SERVICE NETWORK DESIGN IN INTERMODAL BARGE TRANSPORT

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Abstract

Consolidation of freight flows is often suggested to improve the efficiency of intermodal operations. Inland terminals may cooperate with the objective to create denser freight flows and achieve economies of scale. In this paper cooperation between intermodal barge terminals in a hinterland network is analyzed from a network design perspective. A general overview of service network design in freight transport is given. A generic model is adapted to incorporate the characteristics of intermodal barge networks. The model formulation is further elaborated by means of a small-scale fictitious network.

1. Introduction

Intermodal transport, by definition, involves several decision makers who need to work in collaboration in order for the transport system to run smoothly. An increased level of coordination is necessary to organize the intermodal transport flow. Decision-making support tools may assist the many actors and stakeholders involved in intermodal operations. Van der Horst and De Langen (2008) emphasize the need for coordination in hinterland container transport chains. The objective of our research is to analyze whether cooperation between intermodal barge terminals in a hinterland network is interesting from a network design perspective. The hinterland network is studied as a whole to see whether or not inland terminals in the network should cooperate. Cooperation between inland terminals may lead to denser freight flows and economies of scale in the network. In this way, the attractiveness of intermodal barge transport could be improved. This paper describes a first exploratory research on this topic.

A generic framework for transport network design can be found in Woxenius (2007). Six principles for the design of transport systems are described and applied to intermodal freight transport. Rail-based innovative bundling networks are evaluated by Janic et al. (1999). Major bundling concepts in intermodal rail operations are also presented by Kreutzberger (2003). When looking at opportunities for consolidation in intermodal barge transport, two options can be discriminated. Bundling may take place in the hinterland network or freight may be bundled in the port area. Cooperation between inland terminals implies bundled freight flows in the hinterland. Trip and Bontekoning (2002) explore the possibility of implementing innovative bundling models in the hinterland as a means to integrate small flows, mainly from outside economic areas, in the intermodal transport system. Groothedde et al. (2005) describes the design and implementation of a collaborative hub network for the distribution of fast moving consumer goods using a combination of trucking and inland barges. Theys et al. (2008) analyze how cooperative game theory may be applied to evaluate the feasibility and efficiency of cooperative projects in intermodal barge transport. Freight may also be bundled in the port area. Konings (2003) presents a framework to identify possible improvements in the performance of intermodal barge transport by redesigning barge networks. Vessel size and circulation time directly influence the cost and quality performance of barge transport. These factors are determined by the network design, transport market and waterway infrastructure. An alternative network design for bundling freight flows in the port area of Rotterdam is proposed in Konings (2007). The author presents and evaluates a consolidation strategy for intermodal transport by barge based on a marginal cost model. Caris et al. (2008a) analyze bundling strategies for container barge transport in the port of Antwerp by means of simulation. The construction of a simulation model allows demonstrating to what extent the waiting times in the port area and the turnaround time of inland barges may be reduced.

In this paper the design of the service network in intermodal barge transport is studied. The network of inland barge terminals is modeled as a whole to demonstrate potential cooperations. In section 2 service network design is discussed and a generic model is presented. This model is adapted for intermodal barge transport in section 3. In section 4 the methodology is illustrated by means of a fictitious example. Finally, conclusions are drawn and directions for further research are given.

2. Service network design

Consolidation in freight transport concerns decisions at the tactical planning level. According to Crainic and Laporte (1997) service network design involves the selection of routes on which services are offered and the determination of characteristics of each service, particularly their frequency. The authors describe service network design in intermodal transportation as a major case at the tactical decision level. Formulations are classified into two main groups: network simulation and optimization models. Simulation models show a high level of detail, but may require prohibitive data input and running times. Network optimization models are less detailed but enable a fast generation, evaluation and selection of integrated, network wide operating strategies. Magnanti and Wong (1984) suggest that integer programming could be used to generate potential investment strategies that could then be tested by simulation analysis. The authors present a general overview of network design problems and show that many combinatorial problems that arise in transportation planning are specializations and variations of a generic design model.

State-of-the-art reviews on service network design in freight transportation are given by Crainic (2000) and Wieberneit (2008). Service network design arises in transportation systems where service cannot be tailored for each customer individually and a single vehicle carries freight of different customers with possibly different origins and destinations. The service network design problem concerns the selection of routes on which services are offered and the determination of the characteristics of each service, particularly their frequency. For each origin-destination pair a route needs to be specified. A decision may be made about the type of consolidation network, general operating rules for each terminal in the network and work allocation among terminals. Empty balancing and crew and motive power scheduling may also be included in the design of the service network.

2.1 Generic model

The path-based multicommodity capacitated network design formulation (PMCND) of Crainic (2000) is presented next. This general formulation will be adapted in section 3 to model a service network in intermodal barge transport. The problem is defined on a graph $G = (N, A)$ with N the set of nodes and A the set of arcs in the network. P is the set of products to be transported. In intermodal barge transport each origin-destination pair may represent a product. A path-based formulation permits to define a set of possible paths for each origin-destination pair in advance. The decision variables in the model are:

y_{ij} = 1 if link (i,j) is open

h_l^p= flow of commodity p on path l

The following notation is used:

P = set of products (origin-destination pairs)

L = set of all paths in the network

L^p = set of paths for product p

f_{ij} = fixed cost of opening link (i,j)

w^p = total demand of product p

k_l^p= transportation cost of product p on path l

c_{ij}^p = transportation cost per unit of product p on link (i,j)

δ_{ij}^{lp} = 1 if arc (i,j) belongs to path $l \in L^p$ for product p

u_{ij} = capacity of link (i,j)

Minimize $$\sum_{(ij)\in A} f_{ij} y_{ij} + \sum_{p\in P} \sum_{l\in L} k_l^p h_l^p$$

Subject to

$$\sum_{l\in L^p} h_l^p = w^p \qquad \forall p \in P \qquad (1)$$

$$\sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ij}^{lp} \le u_{ij} y_{ij} \qquad \forall (i,j)\in A \quad (2)$$

$$y_{ij} \in Y \qquad \forall (i,j)\in A \quad (3)$$

$$h_l^p \ge 0 \qquad \forall p\in P,\ \forall l \in L^p \quad (4)$$

The objective function minimizes total costs of transporting products *p* through the network. The decision variable y_{ij} may be restricted to $Y = \{0,1\}$ or may take on a positive integer number ($Y = N_+^A$) . A fixed cost f_{ij} is incurred for each unit of capacity or service level offered. The transportation cost of product *p* on path *l* is calculated as: $k_l^p = \sum_{(ij)\in A} c_{ij}^p \delta_{ij}^{lp}$.

Constraints (1) ensure that the demand for all products is met. The second group of constraints represents capacity restrictions on links in the network. The total flow on a link cannot exceed its capacity and must be zero when the link is not chosen in the network (y_{ij} = 0). Constraints (3) and (4) define the formulation as a mixed-integer programming problem.

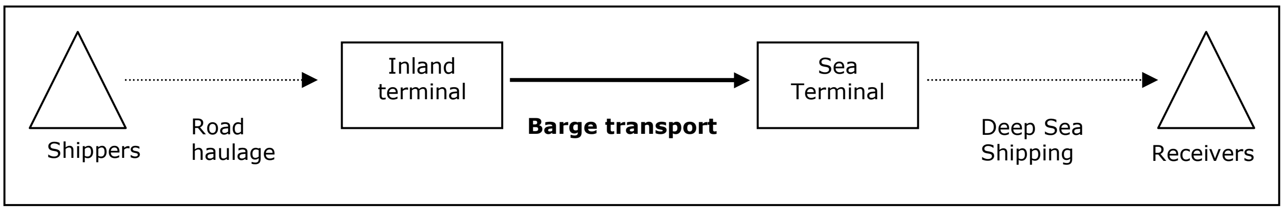
2.2 Applications in intermodal transport

Caris et al. (2008b) give an overview of planning problems in intermodal freight transport. The authors identify the design of the intermodal service network and in particular the determination of an optimal consolidation strategy as an interesting field requiring more research attention. Kim (1997) presents a general description of large scale transportation service network design and applies the model in the express package delivery industry. A first application of service network design in intermodal freight transport can be found in Newman and Yano (2000). The authors compare a variety of decentralized planning approaches with a centralized approach for scheduling trains in an intermodal network. Their decentralized scheduling approaches lead to near-optimal solutions within significantly less computational time than the centralized approach. Racunica and Wynter (2005) formulate a frequency service network design model to determine the optimal location of intermodal hubs in a hub-and-spoke network with (semi-) dedicated freight rail lines. A concave cost function is applied in order to capture cost reductions obtained by consolidation at hub nodes. The resulting model is a non-linear, mixed-integer program. The concave increasing cost function is approximated by a piecewise linear function as to obtain a linear program. This linear program is solved by two variable-reduction heuristics, which solve a sequence of relaxed subproblems. The solution method is tested on a case study of the Alpine freight network. A hub location and network design model for a general intermodal transportation network is presented by Yoon and Current (2008).

3. Model formulation for intermodal barge transport

The generic model presented in the previous section is adapted to continental intermodal barge transport. Figure 1 depicts the transport chain of intermodal barge transport in the hinterland area of a seaport. Road haulage stands for the pickup and delivery of goods by truck. Vessels perform roundtrips between inland terminals in the hinterland and sea terminals in the port area. A service network design model is constructed for the network of inland terminals and sea terminals.

Figure 1: Transport chain of intermodal transport by barge



Terminals are represented by nodes in the network. A distinction is made between a set of inland nodes N^I and a set of port nodes N^P. Arcs may provide a connection between the two sets of nodes or connect terminals within a set of nodes. The set of arcs between inland terminals and the port area is indicated with A^B. Arcs linking two inland terminals belong to the set A^I and arcs linking two port terminals are assigned to the set A^P.

$$N^I \cup N^P = N$$

$$N^I \cap N^P = \varnothing$$

$$A^B \cup A^I \cup A^P = A$$

$$A^B \cap A^I = \varnothing,\ A^I \cap A^P = \varnothing,\ A^B \cap A^P = \varnothing$$

Arcs connecting inland nodes symbolize cooperation between these two inland terminals. A variable cost per container is charged for the extra handling of containers. Arcs between port nodes represent the time lost in the port area. A fixed cost is charged for each vessel passing through the arc. A product is defined for each origin-destination pair. Products representing freight which originates at an inland terminal and is destined for a sea terminal belong to the set P^O. Products coming into the country from a sea terminal to an inland terminal are joined in the set P^I. For each product a set of possible paths L^P is defined.

$$P^O \cup P^I = P$$

$$P^O \cap P^I = \varnothing$$

The decision variables in the new model formulation are:

y_{ij} = 1 if link $(i,j) \in A^B$ is open

z_{ij}^p = 1 if link $(i,j) \in A^P$ is used by product p

h_l^p = flow of commodity p on path l

e_{ij} = freight imbalance on link (i,j)

The variable costs are defined as follows:

c_{ij} = handling cost per container on link $(i,j) \in A^I$

Φ_{ij} = concave cost function on link $(i,j) \in A^B$ depending on the volume passing through the link

All other notation is maintained as in the previous section, leading to the non-linear integer programming formulation:

$$\text{Minimize} \quad \sum_{(ij)\in A^B} f_{ij} y_{ij} + \sum_{(ij)\in A^P} f_{ij} \sum_{p\in P^O} z_{ij}^p + \sum_{(ij)\in A^B} \Phi_{ij}\left[\sum_{p\in P}\sum_{l\in L} \delta_{ij}^{lp} h_l^p + e_{ij}\right]\cdot y_{ij} + \sum_{(ij)\in A^I} c_{ij} \sum_{p\in P}\sum_{l\in L} \delta_{ij}^{lp} h_l^p$$

Subject to

$$\sum_{l\in L^p} h_l^p = w^p \qquad \forall p\in P \quad (1)$$

$$\sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ij}^{lp} \le u_{ij} y_{ij} \qquad \forall (i,j)\in A^B \quad (2)$$

$$\sum_{l\in L^P} h_l^p \delta_{ij}^{lp} \le u_{ij} z_{ij}^p \qquad \forall (i,j)\in A^P,\ \forall p\in P \quad (3)$$

$$\sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ij}^{lp} + e_{ij} = \sum_{p\in P}\sum_{l\in L^p} h_l^p \delta_{ji}^{lp} + e_{ji} \qquad \forall (i,j)\in A^B \quad (4)$$

$$y_{ij} \in \{0,1\} \qquad \forall (i,j)\in A^B \quad (5)$$

$$z_{ij}^p \in \{0,1\} \qquad \forall (i,j)\in A^P,\ \forall p\in P \quad (6)$$

$$h_l^p \text{ positive integer} \qquad \forall p\in P,\ \forall l\in L^p \quad (7)$$

$$e_{ij} \text{ positive integer} \qquad \forall (i,j)\in A^B \quad (8)$$

In the objective function a fixed cost is incurred if a link belonging to the set of arcs A^B between inland terminals and port terminals is opened. Arcs connecting two port nodes imply a fixed cost each time a product p originating in the hinterland is sent through the arc. This part of the objective function denotes the cost of a barge passing through the link and spending time in the port area. A concave variable cost function is used on the links in set A^B to model economies of scale achieved by bundling freight flows in the hinterland network. Constraints (1) to (3) are similar to the generic model. Decision variables e_{ij} in the fourth group of constraints measure the imbalance between inbound and outbound freight flows. This imbalance needs to be taken into account in the concave variable cost function of the links between inland nodes and port nodes. The network design variables y_{ij} and $z_{ij}^{\ p}$ are restricted to binary values. Since our aim is to model the transportation of containers, flow variables $h_l^{\ p}$ and e_{ij} are defined to take on a positive integer number.

4. Illustrative example

4.1 Description

The service network design formulation derived in the previous section is applied to a small-scale network for further clarification. The network is presented in figure 2. Nodes 1 and 2 are two inland terminals in the hinterland of a seaport. The inland terminals are situated along the same river axis and could potentially cooperate to bundle their freight flows. Nodes 3 and 4 represent two clusters of sea terminals in the port area. The two clusters are separated by a lock system and barges incur a waiting time when passing through the locks. Arcs between inland nodes and port nodes A^B represent direct connections. Arcs 1-2 and 2-1 symbolize cooperation between the two inland terminals. Arcs 3-4 and 4-3 account for the time spent in the port area. Each inland terminal exports containers to and imports containers from both clusters of sea terminals. Table 1 gives an overview of the set of products P which have to pass through the network. Products are defined by an origin node, destination node and daily demand w^p, expressed in Twenty feet Equivalent Units (TEU).

Figure 2: Example of small-scale network to illustrate methodology

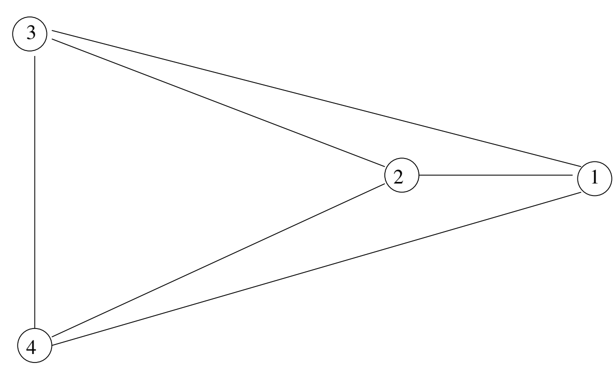


Table 1: Set of products

Product	Origin	Destination	Demand w^p
1	1	3	82
2	1	4	41
3	2	3	185
4	2	4	53
5	3	1	60
6	4	1	25
7	3	2	90
8	4	2	67

The PMCND-formulation requires that for each product p a set of possible paths L^P is specified. Table 2 summarizes four possible paths for each product. Paths for outgoing products P^O are given in the first two columns. Paths for incoming products P^I are mentioned in the last two columns.

Table 2: Set of possible paths for each product

Products P^O	Paths L^P	Products P^I	Paths L^P
1	1-3	5	3-1
	1-2-3		3-2-1
	1-4-3		3-4-1
	1-2-4-3		3-4-2-1
2	1-4	6	4-1
	1-2-4		4-2-1
	1-3-4		4-3-1
	1-2-3-4		4-3-2-1
3	2-3	7	3-2
	2-4-3		3-4-2
	2-1-3		3-1-2
	2-1-4-3		3-4-1-2
4	2-4	8	4-2
	2-3-4		4-3-2
	2-1-4		4-1-2
	2-1-3-4		4-3-1-2

Fixed costs f_{ij} of all network connections are given in Table 3. Cost information has been obtained from contacts with inland barge terminals. The cost of chartering the smallest vessel on a daily basis is allocated to the arcs between inland nodes and port nodes. A fixed cost of 400 euro is assigned to arcs connecting port nodes for taking into account waiting time in the port area.

Table 3: Fixed costs of network connections

	Destinaton *j*			
Origin *i*	1	2	3	4
1	0	0	1200	1200
2	0	0	1000	1000
3	1200	1000	0	400
4	1200	1000	400	0

A variable cost c_{ij} of 8 euro per container is charged for extra handling due to cooperation between the two inland terminals. Variable costs on arcs A^B connecting the port area with the hinterland follow a discrete cost function:

$$\Phi_{ij}(x) = \begin{cases} 0 & x \leq 60 \\ 500 & 60 < x \leq 90 \\ 800 & 90 < x \leq 100 \\ 1100 & 100 < x \leq 200 \\ 2000 & x > 200 \end{cases}$$

These variable costs stand for the additional cost of chartering a larger vessel. The vessel size *x* is expressed in TEU. The nonlinear function captures economies of scale obtained by bundling freight flows. A larger vessel size results in lower costs per container when a volume of at least 100 TEU is reached. Vessel size is expressed in the model formulation as the sum of freight flows and freight imbalance on a link $(i,j) \in A^B$:

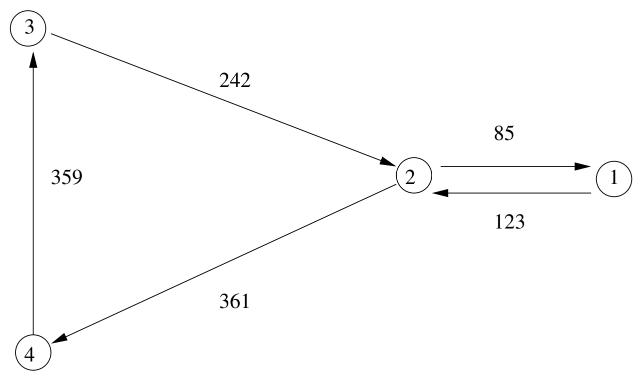
$$\sum_{p \in P} \sum_{l \in L} \delta_{ij}^{lp} h_l^p + e_{ij}$$

The capacity of all network connections is assumed to be unrestricted. A value of 603 TEU is given to the parameters u_{ij}, which equals the total demand for all products. The time frame of the analysis is a single day. It is assumed that a vessel can make a roundtrip within this time window.

4.2 Calculation of scenarios

Total costs of three alternative service network design scenarios are calculated and compared. In the first scenario both inland terminals combine their freight in a single roundtrip through the port area. This leads to the network configuration in figure 3. The numbers next to the selected arcs state the total freight passing through the network link.

Figure 3: Cooperation with a single roundtrip



Total costs of cooperation with a single roundtrip are presented in table 4. In this scenario the two inland terminals fully cooperate with each other, leading to large freight flows on a limited number of network links. A large vessel is chartered to bundle freight from both inland terminals to both port terminals. Costs are assigned to the inland terminals proportionally to their freight flows. Variable costs on the links between inland terminals and port terminals are deducted from the discrete cost function $\Phi_{ij}(x)$.

Table 4: Costs of cooperation with a single roundtrip

Arcs	Fixed costs	Variable costs
1-2	0	123 * 8 = 984
2-4	1000	2000
4-3	400	0
3-2	1000	2000
2-1		85 * 8 = 680
Total costs		**8064**
Terminal 1		2782
Terminal 2		5282

In the second service network design scenario the two inland terminals cooperate but try to avoid waiting times in the port area. Two separate roundtrips are organized, each visiting a single cluster in the port area. The selected network connections and freight flows are depicted in figure 4.

Figure 4: Cooperation with two roundtrips

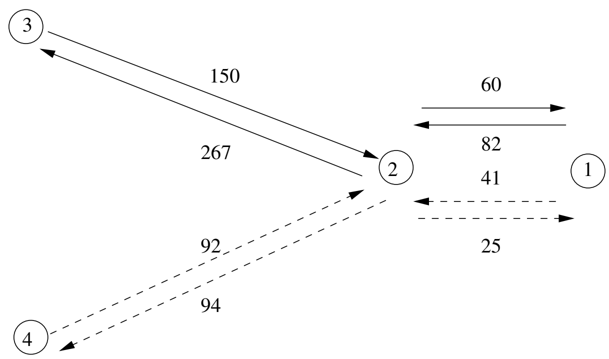


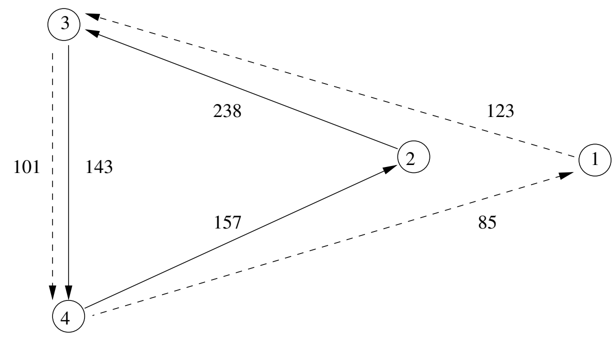
Table 5 summarizes related costs. Total costs are significantly higher than in the previous scenario because two separate vessels are chartered and less economies of scale can be reached. The waiting cost in the port area does not justify the additional cost of organizing two separate roundtrips to the port terminals.

Table 5: Costs of cooperation with two roundtrips

Arcs	**Fixed costs**	**Variable costs**
1-2	0	82 * 8 = 656
2-3	1000	2000
3-2	1000	2000
2-1	0	60 * 8 =480
1-2	0	41 * 8 = 328
2-4	1000	800
4-2	1000	800
2-1	0	25 * 8 = 200
Total costs		**11264**
Terminal 1		3885
Terminal 2		7379

Both cooperation scenarios are compared with the situation in which both inland terminals operate independently. Each terminal organizes its own roundtrip in the port area. Figure 5 shows the relevant network connections.

Figure 5: Independent roundtrips



An overview of fixed and variable network costs is given in table 6. When studying the network as whole, this service network design implies the highest total costs. The inland terminals each carry the cost of their own roundtrip. When comparing their cost with the first scenario, cooperation appears to be beneficial for both inland terminals. However, a comparison of scenario 2 and 3 shows that only inland terminal 1 achieves benefits from this type of cooperation. Inland terminal 2 already has more freight on its own to reach a certain degree of economies of scale. The allocation of benefits is therefore an important aspect in setting up cooperation schemes between inland terminals. Theys et al. (2008) study this issue by making use of game theory. The lowest total costs of all three scenarios are obtained with full cooperation in a single roundtrip as in scenario 1. In the third scenario the service network design formulation presented in section 3 is not yet complete. The imbalance in freight flows should be further extended to incorporate roundtrips combining multiple port nodes.

Table 6: Costs of independent roundtrips

Arcs	**Fixed costs**	**Variable costs**
1-3	1200	1100
3-4	400	0
4-1	1200	1100
2-3	1000	2000
3-4	400	0
4-2	1000	2000
Total costs		**11400**
Terminal 1		5000
Terminal 2		6400

5. Conclusions and further research

In this paper a first exploratory study is presented to apply the methodology of service network design to intermodal barge transport. Service network design of intermodal transport by rail has often been investigated because of its monopolistic nature. On the contrary, intermodal transport by barge is organized by individual decision makers. A methodology is set up to study the service network of intermodal barge transport as a whole in order to demonstrate potential benefits of cooperation between inland terminals. Future work is aimed at incorporating the logic of roundtrips with multiple port nodes into the model formulation. Furthermore, a sensitivity analysis of cost parameters will be performed. Finally, larger time frames may be studied and frequencies may be introduced in the decision making process.

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