Joint Design and Pricing of Intermodal Port - Hinterland Network Services: Considering Economies of Scale and Service Time Constraints

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Abstract

Maritime container terminal operating companies have extended their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of inland terminals in their network by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. These network operators face the following three interrelated decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of the corridors, i.e. capacity of the transport means and frequency of service, and (3) set the prices for the transport services on the network. We propose a bi-level programming model to jointly design and price extended gate network services for profit maximization. The network operator does so while anticipating the decisions of the customers who choose minimum cost paths to their final destinations, and who always have the option to choose direct trucking offered by the competition. The model in this paper extends existing bi-level models in a multimodal format by including service time constraints and economies of scale. Considering the special structure of our problem, we propose a heuristic that provides near optimal solutions to our problem in substantially less time. Through experimental results in some realistic instances, we study optimal network designs while comparing sea port-to-door and sea port to inland port services and situations where transit time requirements do and do not apply. Our results show that when demand is relatively low, there are significant differences in the optimal network design for port-to-door versus port-to-port services. In the case of port-to-door services, the prices of services are determined by the competition and not by the design of the network, so the network is designed against minimum costs, and economies of scale are achieved by consolidating flows through a limited number of extended gates. The case of port-to-port services is different, i.e. revenues are enhanced not so much by reducing costs through the exploitation of economies of scale, but by exploiting the possibilities to dedicate extended gates to market segments for which the competition leaves room for higher port-to-port tariffs.

1 Introduction

Maritime container terminal operating companies around the globe have recently started to actively participate in land-side transport networks to enhance their connectivity to destinations inland while relieving some of the negative effects of freight transportation. Container terminal operators have done so by extending their role from node operators to that of multimodal transport network operators. They have extended the gates of their seaport terminals to the gates of inland terminals in their network by means of frequent services of high capacity transport modes such as river vessels (barges) and trains. Moreover, customs clearance and other added value activities can be postponed until the containers leave the inland terminal gates instead of the seaport terminal gates (Veenstra et al. [2012]). In this format, the notions of extended gate operator and network operator can be used interchangeably, so from now on we will use the term extended gate operator to denote the network operator of our case. The extended gate operator at the tactical design of the land-side transport network faces the following three decisions: (1) determine which inland terminals act as extended gates of the seaport terminal, (2) determine capacities of corridors, i.e. capacity of the transport means and frequency of service, and (3) set the prices for the transport services on the network. The three decisions are interrelated because inland terminals are located in relatively close distances, usually close to industrial regions, so the hinterland of inland terminals is contestable. Thus, the network operator could connect the seaport terminal either to a limited number of inland terminals while using high frequent and high capacity transport services, or it could connect with more inland terminals while using less frequent services or lower capacity transport means. The price per TEU at each corridor should make the routing of all containers through that corridor cost effective compared to the service provided by the competition. It follows that, when a extended gate is meant to attract demand destined to regions other than its captive hinterland, for flow consolidation purposes, the price setting at its corresponding corridor should be low enough to make the path to the distant regions also cost effective. The above reduction in the prices would affect also the revenues the extended gate operators receive from the clients located in the captive hinterland of the extended gate.

Port-Hinterland intermodal transportation is usually referred in literature as combined transport (Frémont and Franc [2010]), so this term will be used throughout this paper, and can take either the rail-road or waterway-road scheme indicating that usually the end haulage trip is performed by trucks. The international shipping of containers can be organized either under merchant haulage or under carrier haulage but port - hinterland transport of containers can also be offered under the so called terminal operator haulage (Notteboom [2008]). In the latter case, transport services are offered either as port-to-port services or port-to-door services. In case of port-to-door services, the terminal operator, that acts as an extended gate operator, orchestrates the transport of containers from the port to their final destination, while under port-to-port services he only offers transport from the seaport terminal to inland terminals. In other words, under port-to-door service the extended gate operator is assumed to control all links and nodes over the inland network while under port-to-port service it controls only flows on the high capacity corridors while the remaining is outsourced to competition. Under port-to-port service the prices should be set low enough such that they make the combined transport path, via the extended gates, at least cost neutral to the best alternative service offered by the competition (Roso and Lumsden [2010]) for all containers routed through it. In this setting, the design of the inland transport network and the pricing scheme are interrelated. On the other hand, under port-to-door service the price of transport from seaport to final destination mainly depends on the best alternative transport service offered by the competition and does not depend on the routing of the container through the network since it is assumed that also the end haulage legs performed by trucks are offered by the extended gate operator. Thus for port-to-door services pricing and network design decisions do not have to be considered jointly. The term competition is used to denote other intermodal carriers or trucking companies that can offer alternative transport solutions to shippers than the ones offered by the extended gate operator. The last leg of transport is usually performed by trucking companies who also benefit from the use of extended gate concept since congested roads to seaport terminals are avoided while the pick up and drop off of containers is performed at the inland terminals, the above can increase sufficiently the number of trips they can perform per day.

The profitability of the extended gate operator apart from the pricing also depends on the cost of delivering the network services, where the effective utilization of high capacity transport means provides the opportunity for economies of scale. Moreover, higher frequency of transport services reduces the average throughput times of containers which enlarges the market potential for such services. The trade-off between customer demand characteristics and carrier strategies should be considered, as it is supposed to lead the development of a variety of possible inland container routing patterns (Notteboom [2008]). Finally, consolidation helps to hedge against demand uncertainty [Lium et al., 2009].

In this paper, we propose a model to jointly design and price extended gate network services to reap possible benefits. We contribute to the existing body of knowledge by extending Joint Design and Pricing bi-level formulations, as proposed by Brotcorne et al. [2005, 2008], to fit the Port-Hinterland multimodal network design by including service time constraints and high capacity modalities. Considering the special structure of our problem we propose a heuristic that provides near optimal solutions to our problem in substantially less time than it takes

CPLEX to solve the MIP equivalent formulation of our problem. Finally, through experimental results in some realistic instances we analyze the optimal network configurations under service type, demand and service time scenarios. Our results show that when demand is relatively low, which can be the case for several inland regions, there is significant difference in the optimal network configuration between considering port-to-port and port-to-door services. Moreover, the consideration of service time constraints in tactical network design shows that demand penetration through frequent services has a larger effect than achieving economies of scale through the use of bigger vessels.

2 Literature Review

In this section, we go through the most relevant literature to our research and position our work accordingly. First, we go through some general literature on intermodal transportation and then we review three steams of literature that we consider relevant for the port hinterland network design and in particular for our modeling approach. Our literature review is not exhaustive but focuses on specific modeling features that could be applied or adapted to facilitate the port hinterland multimodal network design. The development of the supply side of container transport networks has been studied extensively in the literature and is widely known as the service network design problem. Such problem formulations are increasingly used to designate the tactical issues of carriers (Crainic [2000]). The main considerations and several models on intermodal freight transportation can be found in Crainic and Kim [2006]. However, contributions that could be exclusively facilitate the port-hinterland network design area are limited.

A recent overview of the intermodal freight planning research is conducted by Caris et al. [2008]. The authors divide the contributions in the field according to the time horizon in strategic, tactical and operational models. Strategic decisions in intermodal transportation usually relate to long term decisions such as node and link infrastructure investments. When designing the extended gate network of a terminal operator existing infrastructure is used so pricing, capacity and frequency setting on the corridors are at the tactical level. Operational decisions in this context come down to assigning containers to specific transport itineraries such that capacity is effectively utilized and time constraints set by the shippers are met. Decisions at the tactical level though can have a significant effect on the operational performance of such networks.

Some work in our domain is currently in progress. Crainic et al. [2013]discusses the optimization challenges that arise by the development of the dryport concept and proposes a service network design model, in a space-time format, for the rotation planning of barges between seaport and inland terminals. van Riessen et al. [2013]proposes a path-based service network design model that investigates the use of contracted and subcontracted network services for the operation of an extended gate network at a tactical level, while assuming flexible due dates. Their findings show that transhipment cost at terminals should be reduced in order to paths with more than one stops at inland terminals to become cost effective.

The extended gate operator aims at optimizing the design of his hinterland network while anticipating the routing decisions by the shippers of containers. Shippers can route their containers via links controlled by the extended gate operator or by its competitors or by a combination. Bi-level formulations of the network design problem capture the decisions of these three different actors involved.

Port hinterland combined transport services compete with unimodal trucking services both in cost and service time dimensions so both should be considered at the tactical design of such networks. To address the cost effectiveness of combined transport we review and consider the joint design and pricing formulations of such networks. Moreover, we review contributions that model economies of scale when setting up high capacity corridors. Economies of scale achieved by the extended gate operator can lower his prices that are faced by the shippers and thus offset the additional handling charges of containers at terminals and provide cost incentives for the market penetration of such services. The market penetration of combined transport also depends on the expected service time of such services, which consist of transit times at the links and dwell times at the terminals. The dwell times depend on interdeparture times of barges and trains, i.e. the frequency of their departures which by definition depend on the design of the network so should also be considered at the tactical port hinterland network design.

2.1 Joint Design and Pricing of Transport Services

The joint design and pricing of transportation networks is mainly modeled by bi-level mathematical models. Bi-level models are seen as a static version of the non-cooperative Stackelberg game. Most of them have in common that they try to maximize the revenues of an actor that is considered to be the leader and controls a set of arcs and nodes of the network while minimizing the total cost faced by the users of the network. These features are in line with our view of an extended gate operator that endeavors to maximize his profitability by attracting flows through his network. The proposed network design must add value to the shippers by reducing their total cost. The main assumption of such formulations is that the competitors do not react to the final configuration proposed by the leader of the network. Due to the difficulties that arise when solving such formulations, which are proven to be NP-hard even in the simplest linear case, most papers focus on alternative modeling formulations of the problem and on the development of novel solution procedures. Contributions with managerial relevance in the sense of what is the impact of considering joint design and pricing in a network are yet limited.

Brotcorne et al. [2000] introduce the freight tariff setting problem in which the objective is to maximize the revenues of a carrier who controls a set of arcs of the network, by setting the tariffs for using these arcs, while the flows over the network are determined in the second level minimizing the total transport cost faced by the users of the network. This is the simplest formulation since all terms are assumed to be continuous. The authors develop the single level equivalent bi-linear formulation of the problem with disjoint constraints, and solve it with heuristics based on the primal-dual heuristic proposed by Gendreau et al. [1996]. Brotcorne et al. [2001] extend their previous work by considering a multicommodity network in which the leader maximizes his revenues by setting the tolls on the set of arcs he controls. In this setting, again a primal-dual based heuristic is used with an extension that forces tolls applied for each commodity to be equal and moreover an arc sequential heuristic is proposed.

Brotcorne et al. [2005] further extend their previous model by considering the joint pricing and capacity setting problem in a multicommodity transportation network. This problem is formulated as a mixed integer bi-level program and is again solved by using a primal-dual based heuristic. This model incorporates the tradeoffs between revenue and cost generated for the leader when designing his network; it is stated that until then these issues were treated separately although they are intrinsically linked and should be treated jointly. The economies of scale principle is assumed to be satisfied by assuming the marginal cost of increasing capacity to be decreasing. In Brotcorne et al. [2008] the authors consider the joint design and pricing of a network by assuming that investment fixed cost apply to the leader for operating arcs over the network. This case is formulated as a mixed integer bi-level program with binary decision variables indicating whether or not an arc is used in a multicommodity transportation network. A novel heuristic based on Lagrangian relaxation is applied to incorporate the binary design variables in the solution method. An exact algorithm for solving the pricing problems on a network by partially and efficiently generating candidate solutions is presented in Brotcorne et al. [2011] while a tabu search algorithm is presented in Brotcorne et al. [2012].

To the best of our knowledge, only a few bi-level formulations of the intermodal network design problem exist in the literature. Crevier et al. [2012] propose a path based bi-level formulation of the rail-road integrated operations planning and revenue management problem, at an operational level, while proposing some exact algorithms for its solution. The pricing of services depends on the prices set by the competition for the different service levels while the capacities of the corridors are obtained by solving a service network design model at the tactical level.

The joint design and pricing of an intermodal network has been addressed also in other than bi-level programming formats. Li and Tayur [2005] jointly design and price an intermodal network by using a traditional marketing research approach for the pricing part. In this approach, a customer chooses an intermodal service based on its expected service level and is charged based on the best alternative transport solution cost which provides the same service level. The paradox of this approach is that customers with different service level characteristics pay different prices while experiencing the same service level.

2.2 Service time constraints

The time dimension in service network design is usually incorporated at the operational level by considering time windows for the pick up and delivery of cargo. The service times are considered either by applying penalty cost for late deliveries or by imposing due date constraints. The consideration of the time-dimension at both tactical and strategic intermodal network design is identified as a major research challenge by Crainic and Kim [2006]. Its importance is further enhanced by the fact that shippers tend to choose their carriers based on the perception of the service quality that they will receive (Crevier et al. [2012]). In the intermodal network design, the service quality perception can be associated with the service times of intermodal paths which depends among others on the frequency of services (Li and Tayur [2005]). It follows that the market penetration of combined services depends also on the tactical and strategic design of such networks in addition to their operational performance.

Very few modeling contributions at a tactical level seem to take the time dimension explicitly into account. In Crainic [2000] the main service network design formulations are reviewed; the service level is considered by the application of a minimum frequency constraint on specific links over the network if they are opened. Such formulations cannot capture the demand penetration of a carrier based on the service level offered. In order to capture this effect, multicommodity formulations with differentiated characteristics among the commodities should be developed. In Crainic and Rousseau [1986] this interaction is captured by considering unit delay cost in the objective function differentiated per commodity which depend on both connection frequency delays and transit times in each link over the network. First, unit delay cost can be difficult to approximate for each commodity, compared to setting a desired service time or a minimum frequency constraint per commodity. Second, the routing of containers in the network may greatly rely on the values of the penalty delay cost compared to the cost structure over the network, but still the potential of loosing some market to competition is not captured in such models. Li and Tayur [2005] consider the expected total service time constraints set by the clients of the network and model that frequency dependent service time of paths consisting of link, capacity and frequency delays; the service frequency on the links is then bounded from below to satisfy the time constraints set by the clients. The last formulation of service level constraints seems to be the most considerable but the uni-modal formulation of the model as much as the non consideration of competition limits the capturing effect of market penetration based on the service quality offered.

2.3 Network Flows and Economies of scale

Economies of scale are usually incorporated in Hub and Spoke network formulations. Most of these contributions apply a discount factor a, $0 \leq a \leq 1$, to the transportation cost between any two of the selected nodes of the network that will act as hubs. It is clear that this simplistic approach does not take into account the amount of flow that will pass through the inter-hub link, so post-assessment and post-validation of the solutions is needed. Considering the above can explain the shift to flow dependent economies of scale. Several authors consider piecewise linear functions to depict the economies of scale (O'Kelly and Bryan [1998], Horner and O'Kelly [2001], Klincewicz [2002]). Marginal cost is positive and decreasing in flow volumes.

The former approach is considered to be wrong since assuming that the discount factors are independent of the flows can lead to false hub allocations and result interpretation (Kimms [2006]). The latter approach with flow dependent discount factors could be valid if the transportation is performed by a third party. Kimms [2006] proposes an alternative formulation of economies of scale as a non continuous increasing function of the flows, with break points denoting the multiples of the capacity of the mode in reference. We agree in principle with Kimms [2006] but we argue that the variable cost per unit transferred is minor compared to the fixed cost associated with operating (leasing) high capacity modes such as barges and trains; that is that the slope of the piecewise linear parts of the function should be close to zero. On the other hand, economies of scale exist when higher capacity assets are used even for the same modality, as we discuss in the cost formulation of our model.

3 Modeling

The extended gate operator aims to design the capacities, frequencies, and prices of combined transport services on its network in such a way that profits are maximized. He does so while anticipating the decisions of the customers who choose minimum cost paths to their final destinations, possibly under service time related constraints.

We model the extended gate operator as a Stackelberg leader, followed by its customers. We formulate the above situation as a bi-level mathematical program where on the first level, the extended gate operator maximizes its profits which are given by the revenue of the extended gate services minus the fixed and variable costs of operating the extended gates. On the second level, the collective of customers minimizes the total system cost which consist of transportation cost and handling charges at the container terminals. The total network consists of links and nodes controlled either by the extended gate operator or by the competition. In particular, each hinterland destination can also be served by a direct trucking option offered by the competition. Therefore, prices set by the extended gate operator are always constrained by a competitive price from above. The model formulation extends the one proposed by Brotcorne et al. [2008] in a multimodal format by the consideration of economies of scale when assigning high capacity modalities to corridors and by the formulation of connection frequency dependent service times.

3.1 Notation

Let us consider an underlying network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ with node set $\mathcal{N}$ and arc set $\mathcal{A}$. We assume that a node can be a supply, demand or a transhipment node in case it represents a deep sea terminal, client, and inland terminal, respectively. The set of arcs $\mathcal{A}$ is partitioned in two subsets; the set $\mathcal{A}_1$ which represents the candidate corridors to extended gates which are controlled by the leader and the set $\mathcal{A}_2$ which represents all remaining arcs which are controlled by the competition.

We consider the multicommodity formulation of the problem in which each commodity, $c \in \mathcal{C}$, represents a share of the weekly container demand for a specific Origin and Destination

(OD) pair, $(O^c, D^c) \in \mathcal{N} \times \mathcal{N}$, under some service time constraint. The demand volume of a commodity c expressed in TEUs is denoted by d^c, and represents the level of demand for both inbound and outbound flows regardless of whether the containers are full or empty. The inbound and outbound flows of containers are assumed to be balanced, since any inbound flow of full containers would lead to the return of an empty and vice versa. In reality, some empty containers dwell at the inland terminals until some demand for export containers is generated so they are full also on their return trip. Usually there exist weight and balance constraints for the loading of containers on barges and trains but such issues are addressed at an operational level and are out of the scope of this paper. The desired service level is assumed to be expressed either as an upper bound for the expected service time, t^c, or as a minimum weekly frequency constraint, f^c_{ij} for all $(i,j) \in \mathcal{A}_1$, for the combined transport services. Considering the above demand formulation, we aim at analyzing the market penetration of combined services compared to direct transport based on the service frequency of high capacity modalities. The demand data requirements for the model can be derived by analyzing historical data or by having experts in the field approximating them. To facilitate our modeling, we use

$$d^c_j = \begin{cases} d^c, & j = D^c \\ -d^c, & j = O^c \\ 0, & otherwise \end{cases} .$$

We assume that cost of transport operated by the competition is linear in volume. The transport cost per unit (TEU) on an arc is denoted by C_{ij} for all $(i,j) \in \mathcal{A}_2$ and the container handling charges at the transhipment nodes are also linear in volume and denoted byH_{ij} for all $(i,j) \in \mathcal{A}_1 \bigcup \mathcal{A}_2$. The handling cost applies to all arcs since every arc starts or ends at a seaport or inland terminal; the main difference between combined and road transport is that in the former handling charges are applied twice both at the seaport and the inland terminal compared to just the seaport handling charges that apply in the latter.

We consider a set of barges, $b \in \mathcal{B}$, with different cost and capacity characteristics. The cost of operating barges, from a barge operators perspective, consists of several components, such as assets, crew, fuel, and maintenance (Braekers et al. [2012]). On the other hand, the cost faced by the extended gate operator, assuming that it does not use its own barges, is the price scheme proposed by barge operating companies which consists of the above costs enhanced by a profit margin for the barge operator. The leasing cost of a barge for a week is denoted by w^b for all $b \in \mathcal{B}$ which includes both asset and staff cost required to navigate and operate the barges. Economies of scale apply in this leasing cost when higher capacity barges are selected; crew cost for barge navigation and operation are concave in the capacity of the vessel. A variable cost per round trip, v_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$, is also considered to represent the fuel cost of barges which is assumed to be linear to distance traveled but variable to the size (capacity), Q^b, of the barge. The number of round trips that a barge can perform to an extended gate, n_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ is bounded from above by physical and technical characteristics like the distances traveled, sailing speed, handling times on seaport and inland terminals, and delays.

At the first level, the extended gate operator designs and prices its services. First, the prices T_{ij} for all $(i,j) \in \mathcal{A}_1$ are modeled as the price per TEU transferred through a corridor to and from an extended gate. This decision variable determines the revenue for the extended gate operator at the first level and part of the cost faced by the shippers at the second level. Second, the design variables u_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ denote the number of barges of type b that are assigned to each extended gate while the integer design variables y_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ denote the number of trips a barge of type b will perform at corridor (i,j), and y_{ij} for all $(i,j) \in \mathcal{A}_1$ denote the frequency of service on the candidate extended gate corridors. We also introduce the auxiliary Boolean variable $\tilde{y}_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ that denotes whether commodity c can be routed through link $(i,j) \in \mathcal{A}_1$ with respect to the time constraints. On the second level, the collective of customers chooses the minimum cost paths to transport their containers by deciding on the flow variables, Y_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and X_{ij}^c for all $(i,j) \in \mathcal{A}_2, c \in \mathcal{C}$ which denote the amount of TEUs assigned to each arc of the network.

We assume the transport times, t_{ij}^b for all $(i,j) \in \mathcal{A}_1, b \in \mathcal{B}$ and t_{ij}^t for all $(i,j) \in \mathcal{A}_2$ for barges and trucks respectively. The expected dwell time of containers at seaport terminals is assumed to consist of two components. First, a customs delay t_{ij}^n for all $(i,j) \in \mathcal{A}_1 \bigcup \mathcal{A}_2$ that would be the average time it takes for a container to be released by customs so that containers could leave the seaport terminal. Under the extended gate concept, containers are transported to the inland terminals under the customs license of the extended gate operator so these customs delays are considerably lower than the ones realized by direct trucking. Second, the frequency delays t_{ij}^d for all $(i,j) \in \mathcal{A}_1$ which are assumed to be inversely proportional to the connections frequency and can be calculated by $t_{ij}^d = \frac{1}{2y_{ij}}$. The frequency delays represent the expected time a container would have to dwell at the seaport terminal until the next barge itinerary would depart. For arcs served by trucks infinite frequency is assumed and thus zero frequency delays are considered for direct truck transport. The frequency of connections is a design variable in our model and thus the service time of combined transport is also a design variable that determines the market penetration of combined services.

The parameter M represents a relatively large value for which we assume that $M \geq \sum\limits_{c \in \mathcal{C}} d^c$.

3.2 The Model

3.2.1 First Level (FL)

$$FL: \max_{T,Y,u,y} \sum_{c \in \mathcal{C}} \sum_{(i,j) \in \mathcal{A}_1} T_{ij} Y_{ij}^c - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} w^b u_{ij}^b - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} v_{ij}^b y_{ij}^b \tag{1}$$

$$\sum_{c \in \mathcal{C}} Y_{ij}^c \leq \sum_{b \in \mathcal{B}} Q^b y_{ij}^b \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{2}$$

$$y_{ij}^b \leq n_{ij}^b u_{ij}^b \qquad \forall\, (i,j) \in \mathcal{A}_1, b \in \mathcal{B} \tag{3}$$

$$y_{ij} = \sum_{b \in \mathcal{B}} y_{ij}^b \qquad \forall\, (i,j) \in \mathcal{A}_1 \tag{4}$$

$$\tilde{y}_{O^c k}^c \leq 2 \cdot \left(t^c - t_{O^c k}^n - t_{O^c k}^b - t_{k D^c}^t \right) \cdot y_{O^c k} \qquad \forall\, (O^c, k) \in \mathcal{A}_1, c \in \mathcal{C} \tag{5}$$

$$Y_{ij}^c \leq \tilde{y}_{ij}^c M \qquad \forall\,(i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{6}$$

$$\tilde{y}_{ij}^c \in \{0,1\} \qquad \forall\,(i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{7}$$

$$y_{ij} \in \mathbb{N}^0 \qquad \forall\,(i,j) \in \mathcal{A}_1 \tag{8}$$

$$u_{ij}^b \in \mathbb{N}^0 \qquad \forall\,(i,j) \in \mathcal{A}_1, b \in \mathcal{B} \tag{9}$$

The first level objective (1) represents the profits of the extended gate operator and consists of the revenue from the extended gate services diminished by the cost of operating the extended gate corridors. The capacity constraints are given in (2) which guarantee that the sum of the flows in each corridor is less than its capacity. Constraints (3) and (4) determine the service frequency in a corridor when several barges are assigned to it. Service time constraints are introduced in (5) and (6) that guarantee that the expected service time for each commodity should be less or equal than its desired service time, t^c. It should be noted that in order to obtain a feasible solution it should hold that $t^c \geq t_{O^cD^c}^n + t_{O^cD^c}^t$ for all $c \in \mathcal{C}$; that is that the time restriction set by each commodity can always be satisfied by the quickest path, which is direct trucking.

Constraints (5) are the linear equivalent of constraint (10) in which the left hand side expresses the expected service time for combined transport while the right hand side is the desired level of service time as expressed by the shippers for each commodity.

$$\tilde{y}_{O^ck}^c \left(\frac{1}{2y_{O^ck}} + t_{O^ck}^n + t_{O^ck}^b + t_{kD^c}^t \right) \leq t^c \qquad \forall\,(O^c,k) \in \mathcal{A}_1, (k, D^c) \in \mathcal{A}_2, c \in C \tag{10}$$

The service time constraints could also be expressed as a minimum frequency at each corridor, f_{ij}^c, so in that case constraints (5) should be substituted by constraint (11). The minimum frequency requirements f_{ij}^c can be derived from the desired service time t^c according to $f_{ij}^c = \left\lceil \frac{1}{2 \cdot \left(t^c - t^n_{O^c k} - t^b_{O^c k} - t^t_{k D^c}\right)} \right\rceil \quad \forall \, (O^c, k) \in \mathcal{A}_1, (k, D^c) \in \mathcal{A}_2, c \in C.$

$$f_{ik}^c \tilde{y}_{ik}^c \leq y_{ik} \qquad \forall \, (i, k) \in \mathcal{A}_1, c \in \mathcal{C} \tag{11}$$

In general bilevel programs, constraints that contain decision variables of both the first and second level should apply at the second level. Moving such constraints between the levels changes both the feasible region and the optimal solutions of the problem. So constraints $(2) - (9)$ should originally apply at the second level. As it is shown by Brotcorne et al. [2008] these constraints can be moved from the second level to the first level for this special class of joint design and pricing problems.

3.2.2 Second Level (SL)

$$SL: \min_{X,Y} \sum_{ij \in \mathcal{A}_1} (T_{ij} + H_{ij}) \sum_{c \in \mathcal{C}} Y_{ij}^c + \sum_{ij \in \mathcal{A}_2} (C_{ij} + H_{ij}) \sum_{c \in \mathcal{C}} X_{ij}^c \tag{12}$$

$$\sum_{i \in \mathcal{N}} \left(Y_{ij}^c + X_{ij}^c\right) - \sum_{i \in \mathcal{N}} \left(Y_{ji}^c + X_{ji}^c\right) = d_j^c \qquad \forall j \in \mathcal{N}, c \in \mathcal{C} \tag{13}$$

$$X_{ij}^c, Y_{ij}^c \geq 0 \qquad \forall \, (i, j) \in \mathcal{A}_1, \mathcal{A}_2, c \in \mathcal{C} \tag{14}$$

The second objective (12) minimizes the total system cost. This cost consists of transport cost in arcs controlled both by the extended gate operator (what is seen as revenue for the leader is seen as cost for the follower) and by the competition, and of the container handling charges on both seaport and inland terminals. Constraints (13) are the flow conservation constraints.

3.3 MIP Equivalent Formulation (MIP_EQ)

In this section, we define the MIP equivalent formulation of our problem in order to be able to solve to optimality instances of our problem using commercial solvers like CPLEX. The difficulty in solving this problem lies in the bilevel structure of our model and in the bilinear term,$T_{ij}Y^c_{ij}$, in the objectives. The bilinear term in the objective is usually eliminated by the use of its complementarity slackness constraints while the second level objective is replaced by its primal dual optimality conditions (Brotcorne et al. [2008, 2005]). This approach in addition to the constraints that force the equality of the primal and dual lower level objectives restrict every commodity to be routed exclusively through its minimum cost path. The above may be sufficient if one considers the uncapacitated version of the problem, where routing through the minimum cost path always provides the optimal solution for both the upper and lower levels of the problem, but can have significant impact when capacities over the arcs of the network are considered. In the latter case, the flows of a commodity might be routed through several paths either controlled by the extended gate operator or by the competition if the total flows on a corridor exceed its capacity. Flows of containers are attracted to corridors controlled by the extended gate operator when they result in path cost lower or equal to the minimum cost path offered by the competition.

We propose an alternative approach to address the problems arising by the bilinear term in the objective, in which we obtain a linear equivalent formulation of this term. In our case, every port-to-door path can go through at most one tariff arc controlled by the extended gate operator. This simplifies the pricing scheme, since prices in different corridors do not interact. So we introduce the equilibrium level of the prices, γ^c_{ij} for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, that would make the routing of a commodity through a corridor economically effective. Setting the price at a corridor above or below that equilibrium level would prohibit or allow the flow of the corresponding commodity through that corridor. These level of prices prices should make the combined transport path cost neutral to the tariff free path offered by the competition, and we can obtain them according to $\gamma^c_{O^cj} + H_{O^cj} + C_{jD^c} + H_{jD^c} = C_{O^cD^c} + H_{O^cj}$ for all $(O^c, j) \in A_1, c \in \mathcal{C}$. The γ^c_{ij} takes both positive and negative values but of course the optimal price at a corridor, T_{ij}, will take positive values such that revenues will be generated and will take the value of the equilibrium level of price for some commodity. The auxiliary Boolean variable, β^c_{ij} for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, denotes which exactly equivalent level of price of commodities will be the price at each corridor such that $T_{ij}Y_{ij}^c = \gamma_{ij}^e \beta_{ij}^e Y_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}, e \in \mathcal{C}$. The new formulation of the revenues is still bilinear, since it is the product of Boolean and continuous variables, but such a bilinearity can be easily linearized by the introduction of a continuous variable, $\delta_{ij}^{c,e} = \beta_{ij}^e Y_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}, e \in \mathcal{C}$ and the set of constraints $(16) - (20)$.

We substitute the second level (SL) problem with its optimality conditions $(21) - (26)$. For this purpose some additional notation is used. The auxiliary Boolean variables $\tilde{Y}_{ij}^c$ for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and $\tilde{X}_{ij}^c$ for all $(i,j) \in \mathcal{A}_2, c \in \mathcal{C}$ denote whether flows from commodity c can be routed through the associated links with respect to the total cost of the path they belong to. The price per commodity and arc is denoted by T_{ij}^c for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$ and is restricted to take the same value for containers routed through the same corridor by constraints $(24) - (25)$. Constraints (23) impose that flows can be routed through a corridor controlled by the leader only if they result in path cost lower than the one offered by the competition; that means that the total system cost is decreased when flows go through the corridors and thus the lower level objective is satisfied.

The capacity (2), frequency (3) and (4), service time (5) and (6), feasibility $(7) - (9)$ and (14), and flow conservation (13) constraints that apply in the original model should also apply in this model, but their are not duplicated here for space reduction.

$$MIP\_EQ: \quad \max_{T,X,Y,u,y,\beta,\delta} \sum_{e \in \mathcal{C}} \sum_{c \in \mathcal{C}} \sum_{(i,j) \in \mathcal{A}_1} \gamma_{ij}^c \delta_{ij}^{c,e} - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} w^b u_{ij}^b - \sum_{b \in \mathcal{B}} \sum_{(i,j) \in \mathcal{A}_1} v_{ij}^b y_{ij}^b \tag{15}$$

$$\delta_{ij}^{c,e} \le M \beta_{ij}^e \qquad \forall\, (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{16}$$

$$\delta_{ij}^{c,e} \le Y_{ij}^c \qquad \forall\, (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{17}$$

$$\delta_{ij}^{c,e} \ge Y_{ij}^c - M\left(1 - \beta_{ij}^e\right) \qquad \forall\, (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{18}$$

$$T_{ij} = \sum_{c \in \mathcal{C}} \gamma_{ij}^c \beta_{ij}^c \qquad \forall (i,j) \in \mathcal{A}_1 \tag{19}$$

$$\sum_{c \in \mathcal{C}} \beta_{ij}^c \leq 1 \qquad \forall (i,j) \in \mathcal{A}_1 \tag{20}$$

$$Y_{ij}^c \leq M \cdot \tilde{Y}_{ij}^c \qquad \forall (i,j) \in \mathcal{A}_1 \tag{21}$$

$$X_{ij}^c \leq M \cdot \tilde{X}_{ij}^c \qquad \forall (i,j) \in \mathcal{A}_2 \tag{22}$$

$$T_{O^c j}^c + H_{O^c j} \tilde{Y}_{O^c j}^c + \left(C_{jD^c} + H_{jD^c} \right) \tilde{X}_{ij}^c \leq C_{O^c D^c} + H_{O^c D^c} \qquad \forall (O^c, j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{23}$$

$$-M \cdot \left(1 - \tilde{Y}_{ij}^c \right) \leq T_{ij}^c - T_{ij} \leq M \cdot \left(1 - \tilde{Y}_{ij}^c \right) \qquad \forall (i,j) \in \mathcal{A}_1, c \in C \tag{24}$$

$$-M \cdot \tilde{Y}_{ij}^c \leq T_{ij}^c \leq M \cdot \tilde{Y}_{ij}^c \qquad \forall (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{25}$$

$$\beta_{ij}^c,\, \tilde{Y}_{ij}^c,\, \tilde{X}_{ij}^c \in \{0, 1\} \qquad \forall (i,j) \in \mathcal{A}_1, c \in \mathcal{C} \tag{26}$$

$$\delta_{ij}^{c,e} \geq 0 \qquad \forall (i,j) \in \mathcal{A}_1, c, e \in \mathcal{C} \tag{27}$$

3.4 Modeling Considerations

In this section, we discuss some of the main assumptions that underlie the Joint Design and Pricing models and compare them with the assumptions that underlie the usual network design models. Moreover we propose a transformation of our original model in a single level network design model to assess the effect of joint design and pricing.

3.4.1 Port-to-port service

Our model in the present format fits the definition of port-to-port transport service. That is that the extended gate operator provides transportation services only among the seaport and inland terminals with high capacity modalities while the last leg of the transportation path from the inland terminal to the customer premises is organized by the competition. It follows that the prices over the extended gate services should be such that the total cost of the path through the extended gates should be at least cost neutral to the direct path provided by the competition.

3.4.2 Port-to-door service

In other cases the extended gate operator can offer port-to-door transport services. If so, prices do not depend on the routing of the containers but on the best alternative transport solution to that specific destination. Thus we can derive an alternative port-to-door network design model by fixing the prices per commodity for the entire path, T^c. This will determine the revenues of the carrier which will be diminished by all costs for leasing and operating the barges as much as the transport cost and handling charges in order to obtain its profits, so the objective function will be equal to (28). The capacity (2), frequency (3) and (4), service time (5) and (6), feasibility (7) – (9) and (14), and flow conservation (13) constraints that apply in the original model should also apply in this model. Since the prices are considered fixed the bilinear term in the objective is eliminated, so a classical single level MIP is considered.

$$\max_{X,Y,u,y} \sum_{c\in\mathcal{C}} T^c d^c - \sum_{(i,j)\in\mathcal{A}_1} H_{ij} \sum_{c\in\mathcal{C}} Y_{ij}^c - \sum_{(i,j)\in\mathcal{A}_2} (C_{ij}+H_{ij}) \sum_{c\in\mathcal{C}} X_{ij}^c - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} w^b u_{ij}^b - \sum_{b\in\mathcal{B}} \sum_{(i,j)\in\mathcal{A}_1} v_{ij}^b y_{ij}^b \tag{28}$$

3.4.3 Extensions

Some extensions of the model could considered to enhance the applicability of the model in real cases. First, a discount factor, α^c for all $c \in \mathcal{C}$ with $0 \leq \alpha^c \leq 1$, could be considered if one assumes that a client would be willing to shift to services offered by the extended gate operator only when they would lead to a cost reduction of his total cost. In this case the right hand side of constraints (23) would become $(1 - \alpha^c)\,(C_{O^c D^c} + H_{O^c D^c})$.

Second, the cost and service time associated with transport services offered by the competition could be further distinguished between trucking services with cost, C^t_{ij} for all $(i,j) \in \mathcal{A}_2$ and service time t^t_{ij} for all $(i,j) \in \mathcal{A}_2$, and combined transport services with cost C^b_{ij} for all $(i,j) \in \mathcal{A}_2$ and service time t^b_{ij} for all $(i,j) \in \mathcal{A}_2$.

4 Solution Approach

We develop a heuristic to provide high quality solutions to our problem in an efficient way. Although complex heuristic and algorithmic procedures have been proposed for the general case of the Joint Design and Pricing problem (Brotcorne et al. [2005, 2008]) that could also apply here, we take advantage of the special structure of our problem and propose a simple heuristic that provides near optimal solutions at substantially less time compared to the time it takes CPLEX to solve the MIP equivalent formulation of our problem. In our case, every port to hinterland path can go through one tariff arc controlled by the extended gate operator.

4.1 Heuristic Development

Algorithm 1

Step 0
Initialization.
$\gamma^c_{O^c j} \leftarrow C_{O^c D^c} - C_{jD^c} + H_{jD^c} \quad \forall \left(O^c, j\right) \in \mathcal{A}_1, c \in \mathcal{C}$.
Step 1
For each $(i,j) \in A_1$, set $\tilde{Y}^c_{ij'} = 0 \mid \forall \left(i, j'\right) \neq (i,j), c \in \mathcal{C}$ and solve MIP_EQ.
$\Longrightarrow T^*_{ij}$,$\tilde{Y}^{c*}_{ij}$.
Step 2
Take $T^*_{ij} \forall (i,j) \in A_1$, $\tilde{Y}^{c*}_{ij} \forall (i,j) \in \mathcal{A}_1, \forall c \in \mathcal{C}$ as input to Fl_A and solve the FL_A.
$\Longrightarrow z^*$.
Step 3
Let $\mathcal{C}_1 = \left\{ c \in \mathcal{C} \mid \sum\limits_{(i,j) \in A_1} \tilde{Y}^c_{ij} \geq 2 \right\}$.
Step 4
Let $\mathcal{C}_2 = \left\{ c \in \mathcal{C} \mid \gamma^c_{\bar{ij}} = T_{\bar{ij}} \, \exists (\bar{i,j}) \in \mathcal{A}_1 \right\}$.
Step 5
IF $\mathcal{C}_1 \cap \mathcal{C}_2 \in \emptyset$
THEN go to Step 8
ELSE go to Step 6.
Step 6
For each $c \in \mathcal{C}_1 \cap \mathcal{C}_2$,
$\tilde{Y}^c_{\bar{ij}} \leftarrow 0$ and $T_{\bar{ij}} \leftarrow \gamma'_{\bar{ij}}$ when $\gamma'_{\bar{ij}} = min \left(\gamma^c_{\bar{ij}} \mid Y^{c*}_{\bar{ij}} = 1 \right)$ and solve the FL_A problem.
$\Longrightarrow z_c$.
$\Longrightarrow \tilde{z} = max \left(z_c\right)$ and $\tilde{c}$ be the corresponding commodity.
Step 7
If $\tilde{z} > z^*$then
$z^* \longleftarrow \tilde{z}$
$T^*_{\bar{ij}} \longleftarrow \gamma'_{\bar{ij}}$
$\tilde{Y}^{c*}_{ij} \longleftarrow 0$
go to Step 3
else
go to Step 8
Step 8
For fixed $T^*_{ij} \forall (i,j) \in \mathcal{A}_1$ solve the MIP_EQ
$\Longrightarrow z^*$,u^{b*}_{ij},y^*_{ij} Y^{c*}_{ij} & X^{c*}_{ij}
Notation:$\leftarrow$Assign Value to a parameter, $\Longrightarrow$Output is generated by a program

---

In the Step 0, we set the value of the equilibrium level of prices, γ^c_{ij} for all $(i,j) \in \mathcal{A}_1, c \in \mathcal{C}$, as it is discussed in section 3.3 of this paper.

In Step 1 we solve $\mid \mathcal{A}_1 \mid$times the MIP Equivalent formulation of our problem, each time allowing only one corridor controlled by the extended gate operator to open. This reduces sufficiently the size of the problem and thus CPLEX can solve the problem in substantially less time, as reported by Labbé et al. [1998]. Allowing only one corridor to open has the effect of concentrating the flows that would maximize the profitability of the extended gate operator in one corridor; thus the optimal price is set such that the cost for all commodities routed through the corridor is at least cost neutral to their best tariff free path. It follows that there is some revenue increase opportunity from commodities that had higher equilibrium prices than the price set on the corridor. It is clear that, if all corridors were available, the extended gate operator could increase the prices in some corridors to segment the market in favor of his revenue maximization. One might expect that for this reason $T^* \leq T^{opt}$. Although this does not hold true for the general capacitated version of the problem it holds true for the uncapacitated version of the problem.

In Step 2, we aggregate all the individual solutions generated in Step 1 in one feasible solution by solving for a given price vector, T^*, the FL_A model which is a constrained version of the first level (FL) problem, as explained below.

The FL_A model is a constrained version of the FL model, and it takes the values of T_{ij} and $\tilde{Y}_{ij}^c$ as inputs. The prices are fixed to the values defined by the heuristic, so the bilinear term in the objective function is eliminated. Second, constraints (21) from the MIP equivalent formulation of the problem are included. Constraints (21) for the given values $\tilde{Y}_{ij}^c$, defined by the heuristic, substitute the second level objective since they prohibit the assignment of flows to corridors that are part of paths with higher cost than the one offered by competition. Last, constraints (29) substitute the demand conservation constraints (13) of the second level, in the sense that the summation of flows of one commodity in all corridors should not exceed its demand volume. Some commodities can be routed through several corridors controlled by the extended gate operator since their resulting path cost is lower than the one offered by competition. Considering the price vector of the extended gate operator, they will be routed through the paths that generate the highest profit for the extended gate operator. The solution of this problem is feasible since both capacity and service level constraints are considered while the feasibility of the second level is guaranteed by constraints (21) and (29).

$$\sum_{(i,j)\in A_1} Y_{ij}^c \leq d^c \qquad \forall c \in \mathcal{C} \tag{29}$$

In Step 3, we identify which commodities are assigned to more than one extended gate corridors. If no commodities are assigned in more than one corridors, the aggregation of the individual solutions is the optimal solution.

In Step 4, we identify the commodities for which their equilibrium level of prices is equal to the prices set on the corridors controlled by the extended gate operator.

In Step 5, we check whether the intersection of the two sets of commodities obtained in Steps 3 and 4 is empty. If it is empty, our heuristic terminates in Step 8. Otherwise it continues to Step 6. In case a commodity, c, satisfies both conditions in Steps 3 and 4, then one may opt to increase the price at the corresponding extended gate corridor and thus prohibit its routing through it. In this manner, the commodity is guided via extended gates where the prices are higher, although it remains competitive. The remaining flows in the former extended gate corridor will also generate higher revenues.

In Step 6, for each commodity that satisfies the conditions in Steps 3 and 4, we try to increase the price on the corresponding corridors and solve the FL_A problem while keeping the optimal solutions.

In Step 7, we check whether the maximum among the solutions obtained in Step 6 is higher than the best solution found until now. If it is better, the corresponding variables are updated and the heuristic makes another iteration from Step 4 else it terminates in Step 8.

In Step 8, we solve the MIP equivalent formulation of our original problem for the tariffs obtained such that the design and flow decision variables are determined.

4.2 Heuristic Assessment

In order to assess the performance of the heuristic described in section 4.1, we generated instances randomly and we solved them by both the MIP equivalent program using CPLEX 12, and by our heuristic. Both the heuristic and the MIP equivalent program were formulated

Instance	Inland Terminals	Client Nodes	Commodities	CPLEX CPU (Sec)	Heuristic CPU (Sec)	Objective
1	10	20	30	25.53	4.46	99.38%
2	10	20	60	141.97	10.62	98.56%
3	10	30	30	32.67	4.29	98.22%
4	10	30	60	367.48	13.62	97.99%
5	20	20	30	395.95	6.34	99.77%
6	20	20	60	500.13	18.60	99.58%
7	20	30	30	320.56	8.23	99.30%
8	20	30	60	500.27	26.24	99.28%

Table 1: Heuristic Assessment

and solved in MATLAB 2012b, while we set for CPLEX a time limit of 500 sec to solve the problem. For the cases where this limit was exceeded, we consider the optimal upper bound achieved.

The instance generator works as follows: first the skeleton of the network is generated by defining the number of source, sink and transhipment nodes, the coordinates of which are randomly generated in two-dimensional space following the uniform distribution within a radius defined by the user. The source nodes are connected with the sink nodes directly with arcs, and then the source nodes are connected with the transhipment nodes; these will be the arcs controlled by the leader, finally the transhipment nodes are connected with all the sink nodes. The lengths of all arcs are equal to the Euclidean distances between the nodes, and moreover the associated cost is determined by a fixed cost and a variable cost linear in the distance of each arc. Finally, the commodities are randomly generated by defining the sink and source nodes, the amount of flow and service level requirements in terms of minimum frequency required to assign the flows in a specific arc. We solved ten instances for every setting in order to assess the performance of the algorithm.

The results are summarized in Table 1 where the average computation times and the average gap from the optimal solutions are presented for 10 randomly generated instances with the specifications stated in the first three columns of the matrix. CPLEX needs significantly more computation time on average even for small or medium sized instances, while we see that in both cases the computation time mainly depends on the number of commodities considered while the number of nodes of the network has significant effect only on the computation time of CPLEX. The gap between the optimal solution and the one obtained by the heuristics seems to be less than 2% in average. By the construction of our heuristic we know that if the optimal tariffs are reached then the optimal solution will be reached.

5 Experimental Results

In this section we formulate a stylized but realistic example and run experiments in order to assess the effect of the different considerations on network design problem. In particular, we study whether there are any differences in the optimal network design when we assume port-to-port versus port-to-door services and also we assess the effect of considering service level constraints in the tactical service network design. The optimal multimodal network design are case specific and may depend on physical characteristics of the network, the demand distributions over the network and other parameters, so our results may not be generalized but they do demonstrate the capabilities of our model to capture the tradeoffs among revenue maximization in offering services, cost minimization in setting up the combined transport network, and of demand penetration through frequent services on corridors.

Although we develop a stylized example, all cost structures considered in this paper are obtained by real costs covered by a confidentiality factor so we use monetary units, m; full details on the cost structures can be found in van Riessen et al. [2013]. We consider a network consisting of one seaport terminal and 3 inland terminals; see Figure 1. The inland terminals are located closely to each other, so their hinterland can be considered contestable. That means that container demand for one inland region can be served via an extended gate located in another region. The costs of road transport are presented in Table 2 and are calculated based on the formula: $C_{ij} = 76.4 + 1.06 \cdot distance\,(i, j)$. In order to simplify the network we assume that demand is destined to the inland regions of inland terminals, so only the fixed cost applies for the end haulage leg from the inland terminal to the customers premises located in the same region. The weekly fixed costs for barge leasing and the variable costs per barge trip

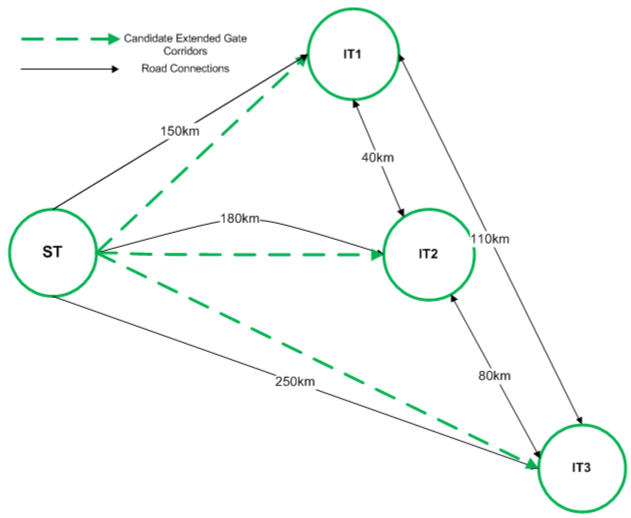

Figure 1: Stylized Example Physical Network

	ST	IT1	IT2	IT3
ST	76.4	232.4	263.6	336.4
IT1	232.4	76.4	118	190.8
IT2	263.6	118	76.4	159.6
IT3	336.4	190.8	159.6	76.4

Table 2: Transportation Cost via Road (m/TEU)

are presented in Table 3. The additional handling charges at inland terminals is set equal to 23m/TEU.

In order to assess the performance and the main differences of using the different network design formulations we set up an experiment by differentiating the demand volumes over the stylized network, which ranges from 180 to 2.340 TEUs per week. We assume that the demand is equally distributed among the OD pairs. Finally, the demand is further organized in commodities to capture the different service time requirements which are shown by the minimum service frequency (Table 4).

#	Capacity (TEUs)	Weekly Leasing Cost	Variable Cost per Trip			Number of Round Trips		
			ST-IT1	ST-IT2	ST-IT3	ST-IT1	ST-IT2	ST-IT3
1	100	7.500m	225m	270m	375m	3	3	2
2	200	10.000m	285m	342m	475m			

Table 3: Barge Types and Characteristics

OD pair	Com	Minimum Service Frequency	Percentile
ST-IT1	1	1	20%
	2	3	50%
	3	6	30%
ST-IT2	4	1	20%
	5	3	50%
	6	6	30%
ST-IT3	7	1	20%
	8	3	50%
	9	6	30%

Table 4: Experimental Setting

5.1 Port-to-port vs Port-to-door haulage

In this section we study whether any significant differences appear when assuming port-to-port versus port-to-door services while solving the two models discussed in sections 3.4.1 and 3.4.2. The graphs in Figure 2 should be evaluated with care and be read as follows; In the horizontal axis of each graph there is the weekly demand of containers, a variable in our experiment, which is considered to be equally distributed over the three inland regions and also further organized in commodities according to Table 4. The optimal capacity setting (Figure 2. a and b), connection frequency on the corridors (Figure 2. c and d) and the flows of containers (Figure 2. e and f) over the network are shown. The results shown in Figure 2 are interrelated and should be read together. In Figures 3 and 4 the optimal network configurations for some cases are graphically presented.

We observe that when demand is relatively low all the flows are consolidated in one corridor namely the central one ST-IT2 which is opened with 2 small barges achieving a frequency of 6 trips per week; that means that service time constraints for all commodities are met when routed through the ST-IT2 corridor. In case port-to-door service is assumed this remains the optimal design until the demand over the network exceeds the capacity of the corridor (Figures 4.a and b). On the other hand, if port-to-port service is assumed the ST-IT1 corridor is opened earlier for the achievement of revenue maximization through pricing (Figure 3.b). In both cases, there is a range of demand where both ST-IT1 and ST-IT2 corridors are opened by assigning to them one (3 trips per week) and two (6 trips per week) small barges respectively (Figures 3.b and 3.c), where containers destined to the IT1 region with high service level requirements (Commodity 3) are routed through the ST-IT2 corridor.

It is obvious that considering joint design and pricing has a significant effect on the optimal network configurations compared to usual cost minimization network design. First, considering the port-to-door services provides more flexibility of the routing on containers through the network with the result of more flow consolidation in fewer corridors especially when demand is low. Second, when port-to-port services are considered, revenue maximization has a significant effect and high frequency is set in all corridors to service frequency requirements of all commodities such that more dedicated services are offered.

Assuming that demand originates or is destined at the inland regions and that demand is equally distributed among the inland regions may not be realistic. Nevertheless, our results show significant differences in the optimal network design and assuming unbalanced demand and the actual locations of shippers only has greater effect on the differences among the optimal network design between assuming port-to-port and port-to door services.

5.2 Impact of Service level constraints

In this section we solve the same instances without considering the service time constraints and compare them with the results presented in the previous section. The graphs in Figure 5 should be read in contrast to those presented in Figure 2.

First we observe that considering service level constraints has a significant impact on the optimal network design, especially when demand is relatively low. We observe that the effect of economies of scale through the use of bigger barges dominates the optimal network configurations. So high frequent connections are achieved only when demand is high. Second, we observe that all corridors are opened for lower demand realizations; that is because for this case it is assumed that all demand can be satisfied even with low frequency services. That means that beyond a demand threshold in each region, a corridor to that region is opened. Higher demand will also be covered by the same corridor although the capacity on that corridor will increase accordingly. This means that the quality of service provided in each corridor, controlled by its frequency, does not influence the routing of containers based on their service time characteristics. Again one can observe differences between assuming port-to-door and port-to-port services since in the latter the revenue maximization through pricing forces the extended gates to open earlier than they do in the former.

6 Conclusions

In this paper we presented two models for the tactical design of multimodal port-hinterland transport services, namely for the design of port-to-port and port-to-door services. The models capture the tradeoffs among revenue maximization, economies of scale and market penetration through setting frequency of services. We contribute to the existing body of modeling literature by extending the joint design and pricing bilevel formulations to the multimodal nature of such services and we add service time constraints to capture the different transport time performance among different modalities. We propose a simple heuristic approach that provides near optimal solutions in substantial less time than CPLEX.

In addition to the modeling contributions of this work some managerial insights, can be drawn from our research. First, it seems that the cost of installing capacity on corridors compared to the possible realization of revenues does not prohibit the setting up of high frequent services to meet service time constraints and increase their market penetration. High frequent connections are set up even for instances with low demand and bigger vessels are selected only after high frequent services are established. In most of the solutions though it is clear that the installed capacity on the corridors is underutilized; this can be explained by the low break-even utilization points of barges use. Installing high capacity corridors both lowers total cost and provides buffer capacity to carriers to hedge against demand variability (Lium et al. [2009]).

Considering port-to-door services provide more consolidation opportunities because it gives more flexibility in the routing of commodities due to the disconnect between routing and pricing. When port-to-port services are assumed the revenue management (or market segmentation) through pricing that results in more dedicated services is more important than achieving economies of scale through the use of bigger vessels. It should be noted though that different assumptions underlie the two different service types and this leads to different optimal combined transport network configurations. So in case of port-to-port services, where not all links are controlled by the same authority, the optimization models should be adjusted accordingly. The model we propose in this paper is in this direction.

Moreover our results show that when an extended gate operator serves several close regions, he has more flexibility in the design of its hinterland network. For example, he can set up frequent services in one central corridor (or with higher flows) to satisfy fast moving containers for all close regions while also setting up services of lower frequency to transport slow moving containers with lower total cost.

The present paper consider the competitive environment to be exogenous. An extension of the research in this paper could concern the interaction between two or more extended gate operators that both design and price sub-networks to serve the needs of a contestable hinterland, The above would require an MPEC formulation of the problem which is still not studied extensivily in literature, but could also capture the seaport calling selection of shipping lines based on their hinterland connectivity.

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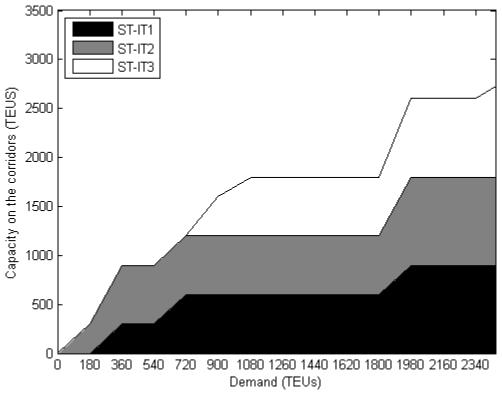
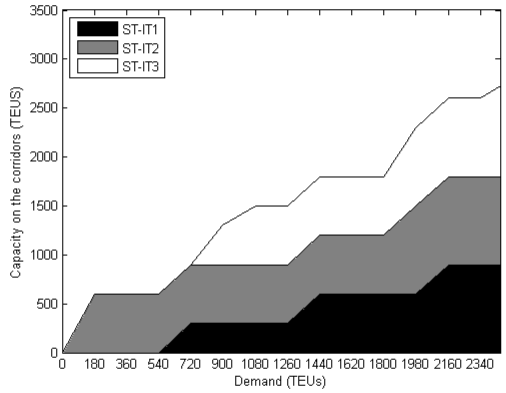


(a) port-to-port



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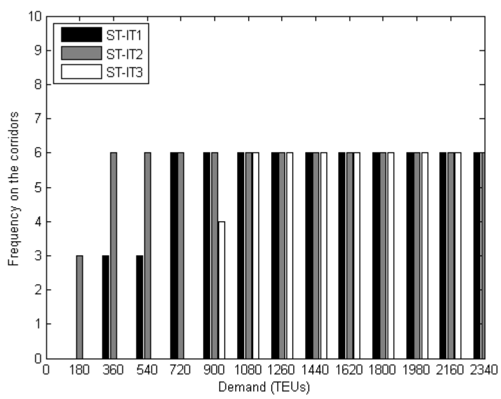

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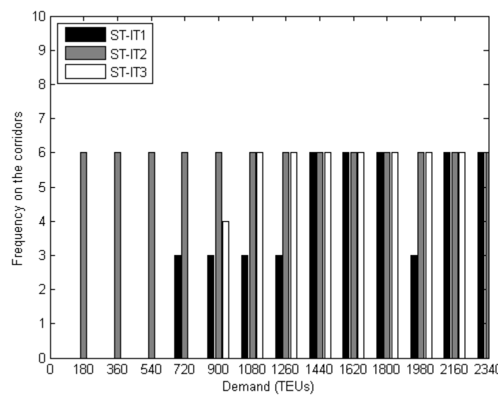

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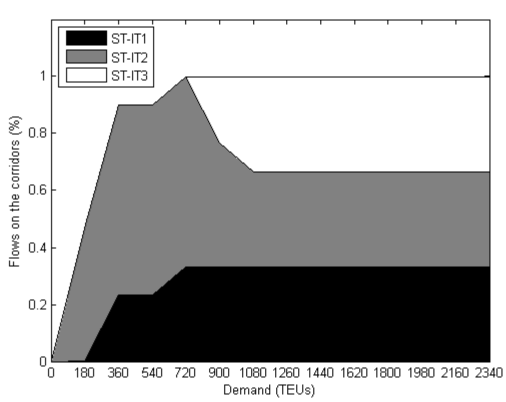

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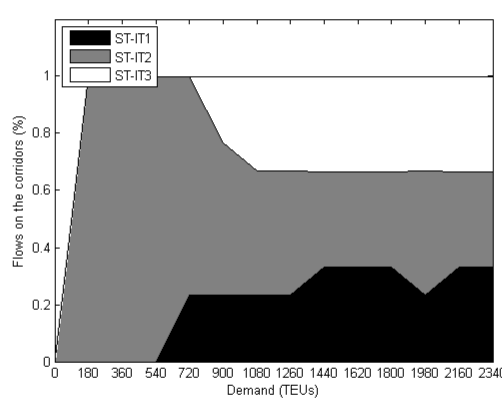
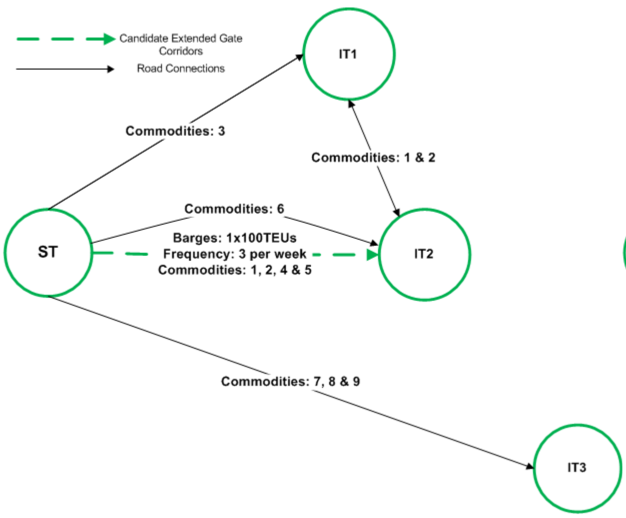
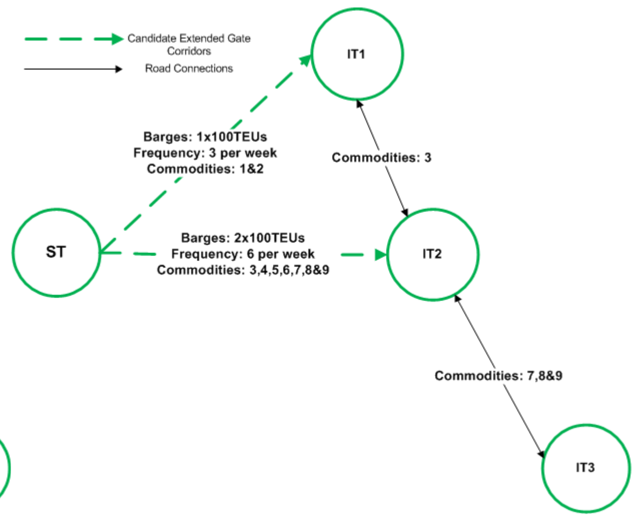


(f) port-to-door

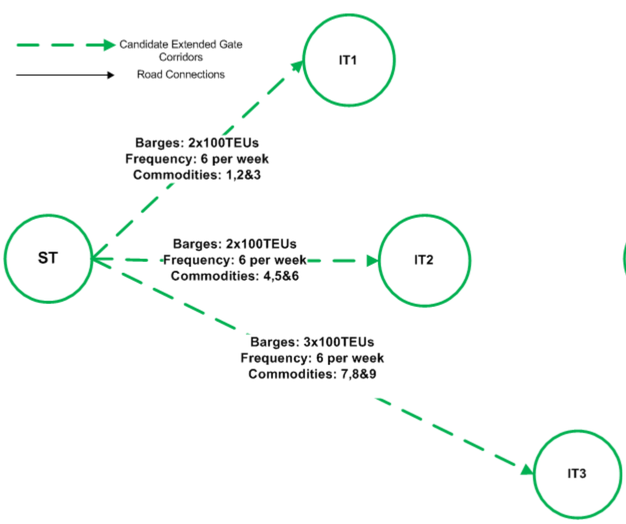
Figure 2: Experiment results - With service level constraints



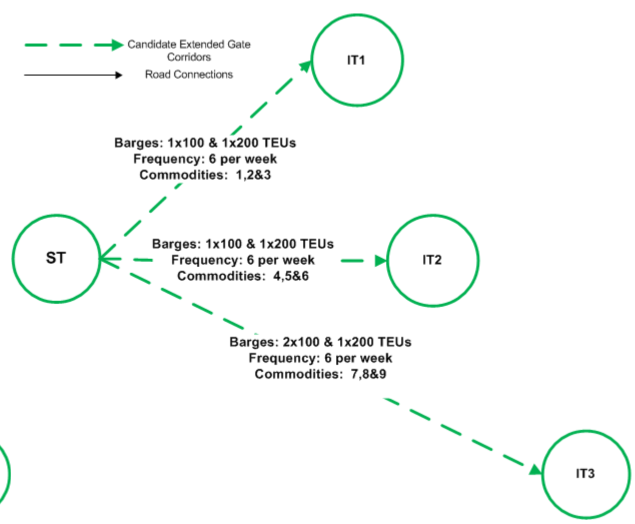
(a) Demand =180TEUs per week



(b) Demand = 540TEUs per week

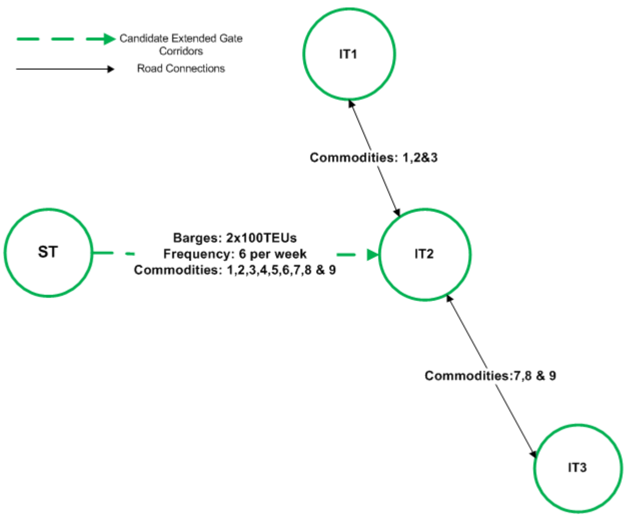


(c) Demand=1080 TEUs per week

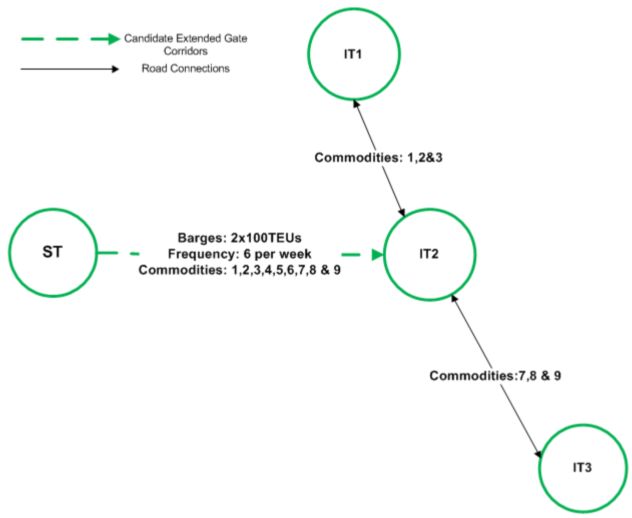


(d) Demand=1980 TEUs per week

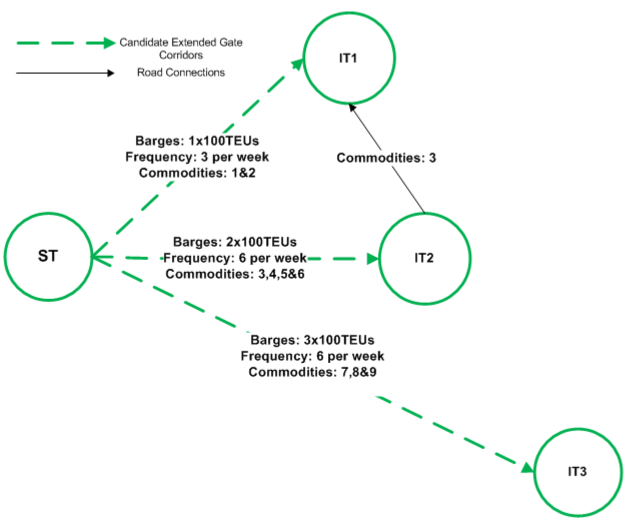
Figure 3: Optimal Network Configurations port-to-port haulage



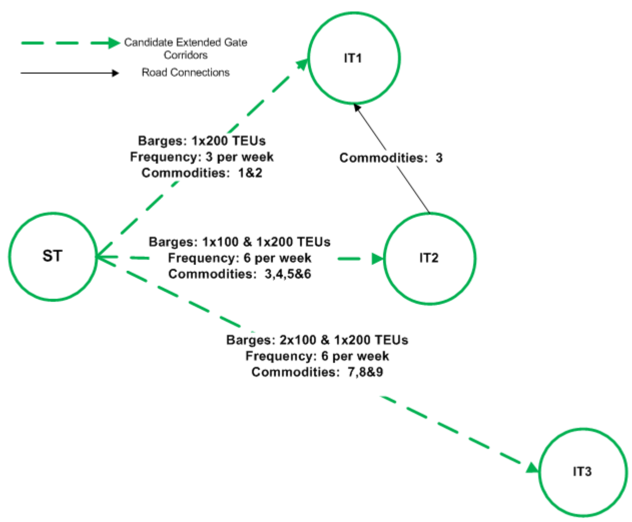
(a) Demand =180TEUs per week



(b) Demand = 540TEUs per week

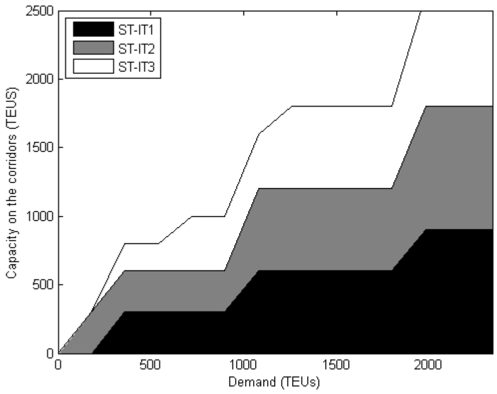


(c) Demand=1080 TEUs per week

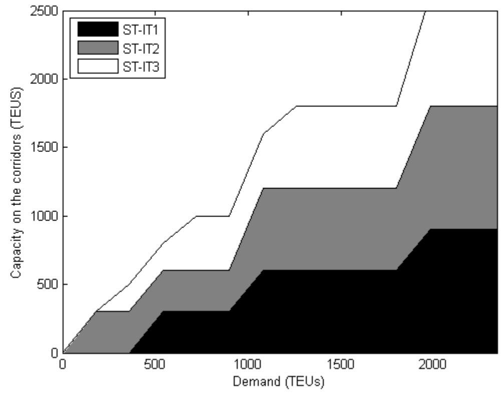


(d) Demand=1980 TEUs per week

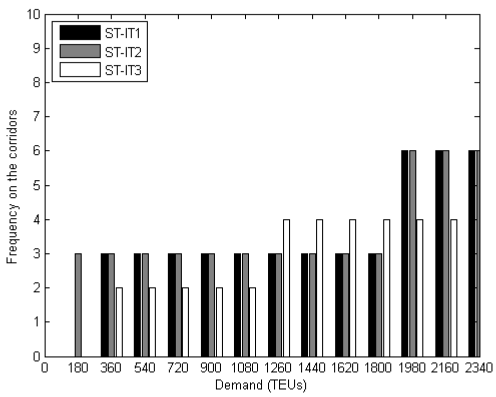
Figure 4: Optimal Network Configurations port-to-door haulage



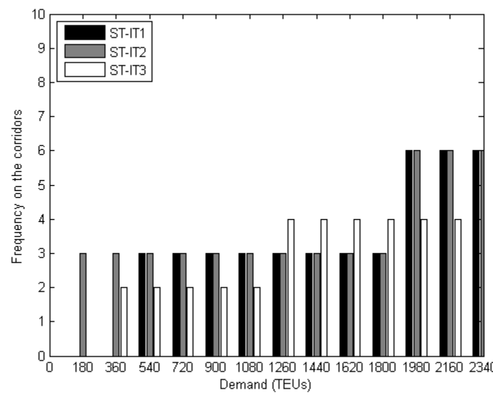
(a) port-to-port



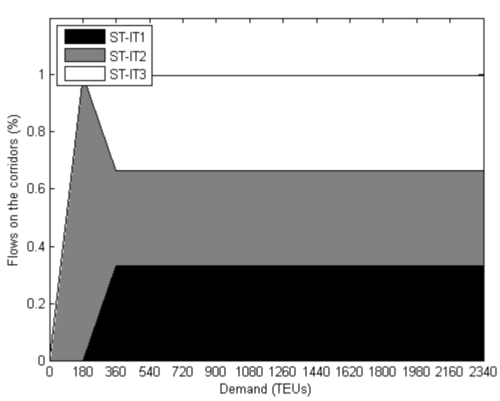
(b) port-to-door



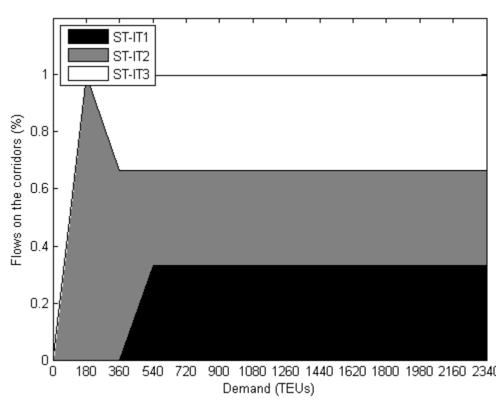
(c) port-to-port



(d) port-to-door



(e) port-to-port



(f) port-to-door

Figure 5: Experiment results - Without service level constraints

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