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Inland Navigation Systems Analysis

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The objectives of the inland navigation systems analysis program are to develop within the U.S. Army Corps of Engineers the capability to optimize the design and schedule for implementation of future improvements to U.S. inland waterways and improve the operating efficiency of inland navigation. The program is an integrated system of four computer models, data, and planning procedures to (a) forecast commodity flows, (b) predict modal shares of traffic, (c) simulate and monitor inland waterway transportation, (d) predict economic impacts of inland waterway improvements, and (e) select the best size, location, and timing of inland waterway improvements.

The inland navigation systems analysis (INSA) program of the U.S. Army Corps of Engineers is designed to help Corps planners make the best possible decisions concerning the development of the inland waterway system and specifically to help them achieve two goals: to operate and maintain the inland waterway system as efficiently as possible and to select the best size, location, and timing of inland waterway improvements.

INSA essentially provides a planning capability and comprises an integrated system of four models, data, and planning procedures. Because the program recognizes that waterway transportation is a dynamic physical system embedded in an equally dynamic multimodal transportation market and national economic system, the system of models is designed to mimic the national market system and the role of inland waterway transportation within that market system. INSA simulates the market forces by use of a commodity-flow model and a multimodal model. The commodity-flow model is a multiregional input-output model designed to reproduce the market conditions of the U.S. economy, and the multimodal model gives modal transportation supply conditions. When these models operate together, they simulate the interplay of the national economy and the modal transportation system in bulk commodity movement.

Another pair of models simulates inland waterway transportation. Interaction among commodity traffic, the towing industry, and the waterway are simulated by a flotilla model and a navigation simulation model. The flotilla model represents the towing industry's response to commodity traffic, physical waterway characteristics, and operating delays caused by congestion. Given the waterway network, commodity traffic patterns, and expected operating delays, the flotilla model generates a least cost fleet or mix of towboats and barges required for the movement of commodities. The inland navigation simulation model is intended to represent inland waterway navigation as a large interacting system and to test by simulation the local and system-wide performance impact of a replacement structure, a new channel configuration, or an entirely new waterway. The navigation simulation model can also test new lock operating policies, variations in lock design, changes in channel depth, and many other controllable factors. Together the two models can estimate waterway network cost and capacity for providing freight transportation, and those estimates in turn can be used to estimate economic impacts, costs, and benefits.

The four INSA models are shown schematically in Figure 1 and described below. These four models can be operated together as a unit or as individual models by using any means or models other than those of INSA as input.

This paper summarizes the results of several years of intensive research. Because of the extent and complexity of the study, it is not possible to present more than the general concept of the models.

COMMODITY-FLOW MODEL

The purpose of the INSA commodity-flow model is to forecast the demand for interregional bulk commodity transportation. The commodity-flow model is largely concerned with predicting the size and shape of particular sectors of an economic system. In the model, an economy consists of a set of regions, each of which contains a set of economic sectors or industries. These economic sectors produce an output product to satisfy perceived domestic and export demand. The production process in each sector requires using a combination of inputs (raw materials, labor, and capital goods) to produce the output product. The mix and sources of inputs to the production process depend primarily on delivered input prices, including the price of transportation, as each sector seeks efficient input combinations. Commodity flows occur in this system as raw materials travel to production sites and commodities move to satisfy domestic and export demand.

The commodity-flow model is a multiregional input-output model in which market dynamics determine the location, composition, and pricing of output and the behavior of economic aggregates determines the level of output. In this system consumers select commodity

suppliers and producers compete for customers on the basis of delivered commodity price, which includes the price of transportation for inputs and the price of transportation from suppliers to consumers. The commodity-flow model then generates a demand for commodities that depends on transportation price.

The commodity-flow model functions as the interacting components of production and consumption, which generate the demand for transportation based on economic transactions across geographic space. The result is commodity flow. The information flow for the commodity-flow model is shown in Figure 2. Figure 3 shows the elements of the model based on input requirements, processing procedures, and output reports.

Input

The following types of economic data and information are represented in the model:

1. Economic activities—Commodities are identified as output from an economic activity. Each activity has a specified type of production function—either Cobb-Douglas or constant elasticity of substitution—and speci-

Figure 1. INSA system.

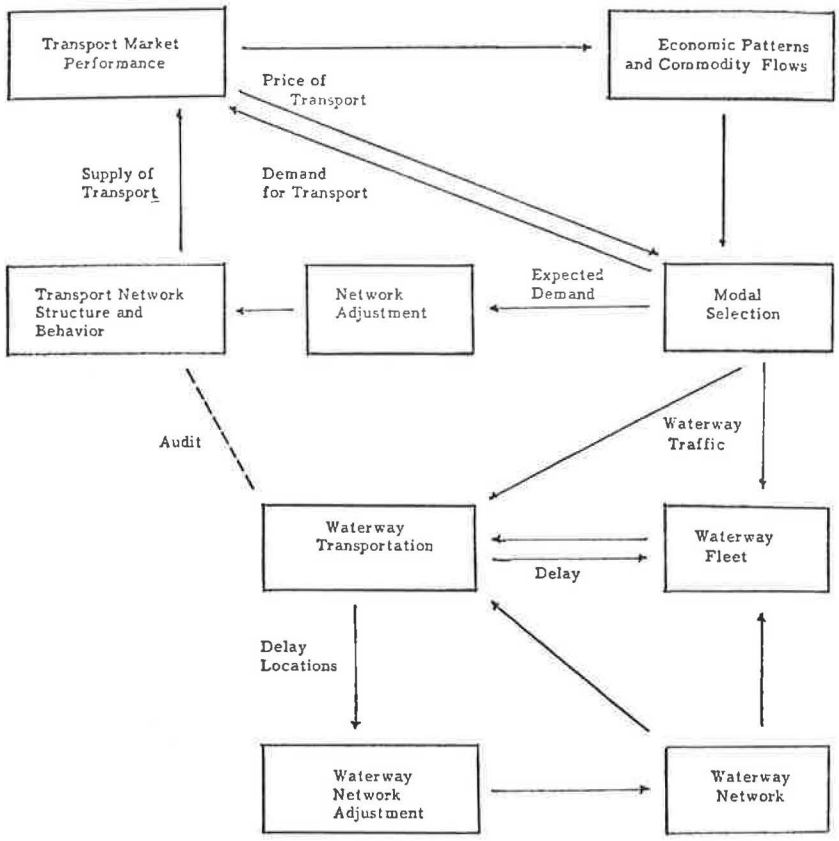
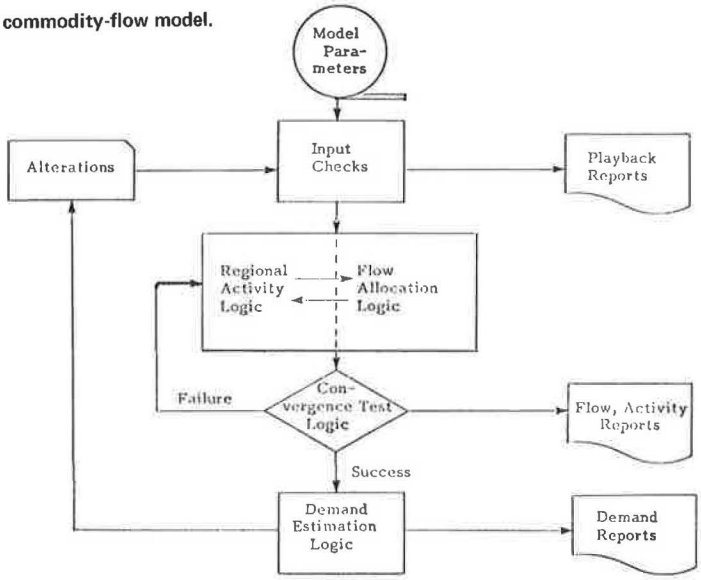


Figure 2. Structure of INSA commodity-flow model.



fies its production requirements for raw materials, labor, and capital goods as well as prices of those requirements. The value of output is given, but output level is generated by the model.

2. Regional attributes—This model uses the U.S. Department of Commerce delineation of 173 Bureau of Economic Analysis (BEA) areas to give commerce flows from area to area. Other regional approaches may also be used. BEA data are collected on the characteristics of an area, including earned income, work force, wages, population, return on capital, and consumption expenditures.

3. Demand—Demand is based on domestic and export conditions. Export demand is treated as an exogenous factor and must be specified by the analyst. Domestic demand is estimated by the model and is assumed to be of unitary elasticity with respect to price. All demand is measured in physical rather than monetary units. Domestic conditions must be estimated for first-year forecasts; the model then estimates demand for subsequent years.

4. Transportation costs—Data on the cost of shipping between all regions by commodity must be specified and may be obtained from the INSA multimodal model or an alternative source. Transportation cost is needed to determine delivered commodity price.

Operations

The following operations are performed by the model:

1. Determination of minimum cost and location—Initial calculations are made to determine the minimum delivered price of each commodity for each supply region and for each consuming region.

2. Computation of consumption—Regional income is derived from earned income by area, wages paid by each sector, and distributed returns to capital, allocated on the basis of per capita earned income. Regional income is then spent or converted to demand for commodities and services by using a consumer expenditure function.

3. Determination of demand—The demand for commodities is based on regional historical evidence and augmented by regional consumption patterns.

4. Organization of transportation costs—Transportation costs, which consist of transport cost of input and delivery cost of product, are organized by the model and used to determine transportation demand.

5. Forecast of economic activity—Supply region activities are generated based on given inputs and prices and regional production functions.

6. Allocation of commodity flow—The selection of input materials, based on minimum delivered cost, allows the model to determine free-on-board (FOB) prices and, eventually, transportation cost.

Output

The following information is output by the model.

1. Commodity flow report—A list of flow volumes between origin (supply region) and destination (consumption region) is compiled for each commodity. Commodities destined for export are noted.

2. Domestic demand report—Data on wages, work force, income, and demand generated as a result of income and expenditures are given for each region.

3. Origin flow report—Each region's market for all outputs is displayed.

MULTIMODAL MODEL

The basic purpose of the INSA multimodal network model is to provide a device for evaluating within a market concept the economic benefits obtainable from specified capital investments in any one or combination of the following transportation modes: inland waterways, railroads, highways, and pipelines. In such an evaluation the model simultaneously considers all modes and thus reflects important interactions among them. Because of system complexity, the scope and purpose of the model are confined to evaluating particular facility and network improvements. In accomplishing this function, however, the model indicates which portions of transportation modal networks will benefit most from improvement. This information is useful in determining gross allocation of transport investment across modes and suballocations within modes.

The chief distinguishing characteristic of the INSA approach to multimodal analysis is its emphasis on transportation markets and their interplay with commodity markets. In a market context, the transportation system is viewed as a connected set of links and nodes, each offering transportation according to a supply schedule that relates cost to shipment volume. Demand schedules for links and nodes are derived by finding for each shipment the least cost path through the network. Transportation supply and demand interact to determine jointly the equilibrium values of transportation market prices and service levels. Predicted changes in market equilibrium caused by changes in commodity-flow patterns and by adjustments to the transportation network are the principal product of the analysis and can be used to compare and evaluate alternative transportation investments.

A principal function of the model is determining the least cost path for each commodity movement. Each commodity movement is defined by origin and destination regions, tonnage, commodity type, and route restriction, if any. (Because the INSA model uses U.S. customary units, SI equivalents are not given.) The problem is to find, for each movement, the minimum cost path between the origin and destination regions, where a path is defined as a sequence of connecting nodes and links. Figure 4 shows the structure of the multimodal network model, and Figure 5 shows the model elements.

The Modal Network

Determining routes between two points in a network is a familiar problem in transportation analysis, and the multimodal network model uses standard solution techniques that have been developed for finding the least time and least cost route. The cost of traversing a network element is defined as shipment cost (determined from the element's cost function) plus shipper-perceived cost of delay. The latter cost is defined as the product of transit time as determined from the element's capacity function.

The operations of the path-selection algorithm yield the following results:

1. Identification, for each commodity shipment, of the route to which the shipment was assigned;
2. For each link and node of the network, the number of tons assigned;
3. For each commodity shipment, shipping costs incurred for the assigned route; and
4. For each network link and node, shipping costs and transit time of assigned traffic.

To alleviate computational problems, a constraint is imposed on the number of routes considered in the path-

Figure 3. Elements of INSA commodity-flow model.

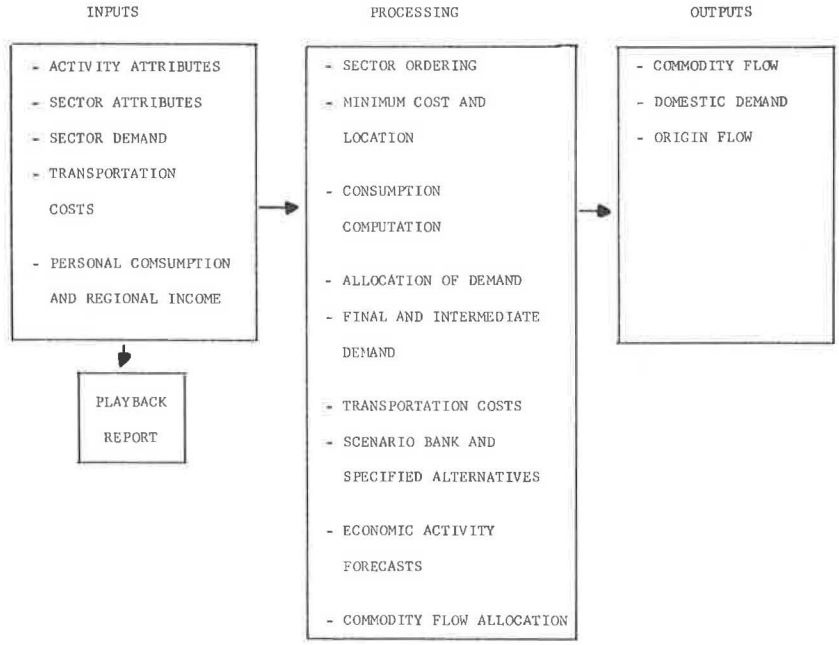
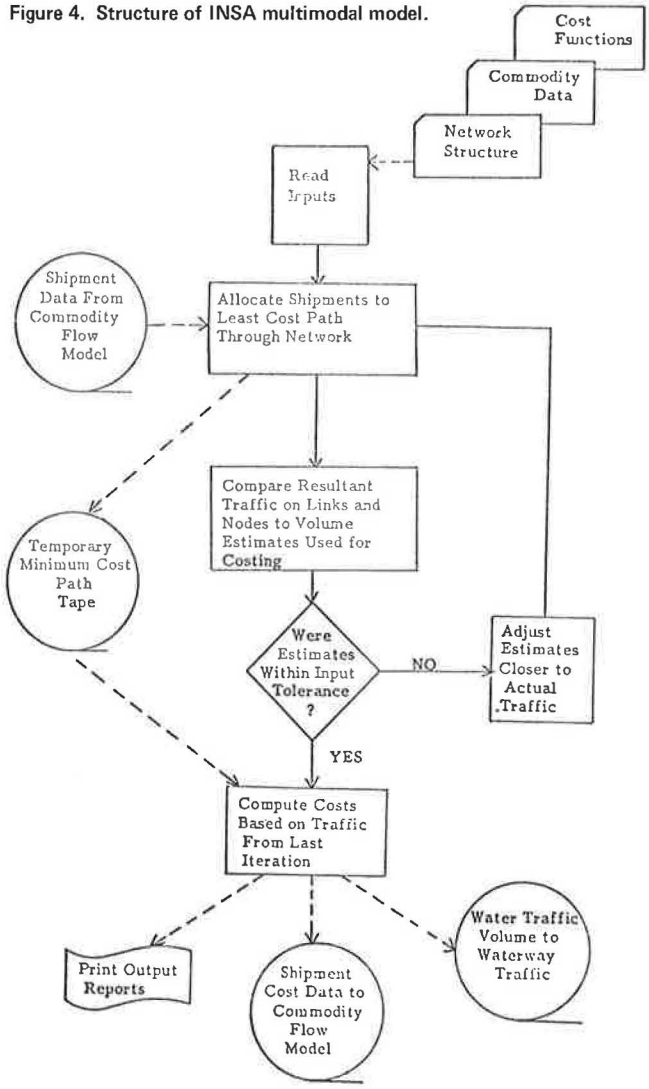


Figure 4. Structure of INSA multimodal model.



selection process by a simple method that assumes that the location of each node is given in terms of geographic coordinates. An ellipse of given eccentricity is then constructed about the origin and destination regions for a particular commodity movement; the major axis of the ellipse is the straight line connecting the centers of the two regions. The path-selection algorithm considers only those routes between the two regions that lie within the ellipse. The algorithm permits the ellipse to automatically increase in size, according to specified criteria, to ensure that at least one route is included. This inclusion ellipse constitutes a circuity constraint that greatly shortens the amount of computer processing time required; the price paid is that circuitous routes that may be less costly than the selected route are ignored.

Commodities may also be restricted as to which modes of transportation they may use. In this case, nodes and links of the disallowed modes are not considered in the path-selection process. For instance, nonpetroleum products are not shipped by petroleum pipeline. Individual shipments may be restricted to following a specified route from origin to destination. Links and nodes are limited to carrying flows below their capacities.

An optional inertia effect is also included in the model, whereby a specified portion of any commodity shipment may be constrained to observe modal-share percentages input by the user for that shipment. Least cost paths for the mode-constrained tonnage are built by using only nodes and links of the specified mode. The balance of the shipment is free to select the best route. This process reflects the realities of long-term shipper contracts and other commitments and prevents oscillation in the model results in response to small cost differences among modes.

An iterative procedure is used to assign shipments to the network. For a base-year case, link and node costs are initially set by entering the performance functions with flow volumes equal to the practical capacity of each element (that flow volume for which delays are normal) or some other user-supplied volume estimate. Shipments with fixed routes are assigned by increasing the loading on each link and node in the route by the amount of shipment. Shipments with a fixed mode choice are assigned by using the path-selection routine and updating

all costs to correspond to the total assigned traffic. This process is repeated in an iterative fashion until assumed and final volumes, and thus costs, agree within some specified tolerance. Then volumes and final costs from one period are used as the initial volume estimates for the next period.

The output routine organizes the results of the processing procedure and presents them in several types of reports, including reports giving the allocations of movement requirements to the elements of the network and the cost associated with such allocations. Because the multimodal network model is designed to interact with other INSA models, the output routines also provide data interface files. Interregional transportation cost is generated for use by the commodity-flow model, and commodity traffic flows from origin node to destination node for a given mode (e.g., port-to-port waterway traffic) are output for use by a modal simulation model.

Features

The following is a brief description of the features of the multimodal model.

Problem Size

The size of problem the model can handle is subject only to computer limitations. There are no inherent restrictions on the number of network elements or commodity shipments.

Transportation Networks

The multimodal transportation network is represented as a set of connected links and nodes. The network description format is very similar to that developed by the U.S. Department of Transportation. Links represent linehaul transportation facilities and are described by the nodes at each end of the link, length, transport mode, capacity, and transit time and cost parameters. Nodes have attributes such as name, number, location (coordinates), mode, capacity, and time and cost parameters. A special class of links, called access links, represent local transportation and connect commodity origin and destination regions to the network. Another special link class represents intermodal transfer facilities and operations and unites the modal subnetwork into an integrated multimodal network.

Figure 5. Elements of INSA multimodal model.

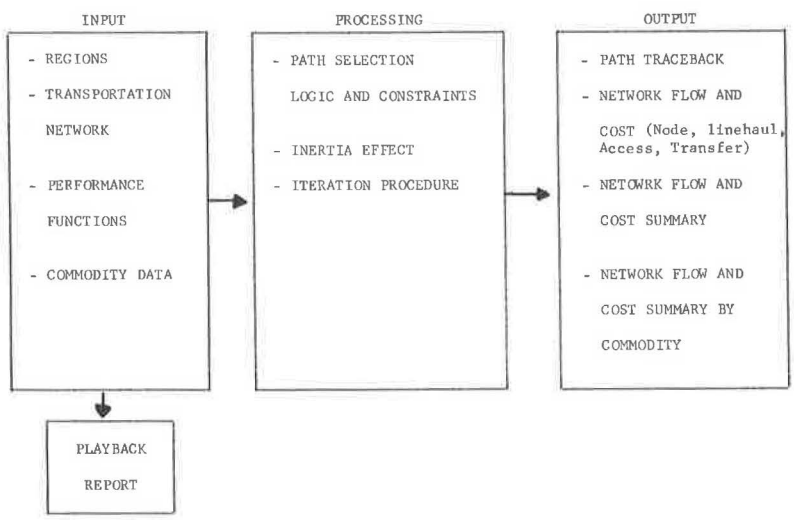


Figure 6. Structure of inland navigation simulation model.

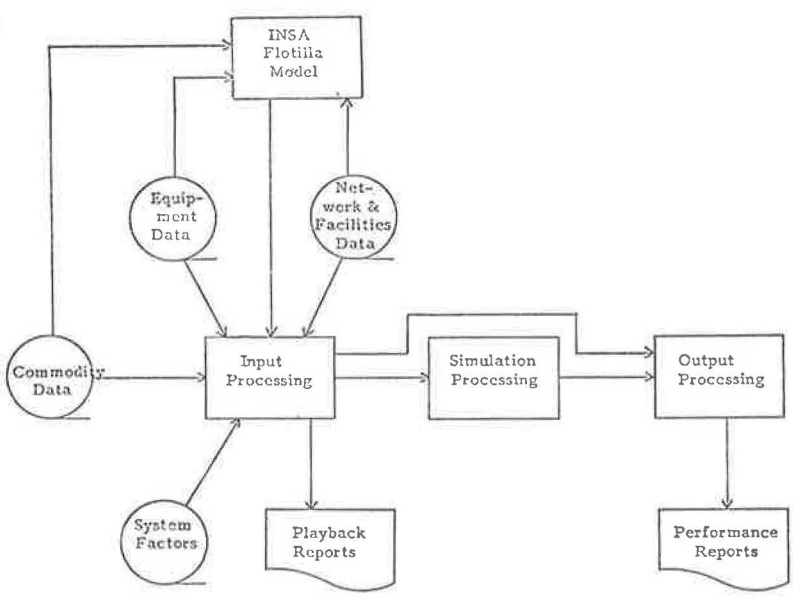


Figure 7. Elements of inland navigation simulation model.

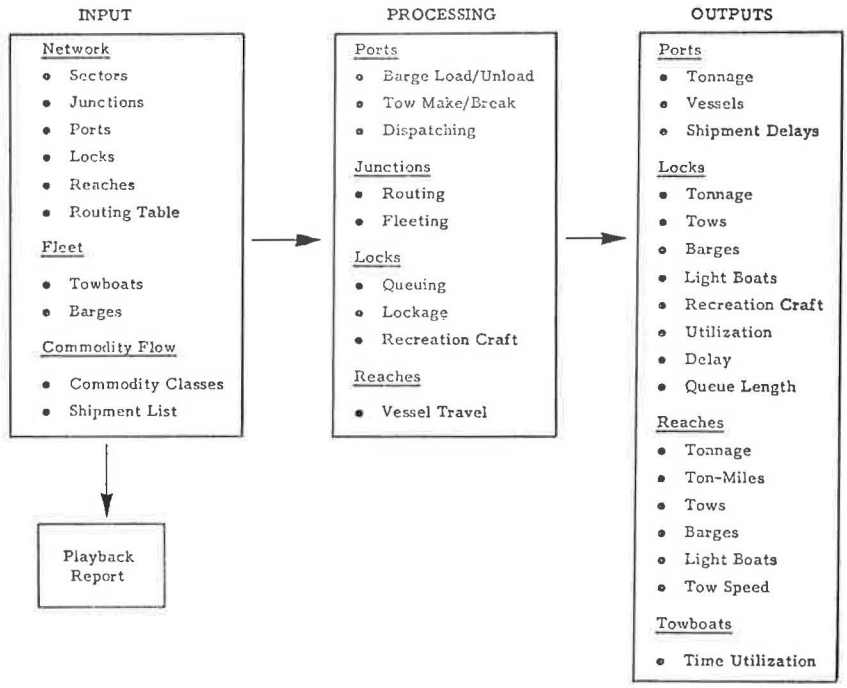
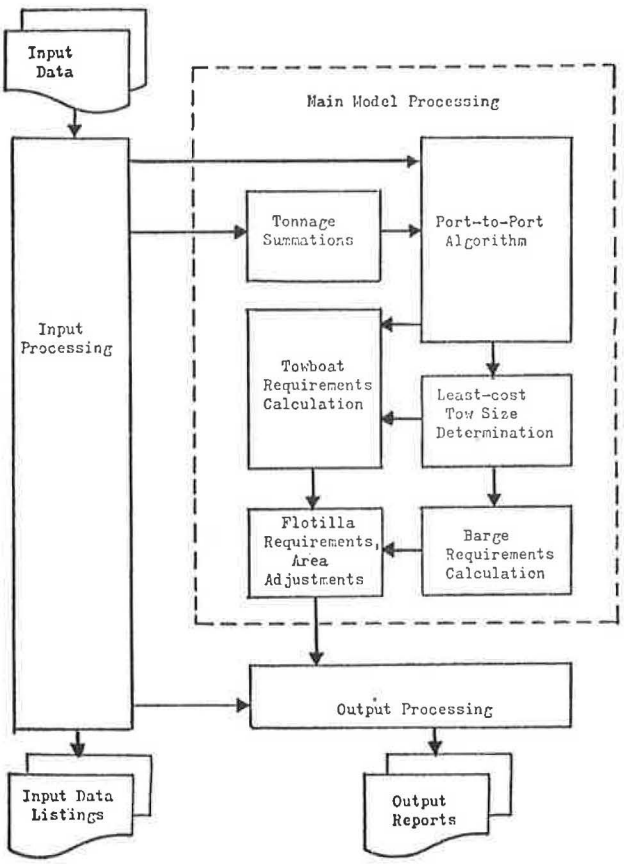


Figure 8. Structure of INSA flotilla model.



Performance Functions

The operating characteristics of links and nodes are represented in abstract form as functions relating the cost of traversing a link or node to the amount of traffic that uses that link or node. These costs are intended to be fully allocated; they may therefore not equal the transportation rates paid by shippers. (The model formulation is general; rates can be used if desired.) Similar functions, called capacity functions, relate transit time to shipment volume. Cost and capacity functions for intermodal transfers and for regional access are also used.

Commodity Movements

Each requirement for transportation is described by origin region, destination region, commodity type, and tonnage. Optional specifications of historical or estimated modal-split percentages and desired route from origin to destination are also permitted. Commodity types are defined by two-digit classification, value, and inventory factor (sensitivity to shipment time).

Transportation Equipment

Individual power units, cargo vehicles, and other transportation equipment are implicitly included in the link and node performance functions. No separate vehicle representation is used.

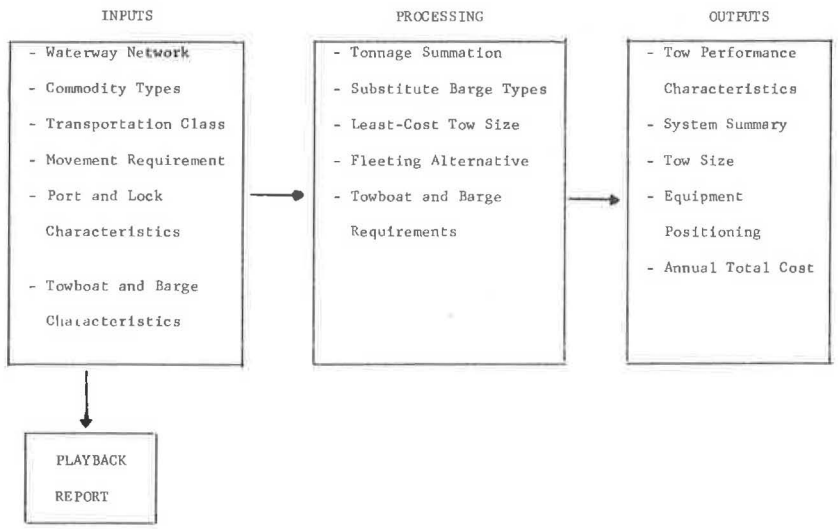
Shipment Routing

Least cost routes (from the shipper's viewpoint) from origin to destination are found for all shipments. Both perceived and economic costs are allowed to vary with shipment volume on each link. Equilibrium-seeking features are included.

WATERWAY SIMULATION MODEL

The purpose of the INSA waterway simulation model is to represent on a computer the movement of commodity flows on the U.S. inland waterway system. Simulation of the system enables observing and predicting its performance under a variety of economic and technical assumptions. These performance predictions are used to assess the adequacy of the existing system and to estimate the economic benefits and environmental impacts

Figure 9. Elements of INSA flotilla model.



of waterway improvements.

The navigation simulator was designed to represent inland navigation as a large interacting system. The model was developed to test by simulation the local and regional performance impact of a replacement structure, a new channel configuration, or an entirely new waterway system. The simulator is also capable of testing such controllable factors as new lock operating policies, variations in lock design, and changes in channel depth.

The inland navigation simulation model assumes a set of waterway traffic shipments determined by transportation markets outside the model, combines these shipments, a fleet, and a waterway network, and then simulates inland waterway transportation as a large, dynamic, interacting system. Figure 6 shows the structure of the simulation model: The commodity-flow model provides inputs on cargo flow and demand, and the flotilla model provides inputs on tow performance and size, towboat and barge positioning, and cost data. Figure 7 shows the primary elements of the simulation model operation—the input requirements, processing procedures, and output reports.

The INSA simulation model is a generalized model that provides explicit representations of individual waterway facilities, cargo consignments, and vessels. The following is a brief description of the model's principal features.

Problem Size

The size of the problem the model can handle is limited only by the computer resources available. There are no inherent restrictions on the number of ports, locks, river segments and tributaries, number and type of towboats and barges, or commodities. The model is specifically designed to accommodate systems as large as the entire Mississippi River-Gulf Coast waterway system.

Waterway Network

Ports, locks (and their chambers), and reaches represent the physical features of the inland waterway system. In the inland waterway network the locations of ports, locks (and their chambers), junction points, and sector boundaries are represented as nodes; links represent reaches and are thus segments between nodes. Contiguous link-node groups are organized into sectors. Sectors and river systems identify and organize the elements of the network for processing and analysis. The effects of specific channel conditions, such as bends and shoals, are normally represented implicitly by their constraining effects on navigation.

River Systems

River systems are groups of sectors that facilitate the collection of statistics and the sorting of output. The simulation model thus enables analysis of waterway sections or regions with common characteristics and can accommodate potential projects involving the evaluation of specific ports, locks, and regions.

Sectors

A sector represents an unbranched section of the network on which limitations on tow operations are uniform. Although a sector typically extends from one river junction to another or to a system end point, it can be divided into two or more sectors if significant differences in characteristics exist along its length. Because sectors always begin and end at ports, a port must be located at each junction and end point of the network.

Ports

Each INSA port is called a port equivalent to avoid confusion between ports and major ports. Because of number and variety of ports and docks and the resultant data base requirements, linear stretches are combined and abstracted as a single point at which cargo originates and terminates. Port processing is thus represented by loading and unloading times and by barge pick-up and drop-off times.

Locks

Each lock facility is explicitly represented in the form of tow processing time for each chamber. Processing time is broken down into approach, entry, chambering, and exit times (in accordance with performance monitoring system data). An optimal simplified lock representation scheme is included; single, setover, multiple-cut, multiple-vessel, and open-pass locks are accommodated; and both "first come-first served" and "N up-N down" queuing disciplines are available. A relatively large number of data are required to describe lock systems. The central abstraction used is random processing time distributions to represent lock operations. The model

considers the following factors in calculating lock operation time:

1. Type of lock—straight single, setover (the model classes as setover all single locks that require reconfiguration), multiple-cut, or multiple-vessel;
2. Direction of travel—upstream or downstream;
3. Type of entry to and exit from the chamber—fly, turnback, or exchange; and
4. Load category of barges in the tow—loaded or empty.

Reaches

A reach is a section of waterway between two ports or locks. Reaches influence tow traffic in two principal ways: (a) The physical characteristics of a reach limit the size and draft and thus the cargo capacity of tows and (b) tow traffic is constrained by the time it takes to travel a reach, which is a function of the length of the reach and the attainable tow speed.

Cargo

Commodity movements enter the model in the form of a list of individual shipments characterized by commodity type, ports of origin and destination, tows, and earliest possible departure time. This list is compiled by a separate interface program that operates on a port-to-port, origin-destination tonnage matrix. The data for the interface program are output from the INSA commodity-flow model.

Dispatching

Tow make-up (allocating shipments to barges and barge groups to towboats) and tow movement (along the waterway network between origins and destinations) are internal to the model. En route drop-off and pick-up of barges as well as fleet operations are represented. Empty barge movements needed to accommodate trade imbalances are scheduled internally by means of decision rules built into the program.

Vessels

Individual towboats and barges are explicitly represented and denoted by identification number, horsepower (towboat only), size, maximum permissible flotilla size, and sectors of operation. Barges in tow are represented as barge groups—one or more barges of common characteristics. Recreational craft are individually represented by arrival at a lock for lock processing, but trip connectivity is not represented for these vessels. Different weekend and weekday arrival rates may be specified.

FLOTILLA MODEL

The INSA flotilla model determines a cost-effective fleet of towboats and barges required to satisfy a given mix of commodity movement requirements while operating in a waterway network of existing or assumed characteristics. Outputs include the required fleet or tow mix, the corresponding total, and ton-mile costs. Results may be used in independent studies of towing industry projections and as inputs to other methods of waterway analysis developed by INSA, particularly the inland navigation simulation model. The flotilla model may be characterized as an expected value simulation of the inland waterway network with an embedded algorithm for calculating least cost tow sizes over a predefined waterway route. The model can consider the entire waterway network, or any portion of it, and provide a level of detail concerning the number of ports, locks, and reaches that is limited only by the study objectives and the computer size.

Data requirements for commodity flows are provided to the model as origin-destination tonnage by season and by commodity class; origin and destination ports are given by the network definition. Any number of towboat and barge types, and their distinguishing operational or cost characteristics, can be accommodated.

Figure 8 shows the overall structure of the flotilla model. The program elements of the model are specified in Figure 9 according to input requirements, processing procedures, and output reports. As shown in Figures 7 and 8, the model formulates flotilla requirements, adjustments, and use.

Basic inputs to the flotilla model include descriptions of the ports, locks, and channels of the waterway system as parts of a connected network. Operating characteristics of ports and locks, as well as descriptions and performance measures of assumed types of towboats and barges, are given. Seasonal commodity flows are input in terms of commodity type, tonnage, and origin and destination ports. After input data are processed, (a) requirements for origin-destination movements are analyzed and (b) various tonnage sums for each season are calculated, including inbound and outbound tonnages for each port, upstream and downstream tonnages for each lock and link (or reach) of the network, and aggregations of tonnage by commodity type into a smaller number of classes having common transportation characteristics.

After initial processing of the input data, a port-to-port algorithm is used to calculate productivity and cost measures for possible tow sizes operating between two ports for a particular class of cargo. An appropriate tow size is selected for each towboat class, and total round-trip operating and delay times and costs are calculated based on port, lock, and waterway operating characteristics and types of utilization coefficients. Towboat type and tow size with least cost per ton mile are determined for tows containing dry and liquid cargo respectively. The types and amounts of equipment required are then adjusted for seasonal effect, and the resulting equipment requirements and costs are aggregated for output purposes.

When the process is completed, towboat and barge requirements, as well as associated ton-mile costs and other results, are accumulated over all movement requirements by output processing routines, and the results are displayed in several types of output reports. The output reports of the flotilla model consist of the projected numbers of towboats and barges by type that are needed to satisfy commodity-flow requirements. These projections are input to the INSA inland navigation simulation model, which investigates the operation of the waterway system as a whole. The simulation model in turn provides refined estimates of lock delay factors and other parameters used by the flotilla model. Both models may share input data describing the network, base-year equipment, commodity flows, and other system features.

Since calculated fleet requirements and associated transportation costs are sensitive to the structural aspects of the inland waterway system, the model may also assist in evaluating alternative capital investment programs and performing benefit-cost analyses. Specialized studies such as fleet distribution requirements in response to seasonal demand or commodity mix, changes in fleet composition indicated by long-term trends in the economy, and studies of other exogenous influences may also benefit from use of the INSA flotilla model.

SUMMARY

The inland navigation systems analysis program was intended to provide the Corps of Engineers with tools to diagnose inland waterway transportation problems. The program attempts to investigate waterway problems for their transportation and economic impacts and also to evaluate actions proposed for coping with these problems. In identifying the problems, reviewing potential solutions, and testing proposed actions, the INSA program has always been operated from the perspective that problems and solutions should be considered in light of their effects on transportation cost and capacity. INSA can thus predict the probable course of problems and the probable impact of proposed actions on inland waterway navigation.

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Port-Funding Dilemmas in a Regional Planning Context

Robert G. Goodwin, Jr., East-West Gateway Coordinating Council, St. Louis

The purpose of this paper is to explore the funding problems that confront those who prepare comprehensive development plans for inland ports. Using as an example the study of the Port of Metropolitan St. Louis conducted by the East-West Gateway Coordinating Council, the paper discusses traditional and innovative funding sources and their applications, advantages, and weaknesses, with reference to the ongoing regional port study. It is concluded that, although the survival of the inland waterway industry as a healthy mode of transportation depends on improved port operations, the existing port authorities and related planning agencies often lack adequate financing for planning port development. It is therefore vital that some type of sole-source funding program be developed to provide the funds necessary for efficient port planning and development.

Although the amount of freight carried on the inland waterways of the United States has grown annually since the 1920s, growth of freight traffic at the Metropolitan Port of St. Louis has not kept pace. Between 1961 and 1970, for example, freight carried on the Mississippi River as a whole grew by 87 percent, but freight at the metropolitan port [based on the 30-km (19-mile) definition] grew by only 10 percent.

The Port of Metropolitan St. Louis, like many other U.S. ports, has been faced with a bewildering dilemma in recent years: an overwhelming need for some kind of development plan that would serve not only to identify areas suitable for industrial and port-related development but also as a rallying point for those who make their living in the waterway industry. The need for such a plan for the port became apparent in 1973. There was general agreement among the business and labor leaders of the community that something had to be done, but that something was not yet defined. To add to the confusion, there was no single port authority to whom they could turn.

THE PROBLEM

In an effort to better understand the current position and problems of the port, community leaders turned to the East-West Gateway Coordinating Council, the regional planning agency, for an investigative analysis of the port. The general objective was to enhance the economy of the St. Louis area by capitalizing on the strategic location of the port of St. Louis on the inland waterways of the United States.

Although an agency had been identified to conduct the study, community leaders were faced with another dilemma: How were they to pay for the study effort? The council was authorized to survey all existing funding sources to determine the best method. Careful analysis revealed that there were no existing programs at the local, state, or federal level to provide funds for the type of effort needed. There was only one ray of hope: Community leaders had been advised by officials in a federal agency that if the local community provided funds for the preliminary investigation as a gesture of its good faith and to indicate how serious it felt the problem to be, the federal government might provide funds to complete the effort. Based on this premise, the study was divided into a series of phases. The first phase was designed to be an investigative effort, with a funding requirement between $50 000 and $60 000. Ultimately, a 35-member task force, organized to provide advice and guidance to the council, raised nearly $57 000 through private sources.

The first phase of the study of the Port of Metropolitan St. Louis was completed in 1973. Its principal recommendation called for the St. Louis region to develop an efficient inland port to serve the industries that are major users of inland waterway transport. However, the task force and the council were again faced with the problem of obtaining the funds needed to prepare a port development plan. Again, the council was charged with the responsibility of surveying all available sources of funds. Now that the first phase of the study had been completed, the staff went to the federal official who had implied that he could provide the funds for completion of the study. No funds were available.

METHODS OF FUNDING

In examining various traditional methods of funding port development, the staff of the East-West Gateway Coordinating Council surveyed the following sources:

1. General obligation bonds,
2. Revenue bonds,