Planning Level Simulation Modeling of Channel Improvements

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Abstract

Waterborne infrastructure investments carried out by the U.S. Army Corps of Engineers (Corps) in the United States require economic justification demonstrated through benefit-cost analysis. To identify and analyze congestion within a coastal port, analysts must understand the large number of vessel calls, the influences of nature (tide or current) and the complicated transit rules imposed throughout the harbor. Accurately predicting and analyzing impacts of random vessel interactions across space and time requires a detailed simulation model. HarborSym is a Corps-developed, non-proprietary, Monte Carlo Simulation Model designed to assist in planning and economic analyses of maritime infrastructure improvements. HarborSym is geographically portable and data-driven, allowing the model to be applied at different ports by changing the input data. Within the HarborSym framework, a set of database, forecasting, statistical analysis and visualization tools supports the analyst in comparing differing improvement alternatives and fleet forecasts. HarborSym has been applied to the port of Tampa Harbor, Florida.

Introduction

As part of its overall mission within the U.S. Federal Government, the Corps assists in the development and improvement of waterborne components within American ports. The improvements of interest relate primarily to waterway enhancements, such as channel widening and deepening projects, and the provision of moorings and turning basins. Prior to investment of Federal funding in such improvements, detailed analyses of the associated economic impacts must be conducted, indicating the project costs are outweighed by resulting benefits. Theoretically, these economic impacts can be estimated by calculating the user's willingness-to-pay (WTP) for waterway enhancements. For navigation improvements, WTP is estimated as the reduction in transportation costs attributable to waterborne improvements (US Water Resources Council, 1983). In practice this is the result of shorter harbor dwell times, loading ships more efficiently (deeper) and allowing the use of larger ships within the harbor. This measure assumes the beneficiaries would be willing to pay at least the amount they save in transportation cost.

Determining the potential transportation cost savings that may result from specific channel modifications is a complicated process relying on complex interactions of vessels within the entire harbor system, both at the time of analysis and into the future. Such estimates may be highly uncertain, including vessel arrival frequency and times to the system, commodity quantities moved and sailing times, all of which must be explicitly incorporated into an overall systems analysis. The HarborSym Model was developed to assist with such analyses in a single transparent, reviewable, and reproducible tool that is readily adaptable to many of the ports dotting the U.S. coastline or elsewhere in the world.

Model overview

HarborSym is a planning-level Monte Carlo Simulation Model of vessels moving within the channels of a port. HarborSym represents a port as a user-defined, tree-structured network of reaches and nodes. Reaches represent channels, while nodes are used to represent docks, anchorages and turning areas. Users assign characteristics specific to individual channel segments, such as length, width, depth, sailing speeds, and transit restrictions, to corresponding reaches in the model. Characteristics of docks or turning areas, including physical dimensions, commodity transfer rates or turning times, are assigned to nodes. This structure allows analysts to parameterize the modeled system to reflect a variety of harbor configurations without modifying the underlying computer code.

Modeling vessel traffic calling at the port involves a series of vessel visits over time, each termed a vessel call. HarborSym attempts to replicate transit restrictions faced by vessels calling at the port. Transit rules, which can be imposed based on the physical dimensions of the channels or vessels, forces of nature (tide or current) or interactions with other ships utilizing the waterway segment, are defined by analysts for each reach. Vessels are aware of any restrictions occurring throughout each portion of their journey and are only permitted to begin sailing (entering the port or leaving a dock) when all reaches are cleared from conflict.

As vessel calls are processed, HarborSym accumulates statistics relating to transit times, waiting times and commodity throughput. Simulating existing channel and dock configurations with an historical vessel calls list can enable users to identify where congestion exists within the system and which rules cause vessel delays. Sufficient detailed output is available from the model to verify behavior and trace each vessel and its interaction with other vessels. Comparison of simulations made with existing conditions and current fleets to those made with alternative channel dimensions, sets of transit restrictions or vessel call lists, provides the necessary information to quantify potential transportation cost differentials. An overview of the model is provided in Moser (2004).

Data requirements

The portability of HarborSym is achieved by requiring 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. Seven general categories of information are required to be available in the databases that make up HarborSym input:

1. Parameters of the simulation run—start date, duration, number of iterations, wait time before rechecking rules, level of 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 triangular 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 "synthetic vessel call generator." This requires definition of the physical characteristics of the fleet calling at the port during the period of simulation;
7. Dock specific commodity forecasts used by the synthetic vessel call generator.

HarborSym model behavior

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 queue based on arrival time. When a vessel arrives at the port, the route to all of the docks in the vessel call is determined. This route is comprised of discrete legs (contiguous sets of reaches, from the entry to the dock, from a dock to another dock, and from the final dock to the exit). The vessel attempts to move along the initial leg of the route. Potential conflicts with other vessels that have previously entered the system are evaluated according to the user-defined set of rules for each reach within the current leg, based on information maintained by the simulation as to the current and projected future state of each reach.

If a rule activation occurs, then the arriving vessel must either delay entry or proceed as far as possible to an available anchorage, waiting there until it can attempt to continue the journey. Vessels move from reach to reach, eventually arriving at the dock that is the terminus of the leg. After the cargo exchange calculations are completed and the time the vessel spends at the dock has been determined, the vessel attempts to exit the dock, starting a new leg of the vessel call; rules for moving to the next destination (another dock or an exit of the harbor) are checked in a similar manner to the rule checking on arrival, 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.

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. 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.

Commodity driven synthetic vessel call list generator

Often, as fleets and vessel calls grow, congestion within a harbor system will increase and the anticipated delays will grow. Defining vessel calling patterns at the study port throughout the recent past can be done using a compilation of existing data sources. Determining the pattern with which vessels will call the port in future years, due to technological advancements in ship design, shifting commodity demands or changes in the physical layout of the harbor, requires more complex forecasting. To address this complication, HarborSym contains a module that can be utilized to generate synthetic lists of vessels and their forecasted loading in future years based on user defined statistics.

The user provides specification of:

1. Commodity forecasts (import/export) at each dock.
2. Dock depth limitations at each dock, for the project alternative being considered.
3. Description of the available fleet, by vessel class.
4. Logical constraints describing commodities that can be carried by each vessel class and vessel classes that can be serviced at each dock.
5. Parameters, defined at the vessel class/commodity level, for determination of how individual calls and commodity transfers are generated. This includes statistical information relating to physical characteristics of a vessel class and user specification to control the loading process (i.e., how much of vessel capacity is loaded, whether the loading is export-only, import-only or both import/export, etc.).

The call list generator then generates a synthetic fleet (based on statistics on the physical characteristics of each vessel class) and attempts to load vessels to satisfy the user input commodity forecasts at the dock, creating a vessel call (a movement, at a specific time of an individual vessel to a specific dock, with associated commodity transfers). All of this information is stored in a generated vessel call data, which can then be run through HarborSym. The synthetic call list generator requires explicit statements of fleet characteristics and commodity forecasts. The process followed reveals any inconsistencies in these two separate inputs, such as insufficient fleet to carry the forecasted quantity or excess fleet assumptions. A detailed overview of the approach is provided by Hofseth (2006).

Model application – Tampa harbor

Overview

The Corps and the Tampa Bay Port Authority recently applied HarborSym to evaluate economic impacts from a suite of channel enhancements in Tampa Harbor, Florida. This coastal navigation system, on the Gulf of Mexico midway along the west coast of Florida, serves both U.S. domestic and international cargo movements. The operations of this port are complicated by the dual presence of an emerging cruise ship industry and an established bulk import/export community moving petroleum products, chemicals, and crude. Large cruise ships and tankers carrying liquid petroleum gas (LPG) are given priority access to the channel segments, which force all other ship types to yield while they utilize the harbor. Investigations into harbor improvements were initiated after reports of extensive delays faced by large, piloted vessels resulting from these competing demands on the waterway.

HarborSym was selected as the economic analysis tool to evaluate channel modifications due to the complex interactions of vessels moving through the system. The congestion issues faced within Tampa Harbor were largely attributable to the multiple vessel transit rules and to tidal related depth restrictions. These elements are timing dependent and difficult to predict; for example, only when a priority vessel (cruise ship or LPG tanker) and another ship desire simultaneous use of the channel will a conflict arise. Likewise, draft-related transit problems only occur when heavily laden vessels desire to sail at low tide. Calculating such random interactions in flat spreadsheet models, as has historically been done for similar studies, would have ignored timing complexities and behavioral uncertainties within the Tampa system.

Tampa network

Analyzing congestion based delays in Tampa Harbor first required representing the waterway within the HarborSym framework. A series of 44 reaches, representing some 80 miles of channel within the port, were used to define the segments as a tree-structure network in HarborSym. The determination of reach start and endpoints was based on changes in existing or proposed physical channel dimensions (depth or width), changes in defined ship operations, transit rule restrictions or geographic changes, such as branch channels from the main shipping artery. Individual docks were aggregated to a set of eleven representative node docks in HarborSym based on close physical proximity. Characteristics of these docks were itemized in the model, including depth, capacity, vessel types and commodities serviced, commodity transfer rates and docking times. Additional elements were defined as nodes, including the ocean entrance point, eight turning basins and one main channel anchorage. The network is shown in Figure 1.

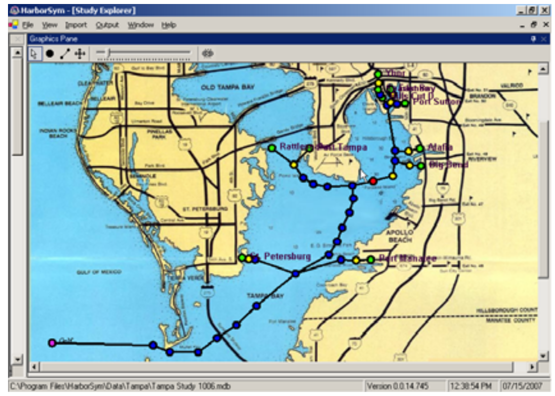

Figure 1. Tampa Bay HarborSym Network

Tampa transit rules

While correctly developing a representative link-node network was key to configuring the physical layout of the harbor, selecting and parameterizing appropriate transit rules was necessary to represent vessel behavior in the system. From the existing list of defined rules contained within HarborSym, appropriate single and multiple vessel transit rules were applied to each of the 44 reaches within the network. Single vessel transit rules limit individual vessels within a reach, independent of any other traffic. Typically, these rules include sailing restrictions based on the physical dimensions of the channel or the vessel and environmentally based restrictions, such as tide or current. Multiple vessel rules, also prevalent throughout the Tampa system, are triggered dependent on the coincidence of two or more vessels desiring simultaneous use of a single reach. These restrictions are generally based on combined physical dimensions of the vessels, either in absolute values or in relation to the channel, or by type of vessel or commodity carried, as is the case with priority vessel restrictions. Multiple vessel rules also describe one-way sailing conditions, by completely restricting vessels meeting in the channel. The parameters of application for all rules are assigned by users, allowing individual specifications relevant to the particular harbor being studied. A passing restriction, for example, may limit meeting of vessels if their combined beam width exceeds some fraction of the channel width. The behavior of this restriction is built into the model but the user defines the appropriate channel width necessary to make the rule applicable to the study area.

Through discussions with the Tampa Bay Pilots Association and other pertinent local entities, the extensive traffic restrictions imposed throughout Tampa were defined using the existing rule types in HarborSym. The most critical multiple vessel rules defined the priority vessel movement behavior for cruise ships and LPG tankers. The single vessel rules of greatest influence were environmentally triggered, restricting movement to high tide and low current conditions. While not exhaustive, Table 1 provides a list of some rules assigned in the Tampa sample study and the user-defined parameters of application.

Table 1. Tampa harbor reach-rule restrictions

Rule description	**Application parameters**
Multiple vessel rules	
Combined beam width restriction	No meeting if beams exceed 42% of channel width
Restricted movement with priority vessels	No overtaking, passing or meeting
Single vessel rules	
Restricted movement by vessel LOA, beam or capacity	LOA (800’ maximum)
Draft limit	43’ maximum draft
Single vessel environmental rules	
Maximum draft plus tidal allowance	40’ + tide max draft (Area 1)
Maximum draft plus tidal allowance	33’ + tide max draft (Area 2)

Tampa vessel call list

The vessel call data used to simulate the existing conditions in Tampa Harbor was based on year 2004 trips. This data was compiled from Federal and local governmental entities and placed into a spreadsheet format directly readable by HarborSym. Approximately 2,700 vessel calls were included in the 2004 dataset, comprised of 10 different vessel types. Ship types were user defined to reflect the Tampa call list, based on the unique shape of the vessel, type of commodity carried or type of propulsion system. Table 2 shows selected ship type and commodity quantities carried in the 2004 dataset. The vessel call list includes information on the vessel journey through the system, specific physical parameters and vessel operating costs. Required information includes vessel arrival time at the ocean entrance point, commodity carried, destination dock, vessel length, beam, draft and tons per inch immersion. Additional data elements, such as arrival or departure time at the dock, are calculated by the model and thus not required as user inputs.

Table 2. Tampa harbor base condition vessel calls and tonnage by vessel class (selected classes)

Vessel class	Import tons	Export tons	Vessel calls
Large tanker	8657625.54	5744.14	290
Ocean tank large	8358189.84	0.00	397
Ocean dry all	4422056.36	4024677.60	298
Large bulk	2852159.14	1333596.52	95
Medium bulk	2244840.38	4792327.96	351
Medium tanker	1894981.05	78623.15	132
Large LPG	1414704.91	0.00	54
Container large	629782.98	157461.40	37
Large Gen Cargo	572725.37	358388.40	68
Small gen cargo	123995.95	626564.78	265
Protocol 2	30371.80	28882.40	138
Protocol 1	7760.20	7309.90	98

Tampa Harbor HarborSym application

Applying this logic and the described input parameters, HarborSym was utilized to generate total transportation costs for Tampa Harbor. By comparing transportation costs under the existing conditions and the proposed alternatives, benefits in terms of reduced delay times, were identified. The proposed improvements included widening several reaches along the main artery channel. It was predicted that, if implemented, these enhancements will allow greater flexibility in vessel movements, including potential areas for passing protocol vessels (cruise ships and LPG tankers with priority of movement). Modifying the physical dimensions under these improvements and the transit rule restrictions in the HarborSym reaches, it was possible to simulate the changes in vessel interactions under the different scenarios. Table 3 outlines the transit times and transportation costs for the existing channel conditions and one of several channel enhancements considered, both using the 2004 vessel call list, showing the quantification of the potential benefits from these modifications in terms of decreased delays and operating costs.

Table 3. Example Transit times and delay costs for existing condition and improvement, 2004 vessel calls (10 iterations)

	Existing channel	Proposed enhancement
Average Vessel Time in System (hours)	30.1	29.7
Average Vessel Delay Time (hours)	3.2	2.7
Total Transportation Costs ($)	74,898,000	73,745,000

Multiple iterations of each simulation are processed to generate long run stability among the variable parameters within the model. In each iteration, specific values are selected from within the user defined distributions for the uncertain data elements, such as commodity transfer rates, time to dock vessels, or duration of turning maneuvers. By incorporating distributions instead of providing a fixed value allows better representation of the unpredictability of actual harbor operations. Figure 2 shows the variability of average time vessels spent in the Tampa system in each of 10 iterations for the existing condition and an alternative.

Fleet forecasts for future and with-project conditions

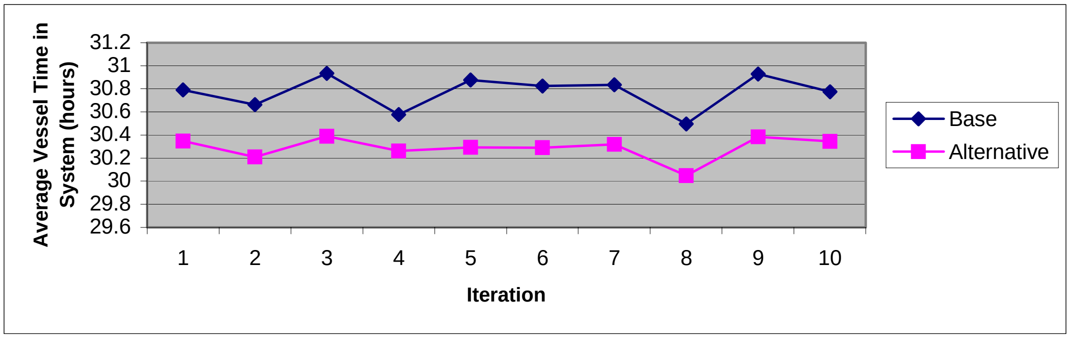

Figure 2. Comparison of base condition and alternative

Often, as fleets and vessel calls grow, congestion within a harbor system will increase and the anticipated delays will grow. Defining vessel calling patterns at the study port throughout the recent past can be done using a compilation of existing data sources. Determining the pattern with which vessels will call the port in future years, due to technological advancements in ship design, shifting commodity demands or changes in the physical layout of the harbor, requires more complex forecasting. In the Tampa application, forecasts were done manually out to the year 2060 at 10 year increments, based on local knowledge and estimates of increased port traffic, particularly with regard to tanker traffic, allowing for testing of projected future vessel calls against each of the alternatives.

Visualization and statistical analysis

The database structures of HarborSym have allowed for the development of a set of tools for visualization and statistical analysis of simulation behavior and results. In addition to identifying data anomalies, the results of this analysis can assist users in better understanding the traffic patterns at a particular port, pinpoint portions of the fleet impacted by transit restrictions, and provide a basis for the development of future call lists.

The HarborSym Animation Module (Rogers 2005, Hofseth 2006) provides the user with the capability to perform post-processing animation of simulation runs, as shown in Figure 3, aiding in visualization of potential problems.

Figures 4, 5, 6, 7 and 8 are a representative portfolio of plots obtained from the HarborSym Analyzer Module. The Analyzer Module allows the user to identify a set of HarborSym databases and easily obtain plots and reports. Figure 4 is a results comparison analysis, showing the average vessel time waiting, by vessel class, for the Tampa Harbor analysis discussed above, showing the reduction with the improvement alternative (bottom horizontal bars). This graphic is useful in determining which class of vessels face the greatest delays and which have the greatest potential to benefit from channel improvements. In Tampa Harbor, large general cargo vessels encountered the greatest wait times, while large LPG tankers, which maintain priority status, suffered nearly no delays.

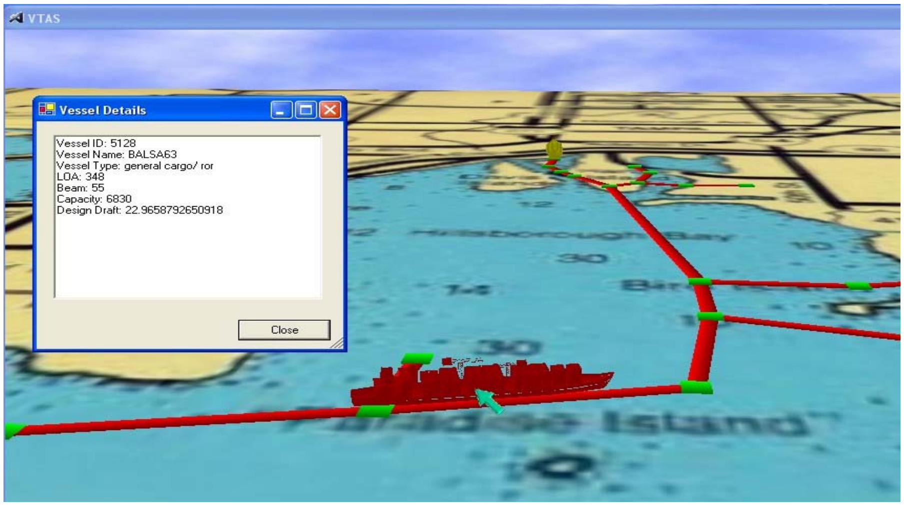

Figure 3. Post-processing animation

Figure 5 shows a display of the import tonnage carried annually by each vessel class. Figure 6 shows the distribution of vessel calls, similarly organized by vessel class. Figure 7 is a pie chart showing the relative import tonnage by dock, and Figure 8 shows the total port commodity flows by week of the year.

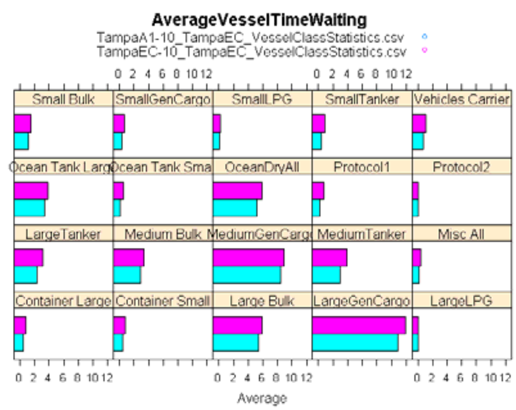

Figure 4. Results visualization

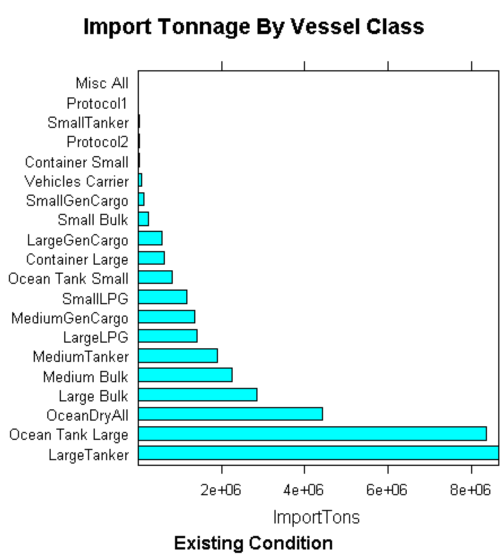

Figure 5. Import tonnage by vessel class

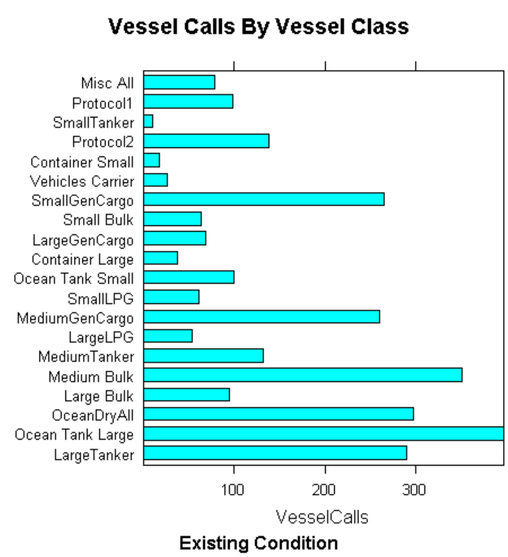

Figure 6. Distribution of vessel calls by vessel class

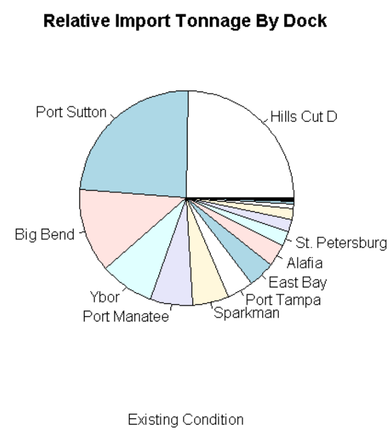

Figure 7. Relative import tonnage by dock

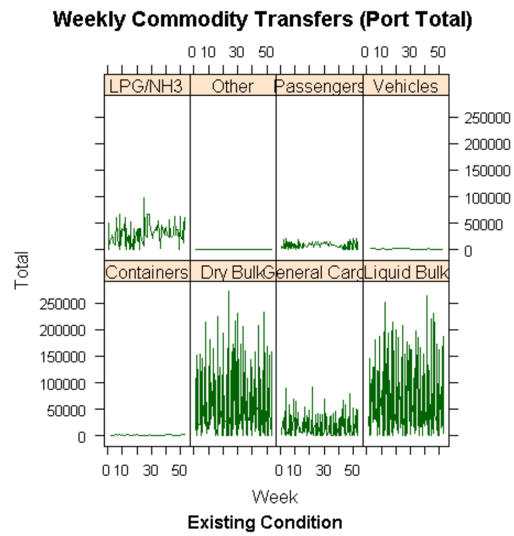

Figure 8. Weekly commodity transfers (port total)

Future directions

Integration of the various modules of HarborSym (deepening, synthetic vessel call generation, data analysis and visualization) into a single package is currently being carried out.

One promising aspect of the HarborSym Model will be the ability to estimate and forecast emissions from fleet operations at the harbor. With the detailed data on vessel movements forecasted over time, the analyst will be able to estimate emissions by time period, vessel class, commodity carried, dock visited and other perspectives of interest. Also, how emissions change given prospective waterway improvements will also be estimated. This information will allow decision makers to consider using quantitative estimates to predict how harbor activities affect the air quality of the region.

Conclusions and summary

HarborSym has proven to be a worthwhile tool for economic analysis of the large-scale harbor infrastructure improvements that are undertaken by the Corps for U.S. ports. The visualization tools for data analysis, results viewing and animation of the simulation assist the analyst to calibrate the model and communicate the results. These tools also allow significant transparency of the analysis appropriate for public investment decisions. The data-driven architecture allows HarborSym to be used for many ports and improvement alternatives, without significant recoding. This allows the Corps to give consistent analytical treatment to harbors across the country.

Currently, only the widening version of HaborSym is available for download http://www.pmcl.com/harborsym. The widening model and post-processing animation tool HSAM are available as beta test versions (available for distribution, but still in testing), with associated documentation. An alpha version of HarborSym which includes deepening analysis, the commodity-driven synthetic call generator and the statistical analysis tool will be available in early 2008 at the same site.

Acknowledgements

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