The Navigation Economic Technologies Program

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HARBORSYM

A Data-Driven Monte Carlo Simulation Model Of Vessel Movement In Harbors

US Army Corps of Engineers®

IWR Report 04-NETS-P-02

Navigation Economic Technologies

The purpose of the Navigation Economic Technologies (NETS) research program is to develop a standardized and defensible suite of economic tools for navigation improvement evaluation. NETS addresses specific navigation economic evaluation and modeling issues that have been raised inside and outside the Corps and is responsive to our commitment to develop and use peer-reviewed tools, techniques and procedures as expressed in the Civil Works strategic plan. The new tools and techniques developed by the NETS research program are to be based on 1) reviews of economic theory, 2) current practices across the Corps (and elsewhere), 3) data needs and availability, and 4) peer recommendations.

The NETS research program has two focus points: expansion of the body of knowledge about the economics underlying uses of the waterways; and creation of a toolbox of practical planning models, methods and techniques that can be applied to a variety of situations.

Expanding the Body of Knowledge

NETS will strive to expand the available body of knowledge about core concepts underlying navigation economic models through the development of scientific papers and reports. For example, NETS will explore how the economic benefits of building new navigation projects are affected by market conditions and/or changes in shipper behaviors, particularly decisions to switch to non-water modes of transportation. The results of such studies will help Corps planners determine whether their economic models are based on realistic premises.

Creating a Planning Toolbox

The NETS research program will develop a series of practical tools and techniques that can be used by Corps navigation planners. The centerpiece of these efforts will be a suite of simulation models. The suite will include models for forecasting international and domestic traffic flows and how they may change with project improvements. It will also include a regional traffic routing model that identifies the annual quantities from each origin and the routes used to satisfy the forecasted demand at each destination. Finally, the suite will include a microscopic event model that generates and routes individual shipments through a system from commodity origin to destination to evaluate non-structural and reliability based measures.

This suite of economic models will enable Corps planners across the country to develop consistent, accurate, useful and comparable analyses regarding the likely impact of changes to navigation infrastructure or systems.

NETS research has been accomplished by a team of academicians, contractors and Corps employees in consultation with other Federal agencies, including the US DOT and USDA; and the Corps Planning Centers of Expertise for Inland and Deep Draft Navigation.

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HARBORSYM: A DATA-DRIVEN MONTE CARLO SIMULATION MODEL OF VESSEL MOVEMENT IN HARBORS

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ABSTRACT

HarborSym is a planning-level model developed by the U.S. Army Corps of Engineers to assist in economic analyses of proposed deep draft channel improvements. The model creates an event driven simulation based on data stored in a database, instead of customization within a simulation environment. Included in this data are the user specified transit rules that the model processes with each vessel call in order to calculate delays within the system. Users can define alternative sets of channel dimensions or rules reflecting harbor improvements to determine potential transportation cost savings resulting from reduced delays.

NEED FOR MODEL

Corps of Engineers Role

The U.S. Army Corps of Engineers (Corps), as part of its overall mission, assists in the development and improvement of U.S. ports. The improvements of interest relate primarily to waterway enhancements, such as channel widening and deepening, and provision of moorings and turning basins. Economic analyses of such improvements require estimating the reduction in transportation costs directly attributable to any proposed enhancement. As the efficacy of any improvement depends on interactions within the entire system, these analyses are complex. Also, there is considerable uncertainty concerning the interaction of vessels in the channels. To properly evaluate the economic efficacy of any waterway improvement, a systems analysis explicitly incorporating uncertainty is required.

Expenditure of Federal dollars for navigation improvements requires authorization and appropriation by Congress and the President. This process involves review of the proposed plans by stakeholders and other non-government organizations as well as the Corps. One focus of the debate in this review process has been the models used to evaluate projects. The nature of the Corps planning process and project review would be much enhanced if evaluation models were peer reviewed and as transparent as possible.

The Corps currently has no commonly adopted model for the evaluation of proposed deep draft navigation improvements. In fact, any of the Corps 37 districts may develop new tools and evaluation methods for each study. These models are often "black boxes" understood by only a few practitioners. Such models generally have had limited peer review and each may have its own set of assumptions regarding key parameters. Reviews of past efforts have revealed simple computational errors. Limited attention has been given to the quantification of uncertainty and the changes in risk as a result of a navigation improvement. Even less effort has been made to explicitly provide summary measures of project performance in probabilistic terms. HarborSym has been developed in an attempt to address these issues.

HARBORSYM GENERAL DESIGN APPROACH

Data Driven

The Corps Institute for Water Resources (IWR) is developing a suite of systems tools for the evaluation of waterway improvements that incorporate uncertainty with respect to various aspects of the problem. This suite standardizes the way projects are evaluated across the country. The models must be flexible enough to be used in different studies, yet robust enough for appropriate analysis in each situation. To accomplish these goals this suite of tools is being developed as data driven models.

Data driven means that users can customize the model to their port by changing data rather than recoding the model. Users are able to develop and apply the model directly by entering data, without knowledge of computer programming or a proprietary simulation environment. This approach is possible because the quantities computed, such as transit times, delay times, and transportation costs, and also the method of computation, are common to all navigation investment evaluations.

Transparency / Glass Box

IWR has adopted a "glass-box" software design philosophy. The goal is to have an independently peer reviewed computational kernel and through the use of a graphical user interface (GUI) allow stakeholders to "see" the data, simulation and results.

HarborSym has four components: a Graphical Builder; a Graphical User Interface; the Computational Kernel; and a Results Viewer. A graphical user interface allows the input data as well as simulation results to be accessible to all reviewers and stakeholders. This should facilitate the public debate by placing the focus on the data and analysis, rather than which model or assumptions were used.

Graphical Builder

HarborSym simulates all pertinent navigation features, such as docks, moorings, turning basins, anchorages, existing channel features and proposed channel features. These features are all represented as nodes, connected by reaches, which together form the link-node network. This entire network is assembled using the Graphical Builder (Graphical User Interface, or GUI), through which the user can "point and click" to define the network and features.

Data Entry

As a data driven model, all calculations and assumptions are based upon data and information directly provided by the analyst. This includes vessel operating costs, commodity and fleet forecasts, and traffic rules. These data can be entered through the GUI or imported from Excel ™ spreadsheets.

Kernel and Results Viewer

One benefit of the model is its ability to take given data and determine when transit rules will be activated and calculate the accompanying cost in terms of vessel delay. The kernel simulates vessel movements along the reaches, from an entrance to one or more docks where cargo is loaded and unloaded, and then to an exit from the port. As vessel calls are processed, statistics are accumulated relating to transit and waiting times and commodity throughput. Detailed output is available from the results viewer to verify behavior and demonstrate project impacts.

TECHNICAL APPROACH

Overview of Usage

HarborSym represents a port as a tree-structured network of reaches and nodes. Reaches represent channels, while nodes are used to represent docks, anchorages, and turning areas. Each vessel visit to the port is termed a vessel call. Vessel movements within a vessel call are subject to transit restrictions based on channel width, depth, tide, and rules on passing other vessels for each reach, resulting in delays until the restriction is no longer present. As vessel calls are processed, statistics are accumulated relating to transit and waiting times and commodity throughput. Alternative channel dimensions and/or sets of rules can be tested to determine the impact on port traffic. As rule restrictions are relaxed due to proposed harbor improvements (such as channel widening), simulated delays are reduced. Using the model, analysts can estimate transportation cost savings, in the form of delays reduced, of each project alternative, allowing for a comparison of various proposed plans. Sufficient detailed output is available from the model to verify behavior and trace each vessel and its interaction with other vessels.

High Level Architecture

Four interacting modules make up the system. A Microsoft Access™ database stores descriptive data including definition of the reaches, nodes, vessel classes, and transit rules. A graphical user interface module, written in Microsoft Visual Basic™, reads and writes the database, allowing for easy construction of port networks, specification and modification of data, and viewing of results. A computational simulation kernel written in C++ using object-oriented techniques reads information from the database, carries out the Monte Carlo simulation, writes results back into the database, and generates additional detailed output that is used for the post-simulation visualization module, which also reads from the database. This modular structure allows for the choice of an appropriate programming language/tool to address different parts of the problem. The system is designed to run on computers using Microsoft Windows 2000 and above.

Model Features

Key features of the model are:

- User defined network describing the port;
- Historical vessel calls, with multiple commodities and docks;
- Ability to generate synthetic vessel calls based on fleet and commodity forecasts;
- User definition of vessel classes and commodity types;
- Tidal influence and internal calculation of tide height and current by reach;
- Transit analysis based on user-parameterized rules;
- Intra-harbor vessel movements;
- Use of turning areas and anchorages;
- Multiple entry and exit points;
- Within-Simulation visualization and animation.

Data Requirements

As a data-driven model, HarborSym requires the user to define almost all of the information that specifies the simulation conditions, with as little as possible "hard-coded" in the programming languages. Six general categories of information are required to be available in the database:

1. Parameters of the simulation run: start date, duration; number of iterations; wait time before rechecking rules; level of detail for results output;
2. Physical and descriptive characteristics of the port network: node location and type (dock, turning area, anchorage, port entry and exit points, intermediate nodes); definition of reaches (as node origin-destination pairs, with length, width, and depth); identification of tide and current stations used for predictions;
3. General Information on vessel and commodity classes (user-defined), commodity transfer rates at each dock as distributions, and specification of turning area usage associated with each dock;
4. Loaded and light vessel speeds in each reach by vessel class;
5. Transit rules for each reach, to govern allowable vessel movements based on vessel size, tide, current, draft, and rules on meeting, passing, and overtaking, including the conditions under which the rules apply;
6. Specification of vessel calls, either through historical data, or through parameters of a "vessel generator". This requires definition of the physical characteristics of the fleet calling at the port during the period of simulation;

In general, there is a rough correspondence between the data elements described above, the database structures that store these elements in the database, and the internal objects used in the C++ simulation kernel. That is, within the simulation, there are objects representing nodes, reaches, docks, vessels, vessel calls, routes, rules, tide stations, and commodity transfers, that are parameterized by information in the corresponding table in the database.

Key Concepts

Vessel Call The driving parameter for the Monte Carlo simulation is a vessel call at the port. A fleet of distinct vessels services a port, with any one vessel in the fleet calling one or more times during the period of simulation. Each such vessel call takes place at a known (or generated) date and time, is identified with a specific real (or synthetically generated) vessel, and includes one or more dock visits (intra-harbor movements are represented by multiple dock visits within a vessel call). Each dock visit consists of one or more commodity transfers. A commodity transfer is an import and/or export of a known quantity of a given commodity. Vessel calls are obtained either from historical data available at the port that is stored in the database, or are generated synthetically, as described later. Historical vessel calls are stored in the Access database as a set of related tables:

1. A table of unique vessels, with physical descriptions
2. A table of vessel calls, giving the arrival date, and the unique vessel making the call
3. A table of dock visits associated with each vessel call, identifying the specific dock that is visited (and, for the case of multiple dock visits, the order of the visit within the vessel call)
4. A table of commodity transfers, giving the import and export amounts of a given commodity type associated with the dock visit.

In this fashion, the historical vessel call information can be stored in a manner suitable for use within the simulation, as well as for detailed statistical analysis of port traffic.

Leg Each complete vessel call (voyage from entry to destination dock(s) through to exit) is considered to be composed of a set of "legs". A leg is a contiguous set of reaches between stopping points. It is assumed that a deep-draft vessel cannot stop except at docks or anchorages. The legs of the vessel call are thus the sets of reaches from the entrance to the first dock (leg 1), from the first dock to the second dock (leg 2), etc., and from the final dock to the exit (leg *n*). A vessel can only start moving within a leg when no transit rule restrictions are activated for any of the reaches in the leg. A key assumption of the simulation is that once a vessel is moving within a leg, it has priority over all other vessels that enter the leg subsequently. If there are activated rule restrictions (as described below), the vessel must wait at the entry, dock, or anchorage, until the rule restriction situation no longer exists, at which time the vessel can enter the leg.

Transit Rules The user assigns transit rules to reaches of the network, from a menu of pre-defined rules that are available within HarborSym. Rules are defined in terms of the type of rule (e.g. no vessel movement, no passing), applicable condition (day, night, any time), and vessel-specific parameters that characterize the rule's application, e.g. beam, draft, length. For example, a rule may state that two vessels may not pass at night in a given reach if their combined beam width exceeds 250 feet (76.2 meters). Other rules within the model relate to vessel movement under maximum current conditions or specific draft limitations. The rules currently implemented are based on procedures of pilots on the Sabine-Neches Waterway (Texas and Louisiana), and the Port of Tampa, (Florida), USA, and were developed by interviews with pilots in those ports. It is recognized that other ports may require additional rules if specific transit behavior cannot be expressed by parameterization of the pre-defined rules. In such cases, recoding the model will be necessary to incorporate the additional behavior, but once the new rules have been added they will be available for subsequent model applications.

Processing Logic

Events HarborSym is an event-driven Monte Carlo simulation model. Each vessel call is modeled individually, and its interactions with other vessels are taken into account. For each iteration, the vessel calls for that iteration are accumulated and placed in a priority queue based on arrival time. The basic events that are handled are:

1. Vessel Arrival at Port
2. Vessel Entry Into Reach
3. Vessel Exit From Reach
4. Vessel Arrival at Dock
5. Vessel Departure from Dock
6. Vessel Arrival at Turning Area
7. Vessel Departure From Turning Area
8. Vessel Arrival at Anchorage
9. Vessel Departure From Anchorage
10. Vessel Exit from Port
11. New Day
12. Start of Daylight
13. End of Daylight

Arrival Event When a vessel arrives at the port, the route to all of the docks in the vessel call is determined algorithmically. (Recall that the network is tree-structured, thus there is only one path between any two given points). This involves determining the turning areas that are used by the arriving vessel class at the dock (as stored in the database), so that the traversal of reaches in the leg properly includes the turning area. Thus, the path a vessel will traverse is determined at the time of vessel entry.

The vessel then attempts to move along the initial leg of the route. Vessel speeds are determined based on user input data; in each reach the user provides two speeds, one for vessels loaded with commodities (importing to the port), the other for vessels light with commodities (exporting from the port), for each vessel class. Upon arrival the condition of the vessel as either loaded or light is known, so the projected arrival time of the vessel in each reach of the leg is estimated based on the reach distances and the appropriate vessel transit speed stored in the database. Potential conflicts with other vessels that have previously entered the system are evaluated according to the user-defined set of rules for each reach, based on information maintained by the simulation as to the current and projected future state of each reach.

If a rule is activated the arriving vessel cannot proceed directly to its destination. It must instead either delay entry or proceed as far as possible to an available anchorage, waiting there until it can attempt to continue the journey. If the vessel can proceed, then a reach entry event is generated for the first reach of the leg, and the projected arrival and departure times of the vessel in all reaches of the leg are stored for each reach. In this fashion, at any given time, each reach is aware of the vessels that are currently in the reach, and those that are projected to be in the reach at times into the future. Also, during processing of the reach entry event, the reach exit time is determined, based on the vessel speed in the reach, and a reach exit event is generated.

If the vessel cannot enter the system due to rule restrictions in the leg, another vessel entry event is generated at some user-specified time increment in the future, when the entry is attempted again. This process is repeated until the vessel can enter the leg. The accumulated waiting time is stored, as well as statistics on the particular transit rules that create rule activations.

Dock Arrival As each event is added to the event queue and processed in turn, vessels move from reach to reach, eventually arriving at the dock that is the terminus of the leg. A dock entry event is then created. The time required for the vessel to exchange its cargo is calculated based upon the commodity type and quantity carried and the dock-commodity specific transfer rates. The commodity exchange rates are determined based upon a user specified distribution and are specific to each commodity type and dock pair. It is recognized that this is a simplification of the actual landside transfer process, but the emphasis of the model is not on the landside operations but on the channel improvements. After the cargo exchange calculations are completed, a dock exit event is generated. A dock exit event represents the start of a new leg of the vessel call; a set of rule testing in reaches, analogous to that which occurs with the arrival event, is carried out before it is determined that the vessel can proceed on the leg. As with the entry into the system, the vessel may need to delay departure and re-try at a later time to avoid rule violations, and similarly, the waiting time at the dock is recorded.

Anchorages A vessel that encounters rule conflicts that would prevent it from completely traversing a leg may be able to move partially along the leg, to an anchorage or mooring. If so, and if the vessel can use the anchorage (which may be impossible due to size constraints or the fact that the anchorage is filled by other vessels), then the vessel can proceed along the leg to the anchorage, where it will stay and attempt to depart periodically, until it can do so without causing rule conflicts in the remainder of the leg.

Total Time in System The determination of the total time a vessel spends within the system is the summation of time waiting at the dock, time transiting the reaches, time turning, time transferring cargo, and time delayed at docks or anchorages. An input requirement is the time the vessel arrives at the system but all other times result from simulation calculations.

Sources of Uncertainty

The major sources of uncertainty represented in the model depend upon whether the simulation is being run for historical data or for synthetic data. For historical vessel calls, the primary uncertainties are in time spent at the docks and turning areas, and in vessel arrival times. Arrival times are perturbed slightly (randomly within 24 hours) from historical arrival times, to give different arrival patterns. For synthetically generated vessel calls, there is additional uncertainty in:

1. Vessel Arrival Times and Sequences
2. Commodity Quantities
3. Vessel Physical Characteristics
4. Vessel Reach Speeds

Synthetic Vessel Call Generation

HarborSym can operate on either historical vessel call data or synthetically generated data. The historical vessel calls are used for calibration and testing of the model. For analysis purposes, the model must also be used to examine future conditions, where no historical data are available, requiring synthetic vessel calls. Pachakis and Kiremidjian (2003) describe a ship traffic generator for a simulation model of a container port, using historical data for parameterization. They discuss two basic types of generators used for simulations: 1) use of historical vessel data for ship characteristics, assumption of Poisson interarrivals, and assignment of vessels randomly; and 2) division of ship traffic into vessel classes, and use of distributions to assign cargo and ship characteristics. In both cases, the driving force is the vessel interarrivals.

Commodity-Driven Approach In contrast to the “vessel-driven” approaches, the driving force for generating vessel calls in HarborSym is user-specified commodity demands at each dock. This is combined with a user-specified fleet that can carry the required commodities. Thus, it is the need for commodities that determines the trips, as in the real world, rather than the trips that determine commodity quantities. This is more consistent with the economic forecasting approaches used by the Corps, in which commodity demands are forecasted, as well as assumptions about the future fleet.

Simplifying Assumptions The vessel generator works on a single user-defined period, and assumes no seasonality. Each vessel carries a single commodity, for either import or export, and services a single dock. Each vessel is loaded to a user-defined maximum capacity. It is recognized that these assumptions will need to be relaxed and the generator improved for future efforts, in particular for container ports where both import and export take place simultaneously.

Required Data The vessel generator requires the following types of data:

1. Commodity List – what commodities are imported/exported;

2. Quantity demands (import/export) for the year, by dock and commodity;
3. Vessel Class Description – describing the physical characteristics of vessels in each class (either as a representative vessel, or as a range of parameters);
4. Fleet Specification - a vessel class, an allocation priority for this fleet, the number of vessels in the class, and the number of possible calls at the port by each vessel in a year (or the interarrival statistic);
5. Constraints - which vessel classes are allowable at specific docks, and which vessel classes can carry specific commodities.

Algorithm The vessel generation algorithm attempts to satisfy the commodity demands at each dock by loading vessels from the available fleet. Each fleet specification, as described above, provides a set of vessels that can be loaded (subject to the constraints) and each such vessel can make multiple trips. Thus, the goal is to satisfy the demand by allocating trips to vessels with the highest allocation priority (presumed to be the most efficient).

At the beginning of the process, the synthetic fleet is generated, based on the fleet specification. The program uses object-oriented approaches. The vessel allocator object keeps track of all the vessels in the fleet. Each vessel is aware of how many trips it can make, how much it can carry, how many trips it has been allocated, and the precise nature of each allocated trip. The commodity forecast object requests that the vessel allocator satisfy the commodity demands. The vessel allocator examines all of the vessels in the fleet, in priority order, asking each one if it can service the demand. Each vessel, based on its vessel class, determines if it can call at the dock, handle the requested commodity, and has trips available. If a trip is available, then the vessel generator determines the vessel call-specific initial draft and commodity carried from the distributions associated with the vessel class and commodity type. Trip availability is determined with a gamma distribution based on the user provided vessel interarrival time.

Demands for commodity types are fulfilled alternatively at each dock. In each cycle, a single vessel trip is assigned to each dock requesting the commodity, in turn. The number of available trips for the allocated vessel is decremented. The loop continues through all commodity types and then starts again at the first type demanded, until it is impossible to assign any more demand to a vessel (either because the available fleet has been exhausted, or all commodity demands that could be satisfied subject to the constraints have been satisfied).

Assignment of Trip Start Time At the end of the generation process, each vessel that has allocated trips is examined, to randomize the start time of the first trip. This is calculated by taking the total time of all trips (assuming a zero start time), and determining how much time remains in the year. For example, if the total time for a vessel is 360 days in trips, then 5 days are available within which to randomize the start time. This is carried out, based on a uniform distribution between 0 and the "time available", and this quantity is added to the start time of each trip. Note that this is a uniform shift, rather than distributing the slack time across all available trips, and thus maintains the previously randomized interarrival time.

At the end of the process, information is available on the simulated commodity flows, fleet capacity utilization, and complete information on the vessel calls, including vessel characteristics, arrival time, cargo type and quantity, and destination dock(s). HarborSym processes this information to simulate the vessel trip through the system.

GRAPHICAL USER INTERFACE

Overview and Guiding Principles

The HarborSym Graphical User Interface (GUI) serves as a window to HarborSym's object model, simulation routine and complex data relationships. The GUI provides model users with a highly organized set of forms, menus, drawing tools and organizational aids. These tools allow users to navigate the vast array of data contained in the model in an organized fashion while presenting complex data relationships in an understandable and transparent manner.

The overriding design principles of the HarborSym GUI are to provide mechanisms that are intuitive enough to enable users to quickly learn model navigation basics, understand data requirements and easily execute the underlying simulation routines. The key interface requirements of the GUI were the ability to make the model transparent to the user, mask the complexity of the underlying relational database and simulation process, and provide visualization of information to help the user interpret data and calibrate the model. Incorporation of these key features while keeping with the overriding design principles has created a powerful and robust interface that is intuitive, extensible and easy to use.

Interface Architecture

The GUI is focused upon a single form for viewing, editing, navigating, and visualizing model information. This form is called the Study Explorer form, and it consists of three resizable panes that work in concert to manage the model information. Specifically, these three panes are the Navigation Pane, Graphics Pane, and Data Pane. When a data element is selected in any pane, the data in the other panes coordinate to display appropriate related information. Figure 1 below displays the Study Explorer form and associated panes.

Navigation Pane

The Navigation Pane categorizes and organizes all of the data elements inputted into the model and enables users to locate particular data elements in an efficient, simple and organized manner. The Navigation Pane utilizes a tree structure for organizing data in a hierarchical manner. The order in which items appear in the Navigation Pane are purposefully aligned with the order in which the model expects information to be entered. This essentially creates a task list for the user which hides the models complexity while allowing for transparency of information requirements.

Graphics Pane

The Graphics Pane is a visual instrument that quickly and intuitively permits the user to generate and manipulate the traffic lanes (reaches) and points where vessels may load, unload, or make turns in the port (ex. docks, turning basins, bars, entry/exit locations). The power of the Graphics Pane is that it provides a visual representation of the port structures while masking the complexity of the information that composes the network within the port. The Graphics Pane provides the user with a drawing tool to create and manage physical characteristics of the port. An image (such as a map) of the actual port can be used as the background of the Graphics Pane to assist the user in creating and locating the port structures in a familiar environment. Mouse clicks, mouse hovers, popup menu items, and the ability to customize the look and feel of the Graphics Pane add significantly to its ease of use.

Data Pane

The Data Pane provides the user with a very simple and familiar method of data entry that provides for data integrity checking before updating information into the underlying relational data model. The pane contains grids, or spreadsheets, of information that have been designed individually for each specific set of data elements displayed. The grids contains drop-down lists of allowable selections for the data elements, color coded cells to identify required entries, tabs for displaying multiple grids of related information, and when necessary, an editing matrix where the user only has to fill in missing information.

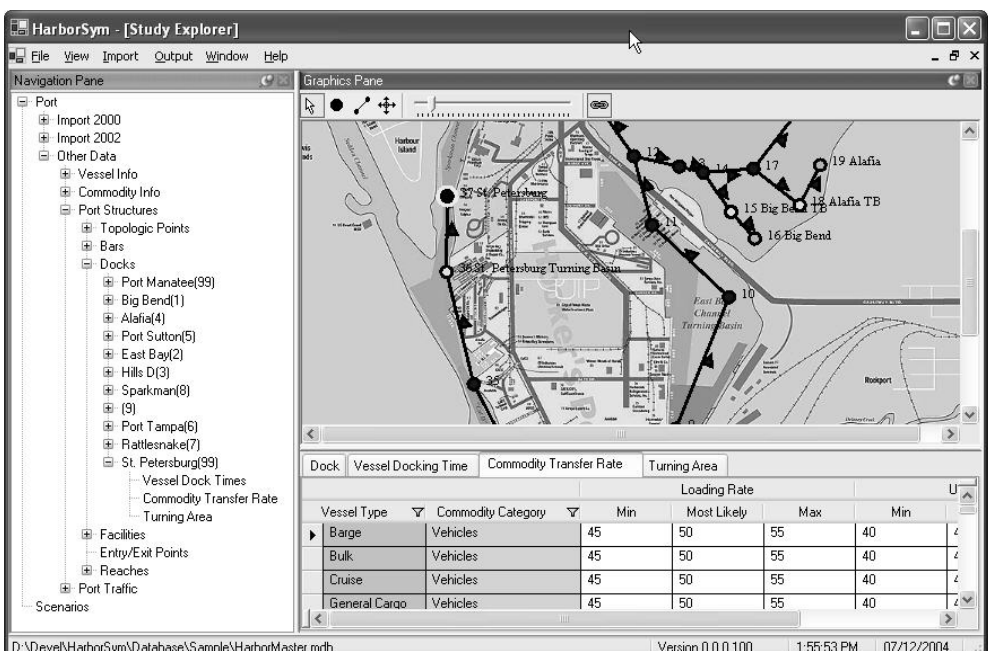

Figure 1 – HarborSym GUI

The HarborSym GUI allows users to interact with model information in an intuitive and flexible manner through the Study Explorer. Additional features have also been incorporated to automate common or complex tasks. Importing vessel calls from external sources, management of the underlying databases and windows for displaying reports and graphs have all been incorporated. These additional features provide a complete set of tools to users of the model.

Developing Alternative Projects

The GUI enables the user to easily compare results from simulating different conditions in the study area. Within a study, multiple projects using the same base data set can be created by cloning an existing project. These projects are stored within multiple Access™ databases but organized and presented to the user as a single study. Alternative channel dimensions, different application of rules, and variation in commodity transfer rates can be modeled in HarborSym. After cloning, users can make modifications in the data pane to reflect the proposed harbor improvements while preserving the original set of conditions for comparison.

OUTPUTS

Model outputs for a complex simulation model such as HarborSym must serve a variety of purposes: 1) synthesize the results in a form usable for analysis; 2) allow for detailed debugging and validation of the model, and examination of the internal behaviors of all model components; 3) assist in explaining the behavior of the model to others. To this end, a variety of forms of output are provided:

- An ASCII summary file of model behavior;
- Results stored in an Access database, to allow for reports and comparison across runs (available through the HarborSym GUI);
- Detailed ASCII files that track every event, vessel movement, commodity transfer, every rule imposition, and other events for each iteration of a simulation;
- Within-simulation visualization, that provides animation and user interactivity to allow for examination of the movement of each vessel, display of tide for each tidal station and reach, and commodity transfers during the simulation. An important feature is the ability to click on a vessel and get information about the status of the vessel, on demand.

The model is structured to allow for easy analysis of the impacts of different possible improvements within a harbor. Each proposed project is processed individually, the same statistics are gathered for each run, and then compared. Mean, standard deviation, maximum, and minimum of critical parameters of model behavior are collected. Among the parameters collected and stored are: number of vessels entering the system; number of vessels exiting the system; average time in system, total cost (hours resident in port times cost); average vessel cost; statistics on vessel time waiting at the entry and docks; time spent in turning areas and anchorages/moorings; time spent docking, undocking, and loading/unloading; total commodity quantities transferred; and commodity throughput at the port (commodity quantity/total vessel time). Another important output is the display of the rule conflicts that take place during a simulation, by reach and rule type. This allows the user to identify the specific reaches and rules that are triggering delays, which can be helpful in identifying potential areas of improvement within the harbor.

FUTURE EXTENSIONS

HarborSym development is still under way, including the creation of a post-processing animation that allows for a more complex and visually pleasing examination of a previously-run simulation, based on use of the detailed ASCII output files and a custom animation program. Improvements that will relax several of the current assumptions built into the vessel generator module are planned, including building the capability of generating vessels that carry multiple commodities and make intra-harbor movements. Creating a more robust vessel generator will allow HarborSym to analyze channel-deepening improvements in addition to its current functionality. Other proposed enhancements include the relaxation of the requirement of a tree-structured network, allowing for alternative route choices, adaptive route choice when an alternative route will have less delay, and more sophisticated treatment of vessel speed with respect to draft and commodity loading.

APPLICATION EXAMPLE

Study Background

The Sabine-Neches Waterway is located in southeastern Texas, along the Gulf Coast of the United States. This system includes the ports of Beaumont, Port Arthur, and Port Neches, stretching 45 miles from the deep draft entrance point at the Gulf to the northernmost dock. In addition to the ocean-going traffic entering the system from the Gulf, shallow draft barges travel along the Gulf

Intercoastal Waterway that intersects the main navigation channel. In 2000 the combined Sabine-Neches Waterway was the fourth largest U.S. port in tonnage volume, moving 97 million tons (88 million metric tons) of cargo. Primary commodities moved in or out of the port include crude petroleum, petroleum products and chemicals. The one-year HarborSym simulation of this port included 1,860 deep draft vessel movements. According to data provided by the Corps' Waterborne Commerce Statistics Center (WCSC), 133 separate docks within the Sabine-Neches system received vessel calls in 2000. For simplicity in modeling, these docks were grouped by geographic proximity into eleven virtual or aggregate docks, which were each represented by a node in the network. These aggregate docks captured between 90-95 percent of the actual cargo moved and vessel calls in 2000. The system's ten turning basins were each represented by "facility nodes", which could also be used as temporary anchorages and sidings to allow passing in narrow channels. Existing and proposed channel features were represented by nodes, such as where the existing entrance channel narrows from 800 feet to 500 feet wide. In total, the system was composed of 48 nodes connected with 47 different reaches.

Rules

Current conditions in the port include several extremely narrow reaches with many bends. In order to ensure safe passage within these sections of the channel, the Sabine Pilots Association, in conjunction with the U.S. Coast Guard, have developed several transit rules to restrict vessel movements. These rules can be grouped into three general categories:

- Daylight only sailing restrictions, applied based on deadweight tonnage, length, and breadth.
- No meeting at night based on draft limitations.
- No meeting either night or day based on deadweight tonnage, length, breadth, or draft.

Rules were applied to individual reaches, with the specific parameters of application set in data by the user. For example, a no meeting rule was applied in the main channel reaches for any vessels with combined beam widths exceeding one-half the channel width.

Data

The model was populated using data on vessels that actually called at the waterway during the 2000 calendar year. Transit data were obtained from information collected by the Sabine Pilots Association and detailed data collected by WCSC. WCSC provided details on vessel characteristics, commodity types and quantities, system entrance point, and destination dock. The Pilots' logs traced vessels as they moved through the system, providing necessary information on when the vessels arrived in the system, time spent delayed at the Gulf entrance, transit times within reaches, time at dock, and turning basin usage. Between the data in these two sources the 2000 vessel movements were reconstructed. Shallow draft movements were not included in the simulations. This decision was made based upon the methodology used to develop deep draft vessel transit speeds. The Pilots recorded sailing times at several different locations throughout the waterway; speeds were calculated using the transit times and distances between these locations. Because historical data were used, delays that occurred when a deep draft vessel was forced to slow sail behind a barge were already built into the speed estimates. To include the barge movements in the simulation would have served to double count the delays they inflict. Through interviews with the Pilots Association and vessel operators it was determined that these delays would not be influenced by any of the proposed channel improvements.

Taking the form of a vessel call list, the WCSC and Pilots' data was supplied to the model, which routed all the vessels through the system in accordance with the user defined transit rules. The vessel call list included an arrival time at the system for each vessel call, as well as its destination dock, and general ship characteristics (LOA, beam, draft, and DWT). This information, supplemented with reach-specific rules, vessel speeds, cargo transfer rates at each dock, and turning basin usage, allowed the model to estimate each vessels journey through the system. A vessel arrived at the system based on an actual historical arrival record but the model calculated all other events that occurred between its arrival and departure from the system.

Simplifications between actual and modeled vessel calls include the commodities carried and dock calls. The Sabine application of HarborSym was completed using an earlier version of the model that limited commodities per ship to one and allowed only a single dock visit per vessel trip. The nature of commodities moved in this port made such simplifications reasonable. Multiple dock movements occurred only infrequently and most vessels were moving only one type of commodity.

Figure 2 below shows a screen capture from the within simulation animation of HarborSym while processing Sabine Neches data. The system is represented here as the link node network with several vessels transiting the reaches. One vessel is identified as waiting to enter the system. This animation was helpful during the calibration phase by making it easier to identify delayed vessels and pinpoint the cause of their delay.

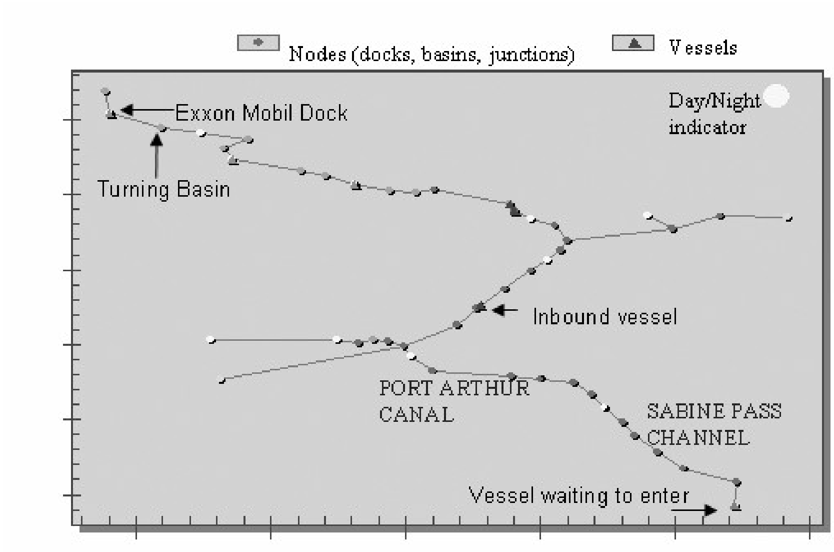

Figure 2. HarborSym Screen Capture of Sabine-Neches Waterway

Calibration

Simulating historical data with existing rules aided in model calibration. By comparing the simulation results to recorded statistics it was possible to identify any problems with the model's representation of the system. Historical average vessel time in system, time at dock, and time delayed at the bar were calculated using the Pilots records. A comparison of the historical and simulation outputs for these variables is included in Table 1. As can be expected, the total time from the simulation is less than historical due to the perfect foresight of the model on the vessel leg clearance times.

Table 1. Comparison of Historical and Model Outputs

	Historical Average	Simulation Average
Total Time in System	78.07[1]	71.83
Time at Dock	53.26	49.10
Time Delayed at Bar	6.20	3.90

[1] Time in hours

Interviews with the Sabine Pilots Association provided insight as to potential sources for the discrepancies between historical and simulation output values. Some activities conducted within the port are not included in the model, such as bunkering and ballasting. In Sabine these activities are not always conducted at the dock and the time required to complete them is not recorded by any agency; this time is not accounted for in the model. Inaccuracies in the cargo exchange rates may be partially responsible for a lower simulation average time at dock. Commodity transfer rates were initially provided by port operators but early testing using these rates resulted in even shorter vessel time at dock. This was partially due to vessel lay time at the dock; in addition to the time spent exchanging cargo, vessels conduct other activities at the dock, including voluntary delays. Instead of using the operator supplied rates, alternative values were developed using the pilots records. This was an imprecise method given the model's use of aggregate docks. Fog delays were not included in the model, which may contribute to the additional wait time at the bar; under fog conditions in the waterway, vessels are forced to wait extended periods at the Gulf entrance point.

The Sabine Pilots Association was engaged in the calibration process, including confirming the model application of transit rules. The Pilots revealed the fact that often their rules are not enforced absolutely; rather each individual pilot is empowered to use his or her professional judgment in marginal situations. As the model does enforce rules absolutely, this discrepancy was identified as a source of potential discrepancy between model results and actual operating practices.

Economic Analysis

Economic analyses in the Corps of Engineers require a comparison of the without project conditions to all of the alternative with project conditions over a 50-year period of analysis. The without project condition includes existing channel conditions and any anticipated channel improvements that will be implemented in absence of the particular Federal investment being investigated. Additionally, the without project condition includes future vessel traffic and commodity volume forecast without the project. With-project conditions describe the system as it will exist if the Federal Government implements the study plan. Such an analysis is easily completed with a data driven model. To simulate the without project conditions the reaches were defined in the model as they are currently maintained. Existing rules and their parameters of applications were supplied to the model, so that when the shipment list was simulated it provided a reasonable representation of the current reality. Future conditions were defined in the data to represent proposed channel improvements. These improvements typically allow the relaxation of transit rules in the affected reach. Like the without project future condition, the with project includes forecasts of future vessel traffic and commodity volumes.

Channel widening benefits were evaluated for the channel to Port Arthur including the Port Arthur Canal and the Sabine Pass Channel (identified in Figure 2). In particular, the investigation considered the possibility of widening these reaches from an existing 500-foot width to 700 feet. As part of the with-project condition, the channel depth was changed in the simulation from an existing depth of 40 feet to 50 feet to reflect a concurrent study considering the benefits of channel deepening.

Simulations showed the proposed improvements decreased the delay times predicted for vessels in the system. This results from the relaxation of transit rules under the with-project condition compared to the without project. Under the existing conditions passing in the main channel is restricted to vessels with a combined beam width less than one half the channel width. Thus, two vessels with combined beam widths exceeding 250 feet (76.2 m) cannot meet. With the proposed improvements in place, the restriction is placed on vessels with combined beam widths exceeding 350 feet (106.8 m). This allows vessel to pass that otherwise would have been delayed. The application of other rules under the with-project conditions was established based on interviews with the Pilots. Specifically in the Port Arthur Canal reaches, the Pilots indicated that a 700-foot (213.4 m) channel would allow them to relax the rules restricting vessels meeting based on either draft or deadweight tonnage. Under current conditions meetings are prohibited if either vessel has a draft of 30 feet (9.1 m) or greater, or deadweight tonnage equal to or exceeding 48,000. With the larger, 700-foot channel, the pilots would completely remove this restriction.

Results

The estimated transit time savings resulting from these different improvements are displayed below. Table 2 compares the results from 100 iteration simulations of the without project condition (existing channel conditions and expected channel deepening) and the most comprehensive widening alternative. This alternative proposed widening two main reaches and deepening all the turning basins. Transit times in each iteration differ slightly, as a result of the variation in individual vessel times. For each time category reported in the table, the average, minimum, maximum, and standard deviation are shown to reflect this variability.

TABLE 2. Results Distributions From Two Simulations

	Without Project				SPC & PAC with TB[1]			
	Av.	Std. Dev.	Min.	Max.	Av.	Std. Dev	Min.	Max.
Time in System	71.2[2]	36.5	10	290.9	68.8	35.5	10	276.9
Time Waiting	10.2	12.9	0	158	7.9	10.4	0	118.3
Wait Entry	3.9	5.9	0	65	2.5	4.3	0	19
Wait at Dock	4.9	9.3	0	143	2.7	5.5	0	112.1
Wait at FN[3]	1.4	5.2	0	139.5	2.7	6.6	0	113

[1] SPC is Sabine Pass Channel; PAC is Port Arthur Canal; TB is Turning Basin

[2] Time in hours

[3] FN is "facility node", either turning area or anchorage

Table 3 shows the estimated times for the without project condition and each of the proposed improvements. This table displays the average times resulting from 100 iterations. Without the in-simulation animation, HarborSym calculates 100 iterations of one year of data in 30-45 minutes.

TABLE 3. Average Vessel Times Under Proposed Channel Improvements

	W/O Project Condition	Port Arthur Canal	Sabine Pass Channel	SPC & PAC[1]	SPC & PAC & Turning Basins
Avg Ves Time in System	71.20[2]	70.10	70.20	69.30	68.80
Avg Ves Time Waiting	10.20	9.20	9.20	8.30	7.90
Avg Ves Time Wait Entry	3.90	3.30	2.80	2.50	2.50
Avg Ves Time Wait Dock	4.90	4.60	5.00	4.60	2.70
Avg Ves Time Waiting FN[3]	1.40	1.20	1.50	1.30	2.70

[1] SPC is "Sabine Pass Channel", PAC is "Port Arthur Canal".
[2] Time in hours.
[3] FN is "facility node"; either turning area or anchorage.

Potential benefits from these proposed improvements resulted from decreased transportation time. These times and time savings can be converted into monetary values using Corps standard vessel operating costs for different vessel types. The incremental benefits from each proposed alternative were calculated using these costs and the decreased total time in system provided by HarborSym. Although all aspects of the study are not yet completed, interim results are displayed in Table 3 for illustration purposes.

Table 4. Transportation Cost and Incremental Benefits

	Total Annual Transportation Cost ($1000)	Annual Incremental Benefit ($1000)
Without Project	$110,635.90	
With Sabine Pass Channel	$109,199.60	$1,436.30
With SPC & PAC	$107,730.70	$1,388.90
With SPC, PAC, & TB	$107,442.10	$288.60

Figures shown in 2002 dollars, based on 100 iteration simulations
SPC is "Sabine Pass Channel", PAC is "Port Arthur Canal

CONCLUSION

Given the complexity of the problem of port simulation, it is important to be clear about the specific purposes and limitations of a model. All models require necessary compromises between a faithful and complete system representation, data requirements, and development cost and time. The goal is to have a useful model that captures the behavior important to the necessary analyses. HarborSym has proven to be a worthwhile tool for economic analysis of the large-scale harbor infrastructure improvements that are undertaken by the Corps of Engineers for U.S. ports. HarborSym is a planning-level model, rather than a detailed operational model, but it does attempt to capture many characteristics of vessel behavior. The model focus is on congestion issues in the waterway, not on land-side operations, thus issues of dock capacity, loading and unloading times, crane availability, etc., which are treated in much greater detail in other port simulation models, are handled in an approximate fashion. At present, the model is applied primarily for issues of channel widening and improvements to anchorages. Channel deepening presents many additional issues related to induced fleet change, requiring analyses of a broader scope than the single-port emphasis of HarborSym. As such, HarborSym properly fits within a larger framework of navigation analysis models that are currently being developed by the US Army Corps of Engineers to examine the full scope of deep-draft and inland navigation issues.

The data-driven architecture allows HarborSym to be used for many ports and improvement alternatives, without significant recoding. It is, however, a highly data-intensive model, and data development for this type of model can be complex and limited by information availability. Data at different ports comes in a variety of formats, from different sources with varying degrees of quality, consistency, and coverage, and with often incompatible formats. HarborSym provides a uniform relational data structure that is useful for describing vessel movements at ports, but getting data into this format from the variety of information that is available requires additional effort, which can be significant. Inconsistencies and gaps in the data are often revealed during this process.

The advantage of a model such as HarborSym is in its data-driven character, transparency, ease of use and lower application development cost, as compared to port-specific, custom-programmed, discrete event simulations. It is recognized that each port is different, with different operational rules, but there appears to be considerable overlap in the nature of the rules. As HarborSym is applied at other ports, it is expected that it will become more general through the incorporation of additional rules as needed.

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The NETS research program is developing a series of practical tools and techniques that can be used by Corps navigation planners across the country to develop consistent, accurate, useful and comparable information regarding the likely impact of proposed changes to navigation infrastructure or systems.

The centerpiece of these efforts will be a suite of simulation models. This suite will include:

- A model for forecasting international and domestic traffic flows and how they may be affected by project improvements.
- A regional traffic routing model that will identify the annual quantities of commodities coming from various origin points and the routes used to satisfy forecasted demand at each destination.
- A microscopic event model that will generate routes for individual shipments from commodity origin to destination in order to evaluate non-structural and reliability measures.

As these models and other tools are finalized they will be available on the NETS web site:

http://www.corpsnets.us/toolbox.cfm

The NETS bookshelf contains the NETS body of knowledge in the form of final reports, models, and policy guidance. Documents are posted as they become available and can be accessed here:

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