Port Hinterland in Terms of Transportation Cost

Let $\mathbf{C}_{xy}$ denote a row vector of the random transportation costs of all routes in the set $R(x,y)$, namely,

$$\mathbf{C}_{xy} = \left(C_{1_{xy}}, C_{2_{xy}}, \cdots, C_{I_{xy}}\right) \tag{3.9}$$

where I_{xy} is the cardinality of set $R(x,y)$. The expected value of the random row vector $\mathbf{C}_{xy}$ is denoted by a row vector $\mathbf{c}_{xy}$,

$$\mathbf{c}_{xy} = \left(c_{1_{xy}}, c_{2_{xy}}, \cdots, c_{I_{xy}}\right) \tag{3.10}$$

Based on the assumption that intermodal operators will choose the route having the best value of the concerned attribute (minimum transportation cost) from set $R(x,y)$ to transport containers from the location (x,y) of shippers to destination *d*, the probability of intermodal operators choosing port *P* is given as follows,

$$P(x,y) = \sum\nolimits_{r_{xy} \in R_P(x,y)} \Pr\left[C_{r_{xy}} < \min\left(C_{k_{xy}}, \forall k_{xy} \in R(x,y) \text{ and } k_{xy} \neq r_{xy}\right)\right] \tag{3.11}$$

where $R_P(x,y)$ is the set of the routes traversing through P. Given $\mathbf{C}_{xy}$ multivariate normally distributed, the probability of choosing a route $r_{xy} \in R_P(x,y)$ can be explicitly expressed by the multiple integral given in the following equation,

$$\Pr\left(C_{r_{xy}} < \min\left(C_{k_{xy}}, \forall k_{xy} \in R(x,y) k_{xy} \neq r_{xy}\right)\right) = \int_{c_{r_{xy}} < c_{1_{xy}}} \dots \int_{c_{r_{xy}}=-\infty}^{c_{r_{xy}}=\infty} \dots \int_{c_{r_{xy}} < c_{I_{xy}}}$$
$$\left((2\pi)^{I_{xy}} \left|\Sigma_{xy}\right|\right)^{0.5} \times \exp\left[-0.5\left(\mathbf{x}_{xy} - \mathbf{c}_{xy}\right)' \left(\Sigma_{xy}\right)^{-1} \left(\mathbf{x}_{xy} - \mathbf{c}_{xy}\right)\right] dx_{1_{xy}} dx_{2_{xy}} \dots dx_{I_{xy}} \quad (3.12)$$

Let parameter $\alpha \in [0,1]$ denote the probability that intermodal operators select port P to transport containers from location (x, y) to destination *d*, the probabilistic hinterland of *P* can be defined to be an area over which intermodal operators select P to transport containers with a probability exceeding α. This area can be mathematically formulated by the set:

$$\psi_P(\alpha) = \{(x,y) \mid P(x,y) \geq \alpha\}. \quad (3.13)$$

The boundary of the probabilistic hinterland of *P* with respect to α is identified by the curve given in Eqn. (3.14).

$$\overline{\psi}_P(\alpha) = \{(x,y) \mid P(x,y) = \alpha\} \quad (3.14)$$

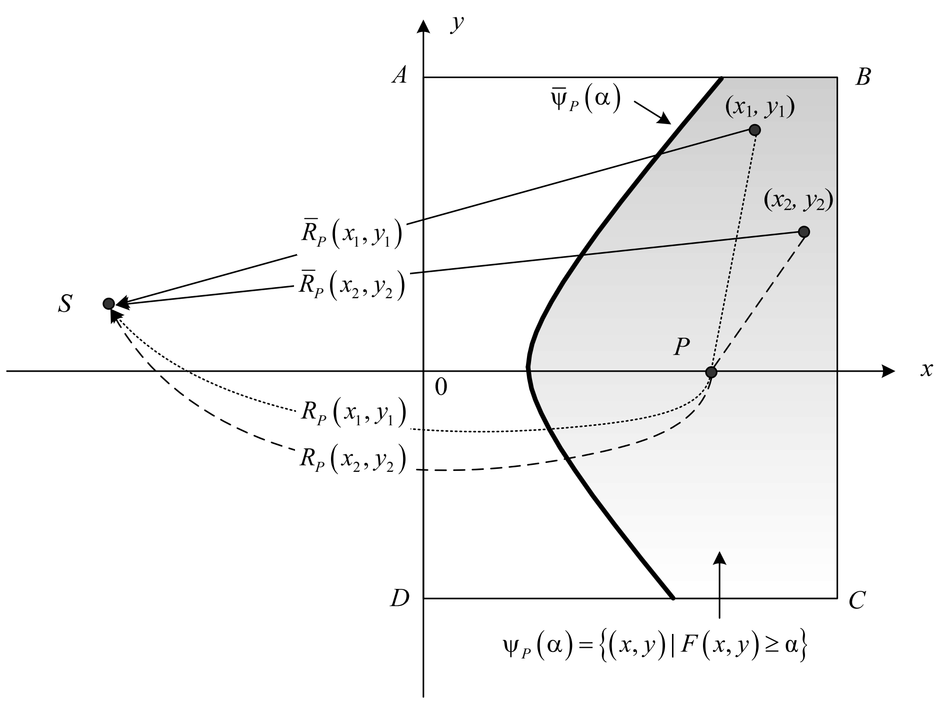


Fig. 3.3 Illustration of the probabilistic hinterland of an interested port *P*

The entire concept of port hinterland is illustrated with the aid of Fig. 3.3. The gray area in the figure is the hinterland of the interested port *P* and the boundary curve $\overline{\psi}_P(\alpha)$ is indicated by the bold curve. Confined in the hinterland $\psi_P(\alpha)$, from any point intermodal operators have various candidate intermodal routes to deliver containers to destination *d*, and the summation of the probabilities of intermodal operators choosing all individual routes passing through *P* results in total probability equal to or greater than α. At all points on boundary $\overline{\psi}_P(\alpha)$, the probability that intermodal operators choose the routes passing through port *P* remains constant i.e. α.

It has to be noted that the piecewise linear characteristics possessed by intermodal routes may result in a non-continuous boundary curve as defined in Eqn. (3.14) in the x-y plane. A method that can graphically depict non-continuous boundary curves is necessitated.

3.4 Solution Algorithm

Let Ω denote an interested area containing the port hinterland of port *P* in the *x*-*y* plane. Estimating the probability of intermodal operators choosing a particular intermodal freight transportation route which connects origin (x, y) and destination *d* and traverses through *P* is considered as a key to obtain the hinterland. In order to compute the probability, we discretize the area Ω by drawing regularly spaced horizontal and vertical lines in the *x*-*y* plane. For each point intersected between a horizontal and a vertical line, the crude Monte Carlo simulation method (Gassmann et al., 2002) is employed to estimate the probability that intermodal operators choose the routes passing through port P. The boundary curve defined by Eqn. (3.14) can thus be approximated using a curve fitting method. The entire solution algorithm involves 4 steps as follows,

Monte Carlo simulation based method

Step 1 (Discretization) Discretize area Ω by generating horizontal and vertical lines with regular space Δy between two consecutive horizontal lines and regular space Δx between two successive vertical lines. Let $\bar{\Omega}$ denote the set of all the points intersected by these horizontal lines and vertical lines.

Step 2 (Monte Carlo simulation) For each point (x, y) intersected by a horizontal line and a vertical line i.e. $(x, y) \in \bar{\Omega}$, perform the following operations:

Step 2.1 (Mean and covariance calculation) Compute the vector of all expected values, $\mathbf{c}_{xy}$, and covariance matrix $\mathbf{\Sigma}_{xy}$ as per the Eqn. (3.10) and Eqn.(3.8).

Step 2.2 (Sampling) Generate N pseudorandom samples of vector $\mathbf{C}_{xy}$ following multivariate normal distribution with mean value $\mathbf{c}_{xy}$ and covariance matrix $\mathbf{\Sigma}_{xy}$, denoted by following set:

$$\Gamma(x, y) = \left\{ \left(c_{1_{xy}}^{(i)}, c_{2_{xy}}^{(i)}, \ldots, c_{I_{xy}}^{(i)} \right) \middle| i = 1, 2, \cdots, N \right\} \tag{3.15}$$

Step 2.3 (Probability estimation) Estimate the probability according to the formula:

$$\hat{P}(x, y) = \sum_{r_{xy} \in R_P(x,y)} \left(K_{r_{xy}} / N \right) \tag{3.16}$$

where $K_{r_{xy}}$ is the number of those vectors (samples) in set $\Gamma(x, y)$, in each of which the observation representing the transportation cost of route r_{xy} is the minimum one. $K_{r_{xy}}$ is the cardinality of the following subset of set $\Gamma(x,y)$:

$$\Theta(r_{xy}) = \left\{ \left(c_{1_{xy}}^{(i)}, c_{2_{xy}}^{(i)}, ..., c_{I_{xy}}^{(i)}\right) \in \Gamma(x,y) \middle| c_{r_{xy}}^{i} \le c_{k_{xy}}^{i},\ \forall k_{xy} \in R(x,y), k_{xy} \ne r_{xy} \right\} \quad (3.17)$$

Step 3 (Determination of points on the boundary curve) For any given probability α, find a set of points (x,y) in the discretized area $\bar{\Omega}$, denoted by $\hat{\psi}_P(\alpha)$, such that $\hat{P}(x,y) \in [(\alpha - \varepsilon_1),(\alpha + \varepsilon_1)]$, where ε_1 is a tolerable error, namely:

$$\hat{\psi}_P(\alpha) = \left\{ (x,y) \in \bar{\Omega} \middle| \alpha - \varepsilon_1 \le \hat{P}(x,y) \le \alpha + \varepsilon_1 \right\} \quad (3.18)$$

Step 4 (Boundary curve fitting) For set $\hat{\psi}_P(\alpha)$ obtained in Step 3, execute the two substeps as follows:

Step 4.1 (Cluster analysis) Partition all the points in $\hat{\psi}_P(\alpha)$ into *k* exclusive sub-sets, denoted by $\hat{\psi}_P^1(\alpha), \hat{\psi}_P^2(\alpha), ..., \hat{\psi}_P^k(\alpha)$, by the *k*-means cluster analysis method. The predetermined number of clusters *k* can be identified as a priori or by the elbow criterion.

Step 4.2 (*Polynomial curve fitting*) Find a polynomial function $\hat{f}_\alpha^j(y) = \sum_{i=0}^{n} a_i y^i$ that can well fit points in the sub-set $\hat{\psi}_P^j(\alpha), j = 1,2,...,k$ by the least squares estimation technique.

The Monte Carlo simulation (Step 2) and the boundary cure fitting procedure (Step 4) are two crucial components of the foregoing solution algorithm to estimate the probabilistic port hinterland. It is well known that the precision of probability estimation depends on the sample size adopted in the simulation. Given a demand precision in the probability estimation with 95% level of significance, we need to determine a lower bound for the sample size used in Step 2.2, which is examined in Section 3.4.1 below. As the transportation cost of an intermodal route is a piecewise-linear function of travel distance, it may result in discontinuous probabilistic boundary curves in the *x*-*y* plane. Therefore, it is imperative to work out all the connected components of the curves. To achieve that, we first employ a cluster analysis approach in the pattern classification (Duda et al, 2001) to segment all the points with respect to same probability into several groups (Step 4.1), and then perform the polynomial function fitting method for each of the groups in Step 4.2, as presented in the following Section 3.4.2.

3.4.1 A Lower Bound for the Sample Size

For each $(x, y) \in \bar{\Omega}$, sampling process is executed as in Step 2.2 of the proposed solution algorithm to generate multivariate normal samples with given mean value and covariance matrix. Several methods can be utilized to realize that, which have already been integrated into software packages such as MATLAB and MINITAB. We use MATLAB to generate those samples.

It might be of interest to examine the relationship between sample size N and the precision in probability estimation. Based on Step 2.3, the probability of intermodal operators choosing a particular route $r_{xy} \in R(x, y)$, $\hat{p}_{r_{xy}}$, can be estimated by,

$$\hat{p}_{r_{xy}} = K_{r_{xy}} / N, r_{xy} \in R(x, y). \tag{3.19}$$

where $K_{1_{xy}}, K_{2_{xy}}, ..., K_{I_{xy}}$ follow a multinomial distribution with N independent Bernoulli trials and the success probabilities $p_{1_{xy}}, p_{2_{xy}}, ..., p_{I_{xy}}$, where $p_{r_{xy}}$ is the probability that route r_{xy} is the minimum one among all routes in set $R(x, y)$ in terms of transportation cost. The expected value and variance of the estimator $\hat{P}(x,y)$, as in Eqn.(3.16), can thus be calculated by

$$E\left[\hat{P}(x,y)\right]=\sum\nolimits_{r_{xy}\in R_P(x,y)}E\left(\hat{p}_{r_{xy}}\right)=\sum\nolimits_{r_{xy}\in R_P(x,y)}p_{r_{xy}} \tag{3.20}$$

$$\begin{aligned}\operatorname{var}\left[\hat{P}(x,y)\right]&=\sum_{r_{xy}\in R_P(x,y)}\operatorname{var}\left(\hat{p}_{r_{xy}}\right)+\sum_{\forall r_{xy},k_{xy}\in R_P(x,y);r_{xy}\neq k_{xy}}\operatorname{cov}\left(\hat{p}_{r_{xy}},\hat{p}_{k_{xy}}\right)\\&=\sum_{r_{xy}\in R_P(x,y)}\left[p_{r_{xy}}\left(1-p_{r_{xy}}\right)/N\right]-\sum_{\forall r_{xy},k_{xy}\in R_P(x,y);r_{xy}\neq k_{xy}}\left(p_{r_{xy}}p_{k_{xy}}/N\right)\end{aligned} \tag{3.21}$$

As $\hat{P}(x,y)$ can be approximated by a normal distribution with a large N, the confidence interval at a significance level of 95% in estimating probability $P(x,y)$ can be represented by

$$\hat{P}(x,y)\pm1.96\sqrt{\sum_{r_{xy}\in R_P(x,y)}\left[p_{r_{xy}}\left(1-p_{r_{xy}}\right)/N\right]-\sum_{\forall r_{xy},k_{xy}\in R_P(x,y);r_{xy}\neq k_{xy}}\left(p_{r_{xy}}p_{k_{xy}}/N\right)} \tag{3.22}$$

In **Appendix A**, we demonstrate that the square root shown in Eqn. (3.22) has an upper bound as follows:

$$SR_{\max}=\begin{cases}0.5\sqrt{1/N}, & \left|R_P(x,y)\right|=1\\ \dfrac{\sqrt{\left|R_P(x,y)\right|/N}}{\left(\left|R_P(x,y)\right|+1\right)}, & \left|R_P(x,y)\right|\geq2\end{cases} \tag{3.23}$$

where $\left|R_P(x,y)\right|$ denotes the number of the routes passing though port P from origin (x,y) to destination d. Hence, we can expect (with 95% confidence) to obtain an estimation of probability $P(x,y)$ in Step 2.3 with an error not exceeding $\gamma\in(0,1)$ if we take the sample size,

$$N \geq \begin{cases} (1.96)^2 \times (0.5) / \gamma^2, & |R_P(x,y)| = 1 \\ (1.96)^2 \times \dfrac{|R_P(x,y)|}{\gamma^2 \left(|R_P(x,y)| + 1\right)^2}, & |R_P(x,y)| \geq 2 \end{cases} \tag{3.24}$$

For example, if $\gamma = 0.01$ and $|R_P(x,y)| = 4$, the sample size $N \geq 6146$ according to Eqn. (3.24). To gain high accuracy, a large sample size is essential. With development of distributed computing techniques (Attiya and Welch, 2004), computational time used for the sampling in Step 2.2 will be affordable.

3.4.2 Cluster Analysis and Polynomial Function Fitting

Step 4 of the solution algorithm involves determination of several polynomial fitting functions approximating hinterland boundary curves. To deal with the non-connectivity issue, we employ cluster analysis (Step 4.1) to segment the points in set $\hat{\psi}_P(\alpha)$.

Given the predetermined number of clusters *k*, all points in $\hat{\psi}_P(\alpha)$ can be partitioned into *k* exclusive groups $\hat{\psi}_P^1(\alpha)$, $\hat{\psi}_P^2(\alpha), \cdots,$ $\hat{\psi}_P^k(\alpha)$ by the *k*-means cluster analysis method (MacQueen, 1967) which minimizes the total within-cluster variance:

$$\sum_{j=1}^{k} \sum_{(x,y)\in\hat{\psi}_P^j(\alpha)} \left[\left(x - \bar{x}_j\right)^2 + \left(y - \bar{y}_j\right)^2 \right] \tag{3.25}$$

where $(\bar{x}_j, \bar{y}_j)$ is the centroid of cluster $j\,(j = 1,2,...,k)$ in the *x*-*y* plane. The number of clusters *k* plays an important role in performing the *k*-means clustering analysis method. It can be determined as a priori according to dispersion style of the scattering simulation points or by the elbow criterion (Ketchen and Shook, 1996). Note that the elbow criterion is utilized to select an integer *k* such that adding additional clusters does not add sufficient between-cluster variance. In general, an adequate *k* can be obtained by graphing percentage of variance explained by clusters, which is defined as a ratio of between-cluster variance to the total variance, against the number of clusters. The adequate k can be visually captured at the point where marginal gain of percentage of variance explained by clusters abruptly falls.

Having had all sets $\hat{\psi}_P^j(\alpha), j = 1, 2, \cdots, k$, we could use the classical least squares estimation method to determine polynomial functions that well fit the points in the sets, which are regarded as approximation of the boundary curve corresponding to probability α . In other words, given a subset $\hat{\psi}_P^j(\alpha)$, we need to determine coefficients $a_i, i = 0, 1, \cdots, n$ and the highest order n of the polynomial function $f_\alpha^j(y) = \sum_{i=0}^{n} a_i y^i$ such that the following curve fitting error is minimized for each $j = (1, 2, ..., k)$.

$$Error_n^j(n, a_0, ..., a_n) = \sum_{(x,y)\in\hat{\psi}_P^j(\alpha)} \left(x - \sum_{i=0}^{n} a_i y^i \right)^2 \quad (3.26)$$

The order n can be gradually increased to obtain a better fitting function with the stop criterion:

$$\left[\min\left(Error_n^j\right) - \min\left(Error_{n+1}^j\right) \right] / \min\left(Error_n^j\right) \leq \varepsilon_2 \quad (3.27)$$

where ε_2 represents a tolerable error in the curve fitting process. Following the stop criterion, after having obtained the order n^* and parameters $a_i^*(i = 1, 2, ..., n)$ minimizing Eqn. (3.26), the boundary $\overline{\psi}_P^j(\alpha)$ can be approximated by the fitting polynomial function:

$$f_\alpha^j(y) = \sum_{i=0}^{n^*} a_i^* y^i \ . \quad (3.28)$$

3.5 Illustrative Examples

The model and the corresponding solution algorithm developed above provide a useful tool to estimate the probabilistic hinterland of a port for policymakers and port operators. In order to display the effectiveness and to illustrate the application of the methodology, the hypothetical network involving three intermodal routes is presented in Fig. 3.4 and used to estimate the hinterland of Shanghai port. The study area considered in this regard involves China and Mainland Southeast Asia (CMSA).

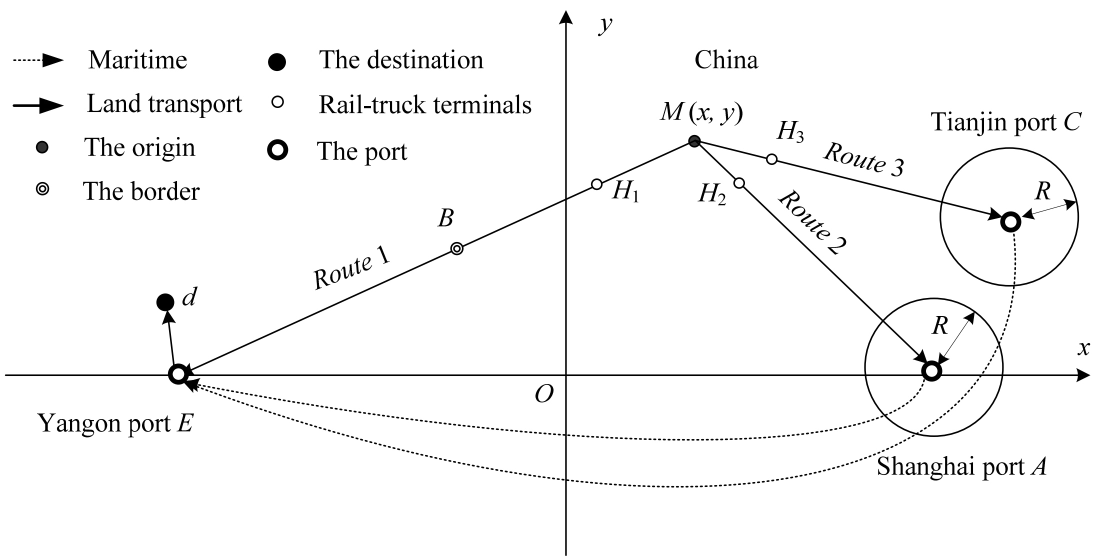


Fig. 3.4 The example intermodal freight transportation network

For transcontinental containerized cargo delivery among the countries in CMSA, intermodal operators commonly employ the intermodal routes combining short-haul truck services, transshipments at home ports and maritime transport services. For instance, in the service network, containers shipped from Mainland China to Myanmar may be transported to Shanghai port by only using truck services or utilizing a combination of truck and rail services, and then to Yangon port in Myanmar by maritime via the Strait of Malacca. Such a route choice of intermodal operators reflects the optimistic market shares and broad hinterlands possessed by the ports in Eastern China. Intermodal operators can also choose the landbridge (Route 1) represented in Fig. 3.4 which integrates short-haul truck and long-haul rail services to transport goods from China to Myanmar with border crossings. However, port operators in Eastern China are likely to experience the decrease in their port hinterlands with the incorporation of the Trans-Asian railway and Asian highway systems in CMSA (UNESCAP, 2008*a* and 2008*b*). It becomes important for them to estimate the port hinterlands to make well-informed decisions in terms of their market policies.

In Fig. 3.4, nodes H_1, H_2 and H_3 represent rail-truck terminals switching cargo flow from short-haul truck service to long-haul rail service. Node B denotes a border crossing terminal located at the border between China and Myanmar. In the figure, Shanghai port, Tianjin port and Yangon port are denoted by nodes A = (2171km, 0), C = (2171 km, 950 km) and E = (-2171 km, 0), respectively. The study area can be defined by a set given by Eqn. (3.29).

$$\Omega = \left\{ (x, y) \middle| x \in [0, 3{,}000 \text{ km}], y \in [-1{,}500 \text{ km}, 1{,}500 \text{ km}] \right\} \tag{3.29}$$

Containers are assumed to be carried from any given origin M = (x, y) in the study area to destination d situated in the circular area with radius R = 200 km and centered at node E. Three intermodal routes, namely Route 1, Route 2 and 3, presented in Fig. 3.4 can be used to accomplish the delivery. Route 1 directly transports containers from nodes M to E by the landbridge integrating short-haul truck service MH_1, long-haul rail service H_1E, and border crossing at node B, before transporting them to the final destination d by truck service. Route 2 combines land transport MA, maritime transport AE and short-haul truck service Ed to transport shipments, while Route 3 carries containers to destination d

passing through Tianjin port. It should be noted that three routes share the common link *Ed*. The expected values of transportation costs on the three routes are calibrated based on public resources presented in Section 3.5.1.

3.5.1 Transport Cost Calibration

When any given origin M is more than 200 km away from A or C a domestic intermodal route combining truck, rail and rail-truck transfer in China is utilized to transport containers to A or C otherwise, only truck service is used. Available data obtained based on North American landbridge operations (Shipmentlink, 2008) are used for calibrating transportation cost of landbridges in CMSA.

3.5.1.1 Costs for Short-haul Truck and Long-haul Rail Services

Trucking transport is a dominant solution for short-haul cargo delivery because of its ability to provide door-to-door service. It is estimated that delivering a container load unit (TEU or FEU) for 100 km by truck costs about 150 USD in the U.S. (USCC, 2006). The charge for transporting over 200 km can thus be estimated at 300 USD. We assume that the cost for transporting one TEU for a distance not exceeding 200 km remains 300 USD. We obtain the following cost-distance function for long-haul rail transport from Wang et al. (2009).

$$c(l) = 268 + 0.267l \quad R^2 = 0.717 \tag{3.30}$$

where l denotes travel distance and $c(l)$ represents the expected value of transportation cost corresponding to the distance l.

3.5.1.2 Costs for Rail-Truck Hub and Border Crossing Operations

The constant value 268 USD in Eqn. (3.30) is interpreted as the charge incurred for inventory, loading and unloading operations at a rail-truck terminal. UNESCAP (2003) shows that the cost incurred in the border crossing process between China and Mongolia is about 293 USD. The border crossing time is around one to five days. We thus take 293 USD as the border crossing cost between China and Myanmar.

3.5.1.3 Costs for Maritime Transport and Port Operations

Table 3.1 Expected values and variances of three intermodal routes

Route 1	Cost (USD)	σ_C^2	Route 2 (route 3)	Cost (USD)	σ_C^2
MH_1	300	60.0^2	MH_2 (MH_3)	300	60.0^2
At H_1	268	53.6^2	At H_2 (H_3)	268	53.6^2
H_1E	C_{H_1E}	$\left(0.2C_{H_1E}\right)^2$	H_2A (H_3C)	$C_{H_2A}\left(C_{H_3C}\right)$	$\left(0.2C_{H_2A}\right)^2\left[\left(0.2C_{H_3C}\right)^2\right]$
At B	293	58.6^2	At A (C)	387 (80)	77.4^2 (16^2)
Ed	300	60.0^2	AE (CE)	850 (1000)	170^2 (200^2)
			Ed	300	60.0^2

Note: when the port A or C is less than 200 km away from M, only the cost for short-haul truck service is involved in the domestic land transport

The costs for maritime transport and container handling processes at Shanghai port A, Tianjin port C and Yangon port E can roughly be estimated by using the data from OOCL (2008), ASEAN (2001), UNCTD (2007), Shipmentlink (2008) and MPA (1998). These data are tabulated in the second and fourth column of Table 3.1. In Table 3.1, the symbol C with a subscripted letter representing the name of corresponding component denotes transportation cost incurred on the component. For instance, C_{H_1E} denotes the cost on link H_1E.

3.5.1.4 Three Piecewise Linear Functions and the Covariance

Using the data shown in Table 3.1 and long-haul rail transport cost expressed by Eqn. (3.30), the piecewise linear functions for the expected values of transportation costs on the three intermodal routes can be determined as shown in Fig. 3.5.

In Fig. 3.5, each of the piecewise linear curves comprises several components representing the costs incurred at nodes and links. The abrupt changes in a curve represent the costs expended at ports, borders or rail-truck terminals. The linear parts in the curves stand for the costs expensed in container carrying processes on links. Since the precise data is unavailable in public resources, the standard deviation of the cost incurred at a node or on a link is estimated at 20% of its mean value as shown in Table 3.1. The covariance of the three intermodal routes in terms of cost is determined by the variance of their common link *Ed*.

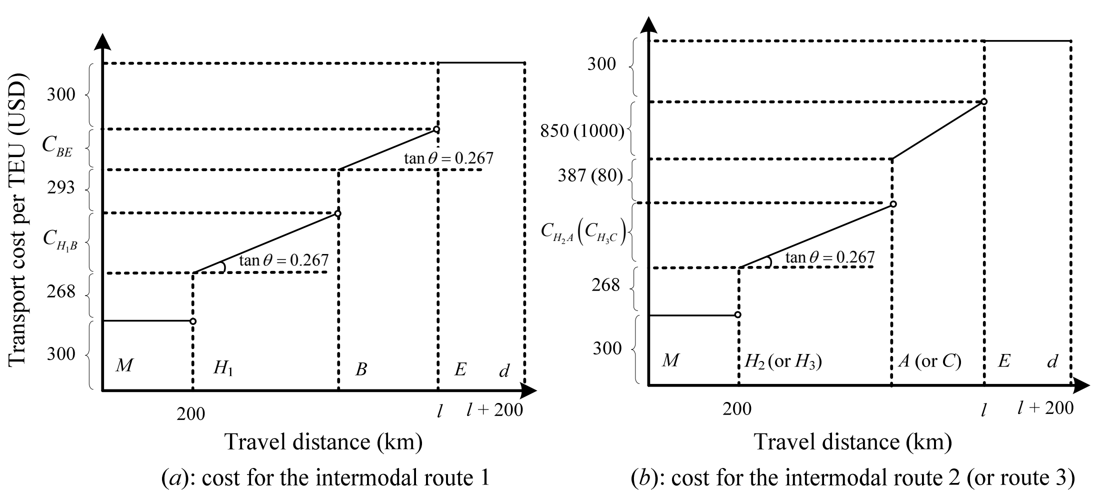


Fig. 3.5 The piecewise-linear functions for three intermodal routes

3.5.2 Example 1: Two Competing Routes

In this example, only Routes 1 and 2 as shown in Fig. 3.4 are considered for port hinterland estimation. As the transportation costs of these two routes follow a bivariate normal distribution, analytical expressions of boundaries of the probabilistic hinterland of Shanghai port can be derived. Based on Eqns. (3.12) - (3.13), when a given origin *M* $=(x,y)$ is less than 200 km away from Shanghai port *A*, the hinterland with given probability α can be represented by the analytical expression as follows.

$$\psi_P(\alpha)=\left\{(x,y)\middle|\left(C_{H_1E}-676\right)/\sqrt{48400+\left(0.2C_{H_1E}\right)^2}\geq\Phi^{-1}(\alpha)\right\} \tag{3.31}$$

where $\Phi^{-1}(\cdot)$ is the reverse cumulative distribution function of the standard normal distribution, and

$$C_{H_1E}=0.267\left(\sqrt{(x+2171)^2+y^2}-200\right) \tag{3.32}$$

Otherwise, the hinterland can be expressed as the area represented by the analytical expression as follows,

$$\psi_P(\alpha)=\left\{(x,y)\middle|\frac{C_{H_1E}-C_{H_2A}-944}{\sqrt{51271+\left(0.2C_{H_1E}\right)^2+\left(0.2C_{H_2A}\right)^2}}\geq\Phi^{-1}(\alpha)\right\} \tag{3.33}$$

where $\Phi^{-1}(\cdot)$ is the reverse cumulative distribution function of a standard normal distribution, and the cost on H_2A is represented by

$$C_{H_2A}=0.267\left(\sqrt{(x-2171)^2+y^2}-200\right) \tag{3.34}$$

The study area is divided into two parts by the circle with radius R = 200 km and centered at A. Inside the circle, based on Fig. 3.5, the expected values of transportation costs on Route 1 and Route 2 can be expressed by the vector shown in Eqn.(3.35).

$$\mathbf{c}_{xy} = \left(c_{1_{xy}} = C_{H_1E} + 1161, c_{2_{xy}} = 1837 \right)' \tag{3.35}$$

The covariance matrix for the two routes in terms of transportation cost is given by

$$\Sigma_{xy} = \left(13507 + \left(0.2C_{H_1E} \right)^2, 3600; 3600, 42093 \right) \tag{3.36}$$

In the area outside the circle, the transportation costs and the covariance matrix of the two routes are represented as follows,

$$\mathbf{c}_{xy} = \left(c_{1_{xy}} = C_{H_1E} + 1161, c_{2_{xy}} = C_{H_2A} + 2105 \right)' \tag{3.37}$$

$$\Sigma_{xy} = \left(13507 + \left(0.2C_{H_1E} \right)^2, 3600; 3600, 44964 + \left(0.2C_{H_2A} \right)^2 \right) \tag{3.38}$$

In order to estimate the hinterland, the Monte Carlo simulation based algorithm is coded using MATLAB and is executed by using a desktop with CPU of Pentium 4 3.00 GHz and 4G RAM. Let parameters $\Delta x = \Delta y = 5$ km, $\varepsilon_1 = 10^{-4}$, $\varepsilon_2 = 10^{-8}$, $\gamma = 0.01$ and N = 20000. We adopt k = 1 for the cluster analysis in the solution algorithm in order to obtain the polynomial fitting curves with respect to probabilities α = 0.1, 0.2, 0.5 and 0.90. The resultant fitting curves as well as the curves representing the analytical expressions defined in Eqns. (3.31) and (3.33) are shown in Fig. 3.6.

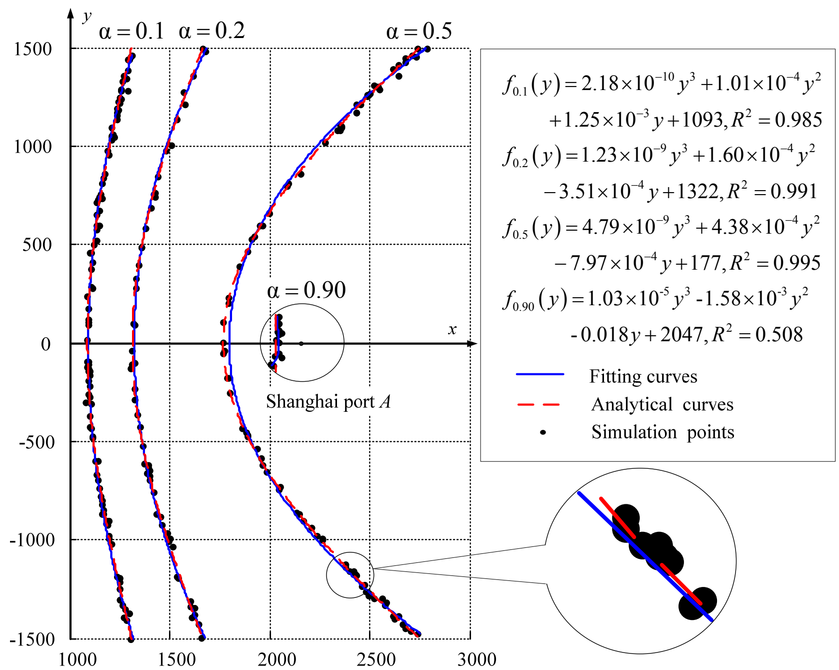


Fig. 3.6 The analytical and numerical hinterland boundary curves in Example 1

It can be seen that the fitting curves obtained based on simulation are nearly coincident with the curves obtained based on analytical closed-form expressions. To some extent, the coincidence demonstrates the suitability of the proposed solution algorithm for port hinterland estimation.

3.5.3 Example 2: Three Competing Routes

As shown in Fig. 3.5, the study area is partitioned into three subareas by two circles which have the radius R = 200 km and are centered at Shanghai port A and Tianjin port C, respectively. When a given origin $M = (x, y)$ falls in circular area around A, the expected values and covariance matrix of the three routes in terms of transportation cost are represented as follows.

$$\mathbf{c}_{xy}=\left(c_{1_{xy}}=C_{H_1E}+1161, c_{2_{xy}}=1837, c_{3_{xy}}=C_{H_3C}+1948\right)' \tag{3.39}$$

$$\Sigma_{xy} = \begin{bmatrix} 13507+\left(0.2C_{H_1E}\right)^2, 3600, 3600; 3600, 42093, 3600; \\ 3600, 3600, 50328+\left(0.2C_{H_3C}\right)^2 \end{bmatrix} \tag{3.40}$$

where C_{H_1E} is given by Eqn. (3.32), and C_{H_3C} is expressed by,

$$C_{H_3C} = 0.267\left[\sqrt{\left(x-2171\right)^2+\left(y-950\right)^2}-200\right] \tag{3.41}$$

If the origin (x, y) is located in the circular area centered at B, we have

$$\mathbf{c}_{xy} = \left(c_{1_{xy}} = C_{H_1E}+1161, c_{2_{xy}} = C_{H_2A}+2105, c_{3_{xy}} = 1680\right)' \tag{3.42}$$

$$\Sigma_{xy} = \begin{bmatrix} 13507+\left(0.2C_{H_1E}\right)^2, 3600, 3600; 3600, 44964+\left(0.2C_{H_2A}\right)^2, 3600; \\ 3600, 3600, 47456 \end{bmatrix} \tag{3.43}$$

If the origin (x, y) is in the area outside the two circles, it obtains that

$$\mathbf{c}_{xy} = \left(c_{1_{xy}} = C_{H_1E}+1161, c_{2_{xy}} = C_{H_2A}+2105, c_{3_{xy}} = C_{H_3C}+1948\right)' \tag{3.44}$$

$$\Sigma_{xy} = \begin{pmatrix} 13507+\left(0.2C_{H_1E}\right)^2 & 3600 & 3600 \\ 3600 & 44964+\left(0.2C_{H_2A}\right)^2 & 3600 \\ 3600 & 3600 & 50328+\left(0.2C_{H_3C}\right)^2 \end{pmatrix} \tag{3.45}$$

Set parameters $\Delta x = \Delta y = 5$ km, $\varepsilon_1 = 10^{-4}$, $\varepsilon_2 = 10^{-8}$, $\gamma = 0.01$ and N = 30000. For probabilities α = 0.015, 0.1, 0.2 and 0.80 we let k = 1 and obtain four fitting curves representing hinterland boundaries corresponding to these probabilities as shown in Fig. 3.7.

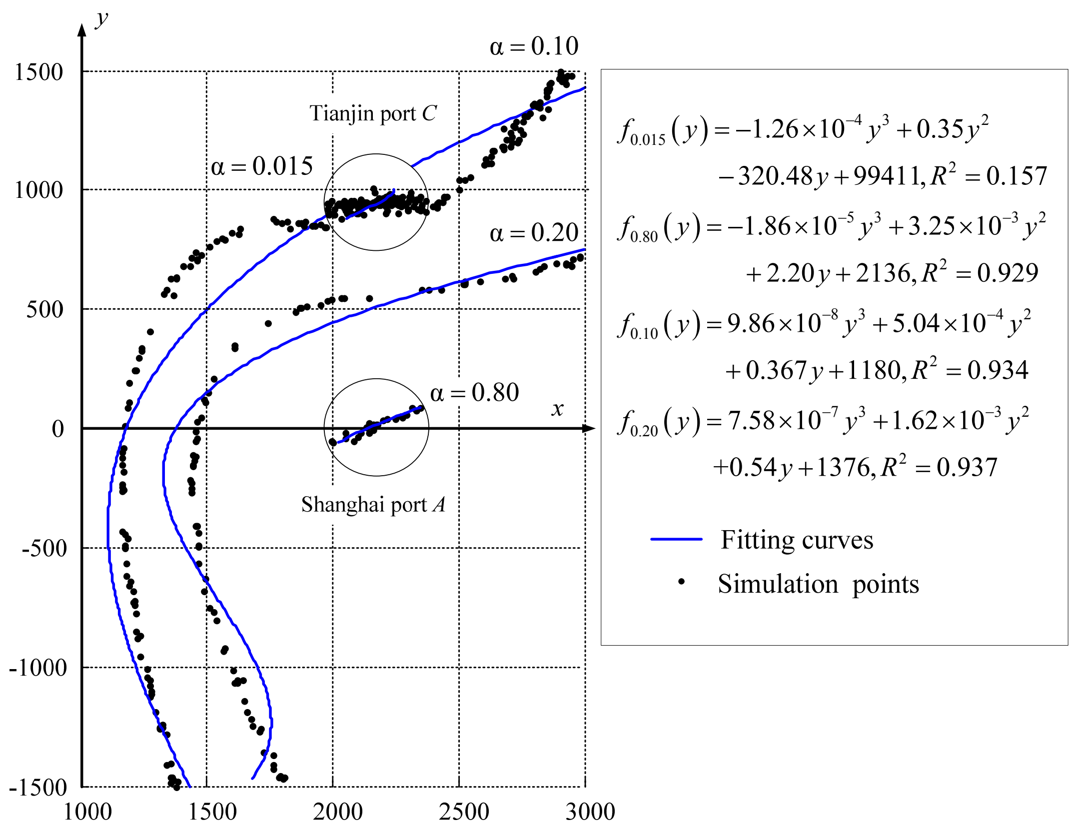
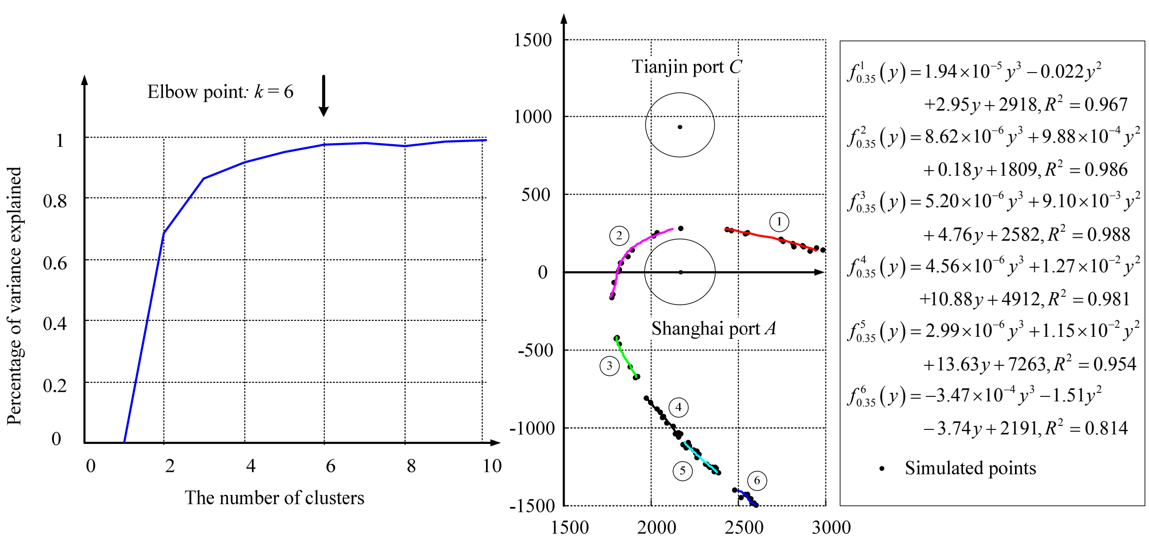


Fig. 3.7 The hinterland boundary curves in Example 2



(*a*) Elbow criterion for the number of clusters

(*b*) Fitting curves corresponding to probability 0.35

Fig. 3.8 Elbow criterion and curving fitting for the probability 0.35

As for α = 0.35, k = 6 is adopted according to the elbow criterion shown in Fig. 3.8*a*. Six polynomial curves are obtained to fit the points in the set $\hat{\psi}_P(\alpha = 0.42)$ which have been classified into six groups by the cluster analysis. Fig. 3.8*b* shows the fitting curves representing the boundary with respect to α = 0.35. The figure demonstrates the effectiveness and the application of the developed methodology when unconnected components on a hinterland boundary are involved.

3.5.4 Findings and Discussions

According to Fig. 3.6 and Fig. 3.7, it can be seen that the closer the shippers are located by Shanghai port, the higher the probability for intermodal operators to choose Route 2 is. Particularly in the circular area centered at Shanghai port, as only the short-haul truck service is assumed for Route 2, it is less costly to accomplish the delivery, resulting in that most of containers will visit (90%) Shanghai port as the transit terminal. This result indicates that an efficient and economical short-haul truck service is important for increasing the attraction of a port to the intermodal operators.

Fig. 3.7 shows boundary curves in the condition that three competing routes are involved. Both Routes 2 and 3 integrate the domestic land transport in China and maritime transport. With incorporation of Route 3, the extent of probabilistic hinterland of Shanghai port deceases. For instance, the boundary curve with probability 0.2 is pushed down and the port hinterland with probability 0.2 is compressed in Fig. 3.7 compared to that in Fig. 3.6. However, in the circular area nearby the port, the probability of choosing route 2 and the Shanghai port holds at 80%. Inside the circle centered at Tianjin port, the boundary curves with the probability 1.5% is obtained. It means that the Shanghai port still has some attractiveness even in the region nearby the Tianjin port.

The significance of travel distance to the hinterland of a port can be seen from the figures. The travel distance away from the interested port is negatively related to the probability of intermodal operators choosing the port. Particularly in the circular area centered at the port, since only the economical truck service is utilized for short-haul transport, most of intermodal operators in the area choose Shanghai port as the transit terminal. This result also indicates the importance of an efficient and economical short-haul truck service in increasing the extent of port hinterland. In addition, with the incorporation of Route 3, the hinterland of Shanghai port corresponding to same probability deceases.

In reality, the fitting curves representing boundaries of probability-based hinterland of Shanghai port illustrated in Fig. 3.6 and Fig. 3.7 construct a series of contours to specify spatial domain where intermodal operators choose routes traversing Shanghai port to handle containers with some probabilities in the context of intermodal container transportation. With the use of these contours, decision makers are able to predict competitiveness of their ports and corresponding adjustment of current market policies can be made to win in the competition. For instance, shippers located in the area with higher probability can be treated as the loyal and constant customers and more attractive and economical strategies shall be offered to them to hold these customers. In addition, efforts should be made to attract the shippers around the boundaries with the low probability, as they can be regarded as the potential customers.

3.6 Conclusions

In this chapter we proposed a novel concept of the attribute-based probabilistic port hinterland in intermodal freight transportation systems. The probabilistic port hinterland was mathematically formulated as an area in the *x*-*y* plane by taking transportation cost as an instance of a concerned attribute. The piecewise-linear characteristics of intermodal routes were taken into account in the model formulation. To identify the port hinterland, a Monte Carlo simulation based algorithm, which includes a cluster analysis method and a boundary curve fitting approach, was designed. One illustrative example was performed to demonstrate the effectiveness of the model and the designed algorithm. The other was conducted to show the application of the proposed methodology in quantitatively analyzing the impact of landbridge on port hinterland. As for the future research, utility-based probabilistic port hinterland estimation by simultaneously involving transportation cost and time will be examined in CHAPTER 4

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CHAPTER 4

UTILITY-BASED PROBABILISTIC PORT HINTERLAND ESTIMATION

4.1 Introduction

In the last chapter, an attribute-based probabilistic port hinterland estimation approach was developed. The approach contributes a new methodology to current port hinterland estimation literature; however, it takes into account individual attributes rather than consider them in a synchronous way. Moreover, the approach was proposed based on an intermodal network, in which it is assumed that there always exist shippers at each point. This assumption actually limits the port hinterland estimation in a hypothetically continuous network, which is somewhat unrealistic for intermodal freight transportation operations. To investigate the hinterland estimation problem in a more realistic way, this chapter continues with the work of the last chapter and aims to develop a utility-based port hinterland estimation approach in a realistic intermodal freight transportation network, which provides a generalized approach for involving multiple attributes in port hinterland estimation. For such a purpose, a more generalized probabilistic port hinterland is defined as follows: the area served by a specific port, over which intermodal operators choose the port with a probability within a certain range $[\alpha_1, \alpha_2]$, where parameters $\alpha_1, \alpha_2 \in [0,1]$, in order to transport containers from shippers to a given destination.

As discussed in the last chapter, the probabilistic hinterland of a specific port is determined by the behavior of intermodal operators in route choice for a given intermodal freight transportation network. As for an intermodal operator who can have an access to the specific port and is given a delivery destination by a shipper, he/she needs to choose intermodal routes from a set of available alternatives to transport containers from the shipper' location to the given destination. The shippers whose containers are transported via the port are considered to be located in the port's hinterland.

When faced with route choice, an intermodal operator's individual preference toward an intermodal route can be depicted by a utility function in terms of attributes of the route. As per the literature review of port selection criteria studies, transportation cost and time are two major factors determining intermodal operators' port selection. They should also be simultaneously taken into account to specify route utilities. The utility of an intermodal route perceived by intermodal operators can be thus defined as the sum of transportation cost per container along the route and transportation time of the route multiplied by vale of time (VOT) of intermodal operators.

Transportation cost and time incurred on links usually vary based on intermodal carriers such as liners and transport companies and transportation market prices. Traffic congestion at a transfer terminal is another critical factor resulting in fluctuation of transportation time due to limited handling capacity of the terminal. In reality, at a transfer terminal, the container transshipment process can be naturally formulated as a queuing system and transfer time for a particular container comprises waiting time in queue and handling time in service. Uncertainty does exist in the transfer time owing to stochastic container arrival pattern and terminal handling time. In addition, transshipment cost expensed at a transfer terminal may vary owing to fluctuating terminal handling charges. Uncertainties sourced from links and terminals give rise to random route travel time and cost. Therefore, the route utility specified in terms of transportation time and cost can be rationally formulated as a random variable.

According to the utility-maximization principle, intermodal operators would choose the route with the maximum utility from available alternatives. Since route utilities are randomly distributed, this would yield a probability of intermodal operators choosing the routes traversing through a specific port. Hence, in an intermodal transportation network, the probabilistic hinterland of the port should be explored based on random utilities of intermodal routes, which may be affected by transfer times, as intermodal routes may traverse several transfer terminals.

4.2 Random Route Utility and the Utility-Based Probabilistic Port Hinterland

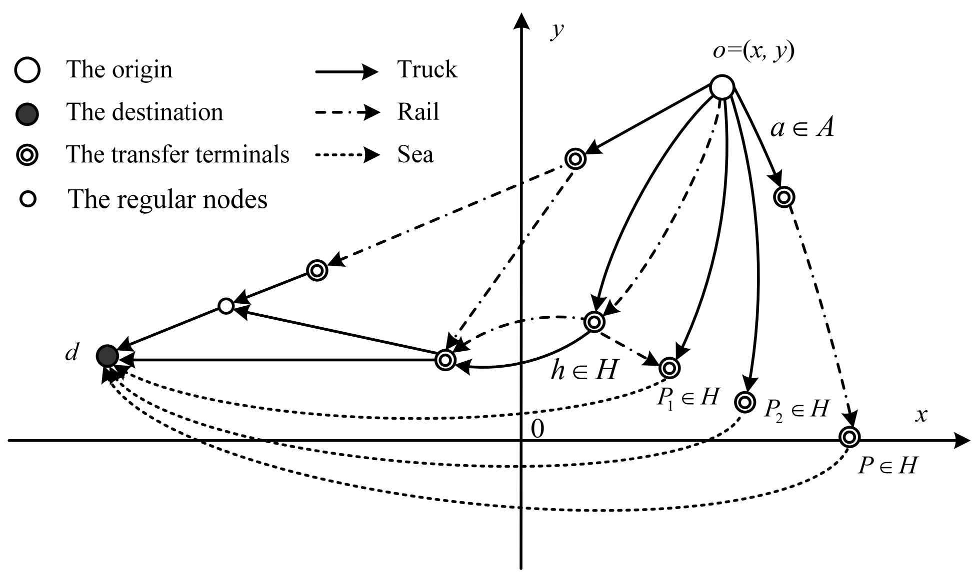

Fig. 4.1 An example network for intermodal freight transportation

As shown in Fig. 4.1, an intermodal freight transportation network involving a particular port P is located in an x-y plane coordinate system, in which port P is on the x-axis. The network may also include several other available ports such as P_1 and P_2. The network is represented by directed graph $\mathcal{G}=(\mathcal{N},\mathcal{A})$, where $\mathcal{N}$ and $\mathcal{A}$ represent the sets of nodes and links, respectively. Let $\mathcal{H} \subseteq \mathcal{N}$, $O \subseteq \mathcal{N}$, $\mathcal{D} \subseteq \mathcal{N}$ be the sets of transfer terminals, origins and destinations in network $\mathcal{G}$, respectively. In Fig. 4.1, it can be seen that ports P, P_1, and P_2 are also transfer terminals, i.e., $P, P_1, P_2 \in \mathcal{H}$.

Let $o = (x, y) \in O$ denote an origin node with coordinates (x, y). Shippers located around o desire to hire a common intermodal operator to transport containers from o to a given destination $d \in \mathcal{D}$. All the intermodal routes available to the intermodal operator are denoted by set $\mathcal{R}_{od}$. Let r be an intermodal route included in $\mathcal{R}_{od}$, i.e., $r \in \mathcal{R}_{od}$. Route r commonly consists of several transfer terminals and links. Indicator δ_{od}^{ra} equals one if route r passes through link $a \in \mathcal{A}$; zero otherwise. The value of indicator δ_{od}^{rh} is taken as one if a transfer terminal $h \in \mathcal{H}$ is on route r and the containers transported along r are transshipped at the terminal; zero otherwise.

The following assumptions are made throughout this chapter:

(i) transportation cost and time incurred on a link $a \in \mathcal{A}$, denoted by C_a and T_a, respectively, are reasonably assumed to be randomly distributed, since they vary based on intermodal carriers, operational conditions and market prices for transportation services,

(ii) transshipment cost incurred at a transfer terminal $h \in \mathcal{H}$, C_h , is also assumed as a random variable,

(iii) at a transfer terminal, containers arrive in batches in accordance to a compound Poisson process,

(iv) the time for handling a particular container at a transfer terminal is a generally distributed random variable,

(v) transportation times and costs incurred on links and at transfer terminals are assumed to be independent, as operational processes on them can be considered to be mutually independent, and

(vi) intermodal operators are assumed to choose the route with maximum utility from $\mathcal{R}_{od}$ to transport containers from the location o with coordinates (x, y) to destination d.

It obtains based on assumptions (i) and (ii) that

$$C_a = c_a + \xi_a, T_a = t_a + \omega_a, a \in \mathcal{A} \tag{4.1}$$

$$C_h = c_h + \xi_h, h \in \mathcal{H} \tag{4.2}$$

where c_a, t_a and c_h are expected values of C_a, T_a and C_h, respectively. ξ_a, ω_a and ξ_h are three random error terms with zero means which reflect the variations in transportation cost, time of link $a \in \mathcal{A}$ and transfer time of $h \in \mathcal{H}$ respectively. Furthermore, assumptions (iii) and (iv) give rise to a random transfer time at $h \in H$, denoted by $\tilde{T}_h$,

$$\tilde{T}_h = t_h + \omega_h, h \in \mathcal{H} \tag{4.3}$$

where t_h is expected value of $\tilde{T}_h$ and ω_h represents the random error term with zero mean. It is worth noticing that the probability distributions followed by the random variables defined in Eqns. (4.1) - (4.3) depend on data calibration process and need to be predetermined.

According to assumption (v), transportation cost and time of route $r \in \mathcal{R}_{od}$ can be written as,

$$C_r = \sum_{a \in \mathcal{A}} C_a \delta_{od}^{ra} + \sum_{h \in \mathcal{H}} C_h \delta_{od}^{rh} \tag{4.4}$$

$$T_r = \sum_{a \in \mathcal{A}} T_a \delta_{od}^{ra} + \sum_{h \in \mathcal{H}} \tilde{T}_h \delta_{od}^{rh} \tag{4.5}$$

The random utility of route *r*, U_{od}^r, can be thus defined as follows,

$$U_{od}^r = -C_r - \phi(x, y) T_r \tag{4.6}$$

where $\phi(x, y)$ is VOT perceived by shippers located at *o* with coordinates (*x*, *y*) and able to convert time to a monetary value. VOT reflects value of time perceived by intermodal operators and it quantitatively gauges the weight of transportation time in determining an intermodal operator's preference toward intermodal routes. VOT generally needs to be calibrated based on statistical data or survey.

Under assumption (vi), the utility-based probabilistic port hinterland estimation problem aims to identify an area surrounding port *P*, over which intermodal operators select the intermodal routes traversing though *P* with a probability within a certain range $[\alpha_1, \alpha_2]$, where parameters $\alpha_1, \alpha_2 \in [0,1]$, in order to transport containers from origin *o* with coordinates (*x*, *y*) to the given destination *d*.

4.3 Random Transfer Time at a Transfer Terminal

At transfer terminal $h \in \mathcal{H}$, arriving containers are regarded as customers and all the facilities providing various services in container handling process at the terminal, such as storing, loading, unloading and inspecting, are simply modeled by a single server. The various services necessitated in handling a particular container from arrival of the container to its departure from the terminal are considered to be provided by the single server. By this simplification, the transfer time of a container at h can be approximately estimated by formulating the container transshipment process as an $M^{[X]}/G/1$ queue.

The queue is described by Kendall's notation $M^{[X]}/G/1$, in which the number "1" implies that various handling services involved in the entire handling process at a transfer terminal is considered to be provided by a single server. G means that time incurred for handling a container by the server follows a general distribution. $M^{[X]}$ represents that containers arrive at the terminal in batches in accordance with a homogeneous compound Poisson process with arrival rate λ of batches and random batch size X. Arrival rate λ represents expected value of the number of batches arriving to the terminal during a time unit and the expected value of batch size X is denoted by $\bar{X}$. In practice, the product of λ and $\bar{X}$ corresponds to the total number of arriving containers during the time unit.

As for a specific container, transfer time $\tilde{T}_h$ is equal to the summation of waiting time W of the container in the queue before being served and container handling time $\tilde{W}$. Waiting time W can be further partitioned into two components: (i) waiting time of the first container arriving in the same batch with the specific container, W_1 and (ii) delay caused by the service times of the containers prior to the specific container in the same batch, W_2. Handling time $\tilde{W}$ is a generally distributed random variable having expected value $1/\mu$ and probability density function (PDF) $\tilde{w}(t)$. It can be inferred that W_1 and W_2 are also two random variables highly associated with the stochastic batch flow and random batch size, respectively. Transfer time $\tilde{T}_h$ can thus be written as

$$\tilde{T}_h = W_1 + W_2 + \tilde{W} \tag{4.7}$$

Summing random variables W_1, W_2 and $\tilde{W}$ gives a randomly distributed transfer time $\tilde{T}_h$ which does not certainly possess an analytically PDF such as normal or exponential distribution. This is because the PDF heavily relies on the probability distributions of batch size X and handling time $\tilde{W}$. As a result, PDF of a route utility may not have an analytical expression.

It is worthwhile to notice that both parameters λ and μ are usually based on a same time unit such as a season or a year and μ corresponds to the practical handling capacity of a transfer terminal, i.e., the number of containers the terminal can handle during the time unit.

Based on Eqn. (4.7) and **Appendix B**, the Laplace transform of PDF $\tilde{f}_h(s)$ of transfer time $\tilde{T}_h$ at the transfer terminal can be obtained and represented by

$$\tilde{f}_h^e(s) = \frac{s(1-\rho)}{s-\lambda\left[1-P_X\left(\tilde{w}^e(s)\right)\right]} \frac{1-P_X\left[\tilde{w}^e(s)\right]}{\bar{X}\left[1-\tilde{w}^e(s)\right]} \tilde{w}^e(s) \tag{4.8}$$

where $P_X(z)$ is the probability generating function (PGF) of batch size X defined as

$$P_X(z) = \sum_{i=1}^{\infty} \beta_i z^i \tag{4.9}$$

in which β_i is the probability of batch size X equal to i (i = 1,2,…) and z is a parameter in some interval to guarantee convergence of $P_X(z)$. Parameter ρ represents traffic load of the transfer terminal which is the proportion of the expected value of the number containers to the terminal handling capacity associated with a time unit and required to satisfy

$$\rho = \lambda \bar{X} / \mu < 1 \tag{4.10}$$

to guarantee existence of steady-state distribution possessed by the $M^{[X]}/G/1$ queue. $\tilde{w}^e(s)$ is the Laplace transform of the PDF $\tilde{w}(t)$ of handling time $\tilde{W}$, which can be expressed by,

$$\tilde{w}^e(s) = \int_0^\infty e^{-st}\tilde{w}(t)dt \tag{4.11}$$

where parameter s is a complex number with a nonnegative real part.

Traffic load ρ is a key indicator to reflect handling efficiency of a transfer terminal. According to Eqn. (4.10), ρ is inversely proportional to parameter μ that corresponds with the container handling capacity of a terminal, and product of λ and $\bar{X}$ can practically be approximated by the container throughput of a transfer terminal with regard to a certain time unit. Therefore, impact of changes in the handling capacity of a port on the port's hinterland can be analyzed based on the investigation of the port hinterland under various traffic loads.

The PDF $\tilde{f}_h(s)$ of transfer time $\tilde{T}_h$ can be obtained by solving the inverse Laplace transform of $\tilde{f}_h^e(s)$,

$$\tilde{f}_h(t) = \frac{1}{2\pi i}\int_{\gamma-i\infty}^{\gamma+i\infty} e^{st}\tilde{f}_h^e(s)ds \tag{4.12}$$

where i^2 = -1 and s is a complex variable. The integration is required to be conducted along the vertical line $\mathrm{Re}(s) = \gamma > 0$ in a complex plane such that all the singularities of $\tilde{f}_h^e(s)$ lie to the left of the line. This integral is somewhat difficult to solve since it requires contour integration in a complex plane. Fortunately, given explicit distributions of batch size X and handling time $\tilde{W}$, the inverse Laplace transform can be identified by referring to the Laplace transform table or using software packages such as MATLAB.

4.4 Mathematical Expression for Utility-Based Probabilistic Port Hinterland

Let vector $\mathbf{U}_{od}$ denote utilities of all intermodal routes in set $\mathcal{R}_{od}$ between O/D pair (o,d), where $o \in \mathcal{O}, d \in \mathcal{D}$, and I_{od} be cardinality of set $\mathcal{R}_{od}$. $\mathbf{U}_{od}$ can be written as

$$\mathbf{U}_{od} = \left(U_{od}^{r}, r \in \mathcal{R}_{od}\right) \tag{4.13}$$

The expected value and variance of $U_{od}^{r}, \left(r \in \mathcal{R}_{od}\right)$ are calculated by

$$E\left(U_{od}^{r}\right) = -\sum_{a \in \mathcal{A}} \left[c_a + \phi(x,y) t_a\right] \delta_{od}^{ra} - \sum_{h \in \mathcal{H}} \left[c_h + \phi(x,y) t_h\right] \delta_{od}^{rh} \tag{4.14}$$

$$\begin{aligned} \operatorname{var}\left(U_{od}^{r}\right) = & \sum_{a \in \mathcal{A}} \left[\operatorname{var}(\xi_a) + \phi^2(x,y) \operatorname{var}(\omega_a)\right] \delta_{od}^{ra} \\ & + \sum_{h \in \mathcal{H}} \left[\operatorname{var}(\xi_h) + \phi^2(x,y) \operatorname{var}(\omega_h)\right] \delta_{od}^{rh} \end{aligned} \tag{4.15}$$

The covariance between two random route utilities U_{od}^{r} and $U_{od}^{k}, \left(r, k \in \mathcal{R}_{od}\right)$ can be computed by

$$\begin{aligned} \operatorname{cov}\left(U_{od}^{r}, U_{od}^{k}\right) = & \sum_{a \in \mathcal{A}} \left[\operatorname{var}(\xi_a) + \phi^2(x,y) \operatorname{var}(\omega_a)\right] \delta_{od}^{ra} \delta_{od}^{ka} \\ & + \sum_{h \in \mathcal{H}} \left[\operatorname{var}(\xi_h) + \phi^2(x,y) \operatorname{var}(\omega_h)\right] \delta_{od}^{rh} \delta_{od}^{kh} \end{aligned} \tag{4.16}$$

Based on the decision behavior assumption of intermodal operators, summing probabilities of intermodal operators choosing an intermodal routes traversing through *P* to transport containers from *o* with coordinates (*x*, *y*) to the given destination *d* gives the probability of them selecting port *P* to transport containers, which is denoted by $F(x,y)$, namely,

$$F(x,y) = \sum_{r \in \mathcal{R}_{od}} \delta_{od}^{rP} P_{od}^{r} \tag{4.17}$$

where P_{od}^{r} is the probability of route *r* possessing maximum utility among all the routes in set $\mathcal{R}_{od}$, namely,

$$P_{od}^{r} = \Pr\left[U_{od}^{r} \geq U_{od}^{k} \middle| \forall k \in \mathcal{R}_{od} \text{ and } k \neq r\right], \forall o = (x,y) \in O, d \in \mathcal{D}, r \in \mathcal{R}_{od} \tag{4.18}$$

The probabilistic hinterland of port *P* is an area, over which shippers will choose *P* to transport containers to destination *d* with a probability within a certain range $\left[\alpha_1, \alpha_2\right]$

where parameters $\alpha_1, \alpha_2 \in [0,1]$. The utility-based probabilistic port hinterland can thus be mathematically expressed by

$$\Omega_p(\alpha_1, \alpha_2) = \left\{(x, y) \middle| \alpha_1 \leq F(x, y) \leq \alpha_2, \alpha_1, \alpha_2 \in [0,1]\right\} \tag{4.19}$$

of which, $\alpha = (\alpha_1 + \alpha_2)/2$ is regarded as the hinterland share of port P in the hinterland area.

The calculation of probability $F(x, y)$ shown in Eqn. (4.17) is a key to find the probabilistic port hinterland. Eqn. (4.17) shows that $F(x, y)$ can be calculated by comparing the random utilities of intermodal routes in set $\mathcal{R}_{od}$, which can be realized by investigating a large number $\hat{N}$ of samples of the route utilities generated using Monte Carlo simulation methods. As indicated by Eqns. (4.14)-(4.16), the expected value of a route utility is the negative summation of costs of the links and transfer terminals on the route and times of them multiplied by VOT and the covariance between two intermodal routes is only determined by the variances of common links and transfer terminals shared by them. Hence, the samples of route utilities can be derived from those of random costs and times of links and transfer terminals with predetermined or calibrated distributions.

4.5 A Monte Carlo Simulation Based Algorithm

Let ψ denote the study area involving port P in the x-y plane. We propose a Monte Carlo simulation based algorithm to find the utility-based probabilistic hinterland of port P as follows.

Monte Carlo Simulation Based Algorithm

Step 1: (*Discretization*). Discretize study area ψ by a series of regularly spaced vertical and horizontal lines with interdistances Δx and Δy, respectively. Let set $\hat{\psi}$ include all the discrete points intersected by horizontal and vertical lines.

Step 2: (*Sampling*). For each point $o=(x,y)$ with coordinates (x,y) intersected by a vertical and horizontal line, conduct the following substeps.

Step 2.1: (*Sampling for links and transfer terminals*). Based on the probability distributions of $C_a(a\in\mathcal{A})$, $T_a(a\in\mathcal{A})$, and $C_h(h\in\mathcal{H})$, generate $\hat{N}$ pseudorandom samples from the distributions respectively by using the inverse CDF (Cumulative Distribution Function) method. These samples are denoted by vectors $\hat{\mathbf{C}}_a$, $\hat{\mathbf{T}}_a$ and $\hat{\mathbf{C}}_h$ respectively, namely,

$$\hat{\mathbf{C}}_a=\left[\hat{C}_a^{(i)},i=1,2,...,\hat{N}\right],a\in\mathcal{A} \tag{4.20}$$

$$\hat{\mathbf{T}}_a=\left[\hat{T}_a^{(i)},i=1,2,...,\hat{N}\right],a\in\mathcal{A} \tag{4.21}$$

$$\hat{\mathbf{C}}_h=\left[\hat{C}_h^{(i)},i=1,2,...,\hat{N}\right],h\in\mathcal{H} \tag{4.22}$$

Based on the probability distributions of batch size X and handling time D for $h\in\mathcal{H}$, derive $\tilde{f}_h(t)$ according to Eqns. (4.8)-(4.12) and then generate $\hat{N}$ samples from $\tilde{T}_h\sim\tilde{f}_h(t)$ using the inverse CDF method, namely,

$$\hat{\mathbf{T}}_h=\left[\hat{T}_h^{(i)},i=1,2,...,\hat{N}\right],h\in\mathcal{H} \tag{4.23}$$

Step 2.2: (*Route utility calculation*). With VOT $\phi(x,y)$, the samples of utilities of all the intermodal routes in set $\mathcal{R}_{od}$, where $o=(x,y)$, can be represented by set $\Gamma(x,y)$.

$$\Gamma(x,y)=\left\{\left(\hat{U}_r^{(i)}, r\in\mathcal{R}_{od}\right)\middle| i=1,2,\cdots,\hat{N}\right\} \tag{4.24}$$

where

$$\hat{U}_r^{(i)}=-\sum_{a\in\mathcal{A}}\left[\hat{C}_a^{(i)}+\phi(x,y)\hat{T}_a^{(i)}\right]\delta_{od}^{ra}-\sum_{h\in\mathcal{H}}\left[\hat{C}_h^{(i)}+\phi(x,y)\hat{T}_h^{(i)}\right]\delta_{od}^{rh}, i=1,2,...,\hat{N} \tag{4.25}$$

Step 3: (*Probability estimation*). Compute probability $F(x,y)$ by the following estimator:

$$\hat{F}(x,y)=\sum_{r\in\mathcal{R}_{od}}\delta_{od}^{rP}K_r\big/\hat{N} \tag{4.26}$$

where K_r is the number of those vectors (samples) in set $\Gamma(x,y)$, in each of which the observation representing the utility of route *r* is the maximum one.

Step 4: (*Determining the port hinterland*). Given any $\alpha_1,\alpha_2\in[0,1]$, points located in the port hinterland with respect to range $[\alpha_1,\alpha_2]$ can be determined by the set:

$$\hat{\Omega}_p(\alpha_1,\alpha_2)=\left\{(x,y)\in\hat{\psi}\middle|\alpha_1\le\hat{F}(x,y)\le\alpha_2,\alpha_1,\alpha_2\in[0,1]\right\} \tag{4.27}$$

In Step 3, probability of intermodal operators choosing a particular route $r\in\mathcal{R}_{od}$, $\hat{P}_{od}^r$, can be estimated by

$$\hat{P}_{od}^r=K_r/\hat{N}, r\in\mathcal{R}_{od} \tag{4.28}$$

where K_r's$(r\in\mathcal{R}_{od})$ follow a multinomial distribution with $\hat{N}$ independent Bernoulli trials and success probabilities P_{od}^r's$(r\in\mathcal{R}_{od})$, where P_{od}^r has been defined in Eqn. (4.18). The expected value of $\hat{F}(x,y)$, shown in Eqn. (4.26), can be calculated by

$$E\left[\hat{F}(x,y)\right]=\sum_{r\in\mathcal{R}_{od}}\delta_{od}^{rP}E\left(\hat{P}_{od}^r\right)=\sum_{r\in\mathcal{R}_{od}}\delta_{od}^{rP}P_{od}^r \tag{4.29}$$

Eqn. (4.29) indicates that $\hat{F}(x,y)$ is a unbiased estimation of $F(x,y)$. It is thus reasonable to use $\hat{F}(x,y)$ as an estimator of $F(x,y)$.

4.6 Illustrative Cases

Two illustrative cases are given to estimate the probabilistic hinterland of Shanghai port with respect to varying VOT and traffic load of Shanghai port, in order to test impacts of VOT and handling capacity of the port on the hinterland and to compare hinterland shares of the Shanghai port, Tianjin port and Shenzhen port, as defined in Eqn. (4.19). Fig. 4.2 shows an intermodal container transportation network employed for case analysis. The intermodal network is located in an *x*-*y* plane system, in which the origin point (0, 0) corresponds to the location with geographical coordinates (*N*31º15′, *E*103º50′) in latitude and longitude form. Seven transfer terminals located in Mainland China are Lanzhou (0, 500*km*), Shanghai (1,678*km*, 0), Tianjin (1,150*km*, 855*km*), Zhengzhou (883km, 386*km*), Chongqing (250*km*, -175*km*), Changsha (900*km*, -330*km*) and Shenzhen (1,050*km*, -960*km*).

As shown in Fig. 4.2, we consider the entire Mainland China as study area. Shippers located in Mainland China are assumed to transport containerized cargo to Chicago in US, denoted by *d*. Regardless of locations of shippers, they are assumed to be able to hire an intermodal operator to access the nearest transfer terminals away from them in terms of Euclidean travel distance as the first transshipment points by truck services. After being transshipped from trucks to railroads, containers are then hauled to home ports in China, including Tianjin port, Shanghai port and Shenzhen port by railroads without being handled when traversing other transfer terminals during the process. As for the intermodal operators choosing home ports as the nearest transfer terminals, they only need to use truck services to transport containers to the chosen ports. After transshipments at home ports, containers are shipped to US ports by maritime and finally transported to the destination by rail.

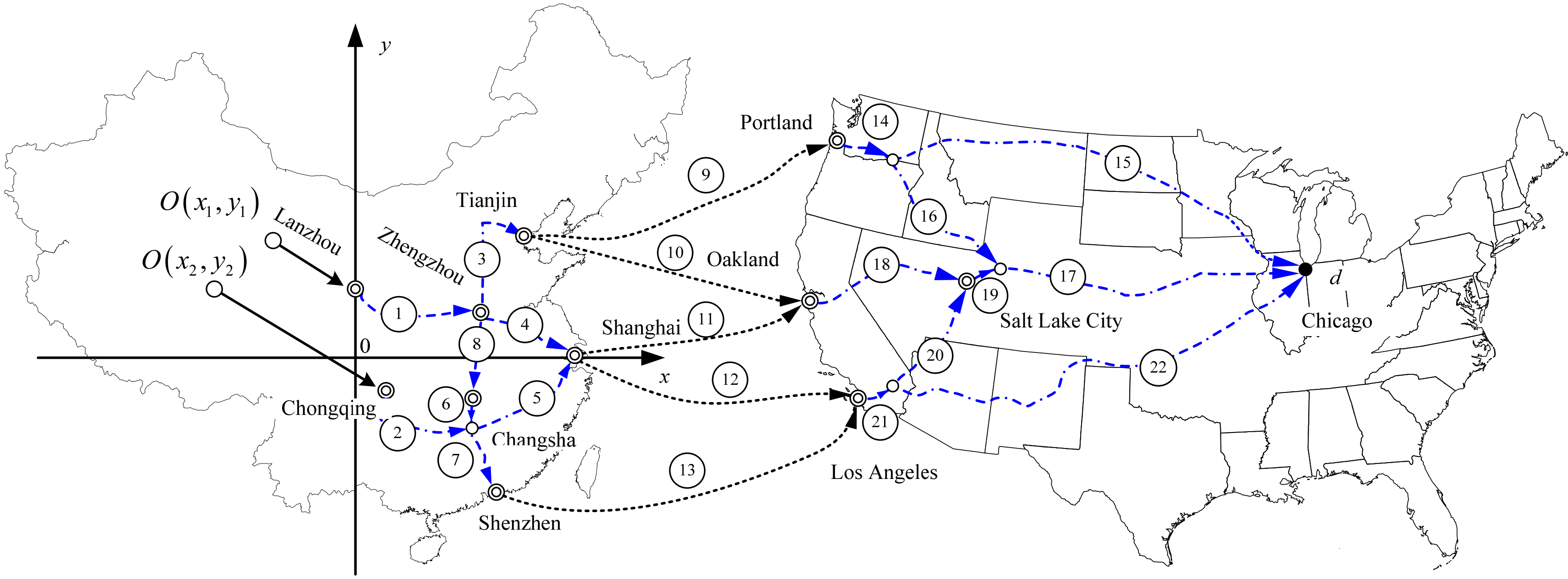

Fig. 4.2 An intermodal container transportation network

4.6.1 PDF of Transshipment Time

At transfer terminal *h*, containers arrive in accordance with a Compound Poisson process with arrival rate λ. The prerequisites for deriving PDF of transshipment time T_h are probability distributions of batch size *X* and handling time $\tilde{W}$. In this case study, it is assumed that handling time $\tilde{W}$ is exponentially distributed with parameter μ and batch size *X* follows a geometric distribution having the PMF (Probability Mass Function):

$$P(X=i)=\beta(1-\beta)^{i-1}, \beta\in(0,1), i=1,2,... \tag{4.30}$$

which gives that the expected value of batch size X can be represented by

$$E(X)=1/\beta \tag{4.31}$$

Furthermore, we adopt the time unit of a year for parameters λ and μ.

Applying the PMF defined in Eqn. (4.30) into Eqns. (4.8) and (4.9) results in that

$$\tilde{f}_h^e(s)=\frac{\beta\mu-\lambda}{s+\beta\mu-\lambda} \tag{4.32}$$

Eqn. (4.32) indicates that $\tilde{T}_h$ is an exponentially distributed random variable with parameter $(\beta\mu-\lambda)$.

Parameter μ corresponds to annual container handling capacity of a terminal. The annual throughput of terminal *h*, V_h, can be regarded as the product of arrival rate λ and the expected value of batch size *X*. It readily obtains that,

$$V_h=\lambda/\beta \tag{4.33}$$

The annual container throughputs for transfer terminals can be conveniently collected from public sources (AAPA, 2009; KPMG, 2009). The data in terms of tonnes have been converted to TEUs by using the following relationship calibrated by Wang and Meng (2010):

$$1\ TEU \approx 13.3 \text{ tonnes} \tag{4.34}$$

Calibration of $1/\beta$ is a challenge issue due to scarcity of data. We thus take the estimates of them as shown in Table 4.1. Based on β and V_h, arrival rate λ can be calculated using Eqn. (4.33), as tabulated in Table 4.1. Traffic load ρ for a transfer terminal can be written as.

$$\rho = \lambda/(\beta\mu) \tag{4.35}$$

In order to examine the impact of handling capacity of Shanghai port on the port's hinterland, we identify the port hinterland under various traffic loads of Shanghai port while keeping traffic loads of other transfer terminals as a constant 0.95.

4.6.2 Determination of Transshipment Cost

Table 4.1 Parameter Values for Transfer Terminals

Terminal No.	Transfer Terminals	1/β (TEUs per batch)	λ (batches per year)	c_h (USD)	var(ξ_h) (USD^2)
1	Lanzhou	5	2,374	27.0	5.4^2
2	Zhengzhou	20	2,632	23.4	4.7^2
3	Chongqing	20	5,964	27.0	5.4^2
4	Changsha	50	396	23.4	4.7^2
5	Tianjin	1,500	4,735	208.0	41.6^2
6	Shanghai	4,000	6,538	387.0	77.4^2
7	Shenzhen	5,000	4,221	386.0	77.2^2
8	Portland	50	5,203	694.0	138.8^2
9	Oakland	500	4,776	748.0	149.6^2
10	Los Angeles	1,500	5,570	901.0	180.2^2

Note: data complied based on references (Wang et al., 2009; GZ56W, 2009; ShippingChina, 2009)

The transshipment costs incurred at transfer terminals are assumed to be normally distributed random variables. As shown in Table 4.1, the expected values of the costs can be extracted from relevant sources (Wang et al., 2009; GZ56W, 2009; ShippingChina, 2009). Since it is very difficult to obtain the precise variances of the costs due to limited and inaccurate data sources, the standard deviation of each cost is estimated as 20% of its expected value. In the following section, we also assume the costs and times of links as normal random variables and the standard deviation of each variable is estimated at 20% of its expected value.

4.6.3 Cost and Time of Maritime Transportation

Table 4.2 Link Cost and Time and Normal Distribution Test Results

Link No.	Link Mode	Distance (km)	p-value	Sample Size	c_a (USD)	var(ξ_a) (USD^2)	t_a (Day)	var(ω_a) (Day^2)
1	Rail	1110.2	–	–	139.0	27.8^2	1.4	0.3^2
2	Rail	1092.4	–	–	137.2	27.4^2	1.4	0.3^2
3	Rail	875.0	–	–	114.6	22.9^2	1.1	0.2^2
4	Rail	1013.4	–	–	129.0	25.8^2	1.3	0.3^2
5	Rail	1144.2	–	–	142.6	28.5^2	1.4	0.3^2
6	Rail	49.2	–	–	28.6	5.7^2	0.1	0
7	Rail	823.7	–	–	109.2	21.8^2	1.0	0.2^2
8	Rail	959.3	–	–	123.3	24.7^2	1.2	0.2^2
9	Maritime	–	0.026	15	1429.0	488.9^2	15.0	3.0^2
10	Maritime	–	0.013	18	795.4	143.2^2	15.0	3.0^2
11	Maritime	–	0.027	115	726.5	71.1^2	11.0	2.2^2
12	Maritime	–	0.007	133	721.1	64.7^2	13.0	2.6^2
13	Maritime	–	0.030	40	682.2	56.2^2	12.0	2.4^2
14	Rail	390.0	–	–	104.1	20.8^2	0.6	0.1^2
15	Rail	3157.0	–	–	842.9	168.6^2	4.5	0.9^2
16	Rail	1015.5	–	–	271.1	54.2^2	1.5	0.3^2
17	Rail	2122.4	–	–	566.7	113.3^2	3.0	0.6^2
18	Rail	1176.6	–	–	314.2	62.8^2	1.7	0.3^2
19	Rail	136.2	–	–	36.4	7.3^2	0.2	0.0^2
20	Rail	927.7	–	–	247.7	49.5^2	1.3	0.3^2
21	Rail	185.1	–	–	49.4	9.9^2	0.3	0.1^2
22	Rail	3068.8	–	–	819.4	163.9^2	4.4	0.9

Note: – indicates that the data are unavailable.

Fig. 4.2 shows that five shipping links can be used to transport containers from China to US. The probability distribution of maritime transportation cost can be further examined based on the prices published by various maritime service providers.

Table 4.2 records the results of normal distribution tests for the five maritime transportation links, i.e. links No. 9-13, based on the reported market prices (ShippingChina, 2009). The results imply that a maritime transportation link approximately follows the normal distribution in terms of transportation cost, since a *p*-value larger than 0.05 can be obtained for each tested link. It further complements the rationale behind formulating maritime transportation costs as normally distributed random variables. The expected values and standard deviations of costs of links No. 9-13 can be estimated based on (ShippingChina, 2009), as tabulated in Table 4.2.

4.6.4 Cost and Time of Rail Transport

According to Wang et al. (2009), the cost and time for transporting one TEU by US rail can be calculated by

$$c = 268 + 0.267l \tag{4.36}$$

$$t = 2.05 + 0.00143l \tag{4.37}$$

where l denotes travel distance (*km*) and c and t represent the incurred cost (USD) and time (day) corresponding with l, respectively. Since constant values 268 and 2.05 have been respectively interpreted as time and cost incurred in container handling processes at terminals as well as unpredictable expense, only the variable cost, which increases proportionately to travel distance, is used to calculate transportation cost for US rail links.

According to MRC (2009), cost for transporting one TEU by Chinese railways can be calculated by

$$c = 161 \times 0.146 + 0.7128l \times 0.146 \tag{4.38}$$

in which c and l are defined as above in Eqn. (4.36). The value 0.146 converts Chinese Yuan to USD based on the currency on 16 July 2009. As reported by NBSC (2009), the running speed of Chinese freight trains is averagely estimated at 33.2 *km/h*. Transportation time t (day) can thus be calculated by

$$t = l / (33.2 \times 24) \tag{4.39}$$

where t and l are defined as above in Eqn. (4.37).

As tabulated in Table 4.2, for each link, the expected values of transportation cost and time can be calculated based on Eqns. (4.36)-(4.39) with travel distance l replaced by link length.

4.6.5 Cost and Time of Truck Transport

Truck services are only used in this illustrative case study for collecting containers to transfer terminals. As reported by Wang, et al. (2009), the cost c and time t of transporting one TEU by Chinese highways are computed by

$$c = 5.5 \times 0.146l = 0.803l \tag{4.40}$$

$$t = 0.0015l \tag{4.41}$$

where l denotes travel distance.

Cost and time for a truck service are considered as two normal random variables with expected values computed using Eqns. (4.40)-(4.41).

4.6.6 Simulation Results and Discussions

The proposed Monte Carlo simulation based algorithm is coded using MATLAB and executed by using a desktop with CPU of Pentium 4 3.00 GHz and 4G RAM. Let parameters $\Delta x = \Delta y = 75km$ and $\hat{N} =$ 3000. The shapes and extents of the hinterland is illustrated in Fig. 4.3 for $\mathrm{VOT} = 0, 5\ \mathrm{USD/hr}$ and $\rho = 0.50, 0.95$. Fig. 4.4 gives the changes of hinterland shares of Shanghai port, Tianjin port and Shenzhen port in areas I and II with respect to varying VOT when $\rho = 0.95$ and traffic load of Shanghai port when $\mathrm{VOT} = 5\ \mathrm{USD/hr}$.

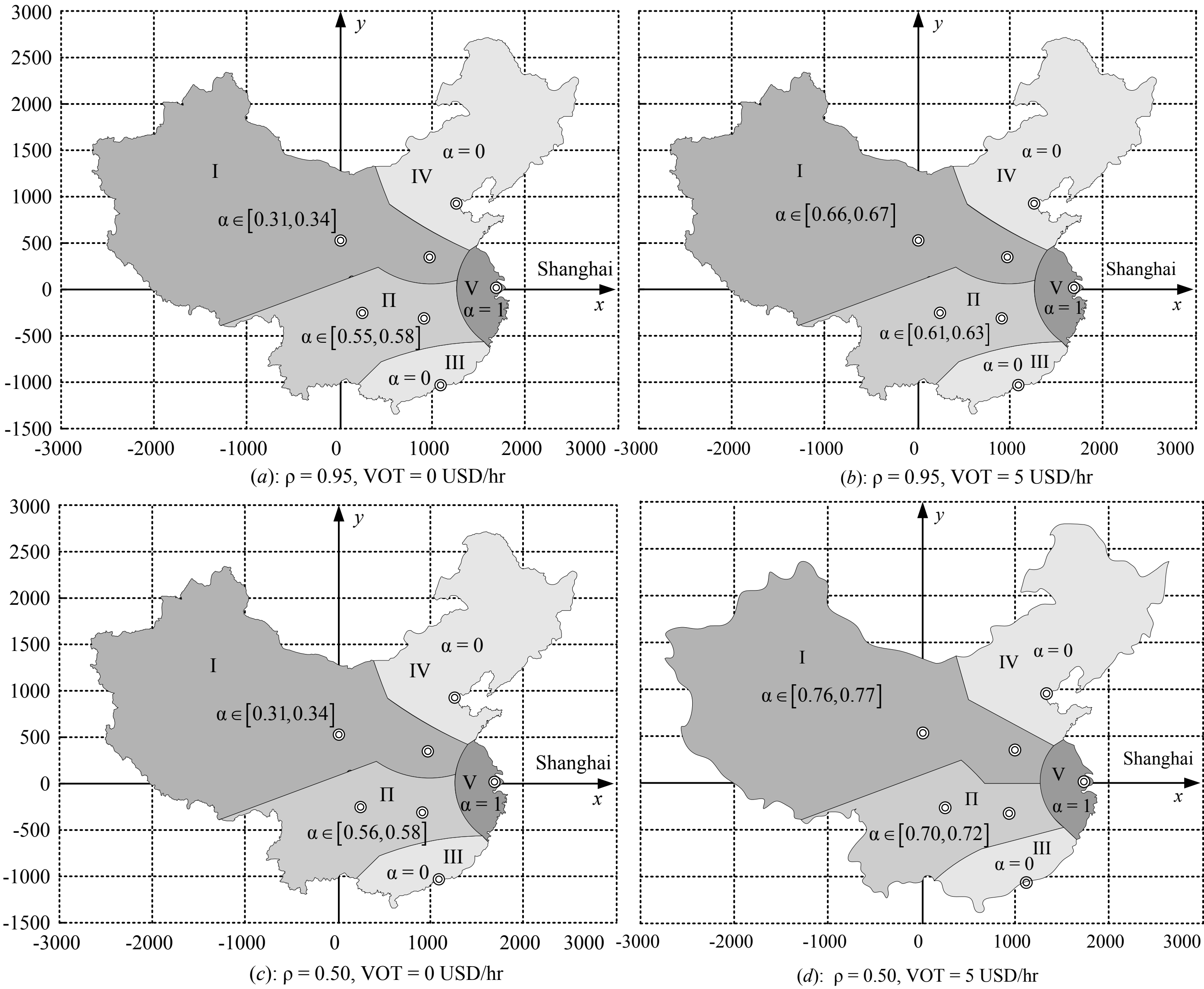

Fig. 4.3 The probabilistic hinterland of Shanghai port

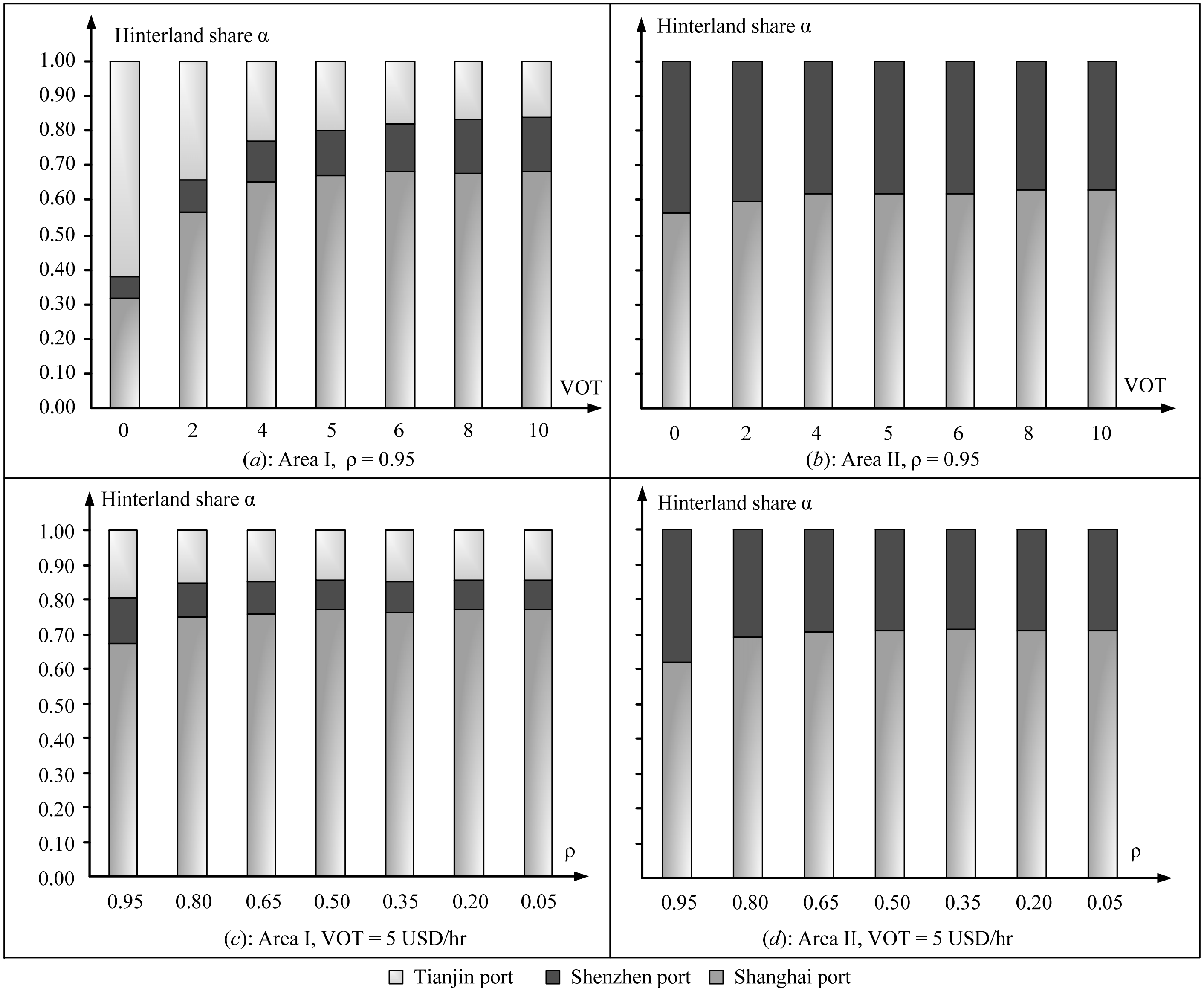

Fig. 4.4 Hinterland shares of the three ports in areas I and II for varying traffic load of Shanghai port and VOT

In Fig. 4.3 , the entire study area is visually decomposed into five areas regardless of variation in the traffic load. Each area is associated with a probability range and its extent almost maintains unchanged. This phenomenon is caused by the fact that intermodal operators usually choose the nearest transfer terminals as the first transshipment points. The intermodal operators, who are employed by the shippers located in different points in Mainland China and select transfer terminals (or an identical one) near the shippers as the first transshipment points, share long-distance paths connecting the first transshipment points to destination. For these intermodal operators, the route utilities differ only based on truck services. The fact that truck services are not dominant in determining intermodal operators' route utilities gives the intermodal operators with the similar probabilities to choose a same port. Besides, since the intermodal operators constantly choose Shenzhen port and Tianjin port as their export ports to transport containers for the shippers situated in areas III and IV, respectively, probabilities for them to choose Shanghai port is zero. The intermodal operators will certainly select Shanghai port as their export port to transport containers for the shippers located in area V.

4.6.6.1 Impact Analysis of Traffic Load of Shanghai Port

Fig. 4.3*a* and Fig. 4.3*c* actually reflect the port hinterland in terms of transportation cost because VOT = 0. When $\mathrm{VOT} = 0$, the probability ranges related to five areas keeps unchanged for varying traffic load, which implies that the port handling capacity will not affect port hinterland if value of time is not considered.

As shown in Fig. 4.4*c* and Fig. 4.4*d* and Fig. 4.3*b* and Fig. 4.3*d*, when the container handling capacity goes up (ρ reduces), the hinterland shares of Shanghai port in areas I and II increase. It implies that the improvement of container handling capacity of

Shanghai port will make the port attract more intermodal operators and share bigger market area, compared with the other two ports. However, the probability growth rate seems to have a trend to decrease after $\rho = 0.65$. This indicates that continuously increasing handling capacity does not contribute much to expanding the port hinterland after some threshold.

4.6.6.2 Impact Analysis of VOT

As illustrated in Fig. 4.4*a* and Fig. 4.4*b*, with increase of VOT from 0 to 10 USD/hr, the hinterland shares in areas I and II change from 0.33 to 0.68 and from 0.56 to 0.63, respectively, and the hinterland shares of the other ports correspondingly decrease. It suggests that, in areas I and II, Shanghai port is more attractive to the intermodal operators who are sensitive to transportation time than those who do not take into consideration VOT. According to Eqn. (4.32), the expected value of transshipment time at Shanghai port is $1/(\mu\beta\text{-}\lambda) = 1.06$ days which is less than that of Tianjin port (1.46 days) and that of Shenzhen port (1.64 days). While VOT rises, Shanghai port will take more advantage of its short transshipment time and attract more intermodal operators in areas I and II to select it.

4.7 Conclusions

This chapter proposes an interesting analytical approach to estimate the utility-based port probabilistic hinterland. The port hinterlands are represented as a series of areas each indicating a range of probabilities that an intermodal operator will select the port to transport containers for the shippers located in the area. The proposed approach, by means of route choice based on discrete choice theory, evaluates the probability of intermodal operators selecting the intermodal route traversing the concerned port. The areas associated with various probability ranges graphically depict the probabilistic port hinterland.

The approach is developed based on route utilities which are specified as a function of transportation cost and time. To specify route utilities, transshipment time at a transfer terminal is probed in depth by formulating the transshipment process as a batch-arrival queuing model. The transshipment time can be mathematically formulated as a random variable with a PDF derived from the queuing theory. A Monte Carlo simulation based algorithm is proposed to find the probabilistic port hinterland.

The illustrative cases demonstrate that the proposed probabilistic port hinterland estimation approach can be applied to study the changes in the hinterland of a port rendered by handling capacity of the port and varying VOT perceived by intermodal operators. It can also provide quantitative assessment of the relative competitiveness of a competing port against other ports located in the same study area.

CHAPTER 5

INTERMODAL HUB-AND-SPOKE NETWORK DESIGN WITH UNI-TYPE CONTAINERS

5.1 Introduction

As introduced in CHAPTER 1, the investigation of the IHSND problem would provide a basis for solving the port hinterland optimization problem, and a useful analytical tool for port operators and network planners to organize an optimal intermodal freight transportation network. The IHSND problem is defined as follows: given an existing intermodal network, the network planner attempts to re-design the network as a hub-and-spoke network by locating transfer terminals from a set of candidate transfer terminals (hubs), establishing new links, expanding existing links, building new transshipment lines and enhancing current transshipment lines with the aim to minimize the total network cost of carriers, while simultaneously taking into account the interactions among the network planner, carriers and intermodal operators. The IHSND problem is distinguished from the conventional HSND problem and its variants (O'Kelly, 1987; Campbell, 1994) due to the following characteristics.

Mode change is one of the prominent characteristics of an intermodal transportation system and the process is accomplished by using transshipment lines at transfer terminals. Since container handling is generally involved in the mode change process, cost and time will be correspondingly incurred. Besides transfer terminal locations and link establishments as addressed in the conventional HSND problems, the IHSND problem needs to identify the optimal strategy to either establish new transshipment lines or enhance current ones. It must be noted that container handling procedure may be involved even if transport mode does not change. For instance, containers are usually unloaded, inspected and reloaded for customs clearance at a border crossing terminal without change of transport mode. Such a process is also regarded as one type of mode changes.

Furthermore, the IHSND problem involves three kinds of stakeholders: the network planner, carriers and intermodal operators. Given a limited budget, the planner intends to design and build an optimal intermodal hub-and-spoke network. Given a network design decision made by the planner, the container flow distribution over the network is essentially determined by the decision behavior of intermodal operators in route choice. An intermodal operator deals with route choice according to his/her perceived utilities of all available candidate routes, which actually represent the preferences of the intermodal operator toward these routes. Practically, the utility of an intermodal route perceived by a particular intermodal operator can be expressed as a negative sum of the actual freight rate and transportation time multiplied by value of time (VOT) along the route. The actual freight rate (expenditure) is charged by carriers from the intermodal operator according to specific rate tables. It can be regarded as a reward for the carriers who provide container delivery or transshipment services for the intermodal operator.

Uncertainties do exist in the actual freight rate and transportation time due to the fluctuating average transportation market price, varying transportation technologies and competition pressure faced by carriers, thus resulting in a varying route utility. Moreover, different intermodal operators may perceive the route utility distinctly. To take into consideration the uncertainties in route utilities and perceived errors of intermodal operators, route utilities are represented as random variables as addressed by Sheffi (1985) in the traffic assignment problem. It is thus reasonable to assume that an intermodal operator's route choice would follow the stochastic user equilibrium (SUE) principle in accordance with randomly distributed utilities of intermodal routes perceived by the intermodal operator. Considering the interactive decision process between planner, carriers and intermodal operators, the IHSND problem can be naturally formulated as an MPEC model.

Additionally, a non-increasing unit transport cost function is usually employed in conventional HSND studies to reflect economies of scale exhibited in transport of shipments. However, as emphasized by Friesz and Holguín-Veras (2005), the unit cost function for freight transportation should have a "U" shape that reflects transition from economies of scale to diseconomies of scale in different flow regimes. The U-shaped unit cost function normally results in a non-convex non-differential IHSND problem, which presents a major challenge in devising an effective algorithm to solve the problem.

Though practically motivated, however, the IHSND problem has not been fully examined in the past relevant studies as indicated by the literature review due to mode change, the SUE-based route choice behavior of intermodal operators and non-convexity of cost function in intermodal freight transportation operations. There is thus a research need to develop a mathematical model and effective solution algorithm for the IHSND problem with multiple stakeholders, and this chapter aims to develop an MPEC model and solution algorithm for this issue.

Meanwhile, multi-type containers such as TEUs, FEUs, and tank containers may be involved in intermodal freight transportation operations, which may give rise to a more complicated IHSND problem. As the first-step research, we confine our attention on uni-type container transportation in this chapter. In the following sections of this chapter, we use TEU as the uni-type container for the sake of presentation.

5.2 Network Representation

Consider an existing intermodal freight transportation network for container delivery, consisting of the set of spoke nodes , $\mathcal{N}_0$, the set of transfer terminals, $\mathcal{N}_1$, the set of all direct links connecting two spoke nodes (spoke links), $\mathcal{A}_0$, and the set of transfer terminal links and spoke-transfer terminal links, $\mathcal{A}_1$. A planner attempts to re-design the existing network as an intermodal hub-and-spoke network by locating new transfer terminals from a set of given potential candidates , $\mathcal{N}_2$, building transshipment lines at the selected transfer terminals, and adding new links selected from a set of predetermined candidate links denoted by set $\mathcal{A}_2$. To facilitate model formulation for this intermodal hub-and-spoke network design problem, we define two networks – physical network and operational network. The physical network is a collection of all possible physical intermodal network elements interested by the network design planer. The operational network is derived based on the physical network and explicitly reflects the roles of carriers and transfer terminal operators and involves container transshipment processes at transfer terminals. Also, the operational network will be used for intermodal operators to work on intermodal route choice.

5.2.1 Physical network

Let directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ be a collection of all possible physical network elements interested by the network design planner, where $\mathcal{N} \equiv \mathcal{N}_0 \cup \mathcal{N}_1 \cup \mathcal{N}_2$ is the set of nodes and $\mathcal{A}=\mathcal{A}_0\cup\mathcal{A}_1\cup\mathcal{A}_2$ is the set of all links. The set of all transfer terminals is represented by $\mathcal{H}=\mathcal{N}_1\cup\mathcal{N}_2$. In the graph, the sets of transportation modes and carriers are represented by $\mathcal{M}$ and $\mathcal{E}$, respectively. The carrier set includes container transport service providers and transfer terminal operators.

Each link $a\in\mathcal{A}$ is described by a triplet $\left(\tilde{h}_a,\tilde{t}_a,m_a\right)$, where $\tilde{h}_a$, $\tilde{t}_a\in\mathcal{N}$ denote the head and tail of link *a*, respectively, and $m_a\in\mathcal{M}$ is a transportation mode available on the link. It can be thus seen that

$$\mathcal{A}_0\subseteq\mathcal{N}_0\times\mathcal{N}_0\times\mathcal{M} \tag{5.1}$$

$$\mathcal{A}_1\subseteq\left(\mathcal{N}_0\cup\mathcal{N}_1\right)\times\mathcal{N}_1\times\mathcal{M} \tag{5.2}$$

$$\mathcal{A}_2\subseteq\mathcal{N}\times\mathcal{N}_2\times\mathcal{M} \tag{5.3}$$

Let Γ_a be the current traffic capacity of link a, the maximum number of standard vehicles that can pass though this link during some time unit such as a day or year. The traffic volume in terms of standard vehicles over a link can be practically estimated by converting various types of vehicles to a standardized vehicle type associated with the link mode. For example, we can convert buses and trucks to passenger car units for road mode, transform passenger and freight trains to rolling stocks for rail mode, and convert bulk, oil and container vessels to standard containerships for maritime mode. This principle is consistent with the "passenger car equivalent" (p.c.e) concept that is now widely used and accepted by researchers and engineers (Daganzo, 1983; TRB, 2000). Note that current traffic capacity $\Gamma_a=0$ for each candidate link $a\in\mathcal{A}_2$ since it is to be built in future.

Each transfer terminal $h \in \mathcal{H}$ may possess one or several distinct directed mode-change transshipment lines/facilities that switch containers between various transportation modes at the transfer terminal. The examples of these facilities are gantry cranes, AGVs and trucks. Let $\mathcal{B}_h^1$ and $\mathcal{B}_h^2$ be the sets of existing and potential transshipment lines at transfer terminal h, respectively. The set $\mathcal{B}_h = \mathcal{B}_h^1 \cup \mathcal{B}_h^2$ thus includes all transshipment lines at the transfer terminal. Each transshipment line $b \in \mathcal{B}_h$ can be represented by a duplet $b = (m_1, m_2)$ and all the containers that need to be transferred from modes $m_1 \in \mathcal{M}$ to $m_2 \in \mathcal{M}$ at transfer terminal h will traverse through b. It thus follows that $\mathcal{B}_h \subseteq \Phi = \mathcal{M} \times \mathcal{M}$. In addition, we designate $\mathcal{B}_1 = \bigcup_{h \in \mathcal{H}} \mathcal{B}_h^1$, $\mathcal{B}_2 = \bigcup_{h \in \mathcal{H}} \mathcal{B}_h^2$ and $\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_2$ to be the sets of existing, potential and all possible transshipment lines in graph $\mathcal{G}$, respectively.

Each existing transshipment line $b \in \mathcal{B}_1$ has a current transshipment capacity Γ_b which is defined as the maximum number of standardized containers allowed to be transferred via transshipment line b during some time unit. This capacity is determined by the transshipment line's facilities, labors and operational productivity. Note that for each potential transshipment line $b \in \mathcal{B}_2$, the current capacity $\Gamma_b = 0$. The container volume in terms of standard containers loaded on a transshipment line $b \in \mathcal{B}$ can be calculated by converting flows of multi-type containers over b to that of a twenty-foot equivalent unit (TEU).

Let set $O \subseteq \mathcal{N}$ consist of all origin nodes and $\mathcal{D} \subseteq \mathcal{N}$ comprise all destination nodes. Intermodal operators intend to transport containers between an O/D pair (o, d)

where $o \in \mathcal{O}, d \in \mathcal{D}$ by purchasing transportation and transshipment services from carriers. Let T_{od} be the transport demand of containers for O/D pair (o,d).

In addition to the above notations, we use letter n with a subscripted letter representing a set to denote cardinality of the set throughput this chapter, e.g. $n_{\mathcal{M}}$ represents the number of container types in set $\mathcal{M}$.

5.2.2 Operational network

An operational network can be spawned based on physical network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where each carrier link or transshipment line is assumed to be operated by an individual carrier. Let directed graph $G = (N, A, T)$ denote the operational network derived from $\mathcal{G}$, where N, A, and T represent the sets of nodes, carrier links and transfers in the operational graph, respectively.

Let $\mathcal{E}_a \subseteq \mathcal{E}$ be the set of carriers operating over physical link $a \in \mathcal{A}$, and each carrier in set $\mathcal{E}_a$ can further be represented by a carrier link. Let A_a be the set of carrier links generated from physical link a, in which each carrier link solely corresponds with a particular carrier in set $\mathcal{E}_a$.

As for each node $n \in \mathcal{N}$, let $A_n^1 \subseteq A$ be the set of carrier links pointing into the node (before n) and $A_n^2 \subseteq A$ be the set of carrier links originated from the node (after n). As suggested by Guélat et al. (1990), as for each carrier link $\bar{a} \in A_h^1$, where $h \in \mathcal{H}$, a unique virtual node $\tilde{h}_{\bar{a}}$ can be added as the head of the carrier link. Let N_h^1 be the set of all the virtual nodes corresponding with the carrier links in set A_h^1. In a similar way, as for each carrier $\bar{a} \in A_h^2$, a unique virtual node $\tilde{t}_{\bar{a}}$ is added as the tail of the carrier link.

Let N_h^2 be the set of the virtual nodes corresponding with the carrier links in set A_h^2. Hub h can therefore be represented by a set of virtual nodes, namely, $N_h = N_h^1 \cup N_h^2$. By involving the virtual nodes generated at transfer terminals, the set of all nodes, N, is represented by,

$$N = \left(\bigcup_{h\in\mathcal{H}} N_h\right) \cup \mathcal{N}_0 \tag{5.4}$$

Hence, each carrier link $\overline{a} \in A_a$, where $a \in \mathcal{A}$, can be characterized by a quadruplet $\left(\tilde{h}_{\overline{a}}, \tilde{t}_{\overline{a}}, m_{\overline{a}}, e_{\overline{a}}\right)$, where $\tilde{h}_{\overline{a}}$, $\tilde{t}_{\overline{a}}$, and $m_{\overline{a}}$ are the head, tail and mode of the carrier link, respectively, with $m_{\overline{a}} = m_a$, $\tilde{h}_{\overline{a}}, \tilde{t}_{\overline{a}} \in N$, and $e_{\overline{a}} \in \mathcal{E}_a$ represents the carrier operating on the carrier link. In addition, carrier link $\overline{a}$ has a transportation capacity $\Gamma_{\overline{a}}^p$, which is defined as the maximum number of containers that carrier $e_{\overline{a}}$ can deal with during some time unit. The set of all carrier links, A, is thus represented by,

$$A = \bigcup_{a\in\mathcal{A}} A_a \subseteq \mathcal{A} \times \mathcal{E} \tag{5.5}$$

At each transfer terminal $h \in \mathcal{H}$, the container transfer process from carrier links $\overline{a}_1 \in A_h^1$ to $\overline{a}_2 \in A_h^2$, can be represented by a transfer $\overline{l} = \left(\tilde{h}_{\overline{a}_1}, \tilde{t}_{\overline{a}_2}\right)$, where $\tilde{h}_{\overline{a}_1} \in N_h^1$ and $\tilde{t}_{\overline{a}_2} \in N_h^2$. Let T_h be the set of all transfers at transfer terminal h, namely,

$$T_h \subseteq N_h^1 \times N_h^2 \tag{5.6}$$

The set of all transfers in the operational graph is thus represented by,

$$T = \bigcup_{h\in H} T_h \tag{5.7}$$

Each transfer $\overline{l} \in T_h$ traverses a unique directed transshipment line at transfer terminal h. In order to reflect the incidence relation between transfers and transshipment lines, let T_b be the set of transfers traversing through transshipment line $b \in \mathcal{B}_h$ and it follows,

$$T_b = \left\{ \bar{l} = \left(\tilde{h}_{\bar{a}_1}, \tilde{t}_{\bar{a}_2} \right) \in T_h \middle| m_{\bar{a}_1} = m_1, m_{\bar{a}_2} = m_2 \right\}, \forall b = (m_1, m_2) \in \mathcal{B}_h, h \in \mathcal{H} \quad (5.8)$$

Fig. 5.1 shows an example process how to derive the operational network G from physical network $\mathcal{G}$.

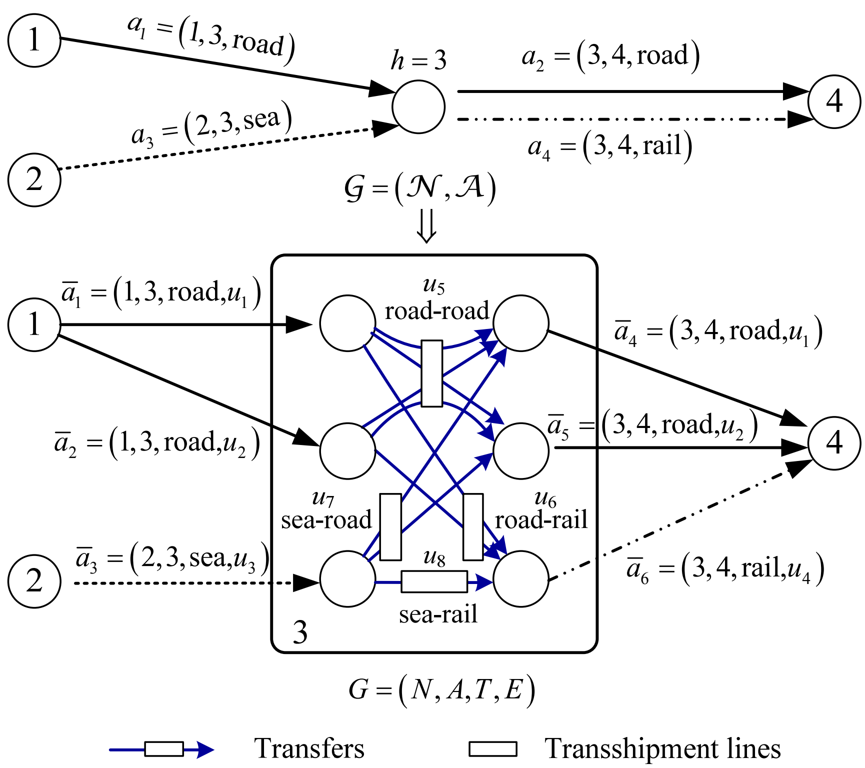

Fig. 5.1 An example for physical and operational network representation

As for each node $i \in N_h^1$, where $h \in \mathcal{H}$, let $\bar{a}_i^1$ be the carrier link with node i as its head and $T_i^2 \subseteq T_h$ be the set of transfers emanating from node i. As for each node $j \in N_h^2$, where $h \in \mathcal{H}$, let $T_j^1 \subseteq T_h$ be the set of transfers pointing into node j and $\bar{a}_j^2$ be the carrier link with j as its tail.

The delivery of containers between (o, d), where $o \in \mathcal{O}, d \in \mathcal{D}$, can be accomplished by traversing a sequence of transfers and carrier links. The sequence of transfers and carrier links traversed by the delivery process can be defined as an operational intermodal route. The operational intermodal route is distinct from the intermodal route described in the previous chapters, since the former is composed of various carrier links and transfers, while the latter consists of realistic infrastructure facilities such as physical links and transshipment lines. In the following portion of this work, all intermodal routes actually refer to operational intermodal routes.

Let R_{od} be the set of all available operational intermodal routes for container delivery between (o,d). An intermodal route $\bar{r} \in R_{od}$ may traverse a sequence of carrier links and transfers. Let $\delta_{od}^{\bar{r}\bar{a}} = 1$ if $\bar{r}$ traverses carrier link $\bar{a} \in A$; zero otherwise. Let $\delta_{od}^{\bar{r}\bar{l}} = 1$ if $\bar{r}$ traverses transfer $\bar{l} \in T$; zero otherwise.

5.3 Problem Statement

5.3.1 Decision Variables

In addressing the IHSND problem, following assumptions are made throughout the chapter: (i) spoke nodes cannot serve as transshipment points and (ii) no new direct links between spoke nodes will be established. To design an intermodal hub-and-spoke network, the planner needs to make a series of decisions:

(i) expanding the current traffic capacities of existing links in set $\mathcal{A}_1$ by adding more lanes or conducting road maintenances and rehabilitations,

(ii) establishing new links chosen from set $\mathcal{A}_2$ with specified traffic capacities,

(iii) enhancing existing transshipment lines in set $\mathcal{B}_1$ by extending the current capacities,

(iv) selecting new transfer terminals from set $\mathcal{N}_2$, and

(v) building new transshipment lines with specified capacities for the selected transfer terminals.

As for the existing spoke links in set $\mathcal{A}_0$, it is assumed that no decisions are made for them. These decisions can be mathematically expressed by the variables:

$$x_a = \begin{cases} 1, & \text{if traffic capacity of link } a \text{ is expanded} \\ 0, & \text{otherwise} \end{cases}, \forall a \in \mathcal{A}_1 \tag{5.9}$$

$$x_{\hat{a}} = \begin{cases} 1, & \text{if link } \hat{a} \text{ is established} \\ 0, & \text{otherwise} \end{cases}, \forall \hat{a} \in \mathcal{A}_2 \tag{5.10}$$

$$y_b = \begin{cases} 1, & \text{if capacity of transshipment line } b \text{ is enhanced} \\ 0, & \text{otherwise} \end{cases}, \forall b \in \mathcal{B}_1 \tag{5.11}$$

$$y_{\hat{b}} = \begin{cases} 1, & \text{if transshipment line } \hat{b} \text{ is established} \\ 0, & \text{otherwise} \end{cases}, \forall \hat{b} \in \mathcal{B}_2 \tag{5.12}$$

$$z_h = \begin{cases} 1, & \text{if hub } h \text{ is selected} \\ 0, & \text{otherwise} \end{cases}, \forall h \in \mathcal{N}_2 \tag{5.13}$$

For the sake of presentation, let $x_a = 0$, $z_h = 1$ and $z_n = 0$ for any existing spoke link $a \in \mathcal{A}_0$, any existing transfer terminal $h \in \mathcal{N}_1$, and spoke node $n \in \mathcal{N}_0$, respectively. These decision variables are grouped into three vectors of decision variables: $\mathbf{x} = (x_a, a \in \mathcal{A})$, $\mathbf{y} = (y_b, b \in \mathcal{B})$ and $\mathbf{z} = (z_n, n \in \mathcal{N})$ in accordance with physical links, transshipment lines and nodes. Let vector $\mathbf{s} = (\mathbf{x}, \mathbf{y}, \mathbf{z})$ and $n_\mathbf{s}$ denote the number of decision variables in vector **s**, where $n_\mathbf{s} = n_\mathcal{A} + n_\mathcal{B} + n_\mathcal{N}$. Vector **s** can be further represented by,

$$\mathbf{s} = (s_i, i = 1, 2, ..., n_\mathbf{s}) \tag{5.14}$$

Moreover, let T_{oi} be the decision variable representing the container flow originated from origin $o \in O$ and unloaded at node $i \in N_h^1$, where $h \in \mathcal{H}$.

Various investment actions are coupled with the network design decisions. No investments are allocated for existing spoke links. It costs B_a to enhance the traffic capacity of an existing link $a \in \mathcal{A}_1$ from Γ_a to Θ_a and $B_{\hat{a}}$ to build a new link $\hat{a} \in \mathcal{A}_2$ with capacity $\Theta_{\hat{a}}$. If the capacity of an existing transshipment line $b \in \mathcal{B}_1$ is enhanced, a cost F_b is required to extend its capacity from Γ_b to Θ_b. When a new transshipment line $\hat{b} \in \mathcal{B}_2$ is established with capacity $\Theta_{\hat{b}}$, a cost $F_{\hat{b}}$ will be required to establish the transshipment line. Once a transfer terminal $h \in \mathcal{N}_2$ is selected to be built, at least one transshipment line should be established at the transfer terminal; it will degenerate to a spoke node otherwise. Meanwhile, the direct links connecting the degenerated transfer terminal and other spoke nodes will not be established.

5.3.2 Route Choice Model for Intermodal Operators: SUE principle

Given a feasible intermodal hub-and-spoke network design solution **s**, intermodal operators will route their containers based on the resulting operational network G determined by **s**. The container flow distribution over the operational network results from the behaviors of intermodal operators in route choice. According to the SUE principle (Sheffi, 1985), no intermodal operator could increase his/her perceived transportation utility by unilaterally shifting to choose another route when he/she is faced with route choice for transporting one container (TEU) between each O/D pair in operational network G.

Let $v_{\bar{a}}^{o}$ and $v_{\bar{l}}^{o}$ denote the container flows loaded on carrier link $\bar{a} \in A$ and transfer $\bar{l} \in T$ with origin $o \in O$, respectively, and $v_{\bar{a}}$ and $v_{\bar{l}}$ be the total container flows along carrier link $\overline{a} \in A$ and transfer $\overline{l} \in T$, respectively. The vector of container flows on all carrier links and transfers (network flow pattern) is represented by

$$\mathbf{v} = \left(v_{\overline{a}}, \overline{a} \in A; v_{\overline{l}}, \overline{l} \in T \right) \tag{5.15}$$

For any given intermodal hub-and-spoke network design solution $\mathbf{s}$, we define the set of feasible container flows distributed over G as follows,

$$\Omega(\mathbf{s}) = \left\{ \mathbf{v} \mid v_{\overline{a}} = \sum_{o \in O} v_{\overline{a}}^{o}, \forall \overline{a} \in A; v_{\overline{l}} = \sum_{o \in O} v_{\overline{l}}^{o}, \forall \overline{l} \in T \right. \tag{5.16}$$

$$\sum_{\overline{a} \in A_n^1} v_{\overline{a}}^{o} = T_{on}, \forall n \in \mathcal{N}_0, o \in O, o \neq n \tag{5.17}$$

$$v_{\overline{a}_i^1}^{o} - T_{oi} = \sum_{\overline{l} \in T_i^2} v_{\overline{l}}^{o}, \forall i \in N_h^1, h \in \mathcal{H}; o \in O, o \neq i; \tag{5.18}$$

$$\sum_{\overline{l} \in T_j^1} v_{\overline{l}}^{o} = v_{\overline{a}_j^2}^{o}, \forall j \in N_h^2, h \in \mathcal{H}; o \in O, o \neq j; \tag{5.19}$$

$$\sum_{d \in \mathcal{D}} T_{od} = \sum_{\overline{a} \in A_o^2} v_{\overline{a}}^{o}, \forall o \in O \cup \overline{\mathcal{H}} \tag{5.20}$$

$$\sum_{d \in \mathcal{D}} T_{od} = \sum_{\overline{l} \in T_o^b} v_{\overline{l}}^{o}, \forall b \in \mathcal{B}_o, \forall o \in \mathcal{H} \tag{5.21}$$

$$\sum_{i \in N_h^1} T_{oi} = T_{oh}, \forall h \in \mathcal{H}, o \in O \tag{5.22}$$

$$v_{\overline{a}} \leq M x_a, \forall \overline{a} \in A_a, a \in \mathcal{A} \tag{5.23}$$

$$v_{\overline{l}} \leq M y_b, \forall \overline{l} \in T_b, b \in \mathcal{B}_h, h \in \mathcal{H} \tag{5.24}$$

$$\left. v_{\overline{a}}^{o} \geq 0, \forall \overline{a} \in A; v_{\overline{l}}^{o} \geq 0, \forall \overline{l} \in T \right\} \tag{5.25}$$

where Eqns. (5.16) represents the relation between origin-based containers flows and the total container flows along carrier links and transfers, and Eqns. (5.17)-(5.20) denote the flow conservation condition for each origin $o \in O$ and node $n \in \mathcal{N}$, where $o \neq n$. Eqn. (5.21) ensures that all flows originated from a hub will transfer at the hub. Eqn. (5.22) guarantees that the sum of the container flows discharged at all the virtual nodes of transfer terminal $h \in \mathcal{H}$ with origin $o \in O$ equals the container flow originated from node o and destined to transfer terminal h. Constraint (5.23)-(5.24) represents the relation between network design decisions and network flow pattern and M is an arbitrarily big number. Constraint (5.25) guarantees nonnegative container flows on carrier links and transfers.

5.3.2.1 The Perceived Transportation Utilities of Intermodal Routes

Consider a population of intermodal operators who are about to route containers between a given O/D pair. The transportation utility of a carrier link or transfer to a specific intermodal operator can be expressed as a function of two observed attributes of the carrier link or transfer - container handling time and actual container handling rate. Involving container handling time into the utility function enables us to take into account the impact of congestion on the route choice of the intermodal operator. Congestion phenomena can simply be observed at transfer terminals and on links owing to the capacity constraint of transshipment lines and physical links. For instance, the congestion that results from the unscheduled delays of fast trains being caught behind slower ones often occurs on rail links. Since congestion at any transfer terminal or physical link may result in traffic delays in the whole operational network, the transportation or transfer time is generally regarded as a function of network flow pattern $\mathbf{v}$. Furthermore, the transportation or transfer time is associated with network design solution $\mathbf{s}$, because the solution determines the capacities of physical links and transshipment lines. The actual container handling rate indicates the fee charged by a carrier or transfer terminal operator according to a particular rate table, which is directly paid by the intermodal operator for transporting or transferring one TEU on the carrier link or transfer.

Uncertainty does exist in the transportation utility due to variations in container handling time, actual rate and perception of intermodal operators on the utility. First, the container handling process on the carrier link or transfer can be essentially regarded as a stochastic queueing system and the handling time generally differs with the varying handling technique and productivity. Second, the actual container handling rate is generally reported by the carrier to the intermodal operator, and it may vary based on the average price of transportation service market and competition pressure of the carrier. Additionally, each intermodal operator may perceive the reported actual rate and the value of the container handling time differently, thus resulting in a distinctly perceived transportation utility. It is thus natural to model the perceived transportation utility of carrier link or transfer as a random variable distributed across the population of intermodal operators, which is a function of network flow pattern **v** and network design solution **s**.

To treat this problem analytically, let $G_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)$ and $G_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)$ be the perceived transportation utilities of carrier link $\bar{a} \in A$ and transfer $\bar{l} \in T$, respectively, which have the forms,

$$G_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right) = -\left(r_{\bar{a}} + \phi_{\bar{a}} t_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)\right) + \xi_{\bar{a}} \tag{5.26}$$

$$G_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right) = -\left(r_{\bar{l}} + \phi_{\bar{l}} t_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)\right) + \xi_{\bar{l}} \tag{5.27}$$

where $r_{\bar{a}}$ and $r_{\bar{l}}$ are the actual container handling rates, $t_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)$ and $t_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)$ denote the container handling time as a function of network flow pattern **v** and network design solution $\mathbf{s}$, and parameters $\phi_{\bar{a}}$ and $\phi_{\bar{l}}$ are two constants representing the VOTs on carrier link $\bar{a}$ and transfer $\bar{l}$, respectively. Error terms $\xi_{\bar{a}}$ and $\xi_{\bar{l}}$ are assumed to be normally distributed with zero means and flow-independent variances, namely,

$$\xi_{\bar{a}} \sim N\left(0,\left(\varphi_{\bar{a}}\left(r_{\bar{a}}+\phi_{\bar{a}}t_{\bar{a}}^{0}\right)\right)^{2}\right) \tag{5.28}$$

$$\xi_{\bar{l}} \sim N\left(0,\left(\varphi_{\bar{l}}\left(r_{\bar{l}}+\phi_{\bar{l}}t_{\bar{l}}^{0}\right)\right)^{2}\right) \tag{5.29}$$

where $\varphi_{\bar{a}}$ are $\varphi_{\bar{l}}$ are proportionality constant parameters with respect to carrier link $\bar{a}$ and transfer $\bar{l}$, respectively, and $t_{\bar{a}}^{0}$ and $t_{\bar{l}}^{0}$ are the flow-free transportation time and transfer time on carrier link $\bar{a}$ and transfer $\bar{l}$, respectively. The vector of the expected values of utilities of all carrier links and transfers is represented by,

$$\mathbf{g}\left(\mathbf{v},\mathbf{s}\right)=\left(g_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right),g_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right),\bar{a}\in A,\bar{l}\in T\right) \tag{5.30}$$

where,

$$g_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)=-\left(r_{\bar{a}}+\phi_{\bar{a}}t_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)\right) \tag{5.31}$$

$$g_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)=-\left(r_{\bar{l}}+\phi_{\bar{l}}t_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)\right) \tag{5.32}$$

One should calibrate the functional forms of container handling time $t_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)$ and $t_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)$ by using historical data. As a widely-used instance, the BPR-form transportation time functions have been employed in many freight transportation studies (Fernádez et al., 2003; Yamada et al., 2009). We now examine the expressions of the BPR-functions in container transportation operations. Let β_a be the factor that converts one TEU into to a standard container vehicle unit on physical link $a\in\mathcal{A}$. For instance, one TEU is equivalent to 0.5 standard container trucks on road links, 0.001 standard containerships on maritime links, or 0.25 flatcars on rail links. Let κ_a be the factor that converts a standard container vehicle into a standardized vehicle equivalent on link a such as passenger car on road links, rolling stock on rail links and containership of 1000 TEUs on maritime links. Assume that the transportation time for transporting one TEU over carrier link $\bar{a} \in A_a$ where $a \in \mathcal{A}$ will be affected by both container vehicles and non-container vehicles that share a same physical link a. Let η_a denote the proportion of the flow of standard vehicles brought about by container vehicles to the total traffic volume in terms of standard vehicles on physical link a. The BPR-form transportation time function can be expressed by

$$t_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right) = t_{\bar{a}}^{0} + \chi_{\bar{a}} t_{\bar{a}}^{0} \left(\frac{\kappa_a \beta_a v_{\bar{a}} + k_{\bar{a}}\left(v_a - \kappa_a \beta_a v_{\bar{a}}\right)}{\Gamma_a\left(1 - x_a\right) + \Theta_a x_a} \right)^{\omega_{\bar{a}}} \tag{5.33}$$

where $k_{\bar{a}}$ is the asymmetry factor that reflects interactions between container flows transported by the carriers which share physical link a and $\chi_{\bar{a}}$ and $\omega_{\bar{a}}$ are two parameters to be calibrated. The total traffic volume in terms of standard vehicles loaded on link a, v_a, can be evaluated by

$$v_a = \kappa_a \beta_a \sum_{\bar{a} \in A_a} v_{\bar{a}} / \eta_a \tag{5.34}$$

We assume that the container flow on any transfer $\bar{l} \in T_h^b$, where $b \in \mathcal{B}_h$ and $h \in \mathcal{H}$, is only correlated with the container flow on transshipment line b. The time for handling one TEU over $\bar{l}$ can be thus computed by

$$t_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right) = t_{\bar{l}}^{0} + \chi_{\bar{l}} t_{\bar{l}}^{0} \left(\frac{v_{\bar{l}} + k_{\bar{l}}\left(v_b - v_{\bar{l}}\right)}{\left(1 - y_b\right)\Gamma_b + y_b \Theta_b} \right)^{\omega_{\bar{l}}} \tag{5.35}$$

where $k_{\bar{l}}$ is the factor reflecting the interactions between transfer flows on transshipment line b and $\chi_{\bar{l}}$ and $\omega_{\bar{l}}$ are two parameters to be calibrated. The container flow on transshipment line b, v_b, is expressed by

$$v_b = \sum_{\bar{l} \in T_h^b} v_{\bar{l}} \tag{5.36}$$

Let $U_{od}^{\bar{r}}(\mathbf{v},\mathbf{s})$ be the perceived utility of intermodal route $\bar{r} \in R_{od}$, where $o \in \mathcal{O}, d \in \mathcal{D}$. By assuming additive intermodal route utility, it follows that,

$$U_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}) = \sum_{\bar{a} \in A} \delta_{od}^{\bar{r}\bar{a}} G_{\bar{a}}(\mathbf{v},\mathbf{s}) + \sum_{\bar{l} \in T} \delta_{od}^{\bar{r}\bar{l}} G_{\bar{l}}(\mathbf{v},\mathbf{s}) \tag{5.37}$$

According to Eqns. (5.26)-(5.29), the intermodal route utility defined in Eqn. (5.37) is a normally distributed random variable which has the form,

$$U_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}) = u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}) + \zeta_{od}^{\bar{r}} \tag{5.38}$$

where the expected value of the route utility,

$$u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}) = \sum_{\bar{a} \in A} \delta_{od}^{\bar{r}\bar{a}} g_{\bar{a}}(\mathbf{v},\mathbf{s}) + \sum_{\bar{l} \in T} \delta_{od}^{\bar{r}\bar{l}} g_{\bar{l}}(\mathbf{v},\mathbf{s}) \tag{5.39}$$

error term $\zeta_{od}^{\bar{r}}$ is normally distributed with zero mean and variance,

$$\operatorname{var}\left(\zeta_{od}^{\bar{r}}\right) = \sum_{\bar{a} \in A} \delta_{od}^{\bar{r}\bar{a}} \left(\varphi_{\bar{a}}\left(r_{\bar{a}} + \phi_{\bar{a}} t_{\bar{a}}^{0}\right)\right)^2 + \sum_{\bar{l} \in T} \delta_{od}^{\bar{r}\bar{l}} \left(\varphi_{\bar{l}}\left(r_{\bar{l}} + \phi_{\bar{l}} t_{\bar{l}}^{0}\right)\right)^2 \tag{5.40}$$

The covariance between any two intermodal routes $\bar{r}, \bar{k} \in R_{od}$ in terms of utility is determined by the common carrier links and transfers shared by them and can be computed by,

$$\operatorname{cov}\left(\zeta_{od}^{\bar{r}}, \zeta_{od}^{\bar{k}}\right) = \sum_{\bar{a} \in A} \delta_{od}^{\bar{r}\bar{a}} \delta_{od}^{\bar{k}\bar{a}} \left(\varphi_{\bar{a}}\left(r_{\bar{a}} + \phi_{\bar{a}} t_{\bar{a}}^{0}\right)\right)^2 + \sum_{\bar{l} \in T} \delta_{od}^{\bar{r}\bar{l}} \delta_{od}^{\bar{k}\bar{l}} \left(\varphi_{\bar{l}}\left(r_{\bar{l}} + \phi_{\bar{l}} t_{\bar{l}}^{0}\right)\right)^2 \tag{5.41}$$

The covariance matrix between all intermodal routes in set R_{od} is represented by

$$\Sigma_{od} = \left[\operatorname{cov}\left(\zeta_{od}^{\bar{r}}, \zeta_{od}^{\bar{k}}\right)\right]_{\bar{r},\bar{k}\in R_{od}}, o \in \mathcal{O}, d \in \mathcal{D} \tag{5.42}$$

5.3.2.2 The Fixed-Point Formulation for Intermodal Route Choice Model

Let $\mathbf{u}_{od}(\mathbf{v},\mathbf{s})$ be the vector of the expected values of the intermodal routes between (o,d), where $o \in \mathcal{O}$, $d \in \mathcal{D}$, in terms of route utility, namely,

$$\mathbf{u}_{od}(\mathbf{v},\mathbf{s}) = \left(u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}), \bar{r} \in R_{od}\right), \forall o \in \mathcal{O}, d \in \mathcal{D} \tag{5.43}$$

The number of entities in vector $\mathbf{u}_{od}(\mathbf{v},\mathbf{s})$ is denoted by $\bar{I}_{od}$.

Based on probit-based discrete choice model, the probability of an intermodal route choosing an intermodal route $\bar{r} \in R_{od}$ for transporting one TEU from origin $o \in \mathcal{O}$ to destination $d \in \mathcal{D}$ is denoted by $P_{od}^{\bar{r}}\left(\mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right)$, namely,

$$\begin{aligned} P_{od}^{\bar{r}}\left(\mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right) &= \Pr\left[U_{od}^{\bar{r}}(\mathbf{v},\mathbf{s}) \geq U_{od}^{\bar{k}}(\mathbf{v},\mathbf{s}) \middle| \forall \bar{k} \in R_{od} \text{ and } \bar{r} \neq \bar{k}\right] \\ &= \int_{x_{1_{od}} \leq u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s})} \cdots \int_{u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s})=-\infty}^{u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s})=\infty} \cdots \int_{x_{\bar{I}_{od}} \leq u_{od}^{\bar{r}}(\mathbf{v},\mathbf{s})} \left[(2\pi)^{\bar{I}_{od}} \left|\Sigma_{od}\right|\right]^{-0.5} \\ &\times \exp\left[-0.5\left(\mathbf{x}_{od} - \mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right)^T \left(\Sigma_{od}\right)^{-1} \left(\mathbf{x}_{od} - \mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right)\right] \\ & dx_{1_{od}} dx_{2_{od}} \ldots dx_{\bar{I}_{od}} \end{aligned} \tag{5.44}$$

The probability of the intermodal operator choosing a carrier link $\bar{a} \in A$ or transfer $\bar{l} \in T$ can thus be expressed by,

$$P_{od}^{\bar{a}}\left(\mathbf{g}(\mathbf{v},\mathbf{s})\right) = \sum_{\bar{r}\in R_{od}} \delta_{od}^{\bar{r}\bar{a}} P_{od}^{\bar{r}}\left(\mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right) \tag{5.45}$$

$$P_{od}^{\bar{l}}\left(\mathbf{g}(\mathbf{v},\mathbf{s})\right) = \sum_{\bar{r}\in R_{od}} \delta_{od}^{\bar{r}\bar{l}} P_{od}^{\bar{r}}\left(\mathbf{u}_{od}(\mathbf{v},\mathbf{s})\right) \tag{5.46}$$

The SUE principle implies that the container flow pattern $\mathbf{v}^*$ loaded over the operational network can be obtained by solving the following fixed-point formulations in terms of carrier link and transfer flows: find a vector $\mathbf{v}^* \in \Omega(\mathbf{s})$, such that,

$$v_{\bar{a}}^{*} = \sum_{o \in O} \sum_{d \in D} T_{od} P_{od}^{\bar{a}} \left(\mathbf{g}\left(\mathbf{v}^{*}, \mathbf{s} \right) \right), \forall \bar{a} \in A \tag{5.47}$$

$$v_{\bar{l}}^{*} = \sum_{o \in O} \sum_{d \in D} T_{od} P_{od}^{\bar{l}} \left(\mathbf{g}\left(\mathbf{v}^{*}, \mathbf{s} \right) \right), \forall \bar{l} \in T \tag{5.48}$$

where $\Omega(\mathbf{s})$ is the feasible set of carrier link and transfer flows in operational network *G*.

5.3.3 IHSND Problem Incorporating Planner, Carriers and Intermodal Operators

As explained previously, each carrier link $\bar{a} \in A$ or transshipment line $b \in \mathcal{B}_h$, where $h \in \mathcal{H}$, is operated by an individual carrier. Let $c_{\bar{a}}(v_{\bar{a}})$ and $c_b(v_b)$ be the relevant transportation cost functions for the carrier link and transshipment line, respectively, where container flow loaded over transshipment line *b*, v_b, is defined in Eqn. (5.36). These two cost functions should hold the following properties in order to realistically reflect the cost structure in container transportation operations: (i) increasing with respect to container flow, (ii) zero inputs of container flows are allowed, and (iii) the unit transportation cost function is U-shaped to reflect the transition from economies of scale to diseconomies of scale in different flow regimes.

There are a few types of transportation cost functions that can be adopted for intermodal freight transportation flow analysis, such as hybrid translog cost function, which represents a local and second-order approximation to an arbitrary cost function and exhibits the above three properties. Hybrid translog function is a generalized form of the translog function, which has been extensively employed by economists to describe the cost structure of a multiproduct production system (Caves et al., 1980; Fuss and Waverman, 1981; Baumol et al., 1988). A translog cost function was also deemed to be appropriate for describing cost structure for a freight transportation operation system by Winston (1982). Caves et al. (1981) applied a translog cost function to investigate productivities of US railroads and Wang and Liao (2006) calibrated a translog cost function for examining performance of Taiwan Railway in transporting heterogeneous commodities - passengers and freights. However, translog function with logarithm operators does not allow zero outputs, which can be easily remedied by using a hybrid translog cost function (Baumol et al., 1988).

The container transportation service on a carrier link $\bar{a} \in A$ is provided by a carrier, and the transportation process can be regarded as a production system. Let Q be the set of all inputs required for the carrier to accomplish the container transportation process, such as machinery resource, labor, material and fuel consumption, and π_q be the price of input $q \in Q$. The container flow handled by the carrier can be regarded as the output of this production system. The hybrid translog cost function for the carrier on carrier link $\bar{a}$ can be written as follows:

$$c_{\bar{a}}\left(v_{\bar{a}}\right) = \exp\left(\alpha_{\bar{a}}^{0} + \alpha_{\bar{a}}\left(\left(v_{\bar{a}}\right)^{\theta_{\bar{a}}} - 1\right)/\theta_{\bar{a}} + \sum_{i=1}^{n_Q} \beta_{\bar{a}}^{i} \ln \pi_i + \delta_{\bar{a}}\left(\left(v_{\bar{a}}\right)^{\theta_{\bar{a}}} - 1\right)^2 / \left(2\theta_{\bar{a}}^2\right) \right.$$
$$\left. + \sum_{i=1}^{n_Q}\sum_{j=1}^{n_Q} \gamma_{\bar{a}}^{ij} \ln \pi_i \ln \pi_j / 2 + \sum_{j=1}^{n_Q} \rho_{\bar{a}}^{j} \ln \pi_j \left(\left(v_{\bar{a}}\right)^{\theta_{\bar{a}}} - 1\right)/\theta_{\bar{a}} \right) \tag{5.49}$$

where $\alpha_{\bar{a}}^{0}$, $\alpha_{\bar{a}}$, $\beta_{\bar{a}}^{i}$, $\delta_{\bar{a}}$, $\gamma_{\bar{a}}^{ij}$, $\rho_{\bar{a}}^{j}$ and $\theta_{\bar{a}}$ are the parameters to be calibrated using historical data, and these parameters should fulfill the following conditions:

$$\gamma_{\bar{a}}^{ij} = \gamma_{\bar{a}}^{ji}, i = 1, 2, ..., n_Q, j = 1, 2, ..., n_Q \tag{5.50}$$

$$\sum_{i=1}^{n_Q} \beta_{\bar{a}}^{i} = 1; \sum_{i=1}^{n_Q} \gamma_{\bar{a}}^{ij} = 0, j = 1, 2, ..., n_Q; \sum_{j=1}^{n_Q} \rho_{\bar{a}}^{j} = 0 \tag{5.51}$$

$$\lim_{\theta_{\bar{a}} \to 0} \left(\left(v_{\bar{a}}\right)^{\theta_{\bar{a}}} - 1\right)/\theta_{\bar{a}} = \ln v_{\bar{a}} \tag{5.52}$$

The unit transportation cost function on a carrier link is stipulated to have a U-shaped form that reflects the transition from economies of scale to diseconomies of scale.

This phenomenon may be rendered by the sharp growths of capital and labor costs, when the container flow on the carrier link exceeds the carrier's safe operating capacity. Mathematically, the degree of economies of scale for carrier link $\bar{a}$ is measured by,

$$S_{\bar{a}}\left(v_{\bar{a}}\right)=\frac{c_{\bar{a}}\left(v_{\bar{a}}\right)/v_{\bar{a}}}{dc_{\bar{a}}\left(v_{\bar{a}}\right)/dv_{\bar{a}}} \tag{5.53}$$

The cost function will exhibit economies of scale if $S_{\bar{a}}\left(v_{\bar{a}}\right)>1$ and diseconomies of scale when $S_{\bar{a}}\left(v_{\bar{a}}\right)<1$.

Similarly, the hybrid translog cost function and the degree of scale economies for the carrier operating on transshipment line $b\in\mathcal{B}_h$, where $h\in\mathcal{H}$ can be obtained by using the functions defined in Eqns. (5.49)-(5.53) with $\bar{a}$ replaced by *b*.

It should be pointed out that the hybrid translog cost function is sufficiently flexible for reflecting various properties of the transportation costs of carriers, such as scale economies. Additionally, since it permits zero outputs, the function is capable of mimicking a realistic transportation process where a fixed cost would be incurred even in the absence of outputs. However, the function involves so many parameters that it generally needs to be calibrated by using historical data; meanwhile, the function is non-convex with respect to container flow, which results in hardness in solving the IHSND problem using an efficient analytical method.

Given a physical network $\mathcal{G}$ = ($\mathcal{N}$, $\mathcal{A}$), the IHSND problem aims to construct an intermodal hub-and-spoke network for container transportation within an investment budget limit *B* from the viewpoint of the planner. To achieve this goal, the planner needs to make a series of network design decisions, denoted by a network design solution vector **s**, with the objective to minimize the total network cost of carriers (direct network users). The network design solution **s** is made based on the network flow pattern **v** that is determined by the SUE behaviors of intermodal operators in route choice. On the other hand, intermodal operators make route choice decisions based on the given network design solution **s**. This interactive decision process between the planner and intermodal operators must be taken into account in the IHSND problem.

5.4 Model Formulation

The IHSND problem proposed in this chapter can be formulated as the following mathematical programming with equilibrium constraints (MPEC) model:

$$(IHSND)\ \min f(\mathbf{s},\mathbf{v}) = \sum_{\bar{a}\in A} c_{\bar{a}}(v_{\bar{a}}) + \sum_{b\in\mathcal{B}} c_b(v_b) \tag{5.54}$$

subject to

$$\sum_{a\in\mathcal{A}} B_a x_a + \sum_{b\in\mathcal{B}} y_b F_b \le B \tag{5.55}$$

$$\sum_{b\in\mathcal{B}_h} y_b \ge z_h, \text{for } \forall h\in\mathcal{N}_2 \tag{5.56}$$

$$\sum_{b\in\mathcal{B}_h} y_b \le M z_h, \text{for } \forall h\in\mathcal{N}_2 \tag{5.57}$$

$$x_a \le z_{\tilde{h}_a} + z_{\tilde{t}_a}, \text{for } \forall a\in\mathcal{A}_2 \tag{5.58}$$

$$\kappa_a\beta_a \sum_{\bar{a}\in A_a} v_{\bar{a}} / \eta_a \le (1-x_a)\Gamma_a + x_a\Theta_a, \text{for } \forall a\in\mathcal{A} \tag{5.59}$$

$$v_b \le (1-y_b)\Gamma_b + y_b\Theta_b, \text{for } \forall b\in\mathcal{B}_h, h\in\mathcal{H} \tag{5.60}$$

$$v_b = \sum_{\bar{l}\in T_h^b} v_{\bar{l}},\ \text{for } \forall b\in\mathcal{B}_h, h\in\mathcal{H} \tag{5.61}$$

$$v_{\bar{a}} \le \Gamma_{\bar{a}}, \text{for } \forall \bar{a}\in A \tag{5.62}$$

$$v_{\bar{a}} = \sum_{o\in O}\sum_{d\in D} T_{od} P_{od}^{\bar{a}}(\mathbf{g}(\mathbf{v},\mathbf{s})), \text{for } \mathbf{v}\in\Omega(\mathbf{s}), \bar{a}\in A \tag{5.63}$$

$$v_{\bar{l}} = \sum_{o\in O}\sum_{d\in D} T_{od} P_{od}^{\bar{l}}\left(\mathbf{g}\left(\mathbf{v},\mathbf{s}\right)\right), \text{for } \mathbf{v}\in\Omega\left(\mathbf{s}\right), \bar{l}\in T \tag{5.64}$$

Objective function (5.54) minimizes the sum of transportation costs of carriers. Constraint (5.55) represents budget limit constraint. Constraints (5.56) and (5.57) ensure that once a new transfer terminal is selected, at least one mode-change transshipment line will be established at the transfer terminal; no transshipment line will be built otherwise. According to constraint (5.58) no direct links connecting two spoke nodes are allowed to exist. Constraint (5.59) restricts that the standard traffic flow loaded on a physical link can not exceed its capacity in terms of standard vehicle units. Constraint (5.60) guarantees that the container flow transferred via a transshipment line is not allowed to exceed the handling capacity of the transfer terminal operator over the transshipment line. Eqn. (5.61) indicates that the container flow on a transshipment line is the sum of all container flows transferred via the transshipment line. Constraint (5.62) limits that each carrier over a carrier link can only handle the container flow not exceeding its handling capacity. The fixed-point formulations (5.63) and (5.64) reflects the interaction between the network design decisions and network flow pattern resulting from the SUE-based intermodal route choice of intermodal operators.

In the MPEC model, the objective is to minimize the total transportation cost of carriers in the operational network from the planner's perspective. The model can also flexibly cater with the case that the planner aims to maximize the total profit of carriers when designing the intermodal hub-and-spoke network by simply replacing the objective (5.65) as the following expression,

$$\max f\left(\mathbf{s},\mathbf{v}\right) = \sum_{\bar{a}\in A}\left[r_{\bar{a}} v_{\bar{a}} - c_{\bar{a}}\left(v_{\bar{a}}\right)\right] + \sum_{h\in\mathcal{H}}\sum_{b\in\mathcal{B}_h}\left[\sum_{\bar{l}\in T_h^b} r_{\bar{l}} v_{\bar{l}} - c_b\left(v_b\right)\right] \tag{5.65}$$

5.5 Solution Algorithm

The discrete network design problem has been proved to be a NP-hard problem (Johnson et al, 1978). The IHSND problem is even harder to solve due to the non-convexity and non-differential characteristics of the MPEC model incorporating fixed-point formulations.

The IHSND problem is a mixed-integer nonlinear programming problem with $n_{\mathbf{s}}$ binary variables and $(n_A + n_T)(n_O + 1)$ continuous variables. In this chapter a branch-and-bound algorithm will be used to solve the MPEC model. A bounding strategy that involves the linearization and relaxation of the IHSND problem will be described.

5.5.1 Linearization of The IHSND Problem

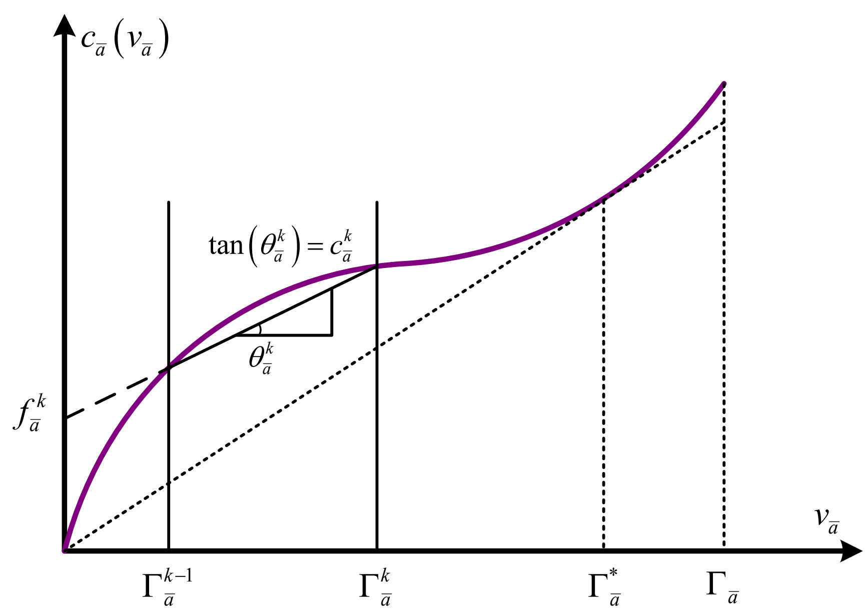

Fig. 5.2 The linearization of the hybrid translog function on carrier link $\bar{a}$

The non-convexity of objective function (5.54) partially results from the use of the hybrid translog cost function (5.49), which can be linearized using a piece-wise linear function. Fig. 5.2 shows the linearization of the hybrid translog cost function on carrier link $\bar{a} \in A$. We characterize the piece-wise linear cost function by its segments. On carrier link $\bar{a}$, the translog function can be divided into a finite number of segments, since the container flow on the carrier link is bounded by capacity $\Gamma_{\bar{a}}$. Let $K_{\bar{a}}$ be the set of all such segments of carrier link $\bar{a}$. On each segment $k \in K_{\bar{a}}$, the original cost function is replaced by a straight line, and let $c_{\bar{a}}^k$ and $f_{\bar{a}}^k$ be the variable cost (slope) and intercept of the linear cost function on segment *k*.

Let $v_{\bar{a}}^k$ be the decision variable representing the container flow on segment *k* and $y_{\bar{a}}^k$ be one if the container flow on the carrier $\bar{a}$ falls on segment *k*; zero otherwise. In a similar way, the non-convex nonlinear cost function on transshipment line $b \in \mathcal{B}$ can also be linearized. All above-defined notations with respect to carrier link $\bar{a}$ can be used for transshipment line *b* with $\bar{a}$ replaced by *b*. We denote the vector of continuous decision variables representing the container flows on segments as,

$$\mathbf{v}' = \left(v_{\bar{a}}^k, k \in K_{\bar{a}}, \bar{a} \in A; v_b^k, k \in K_b, b \in \mathcal{B}\right) \tag{5.66}$$

and the vector of integer decision variables indicating the domain of container flows on segments as,

$$\mathbf{y}' = \left(y_{\bar{a}}^k, k \in K_{\bar{a}}, \bar{a} \in A; y_b^k, k \in K_b, b \in \mathcal{B}\right) \tag{5.67}$$

The linearization of the IHSND problem can be formulated as the following problem IHSND-1,

$$(IHSND\text{-}1) \quad h\left(\mathbf{s}, \mathbf{y}', \mathbf{v}, \mathbf{v}'\right) = \min \sum_{\bar{a} \in A} \sum_{k \in K_{\bar{a}}} \left(c_{\bar{a}}^k v_{\bar{a}}^k + f_{\bar{a}}^k y_{\bar{a}}^k\right) + \sum_{b \in \mathcal{B}} \sum_{k \in K_b} \left(c_b^k v_b^k + f_b^k y_b^k\right) \tag{5.68}$$

subject to

(5.55)-(5.61), (5.63)-(5.64)

$$v_{\bar{a}} = \sum_{k \in K_{\bar{a}}} v_{\bar{a}}^k, \text{ for } \forall \bar{a} \in A \tag{5.69}$$

$$v_b = \sum_{k \in K_b} v_b^k, \text{ for } \forall b \in \mathcal{B} \tag{5.70}$$

$$\sum_{k \in K_{\bar{a}}} y_{\bar{a}}^k \leq 1, \text{ for } \forall \bar{a} \in A \tag{5.71}$$

$$\sum_{k \in K_b} y_b^k \leq 1, \text{ for } \forall b \in \mathcal{B} \tag{5.72}$$

$$y_b^k \Gamma_b^{k-1} \leq v_b^k \leq y_b^k \Gamma_b^k, \text{ for } \forall b \in \mathcal{B}, k \in K_b \tag{5.73}$$

$$y_{\bar{a}}^k \Gamma_{\bar{a}}^{k-1} \leq v_{\bar{a}}^k \leq y_{\bar{a}}^k \Gamma_{\bar{a}}^k, \text{ for } \forall \bar{a} \in A, k \in K_{\bar{a}} \tag{5.74}$$

5.5.2 Lower Bounds Calculation

A detailed discussion of branch-and-bound algorithm can be obtained by referring to Wolsey (1998). A brief introduction is given to introduce necessary notations. The brand-and-bound algorithm is essentially a binary tree search. The complete binary tree has $2^{n_{\mathbf{s}}+1} - 1$ nodes (including a root node) and $2^{n_{\mathbf{s}}}$ branches each representing a complete solution of **s**. Each branch comprises $n_{\mathbf{s}} + 1$ nodes and these nodes range according to the positions of entities in **s**. On the binary tree, each node corresponds with either a partial solution or complete solution of **s**. For example, a partial solution $(1, 0, -, ..., -)$ may be identified with a node q on the tree, where only the first two decision variables have been specified values of 1 or 0 and the remaining $n_{\mathbf{s}} - 2$ decision variables are unspecified. The set of successors of the partial solution is represented by $S(q)$, namely,

$$S(q) = \{\mathbf{s} | s_1 = 1, s_2 = 0, s_i = 0 \text{ or } 1, i = 3, ..., n_{\mathbf{s}}\} \tag{5.75}$$

The set $S(q)$ contains all possible completions of the partial solution identified with node q. If node q is searched in the final depth of the binary tree, a complete solution of $\mathbf{s}$ can be identified with all entities set to fixed values of 1 or 0.

When a node q is added to the binary tree, a lower bound on the objective function (5.54) evaluated at all solutions in the set $S(q)$ needs to be computed. It means that we must compute a lower bound on the optimal value of the following problem $P1$,

$$(P1)\ \min f(\mathbf{s},\mathbf{v}) = \sum_{\bar{a}\in A} c_{\bar{a}}(v_{\bar{a}}) + \sum_{b\in\mathcal{B}} c_b(v_b) \tag{5.76}$$

subject to

$$\mathbf{s} = (\mathbf{x},\mathbf{y},\mathbf{z}) \in S(q) \tag{5.77}$$

(5.55)-(5.64)

However, since the problem $P1$ is non-convex and non-differential, it is hard to obtain the lower bound. An apparent method of computing this lower bound is to solve the linearized problem of problem $P1$ on the values of all successors of node q. More specifically, a lower bound on the optimal value of the following problem $P2$ needs to be calculated.

$$(P2)\quad h(\mathbf{s},\mathbf{y}',\mathbf{v},\mathbf{v}') = \min \sum_{\bar{a}\in A}\sum_{k\in K_{\bar{a}}}\left(c_{\bar{a}}^k v_{\bar{a}}^k + f_{\bar{a}}^k y_{\bar{a}}^k\right) + \sum_{b\in\mathcal{B}}\sum_{k\in K_b}\left(c_b^k v_b^k + f_b^k y_b^k\right) \tag{5.78}$$

subject to

(5.55)-(5.61), (5.63)-(5.64), (5.69)-(5.74), (5.77)

Remark 1: q is some node in the binary tree. According to the linearization process of the IHSND problem described in Section 5.5.1, the lower bound on the optimal value of problem $P1$ evaluated at all possible solutions in set $S(q)$ can be approximated by the lower bound on that of *P*2. The more segments the translog function on a carrier link or transfer is divided into in *P*2, the more accurately the lower bound of *P*1 is approximated.

The problem *P*2 is still hard to solve due to the fixed-point formulations (5.63)-(5.64). We further relax *P*2 as the following mixed-integer linear programming problem *P*3,

$$(P3) \quad h\left(\mathbf{s},\mathbf{y}',\mathbf{v},\mathbf{v}'\right)=\min\sum_{\bar{a}\in A}\sum_{k\in K_{\bar{a}}}\left(c_{\bar{a}}^{k}v_{\bar{a}}^{k}+f_{\bar{a}}^{k}y_{\bar{a}}^{k}\right)+\sum_{b\in\mathcal{B}}\sum_{k\in K_b}\left(c_b^k v_b^k+f_b^k y_b^k\right) \tag{5.79}$$

subject to

(5.16)-(5.25) , (5.55)-(5.61), (5.69)-(5.74), (5.77)

where constraints (5.16)-(5.25) are added to guarantee the feasibility of network flow specified by $\Omega\left(\mathbf{s}\right)$.

Lemma: For any given node q in the binary branch-and-bound tree, the optimal solution of *P*2 is greater than or equal to the optimal solution of *P*3.

Proof: We note that *P*3 has the same feasible values for the integer variables in vector $\left(\mathbf{s},\mathbf{y}'\right)$ as *P*2, where $\mathbf{s}\in S\left(q\right)$ and $\mathbf{y}'$ is a vector comprising $\left(n_A+n_{\mathcal{B}}\right)$ 0-1 variables. In *P*2, the vector of container flows distributed in the operational network, $\left(\mathbf{v},\mathbf{v}'\right)$, is specified by the network design decision **s**, the vector $\mathbf{y}'$ and the SUE-based intermodal route choice behavior of intermodal operators. However, in *P*3, the flow vector $\left(\mathbf{v},\mathbf{v}'\right)$ is only determined based on $\left(\mathbf{s},\mathbf{y}'\right)$. It means that, given the same feasible $\left(\mathbf{s},\mathbf{y}'\right)$, vector $\left(\mathbf{v},\mathbf{v}'\right)$ has a bigger feasible domain in *P*3 than in *P*2. Let $\mathbf{I}^*=\left(\mathbf{s}^*,\mathbf{y}'^*,\mathbf{v}^*,\mathbf{v}'^*\right)$ be the optimal solution of *P*2. Then $h\left(\mathbf{I}^*\right)$ is the optimal value for *P*2. Meanwhile, the vector $\mathbf{I}^*$ is a feasible solution for *P*3 with value $h\left(\mathbf{I}^*\right)$ for objective function (5.79). The optimal value of *P*3 is clearly less than or equal to any feasible value. We thus have,

$$h\left(\mathbf{s}^{*}, \mathbf{y}'^{*}, \mathbf{v}^{*}, \mathbf{v}'^{*}\right) \geq h\left(\hat{\mathbf{s}}, \hat{\mathbf{y}}', \hat{\mathbf{v}}, \hat{\mathbf{v}}'\right) \tag{5.80}$$

where vector $\left(\hat{\mathbf{s}}, \hat{\mathbf{y}}', \hat{\mathbf{v}}, \hat{\mathbf{v}}'\right)$ is the optimal solution of *P*3. This completes the proof.

Remark 2: It should be pointed out the current node q should be fathomed if *P*3 is infeasible, since adding child nodes of q can only narrow the feasible space and *P*3 will remain infeasible at these child nodes. If *P*3 is unbounded, child nodes of q still have potential to produce optimal solutions.

5.5.3 The Branch-And-Bound Algorithm

The branch-and-bound algorithm for solving the IHSND problem is described in the following steps.

Branch-and-bound Algorithm

Step 0. (*Initialization*) At the root node of the binary tree, no integer decision variables in **s** has been specified any value. The root node is marked as an unvisited node and the tree depth at the root node is zero. Find a feasible solution of **s,** namely $\mathbf{s}_0$, satisfying constraints (5.55)-(5.58), such that for the given $\mathbf{s}_0$ the SUE-based network flow pattern $\mathbf{v}_0$ that is specified by (5.63)-(5.64) and computed by using the cost averaging (CA) algorithm (Cantarella, 1997) satisfies constraints (5.59)-(5.62). Let $f\left(\mathbf{s}_0, \mathbf{v}_0\right)$ be the initial incumbent value and go to step 1.

Step 1. (*Node selection*) An unvisited node q at the deepest level is selected and the branch-and-bound algorithm carries out a depth-first search. Go to step 2.1 if the tree depth at node q is less than $n_{\mathbf{s}}$; go to step 2.2 otherwise.

Step 2. (*Constraint validation*) The partial solution or complete solution identified with node q is validated in this step.

Step 2.1. In the partial solution identified with node q, the integer decision variables which have been specified values of 1 or 0 must satisfy the budget constraint (5.55), i.e., the total cost resulting from the investment decisions which have been made must be less than or equal to the given budget. In addition, these decision variables with fixed values must also satisfy constraints (5.56)-(5.58) if applicable. Mark node q as a visited node that will not be further explored and go to step 7 if any of these constraints is violated; go to step 4 otherwise.

Step 2.2. Given the complete solution of $\mathbf{s}$ identified with node q, $\mathbf{s}_q$, the SUE-based network flow pattern defined by (5.63)-(5.64), $\mathbf{v}_q$ as a possible solution of $\mathbf{v}$, can be computed by calling the CA algorithm. The solution $\left(\mathbf{s}_q, \mathbf{v}_q\right)$ must satisfy the constraints (5.55)-(5.62). Mark node q as a visited node and go to step 7 if any of these constraints is violated; go to step 3 otherwise.

Step 3. (*Updating the incumbent value*) Replace the current incumbent value by $f\left(\mathbf{s}_q, \mathbf{v}_q\right)$, mark node q as a visited node, and go to step 7 if $f\left(\mathbf{s}_q, \mathbf{v}_q\right)$ is less than the current incumbent value; go to step 7 without updating the incumbent value otherwise.

Step 4. (*Lower bound calculation*) Calculate the lower bound on the objective function of $P1$ evaluated on $S(q)$ by solving the problem $P3$ using any applicable method such as Benders' Decomposition or CPLEX software package. Go to step 5.

Step 5. (*Pruning*) Node q is fathomed and marked as a visited node if the lower bound value is greater than the current incumbent value or $P3$ is infeasible and go to step 7; go to step 6 otherwise.

Step 6. (*Branching*) Two child nodes will be spawned from node q. The integer decision variable corresponding with the left child node is set to zero and that corresponding with the right child node is set to one. Node q is marked as a visited node and go to step 1.

Step 7. (*Stopping test*) The algorithm stops if all nodes are visited. The current incumbent solution is the optimal solution of $P1$; go to step 1 otherwise.

The cost averaging algorithm is used in Steps 0 and 2.2 to solve the SUE-based network flow pattern specified by the two fixed-point formulations (5.63)-(5.64). We take Step 2.2 for example to describe the CA algorithm in the following five substeps:

Cost Averaging Algorithm

Step 2.2.0. (*Initialization*) Given the feasible $\mathbf{s}_q$, let the initial flow pattern $\mathbf{v}^0 = \mathbf{0} \in \Omega(\mathbf{s}_q)$. This generate a vector of expected values of utilities of carrier links and transfers $\mathbf{g}^1 = \left(g_{\bar{a}}^1 = g_{\bar{a}}\left(\mathbf{v}^0, \mathbf{s}_q\right), \forall \bar{a} \in A; g_{\bar{l}}^1 = g_{\bar{l}}\left(\mathbf{v}^0, \mathbf{s}_q\right), \forall \bar{l} \in T \right)$. Set: n = 1.

Step 2.2.1. (*Update flow*) Perform a stochastic network loading procedure based on $\mathbf{g}^n$, yielding a network flow pattern $\mathbf{v}^n \in \Omega\left(\mathbf{s}_q\right)$.

Step 2.2.2. (*Find the descendent direction*) Obtain a vector of utilities of carrier links and transfers, $\mathbf{f}^n$, by using,

$$\mathbf{f}^n = \left(g_{\bar{a}}\left(\mathbf{v}^n, \mathbf{s}_q\right), \forall \bar{a} \in A; g_{\bar{l}}\left(\mathbf{v}^n, \mathbf{s}_q\right), \forall \bar{l} \in T \right) \tag{5.81}$$

Step 2.2.3. (*Move*). Finding the new utility vector by setting,

$$\mathbf{g}^{n+1} = \mathbf{g}^n + \left(1/n\right)\left(\mathbf{f}^n - \mathbf{g}^n\right) \tag{5.82}$$

Step 2.2.4. (*Stopping test*). Stop and let $\mathbf{v}^n = \mathbf{v}_q$ if condition (5.83) is fulfilled,

$$\left\| \mathbf{g}^{n+1} - \mathbf{g}^n \right\|_2 \le \varepsilon_1 \tag{5.83}$$

Set n: = n +1 and go to Step 2.2.1 otherwise.

The CA algorithm has been proved to be a convergent algorithm for solving the probit-based asymmetric SUE problem (Cantarella, 1997). The probit-based stochastic network loading procedure embodied in Step 2.2.1 of the CA algorithm can be described in the following steps,

Probit-based stochastic network loading algorithm

Step 2.2.1.0. (*Initialization*) Set l: = 1.

Step 2.2.1.1. (*Sampling*) Generate sample $G_{\bar{a}}^l$ from the normal distribution,

$$N\left(g_{\bar{a}}^n, \left(\varphi_{\bar{a}}\left(r_{\bar{a}} + \phi_{\bar{a}} t_{\bar{a}}^0 \right)\right)^2 \right) \tag{5.84}$$

for each $\bar{a} \in A$ and sample $G_{\bar{l}}^{l}$ from the normal distribution,

$$N\left(g_{\bar{l}}^{n},\left(\varphi_{\bar{l}}\left(r_{\bar{l}}+\phi_{\bar{l}}t_{\bar{l}}^{0}\right)\right)^{2}\right) \tag{5.85}$$

for each $\bar{l} \in T$.

Step 2.2.1.2. (*All-or-nothing assignment*) Based on $\left(G_{\bar{a}}^{l},\forall\bar{a}\in A;G_{\bar{l}}^{l},\forall\bar{l}\in T\right)$, assign container demand T_{od} to the shortest path connecting $\left(o\in O,\, d\in \mathcal{D}\right)$, thus giving rise to a vector of flows on carrier links and transfers $\mathbf{v}^{l}=\left(v_{\bar{a}}^{l},\forall\bar{a}\in A;v_{\bar{l}}^{l},\forall\bar{l}\in T\right)$.

Step 2.2.1.3. (*Flow averaging*) Let $\bar{\mathbf{v}}^{l}=\left(\bar{v}_{\bar{a}}^{l},\forall\bar{a}\in A;\bar{v}_{\bar{l}}^{l},\forall\bar{l}\in T\right)=\left(\left(l-1\right)\bar{\mathbf{v}}^{l-1}+\mathbf{v}^{l}\right)/\,l$.

Step 2.2.1.4. (*Stopping test*) Stop if the following conditions is satisfied,

$$\left\|\bar{\mathbf{g}}^{n+1}-\bar{\mathbf{g}}^{n}\right\|_{2}/\left\|\bar{\mathbf{g}}^{n}\right\|_{1}<\varepsilon_{2} \tag{5.86}$$

where ε_2 a positive small number indicating the required accuracy and

$$\bar{\mathbf{g}}^{n}=\left(1/m\right)\sum_{l=0}^{m-1}\mathbf{g}^{n-l} \tag{5.87}$$

with a predetermined m; set l: = l + 1 and go to step 2.2.1.1 otherwise.

5.6 Numerical Examples

Fig. 5.3 and Fig. 5.4 show a small-size and a large-size example freight transportation networks, respectively, which are used to show the applications of the proposed IHSND model and branch-and-bound algorithm. In these two networks, let mode set M = {rail, truck, maritime}, and Φ = {1 = rail-rail, 2 = rail-truck, 3 = rail-maritime, 4 = truck-truck, 5 = truck-rail, 6 = truck-maritime, 7 = maritime-maritime, 8 = maritime-rail, 9 = maritime-truck}. Each link or transshipment line is assumed to be operated by an individual carrier. Let l_a be the length of physical link $a \in \mathcal{A}$ and $\pi_q = 1$, where $q \in \mathcal{Q}$ for hybrid translog cost functions. Table 5.1 shows the parameter values for cost functions.

Table 5.1 Parameter Values for Hybrid Translog Cost Functions

$\bar{a} \in A_a, a \in \mathcal{A}$	$\alpha^0_{\bar{a}}$	$\alpha_{\bar{a}}$	$\delta_{\bar{a}}$	$\theta_{\bar{a}}$
rail	-9 + ln(l_a)	0.109	0.099	0.0001
truck	-9 + ln(l_a)	0.109	0.099	0.0001
maritime	-9 + ln(l_a)	0.109	0.099	0.0001
$b \in \mathcal{B}$	α^0_b	α_b	δ_b	θ_b
	-2	0.011	0.0117	0.0001

Let $s^0_{\bar{a}}$ represent the free-flow speed for transporting one TEU along carrier link $\bar{a} \in A_a, a \in \mathcal{A}$, and the free-flow transportation time $t^0_{\bar{a}}$ defined in Eqn. (5.33) can be computed using link length l_a divided by $s^0_{\bar{a}}$. The parameter values for utility functions are shown in Table 5.2.

Table 5.2 Parameter Values for Utility Functions in the Large-size Example

$\bar{a} \in A$	$s^0_{\bar{a}}$ **(km/h)**	$r_{\bar{a}}$ **(USD/km)**	$\phi_{\bar{a}}$ **(USD/h)**	$\omega_{\bar{a}}$	$\chi_{\bar{a}}$	$\varphi_{\bar{a}}$	$k_{\bar{a}}$	$\Gamma_{\bar{a}}$
rail	33.3	0.1	0.1	2.0	2.5	0.2	0.5	8000
truck	27.7	0.8	1.5	2.0	2.5	0.2	0.5	10000
maritime	21.6	0.2	0.1	2.0	2.5	0.2	0.5	8000
$\bar{l} \in T$	$t^0_{\bar{l}}$ **(h)**	$r_{\bar{l}}$ **(USD)**	$\phi_{\bar{l}}$ **(USD/h)**	$\omega_{\bar{l}}$	$\chi_{\bar{l}}$	$\varphi_{\bar{l}}$	$k_{\bar{l}}$	
ports	24	387	5.0	2.0	2.5	0.2	0.5	
inland transfer terminals	12	27	5.0	2.0	2.5	0.2	0.5	
borders	48	293	5.0	2.0	2.5	0.2	0.5	
$a \in \mathcal{A}_2$	Θ_a **(1000 std vehicle/yr)**		Γ_a	κ_a	η_a	β_a	B_a	
rail	8000		0	1.0	0.5	0.25	4.0	
truck	10000		0	2.0	0.1	0.5	2.5	

maritime	8000	0	1.0	0.6	0.001	1.0
$b \in \mathcal{B}$	Θ_b **(1000 TEUs/yr)**	Γ_b		β_b		F_b
potential	10000	0		1.0		2
existing	-	10000		1.0		-

The parameter values tabulated in Table 5.1 and Table 5.2 are collected and compiled based on Wang et al. (2009). The branch-and-bound algorithm is coded using MATLAB and executed by using a desktop with CPU of Core 2 Duo 3.00 GHz and 4G RAM. The lower bound is obtained by solving problem *P*3 using CPLEX 12.1. Let parameters $m = 3$, $\varepsilon_1 = 10$, and $\varepsilon_2 = 0.01$, and the total budget *B* is assigned values of 40 and 30 for the small-size and large-size examples, respectively.

5.6.1 The Small-Size Example

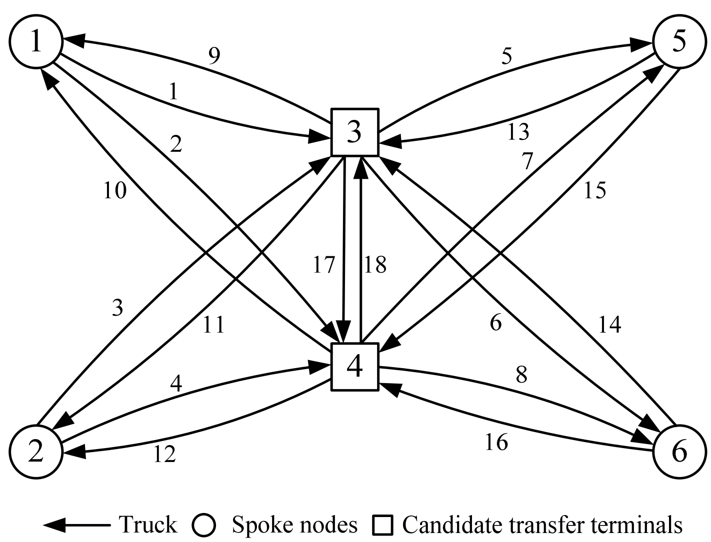

Fig. 5.3 The small-size example network

In the small-size network shown in Fig. 5.3, we hypothesize that all physical links are candidate links to be built, i.e. $\mathcal{A} = \mathcal{A}_2$, and all potential transshipment lines exist at candidate transfer terminals, i.e. $\mathcal{B}_2 = \bigcup_{h \in \mathcal{N}_2} \mathcal{B}_h^2$. Investment actions related to transshipment lines are taken only for these candidate lines. Let $l_a = 10$, $\Gamma_a = 0$ and $\Theta_a = 2000$ for each physical link $a \in \mathcal{A}$ and $\Gamma_b = 0$ and $\Theta_b = 1000$ for each potential transshipment line $b \in \mathcal{B}$. In this example, the IHNSD problem has 22 binary variables and 782 continuous variables. The O/D demand matrix is shown in Table 5.3.

Table 5.3 O/D Demand Matrix for the Small-size Example

origin o	destination d				
	1	2	3	5	6
1	0.00	26.29	8.40	18.78	5.77
2	26.29	0.00	46.28	103.59	31.79
3	8.40	46.28	0.00	33.53	10.31
5	18.78	103.59	33.53	0.00	23.03
6	5.77	31.79	10.31	23.03	0.00

Table 5.4 Computational Results for the Small-size Example

NO. of segments	Objective value	Running time	NO. of searched tree nodes
10	248.75	1.06 hours	6033
30	248.75	0.53 hours	2401
50	248.57	0.70 hours	2207
70	248.57	0.59 hours	1305
90	**248.32**	**1.20 hours**	**2095**
110	248.57	1.09 hours	1315
130	248.57	2.02 hours	2215
150	248.75	1.98 hours	1473

Table 5.4 shows the computational results with respect to the number of segments in linearization of hybrid translog cost functions. As indicated by Table 5.4, the optimal objective value initially decreases with the growth of the number of segments, but exhibits an increase trend after the segment number exceeds 90. It is implied that increasing the number of linear pieces of cost functions does not necessarily result in a better solution. The impact of cost function linearization on the objective solution needs

to be further explored in the future study. Moreover, according to the number of searched tree nodes, the branch-and-bound algorithm is found to be effective in pruning the nodes that lose potentials to become optimal solutions.

5.6.2 The Large-Size Example

Fig. 5.4 shows a directed intermodal transportation network located in China and Mainland Southeast Asia (CMSA) which is compiled by referencing the working plans of Trans-Asian Railway and Asian Highway projects initiated by UNESCAP (2008*a* and 2008*b*).

Fig. 5.4 The large-size intermodal transportation network

The network comprises 25 transfer terminals that are classified into three types: ports, border crossing terminals and inland transfer terminals (e.g. rail-truck transfer terminals), 10 spoke nodes, 96 links (bi-directional), 180 transfers and 40 transshipment lines. Table C.1 shows physical links and nodes in the large-scale example. As reported by UNCTD (2008), the intra-Asia trade is estimated at 40 million TEUs in 2007. We distribute the intra-Asia container traffic over 17 O/D pairs by using doubly constraint gravity model with transportation time as the deterrence, and the resulting O/D demand matrix is tabulated in Table C.2.

Table 5.5 shows the investment actions to be taken on the large-scale network as well as the optimal decisions obtained with the number of segment = 5 for each link and transshipment line.

Table 5.5 Candidate Network Elements and Optimal Decisions for the Large-size Example

Potential Physical links	Yes/No	Candidate Transfer terminals			
		Name	Yes/No	Transshipment Lines	Yes/No
Lhasa--Quxam	Yes	Lanzhou	No	{rail-rail}	No
Quxam--Chittagong	Yes	Xian	No	{rail-rail}	No
Hanoi--Langson	Yes	Lhasa	Yes	{rail-rail}	Yes
Nanning--Langson	Yes	Zhengzhou	Yes	{rail-rail}	Yes
Quxam--Lhasa	Yes	Wuhan	No	{rail-rail}	No
Chittagong--Quxam	Yes	Zhuzhou	Yes	{rail-rail}	Yes
Langson--Hanoi	No	Kunming	No	{rail-rail}	No
Langson--Nanning	No	Shangyong	No	{rail-rail}	No

5.7 Conclusions

In this chapter we addressed the IHSND problem with stochastic equilibrium flows. To formulate the problem, we represented a given intermodal network as two-tire directed networks - a physical network that a network planner attempts to design and an operational network that intermodal operators make route choice based on. A transportation cost function that possesses a U-shaped unit cost function to reflect the transition from scale economies to scale diseconomies in distinct flow regimes was suggested to describe a carrier's cost structure in container transportation. A utility function consisting of actual transportation charge and congestion impact was proposed to describe an intermodal operator's preference toward a carrier.

By using the cost and utility functions, the IHSND problem was formulated as an MPEC model minimizing the total network cost of carriers. The model incorporates two fixed-point formulations to reflect the interaction between the SUE based route choice of intermodal operators and the network design decision of the planner. To solve the MPEC model, we linearized the original model by reformulating the cost functions as piece-wise linear functions. A branch-and-bound algorithm was then designed with an embedded cost averaging algorithm for solving the SUE-based network flows. Two numerical examples are finally given to test the applicability of the proposed modal and solution algorithm.

CHAPTER 6

INTERMODAL HUB-AND-SPOKE NETWORK DESIGN WITH MULTI-TYPE CONTAINERS

6.1 Introduction

CHAPTER 5 developed a modeling approach to solving the IHSND problem with multiple stakeholders and uni-type containers. However, multi-type containers are widely seen in intermodal freight transportation operations such as TEUs, FEUs, refrigerated TEUs and tank containers. To extend the work to involve multi-type containers, this chapter aims to develop a mathematical model and solution algorithm to solve the IHSND problem with multiple stakeholders and multi-type containers.

The IHSND problem concerned in this chapter distinguishes itself from that investigated in CHAPTER 5 by involving multi-type containers, which may result in a more complicated transportation cost function for carriers. In general, a carrier cannot only transport uni-type containers such as the most widely seen TEUS, but also provide multi-type container transportation services for intermodal operators. As a result, a joint transportation cost function of multi-type containers should be proposed to describe multi-type container transpiration cost structure of carriers, and the function should be able to reflect the scale economies exhibited in multi-type container transportation. In addition to scale economies, the function should be capable of reflecting the cost savings resulting from the transport of multi-type containers by a carrier, i.e., economies of scope. The hybrid translog function used to describe the cost structure of a carrier in uni-type container transportation can also be applied to serve these three purposes by adequate adaptations. The hybrid translog function used for multi-type container transportation is essentially a multiproduct cost function. However, once incorporating a hybrid translog cost function into the IHSND problem for describing the cost structure of carriers, it would be problematic to design an exact or approximation algorithm to solve the IHSND problem because the hybrid translog cost function for multi-type container transportation is non-convex and cannot be easily linearized. We thus propose a hybrid GA to solve the IHSND problem with multi-type containers.

In addition, the interactive decision process for IHSND problem with multi-type containers is different from the IHSND problem incorporating uni-type containers by taking into account a different decision behavior of intermodal operators in route choice, i.e., UE-based rather than SUE-based route choice behavior. The consideration of UE-based route choice behavior of intermodal operators in multi-type container transportation simply stems from the fact that the SUE-based route choice theory for multi-type commodity transportation has not been fully developed. As an assumption, intermodal operators choose intermodal routes according to the UE principle, i.e., no intermodal operator would increase his/her transportation utility by unilaterally shifting to choose another route when transporting a container of some type between a given O/D pair.

6.2 Assumptions, Notations and Problem Statement

The network presentation, description of network decision decisions and decision variables can be found by referring to Sections 5.2 and 5.3. Before moving forward to the problem statement, we introduce the route choice model of intermodal operators and multi-type container transportation cost function for carriers.

6.2.1 Route Choice Model for Intermodal Operators: UE Principle

Let $\mathcal{P}$ be the set of container types, R_{od}^{p} be the set of all available operational intermodal routes for container type p between $(o \in \mathcal{O}, d \in \mathcal{D})$ and T_{od}^{p} be the set of transport demand for container type p between $(o \in \mathcal{O}, d \in \mathcal{D})$. An intermodal route $\bar{r} \in R_{od}^{p}$ may traverse a sequence of carrier links and transfers in operational network G. Let $\delta_{od\bar{r}}^{\bar{a}p} = 1$ if route $\bar{r}$ traverses carrier link $\bar{a} \in A$; zero otherwise, $\delta_{od\bar{r}}^{\bar{l}p} = 1$ if route $\bar{r}$ traverses transfer $\bar{l} \in T$; zero otherwise. Meanwhile, route $\bar{r}$ concurrently passes through a sequence of physical links and transshipment lines in network $\mathcal{G}$. Let $\mathcal{A}_{\bar{r}}$ and $\mathcal{B}_{\bar{r}}$ be the sets of physical links and transshipment lines traversed by route $\bar{r}$, respectively, namely,

$$\mathcal{A}_{\bar{r}} = \left\{ a \in \mathcal{A} \,\middle|\, \sum_{\bar{a} \in A_a} \delta_{od\bar{r}}^{\bar{a}p} \geq 1 \right\}, \forall \bar{r} \in R_{od}^{p}, o \in \mathcal{O}, d \in \mathcal{D}, p \in \mathcal{P} \tag{6.1}$$

$$\mathcal{B}_{\bar{r}} = \left\{ b \in \mathcal{B}_h, h \in \mathcal{H} \,\middle|\, \sum_{\bar{l} \in T_h^b} \delta_{od\bar{r}}^{\bar{l}p} \geq 1 \right\}, \forall \bar{r} \in R_{od}^{p}, o \in \mathcal{O}, d \in \mathcal{D}, p \in \mathcal{P} \tag{6.2}$$

Given a feasible network design solution $\mathbf{s} = (\mathbf{x}, \mathbf{y}, \mathbf{z})$, intermodal operators will route multi-type containers over the operational network relying on $\mathbf{s}$, and the network flow distribution will result from their behavior in intermodal route choice. According to the UE principle, no intermodal operator could unilaterally increase his/her transportation utility by shifting to choose another route when he/she is faced with route choice for transporting one container of type $p \in \mathcal{P}$ between $(o \in \mathcal{O}, d \in \mathcal{D})$.

The utility along an intermodal route is summed by those of the carrier links and transfers traversed by the route. The utility of a carrier link or transfer perceived by an intermodal operator is composed of two portions: the actual rate charged by the carrier on the carrier link or transfer according to a particular freight rate table, and the monetary value of transportation or transfer time that equals the actual container handling time multiplied with value of time (VOT). In reality, the second portion reflects impact of congestion on the intermodal operator's route choice. Congestion phenomena can simply be observed on physical links transshipment lines due to the limit of capacity.

Over each carrier link $\overline{a} \in A_a$ where $a \in \mathcal{A}$ or transfer $\overline{l} \in T$, transportation or transfer time for one container of type p will not only be associated with multi-type container flows of the carriers who share the same physical link with $\bar{a}$ or transshipment line with $\overline{l}$, but also with those loaded on other carrier links and transfers, since congestion at transfer terminals or physical links may result in traffic delays in the whole network. Additionally, the transportation or transfer time is associated with network design solution **s** which determines the capacities of physical links and transshipment lines. The transportation or transfer time can thus be considered as a function of container flow vector **v** and network design solution **s**, where,

$$\mathbf{v} = \left(v_{\overline{a}}^{p}, \overline{a} \in A; v_{\overline{l}}^{p}, \overline{l} \in T; p \in \mathcal{P} \right) \tag{6.3}$$

in which $v_{\overline{a}}^{p}$ and $v_{\overline{l}}^{p}$ are the flows of container $p \in \mathcal{P}$ loaded on carrier link $\overline{a} \in A$ and transfer $\overline{l} \in T$, respectively.

Let $t_{\overline{a}}^{p}(\mathbf{v},\mathbf{s})$ and $t_{\overline{l}}^{p}(\mathbf{v},\mathbf{s})$ denote the time incurred on carrier link $\overline{a}$ and transfer $\overline{l}$, respectively. The utility of $\overline{a}$ and $\overline{l}$ perceived by intermodal operators can be expressed by,

$$g_{\overline{a}}^{p}(\mathbf{v},\mathbf{s}) = -\left(r_{\overline{a}}^{p} + \phi_{\overline{a}}^{p} t_{\overline{a}}^{p}(\mathbf{v},\mathbf{s}) \right) \tag{6.4}$$

$$g_{\bar{l}}^{p}\left(\mathbf{v},\mathbf{s}\right)=-\left(r_{\bar{l}}^{p}+\phi_{\bar{l}}^{p}t_{\bar{l}}^{p}\left(\mathbf{v},\mathbf{s}\right)\right) \tag{6.5}$$

where $r_{\bar{a}}^{p}$ and $r_{\bar{l}}^{p}$ are the actual freight rates charged by the carriers on physical link $\bar{a}$ and the transshipment line traversed by $\bar{l}$, respectively. $\phi_{\bar{a}}^{p}$ and $\phi_{\bar{l}}^{p}$ are the VOTs perceived by intermodal operators for handling containers of type p on $\bar{a}$ and $\bar{l}$, respectively.

The BPR-form time function developed by the US Bureau of Public Roads (BPR) has been employed in many freight transportation studies (Fernádez et al., 2003; Yamada et al., 2009), since it can reflect the congestion impact in a steady-state transportation system by involving the volume/capacity ratio. The function has also been used in many countries without much effort to calibrate the parameters (Suh, et al., 1990). We assume that the transportation or handling time function in multi-type container transportation has a BRP form. Let β_{a}^{p} be the factor that converts container type p into to a standard container vehicle unit on physical link a. Let κ_{a} be factor that converts a standard container vehicle into a standardized vehicle equivalent on link a. Assume that the transportation time for transporting one container of type p over carrier link $\bar{a}\in A_{a}$ where $a\in\mathcal{A}$ will be affected by both container and non-container vehicles that share the same physical link a. Let η_{a} denote the proportion of the flow of standard vehicles brought about by container vehicles to the total traffic volume of standard vehicles on physical link a. The BPR-form transportation time function can be expressed by,

$$t_{\bar{a}}^{p}\left(\mathbf{v},\mathbf{s}\right)=t_{\bar{a}}^{p0}+\alpha_{\bar{a}}^{p}t_{\bar{a}}^{p0}\left(\frac{\kappa_{a}\beta_{a}^{p}v_{\bar{a}}^{p}+k_{\bar{a}}^{p}\left(w_{a}-\kappa_{a}\beta_{a}^{p}v_{\bar{a}}^{p}\right)}{\Gamma_{a}\left(1-x_{a}\right)+\Theta_{a}x_{a}}\right)^{\omega_{\bar{a}}^{p}} \tag{6.6}$$

where $t_{\bar{a}}^{p0}$ is the free-flow time for transporting one container of type p over $\bar{a}$, and $k_{\bar{a}}^{p}$ is the asymmetry factor that reflects the interaction among multi-type container flows on physical link a. $\alpha_{\bar{a}}^{p}$ and $\omega_{\bar{a}}^{p}$ are two parameters to be calibrated. The traffic volume in terms of standard vehicles loaded over link a is expressed by,

$$v_a = \kappa_a \sum_{\bar{a} \in A_a} \sum_{p \in \mathcal{P}} \beta_a^p v_{\bar{a}}^p / \eta_a \tag{6.7}$$

We assume that a transfer $\bar{l} \in T_h^b$ where $b \in \mathcal{B}_h$, $h \in \mathcal{H}$ is only correlated with the transfers that traverse the same transshipment line with $\bar{l}$. Let β_b^p be the factor converting container type p to one TEU over b. The time for handling one container of type p over $\bar{l}$ can be thus evaluated by,

$$t_{\bar{l}}^{p}\left(\mathbf{v},\mathbf{s}\right) = t_{\bar{l}}^{p0} + \alpha_{\bar{l}}^{p} t_{\bar{l}}^{p0} \left(\frac{\beta_b^p v_{\bar{l}}^p + k_{\bar{l}}^p \left(w_b - \beta_b^p v_{\bar{l}}^p \right)}{\left(1 - y_b\right) \Gamma_b + y_b \Theta_b} \right)^{\omega_{\bar{l}}^{p}} \tag{6.8}$$

where $t_{\bar{l}}^{p0}$ is the free-flow handling time per container p and $k_{\bar{l}}^{p}$ is a factor reflecting the interaction among all transfers via the transshipment line b. The standard container flow in terms of TEUs transferred via b is thus calculated by,

$$v_b = \sum_{\bar{l} \in T_h^b} \sum_{p \in \mathcal{P}} \beta_b^p v_{\bar{l}}^p \tag{6.9}$$

and $\alpha_{\bar{l}}^{p}$ and $\omega_{\bar{l}}^{p}$ are two parameters to be calibrated.

Let $\mathbf{v}_{\bar{a}} = \left(v_{\bar{a}}^p, p \in \mathcal{P} \right)$ and $\mathbf{v}_{\bar{l}} = \left(v_{\bar{l}}^p, p \in \mathcal{P} \right)$ be the vectors of multi-type container flows loaded on $\bar{a}$ and $\bar{l}$, respectively. The flow of container type p on path $\bar{r} \in R_{od}^{p}$ is denoted by $f_{od\bar{r}}^{p}$. Vector utility functions for $\bar{a}$ and $\bar{l}$ are represented by

$$\mathbf{g}_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right) = \left(g_{\bar{a}}^{p}\left(\mathbf{v},\mathbf{s}\right), p \in \mathcal{P} \right) \tag{6.10}$$

$$\mathbf{g}_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right) = \left(g_{\bar{l}}^{p}\left(\mathbf{v},\mathbf{s}\right), p \in \mathcal{P} \right) \tag{6.11}$$

The UE principle implies that the multi-type container flow patterns **v** over G can be obtained by solving the parametric variational inequality (VI),

$$\sum_{\bar{a}\in A} \mathbf{g}_{\bar{a}}\left(\mathbf{v},\mathbf{s}\right)\left(\hat{\mathbf{v}}_{\bar{a}}-\mathbf{v}_{\bar{a}}\right)+\sum_{\bar{l}\in T} \mathbf{g}_{\bar{l}}\left(\mathbf{v},\mathbf{s}\right)\left(\hat{\mathbf{v}}_{\bar{l}}-\mathbf{v}_{\bar{l}}\right)\geq 0 \text{ for any } \hat{\mathbf{v}}\in\Omega\left(\mathbf{s}\right) \tag{6.12}$$

where $\Omega\left(\mathbf{s}\right)$ is the set of feasible multi-type container flow patterns for any given network design solution $\mathbf{s}$ and can mathematically expressed as below,

$$\Omega\left(\mathbf{s}\right)=\Bigg\{\mathbf{v}\mid v_{\bar{a}}^{p}=\sum_{o\in O}\sum_{d\in D}\sum_{\bar{r}\in R_{od}^{p}} f_{od\bar{r}}^{p}\delta_{od\bar{r}}^{\bar{a}p},\forall\bar{a}\in A_{a},a\in\mathcal{A}_{0}\cup\mathcal{A}_{1},p\in\mathcal{P} \tag{6.13}$$

$$v_{\bar{a}}^{p}=\sum_{o\in O}\sum_{d\in D}\sum_{\bar{r}\in R_{od}^{p}} x_{a} f_{od\bar{r}}^{p}\delta_{od\bar{r}}^{\bar{a}p},\forall\bar{a}\in A_{a},a\in\mathcal{A}_{2},p\in\mathcal{P} \tag{6.14}$$

$$v_{\bar{l}}^{p}=\sum_{o\in O}\sum_{d\in D}\sum_{\bar{r}\in R_{od}^{p}} f_{od\bar{r}}^{p}\delta_{od\bar{r}}^{\bar{l}p},\forall\bar{l}\in T_{h}^{b},b\in\mathcal{B}_{h}^{1},h\in\mathcal{H},p\in\mathcal{P} \tag{6.15}$$

$$v_{\bar{l}}^{p}=\sum_{o\in O}\sum_{d\in D}\sum_{\bar{r}\in R_{od}^{p}} y_{b} f_{od\bar{r}}^{p}\delta_{od\bar{r}}^{\bar{l}p},\forall\bar{l}\in T_{h}^{b},b\in\mathcal{B}_{h}^{2},h\in\mathcal{H},p\in\mathcal{P} \tag{6.16}$$

$$T_{od}^{p}=\sum_{\bar{r}\in R_{od}^{p}} f_{od\bar{r}}^{p},\forall o\in O,d\in\mathcal{D},p\in\mathcal{P} \tag{6.17}$$

$$v_{\bar{a}}^{p},v_{\bar{l}}^{p}\geq 0,\forall\bar{a}\in A,\bar{l}\in T,p\in\mathcal{P}\Big\} \tag{6.18}$$

6.2.2 Multi-container Transportation Cost Function for Carriers

The multi-type containers transportation or transshipment process operated by a carrier or transfer terminal operator can be regarded as a production system. Let $\mathcal{Q}$ be the set of all inputs required for the carrier to accomplish container transportation or transfer operation over carrier link $\bar{a}$ or transshipment line b, such as machinery resources, labors, materials and fuel consumption, and π_q be the price of input $q\in\mathcal{Q}$. Multi-type container flows handled by the carrier are the outputs of this system. The hybrid translog cost function (multiproduct cost function) for the carrier operating over carrier link $\bar{a}$ can be written as follows:

$$
\begin{aligned}
c_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right)=\exp\Bigg(\alpha_0 &+\sum_{i=1}^{n_{\mathcal{P}}}\alpha_i\left(\left(v_{\bar{a}}^i\right)^{\theta}-1\right)/\theta+\sum_{i=1}^{n_{\mathcal{Q}}}\beta_i\ln\pi_i \\
&+\sum_{i=1}^{n_{\mathcal{P}}}\sum_{j=1}^{n_{\mathcal{P}}}\delta_{ij}\left(\left(v_{\bar{a}}^i\right)^{\theta}-1\right)\left(\left(v_{\bar{a}}^j\right)^{\theta}-1\right)/\left(2\theta^2\right) \\
&+\sum_{i=1}^{n_{\mathcal{Q}}}\sum_{j=1}^{n_{\mathcal{Q}}}\gamma_{ij}\ln\pi_i\ln\pi_j/2+\sum_{i=1}^{n_{\mathcal{P}}}\sum_{j=1}^{n_{\mathcal{Q}}}\rho_{ij}\ln\pi_j\left(\left(v_{\bar{a}}^i\right)^{\theta}-1\right)/\theta\Bigg)
\end{aligned}
\tag{6.19}
$$

where α_0, α_i, β_i, δ_{ij}, γ_{ij}, ρ_{ij} and θ are the parameters to be calibrated using data, and these parameters should fulfill the following conditions:

$$\delta_{ij}=\delta_{ji},\gamma_{ij}=\gamma_{ji},i=1,2,\ldots,n_{\mathcal{P}},j=1,2,\ldots,n_{\mathcal{Q}} \tag{6.20}$$

$$\sum_{i=1}^{n_{\mathcal{Q}}}\beta_i=1;\sum_{i=1}^{n_{\mathcal{Q}}}\gamma_{ij}=0,j=1,2,\ldots,n_{\mathcal{Q}};\sum_{j=1}^{n_{\mathcal{Q}}}\rho_{ij}=0,i=1,2,\ldots,n_{\mathcal{P}} \tag{6.21}$$

$$\lim_{\theta\to 0}\left(\left(v_{\bar{a}}^p\right)^{\theta}-1\right)/\theta=\ln v_{\bar{a}}^p \tag{6.22}$$

The (ray) unit transportation cost function derived from the hybrid translog function is defined as

$$\bar{c}_{\bar{a}}\left(t\mathbf{v}_{\bar{a}}^0\right)=c_{\bar{a}}\left(t\mathbf{v}_{\bar{a}}^0\right)/t=c_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right)/\sum_{p\in\mathcal{P}}v_{\bar{a}}^p \tag{6.23}$$

where $\mathbf{v}_{\bar{a}}^0$ is a bundle of commodities 1,2,…, $n_{\mathcal{P}}$, represented by

$$\mathbf{v}_{\bar{a}}^0=\left(v_{\bar{a}}^{1*},v_{\bar{a}}^{2*},\ldots,v_{\bar{a}}^{n_{\mathcal{P}}*}\right) \tag{6.24}$$

with

$$\sum_{p\in\mathcal{P}}v_{\bar{a}}^{p*}=1 \tag{6.25}$$

Scale parameter t represents the number of bundles of multi-type containers loaded over carrier link $\bar{a}$. Similarly, the hybrid translog cost function and (ray) unit transportation cost function for the carrier operating on transshipment line b can be obtained by using the functions defined in Eqns. (6.19)-(6.23) with $\overline{a}$ replaced by b. The flow of container p loaded over transshipment line b is computed by,

$$v_b^p = \sum_{\overline{l} \in T_h^b} v_{\overline{l}}^p \tag{6.26}$$

The vector container flow loaded on b is represented by,

$$\mathbf{v}_b = \left(v_b^p, p \in \mathcal{P}\right) \tag{6.27}$$

The unit transportation cost function defined in Eqn. (6.23) is stipulated to have a U-shaped form that reflects the transition from scale economies to diseconomies of scale. This phenomenon may be rendered by the sharp growth of capital and labor costs when the container flow exceeds the safe operating capacity of the carrier.

Mathematically, the degree of economies of scale for carrier link $\overline{a}$ is measured by

$$S_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right) = \frac{c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right)}{\sum_{p \in \mathcal{P}} \frac{\partial c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right)}{\partial v_{\overline{a}}^p} v_{\overline{a}}^p} \tag{6.28}$$

The cost function will exhibit economies of scale if $S_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right) > 1$ and diseconomies of scale when $S_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right) < 1$. Note that $S_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right)$ will equal one when a scale parameter t can be obtained such that

$$d\left[\overline{c}_{\overline{a}}\left(t\mathbf{v}_{\overline{a}}^0\right)\right] / dt = 0 \tag{6.29}$$

In addition, scope economies that reflects cost saving resulting from simultaneously transporting multi-type containers may exist and the degree of scope economies can be mathematically expressed by,

$$SC_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right) = \frac{c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}^{\mathcal{P}_1}, \mathbf{v}_{\overline{a}}^{\mathcal{P}_2} = 0\right) + c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}^{\mathcal{P}_1} = 0, \mathbf{v}_{\overline{a}}^{\mathcal{P}_2}\right) - c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right)}{c_{\overline{a}}\left(\mathbf{v}_{\overline{a}}\right)} \tag{6.30}$$

where $\mathcal{P}_1, \mathcal{P}_2 \neq \varnothing$, $\mathcal{P}_1 \cup \mathcal{P}_2 = \mathcal{P}$, $\mathbf{v}_{\bar{a}}^{\mathcal{P}_1} = \left(v_{\bar{a}}^p, p \in \mathcal{P}_1\right)$ and $\mathbf{v}_{\bar{a}}^{\mathcal{P}_2} = \left(v_{\bar{a}}^p, p \in \mathcal{P}_2\right)$. The cost function exhibits scope economies if $SC_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right) > 0$; diseconomies of scope otherwise.

It should be pointed out that the hybrid translog cost function is sufficiently flexible for reflecting various properties of multi-type container transportation costs for carriers, such as scale and scope economies, and since it permits zero outputs, the function is capable of mimicking a realistic transportation operation process where a fixed cost would be incurred even in the absence of outputs. However, the function involves many parameters and is determined by calibration process based on historical data.

With the notations defined in above, the IHSND problem with multiple stakeholders and multi-type containers can be described as follows: given a physical network $\mathcal{G} = \left(\mathcal{N}, \mathcal{A}\right)$, the IHSND problem aims to construct an intermodal hub-and-spoke network for multi-type container delivery by making decision $\mathbf{s}$ = ($\mathbf{x}$,$\mathbf{y}$,$\mathbf{z}$). To achieve this goal, the network planer needs to make network design decisions with the aim to minimize the total network cost of carriers in multi-type container transportation given the investment budget limit B. Note that a feasible network design solution $\mathbf{s}$ is obtained based on flow pattern $\mathbf{v}$. On the other hand, given a feasible $\mathbf{s}$, the flow pattern $\mathbf{v}$ is assumed to result from the UE based route choice of intermodal operators.

6.3 Model Formulation

The IHSND problem concerned in this chapter can be formulated as the mathematical programming with equilibrium constraints (MPEC):

$$\begin{aligned} \min f\left(\mathbf{s}, \mathbf{v}\right) = & \sum_{a \in \left(\mathcal{A}_0 \cup \mathcal{A}_1\right)} \sum_{\bar{a} \in A_a} c_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right) + \sum_{a \in \mathcal{A}_2} \sum_{\bar{a} \in A_a} x_a c_{\bar{a}}\left(\mathbf{v}_{\bar{a}}\right) \\ & + \sum_{b \in \mathcal{B}_1} c_b\left(\mathbf{v}_b\right) + \sum_{b \in \mathcal{B}_2} y_b c_b\left(\mathbf{v}_b\right) \end{aligned} \tag{6.31}$$

subject to

$$\sum_{a \in \mathcal{A}} B_a x_a + \sum_{b \in \mathcal{B}} y_b F_b \le B \tag{6.32}$$

$$\sum_{b \in \mathcal{B}_h} y_b \ge z_h, \text{for } \forall h \in \mathcal{N}_2 \tag{6.33}$$

$$\sum_{b \in \mathcal{B}_h} y_b \le M z_h, \text{for } \forall h \in \mathcal{N}_2 \tag{6.34}$$

$$x_a \le z_{\tilde{h}_a} + z_{\tilde{t}_a}, \text{for } \forall a \in \mathcal{A}_2 \tag{6.35}$$

$$\sum_{\bar{r} \in R_{od}^p} \left(\prod_{a \in \mathcal{A}_{\bar{r}} \cap \mathcal{A}_2} x_a \cdot \prod_{b \in \mathcal{B}_{\bar{r}} \cap \mathcal{B}_2} y_b \right) \ge 1, \text{for } \forall o \in O, d \in \mathcal{D}, p \in \mathcal{P} \tag{6.36}$$

$$\kappa_a \sum_{\bar{a} \in A_a} \sum_{p \in \mathcal{P}} \beta_a^p v_{\bar{a}}^p / \eta_a \le \left(1 - x_a\right) \Gamma_a + x_a \Theta_a, \forall a \in \mathcal{A} \tag{6.37}$$

$$\sum_{\bar{l} \in T_h^b} \sum_{p \in \mathcal{P}} \beta_b^p v_{\bar{l}}^p \le \left(1 - y_b\right) \Gamma_b + y_b \Theta_b, \forall b \in \mathcal{B}_h, h \in \mathcal{H} \tag{6.38}$$

$$v_{\bar{a}}^p \le \Gamma_{\bar{a}}^p, \text{for } \forall \bar{a} \in A, p \in \mathcal{P} \tag{6.39}$$

$$\sum_{\bar{a} \in A} \mathbf{g}_{\bar{a}}\left(\mathbf{v}, \mathbf{s}\right)\left(\hat{\mathbf{v}}_{\bar{a}} - \mathbf{v}_{\bar{a}}\right) + \sum_{\bar{l} \in T} \mathbf{g}_{\bar{l}}\left(\mathbf{v}, \mathbf{s}\right)\left(\hat{\mathbf{v}}_{\bar{l}} - \mathbf{v}_{\bar{l}}\right) \ge 0, \hat{\mathbf{v}} \in \Omega\left(\mathbf{s}\right) \tag{6.40}$$

Objective function (6.31) minimizes the total network cost of carriers. Constraint (6.32) represents the budget limit. Constraints (6.33) and (6.34) ensure that once a new transfer terminal is selected, at least one transshipment line will be established at the transfer terminal; no transshipment line will be built otherwise. According to constraint (6.35), no new direct links between two spoke nodes are established. Constraint (6.36) ensures that at least one intermodal route exists between each O/D pair for each container type. Constraint (6.37) restricts that the standard traffic flow loaded on a physical link cannot exceed its capacity. Constraint (6.38) is the capacity constraint with respect to each container type for each transshipment line. Constraint (6.39) is the capacity constraint for each carrier. The parametric VI (6.40) reflects the interaction between network design decisions and network flow patterns. *M* is an arbitrarily big number.

In the MPEC model, the objective is to minimize the total transportation cost of carriers from the planner's perspective. The model can flexibly cater with the case that the planner aims to maximize the total profit of carriers through replacing the objective (6.31) by the following expression,

$$\begin{aligned}\max f(\mathbf{s},\mathbf{v}) = &\sum_{a\in(\mathcal{A}_0\cup\mathcal{A}_1)}\sum_{\bar{a}\in A_a}\left[\sum_{p\in\mathcal{P}} r_{\bar{a}}^p v_{\bar{a}}^p - c_{\bar{a}}(\mathbf{v}_{\bar{a}})\right] + \sum_{a\in\mathcal{A}_2}\sum_{\bar{a}\in A_a} x_a\left[\sum_{p\in\mathcal{P}} r_{\bar{a}}^p v_{\bar{a}}^p - c_{\bar{a}}(\mathbf{v}_{\bar{a}})\right]\\ &+\sum_{h\in\mathcal{H}}\sum_{b\in\mathcal{B}_h^1}\left[\sum_{\bar{l}\in T_h^b}\sum_{p\in\mathcal{P}} r_{\bar{l}}^p v_{\bar{l}}^p - c_b(\mathbf{v}_b)\right] + \sum_{h\in\mathcal{H}}\sum_{b\in\mathcal{B}_h^2} y_b\left[\sum_{\bar{l}\in T_h^b}\sum_{p\in\mathcal{P}} r_{\bar{l}}^p v_{\bar{l}}^p - c_b(\mathbf{v}_b)\right]\end{aligned} \tag{6.41}$$

6.4 Solution Algorithm

The discrete network design problem has been proved to be NP-hard (Johnson et al, 1978). The IHSND problem is even harder to solve due to the nonconvexity and nondifferential characteristics of the MPEC model including a parametric VI. We thus have to seek a heuristic method to solve the MPEC model (6.31)-(6.40). In recent decades, genetic algorithms have seen a number of applications in solving bilevel programming models (Ge et al., 2003), which is a special case of MPEC model. We propose a hybrid GA (HGA) with an embedded diagonalization algorithm to solve the IHSND problem. To penalize the candidate solutions violating capacity constraints (6.37) -(6.39), we first define the evaluation function as sum of the objective function and penalty terms as follows:

$$\begin{aligned}h(\mathbf{s},\mathbf{v}) = f(\mathbf{s},\mathbf{v}) &+ \sum_{\bar{a}\in A}\sum_{p\in\mathcal{P}} r_{\bar{a}}\left(\max\left(v_{\bar{a}}^p - \Gamma_{\bar{a}}^p, 0\right)\right)^2\\ &+\sum_{a\in\mathcal{A}} r_a\left(\max\left(w_a - (1-x_a)\Gamma_a - x_a\Theta_a, 0\right)\right)^2\\ &+\sum_{b\in\mathcal{B}} r_b\left(\max\left(w_b - (1-y_b)\Gamma_b - y_b\Theta_b, 0\right)\right)^2\end{aligned} \tag{6.42}$$

where r_a, $r_{\bar{a}}$ and r_b are positive variable penalty coefficients. The hybrid GA for solving the MPEC model (6.31)-(6.40) is presented in the following four steps.

Hybrid Genetic Algorithm

Step 0. (*Initialization*) Randomly determine an initial population consisting of λ distinct chromosomes satisfying constraint conditions (6.32)-(6.36) and denote the population by set $S^n = \left\{ \mathbf{s}_i^n \middle| i = 1, 2, ..., \lambda \right\}$, of which bit string $\mathbf{s}_i^n$ is used to represent chromosome *i*. Let the number of iterations $n = 0$.

Step 1. (*Crossover and mutation*) Perform one-cut-point crossover and mutation operations on the chromosomes selected from S^n based on specified crossover probability p_c and mutation probability p_m respectively. Let $\tilde{S}^n$ be the set of all resulting offspring chromosomes that satisfy constraint conditions (6.32)-(6.36) and μ_n be the cardinality of $\tilde{S}^n$. Replace parent chromosomes in S^n by their corresponding offspring in $\tilde{S}^n$ and go to next step if $\mu_n \geq 1$; re-execute Step 1 otherwise.

Step 2. (*Fitness evaluation*) Two substeps are executed to calculate fitness of each chromosome in population S^n as follows.

Step 2.1. (*Network flow calculation*) For a chromosome $\mathbf{s}_i^n \in S^n \left(i = 1, 2, ..., \lambda \right)$, solve the relevant parametric VI (6.40) using a diagonalization algorithm to obtain the UE flow pattern $\mathbf{v}_i^n$.

Step 2.2. (*Fitness normalization*) Given $\mathbf{s}_i^n$ and $\mathbf{v}_i^n$ $\left(i = 1, 2, ..., \lambda \right)$, calculate evaluation value $h_i^n = h\left(\mathbf{s}_i^n, \mathbf{v}_i^n \right)$ of chromosome i defined in Eqn. (6.42) .

The fitness of each chromosome can be then computed by normalizing its evaluation value using the following equation,

$$\tilde{h}_i^n = \left[h_{\max}^n - h_i^n\left(\mathbf{s}_i^n, \mathbf{v}_i^n\right) + \gamma \right] / \left[h_{\max}^n - h_{\min}^n + \gamma \right], i = 1, 2, ..., \lambda \qquad (6.43)$$

where $h_{\max}^n$ and $h_{\min}^n$ are maximum and minimum ones out of evaluation values of all chromosomes included in S^n, respectively, and $\gamma \in (0,1)$.

Step 3. (*Breed a new population*) Generate a population S^{n+1} of size λ by using a binary tournament selection method (Gen and Cheng, 1997) and the fitness of each chromosome defined in (6.43); set $n = n+1$ and go to Step 1.

Step 4. (*Stopping test*) Stop if $h_{\min}^{(n+1)} - h_{\min}^n < \varepsilon_1$ where ε_1 is a positive tolerance error or $n > N$ where N is an arbitrary population generation number.

The IHSND problem has binary integer variables **x** = ($x_1, x_2, ..., x_{n_\mathbf{x}}$), **y** = ($y_1, y_2, ..., y_{n_\mathbf{y}}$), **z** = ($z_1, z_2, ..., z_{n_\mathbf{z}}$), where $n_\mathbf{x}$, $n_\mathbf{y}$, and $n_\mathbf{z}$ are the number of entities in the three vectors. Each chromosome encodes a possible solution of **s** = (**x**, **y**, **z**) and comprises ($n_\mathbf{x} + n_\mathbf{y} + n_\mathbf{z}$) genes ranging according to the sequence (**x**, **y**, **z**) on the chromosome. Each gene corresponds with a binary decision variable with the same location as the gene. The chromosome is formed in such a way that each gene is assigned value of one if the investment action represented by the gene's corresponding decision variable is implemented; zero otherwise.

Constraint (6.36) actually guarantees the connectivity between an O/D pair for transporting each type of containers. However, it is somewhat problematic to examine the constraint condition since enumerating all intermodal routes between each O/D pair is unacceptably time consuming. Hence, the constraint condition (6.36) is validated by using link-label setting shortest path algorithm that has been employed to find optimum intermodal/multimodal shortest path. The algorithm is sufficiently efficient with time complexity $O\left(n_A + n_T\right)^2$ and it has also been incorporated into the Frank-Wolf algorithm (LeBlanc et al., 1975) that is dedicated to solving the parametric VI in Step 2.1. Given solution **s,** constraint (6.36) is satisfied if at least one intermodal shortest path can be found for each container type between each O/D pair.

The diagonalization algorithm used in Step 2.1 is described in the following substeps:

Step 2.1.1. (*Initialization*) Given a chromosome $\mathbf{s}_i^n \in S^n \left(i = 1, 2, ..., \lambda\right)$, determine an initial flow pattern $\mathbf{v}^0 \in \Omega\left(\mathbf{s}_i^n\right)$ and set $k = 0$.

Step 2.1.2. (*Solve the diagonalized problem*) Apply Frank-Wolf algorithm to solve a general UE problem presented by VI (6.44) to obtain a network flow pattern $\mathbf{v}$ and let $\mathbf{v}^{k+1} = \mathbf{v}$.

$$\sum_{p\in\mathcal{P}} \sum_{\bar{a}\in A} \left(\hat{v}_{\bar{a}}^p - v_{\bar{a}}^p\right) g_{\bar{a}}^{(k)p}\left(v_{\bar{a}}^p, \mathbf{s}_i^n\right) + \sum_{p\in\mathcal{P}} \sum_{\bar{l}\in T} \left(\hat{v}_{\bar{l}}^p - v_{\bar{l}}^p\right) g_{\bar{l}}^{(k)p}\left(v_{\bar{l}}^p, \mathbf{s}_i^n\right) \geq 0, \forall\ \hat{\mathbf{v}} \in \Omega\left(\mathbf{s}_i^n\right) \quad (6.44)$$

where for $\forall i \in A \bigcup T, p \in \mathcal{P}$,

$$g_i^{(k)p} = g_i^p\left[v_i^p, v_i^{\hat{p}} = v_i^{(k)\hat{p}}\left(\hat{p} \in \mathcal{P} \neq p\right), v_j^{\hat{p}} = v_j^{(k)\hat{p}}\left(\forall j \in A \bigcup T \neq i, \hat{p} \in \mathcal{P}\right), \mathbf{s}_i^n\right] \quad (6.45)$$

Step 2.1.3. (*Stopping Test*). If

$$\left\|\mathbf{v}^{(k+1)} - \mathbf{v}^k\right\|_2 / \left\|\mathbf{v}^k\right\|_1 \leq \varepsilon_2 \quad (6.46)$$

where ε_2 is an small positive value, then stop and let $\mathbf{v}_i^n = \mathbf{v}^{k+1}$; set $k = k + 1$ and go to Step 2.1.3 otherwise.

The diagonalization algorithm used in Step 2.1 converges if the Jacobian matrix of utility functions with respect to network flow pattern **v** is diagonally dominant (Dafermos, 1983)

6.5 Numerical Examples

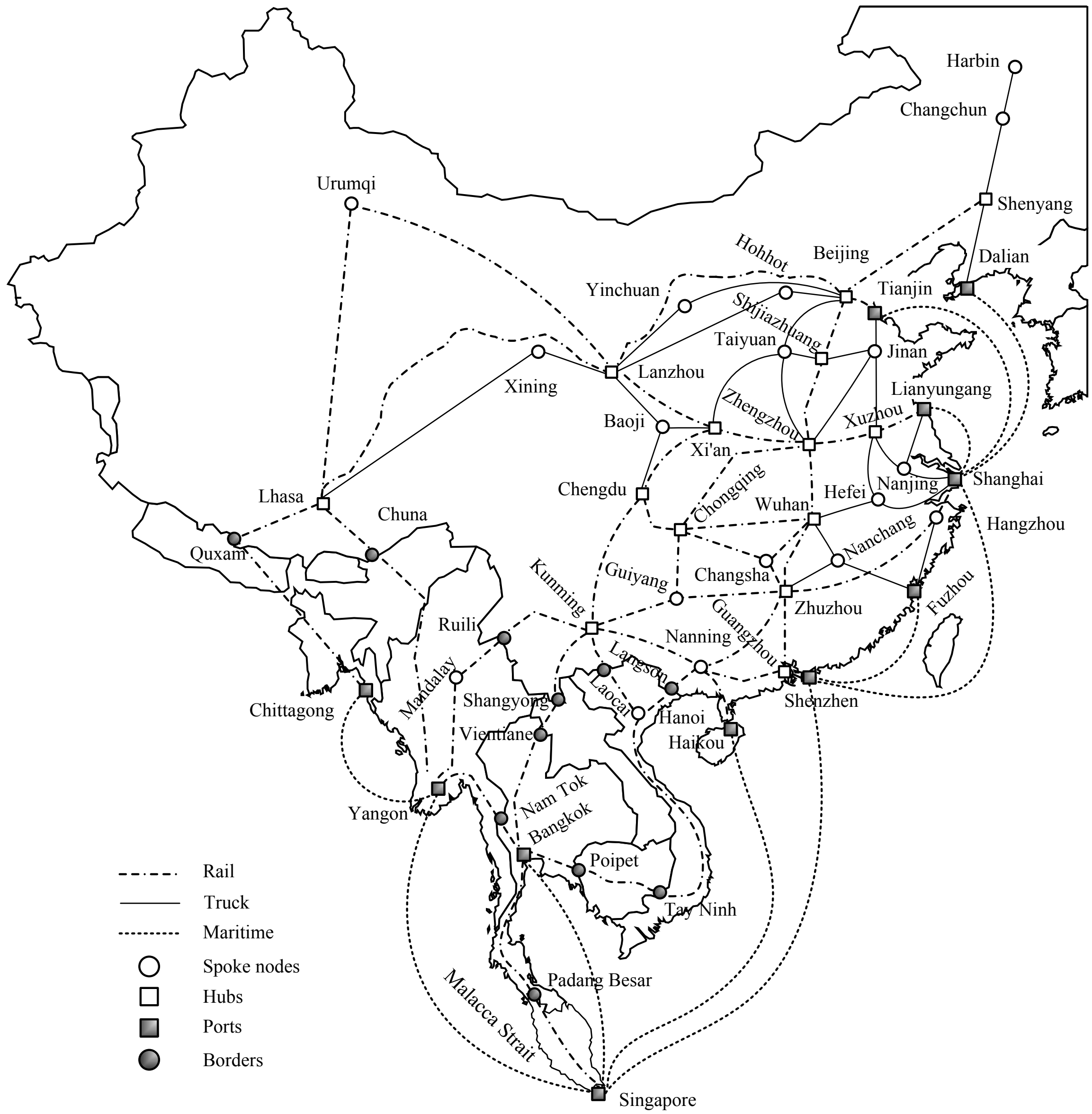

Fig. 6.1 An example intermodal transportation network

Fig. 6.1 shows an example intermodal freight transportation network used for assessing the applicability of the developed MPEC model and hybrid genetic algorithm. The network is compiled by referring to the working plans of the Trans-Asian Railway and Asian Highway projects initiated by UNESCAP (2008*a* and 2008*b*), and involves the mode set $\mathcal{M}$ = {rail, truck, maritime} and container type set $\mathcal{P}$ = {1 = general container, 2 = refrigerated container}. Each link segment contains two physical links in opposite directions. It is further hypothesized that each physical link or transshipment line is operated by an individual carrier. Tables D.1 and D.2 shows the nodes and links in the network in the **Appendix D**, respectively.

As reported by UNCTD (2008), the intra-Asia trade is estimated at 40 million TEUs in 2007. We distribute the intra-Asia container traffic over 25 O/D pairs by using doubly constraint gravity model with transportation time as deterrence, and the resulting O/D demand matrix is tabulated in Table D.3 in **Appendix D**. Furthermore, the demands of general containers and refrigerated containers between each O/D pair are estimated at 10% and 90% of the total container demand, respectively.

Table 6.1 Parameter Values for Utility Functions

$\bar{a} \in A$	$\left(s_{\bar{a}}^1, s_{\bar{a}}^2\right)$ **(km/h)**	$\left(r_{\bar{a}}^1, r_{\bar{a}}^2\right)$ **($/km)**	$\left(\phi_{\bar{a}}^1, \phi_{\bar{a}}^2\right)$ **($/h)**	$\left(\omega_{\bar{a}}^1, \omega_{\bar{a}}^2\right)$	$\left(\alpha_{\bar{a}}^1, \alpha_{\bar{a}}^2\right)$	$k_{\bar{a}}^p$
rail	(33, 33)	(0.1, 0.2)	(0.1, 0.1)	(2.0, 2.0)	(2.5, 2.5)	0.5
road	(23, 23)	(0.8, 1.2)	(1.5, 1.5)	(2.0, 2.0)	(2.5, 2.5)	0.5
maritime	(22, 22)	(0.2, 0.4)	(0.1, 0.1)	(2.0, 2.0)	(2.5, 2.5)	0.5
$\bar{l} \in T$	$\left(t_{\bar{l}}^1, t_{\bar{l}}^2\right)$**(h)**	$\left(r_{\bar{l}}^1, r_{\bar{l}}^2\right)$**($)**	$\left(\phi_{\bar{l}}^1, \phi_{\bar{l}}^2\right)$**($/h)**	$\left(\omega_{\bar{l}}^1, \omega_{\bar{l}}^2\right)$	$\left(\alpha_{\bar{l}}^1, \alpha_{\bar{l}}^2\right)$	$k_{\bar{l}}^p$
ports	(24, 24)	(387, 580)	(5.0, 5.0)	(2.0, 2.0)	(2.5, 2.5)	0.5
transfer terminals	(12, 12)	(27, 40)	(5.0, 5.0)	(2.0, 2.0)	(2.5, 2.5)	0.5
borders	(48, 48)	(293, 493)	(5.0, 5.0)	(2.0, 2.0)	(2.5, 2.5)	0.5
$a \in \mathcal{A}$	Θ_a **(std vehicles/yr)**		κ_a	η_a	$\left(\beta_a^1, \beta_a^2\right)$	B_a
rail	5000		1.0	0.5	(0.25, 0.25)	4.0
road	3000		2.0	0.1	(0.5, 0.5)	2.5
maritime	1000		1.0	0.6	(10^{-3}, 10^{-3})	1.0
$b \in \mathcal{B}$	Θ_b **(1000 TEUs/yr)**		Γ_b **(1000 TEUs/yr)**		$\left(\beta_b^1, \beta_b^2\right)$	F_b
$b \in \mathcal{B}_1$	1000		500		(1.0, 1.0)	1
$b \in \mathcal{B}_2$	1000		0		(1.0, 1.0)	2

Table 6.1 shows the parameter values for utility functions based on Wang et al. (2009). In the table, $s_{\bar{a}}^{1}$ and $s_{\bar{a}}^{2}$ represent the free-flow speeds for transporting one general container and refrigerated container on carrier link $\bar{a}$, respectively, and the free-flow transportation time $t_{\bar{a}}^{10}$ and $t_{\bar{a}}^{20}$ defined in Eqn. (5.33) can be calculated by using link length divided by $s_{\bar{a}}^{1}$ and $s_{\bar{a}}^{2}$ respectively. Table 6.2 gives the parameter values for the hybrid translog cost functions of carriers.

Table 6.2 Parameter Values for Cost Functions

Parameters	α_0	(α_1, α_2)	$(\delta_{11}, \delta_{12}, \delta_{22})$	θ
Rail links	-2	(0.01, 0.01)	(0.01, 0.0359, 0.01)	0.001
Road links	-2	(0.01, 0.01)	(0.01, 0.0543, 0.01)	0.05
Maritime links	-4	(0.01, 0.01)	(0.01, 0.0978, 0.01)	0.001
Transshipment lines	6	(0.01, 0.01)	(0.01, 0.0359, 0.01)	0.057

6.5.1 Comparison of Three Algorithms

We use three numerical examples to validate the effectiveness of the proposed MPEC model and HGA based on the example intermodal network shown in Fig. 6.1. In these three examples, the proposed HGA with a binary tournament selection method, simple GA (SGA) and exhaustive enumeration algorithm (EEA) are employed to solve the IHSND problem with 16 possible projects to be planned for network design, respectively. Table 6.3 shows the projects to be planned in the comparison analysis. In reality, it is somewhat unrealistic to involve too many network design projects in intermodal freight transportation network design, since most network elements currently exist and only key links and transshipment lines need to be established or enhanced (Yamada et al., 2009). Besides, network design projects are highly cost-consuming, and the budget of a network planner normally allows limited number of projects to be planned.

The implementations of the three algorithms are described below.

(i) SGA: the simple GA is implemented according to the normal procedure defined by Gen and Cheng (1997). One-cut-point crossover is conducted between two randomly selected chromosomes in accordance with the crossover probability. The population breeding process generates a new population by drawing chromosome N times, which is different from the hybrid GA described above.

(ii) HGA: the hybrid GA is described as earlier. Initialization, crossover, mutation and fitness evaluation are same as those in the simple GA. After mutation, the algorithm draws two chromosomes N times. At each time, the two individuals are compared in terms of fitness and the best one will be kept in the next population.

(iii) EEA: a binary search tree with 2^{16} nodes at the final depth is used to obtain the optimal solution. The tree contains all feasible solutions, each of which is represented by a particular branch of the tree. All feasible solutions are consecutively tested and the optimal solution is finally obtained.

The algorithms are coded in C++ and executed by using a desktop with CPU of Core 2 Duo 3.00 GHz and 4G RAM. Let parameters $r_{\bar{a}} = r_a = r_b = 10$ for $\bar{a} \in A$, $a \in \mathcal{A}$ and $b \in \mathcal{B}$, crossover probability $p_c = 0.25$, mutation probability $p_m = 0.01$, the total budget B = 30, the number of generations N = 100, population size λ = 50, $\varepsilon_2 = 10^{-6}$ and $\gamma = 0.05$.

Table 6.3 Network Design Projects to be Planned in Comparison Analysis

Actions	Links or Location	Optimal Solution		
		SGA	HGA	EEA
Transfer terminal location	Kunming	1	1	1
Transfer terminal location	Lhasa	0	1	1
Transshipment line establishment	{rail-rail} at Kunming	1	1	1
Transshipment line establishment	{rail-truck} at Lhasa	1	1	0
Transshipment line establishment	{rail-rail} at Lhasa	0	1	1
Transshipment line establishment	{truck-rail} at Lhasa	0	1	1
Rail link establishment	Urumqi → Lhasa	0	1	1
Rail link establishment	Ruili → Kunming	0	0	1
Rail link establishment	Nanning → Langson	1	1	0
Rail link establishment	Kunming → Shangyong	0	1	0
Rail link establishment	Kunming → Laocai	1	1	1
Rail link establishment	Lhasa → Urumqi	0	0	1
Rail link establishment	Kunming → Ruili	1	0	1
Rail link establishment	Langson → Nanning	0	0	0
Rail link establishment	Shangyong → Kunming	1	0	0
Rail link establishment	Laocai → Kunming	0	1	1

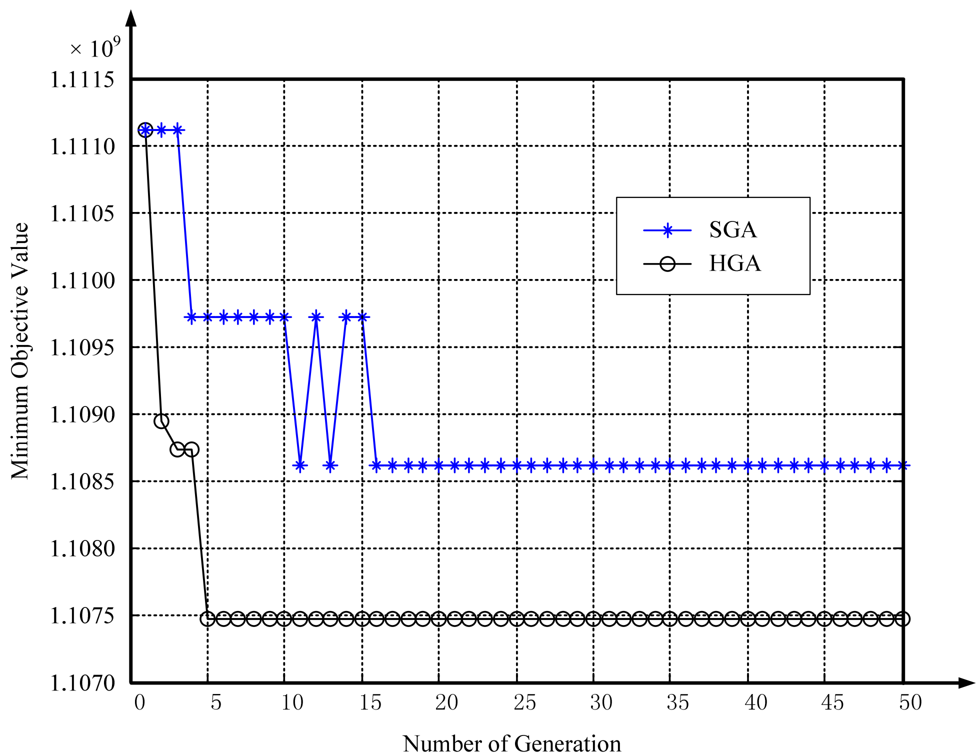

Fig. 6.2 Minimum objective value in each generation for SGA and HGA

Table 6.4 Comparison of the Three Algorithms

	SGA	HGA	EEA
CPU Time	232.08 hours	236.64 hours	1084.8 hours
Min. objective value	1108615849	1107468713	1106710821
Max. objective value	1111109848	1107468713	1575785221

The computational results by using the SGA, HGA and EEA are compared in terms of computational time and objective value are tabulated in Table 6.4. The optimal network design decisions obtained by using the three algorithms are shown in Table 6.3. To compare the SGA and HGA, the initial populations employed in executing the two algorithms are identical.

As indicated by Table 6.4, for running 100 generations, the HGA is better than SGA in terms of optimal (minimum) objective value but worse than SGA as far as the computational time is concerned. However, the time difference between the two genetic algorithms is not remarkable. Regarding the convergence speed, the HGA is found to outperform SGA, since the former converges in 5 iterations and the latter finds the local optimum after 15 iterations, as depicted in Fig. 6.2.

Undoubtedly, the EEA can find the best solution – the global optimal solution by searching the whole feasible space. The HGA can provide a reasonably good solution, which gives a 0.6% bigger objective value than the globally minimum objective value. However, since the IHSND problem is a NP-hard problem, a small increase in the current number of binary variables will give rise to an exponentially increasing computational time, which makes the EEA unacceptable for solving the a larger IHSND problem. Additionally, the computational time per iteration by using the HGA is mainly attributed to executing the diagonalization algorithm for solving the parametric VI. The total computation time would not change much even if a larger number of possible projects are planned in the example network shown in Fig. 6.1. The results thus indicate that the HGA provides the best performance among the three algorithms and gives a reasonably good solution if both computational time and solution quality are considered.

6.5.2 Application of the HGA in a Large-scale IHSND Problem

We apply the proposed HGA to a large-scale IHSND problem based on the example network shown in Fig. 6.1, assuming that all physical links need to be established in addition to planning the transshipment lines and transfer terminals shown in Table 6.5. Let B = 650 units and N = 50, and all remaining parameter values and the operating environment are same as those used in the above three examples. The resulting IHSND problem has 209 possible projects (0-1 variables) to be planned. Fig. 6.3 shows the change in the minimum objective value with respect to the number of generation.

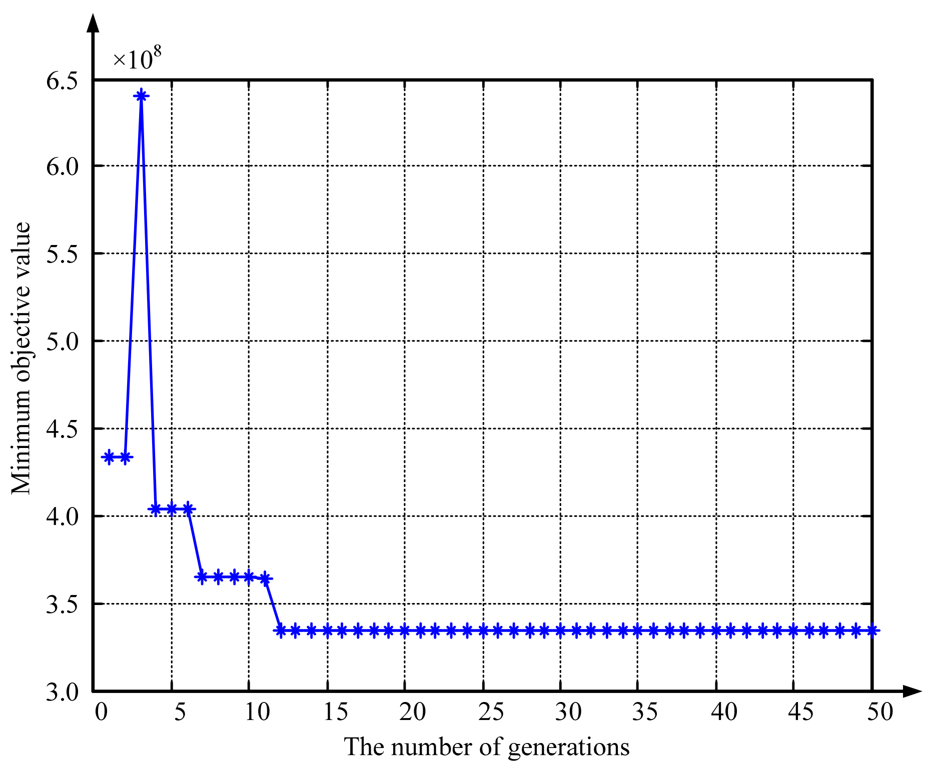

Fig. 6.3 Minimum objective value in each generation for the large-scale example

The optimal solutions for transfer terminal locations and transshipment line establishments are shown in Table 6.5, and those for physical links are given in Table D.2 in **Appendix D**. In the Table D.2, x_{a^*} and $x_{\hat{a}^*}$ represent the optimal solutions with respect to physical links $a \in \mathcal{A}$ and $\hat{a} \in \mathcal{A}$ in the opposite direction of a, respectively.

Table 6.5 Network Design Projects to be Planned in the Large-Scale Example

Transfer terminals/ Transshipment Lines	Optimal Solution	Transfer terminals/ Transshipment Lines	Optimal Solution
Zhengzhou	1	{truck-rail} at Lanzhou	1
Lanzhou	1	{rail-rail} at Kunming	1
Kunming	1	{rail-truck} at Lhasa	1
Lhasa	1	{rail-rail} at Lhasa	1
Xuzhou	1	{truck-rail } at Lhasa	1
Zhuzhou	1	{truck-rail} at Xuzhou	1
{truck-rail} at Zhengzhou	1	{truck-truck} at Xuzhou	1
{truck-truck} at Zhengzhou	0	{rail-rail} at Xuzhou	1
{rail-rail}at Zhengzhou	1	{rail-truck} at Xuzhou	1
{rail-truck} at Zhengzhou	1	{rail-rail } at Zhuzhou	1
{rail-truck} at Lanzhou	1	{rail-truck } at Zhuzhou	1
{rail-rail}at Lanzhou	1	{truck-rail } at Zhuzhou	1
{truck-truck}at Lanzhou	1		

As implied by the results, the {truck-truck} transshipment line should not be established at Zhengzhou. It indicates that container flows originated from Taiyuan and Jinan are not switched via Zhengzhou, and they may be transshipped to each other via Shijiazhuang due to the shorter distance by traversing Shijiazhuang. As shown in Table D.2, most of physical links need to be established to maintain the connectivity of the intermodal network for container delivery between 25 O/D pairs. Since many links in Southeast Asian countries are currently still missing, the Trans-Asian Railway and Asian Highway projects initiated by UNESCAP should be put into a fast progress in order to adapt to the growing containerized cargo trade and economic exchanges in China and Mainland Southeast Asia.

6.6 Conclusions

In this chapter we proposed a novel and realistic IHSND problem for multi-type container flows in the context of intermodal freight transportation operations. The problem is fundamentally different from the conventional HSND problem and its variants by incorporating multiple stakeholders, multi-type containers and container transfer processes at transfer terminals, which necessitates the relaxations of the four assumptions broadly adopted by past HSND studies.

To formulate the problem, we first represented a given intermodal network as two-tire directed networks - a physical network that a network planner attempts to design and an operational network that intermodal operators make intermodal route choice based on. Next, a joint transportation cost function that possesses a U-shaped (ray) unit cost function to reflect the transition from scale economies to scale diseconomies in distinct flow regimes was suggested to describe a carrier's cost structure in transport of multi-type containers. A utility function consisting of actual transportation charges and congestion impact was proposed to reflect the preference of an intermodal operator in route choice. AN MPEC model incorporating a parametric VI was then developed to formulate the IHSND problem with the objective to minimize the total network cost of carriers.

To solve the MPEC model, a HGA embedded with a diagonalization iterative scheme for UE based multi-type container flow assignment was proposed. The proposed HGA was found to have a reasonably good performance in terms of computational time and solution quality compared to the EEA and SGA. The HGA was also applied to solve a large-scale IHSND problem to assess the applicability of the proposed model and algorithm.

CHAPTER 7

PORT MARKET SHARE OPTIMIZATION USING HINTERLAND NETWORK DESIGN

7.1 Introduction

Ports as one type of transfer terminals in intermodal freight transportation networks have been playing a vital role in switching cargo between inland and maritime modes. The world's fast-growing maritime shipping and port industries have enormously intensified competition among container ports, especially those located closely and potentially vying with each other. A port generally serves as the main engine of the economic development of a local area. To maintain a competitive edge in today's global economy, the local government authority or port operator is motivated to maximize the port market share, so as to attract as many container traffic and customers as possible to traverse through the port. The market share of a port is generally identified associated with a specified area. In this study, given a concerned study area, the market share of a particular port is defined as the proportion of the container traffic volume handled by the port to the total traffic demand generated in the study area. The port market share can be considered as an appropriate performance indicator that reflects the competitiveness of the port, since it quantitatively measures the scale of container traffic it attracts when competing with other ports.

As indicated by literature view of port selection criteria, the accessibility and cost effectiveness of port hinterland connections are two key factors influencing port selection of intermodal operators and port market share. Port market share could thus be expanded through organizing a highly accessible and cost-effectiveness port hinterland network. For instance, the city of Rotterdam established a barge-maritime transfer terminal to assist the port of Rotterdam in expanding its market share and retaining its lead as the world largest port in terms of cargo handling weight. The transfer terminal has attracted a massive amount of coal transported from Germany and other countries in the European continent using the economical inland waterway. The hinterland network of a port is essentially an intermodal freight transportation network involving multiple modes and should be designed to have a hub-and-spoke structure. A hub-and-spoke hinterland network can provide intermodal operators with cost-effectiveness connections to the port by taking advantage of economies of scale, which could simultaneously result in an expanded port market share (Crainic and Kim, 2007). It is thus of interest to optimize port market share form the viewpoints of local government authorities, port operators and intermodal operators. This chapter aims to develop a modelling approach to the port market share optimization problem using hinterland network design.

Three types of stakeholders are involved in port market share optimization problem – the hinterland network planner, carriers and intermodal operators. The hinterland network planner represents a local government authority, a port operator or an association of several government authorities. The planner needs to first identify the extent of hinterland network of a particular port and then to re-design it as a hub-and-spoke network. Intermodal operators and carriers are as defined in CHAPTER 1. The container delivery originated from or destined to the study area is realized through an intermodal freight transportation network containing the particular port. The port hinterland network is part of the whole intermodal network, which serves the area of the port's hinterland and connects the port with origins or destinations of container flows. The extent of the hinterland network to be planned can be identified by using the probabilistic port hinterland estimation approach proposed in CHAPTER 4 based on the perspective of the planner. As one instance, the planner can identify the boundaries of the port hinterland with probability 0.5 for some specified destinations, and then obtain the hinterland network by connecting all these boundaries. In this study the port hinterland network to be designed is predetermined as an input.

The port market share is determined by the interactive decision process between the planner and intermodal operators. The planner makes hinterland network design decisions to maximize the port market share based on the container traffic distribution over the whole intermodal network. Given a hinterland network, the container traffic distribution is essentially determined by the decisions of intermodal operators in route choice. Assuming that the route choice follows the SUE principle, the network container flow pattern can be obtained. Based on the network flow pattern, the port market share can be quantitatively estimated by the following procedure. Between each O/D pair, an intermodal operator intends to choose intermodal routes from a set of available alternatives to transport a certain number of containers from the origin to destination. Some of the available alternatives may traverse through the particular port, and the container flow assigned on the intermodal routes traversing through the port are considered as a part of the market quota of the port. Due to the interactive decision process, the port market share optimization (PMSO) using hinterland network design problem can be solved using the IHSND design approach proposed in Chapter 5 with necessary adaptations.

7.2 Assumptions, Notations and Problem Statement

Given a concerned study area *S* and particular port *P*, shippers in the area need to deliver containers to receivers located in the same area through an intermodal freight transportation network containing the particular port *P*. The container transport process is governed and coordinated by intermodal operators on behalf of shippers. The intermodal transportation network serving *S* and containing *P* can be represented by a physical network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, in which the set of origins, O, is composed of the locations of all shippers in *S*, and the set of destinations, $\mathcal{D}$, is composed of the locations of all receivers in *S*. Based on the physical network, an operational network $G = (N, A, T)$ can be derived. The network representation and notations related to these networks are same as those described in CHAPTER 5.

Let directed graph $\tilde{\mathcal{G}} = (\tilde{\mathcal{N}}, \tilde{\mathcal{A}})$ represent the hinterland network to be planned, in which $\tilde{\mathcal{N}} \subseteq \mathcal{N}$ and $\tilde{\mathcal{A}} \subseteq \mathcal{A}$ are the sets of nodes and physical links, respectively. Let $\tilde{\mathcal{N}}_0 \subseteq \mathcal{N}_0$ and $\tilde{\mathcal{N}}_1 \subseteq \mathcal{N}_1$ be the sets of existing spoke nodes and existing transfer terminals in $\tilde{\mathcal{G}}$, respectively. As all network design decisions will be made with respect to hinterland network $\tilde{\mathcal{G}}$, the set of potential transfer terminals can be represented by $\tilde{\mathcal{N}}_2$ with relation $\tilde{\mathcal{N}}_2 = \mathcal{N}_2$. Let $\tilde{\mathcal{H}} = (\tilde{\mathcal{N}}_1 \cup \tilde{\mathcal{N}}_2)$ be the set of all transfer terminals in the hinterland network and it follows that $\tilde{\mathcal{N}} = \tilde{\mathcal{N}}_0 \cup \tilde{\mathcal{H}}$. Port *P* is also one transfer terminal involved in its hinterland network $\tilde{\mathcal{G}}$, i.e., $P \in \tilde{\mathcal{H}}$. Let $\tilde{\mathcal{A}}_0$, $\tilde{\mathcal{A}}_1$ and $\tilde{\mathcal{A}}_2$ be the sets of existing spoke physical links, existing non-spoke physical links and potential non-spoke physical links in $\tilde{\mathcal{G}}$, respectively, with $\tilde{\mathcal{A}}_2 = \mathcal{A}_2$ and we have,

$$\tilde{\mathcal{A}}_0 \subseteq \tilde{\mathcal{N}}_0 \times \mathcal{N}_0 \times \mathcal{M} \tag{7.1}$$

$$\tilde{\mathcal{A}}_1 \subseteq \left(\tilde{\mathcal{N}}_0 \cup \tilde{\mathcal{N}}_1\right) \times \mathcal{N}_1 \times \mathcal{M} \tag{7.2}$$

$$\tilde{\mathcal{A}}_2 \subseteq \mathcal{N} \times \tilde{\mathcal{N}}_2 \times \mathcal{M} \tag{7.3}$$

$$\tilde{\mathcal{A}} = \tilde{\mathcal{A}}_0 \cup \tilde{\mathcal{A}}_1 \cup \tilde{\mathcal{A}}_2 \tag{7.4}$$

Let $\tilde{\mathcal{B}}_1 \subseteq \mathcal{B}_1$ and $\tilde{\mathcal{B}}_2 \subseteq \mathcal{B}_2$ be the sets of existing and potential transshipment lines in graph $\tilde{\mathcal{G}}$, respectively, where $\tilde{\mathcal{B}}_1 = \bigcup_{h \in \tilde{\mathcal{H}}} \mathcal{B}_h^1$ and $\tilde{\mathcal{B}}_2 = \bigcup_{h \in \tilde{\mathcal{H}}} \mathcal{B}_h^2$.

Two assumptions are made throughout this chapter:

(i) spoke nodes cannot serve as transshipment points and,

(ii) no new direct links between spoke nodes will be established,

(iii) the route choice of intermodal operators follows the SUE principle, i.e., no intermodal operator could increase his/her perceived transportation utility by unilaterally shifting to choose another route when he/she is faced with route choice for transporting one container (TEU) between each O/D pair in operational network *G*.

Under these assumptions, the PMSO problem can be described as follows: given study area *S*, intermodal network $\mathcal{G}$, a particular port *P* contained in $\mathcal{G}$, hinterland network $\tilde{\mathcal{G}}$ of the port and a limited budget *B*, the hinterland network planner intends to re-design $\tilde{\mathcal{G}}$ as an intermodal hub-and-spoke network with the objective of maximizing the market share of *P* with respect to *S*.

To achieve this goal, the planner needs to make network design decisions such as transfer terminal location, physical link establishments or enhancements and transshipment line establishments and enhancements. Detailed decisions, the decision variables representing the network design decisions of the planner, and the investment actions associated with the decisions can be obtained based on the description in CHAPTER 5 by replacing $\mathcal{A}_1$, $\mathcal{A}_2$, $\mathcal{B}_1$, $\mathcal{B}_2$, and $\mathcal{N}_2$ by $\tilde{\mathcal{A}}_1$, $\tilde{\mathcal{A}}_2$, $\tilde{\mathcal{B}}_1$, $\tilde{\mathcal{B}}_2$ and $\tilde{\mathcal{N}}_2$.

In addition, for the sake of model formulation, we set,

$$z_h = \begin{cases} 0, & \text{for } \forall h \in \mathcal{N}_0 \\ 1, & \text{for } \forall h \in \mathcal{N}_1 \end{cases} \tag{7.5}$$

These decision variables can be represented by a vector **s** = (**x**, **y**, **z**), which is written as,

$$\begin{aligned} \mathbf{s} &= \left(x_a, a \in \left(\tilde{\mathcal{A}}_1 \cup \tilde{\mathcal{A}}_2 \right); y_a, b \in \left(\tilde{\mathcal{B}}_1 \cup \tilde{\mathcal{B}}_2 \right); z_h, h \in \mathcal{N} \right) \\ &= \left(s_i, i = 1, 2, \ldots, n_{\mathbf{s}} \right) \end{aligned} \tag{7.6}$$

where $n_{\mathbf{s}}$ represents the number of variables included in **s**.

Given a feasible solution of hinterland network design decision **s**, intermodal operators will make route choice to transport containers between all O/D pairs based on the physical and operational networks determined by **s**. The resulting container flow distribution over the operational network, **v**, on the other hand, provides a basis for the planner to make hinterland network design decisions.

7.3 Mathematical Expression of Port Market Share

As for an intermodal operator who intends to transport containers of T_{od} from $o \in O$ to $d \in \mathcal{D}$, summing the probabilities of the intermodal operator choosing those intermodal routes that traverse through the transfers at port *P* gives the probability of the intermodal operator selecting *P* to deal with containers, which is denoted by P_{od}^{P}, namely

$$P_{od}^{P} = \sum_{\bar{l} \in T_P} \sum_{\bar{r} \in R_{od}} \delta_{od}^{\bar{r}\bar{l}} P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right), \forall o \in O, d \in \mathcal{D} \tag{7.7}$$

where $P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right)$ is the probability that route r has the maximum utility among all the routes in set R_{od}, namely,

$$P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right) = \Pr \left[U_{od}^{\bar{r}} \left(\mathbf{v}, \mathbf{s} \right) \geq U_{od}^{\bar{k}} \left(\mathbf{v}, \mathbf{s} \right) \middle| \forall \bar{k} \in R_{od} \text{ and } \bar{r} \neq \bar{k} \right] \tag{7.8}$$

For the probit-based SUE, the probability defined in Eqn. (7.8) can be further represented by,

$$\begin{aligned} P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right) = & \int_{x_{1_{od}} \leq u_{od}^{\bar{r}} (\mathbf{v}, \mathbf{s})} \cdots \int_{u_{od}^{\bar{r}} (\mathbf{v}, \mathbf{s}) = -\infty}^{u_{od}^{\bar{r}} (\mathbf{v}, \mathbf{s}) = \infty} \cdots \int_{x_{\bar{I}_{od}} \leq u_{od}^{\bar{r}} (\mathbf{v}, \mathbf{s})} \left[\left(2\pi \right)^{\bar{I}_{od}} \left| \Sigma_{od} \right| \right]^{-0.5} \\ & \times \exp \left[-0.5 \left(\mathbf{x}_{od} - \mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right)^{T} \left(\Sigma_{od} \right)^{-1} \left(\mathbf{x}_{od} - \mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right) \right] \\ & dx_{1_{od}} dx_{2_{od}} \ldots dx_{\bar{I}_{od}} \end{aligned} \tag{7.9}$$

Based on Eqn. (7.7) and the definition of port market share, the port market share of port P with respect to study area S can thus be mathematically expressed by,

$$\alpha_P \left(\mathbf{v}, \mathbf{s} \right) = \frac{\sum_{o \in O} \sum_{d \in \mathcal{D}} P_{od}^{P} T_{od}}{\sum_{o \in O} \sum_{d \in \mathcal{D}} T_{od}} = \frac{\sum_{o \in O} \sum_{d \in \mathcal{D}} \sum_{\bar{l} \in T_P} \sum_{\bar{r} \in R_{od}} T_{od} \delta_{od}^{\bar{r}\bar{l}} P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right)}{\sum_{o \in O} \sum_{d \in \mathcal{D}} T_{od}} \tag{7.10}$$

Given a solution of $\mathbf{s}$, a feasible SUE-based network flow pattern $\mathbf{v}$ fulfills the following two fixed-point formulations,

$$v_{\bar{a}} = \sum_{o \in O} \sum_{d \in D} \sum_{\bar{r} \in R_{od}} T_{od} \delta_{od}^{\bar{r}\bar{a}} P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right), \forall \bar{a} \in A \tag{7.11}$$

$$v_{\bar{l}} = \sum_{o \in O} \sum_{d \in D} \sum_{\bar{r} \in R_{od}} T_{od} \delta_{od}^{\bar{r}\bar{l}} P_{od}^{\bar{r}} \left(\mathbf{u}_{od} \left(\mathbf{v}, \mathbf{s} \right) \right), \forall \bar{l} \in T \tag{7.12}$$

The port market share $\alpha_P \left(\mathbf{v}, \mathbf{s} \right)$ can thus be rewritten as,

$$\alpha_P \left(\mathbf{v}, \mathbf{s} \right) = \sum_{\bar{l} \in T_P} v_{\bar{l}} \Big/ \sum_{o \in O} \sum_{d \in \mathcal{D}} T_{od} \tag{7.13}$$

7.4 Model Formulation

The PMSO problem can be formulated as the following MPEC model:

$$(PMSO)\ \max\ \alpha_P\left(\mathbf{v},\mathbf{s}\right)=\sum_{\bar{l}\in T_P} v_{\bar{l}}\ /\sum_{o\in O}\sum_{d\in\mathcal{D}} T_{od} \tag{7.14}$$

subject to

$$\sum_{a\in\left(\tilde{\mathcal{A}}_1\cup\tilde{\mathcal{A}}_2\right)} B_a x_a+\sum_{b\in\left(\tilde{\mathcal{B}}_1\cup\tilde{\mathcal{B}}_2\right)} y_b F_b\le B \tag{7.15}$$

$$\sum_{b\in\mathcal{B}_h} y_b\ge z_h,\text{for }\forall h\in\tilde{\mathcal{N}}_2 \tag{7.16}$$

$$\sum_{b\in\mathcal{B}_h} y_b\le Mz_h,\text{for }\forall h\in\tilde{\mathcal{N}}_2 \tag{7.17}$$

$$x_a\le z_{\tilde{h}_a}+z_{\tilde{t}_a},\text{for }\forall a\in\tilde{\mathcal{A}}_2 \tag{7.18}$$

$$\kappa_a\beta_a\sum_{\bar{a}\in A_a} v_{\bar{a}}\ /\ \eta_a\le\left(1-x_a\right)\Gamma_a+x_a\Theta_a,\text{for }\forall a\in\left(\tilde{\mathcal{A}}_1\cup\tilde{\mathcal{A}}_2\right) \tag{7.19}$$

$$\kappa_a\beta_a\sum_{\bar{a}\in A_a} v_{\bar{a}}\ /\ \eta_a\le\Gamma_a,\text{for }\forall a\in\left(\mathcal{A}-\left(\tilde{\mathcal{A}}_1\cup\tilde{\mathcal{A}}_2\right)\right) \tag{7.20}$$

$$\sum_{\bar{l}\in T_b} v_{\bar{l}}\le\left(1-y_b\right)\Gamma_b+y_b\Theta_b,\text{for }\forall b\in\mathcal{B}_h,h\in\tilde{\mathcal{H}} \tag{7.21}$$

$$\sum_{\bar{l}\in T_b} v_{\bar{l}}\le\Gamma_b,\text{for }\forall b\in\mathcal{B}_h,h\in\left(\mathcal{H}-\tilde{\mathcal{H}}\right) \tag{7.22}$$

$$v_{\bar{a}}\le\Gamma_{\bar{a}},\text{for }\forall\bar{a}\in A \tag{7.23}$$

$$v_{\bar{a}}=\sum_{o\in O}\sum_{d\in D} T_{od}P_{od}^{\bar{a}}\left(\mathbf{g}\left(\mathbf{v},\mathbf{s}\right)\right),\text{for }\mathbf{v}\in\Omega\left(\mathbf{s}\right),\bar{a}\in A \tag{7.24}$$

$$v_{\bar{l}}=\sum_{o\in O}\sum_{d\in D} T_{od}P_{od}^{\bar{l}}\left(\mathbf{g}\left(\mathbf{v},\mathbf{s}\right)\right),\text{for }\mathbf{v}\in\Omega\left(\mathbf{s}\right),\bar{l}\in T \tag{7.25}$$

where $\Omega\left(\mathbf{s}\right)$ is the set of feasible container flow pattern in G resulting from the SUE-based route choice of intermodal operators defined as,

$$\Omega(\mathbf{s}) = \Big\{ \mathbf{v} \mid v_{\bar{a}} = \sum_{o\in O} v_{\bar{a}}^{o}, \forall \bar{a} \in A; v_{\bar{l}} = \sum_{o\in O} v_{\bar{l}}^{o}, \forall \bar{l} \in T \tag{7.26}$$

$$\sum_{\bar{a}\in A_n^1} v_{\bar{a}}^{o} = T_{on}, \forall n \in \mathcal{N}_0, o \in O, o \neq n \tag{7.27}$$

$$v_{\bar{a}_i^1}^{o} - T_{oi} = \sum_{\bar{l}\in T_i^2} v_{\bar{l}}^{o}, \forall i \in N_h^1, h \in \mathcal{H}; o \in O, o \neq i; \tag{7.28}$$

$$\sum_{\bar{l}\in T_j^1} v_{\bar{l}}^{o} = v_{\bar{a}_j^2}^{o}, \forall j \in N_h^2, h \in \mathcal{H}; o \in O, o \neq j; \tag{7.29}$$

$$\sum_{d\in \mathcal{D}} T_{od} = \sum_{\bar{a}\in A_o^2} v_{\bar{a}}^{o}, \forall o \in O \cup \bar{\mathcal{H}} \tag{7.30}$$

$$\sum_{d\in \mathcal{D}} T_{od} = \sum_{\bar{l}\in T_o^b} v_{\bar{l}}^{o}, \forall b \in \mathcal{B}_o, \forall o \in \mathcal{H} \tag{7.31}$$

$$\sum_{i\in N_h^1} T_{oi} = T_{oh}, \forall h \in \mathcal{H}, o \in O \tag{7.32}$$

$$v_{\bar{a}} \leq M x_a, \forall \bar{a} \in A_a, a \in \tilde{\mathcal{A}}_2 \tag{7.33}$$

$$v_{\bar{l}} \leq M y_b, \forall \bar{l} \in T_b, b \in \mathcal{B}_h^2, h \in \tilde{\mathcal{H}} \tag{7.34}$$

$$v_{\bar{a}}^{o} \geq 0, \forall \bar{a} \in A; v_{\bar{l}}^{o} \geq 0, \forall \bar{l} \in T \Big\} \tag{7.35}$$

Eqn. (7.14) maximizes the port market share. Constraint (7.15) is budget limit constraint. Constraints (7.16)-(7.17) ensures that if a transfer terminal is chosen to be established in the hinterland network, at least one transshipment line will be established at the transfer terminal; no transshipment line will be established otherwise. Constraint (7.18) assures that no new direct links will be built in the hinterland network. Constraints (7.19)-(7.23) are capacity constraints for physical links, transshipment lines and carrier links. Fixed-point formulations (7.24)-(7.25) gives the SUE-based network flow pattern in the operational network. Eqn. (7.26) represents the relation between origin-based flows and link flows. Eqns. (7.27)-(7.32) represent flow conservation conditions in the operational network and Constraints (7.33)-(7.34) reflects the relation between network design decisions and the network flow pattern. Constraint (7.35) guarantees nonnegative network flows.

7.5 Solution Algorithm

The above-formulated PMSO model is hard to solve due to its non-convexity and non-differential characteristics. A branch-and-bound algorithm with an embedded cost averaging algorithm can be designed to solve the model. The basic principle of the algorithm has been explained in detail in CHAPTER 5.

Unlike the branch-and-bound algorithm proposed in CHAPTER 5, in the algorithm developed in this chapter, the linearization of the objective function is no more needed for solving the PMSO model, since the objective function (7.14) is a linear sum. In addition, upper bounds instead of lower bounds on objective function (7.14) should be calculated in solving the PMSO model that maximizes port market share. The upper bound with respect to the current tree node q with depth of d_q can be computed by solving the following mixed-integer linear programming model,

$$(PMSO\text{-}1)\ \max\ \alpha_P\left(\mathbf{v},\mathbf{s}\right)=\sum_{\bar{l}\in T_P} v_{\bar{l}} \,/ \sum_{o\in O}\sum_{d\in\mathcal{D}} T_{od} \tag{7.36}$$

(7.15)-(7.23), (7.26)-(7.35)

$$\mathbf{s}=\left(\mathbf{x},\mathbf{y},\mathbf{z}\right)\in S\left(q\right) \tag{7.37}$$

in which the set $S(q)$ contains all possible completions of the partial solution identified with node q, namely,

$$S\left(q\right)=\left\{\mathbf{s}\left|\begin{array}{c} s_i \text{ has been assigned value of 0 or 1, } i=1,2,\ldots,d_q; \\ s_j=0 \text{ or } 1,\, j=d_q+1,\ldots,n_{\mathbf{s}} \end{array}\right.\right\} \tag{7.38}$$

The branch-and-bound algorithm for the PMSO problem is briefly described in the following steps.

Branch-and-bound Algorithm

Step 0. (*Initialization*) The root node is marked as an unvisited node and the tree depth at the root node is zero. Find a feasible solution of $(\mathbf{s}, \mathbf{v})$, namely $(\mathbf{s}_0, \mathbf{v}_0)$. Let $\alpha(\mathbf{s}_0, \mathbf{v}_0)$ be the initial incumbent value and go to step 1.

Step 1. (*Node selection*) An unvisited node q at the deepest level is selected and the branch-and-bound algorithm carries out a depth-first search. Go to step 2.1 if $d_q < n_{\mathbf{s}}$; go to step 2.2 if $d_q = n_{\mathbf{s}}$.

Step 2. (*Constraint validation*) The partial solution or complete solution identified with node q is validated in this step.

Step 2.3. In the partial solution identified with node q, the integer decision variables which have been specified values of 1 or 0 must satisfy constraints (7.15)-(7.18) if applicable. Mark node q as a visited node and go to step 7 if any of these constraints is violated; go to step 4 otherwise.

Step 2.4. Given the complete solution of $\mathbf{s}$ identified with node q, $\mathbf{s}_q$, the SUE-based network flow pattern defined by (7.24)-(7.25), $\mathbf{v}_q$ as a possible solution of $\mathbf{v}$, can be computed by using the cost averaging algorithm. The solution $(\mathbf{s}_q, \mathbf{v}_q)$ must satisfy the constraints (7.15)-(7.23). Mark node q as a visited node and go to step 7 if any of these constraints is violated; go to step 3 otherwise.

Step 3. (*Updating the incumbent value*) Replace the current incumbent value by $\alpha(\mathbf{s}_q, \mathbf{v}_q)$, mark node q as a visited node, and go to step 7 if $\alpha(\mathbf{s}_q, \mathbf{v}_q)$ is greater than the current incumbent value; go to step 7 without updating the incumbent value otherwise.

Step 4. (*Upper bound calculation*) Calculate the upper bound evaluated on $S(q)$ by solving *PMSO*-1 using the CPLEX software package. Go to step 5.

Step 5. (*Pruning*) Node q is fathomed and marked as a visited node if the upper bound value is less than the current incumbent value or *PMSO*-1 is infeasible and go to step 7; go to step 6 otherwise.

Step 6. (*Branching*) Two child nodes will be spawned from node q. Node q is marked as a visited node and go to step 1.

Step 7. (*Stopping test*) The algorithm stops if all nodes are visited; go to step 1 otherwise.

The embedded cost averaging algorithm has been described in the solution algorithm section of CHAPTER 5.

7.6 Numerical Example

This section aims to compute the optimal market share of the port of Shenzhen with a concerned study area *S* by using hinterland network design given budget $B = 30$. Fig. 7.1 shows the study area *S* and an intermodal network $\mathcal{G}$ serving the area. In Fig. 7.1, the hinterland network, $\tilde{\mathcal{G}}$, of the port of Shenzhen is indicated by a shadow area. The characteristics of links and nodes and O/D matrix of network $\mathcal{G}$ are shown in Tables C.1 and C.2. The parameter values for cost functions and utility functions are shown in Table

5.1 and Table 5.2, respectively, and the remaining parameter values used in solution algorithm are the same as those adopted in Section 5.6.

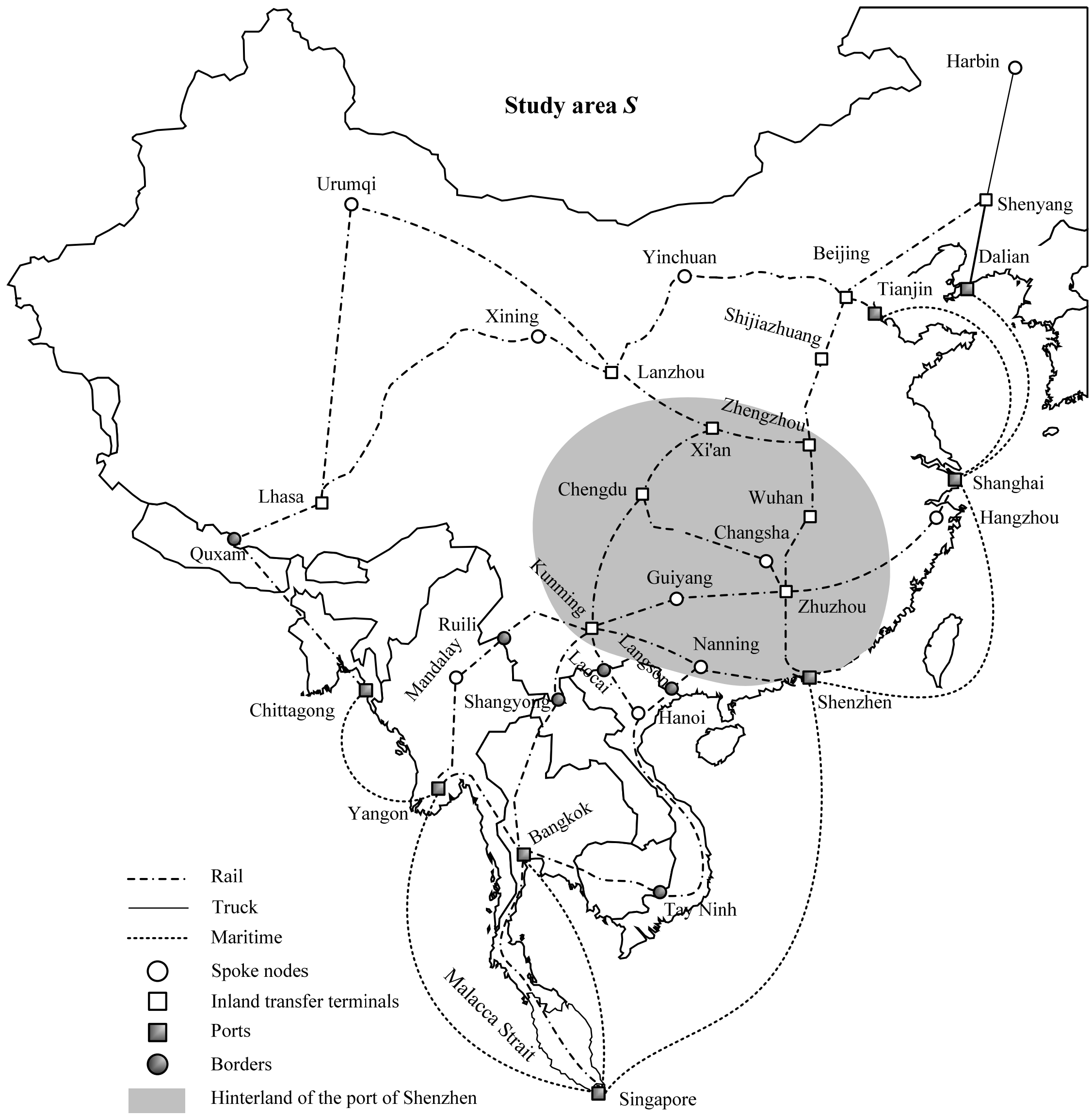

Fig. 7.1 An example intermodal network with hinterland of Shenzhen Port

The physical links, transfer terminals and transshipment lines to be planned in the hinterland of Shenzhen port and the optimal investment decisions, and the hypothetical investment decision with all network elements established are tabulated in Table 7.1.

Table 7.2 shows the market shares of selected Asian ports with respect to the optimal and hypothetical solutions.

Table 7.1 Hinterland Network Elements to be Planned

Network Elements	The Optimal Solution	The Hypothetical Solution
Location of Wuhan	1	1
Location of Zhuzhou	1	1
Location of Kunming	0	1
{rail-rail} at Wuhan	1	1
{rail-rail} at Zhuzhou	1	1
{rail-rail} at Kunming	0	1
Rail link Chengdu → Xi'an	0	1
Rail link Xi'an → Zhengzhou	0	1
Rail link Zhengzhou → Wuhan	0	1
Rail link Wuhan → Zhuzhou	1	1
Rail link Zhuzhou → Shenzhen	1	1
Rail link Xi'an → Chengdu	0	1
Rail link Zhengzhou → Xi'an	1	1
Rail link Wuhan → Zhengzhou	1	1
Rail link Zhuzhou → Wuhan	1	1
Rail link Shenzhen → Zhuzhou	1	1

Table 7.2 Market Shares of Selected Asian Port

Ports	Market Share	
	The Optimal Solution	The Hypothetical Solution
Dalian	0.040498	0.000000
Tianjin	0.069650	0.019756
Shanghai	0.181327	0.085679
Shenzhen	0.691864	0.650523
Bangkok	0.053828	0.049933
Yangon	0.068549	0.040832
Chittagong	0.044707	0.018310
Singapore	0.424915	0.383980

As indicated in Table 7.2, the market share of the port of Shenzhen is maximized by making the optimal network decisions, which is greater than that of other Asian ports. Under the optimal solution, the ports of Shanghai, Tianjin and Singapore also enjoy a favorable market share. These four ports seem to prevail in competing with other selected ports in terms of port market share. The phenomenon somewhat results from the fact that the amount of containers originating from these three ports is sizable.

An interesting finding is that the market share of the port of Shenzhen will experience a loss if the hypothetical network decision is made, i.e., all hinterland network elements are assumed to exist. At the same time, other ports such as the ports of Shanghai and Singapore also witness a decrease in its market shares. This result is rendered by the phenomenon that, once all the hinterland elements is established, intermodal operators will be inclined to choose inland transportation modes rather than maritime services to transport containers. The resultant mode choice of intermodal operators is caused by the fact that establishing all hinterland network elements, on the other hand, gives a highly accessible and efficient inland freight transportation network for intermodal operators. Therefore, an optimal port hinterland network design strategy is crucial for maintaining or expanding the market share of a port. The comparison of port market shares with respect to the optimal and hypothetical solution indicates the importance of the proposed model and algorithm in maximizing the market share of a particular port.

7.7 Conclusions

This chapter aims to solve the PMSO problem using port hinterland network design based on the work carried out in CHAPTER 4 and CHAPTER 5. The mathematical expression of the market share of a particular port was first derived with respect to a concerned study area. An MPEC model was then developed with the aim to maximize the port market share. In the MPEC model, the binary decision variables represent hinterland network design decisions. To solve the model, a branch-and-bound algorithm was designed. Numerical examples were finally given to compute the optimal port market share of Shenzhen port as well the corresponding market shares of several selected Asian ports under the optimal and hypothetical solution. The findings indicate the importance and applicability of the the proposed model and algorithm in solve the PMSO problem.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Overview and Contributions of the Work

This work was performed toward achieving the threefold objectives proposed in CHAPTER 1: (i) to develop a modeling approach for probabilistic port hinterland estimation, (ii) to develop a mathematical model and solution algorithm for solving the IHSND problem, and (iii) to address the port hinterland optimization problem based on the realizations of the first two objectives. The conclusions and contributions of the work are elaborated in the following sections.

8.1.1 Probabilistic Port Hinterland Estimation

To realize the first objective, the attribute- and utility-based probabilistic port hinterland estimation approaches have been developed in CHAPTER 3 and CHAPTER 4, respectively.

8.1.1.1 Attribute-based Probabilistic Port Hinterland Estimation Approach

CHAPTER 3 proposed a quantitative approach to estimating the probabilistic hinterland of a particular port in terms of a concerned attribute of intermodal routes in the context of intermodal freight transportation operations.

A new definition of port hinterland - probabilistic port hinterland - was first proposed with respect to a given destination, which in reality contributes a new insight to examine the competiveness of a port while it is inspired by the discrete choice analysis models. Then a mathematical model was proposed to formulate the probabilistic port hinterland using transportation cost as an instance of the concerned attribute. The model formulation is based on the assumption of multivariate normally distributed intermodal routes between an origin and the given destination in terms of transportation cost and the investigation of piecewise-linear characteristics of an intermodal route in terms of the expected value of route transportation cost. To solve the model, a Monte Carlo simulation based solution algorithm was subsequently designed. The algorithm includes an interesting boundary curve fitting procedure that embeds a cluster analysis approach and the least squares estimation method. In addition, a lower bound on the sample size required in Monte Carlo simulation was derived at a significance level of 95%.

The literature review conducted in CHAPTER 2 explicitly indicates that the study on attribute-based probabilistic port hinterland estimation makes the first initiative to model and quantitatively estimate the probabilistic hinterland of a port. Numerical examples were also given to show the applicability of the model and algorithm.

8.1.1.2 Utility-based Probabilistic Port Hinterland Estimation Approach

CHAPTER 4 proposed a utility-based probabilistic port hinterland estimation approach from the point of view of an intermodal network. The approach extends the work of CHAPTER 3 by taking into account (i) a realistic intermodal network where shippers are not stipulated to exist at each point, (ii) intermodal route utility involving transportation cost and time, and (iii) batch-arrival process of containers at transfer terminals.

To identify the utility-based probabilistic port hinterland for intermodal freight transportation networks, a batch-arrival queuing model was initially utilized to estimate transfer time incurred at a transfer terminal. The queueing model not only practically mimics the realistic transshipment processes at transfer terminals, but also remedies the limitation of those vehicle-oriented stochastic queueing models for analyzing transfer time expensed at transfer terminals at which containers arrive in batches. Such a transfer time results in that the random utility of an intermodal route does not constantly posses an analytically expressed distribution such normal or exponential distribution. The random route utility was further defined as a negative sum of costs incurred in various components of the route and correspondingly incurred times multiplied by VOT.

Assuming that shippers follow the utility-maximization principle to choose a route, the utility-based probabilistic port hinterland was mathematically formulated. Moreover, a Monte Carlo simulation based method was proposed to find the probabilistic port hinterland.

8.1.2 Intermodal Hub-and-Spoke Network Design Methods

To serve the third objective, this study focused on investigating a new IHSND problem, which is defined as follows: given an intermodal freight transportation network and budget limit, the network planner attempts to re-design it as an optimal intermodal hub-and-spoke network by determining hub locations, transshipment line and link configurations with the objective of minimizing the total network cost of carriers.

8.1.2.1 Characteristics of the IHSND problem

The problem has the following unique characteristics, as compared to the conventional HSND problem: (i) an intermodal route may traverse more than two hubs and all hubs are less than fully interconnected, (ii) a flexible cost function reflecting the transition from economies of scale to diseconomies of scale and the relation between multi-type container flows is suggested for carriers, (iii) transshipment lines need to be designed and container transfer processes at hubs are adequately modeled as transfers, (iv) the network design is simultaneously determined by the interactive decisions of multiple stakeholders - the network planner, intermodal operators and carriers -, and (v) multi-type containers may be involved. By considering these five features, this study takes the first initiative to investigate the IHSND problem from a more realistic point of view, which actually contributes a new perspective to network design theories.

To formulate the problem, we first define two correlated networks: physical network and operational network. The planner intends to re-design the former one, and based on the latter one, intermodal operators will route containers via available intermodal routes according to their route choice behaviors. The container transfer processes at hubs in the operational network are modeled as a series of transfers that traverse through specific mode-change transshipment lines.

Next, the IHSND problem was addressed in this study through solving the IHSND problem with uni-type and multi-type containers in CHAPTER 5 and CHAPTER 6, respectively.

8.1.2.2 An MPEC Method for IHSND with Uni-type Containers

In addressing the IHSND problem with uni-type containers, a cost function that is capable of reflecting the transition from scale economies to scale diseconomies in distinct flow regimes was suggested for describing the cost structure of carriers. The utility function that integrates actual transportation charges and congestion impact was proposed to represent an intermodal operator's preference toward a carrier.

An MPEC model was developed for the IHSND problem by using the cost and utility functions. The model includes two fixed-point formulations that reflects the SUE-based route choice of intermodal operators for any given network design decision. To solve the MPEC model, we represented the non-convex cost function in the objective function as a piece-wise linear function. An effective branch-and-bound algorithm with an embedded cost averaging algorithm for solving the SUE-based network flow pattern was subsequently designed. In the solution procedure, the lower bound was obtained by solving a mixed-integer programming model after the linearization and relaxation of the original IHSND problem. Two numerical examples were finally given to show the applicability of the proposed model and solution algorithm.

8.1.2.3 An MPEC Method for IHSND with Multi-type Containers

In addressing the IHSND problem with multi-type containers, a multiproduct cost function that is capable of reflecting the transition from scale economies to scale diseconomies in distinct flow regimes and the relation between multi-type container flows was suggested for carriers. A utility function that integrates actual transportation rates and congestion impacts is proposed for intermodal operators.

An MPEC model was then developed based on these two functions. The model incorporates a parametric VI that reflects the UE behavior of intermodal operators in route choice given any network design decision. The non-convex and multiproduct cost function brings a major challenge in solution algorithm design. To solve this MPEC model, a hybrid genetic algorithm (HGA) with an embedded diagonalization method for solving the asymmetric freight flow assignment problem was developed. The HGA, simple genetic algorithm (SGA) and exhaustive enumeration algorithm (EEA) were compared to assess the effectiveness of the proposed solution algorithm. The comparative analysis of the three algorithms indicates a good performance of the HGA in terms of computational time and solution quality. The applicability of the HGA was also tested in a large-scale IHSND problem.

8.1.3 Port Market Share Optimization using Hinterland Network Design

Based on the realizations of the first two objectives, objective (iii) was achieved by formulating the PMSO problem as an MPEC model and solved by using a branch-and-bound algorithm embedding with a CA algorithm for obtaining the SUE-based network flow pattern in CHAPTER 7. The study on the PMSO makes the first move to investigate port hinterland optimization problem in terms of port market share by using hinterland network design.

To formulate the problem, a mathematical expression of the market share of a particular port was derived by taking into account all O/D demands in a concerned study area from a network's point of view. The port market share contributes a different perspective to gauge the competitiveness of the particular port from port hinterland, and quantifies the market quota taken by the port. An MPEC model was then proposed maximizing the port market share, and a branch-and-bound algorithm was designed to solve the model, in which the upper bound on the objective function with respect to each search node is obtained by solving a relaxed version of the MPEC model. A numerical example was finally given to show the applicability of the proposed model and algorithm.

8.2 Future Research Recommendations

For future research, it would be of high value to address the following recommended research topics based on the work accomplished in this study:

(i) A queueing network model can be developed to formulate the intermodal freight transportation operations in a congested intermodal freight transportation network, based on which analytical closed-form time functions would be derived for transfer time at transfer terminals and transportation time over physical links.

(ii) A SUE-based predictive model for multi-type container flow analysis can be developed by taking into account the interactive decision process between intermodal operators and carriers. A multi-type container transportation cost function (multiproduct cost function) should be used to describe the cost structure of carriers. Analytical transfer and transportation cost functions derived by using the queueing network model proposed in topic (i) should be utilized to describe the time structure of carriers. The cost and time functions of carriers provide a basis for formulating the utility function of intermodal operators.

(iii) The IHSND problem should be revisited by using the predictive analysis model for multi-type container transportation proposed in the second topic.

(iv) The PMSO problem should be resolved by using the IHSND approach developed in topic (iii).

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APPENDIX A

AN LOWER BOUND FOR THE SQUARE ROOT

$$SR = \sqrt{\sum_{r_{xy} \in R_P(x,y)} \left[p_{r_{xy}} \left(1 - p_{r_{xy}} \right) \middle/ N \right] - \sum_{\forall r_{xy}, k_{xy} \in R_P(x,y); r_{xy} \neq k_{xy}} \left(p_{r_{xy}} p_{k_{xy}} / N \right)}$$

Let a row vector $\mathbf{P}_{r_{xy}} = \left(p_{r_{xy}} : r_{xy} \in R_P(x, y) \right)$ and a multivariate function:

$$Z\left(\mathbf{P}_{l_{xy}}\right) = \sum_{r_{xy} \in R_P(x,y)} p_{r_{xy}} \left(1 - p_{r_{xy}}\right) - \sum_{\forall r_{xy}, k_{xy} \in R_P(x,y); r_{xy} \neq k_{xy}} p_{r_{xy}} p_{k_{xy}} \tag{A.1}$$

We build a linearly constrained strictly concave maximization problem as follows:

$$\max Z\left(\mathbf{P}_{r_{xy}}\right) = \sum_{r_{xy} \in R_P(x,y)} p_{r_{xy}} \left(1 - p_{r_{xy}}\right) - \sum_{\forall r_{xy}, k_{xy} \in R_P(x,y); r_{xy} \neq k_{xy}} p_{r_{xy}} p_{k_{xy}} \tag{A.2}$$

subject to

$$\sum\nolimits_{r_{xy} \in R_P(x,y)} p_{r_{xy}} \leq 1 \tag{A.3}$$

$$p_{r_{xy}} \geq 0, \forall r_{xy} \in R_P(x, y) \tag{A.4}$$

In the case of $\left| R_P(x, y) \right| = 1$, where $\left| R_P(x, y) \right|$ denotes the cardinality of set $R_P(x, y)$, it is straightforward to check that the minimization model (A.2) – (A.4) has the optimal objective function value:

$$Z_{\max} = \frac{1}{4} \tag{A.5}$$

If $\left| R_P(x, y) \right| \geq 2$, the optimal solution of the concave maximization model (A.2) – (A.4) should fulfill the Karush-Kuhn-Tucker (KKT) conditions (Bazaraa et al., 2006):

$$2p_{r_{xy}} - 1 + \sum_{k_{xy} \in R_P(x,y), k_{xy} \neq r_{xy}} p_{k_{xy}} + \beta - \mu_{r_{xy}} = 0, \forall r_{xy} \in R_P(x,y) \tag{A.6}$$

$$p_{r_{xy}} \mu_{l_{xy}} = 0, \forall r_{xy} \in R_P(x,y) \tag{A.7}$$

$$\beta\left(\sum_{r_{xy} \in R_P(x,y)} p_{r_{xy}} - 1\right) = 0 \tag{A.8}$$

$$\mu_{r_{xy}} \geq 0, \forall r_{xy} \in R_P(x,y) \tag{A.9}$$

$$\beta \geq 0 \tag{A.10}$$

$$\sum_{r_{xy} \in R_P(x,y)} p_{r_{xy}} \leq 1 \tag{A.11}$$

$$p_{r_{xy}} \geq 0, \forall r_{xy} \in R_P(x,y) \tag{A.12}$$

Solving Eqns. (A.6)-(A.12) yields the optimal solution and Lagrangian multipliers as follows:

$$p^*_{r_{xy}} = \frac{1}{\left|R_P(x,y)\right| + 1}, \forall r_{xy} \in R_P(x,y) \tag{A.13}$$

$$\mu^*_{r_{xy}} = 0, \forall r_{xy} \in R_P(x,y) \tag{A.14}$$

$$\beta^* = 0 \tag{A.15}$$

Substituting the optimal solution shown in Eqn. (A.13) into the objective function of the maximization model, it follows that,

$$Z_{\max} = \left[\frac{\left|R_P(x,y)\right|}{\left(\left|R_P(x,y)\right| + 1\right)^2}\right] \tag{A.16}$$

According to Eqns. (A.5) and (A.16), it follows that

$$SR \le \begin{cases} 0.5\sqrt{\dfrac{1}{N}}, & \left|R_P\left(x,y\right)\right| = 1 \\ \dfrac{1}{\left(\left|R_P\left(x,y\right)\right|+1\right)}\sqrt{\dfrac{\left|R_P\left(x,y\right)\right|}{N}}, & \left|R_P\left(x,y\right)\right| \ge 2 \end{cases} \tag{A.17}$$

APPENDIX B

TRANSFER TIME OF A PARTICULAR CONTAINER AT A TRANSFER TERMINAL

We aim to derive the transfer time for a specific container at a transfer terminal. The transshipment process at transfer terminal $h \in \mathcal{H}$ is modeled as an $M^{[X]}/G/1$ queue, in which containers arrive in batches according to a compound Poisson process with parameter λ. The batch size X is assumed to be a generally distributed discrete random variable having the following PMF (Probability Mass Function),

$$P\left(X=i\right)=\beta_i, i=1,2,... \tag{B.1}$$

The PGF (Probability Generating Function) and mean value of X are denoted by $P_X\left(z\right)$ and $\bar{X}$ respectively and we have

$$P_X\left(z\right)=\sum_{i=1}^{\infty}\beta_i z^i \tag{B.2}$$

Let Y denote the size of the batch including the specific container and the probability that the specific container arrives in a batch of size j can be calculated by

$$P\left(Y=j\right)=\frac{j\beta_j}{\bar{X}}, j=1,2,... \tag{B.3}$$

The first-in-first-out handling discipline is applied between batches and containers within a batch are served in a random order following the discrete uniform distribution. The order at which the specific container arriving in a batch of size j is served is denoted by a random variable Z, which is calculated by

$$P\left(Z=k \middle| Y=j\right)=\frac{1}{j}, k=1,2,...,j \tag{B.4}$$

The handling time for the particular container is denoted by a generally distributed random variable, $\tilde{W}$, with mean value $1/\mu$. Let $\tilde{w}(t)$ be the PDF (Probability Density Function) of $\tilde{W}$ and $\tilde{w}^e(s)$ be its Laplace transform. To guarantee that the queueing system has a steady-state distribution, the following equation must be satisfied,

$$\rho=\frac{\lambda\overline{X}}{\mu}<1 \tag{B.5}$$

Note that the reciprocal of mean value of the handling time at a transfer terminal corresponds to the terminal handling capacity in the practical handling operation.

The transfer time can be obtained by summing the waiting time of the specific container before getting served in the queue, W, and the handling time, $\tilde{W}$, provided by the terminal operator. W can be further partitioned into two components: (i) the waiting time of the first container arriving in the same batch with the specific container, W_1 and (ii) the delay caused by the service times of the containers prior to the specific container in the same batch, W_2, i.e. $W=W_1+W_2$. The Laplace transform of the density function of W_1, $w_1^e(s)$, can be easily derived by regarding the $M^{[X]}/G/1$ queue as a $M/G/1$ queue with arriving batches as individual customers. The $w_1^e(s)$ is written as

$$w_1^e(s)=\frac{s(1-\rho)}{s-\lambda\left[1-P_X\left(\tilde{w}^e(s)\right)\right]} \tag{B.6}$$

Conditioning on that the specific container arrives in a batch of size j and the container is k^{th} handled customer in the batch, W_2 can be rewritten as

$$W_2=\sum_{i=1}^{k-1}\tilde{W}_i \tag{B.7}$$

where $\tilde{W}_i$ is the handling time of the i^{th} container in the batch. All $\tilde{W}_i's$ are identical and independent random variables having the PDF $\tilde{w}(t)$. We thus have

$$\begin{aligned} P(W_2 \le t) &= \sum_{j=1}^{\infty}\sum_{k=1}^{j} P\left(W_2 \le t \middle| Z = k, Y = j\right) P\left(Z = k \middle| Y = j\right) P(Y = j) \\ &= \sum_{j=1}^{\infty}\sum_{k=1}^{j} P\left(\sum_{i=1}^{k-1}\tilde{W}_i \le t\right)\frac{\beta_j}{\bar{X}} \end{aligned} \tag{B.8}$$

The Laplace transform of the density function of W_2, $w_2^e(s)$, can be represented by

$$w_2^e(s) = \sum_{j=1}^{\infty}\frac{\beta_j}{\bar{X}}\frac{1-\left[\tilde{w}^e(s)\right]^i}{1-\tilde{w}^e(s)} = \frac{1-P_X\left[\tilde{w}^e(s)\right]}{\bar{X}\left(1-\tilde{w}^e(s)\right)} \tag{B.9}$$

The transfer time $\tilde{T}_h$ can be thus represented by

$$\tilde{T}_h = W_1 + W_2 + \tilde{W} \tag{B.10}$$

Let $\tilde{f}_h(t)$ be the PDF of $\tilde{T}_h$ and its Laplace transform $\tilde{f}_h(t)$ can be expressed by

$$\tilde{f}_h^e(s) = \frac{s(1-\rho)}{s-\lambda\left[1-P_X\left(\tilde{w}^e(s)\right)\right]}\frac{1-P_X\left[\tilde{w}^e(s)\right]}{\bar{X}\left[1-\tilde{w}^e(s)\right]}\tilde{w}^e(s) \tag{B.11}$$

APPENDIX C

LINKS AND NODES OF THE EXAMPLE NETWORK

IN CHAPTERS 5 AND 7

Table C.1 Physical Links and Nodes in the Large-size Example

Nodes			Links		
Id	**Name**	**Type**	**Segment**	**Mode**	**Length**
1	Harbin	spoke	Harbin - Shenyang	truck	654.6
2	Shenyang	transfer terminal	Shenyang - Dalian	truck	385.7
3	Dalian	port	Shenyang - Beijing	rail	751.9
4	Tianjin	port	Beijing - Shijiazhuang	rail	283.1
5	Beijing	transfer terminal	Beijing - Tianjin	rail	118.9
6	Shijiazhuang	transfer terminal	Tianjin - Shanghai	maritime	1229.0
7	Yinchuan	spoke	Dalian - Shanghai	maritime	1038.0
8	Lanzhou	transfer terminal	Shijiazhuang- Zhengzhou	rail	424.8
9	Xian	transfer terminal	Yinchuan - Beijing	rail	1251.9
10	Urumqi	spoke	Yinchuan - Lanzhou	rail	487.3
11	Lhasa	transfer terminal	Urumqi - Lanzhou	rail	1948.1
12	Xining	spoke	Urumqi - Lhasa	rail	2665.6
13	Zhengzhou	transfer terminal	Xining - Lhasa	rail	1904.4
14	Shanghai	port	Xining - Lanzhou	rail	198.6
15	Wuhan	transfer terminal	Lhasa - Quxam	rail	707.3
16	Hangzhou	spoke	Quxam - Chittagong	rail	1311.7
17	Changsha	spoke	Chittagong - Yangon	maritime	735.5
18	Zhuzhou	transfer terminal	Mandalay - Ruili	rail	416.2
19	Chengdu	transfer terminal	Mandalay - Yangon	rail	661.8
20	Guiyang	spoke	Ruili - Kunming	rail	778.1
21	Kunming	transfer terminal	Lanzhou - Xian	rail	607.9
22	Nanning	spoke	Xian - Chengdu	rail	777.4
23	Shenzhen	port	Xian - Zhengzhou	rail	503.5
24	Ruili	border	Chengdu - Kunming	rail	865.2
25	Shangyong	border	Changsha - Chengdu	rail	1316.6
26	Laocai	border	Changsha - Zhuzhou	rail	49.2
27	Hanoi	spoke	Zhengzhou - Wuhan	rail	563.8
28	Tay Ninh	border	Wuhan - Zhuzhou	rail	445.6
29	Bangkok	port	Hangzhou - Zhuzhou	rail	954.0
30	Mandalay	spoke	Hangzhou - Shanghai	rail	193.0
31	Yangon	port	Shanghai - Shenzhen	maritime	1531.7

32	Chittagong	port
33	Quxam	border
34	Singapore	port
35	Langson	border

Guiyang - Zhuzhou	rail	808.5
Guiyang - Kunming	rail	572.2
Nanning - Kunming	rail	909.1
Nanning - Shenzhen	rail	843.4
Zhuzhou - Shenzhen	rail	838.1
Kunming - Shangyong	rail	721.0
Kunming - Laocai	rail	489.8
Hanoi - Laocai	rail	306.5
Hanoi - Langson	rail	140.8
Nanning - Langson	rail	244.9
Hanoi - Tay Ninh	rail	1391.5
Tay Ninh - Bangkok	rail	805.5
Shangyong - Bangkok	rail	1130.0
Yangon - Bangkok	rail	833.0
Bangkok - Singapore	maritime	1557.1
Shenzhen - Singapore	maritime	2621.7
Yangon - Singapore	maritime	1234.3

Table C.2 O/D Demand Matrix for the Large-size Example (1000 TEUs/yr)

Origin *o*	Destination *d*																
	1	5	7	10	12	14	16	17	20	22	23	27	29	30	31	32	34
1	0.00	11.86	1.26	4.03	0.92	16.98	17.35	10.93	3.67	6.97	30.12	2.48	4.97	0.30	0.59	3.30	143.28
5	11.86	0.00	1.75	5.64	1.28	23.63	24.14	15.23	5.11	9.71	41.96	3.46	6.93	0.41	0.83	4.59	199.12
7	1.26	1.75	0.00	0.61	0.14	2.52	2.59	1.63	0.55	1.05	4.51	0.37	0.75	0.04	0.09	0.50	21.53
10	4.03	5.64	0.61	0.00	0.45	8.12	8.26	5.23	1.79	3.36	14.43	1.20	2.41	0.14	0.29	1.64	69.44
12	0.92	1.28	0.14	0.45	0.00	1.85	1.89	1.20	0.41	0.77	3.31	0.28	0.55	0.03	0.07	0.37	15.89
14	16.98	23.63	2.52	8.12	1.85	0.00	35.66	22.28	7.47	14.20	61.67	5.06	10.14	0.60	1.21	6.70	291.66
16	17.35	24.14	2.59	8.26	1.89	35.66	0.00	22.81	7.64	14.53	63.13	5.18	10.38	0.61	1.23	6.85	299.20
17	10.93	15.23	1.63	5.23	1.20	22.28	22.81	0.00	4.89	9.30	40.22	3.31	6.64	0.39	0.79	4.39	190.82
20	3.67	5.11	0.55	1.79	0.41	7.47	7.64	4.89	0.00	3.16	13.53	1.13	2.26	0.13	0.27	1.50	64.90
22	6.97	9.71	1.05	3.36	0.77	14.20	14.53	9.30	3.16	0.00	25.94	2.16	4.33	0.25	0.51	2.84	124.77
23	30.12	41.97	4.51	14.43	3.31	61.67	63.13	40.22	13.53	25.94	0.00	9.24	18.52	1.09	2.20	12.16	532.49
27	2.48	3.46	0.37	1.20	0.28	5.06	5.18	3.31	1.13	2.16	9.24	0.00	1.56	0.09	0.18	1.02	44.89
29	4.97	6.93	0.75	2.41	0.55	10.14	10.38	6.64	2.26	4.33	18.52	1.56	0.00	0.19	0.38	2.08	92.40
30	0.30	0.41	0.04	0.14	0.03	0.60	0.61	0.39	0.13	0.25	1.09	0.09	0.19	0.00	0.02	0.12	5.39
31	0.59	0.83	0.09	0.29	0.07	1.21	1.23	0.79	0.27	0.51	2.20	0.18	0.38	0.02	0.00	0.25	10.94
32	3.30	4.59	0.50	1.64	0.37	6.70	6.85	4.39	1.50	2.84	12.16	1.02	2.08	0.12	0.25	0.00	59.90
34	143.28	199.11	21.53	69.43	15.89	291.64	299.18	190.81	64.90	124.76	532.46	44.89	92.40	5.39	10.94	59.90	0.00

APPENDIX D

LINKS AND NODES OF THE EXAMPLE NETWORK

IN CHAPTER 6

Table D.1 Nodes in the Example Network

Id	Name	Type	Id	Name	Type
1	Changchun	transfer terminal	28	Chongqing	transfer terminal
2	Shenyang	transfer terminal	29	Kunming	transfer terminal
3	Shijiazhuang	transfer terminal	30	Nanning	spoke
4	Jinan	spoke	31	Lhasa	transfer terminal
5	Hefei	spoke	32	Dalian	port
6	Nanjing	spoke	33	Lianyungang	port
7	Wuhan	transfer terminal	34	Shenzhen	port
8	Nanchang	spoke	35	Xuzhou	transfer terminal
9	Fuzhou	port	36	Zhuzhou	transfer terminal
10	Hangzhou	spoke	37	Baoji	spoke
11	Hohhot	spoke	38	Quxam	border
12	Yinchuan	spoke	39	Chuna	border
13	Xian	transfer terminal	40	Ruili	border
14	Chengdu	transfer terminal	41	Shangyong	border
15	Guiyang	spoke	42	Laocai	border
16	Guangzhou	transfer terminal	43	Langson	border
17	Tianjin	port	44	Vientiane	border
18	Harbin	spoke	45	Hanoi	spoke
19	Beijing	transfer terminal	46	Tay Ninh	border
20	Shanghai	port	47	Poipet	border
21	Urumqi	spoke	48	Bangkok	port
22	Xining	spoke	49	Nam Tok	border
23	Haikou	port	50	Yangon	port
24	Taiyuan	spoke	51	Mandalay	spoke
25	Zhengzhou	transfer terminal	52	Chittagong	port
26	Changsha	spoke	53	Padang Besar	border
27	Lanzhou	transfer terminal	54	Singapore	port

Table D.2 Links in the Example Network

Segment	Mode	Length	$\left(x_{a*}, x_{\hat{a}*}\right)$	Segment	Mode	Length	$\left(x_{a*}, x_{\hat{a}*}\right)$
21 -- 27	rail	1178.2	(1,1)	28 -- 15	rail	406.9	(1,0)
21 -- 31	rail	560.1	(1,1)	7 -- 26	rail	397.3	(1,1)
31 -- 22	truck	751.9	(1,1)	26 -- 36	rail	49.2	(1,1)
22 -- 27	truck	344.8	(1,1)	28 -- 7	rail	1034.6	(1,1)
31 -- 27	rail	309.8	(1,1)	26 -- 28	rail	1084.0	(1,1)
27 -- 12	truck	385.7	(1,1)	7 -- 36	rail	445.6	(1,1)
12 -- 19	truck	487.4	(1,1)	8 -- 7	truck	354.7	(1,1)
27 -- 19	rail	207.9	(1,1)	8 -- 9	truck	638.1	(1,1)
27 -- 11	truck	283.1	(1,1)	8 -- 36	truck	348.1	(1,1)
11 -- 19	truck	118.9	(1,1)	40 -- 29	rail	778.1	(1,1)
19 -- 2	rail	682.5	(1,1)	29 -- 15	rail	572.2	(1,1)
18 -- 1	truck	511.1	(1,1)	15 -- 36	rail	808.5	(1,1)
1 -- 2	truck	1229.0	(1,1)	36 -- 10	rail	954.0	(1,1)
2 -- 32	truck	1038.0	(1,1)	10 -- 9	truck	728.6	(0,1)
19 -- 24	truck	354.3	(0,1)	29 -- 30	rail	909.1	(1,1)
24 -- 3	truck	315.0	(1,1)	30 -- 36	rail	951.0	(1,1)
19 -- 3	rail	298.0	(1,1)	30 -- 16	rail	711.6	(1,1)
19 -- 17	rail	410.0	(0,1)	30 -- 23	rail	516.8	(1,1)
24 -- 13	truck	474.5	(1,1)	30 -- 43	rail	244.9	(1,0)
24 -- 25	truck	175.0	(1,1)	36 -- 16	rail	698.1	(1,1)
17 -- 20	maritime	607.9	(1,1)	16 -- 34	rail	130.0	(1,1)
32 -- 20	maritime	691.0	(1,1)	9 -- 34	maritime	795.6	(1,1)
17 -- 4	truck	503.5	(0,0)	40 -- 51	rail	416.2	(1,1)
4 -- 35	truck	424.8	(1,1)	29 -- 41	rail	721.0	(1,1)
4 -- 3	truck	365.9	(1,1)	29 -- 42	rail	489.8	(1,1)
4 -- 25	truck	232.5	(1,1)	51 -- 50	rail	661.8	(1,1)
27 -- 37	truck	516.0	(1,1)	41 -- 44	rail	456.0	(1,1)
37 -- 13	truck	1220.6	(1,1)	44 -- 48	rail	684.0	(1,1)
27 -- 37	rail	563.8	(1,1)	50 -- 49	rail	623.0	(0,1)
37 -- 14	truck	351.9	(1,0)	49 -- 48	rail	210.0	(1,1)
13 -- 25	rail	343.0	(0,1)	42 -- 45	rail	306.5	(1,1)
3 -- 25	rail	344.8	(1,1)	43 -- 45	rail	140.8	(0,1)
25 -- 35	rail	503.6	(0,1)	34 -- 54	maritime	2621.7	(0,1)
35 -- 33	rail	485.4	(1,1)	23 -- 54	maritime	2377.2	(0,1)
33 -- 20	maritime	193.0	(1,1)	45 -- 46	rail	1391.5	(1,1)
25 -- 28	rail	1531.7	(1,1)	46 -- 47	rail	530.7	(0,1)
25 -- 7	rail	865.2	(1,1)	47 -- 48	rail	274.8	(1,1)
35 -- 5	truck	319.7	(1,1)	48 -- 54	maritime	1557.1	(1,1)
35 -- 6	truck	1178.2	(1,1)	48 -- 53	rail	972.4	(1,1)
6 -- 20	truck	560.1	(1,1)	53 -- 54	rail	809.9	(1,1)
5 -- 20	truck	751.9	(1,1)	54 -- 50	maritime	1234.3	(1,1)

5 -- 7	truck	344.8	(1,1)	50 -- 52	maritime	735.5	(1,1)
10 -- 20	rail	309.8	(1,1)	52 -- 38	rail	1311.7	(1,1)
20 -- 34	maritime	385.7	(1,1)	38 -- 31	rail	707.3	(1,1)
14 -- 29	rail	487.4	(1,1)	31 -- 39	rail	400.0	(1,1)
14 -- 28	rail	207.9	(1,1)	39 -- 50	rail	1737.1	(1,1)

Note: the integer numbers representing segments are node Id’s.

Table D.3 The Total O/D Demand Matrix (1000 TEUs/yr)

Origin	**Destination *d***																								
o	1	4	5	6	8	10	11	12	15	16	18	19	20	21	22	24	26	30	37	45	48	50	51	52	54
1	0.0	26.3	8.4	18.8	5.8	13.0	9.0	0.9	2.8	22.7	6.6	8.9	12.8	3.0	0.7	7.7	8.2	5.2	5.4	1.9	3.7	0.4	0.2	2.5	107.8
4	26.3	0.0	46.3	103.6	31.8	71.9	49.3	5.2	15.2	125.0	35.0	48.7	70.4	16.6	3.8	42.1	45.3	28.9	29.5	10.3	20.6	2.5	1.2	13.7	592.0
5	8.4	46.3	0.0	33.5	10.3	23.3	15.7	1.7	4.9	40.4	11.2	15.5	22.8	5.3	1.2	13.5	14.7	9.3	9.5	3.3	6.7	0.8	0.4	4.4	192.0
6	18.8	103.6	33.5	0.0	23.0	52.2	35.2	3.7	11.0	90.4	25.0	34.8	51.1	11.9	2.7	30.1	32.7	20.9	21.2	7.4	14.9	1.8	0.9	9.8	428.9
8	5.8	31.8	10.3	23.0	0.0	16.1	10.8	1.1	3.4	28.2	7.7	10.7	15.7	3.7	0.8	9.3	10.2	6.5	6.5	2.3	4.6	0.6	0.3	3.1	133.6
10	13.0	71.9	23.3	52.2	16.1	0.0	24.5	2.6	7.6	63.1	17.4	24.1	35.7	8.3	1.9	20.9	22.8	14.5	14.7	5.2	10.4	1.2	0.6	6.8	299.2
11	9.0	49.3	15.7	35.2	10.8	24.5	0.0	1.8	5.2	42.6	12.0	16.7	23.9	5.7	1.3	14.5	15.5	10.0	10.1	3.5	7.1	0.8	0.4	4.7	202.8
12	0.9	5.2	1.7	3.7	1.1	2.6	1.8	0.0	0.6	4.5	1.3	1.8	2.5	0.6	0.1	1.5	1.6	1.0	1.1	0.4	0.7	0.1	0.0	0.5	21.5
15	2.8	15.2	4.9	11.0	3.4	7.6	5.2	0.6	0.0	13.5	3.7	5.1	7.5	1.8	0.4	4.5	4.9	3.2	3.2	1.1	2.3	0.3	0.1	1.5	64.9
16	22.7	125.0	40.4	90.4	28.2	63.1	42.6	4.5	13.5	0.0	30.1	42.0	61.7	14.4	3.3	36.4	40.2	25.9	25.8	9.2	18.5	2.2	1.1	12.2	532.5
18	6.6	35.0	11.2	25.0	7.7	17.4	12.0	1.3	3.7	30.1	0.0	11.9	17.0	4.0	0.9	10.2	10.9	7.0	7.1	2.5	5.0	0.6	0.3	3.3	143.3
19	8.9	48.7	15.5	34.8	10.7	24.1	16.7	1.8	5.1	42.0	11.9	0.0	23.6	5.6	1.3	14.2	15.2	9.7	9.9	3.5	6.9	0.8	0.4	4.6	199.1
20	12.8	70.4	22.8	51.1	15.7	35.7	23.9	2.5	7.5	61.7	17.0	23.6	0.0	8.1	1.9	20.4	22.3	14.2	14.4	5.1	10.1	1.2	0.6	6.7	291.7
21	3.0	16.6	5.3	11.9	3.7	8.3	5.7	0.6	1.8	14.4	4.0	5.6	8.1	0.0	0.5	4.9	5.2	3.4	3.5	1.2	2.4	0.3	0.1	1.6	69.4
22	0.7	3.8	1.2	2.7	0.8	1.9	1.3	0.1	0.4	3.3	0.9	1.3	1.9	0.5	0.0	1.1	1.2	0.8	0.8	0.3	0.6	0.1	0.0	0.4	15.9
24	7.7	42.1	13.5	30.1	9.3	20.9	14.5	1.5	4.5	36.4	10.2	14.2	20.4	4.9	1.1	0.0	13.2	8.4	8.7	3.0	6.0	0.7	0.4	4.0	173.0
26	8.2	45.3	14.7	32.7	10.2	22.8	15.5	1.6	4.9	40.2	10.9	15.2	22.3	5.2	1.2	13.2	0.0	9.3	9.3	3.3	6.6	0.8	0.4	4.4	190.8
30	5.2	28.9	9.3	20.9	6.5	14.5	10.0	1.0	3.2	25.9	7.0	9.7	14.2	3.4	0.8	8.4	9.3	0.0	6.0	2.2	4.3	0.5	0.3	2.8	124.8
37	5.4	29.5	9.5	21.2	6.5	14.7	10.1	1.1	3.2	25.8	7.1	9.9	14.4	3.5	0.8	8.7	9.3	6.0	0.0	2.1	4.3	0.5	0.3	2.9	123.0
45	1.9	10.3	3.3	7.4	2.3	5.2	3.5	0.4	1.1	9.2	2.5	3.5	5.1	1.2	0.3	3.0	3.3	2.2	2.1	0.0	1.6	0.2	0.1	1.0	44.9
48	3.7	20.6	6.7	14.9	4.6	10.4	7.1	0.7	2.3	18.5	5.0	6.9	10.1	2.4	0.6	6.0	6.6	4.3	4.3	1.6	0.0	0.4	0.2	2.1	92.4
50	0.4	2.5	0.8	1.8	0.6	1.2	0.8	0.1	0.3	2.2	0.6	0.8	1.2	0.3	0.1	0.7	0.8	0.5	0.5	0.2	0.4	0.0	0.0	0.3	10.9
51	0.2	1.2	0.4	0.9	0.3	0.6	0.4	0.0	0.1	1.1	0.3	0.4	0.6	0.1	0.0	0.4	0.4	0.3	0.3	0.1	0.2	0.0	0.0	0.1	5.4
52	2.5	13.7	4.4	9.8	3.1	6.8	4.7	0.5	1.5	12.2	3.3	4.6	6.7	1.6	0.4	4.0	4.4	2.8	2.9	1.0	2.1	0.3	0.1	0.0	59.9
54	107.8	592.0	192.0	428.9	133.6	299.2	202.8	21.5	64.9	532.5	143.3	199.1	291.6	69.4	15.9	173.0	190.8	124.8	123.0	44.9	92.4	10.9	5.4	59.9	0.0

ACCOMPLISHMENTS DURING PHD STUDY

Awards Earned

1 President's Graduate Fellowship of NUS

The President's Graduate Fellowship (PGF) is awarded to candidates who show exceptional promise or accomplishment in research. A limited number of NUS Ph.D research students who have passed the Ph.D Qualifying Examination are selected each semester by the University for the award.

2 MOT Innovation Award 2009 of Singapore

I was involved in the research project "Quantitative Risk Analysis (QRA) of Road Tunnels" collaborated between Land Transport Authority of Singapore and National University of Singapore (NUS) and awarded the MOT innovation Award 2009 by the Ministry of Transport of Singapore to recognize the excellent work achieved by my research team.

Publications

Journal Papers

1. **Wang, X.**, Meng, Q., Miao, L. and Fwa, T. F., 2009. Impact of landbridge on port market area: model development and scenario analysis. *Transportation Research Record,* 2097, pp.78-87.
2. Meng, Q. and **Wang, X.**, 2010. Utility-Based estimation of probabilistic port hinterland for networks of intermodal freight transportation. *Transportation Research Record*, 2168, pp.53-62.
3. **Wang, X.** and Meng, Q., 2011. The impact of landbridge on the market shares of Asian ports. *Transportation Research Part E*, 47(2), pp.190-203.

4. Meng, Q. and **Wang, X.**, 2011. Intermodal hub-and-spoke network design: Incorporating multiple stakeholders and multi-type containers, *Transportation Research Part B*, 45(4), pp.724-742.
5. Meng, Q., Qu, X., **Wang, X.**, Yuanita, V., and Wong, S. C., 2010. Quantitative risk assessment modelling for non-homogeneous urban road tunnels, Accepted by *Risk Analysis.* DOI: 10.1111/j.1539-6924.2010.01503.x.
6. **Wang, X.** and Meng, Q., 2010. A note on intermodal hub-and-spoke network design with stochastic equilibrium flows. *Transportation Research Part B.* (submitted).
7. Meng, Q. and **Wang, X.**, 2010. Probabilistic port hinterland estimation in intermodal freight transportation networks: model formulation and algorithm design. *Networks and Spatial Economics* (submitted).

Conference Papers

1. Meng Q., **Wang X.**, Qu X., Yong K. T., Lee S. P. and Wong S. C., 2009. Quantitative risk assessment models for road tunnels: state of the art and their implication for Singapore's road tunnel. In *Proceedings of the Second International Safety Forum*, 20-22 April 2009, Lyon, France.
2. **Wang, X.** and Meng, Q. A mixed-integer linear programming model for shipping hub-and-spoke network design with CO_2 constraint. In *Proceedings of the 7th Asia Pacific Conference on Transportation and the Environment*. 3rd-5th June, 2010, Semarang, Indonesia.