Abridgment

Development of an Inland Port-Location Model

YEAN-JYE LU AND JOSEPH A. WATTLEWORTH

A mixed 0 to 1 integer programming model is proposed for determining the required number of inland ports, their locations and sizes. The characteristics of the model are explored. The proposed inland port-location model is also compared with the standard capacitated warehouse-location model. In addition, computational experience with the proposed model is discussed.

An inland waterway system is composed of four elements: (a) commodities, (b) inland ports, (c) barges and towboats, and (d) inland waterways. This system provides for the complete movement of commodity shipments on inland waterways from their origin to their destination ports. From an operational viewpoint, the major advantage of the inland waterway is energy conservation. Barges and towboats are more energy efficient than either railroads or trucks. It has been estimated that barges or towboats provide 250 ton-miles per gallon of fuel in comparison to 200 ton-miles per gallon for rail, and 58 ton-miles per gallon for trucks *(1)*. The major disadvantage of the inland waterway is the relatively low travel speeds. The travel speeds commonly range from 3 to 6 mph upstream and 5 to 10 mph downstream *(2)*. Therefore, the inland waterway is only useful for movement of bulk commodities in large quantities over medium to long distances. This is why inland waterways have played an important but frequently unrecognized role in freight movement.

Today, as a result of the energy shortage, the inland waterway is receiving greater interest as a low-cost transportation mode for the future. Particularly in some developing countries or mountainous areas, the inland waterway is a more important transportation mode than highway or rail because of the considerations of initial costs and transportation costs. For example, the inland waterway in Honduras will be a great asset to that nation's economic development.

BACKGROUND

Need for the Research

Honduras is the second largest and the most mountainous country in Central America. La Mosquitia Region is located at the extreme northeast of Honduras. This region is a mountainous area where highway and railroad construction is difficult. One of the biggest problems of this region is the lack of transportation means. The intraregional road system is poor and an interregional one does not even exist. The region depends solely on air and sea transportation to communicate with other parts of the country. However, there are some navigable rivers, such as Patuca and Sico, that are potentially serviceable. Therefore, an inland waterway in this region will probably be the only transportation mode suitable for medium- and long-distance movement of freight in the foreseeable future. The Honduras port authority, Empresa Nacional Portuaria (ENP), has encouraged the research presented here on inland waterway development for La Mosquitia Region.

Furthermore, the literature review of this research reveals two problems in the study of inland port locations:

1. The inland port-location study is completely ignored within current planning methodology of inland waterway systems, and
2. None of the previous models in the facility-location analysis can be applied directly to solve the inland port-location problem.

Therefore, an inland port-location study is needed in order to fill these gaps in inland waterway system planning.

Objectives and Scope

The aim of this study is not to solve the inland port-location problem for La Mosquitia Region. Rather, an inland port-location model is developed to serve as the technological and theoretical basis to help the Honduran ENP solve the problem in the future.

Because there is no navigable inland lake existing in La Mosquitia Region, this study focuses only on river and canal ports. Furthermore, because the inland waterway is only suitable for moving large bulk commodities over medium to long distances, this study will emphasize interregional and international commerce only. Fishing, tourism, defense, and domestic commerce are not included.

INLAND PORT-LOCATION MODEL

Mathematical programming models can be defined as sets of equations that describe and represent a real system in terms of its physical, organizational, behavioral, and economic attributes. A mathematical programming model is chosen for the construction of an inland port-location model.

Assumptions

In order to formulate a realistic and solvable model of the inland port problem, several assumptions have to be made to simplify the real system:

Y. J. Lu, Department of Civil Engineering, Concordia University, 1455 De Maisonneuve Blvd. West, Montreal, Quebec, Canada H3G 1M8. J. A. Wattleworth, Civil Engineering Department, University of Florida, Gainesville, Fla. 32611.

1. No route capacity constraints because the capacities of route links connecting inland ports and shipping centers can always meet the shipping demands;
2. Only one coastal port for the study area;
3. Unit transportation cost of the cargo can be predetermined by the owner of the transportation facilities;
4. Average dock capacities because the same type of docks have the same capacity;
5. There is a short route (or a least expensive route) between a shipping center and an inland port; and
6. Economies of scale in shipping commodities and in constructing inland ports are not considered in this study.

Inland Waterway Network Representation

The inland waterway and land transportation networks are represented in this study as connected sets of nodes and links and described as follows.

Node Types

Nodes are used to identify and locate the transportation terminals. The three types of nodes represent:

1. Main coastal ports, which are seaports where the interregional or international commerce takes place;
2. Candidate inland ports, which are the waterway locations where the inland ports can be selected depending on several factors such as (a) sufficient depth, (b) secure anchorage, (c) adequate anchorage area, (d) accessibility, (e) less environmental destruction, and (e) protection against winds, storms, waves, and floods; and
3. Shipping demand center, which represents the location of economic activities generated in its section. Therefore, the center for each section is the point where commodity flow begins or ends.

Link Types

A link makes the connection between two nodes so that a link can be identified by specifying the nodes at each end. The two types of links are

1. Waterway links defined as the river or canal segment connecting two candidate inland ports, or the coastal seaway connecting a candidate inland port and a main coastal port; and
2. Route links defined as the link connecting a shipping center and a candidate port. The major transportation modes traveling in route links include highways, railroads, and pipelines.

Decision Variables and Parameters of the Model

The decision variables are unknowns to be determined from the solution of the model, and the parameters are the givens that represent the controlled variables of the inland port system. On the basis of their characteristics, the decision variables and parameters are divisible into the following five categories.

General

Variables for this section are listed as follows:

where

n = number of candidate ports;
m = number of shipping centers;
$SP(i)$ = a set of candidate ports that can feasibly serve shipping center i, $i = 1, \ldots, n$ (index);
$SC(j)$ = a set of shipping centers that can feasibly be served by candidate port j, $j = 1, \ldots, m$ (index);
y_j = 1, if an inland port is located at candidate port j, and 0, otherwise (decision variable);
UP_j = the upper bound of number of docks at candidate port j, $j = 1, \ldots, n$ (parameter); and
$U(j)$ = a set of nodes including node j and all its upstream nodes.

At candidate port j, $j = 1, \ldots, n$ (decision variable),

$z_{jk} = z_{j1}$, number of dry bulk docks;
$= z_{j2}$, number of liquid bulk docks; and
$= z_{j3}$, number of general docks.

In order to mathematically state the selection of candidate ports, the variable y_j is either 1 or 0 for candidate port j. If candidate port j is selected, y_j is set at 1; otherwise, y_j is set at 0. This means that a candidate port is either selected or not. Furthermore, because a dock cannot be halfway constructed, the number of docks resulting from solving the model will be rounded into their nearest integer values.

Commodity Flow

An inland port contains one or more terminals. Usually a terminal can handle only one type of cargo because a different type of cargo requires a different type of handling equipment. Based on a categorization of the U.S. Department of Commerce *(1)*, commodities in this study are divided into three types of cargo: (a) dry bulk cargo, (b) liquid bulk cargo, and (c) general cargo. Therefore, this study divides docks into three types designated by values of the index k:

$k = 1$, dry bulk cargo,
$= 2$, liquid bulk cargo, and
$= 3$, general cargo.

There are two decision variables and two parameters in this section:

where

x_{ijk} = average annual quantity of exported cargo k transported from shipping center i to candidate port j (decision variable, unit = k-ton);
x'_{jik} = average annual quantity of imported cargo k transported from candidate port j to shipping center i (decision variable, unit = k-ton);

S_{ik} = average annual exported cargo k sent from shipping center i to the coastal port (parameter, unit = k-ton); and

S'_{ik} = average annual imported cargo k sent from the coastal port to shipping center i (parameter, unit = k-ton).

Capacity

There are two types of capacity parameters: waterway capacity and dock capacity. The notations for waterway capacity are listed as follows:

PW_j = downstream capacity of a waterway link between candidate port j and its adjacent downstream candidate port (parameter, unit = k-ton); and

PW'_j = upstream capacity of a waterway link between candidate port j and its adjacent downstream candidate port (parameter, unit = k-ton).

Dock capacity is notated as

PD_k = PD_1, average annual capacity of a dry bulk dock;
= PD_2, average annual capacity of a liquid bulk dock; and
= PD_3, average annual capacity of a general dock (parameters, unit = k-ton).

Cost

Two types of costs are included in this study: transportation and construction costs. There are three parameters relating to the unit transportation cost:

CR_{ijk} = average cost of transporting one unit of cargo k to or from shipping center i to or from candidate port j; for $j \varepsilon SP(i)$ and all i and k (parameter, unit = \$1,000/k-ton);

CW_{jk} = average cost of shipping one unit of exported cargo k from candidate port j to the coastal port, for all j and k (parameter, unit = \$1,000/k-ton); and

CW'_{jk} = average cost of shipping one unit of imported cargo k from the coastal port to candidate port j, for all j and k (parameter, unit = \$1,000/k-ton).

There are two parameters relating to the unit construction cost: the fixed cost of a candidate port and the construction cost of building a dock:

CP_j = fixed cost of candidate port j, $j = 1, \ldots, n$ (parameter, unit = \$1,000/year); and

CD_k = CD_1, construction cost of building a dry bulk dock,
= CD_2, construction cost of building a liquid bulk dock, and
= CD_3, construction cost of building a general dock, (parameter, unit = \$1,000/year-dock).

Coastal Port

The index $j = 0$ denotes the coastal port. The parameter and decision variables for the coastal port are as follows:

$SC(0)$ = a set of shipping centers that can be served directly by the coastal port (index);

x_{i0k} = average annual quantity of exported cargo k transported from shipping center i to the coastal port (decision variable, unit = k-ton); and

x'_{0ik} = average annual quantity of imported cargo k transported from the coastal port to shipping center i (decision variable, unit = k-ton).

Constraints and Objective Function of the Model

The inland port-location model, constructed in this study, can be disaggregated into the following five sections.

Supply-Demand Constraints

The supplies in this study are those exported commodities shipped out of the study area, and the demands are those imported commodities shipped into the study area through the coastal port. Given the forecasted exported and imported cargoes, the supply-demand constraints specify that all exports and imports will be fully met. The supply (exports) constraints are

$$\sum_{j \varepsilon SP(i)} x_{ijk} = S_{ik}, \text{ all } i \text{ and } k \tag{1}$$

The demand (imports) constraints are

$$\sum_{j \varepsilon SP(i)} x'_{jik} = S'_{ik}, \text{ all } i \text{ and } k \tag{2}$$

Waterway Capacity Constraints

The purpose of the waterway capacity constraints is to ensure that the capacity of waterway links will not be exceeded for both the downstream and upstream directions. These constraints can be expressed mathematically as follows:

Downstream

$$\sum_{j \varepsilon U(j)} \left[\sum_{i \varepsilon SC(j)} \sum_{k=1}^{3} x_{ijk} \right] \leq PW_j, \text{ all } j \tag{3}$$

Upstream

$$\sum_{j \varepsilon U(j)} \left[\sum_{i \varepsilon SC(j)} \sum_{k=1}^{3} x'_{jik} \right] \leq PW'_j, \text{ all } j \tag{4}$$

Dock Capacity Constraints

Under the physical restraints of inland port expansion, dock capacity constraints will ensure that there are enough docks to handle the shipping demands. In other words, the size of a candidate port should be large enough to be able to load or unload the freight. The dock capacity constraints can be expressed mathematically as follows:

$$\sum_{i \varepsilon SC(j)} (x_{ijk} + x'_{ijk}) \leq PD_k \cdot z_{jk}, \text{ all } j \text{ and } k \qquad (5)$$

Site Capacity Constraints

Each candidate port has a limited capacity to expand its size because of the physical restrictions posed by socioeconomic, engineering, and environmental considerations. Therefore, the site capacity constraints ensure that none of the required number of docks exceed their upper bound of the number of docks. Furthermore, these constraints also prevent any docks being assigned to a deleted candidate port. The mathematical expression for these constraints is as follows:

$$\sum_{k=1}^{3} z_{jk} \leq UP_j \cdot y_j, \text{ all } j \qquad (6)$$

Because y_j is either 1 or 0, Equation 6 implies two situations: If $y_j = 1$, then

$$\sum_{k=1}^{3} z_{jk} \leq UP_j$$

If $y_j = 0$, then

$$\sum_{k=1}^{3} z_{jk} \leq 0$$

Objective Function

The objective function of the inland port-location model defines the measure of effectiveness of the inland port system as a mathematical function of its decision variables. The objective function for this study is to minimize total costs. Four types of cost are included. The total annual cost (unit equals $1,000 per year) of each type of cost can be expressed as follows.

Route transportation costs

$$\sum_{i=1}^{m} \sum_{j \varepsilon SP(i)} \sum_{k=1}^{3} CR_{ijk} \cdot (x_{ijk} + x'_{jik})$$

Waterway transportation costs

$$\sum_{j=1}^{n} \sum_{k=1}^{3} \left[CW_{jk} \cdot \sum_{i \varepsilon SC(j)} x_{ijk} + CW'_{jk} \cdot \sum_{i \varepsilon SC(j)} x'_{jik} \right]$$

Fixed costs of inland ports

$$\sum_{j=1}^{n} CP_j \cdot y_j$$

Construction costs of docks

$$\sum_{j=1}^{n} \sum_{k=1}^{3} (CD_k \cdot z_{jk})$$

Let

$$CT_{ijk} = CR_{ijk} + CW_{jk}$$

and

$$CT'_{jik} = CR_{ijk} + CW'_{jk}$$

Therefore, the formulation of the inland port-location model, which is the mixed 0 through 1 integer programming model, can be summarized as follows:

$$\text{Min } Z = \sum_{i=1}^{m} \sum_{j \varepsilon SP(i)} \sum_{k=1}^{3} \{CT_{ijk} \cdot x_{ijk} + CT'_{jik} \cdot x'_{jik}\} + \sum_{j=1} CP_j \cdot y_j + \sum_{j=1}^{n} \sum_{k=1}^{3} (CD_k \cdot z_{jk})$$

Subject to the following:

Supply-demand constraints

$$\sum_{j \varepsilon SP(i)} x_{ijk} = S_{ik}, \ \forall \ i \text{ and } k$$

$$\sum_{j \varepsilon SP(i)} x'_{jik} = S'_{ik}, \ \forall \ i \text{ and } k$$

Waterway capacity constraints

$$\sum_{j \varepsilon U(j)} \left[\sum_{i \varepsilon SC(j)} \sum_{k=1}^{3} x_{ijk} \right] \leq PW_j, \ \forall \ j$$

$$\sum_{j \varepsilon U(j)} \left[\sum_{i \varepsilon SC(j)} \sum_{k=1}^{3} x'_{ijk} \right] \leq PW'_j, \ \forall \ j$$

Dock capacity constraints

$$\sum_{i \varepsilon SC(j)} (x_{ijk} + x'_{jik}) \leq PD_k \cdot z_{jk}, \ \forall \ j \text{ and } k$$

$$\sum_{k=1}^{3} z_{jk} \leq UP_j \cdot y_j, \ \forall \ j$$

$$x_{ijk}, x'_{jik} \geq 0, \ \forall \ i, j \text{ and } k$$

$$y_j \ \varepsilon \ (0,1), \ \forall \ j \qquad z_{jk} \geq 0, \forall \ j \text{ and } k$$

CHARACTERISTICS OF THE PROPOSED MODEL

The major characteristics of the model are listed as follows:

1. A distribution-collection transshipment problem: Inland ports are not the origins or destinations of the commodity flows, but the transshipping terminals between land transportation modes and inland waterway modes. The exported commodities will be collected from the shipping centers to several inland ports, and then shipped from the inland ports to the coastal port. In addition, the imported commodities will be shipped from the coastal port to several inland ports, and then distributed from the ports to the many shipping centers.
2. A network discrete location-allocation problem: Not only is a location problem presented, but an allocation problem is also presented. Besides determining the number of inland ports, as well as their locations and their sizes, this study will determine the quantities of exported and imported commodities shipped through each inland port. Optimization of the objective function is sought by locating inland ports and allocating the commodity flows in the inland ports, and by allocating the commodity flows in the inland waterway network.
3. A multicommodity, multifacility and multimodal problem: All kinds of commodities, which are currently or potentially shipped on the inland port transportation system, are dealt with. They are classified into three types of cargo. Each needs a specific type of handling equipment. Therefore, three types of docks may exist in each inland port. Furthermore, the navigable rivers form a natural transportation network, but this depends significantly on the other transportation modes (highways, railroads, or pipelines) to tranship the commodities from the producers to the consumers.
4. Varied port sizes and capacitated waterway links: The size of an inland port in this study will vary with the required demand of commodity flows. The capacity of an inland port should be greater than or equal to the shipping demand. Capacity will be calculated based on number of docks. Furthermore, it is difficult to change the sizes of inland waterways and they are greatly affected by floods and droughts. In this way, capacitated waterway links are imposed in the inland port-location model.

In the field of facility location analysis, the capacitated warehouse-location problem (termed warehouse-location problem) is a well-known problem to which a great deal of research has been devoted. According to Francis et al. *(3)*, the purpose of the warehouse-location model is to design a system of warehouses to serve specific stores. A comparison of these two models shows that the inland port-location model and the standard warehouse model have similar structures. In the inland port-location model, the inland ports play the role of warehouses and the shipping centers play the role of stores. In other words, both the inland ports and warehouses can be considered as the facilities to serve shipping demands.

However, the inland port-location problem is not simply a version of the standard warehouse-location problem. Although these two problems have similar structure, the warehouse-location problem is only a part of the inland port-location problem. The major reasons are

1. Objective function: Facility sizes for the standard warehouse location problem are fixed, but those for the inland port-location problem are varied. The standard warehouse problem considers different fixed costs for acquiring warehouses depending on their sites. On the other hand, not only are different fixed costs, which depend on the locations for acquiring inland ports, studied, but so are different construction costs, which depend on the number of docks for handling cargoes.
2. Constraints: The proposed inland port-location model involves four types of constraints. They are supply-demand, facility capacity, transportation capacity, and site capacity constraints. Conversely, the standard warehouse-location problem includes only supply-demand and facility capacity constraints.

EXAMPLES OF COMPUTATIONAL EFFORTS

The Mathematical Programming System Extended–Mixed Integer Programming (MPSX-MIP) computer package was released by IBM, Inc., in the early 1970s. Because of its availability and comprehensibility, the package was chosen for this study.

Three examples of computer runs using the MPSX-MIP package are given in Table 1. All three runs had the same number of 30 shipping centers, but the number of candidate ports were 7, 8, and 12, respectively. The upper bounds of 10 docks in all candidate ports were assumed. The total computer processing unit (CPU) times are 22.4, 49.5, and 69.5 sec for the examples of 7, 8, and 12 candidate ports, respectively. The results of the runs indicate that when the size of the problem increases, the computer time increases. Furthermore, as indicated in Table 1, problems with the size less than or equal to the combination of 12 candidate ports and 30 shipping centers can be solved within 70 sec CPU time. Therefore, the results of the three runs indicate that the proposed model can be solved within reasonable computer time.

CONCLUSIONS

A mathematical programming model for solving the inland port-location problem was developed in this study. This model is able to represent the physical system adequately. In addition, the model can be solved by using the MPSX-MIP package with a reasonable computational effort. The study will be instrumental for solving

TABLE 1 THREE EXAMPLES OF COMPUTATIONAL EFFORTS

	Problem Size		Variables			CPU Time (sec)						
							Integer Solution					
Run	Candidate Ports	Shipping Centers	Continuous	0–1 Integer	No. of Constraints	Continuous Optimum	First	Optimum	Optimality Proved	Total	No. of Integer Solution Found	Optimal Solution Found
1	7	30	589	7	222	3.8	3.6	5.4	9.6	22.4	4	Yes
2	8	30	672	8	228	5.7	7.8	18.0	18.0	49.5	4	Yes
3	12	30	936	12	252	9.1	9.0	20.4	34.8	73.3	3	Yes

the inland port-location problem in some developing countries and mountainous areas such as La Mosquitia Region, Honduras.

REFERENCES

1. *National Port Assessment 1980-1990.* Maritime Administration, U.S. Department of Commerce, June 1980, 125 pp.
2. CACI Inc. *Executive Summary, Vol. I, Inland Navigation System Analysis.* Coastal Engineering Research Center, U.S. Army Corps of Engineering Research Center, U.S. Army Corps of Engineers, Fort Belvoir, Va., July 1976, 15 pp.
3. R. L. Francis, L. F. McGinnis, and J. A. White. Location Analysis. *European Journal of Operational Research*, Vol. 12, 1983, pp. 220-252.

Publication of this paper sponsored by Committee on Ports and Waterways.

The Role of Ports in Double-Stack Train Service

JOHN H. LEEPER

Double-stack train service is one of the latest technological innovations in the highly competitive business of intermodal shipping of containerized cargo. The double-stack train can carry twice the number of containers as a flatbed rail car, which sharply reduces shipping costs per container. Although steamship companies have taken the lead role in initiating double-stack service from the inland cities to ports, ports can market their facilities and rail connections to attract stack-train service. An overview is given of existing stack-train services, and discusses the impacts of stack trains on port competition and ways that several ports have attracted stack-train service are discussed.

In the past two years, double-stack technology has virtually exploded on the U.S. intermodal transportation industry. At this time, there are over 60 weekly departures of double-stack trains to and from 12 major port cities in the United States. These services, as they were promoted in December of 1985, are given in Table 1.

What is double-stack service? The term double-stack refers to the practice of stacking standard marine containers in two-high configuration on specially designed railroad flatcars. These flatcars have been designed to lower the overall profile and reduce the total weight of the container or flatcar unit. In practical terms, the double-stack car carries four 40-ft ISO containers, as opposed to the two 40-ft containers that are carried on conventional railroad flatcars. The result has been a savings in the cost of moving containers long distances by rail. These savings have been estimated by various railroads providing stack train service to be between 20 percent and 40 percent, depending on the route and rail carrier involved.

Phillips Cartner & Co., Inc., 203 South Union Street, Alexandria, Va. 22314.

Ironically, it was not the railroads that developed and implemented the double-stack service, but the ocean carriers. Since the early 1960s, ocean carriers of all flags have been engaged in a highly competitive battle for high-value cargoes on trade routes between the United States and its trading partners in Europe and the Pacific rim. Faced with competition from lower wage-rate Third World and state-owned carriers, the more progressive U.S. flag carriers relied on technology to improve their productivity and to maintain or increase their market share. Accordingly, carriers such as Sea-Land and American President Lines (APL) introduced container ships, automated container yards, and, finally, low slot-cost vessels as means of improving productivity. Concurrent with their technological development, U.S. flag ocean carriers accelerated their marketing efforts and began to offer through-intermodal service to selected shippers or consignees.

Before the Shipping Act of 1984, the legality of intermodal service was in question and the carriers offered it intermittently and usually as single entities rather than as conferences. In the 1982-1983 recession years, several ocean carriers contracted for inland rail service as part of a through-single-rate service. During that period, international freight rates dropped precipitously, and some ocean carriers found their rail costs were exceeding their revenues on some intermodal shipments. This experience focused the ocean carriers on the inland mode as an area for cost control, and as a possible source of advantage over competition. Meanwhile, the Shipping Act of 1984 was passed, which authorized conferences to offer intermodal service under a single-through-rate and allowed other practices that facilitated intermodal movement. These events culminated in decisions by some ocean carriers to design, test, and purchase double-stack equipment and to enter into agreements with rail carriers to pull the equipment.