Modelling International Intermodal Container Shipping and Application to South Asia

Ryuichi SHIBASAKI [a,*], Tomoya KAWASAKI [b]

[a] *National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism, 1-12 Shinmei-Cho, Yokosuka, Japan*
[b] *Tokyo Institute of Technology, 2-12-1-i4-22, O-okayama, Meguro-ku, Tokyo, 152-8550, Japan*

Abstract: A two-layered network assignment model of international container cargo including both a global maritime and local hinterland shipping network is developed and applied into three South Asian countries. In the lower layer of the model, each assignment submodel with capacity constraint on detail maritime and hinterland network is separately developed. In the upper layer, a stochastic assignment model with unobservable term on the intermodal super-network is developed. The model is applied in South Asia by inputting the level of service in maritime and hinterland shipping and reginal-basis shipping demand of international container cargo. The performance of the developed model is verified, in particular that container throughput in each South Asian port can be well described. Also, two policy simulations to improve the level of hinterland infrastructure including road, rail and ferry are examined by utilizing the model as a sensitivity analysis.

Keywords: Intermodal Shipping Network, Global Maritime Container Cargo Shipping, Hinterland Transport in South Asia, Network Assignment Model

1. INTRODUCTION

Due to globalization of the world economy, the importance of international maritime container shipping has been increasing year by year. Furthermore, economic globalization is strengthening the relationships among containership movements in each region of the world. Liner shipping companies are expanding and strengthening their shipping network on a global (i.e. worldwide) scale, not only by deploying larger containerships, but also through mergers and alliances. Connectivity with hinterlands (i.e. land shipping network) and competition among multiple seaports as gateways have also become focal points in international container shipping.

South Asian countries, including India, Sri Lanka, and Bangladesh, are falling behind the global trend of the maritime shipping market. According to the World Bank Group's rankings of business environment in terms of international trade, these South Asian countries placed 69th (Sri Lanka) at best, followed by 126th (India) and 140th (Bangladesh). The total throughput of international maritime containers which are exported from or imported into South Asia is also relatively less compared with other regions of the world. For example, the total container throughput in India was 10.7 mil. TEU (twenty foot equivalent unit) in 2013, while throughput in China was 174.1 mil. TEU (World Bank, 2015), despite the fact that the populations of both countries are at a similar level.

In order to overcome such situations, many projects to improve the level of logistics

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* Corresponding author. Tel.: +81-46-834-9584; fax: +81-46-834-9843; E-mail: shibasaki-r92y2@mlit.go.jp

infrastructure, including not only port infrastructure but also hinterland (i.e. road, rail and inland waterway) infrastructure, are planned in South Asia. For example, the Jawaharlal Nehru Port Trust (JNPT), which is the largest container port in India located in the suburbs of Mumbai, has been expanding the third container terminal which is operated by DPW (UAE) to be completed in 2016 as well as contracted to develop the forth container terminal with PSA (Singapore) by a concession in 2014, since the port capacity to container handling already reached the limit. As well, in order to increase the level of service (such as shipping time and reliability) in hinterland rail transport, the Dedicated Freight Corridor (DFC), which connects between JNPT and Delhi, a capital of India, by a newly constructed rail dedicated for freight transport, has been planned and constructed, supported by JICA (Japan International Cooperation Agency).

However, there are almost no tools to quantitatively simulate the impact of such logistics policies to the international cargo flow on the integrated network to include both maritime and hinterland shipping network. Although many papers proposed to model a behavior of liner shipping company such as port-of-call selection which was recently reviewed by Christiansen et al. (2013) and Meng et al. (2014) or that of shipper such as shipping route and port selection (for example, Bell et al., 2011 and Tavasszy et al., 2011), the authors consider there are two main issues to be solved; the modelling on the intermodal network including both maritime and hinterland shipping, and the applicability to the actual projects. Regarding the first point, a few exceptions are Fan et al. (2009, 2012) and Meng and Wang (2011) which proposed a model to include both the land and maritime network and applied it to the North American and East Asian intermodal network respectively; however, they still have a problem from the viewpoint of computability when applying it to the global-scale shipping network which has numerous links and alternatives.

The authors (Shibasaki et al., 2016b) developed a two-layered network assignment model of international container cargo including both a global maritime shipping network and a local hinterland shipping network from the shippers' viewpoint. The model focused in Central America (CA) and included the very simplified international road network in four countries in CA which was preliminarily given. In this paper, the model is generalized to incorporate more complicated hinterland network which includes not only road but also rail and inland waterway. Also, a capacity constraint in each mode of hinterland shipping is considered as well as maritime container shipping. Then, the model is applied to South Asia including India, Sri Lanka, and Bangladesh, and examined by a sensitive analysis supposing policy implementation related with logistics.

2. MODEL

The basic concept of the model is similar to Shibasaki et al. (2014) and Shibasaki et al. (2016b). The whole structure of the model is shown in Figure 1. The model is developed from a viewpoint of shippers with two-layered network assignment model which includes a super-network for intermodal shipping in the upper level and two real networks representing each maritime and hinterland shipping in the lower level. The most significant difference from the above models which had been developed by authors is to consider capacity constraint in the lower level, not only in maritime shipping submodel, but also hinterland shipping submodel.

The structure of an intermodal super-network in the upper level is shown in Figure 2. Each shipper is assumed to choose the ports to be used for export and import, given the freight charges for maritime and land transport, and shipping time, on the intermodal network.

A stochastic network assignment model is applied, since it can consider the influence of unobservable elements from the model developer.
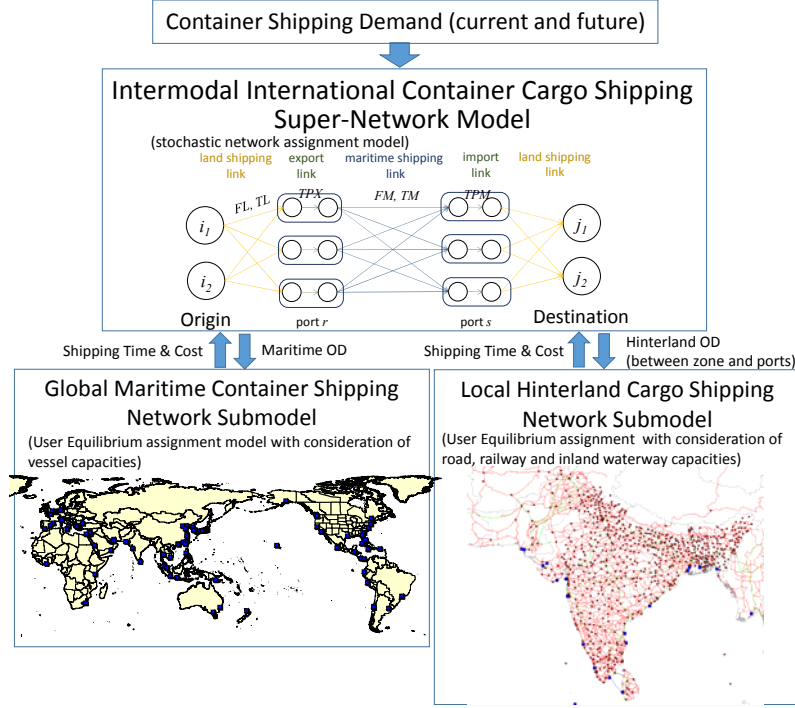

Figure 1. Whole structure of the model

When H_{ij} is the path choice set of cargo shipping demand Q_{ij} (TEU) from region i to region j ($ij \in \Omega$; Ω is the set of OD pair), a path h is chosen for a cargo m so as to maximize utility U_{ijhm}, including an error term ε_{ijhm}, that is,

$$U_{ijhm} > U_{ijh'm}, \quad \forall h \in H_{ij}, \forall h' \in H_{ij}, h \neq h', \forall ij \in \Omega , \tag{1}$$

$$s.t. \quad U_{ijhm} = -G_{ijh} + \varepsilon_{ijhm}, \tag{2}$$

where G_{ijh}: shipping cost (US\$/TEU) of path h from region i to region j. If the error term ε_{ijhm} follows Gumbel distribution, the choice of shipper is formulated as

$$F_{ijh} = Q_{ij} \cdot \frac{\exp(-\theta \cdot G_{ijh})}{\exp(-\theta \cdot G_{ijh}) + \sum_{h' \in H_{ij}} \exp(-\theta \cdot G_{ijh'})}, \tag{3}$$

where F_{ijh}: cargo volume on a path h from region i to region j, and θ: distribution parameter. The shipping cost G_{ijh} for each path is expressed by the equation below.

$$G_{ijh} = GL_{ir} + GPX_r + GM_{rs} + GPM_s + GL_{sj}, \qquad \forall r \in h, \forall s \in h \tag{4}$$

where GL_{ri}, GL_{sj}: generalized hinterland shipping cost from origin region r to port i and from port j to destination region s, GPX_r: generalized port cost of export port r, GM_{rs}: generalized maritime and inland waterway shipping cost from export port r to import port s, and GPM_s: generalized cost of import port s.

The generalized cost of each link is expressed as the sum of freight charge and time cost which is defined by multiplying shipping time by value of time for shippers. Namely,
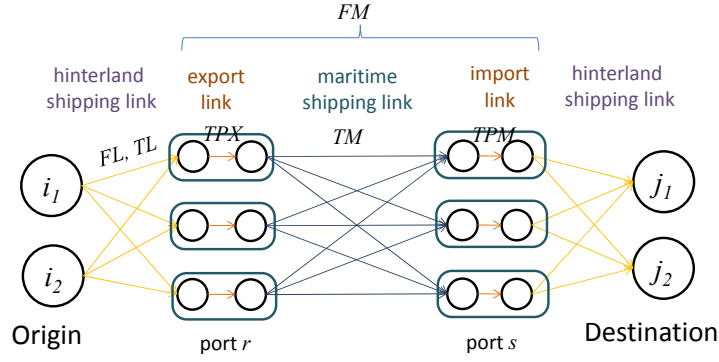
Figure 2. Structure of an intermodal super-network

$$GL_{ir} = FL_{ir} + vt \cdot TL_{ir}, \quad GL_{sj} = FL_{sj} + vt \cdot TL_{sj}, \tag{5}$$

$$GPX_r = vt \cdot TPX_r \tag{6}$$

$$GM_{rs} = FM_{rs} + vt \cdot TM_{rs}, \quad \text{and} \tag{7}$$

$$GPM_s = vt \cdot TPM_s, \tag{8}$$

where vt: value of time for shipper (US\$/TEU/hour), FL_{ir}, FL_{sj}: freight charge of hinterland shipping from origin i to port r and from port s to destination j (US\$/TEU), TL_{ir}, TL_{sj}: hinterland shipping time (hours) from origin i to port r and from port s to destination j, TPX_r: lead time when exporting in port r (hours), FM_{rs}: ocean freight charge from port r to port s (US\$/TEU) including port charges, TM_{rs}: maritime shipping time (hours) from port r to port s, and TPM_s: lead time when importing in port s (hours). Note that any monetary costs are not considered in the port links (i.e. export and import link), since we assume the ocean freight charge, FM_{rs}, includes all port charges, not only for export and import port but also transhipment port on the way of shipping.

The ocean freight charge, FM_{rs}, and maritime shipping time, TM_{rs}, are acquired from calculation results of maritime shipping submodel in the lower level, while the freight charge, FL_{ir} and FL_{sj}, and shipping time, TL_{ir} and TL_{sj}, of hinterland shipping are from hinterland shipping submodel. Detail formulation of both submodels are shown as follows.

2.1 Maritime Shipping Submodel

2.1.1 Calculation of Shipping Time

The maritime shipping submodel on the global container network was independently developed and already applied to South Asia by focusing on the transhipment of container cargo in Colombo Port (Sri Lanka) in Shibasaki and Kawasaki (2016c).

The model is defined as a problem to allocate container cargo on the worldwide liner shipping network made from the containership movement data (the MDS database). Each liner shipping network is structured as shown in Figure 3. Each container of the shipper will choose a link from origin node (O node) of an export port to destination node (D node) of an import port. In this submodel, every container of each OD pair is assumed to choose a route to minimize its total transit time. The shipper chooses a carrier with consideration of only transit time, not freight charge at all. This assumption is based on the idea that the international maritime container shipping market is oligopolistic but a freight charge for an OD pair is the same among carriers if the service is provided and utilized.

Since vessels of each service have their own capacities, there is diseconomy of scale by concentrating into a specific service. Therefore, the congestion of the link is considered and a User Equilibrium (UE) assignment is applied as network assignment methodology.

$$\min_x z(x) = \sum_{a \in A} \int_0^{x_a} t(x_a) dx, \tag{9}$$

subject to
$$x_a = \sum_{(r,s) \in R \times S} \sum_{k \in K_{rs}} \delta_{a,k}^{rs} \cdot f_k^{rs}, \ \forall a, \tag{10}$$

$$\sum_{k \in K_{rs}} f_k^{rs} - q_{rs} = 0, \ \forall r, s, \quad \text{and} \tag{11}$$

$$f_k^{rs} \geq 0, \ \forall k, r, s, \tag{12}$$

where a: link, A: set of link, x_a: flow of the link a, $t_a(.)$: cost function of the link a, $z(.)$: objective function, r: origin, s: destination, R: set of export port, S: set of import port, k: path, K_{rs}: set of path for OD pair rs, δ_{ak}^{rs}: Kronecker delta, f_k^{rs}: flow on the path k, and q_{rs}: cargo shipping demand from r to s. Kronecker delta, δ_{ak}^{rs}, is written as

$$\delta_{a,k}^{rs} = \begin{cases} 1 \text{ if } a \in k \\ 0 \text{ if } a \notin k \end{cases}. \tag{13}$$

For a detailed description of the cost function for each link, please see Shibasaki and Kawasaki (2016c).

Of the networks, only the navigating link has a flow-dependent cost function. The cost functions of other links are flow-independent. Therefore, the UE problem defined in Equation (9) will be solved in the algorithm shown by Sheffi (1985). According to the UE assignment definition, maritime shipping time, TM_{rs}, is defined as

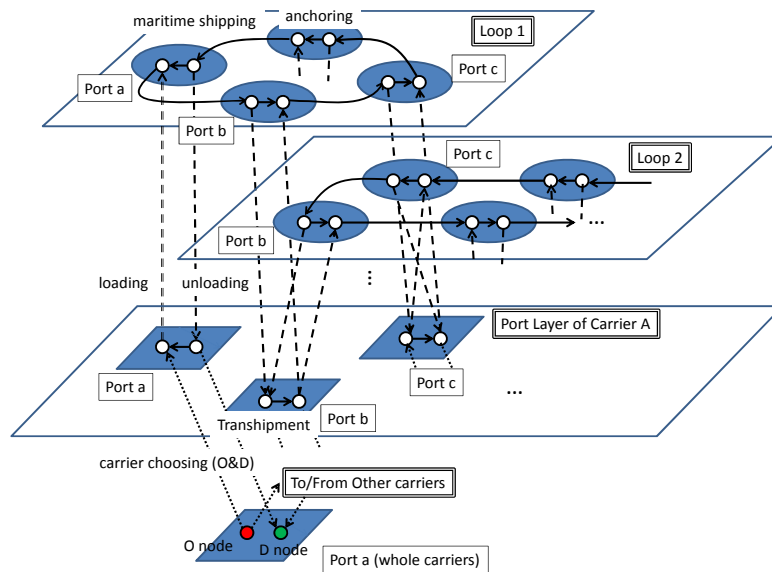$$TM_{rs} = \min_k \left\{ \sum_{a \in k} t(x_a) \right\}. \tag{14}$$

Figure 3. Network structure of an maritime shipping submodel (source: Shibasaki and Kawasaki, 2016c)

2.1.2 Calculation of Ocean Freight Charge

The ocean freight charge on each maritime shipping link, FM_{rs}, provided by carrier is generally different from the monetary cost of the route for the carrier, reflecting the balance of demand and supply on the market. In particular, since the maritime container shipping industry has an oligopolistic market in which surplus of supplier may exist, it should be carefully examined. First, the maritime shipping cost is calculated, and then the methodology to estimate freight charge from the cost information is shown.

(1) Cost of maritime and inland waterway shipping

Shipping cost of each link included in the maritime and inland waterway shipping submodel is defined per TEU as follows.

1) Navigating link

Cost of navigation in the maritime shipping, c_M, consists of the fuel cost, capital cost, operation cost, and canal toll as

$$c_M(x_a) = \left\{ (FC_a + CC_a + OC_a) \cdot \frac{l_a/v_a}{24} + \gamma_a^s \cdot CS(cap_a) \right\} \bigg/ \frac{x_a}{freq_a} + \gamma_a^p \cdot CP \quad (15)$$

where x_a: container cargo flow of the link a (TEU/year), FC_a: fuel cost of container vessel (US\$/vessel/day), CC_a: capital cost of container vessel (US\$/vessel/day), OC_a: operation cost of container vessel (US\$/vessel/day), γ_a^s: dummy variable on the Suez Canal transit (=1: if link a passes through the Suez Canal; =0: in other cases), $CS(.)$: toll function for Suez Canal transit (US\$/vessel), cap_a: average vessel capacity of the service (TEU/vessel), γ_a^p: dummy variable for Panama Canal transit (=1: if link a passes through the Panama Canal; =0: in other cases), CP: toll for Panama Canal transit (US\$/TEU), l_a: distance of the link a (NM), v_a: vessel speed of the link a (knot), and , $freq_a$: service frequency of the loop (vessels/year). The term $x_a/freq_a$ represents the average amount of containers transported in one vessel. Note that the Suez Canal toll is defined by vessel size, which is defined on a TEU-capacity basis in this model, while the Panama Canal toll is defined as per container, according to the tariffs.

The details of each cost item (i.e. FC, CC, OC, CS, and CP) are described in Shibasaki, et al. (2016a).

2) Loading, unloading, berthing, transhipment and carrier choosing link

In these links, port charge and terminal handling charge should be considered. In order to reflect an empirical fact that handling charge for the transhipment is less than double of that for the loading or unloading, cost of each link is defined as

$$c_L(x_a) = SSN, \tag{16}$$
$$c_D(x_a) = SSN, \tag{17}$$
$$c_B(x_a) = SSN, \tag{18}$$
$$c_{TR}(x_a) = (CHX_a + CHM_a)/2*1.5, \tag{19}$$
$$c_{CX}(x_a) = CHX_a, \text{ and} \tag{20}$$
$$c_{CM}(x_a) = CHM_a, \tag{21}$$

where c_L: cost function of loading link (US\$/TEU), c_D: cost function of discharging link (US\$/TEU), c_B: cost function of berthing link (US\$/TEU), c_{TR}: cost function of transhipment

link (US$/TEU), c_{CX}: cost function of carrier choosing export link (US$/TEU), c_{CM}: cost function of carrier choosing import link (US$/TEU), *SSN*: sufficient small number (in this model, we assume *SSN* = 0.01 US$), and CHX_a, CHM_a: container handling charge when container cargo is loaded and unloaded respectively of port *a* (US$/TEU). Note that in order to avoid giving a negative link cost in the transhipment link, the handling charges are imposed in the carrier choosing link, not in the loading and unloading link.

(2) Ocean freight charge
Since the maritime container shipping industry is an oligopolistic market, generally the freight charge is not equal to the marginal shipping cost. However, if we assume the market is in Bertrand competition in which companies compete over prices rather than the capacities, it is well known that price is equal to the marginal cost. Hereinafter, it is assumed that the market of maritime shipping is individually established for each combination of origin and destination port, although each market is related with each other. Individual maritime container shipping market connecting specific export and import port may be relatively easy to enter and leave for the shipping companies that already operate container vessels in the region; therefore, equilibrium price (i.e. ocean freight charge) is considered to approximate the price reached in the perfect competition.

From the above discussion, equilibrium price (ocean freight charge), FM_{rs}, in each market is uniquely set to be equal to the highest average shipping cost in the companies that participate the market (from export port *r* to import port *s*); namely,

$$FM_{rs} = \max_{g \in G} AC_{grs}, \tag{22}$$

where AC_{grs}: average cost of shipping company *g* from export port *r* to import port *s*, *G*: set of shipping company. The average shipping cost is defined as

$$AC_{grs} = \sum_{a \in k_g} c(x_a) \qquad \text{if} \quad TM_{grs} = TM_{rs}, \text{ or} \tag{23-1}$$

$$AC_{grs} = 0 \qquad \text{if} \quad TM_{grs} > TM_{rs}, \tag{23-2}$$

where k_g: path to minimize the generalized shipping cost from export port *r* to import port *s* of shipping company *g*, TM_{grs}: minimum shipping time from export port *r* to import port *s* of shipping company *g*. Namely,

$$k_g = \arg\left[\min_{k'}\left\{\sum_{a \in k'}[c(x_a) + vt \cdot t(x_a)]\right\}\right], \quad \forall k' \in K_g^{rs}, \tag{24}$$

$$TM_{grs} = \min_{k''}\left\{\sum_{a \in k''} t(x_a)\right\}, \quad \forall k'' \in K_g^{rs}, \tag{25}$$

where K_g^{rs}: path set from export port *r* to import port *s* of shipping company *g*.

2.2 Hinterland Shipping Submodel

The hinterland shipping submodel is also defined as a problem to allocate container cargo on the hinterland shipping network in South Asia including road, rail and inland waterway with capacity constraint of each mode. The shipping demand between inland origin i (or destination j) and export port r (or import port s) in South Asia is given. An UE assignment is also applied as assignment methodology. Note that the number of enterprises such as truck companies to join the hinterland shipping market is numerous then the market can be assumed sufficiently competitive. Therefore, the authors assume the freight charge is equal to the marginal shipping cost and the shipper chooses the shipping mode and route to minimize the total generalized cost including not only shipping time but also freight charge. Namely,

$$\min_x z'(x) = \sum_{a \in A} \int_0^{x_a} u(x_a) dx , \qquad (26)$$

subject to
$$x_a = \sum_{(i,r) \in O \times R} \sum_{k \in K_{ir}} \delta_{a,k}^{ir} \cdot f_k^{ir} + \sum_{(s,j) \in S \times D} \sum_{k \in K_{sj}} \delta_{a,k}^{sj} \cdot f_k^{sj} , \qquad \forall a , \qquad (27)$$

$$\left(\sum_{k \in K_{ir}} f_k^{ir} + \sum_{k \in K_{sj}} f_k^{sj} \right) - \left(q_{ir} + q_{sj} \right) = 0 , \; \forall r, s, i, j , \qquad \text{and} \qquad (28)$$

$$f_k^{ir} \geq 0, f_k^{sj} \geq 0, \; \forall k, r, s, i, j , \qquad (29)$$

where $u(.)$: cost function of each link, $z'(.)$: objective function, O: set of origin, D: set of destination. Note that cost function of each hinterland link, $u_a(.)$, is defined as a generalized cost, not shipping time.

The network structure of the hinterland shipping submodel is shown in Figure 4. Road and rail network are connected with a rail connection link, while a ferry link is directly connected with road or rail link. Also, note that cargo origin and destination (i.e. inland origin/destination and export/import port) are connected with only road network by an O/D link, but not rail, since it is assumed that the "last one mile" of container shipping should be served by a trailer.

Of the networks, road, rail, and ferry link has each different flow-dependent cost function respectively, as shown as follows. According to the UE assignment definition, generalized cost of hinterland shipping, GL_{ir} (or GL_{sj}), is defined as

$$GL_{ir} \left(or \; GL_{sj} \right) = \min_k \left\{ \sum_{a \in k} u(x_a) \right\} , \qquad (30)$$
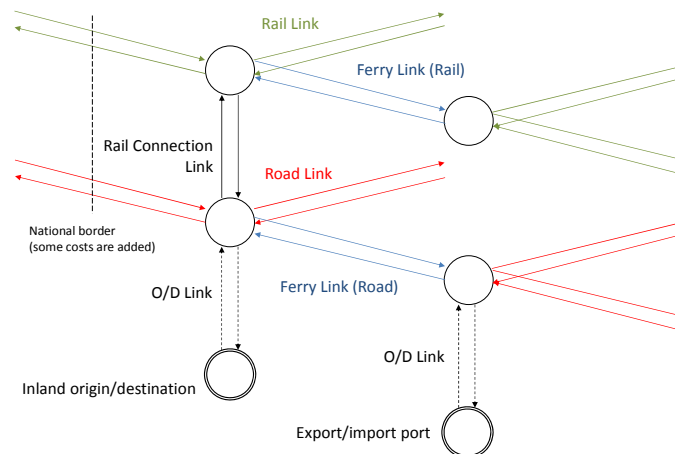
instead of Equation (5).

Figure 4. Network structure of a hinterland shipping submodel

1) O/D link

As the generalized cost, u_{OD}, of an O/D link which connects inland origin/destination or export/import port with road network, the fixed cost of trailers is only considered; namely,

$$u_{OD}(x_a) = CFRo/2, \tag{31}$$

where $CFRo$: fixed charge of container shipping by trailer (US\$/TEU). The fixed term should be considered one time per hinterland shipping; therefore, the fixed cost is equally divided into O link and D link.

2) Road link

Generalized cost of truck transport on road, u_{Ro}, consists of the freight charge and time cost including congestion as

$$u_{Ro}(x_a) = CORo \cdot (2 \cdot l_a) + vt \cdot \frac{l_a}{vRo_a} \cdot \left\{ 1 + b3 \cdot \left(\frac{x_a}{capRo_a} \right)^{b4} \right\}, \tag{32}$$

where x_a: container cargo flow of the link a (TEU/year), $CORo$: coefficient on operational charge of container trailer in proportion to the distance (US\$/km/TEU), l_a: distance of the link a (km), vRo_a: speed of trailer (km/hour), $capRo_a$: annual road capacity for container trailer (TEU/year), and $b3$, $b4$: parameters related to the road congestion. The first term of the equation is the monetary cost of shipping, while the second term represents time cost including the delay due to the congestion. Note that the shipping distance in the operational cost calculation is doubled (i.e. $2 \cdot l_a$) since a trailer usually return to the departure point without any cargo and a tracker charge the repositioning cost to shippers.

3) Rail connecting link

Generalized cost of rail and road connection, u_{Rc}, also consists of the operation and time cost

$$u_{Rc}(x_a) = \frac{CFRo}{2} + CORo \cdot (2 \cdot l_a) + \frac{CFRa}{2} + vt \cdot \left\{ \frac{l_a}{vRo_a} + THRa_a + \frac{TWRa_a}{2} \right\}, \tag{33}$$

where $CFRa$: fixed charge of container shipping by rail (US\$/TEU), $THRa_a$: handling time for loading or discharging cargo into/from rail (hour), and $TWRa_a$: expected waiting time for the rail loading (hour). Note that not only the rail cost such as fixed shipping cost, $CFRa$, the handling time at the rail station, $THRa_a$, and expected waiting time, $TWRa_a$, but the access shipping cost and time by trailers are also included. The fixed cost of trailers, $CFRo$, is also considered, since an additional trailer should be arranged after a container is discharged from a train. The fixed cost of trailer and rail shipping, $CFRo$ and $CFRa$, and expected waiting time, $TWRa_a$, is equally divided in the links when a container is loaded into and discharged from a train.

The expected waiting time for the rail loading, $TWRa_a$, is defined as

$$TWRa_a = \frac{1}{2} \cdot \frac{YH}{freqRa_a}, \tag{34}$$

where YH: constant for conversion from one year to hours (52 (weeks/year) ·7(days/week) ·24(hours/day) = 8,736 (hours/year)), and $freqRa_a$: annual number of trains for container shipping (train/year). The term ($YH/freqRa_a$) represents duration hours of each rail service. The expected waiting time is assumed to be half of that value.

4) Rail link

Generalized cost of rail transport, u_{Ra}, also consists of the operation cost and time cost including congestion as

$$u_{Ra}(x_a) = CORa \cdot l_a + vt \cdot \left\{ \frac{l_a}{vRa_a} + TWRa_{a'} \cdot b5 \cdot \left(\frac{x_a}{capRa_a \cdot freqRa_a} \right)^{b6} \right\}, \quad (35)$$

where $CORa$: coefficient on operational charge of container shipping by rail in proportion to the distance (US\$/km/TEU), vRa_a: speed of railways (km/hour), $TWRa_{a'}$: expected waiting time for the rail loading in the rail connection link a' (hour, shown in Equation (33)), $capRa_a$: rail capacity for container shipping per train (TEU/train), and $b5$, $b6$: parameters related to the rail congestion. Different from shipping by trailers, the shipping distance in the operational cost calculation is not doubled. Also, the coefficient of congestion term is different; the expected waiting time for the loading, $TWRa_{a'}$, is considered, instead of shipping time. Furthermore, since the rail capacity, $capRa_a$, is defined per train, it is multiplied by annual frequency of rail service, $freqRa_a$, in order to calculate the annual rail capacity.

5) Ferry (inland waterway) link

Generalized cost of ferry or inland waterway transport, u_{Fe}, also consists of the operation cost and time cost including congestion as

$$u_{Fe}(x_a) = (2 \cdot CFFe + COFe \cdot l_a)$$
$$+ vt \cdot \left[\frac{l_a}{vFe_a} + 2 \cdot THFe_a + TWFe_a \cdot \left\{ 1 + b7 \cdot \left(\frac{x_a}{capFe_a \cdot freqFe_a} \right)^{b8} \right\} \right], \quad (36)$$

where $CFFe$, $COFe$: fixed term (US\$/TEU) and proportional term to the distance (US\$/km/TEU) of freight charge for container shipping by ferry or inland waterway, vFe_a: speed of ferry or barge (km/hour), $THFe_a$: handling time for loading or discharging cargo into/from vessel (hour), $TWFe_a$: expected waiting time for the ferry/inland waterway shipping (hour), $capFe_a$: capacity for container shipping per vessel (TEU/vessel), $freqFe_a$: annual frequency of the service (vessel/year), and $b7$, $b8$: parameters related to the vessel congestion.

The expected waiting time for the vessel loading, $TWFe_a$, is defined as

$$TWFe_a = \frac{1}{2} \cdot \frac{YH}{freqFe_a}. \quad (37)$$

6) Additional cost at national border

If a road, rail or ferry link crosses national border, additional shipping cost and time cost are added on each cost function. Namely,

$$u(x_a) = u(x_a) + \lambda_a \cdot (CB_a + vt \cdot TB_a) \quad (38)$$

where λ_a: dummy variable (=1: if link a crosses national border; =0: in other cases), CB_a: additional monetary cost in border-crossing (US\$/TEU), and TB_a: additional time in border-crossing (hour/TEU).

3. DATA INPUT

3.1 Ports and Maritime Shipping Network

The world liner shipping network formed by the major shipping companies is covered under this model. In principle, all container ports (in total, 173 ports) at which international throughput was more than 500,000 TEU per year as of 2013 (including empty containers but excluding domestic containers) are included. The port list was made mainly from several reports which covers all over the world such as Drewry Maritime Research (2014a and 2014b) and Lloyd's List, partly complemented by the websites of port or terminal and a past record. In addition, 21 local container ports in South Asia and neighbouring regions are included; therefore, the total number of container ports considered in the model is 194 as shown in Figure 5. The detail of each port including name, throughput and transhipment rate is listed in Shibasaki and Kawasaki (2016c). The handling charge at container terminal for export and import, CHX_r and CHM_s, in Equations (18)-(20) and lead time at terminal when exporting and importing, TPX_r and TPM_s, in Equation (6) and Equation (8) were derived by country from "Ports and terminal handling" in Doing Business website (trading across borders) provided by the World Bank, although it is currently not available.

The maritime shipping network is developed, based on the MDS containership databank. The MDS database provides information for each containership on not only name of service, (co-)operating and slot chartered company(ies), list of port to call and its order, but also vessel speed, v_a, average vessel capacity, cap_a, and frequency, $freq_a$. Since the model focuses on the container flow on the worldwide maritime shipping network and the transhipment of containers in hub ports, some liner services provided by smaller, local companies less involved with South Asia are eliminated for simplicity of calculation. Specifically, the model includes the 20 largest container shipping companies in the world as well as fourteen local companies which have a liner service network in South Asia. The list of shipping companies as well as details for making maritime shipping network is also shown in Shibasaki and Kawasaki (2016c). 932 services are included in the model, covering 68.9% of the annual vessel capacity of the world.

The distance between ports, l_a, is acquired from Toriumi's work (2010) as in the previous model. The distance is calculated from an assumption that every container ship passes through the shortest route on the sea out of the pre-set navigation routes. The dummy variables for Suez and Panama Canal transit, γ_a^s and γ_a^p, are also acquired from it. Some distances to/from several local ports which are newly added to the model as of 2013 are acquired from several websites such as SeaRates.com and Sea-Distances.org.
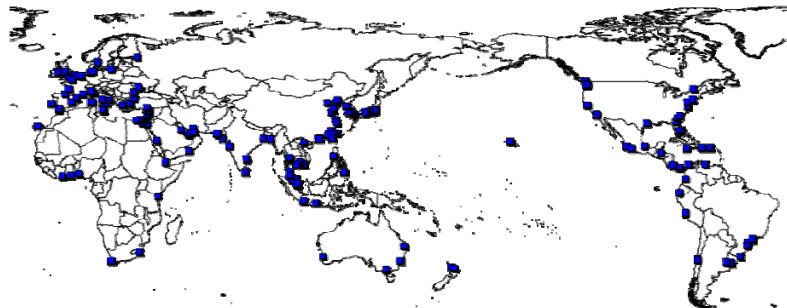

Figure 5. All container ports included in the model (source: authors)

3.2 Hinterland shipping network

The hinterland shipping network is only considered in five South Asian countries (i.e. Bangladesh, Bhutan, India, Nepal, and Sri Lanka). The network is structured based on ADC

WorldMap, from which not only link distance, l_a, but also classification of road is available. After all road networks and selected rail links are extracted from ADC WorldMap, an inland waterway link connecting between Dhaka and Chittagong in Bangladesh are added. Also, two ferry links (i.e. both for road and rail) connecting between India (Tuticorin) and Sri Lanka (Colombo) are prepared for policy simulation which is introduced in 4.3.2.

The trailer speed, vRo_a, and annual road capacity, $capRo_a$, for each road link is set to be 60, 50 and 40 (km/hour) and 1,000,000, 500,000, and 100,000 (TEU/year) respectively, according to road classification ("Motorway", "Primary Route", and "Important Route") in ADC WorldMap in principle. Note that the capacity in several Primary Routes near congested ports (i.e. JNPT and Chennai) are limited to the same level as the Important Route, since very heavy congestion are observed in the roads around these ports (Motono, et al., 2014).

Meanwhile, the railway speed, vRa_a, and ferry speed, vFe_a, are set to be 20 and 10 km/hour respectively. Also, capacity per train, $capRa_a$, and vessel, $capFe_a$, is defined as 90 (in India) or 62 (in Bangladesh and Sri Lanka) for rail (TEU/train) and 128 for ferry (TEU/vessel) respectively, based on our interview survey (for example, A standard Indian railways has 45-wagon train in which each wagon can carry a 40frt container).

The freight charge of each mode and handling time at rail station and ferry port are also decided based on the interview survey and model calibration. Concretely, fixed and operational charge of a trailer, $CFRo$ and $CORo$, is set to be 60.0 (US$/TEU) and 1.0 (US$/km/TEU) respectively. On the other hand, fixed charges of rail and ferry are not considered, i.e. $CFRa$ and $CFFe$ are set to be 0 (US$/TEU), while both operational charges, $CORa$ and $COFe$, set to be 0.5 (US$/km/TEU). The annual number of trains and ferries for container shipping, $freqRa_a$ and $freqFe_a$, is set by link, according to the interview survey, the website of operating company (such as Container Corporation of India, a rail company operating container train in India, **http://www.concorindia.com/ShowService.asp?typeID =International&typeRJ=Train**), and model calibration, while both handling times for loading or discharging cargo into/from rail and vessel, $THRa_a$ and $THFe_a$, are uniquely set to be 24.0 (hours), irrespective of the link.

The additional cost and time in border-crossing, CB_a and TB_a, are acquired from the summation of the cost and time for "documents preparation" and "customs clearance and technical control" in Doing Business website (trading across borders) provided by the World Bank, although it is currently not available. Note that these variables are defined for export and import respectively.
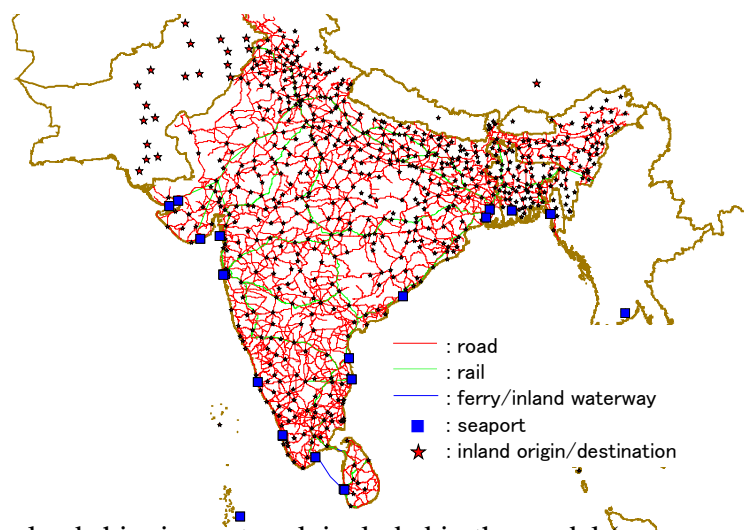

Figure 6. Hinterland shipping network included in the model (source: made by authors based on ADC WorldMap)

3.3 Shipping demand of container cargo (container OD cargo)

The shipping demand of container cargo (container OD cargo), Q_{ij}, from region i to j, as well as initial demand of maritime shipping demand, $q_{rs}^{(0)}$, from port r to s, is estimated as follows.

First, the demand of container cargo shipping (OD matrix) between countries or regions on a TEU-basis is obtained from the World Trade Service (WTS) database provided by IHS, Inc. The current version of the WTS data provides a container shipping demand for each year (from 2000 to 2030) among 117 countries/regions of the world (except for "others", in which certain countries/regions are not clear). However, some countries/regions in the WTS data are landlocked or do not have any seaports which handle more than 500,000 TEU a year. Also, hinterland transport across national borders can be observed in some regions, such as in Europe and North America. Therefore, the OD matrix is aggregated into 46 countries/regions, then divided again into a port-basis according to the port's share of the export and import container cargo throughput of the aggregated region.

Second, containers that will be shipped by the companies which are not included in the model are eliminated. This is necessary for the balanced calculation of the model between the vessel capacity and the amount of containers shipped in each service. This is obtained by first subtracting the total amount of shipping demand by the share of carriers which are not considered in the model for each port based on the share in vessel capacity arriving at and departing from each port. Then, the Frater method is applied to adjust errors by inputting the total amount of shipping demand for each port for the target carriers as given and the OD matrix estimated in the previous section as initial inputs. Until this step, initial demand of maritime shipping demand, $q_{rs}^{(0)}$, from port r to s, is obtained (more detail is described in Shibasaki and Kawasaki, 2016c).

The third step is to estimate a regional-basis OD matrix, Q_{ij}, for five South Asian countries. The port-basis OD matrix acquired in the first step are again aggregated into a county basis. Then, they are divided into a regional basis; namely, India is divided into 575 administrative districts; Bangladesh: 64 districts; Sri Lanka: nine provinces; and Bhutan and Nepal is not divided. The country-basis OD matrix is basically divided into a regional-basis one, by using OD matrix estimated by GSM (Geographical Simulation Model) which has been developed by IDE-JETRO (Institution of Developing Economies, the Japan External Trade Organization) and ERIA (the Economic Research Institute for ASEAN and East Asia). The detail of GSM is described in Kumagai et al. (2013) and Isono et al. (2016). The OD matrix is available by GSM into a regional basis by six trade goods (agriculture, automobile, electricity, textiles, food processing, and other manufacturing), but on a value-basis, not a tonnage-basis. Therefore, the transaction values transported by containers are extracted and multiplied by container ratio with values in the OD matrix. At this time, the share of container ratios is applied for each of the OD pairs. The container ratios between OD pairs are calculated by using WTS data, which is able to differentiate container and non-container cargo in terms of tonnage base, and, goods items are also able to specify for almost the same items of the GSM OD matrix. Finally, total trade volume of the country (Bangladesh, India, and Sri Lanka) in terms of TEU is proportionally distributed to each OD volume on the basis of the container ratio between the OD pairs. However, in the case of India, import/export data provided by Indian Customs Office is used to obtain the container export/import volume for each state. In this case, the model accuracy in terms of reproduction of current cargo flow proves a higher coefficient of variation. Proportional to the distributed container cargo for each state, the share of the OD matrix by IDE is used to calculate the share within the state in order to obtain the container amount of the detailed OD pairs.

4. PERFORMANCE OF MODEL

4.1 Calculation and Convergence

The actual model calculation starts from the lower level as shown in Figure 1; namely, two submodels. The first-term calculation of the maritime shipping submodel is performed by inputting the initial demand of maritime shipping demand, $q_{rs}^{(0)}$, while the first-term calculation of the hinterland shipping submodel is performed on a zero-flow basis, i.e. by shortest path search. Next, the shipping cost and time in the maritime and hinterland shipping, FM_{rs}, TM_{rs}, and GL_{ir} (or GL_{sj}), which are outputs of both submodels, are input into the intermodal super-network model in the upper level, as well as regional-basis shipping demand, Q_{ij}. Then, the shipping demand in the maritime and hinterland shipping, q_{rs} and q_{ir} (or q_{sj}), which are outputs of the super-network model, are input into both submodels in the lower level. These iterative calculations are repeated until the calculation converges or the number of iteration reaches to the upper limit (which is set to be five after several trial calculations). Note that the re-calculation of the maritime shipping submodel is performed once every two iterations since its convergence speed is slower but output is more robust than the hinterland shipping submodel.

The parameters on each congestion function, $b3$, $b4$, $b5$, $b6$, $b7$, and $b8$, distribution parameter of stochastic assignment (defined in Equation (3)), θ, and value of time for shipper, vt, are estimated by model calibration to best fit to the actual. The estimation results are shown in Table 1. The number of links in each network (maritime, hinterland, and super-network) is 82,280, 16,792, and 60,478. The average time for iterative calculation is thirty to forty minutes by using a laptop Windows computer with an Intel® Core™ i7 vPro-5600U™ Processor and 8.00 GB of RAM.

Table 1. Estimation results of unknown parameters included in the model

$b3$	$b4$	$b5$	$b6$	$b7$	$b8$	θ	vt
1.0	3.0	2.0	2.0	2.0	2.0	0.05	0.5 (US$/TEU/hour)

(a) Convergence rate of each iteration (b) Link flow around convergence judgment criteria

Figure 7. Convergence of the hinterland submodel

(a) Convergence rate of each iteration   (b) Change in handling amount in each port
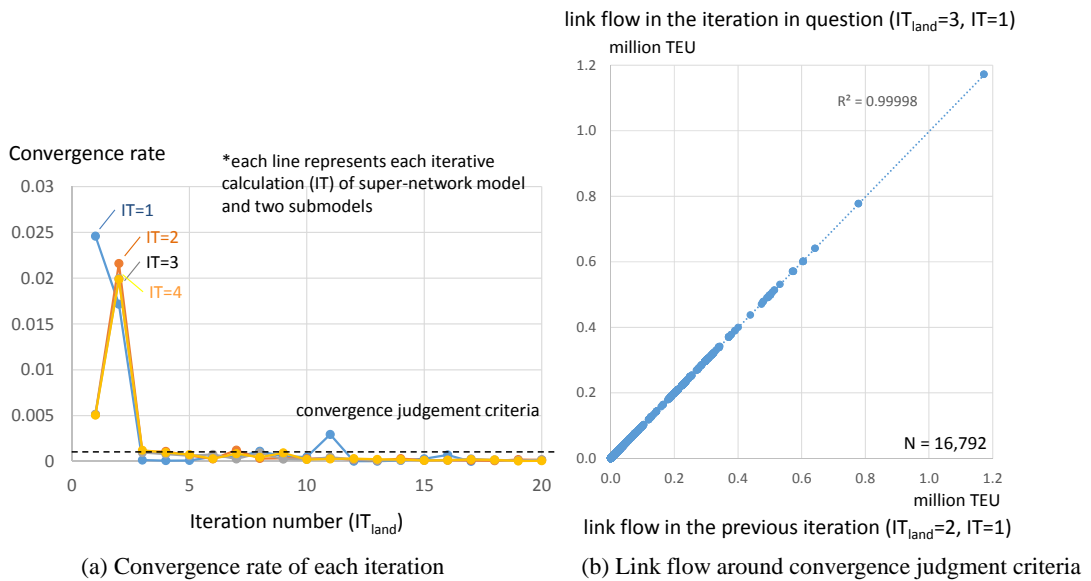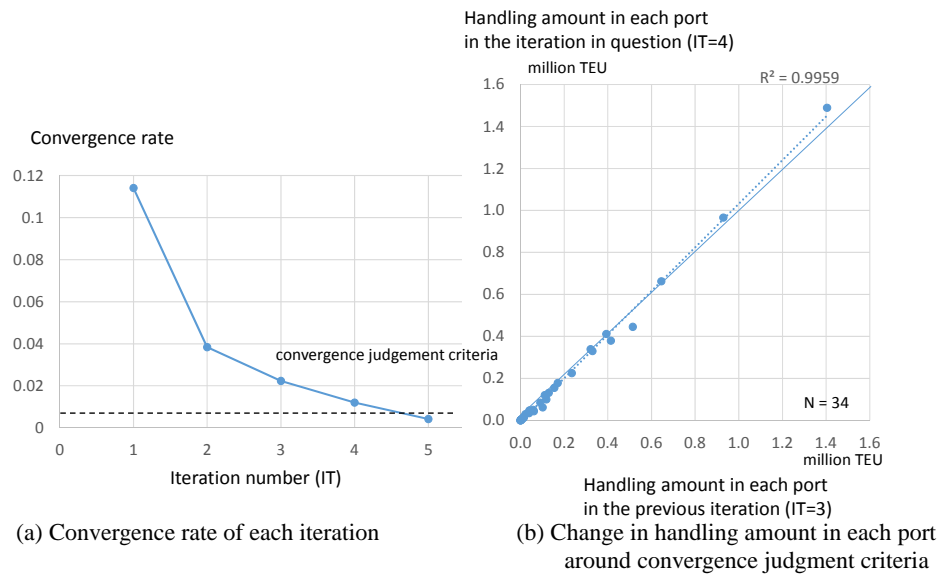around convergence judgment criteria

Figure 8. Convergence of the upper model (intermodal super-network model)

The convergence rates of each iterative calculation (the sum of squares of the differences between the link flow calculated in the iteration and that in the previous iteration) in the hinterland shipping submodel and the comparison between the calculated link flow and that in the previous iteration when the convergence rate first becomes less than 10^{-3} are shown in Figure 7. Also, the convergence rates of each iterative calculation (the sum of squares of the differences between the amount handled in each port calculated in the iteration and that in the previous iteration) in the intermodal super-network model and the comparison between the calculated amount handled in each port and that in the previous iteration when the convergence rate first becomes less than $5.0*10^{-3}$ are shown in Figure 8. (Note that convergence in the maritime shipping submodel is examined in Shibasaki and Kawasaki, 2016.) Considering these results and the calculation time, the above criteria are appropriate to judge that model calculation is sufficiently converged.

4.2 Container Throughput in each port

Figure 9 shows the comparison between the actual and model estimated container throughput at South Asian ports. Also, Figure 10 shows the comparison in terms of share of container throughputs by region. From these figures, the model can describe the actual well in terms of container throughput in each port, although the balance in the same region (e.g. JNPT, Pipavav and Mundra in west coastal ports of India) should be still improved further.
Figure 11 shows the hinterland link flow including road, rail and inland waterway in South Asia. As shown in the figure, several significant cities are located away from the coast and long distance shipping are observed such as between Delhi and JNPT or Mundra port, Nagpur/Hyderabad and JNPT, and Bangalore and Chennai port. Another finding is that national border significantly affects the shipping; for example, the amount shipped by international ferry between India and Sri Lanka is very small. Another example can be observed in "Seven Sisters" in India (Indian northeastern states), almost all cargo to/from which are shipped for an import from/export to Kolkata or Haldia port via Siliguri Corridor (which is known as "Chicken Neck"), not Chittagong port which is the closest to these states and larger in terms of container throughput. Figure 12 shows a comparison between the actual and model estimated share in shipping mode between Dhaka and Chittagong in Bangladesh. As shown in the figure, the model can describe the actual modal split well.
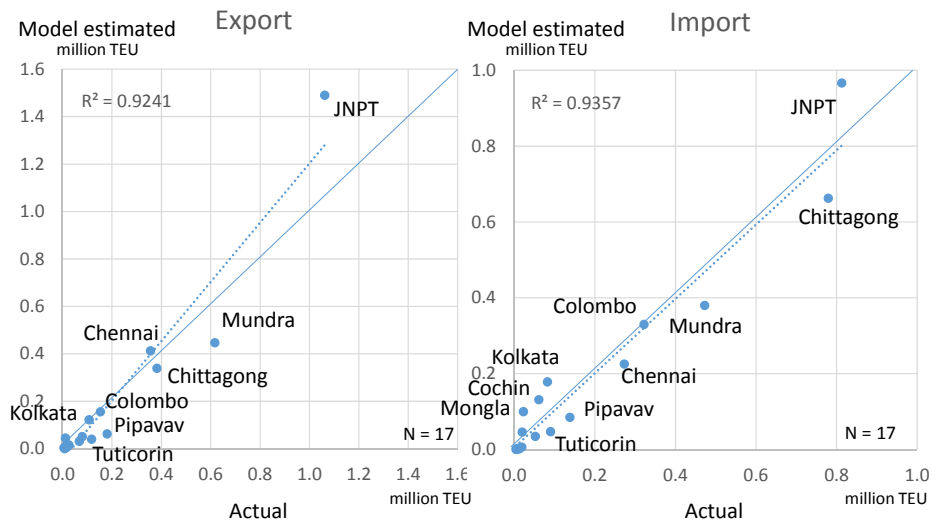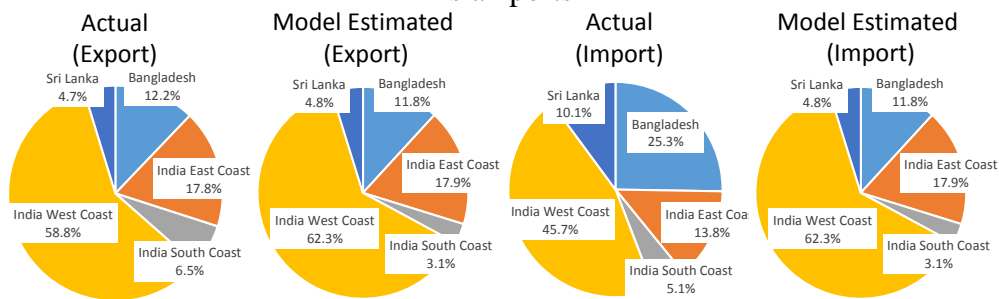
Figure 9. Comparison between the actual and model estimated container throughputs at South Asian ports

*India East Coast: Kolkata, Haldia, Vishakhapatnam, Krishnapatnam, Chennai; India South Coast: Tuticorin, Cochin, New Mangalore; India West Coast: Mormugao, JNPT, Hazira, Pipavav, Kandla, Mundra

Figure 10. Comparison between the actual and model estimated shares of container throughputs by region at South Asian ports
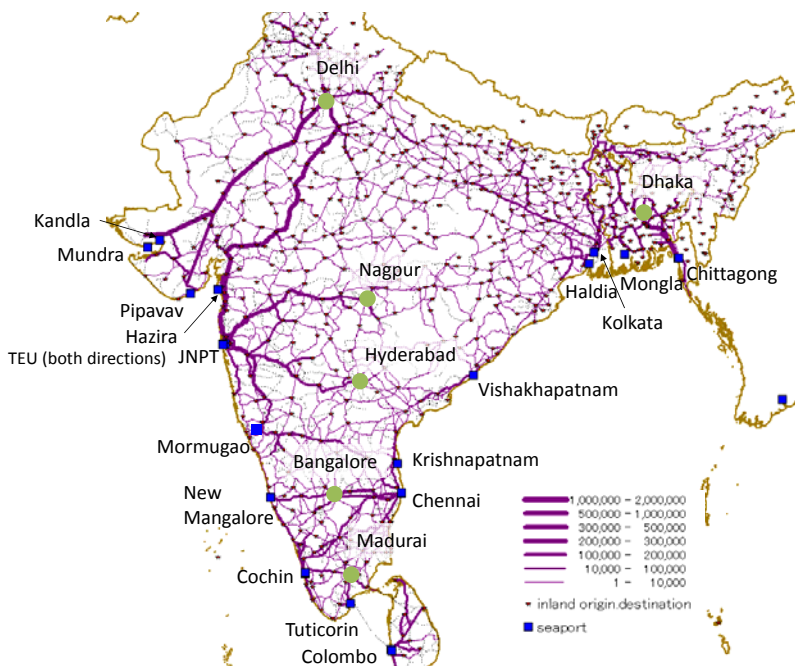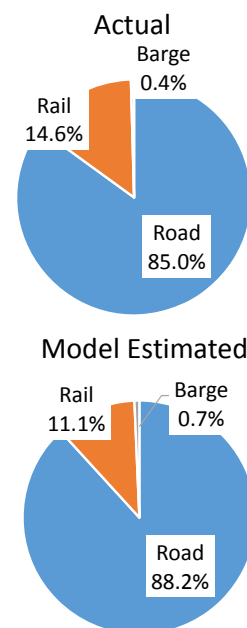

Figure 11. Estimated hinterland link flow

Figure 12. Comparison between the actual and model estimated share in shipping mode between Dhaka and Chittagong (Bangladesh)

4.3 Sensitivity Analysis using the Developed Model

4.3.1 Hinterland Improvement in JNPT

The first simulation assumes that capacities in the hinterland shipping network around JNPT, which is known as very congested port in the land side, are improved due to some investments to the infrastructures. In the "Base Scenario" which results are shown in 4.2, the road capacities around JNPT are assumed to be not sufficient as described in 3.2. On the other hand, in the first scenario (S1-1), their capacities are assumed to be improved from the "Important Route" level to "Primary Route" level for each direction. In addition, in the second scenario (S1-2), the rail capacity is also assumed to be improved, reflecting the dedicated freight corridor (DFC) project which has been undertaken by JICA's support. Concretely, a capacity per train, $capRa_a$, between Delhi and Indian west coastal ports (i.e. not only JNPT but other ports such as Hazira, Pipavav, and Mundra are included) is assumed to increase by four times (i.e. 360 TEU/train), reflecting a double-stack train which length is also doubled will be introduced after the opening of the DFC, according to the interview survey. In addition, a railway speed, vRa_a, is increased as 80 (km/hour), which is four times as fast as that in the Base Scenario; an operational charge, $CORa$, is reduced as 0.25 (US$/km/TEU), which is half of that in the Base Scenario; and service frequency in each link, $freqRa_a$, is increased by four times as much as that in the Base Scenario respectively.

The increased amount of exported and imported containers handled in each Indian port is shown in Figure 13. As shown in the figure, the number of containers handled in JNPT is expected to increase by 140 and 260 thousand TEU respectively, which equals to 5.8% and 10.8% of the total number of exported and imported containers in JNPT in the Base Case. On the other hand, the numbers of containers in other west coast ports such as Hazira, Pipavav, and Mundra, decrease. In particular, the decreased amount in Mundra port is significant. Figure 14 which shows the difference of each link flow between the DFC Scenario (S1-2) and Base Scenario also indicates the containers originated from/destined to Delhi are shifted to JNPT from Mundra and other west coast ports. Note that even in the S1-2 where the rail capacities to other west coast ports are also increased, the cargo are estimated to shift from these ports to JNPT. It implies that the current capacity constraint in JNPT is very significant and some of cargoes currently handled in other ports escapes from JNPT in order to avoid the heavy congestion, which coincides with the results of the interview survey.

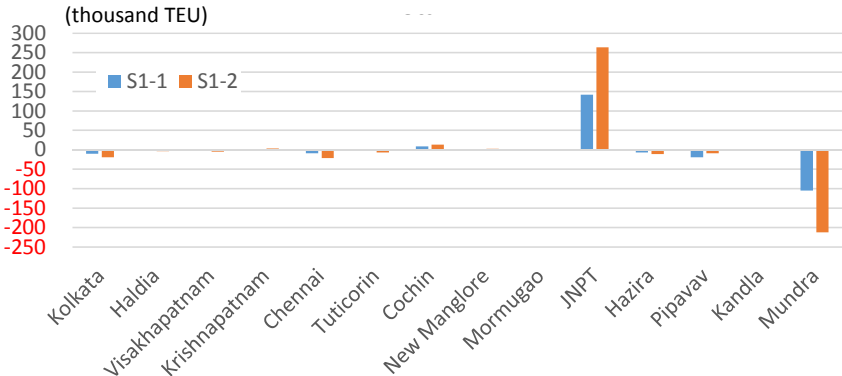**4.3.2 Ferry and Rail Improvement in South India and Sri Lanka**

Figure 13. Increased amount of exported and imported containers handled in each Indian port for each scenario to improve hinterland capacities in JNPT (comparison to the Base Scenario)
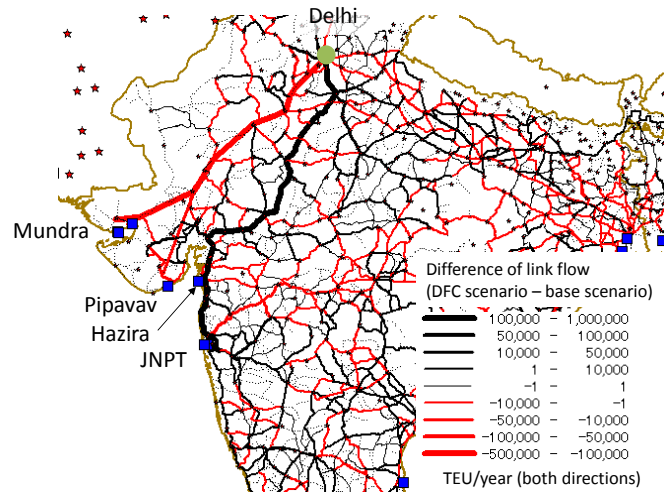
Figure 14. Difference of each link flow between the DFC Scenario (S1-2) and Base Scenario

The second simulation assumes the recommencement of international ferry service connecting between South India (Tuticorin port) and Sri Lanka (Colombo port) which is currently suspended. In addition, rail connection in South India (between Chennai and Tuticorin) is also assumed to be improved. Concretely, a frequency of ferry service, $freqFe_a$, is set to be 28 (for trucks) and 7 (for rail) vessels/week and a vessel speed, vFe_a, is 30 (km/hour), while other level of service (i.e. a vessel capacity, $capFe_a$, fixed and operational cost, $CFFe$ and $COFe$, and a handling time at each port, $THFe_a$) is assumed to be the same as the existing ferry service in other area (i.e. Bangladesh). In addition, a frequency of rail service, $freqRa_a$, is assumed to significantly increase by 14 trains/week from 0.5 trains/week in the Base Scenario as well as an operational charge, $CORa$, to be half in the Base Scenario (i.e. 0.25 US$/km/TEU), while other level of service (i.e. a train capacity, $capRa_a$, and train speed, vRa_a) is assumed to be the same as the existing service unlike the DFC scenario.

Furthermore, the additional cost and time in border-crossing, CB_a and TB_a, between India and Sri Lanka are also assumed to decrease. Since a barrier reduction of border-crossing is considered to significantly affect to the amount of ferry shipping, three scenarios are prepared; namely, CB_a and TB_a are assumed to be half of the existing figures (S2-1), one fourth of those (S2-2), and zero (S2-3), respectively.

Figure 15 shows the estimated amount of exported and imported containers handled in South Indian ports (i.e. Chennai, Tuticorin, and Cochin) and Colombo port for each scenario and the Base Scenario. Also, Figure 16 shows the difference of each link flow between the S2-2 and Base Scenario. The estimated amount of containers transported by ferry between Tuticorin and Colombo is 5,537, 37,942, 141,074 TEU/year for each scenario (i.e. S2-1 to S2-3), including both truck and rail ferry for both direction. Since the annual ferry capacity assumed is 232,960 TEU (= 128 TEU/vessel * 35 vessels/week * 52 weeks/year), the estimated load factor is 2.4%, 16.3%, and 60.6% for each, which reveals that the level of barrier reduction for border-crossing causes the significant difference in the utilization of international ferry as expected.

Another finding is that in both end ports of the ferry service (i.e. Tuticorin and Colombo), the total number of exported and imported containers shipped by containership and ferry increases as the border-crossing barrier is reduced, while that in Cochin port decreases as the barrier is reduced. The impact of barrier reduction to the number of containers handled in Chennai port is not constant. In particular, the number of exported and imported containers in Colombo port seems to significantly increase in S2-3; however, the total number of containers handled in Colombo port including transshipped containers is

almost the same for each scenario (for example, 2,367 thousand TEUs in the Base Scenario while 2,356 thousand TEUs in S2-3). In other words, some containers which are exported from/imported into South India with transshipment in Colombo port in the Base Scenario are considered to shift to utilize the international ferry and handled in Colombo port as exported or imported container in S2-3.
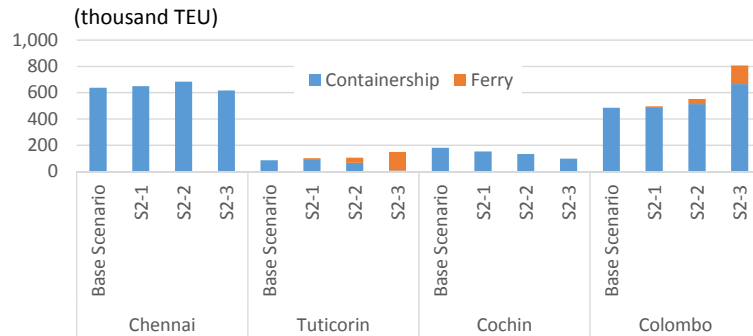

Figure 15. Estimated amount of containers handled in South Indian ports and Colombo port for each scenario to improve rail and ferry connection in South India and Sri Lanka
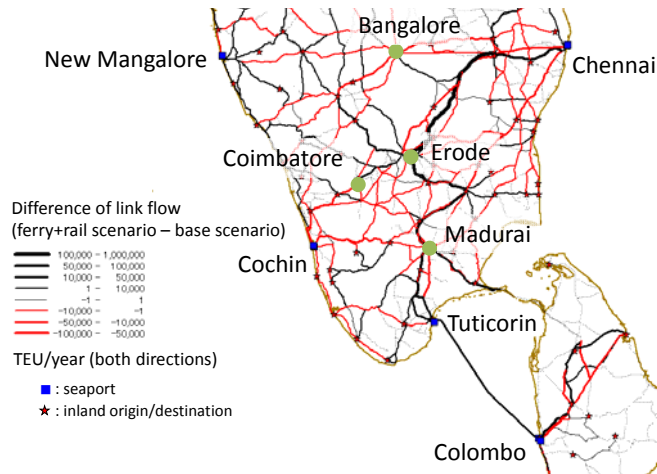

Figure 16. Estimated difference of each link flow between the S2-2 and Base Scenario

5. CONCLUSION

The authors developed a two-layered network assignment model of international container cargo including both a global maritime and local hinterland shipping network from the shippers' viewpoint. In the lower layer of the model, each assignment submodel with capacity constraint on detail maritime and hinterland network is separately developed. In the upper layer, a stochastic assignment model with unobservable term on the intermodal super-network is developed, reflecting the outputs of the lower layer submodels. In particular, the hinterland network submodel was generalized to incorporate more real, complicated hinterland network with capacity constraint which includes not only road but also rail and inland waterway, compared with the past models that the authors had developed.

The model was applied into three South Asian countries including India, Sri Lanka, and Bangladesh by inputting various information such as level of service in maritime and hinterland shipping and reginal-basis shipping demand of international container cargo. Then the performance of the developed model is verified in terms of convergence and reproducibility of the actual container throughput in each South Asian port. Finally, two policy simulations to improve the level of hinterland infrastructure around JNPT and

international connection by ferry between India and Sri Lanka are examined as a sensitivity analysis. As a result, it can be concluded that the developed model can well describe the actual and that its sensitivity to the policies to improve the hinterland infrastructure is reasonable; for example, Indian west coast ports are very competitive each other to acquire the cargo originated from/destined into Delhi, and among them, a capacity constraint of hinterland shipping around JNPT is critical. Another example is that the reduction of cross-border barriers is essential for promoting the international ferry service between South India and Sri Lanka as well as improvement of rail service to be connected with.

As the applications which was shown at the end part of this paper are just examples in order to confirm the sensitivity of the model, many applications utilizing the developed model such as evaluation of each project to improve port and hinterland infrastructure should be implemented as the next step. In particular, future simulations such as whether each project currently planned is sufficient for expected future demand or not should be implemented, by inputting future cargo shipping demand which was estimated by other organizations such as IDE-Jetro (see for example, Kumagai, et al., 2013). In addition, another submodel to decide the future level of service in maritime and hinterland shipping network such as vessel enlargement is also necessary to be developed. In parallel, the authors will apply (or extend) the developed model with other regions of the world such as Central Asia, Southeast Asia, the Pacific Islands and other regions as requested.

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