Navigation System Simulation (NaSS) Design Document

U.S. Army Corps of Engineers
Institute for Water Resources

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by

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For

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Section 1
Introduction

The Navigation Economics Technologies (NETS) research program is an initiative managed by the U.S. Army Corps of Engineers (USACE) Institute for Water Resources (IWR) to marshal the latest research findings to improve navigation economic analysis techniques. A portion of this effort is devoted to improvements to analysis models directed primarily at inland navigation. The current work had as its original objective the development of a design document for a next-generation navigation simulation model that would serve as a successor to previously-developed USACE models such as WAM, Tow Cost/Equilibrium, ORNIM, Essence, NavSym, and LockSym. These models had different frameworks, orientations, emphases, advantages and drawbacks. A unified model that incorporated the development experience gained in these models was seen as the logical next step. Such a model would be flexible and adaptable to a wide variety of inland navigation problems addressed by the USACE. This proposed model was termed the NaSS (Navigation System Simulation) model.

A project development team (PDT) consisting of members experienced in inland navigation model development and usage was formed, consisting of: Mark Lisney, IWR (Project Manager); Virgil L. Langdon, Jr. (LRH); Keith Hofseth, IWR (NETS Technical Director); Professor Paul Schonfeld, University of Maryland; Dr. Shiaau-Lir Wang, University of Maryland; Cory Rogers (CDM); and Richard Males (RMM Technical Services, Inc.). Through review of capabilities of existing models, joint meetings, interchange of documents and conference calls, the PDT developed the framework and approach to the NaSS model, in the process revising the design to that of a suite of models dealing with various aspects of the problem, rather than a single simulation model. This proposal for an evolving modeling suite comes in recognition of the wide variety of problems that must be addressed by USACE personnel when examining inland navigation projects. The evolutionary approach was deemed best due to the difficulties of attempting to build a single overarching model that is large in scope and data-hungry, and a general preference for modular solutions that can be developed and tested independently and used at the appropriate scale of problem, which can then be used in concert as necessary. The central focus, however, remains the design of a discrete-event multi-lock simulation model that generates and moves vessels through a network of waterways and locks, with incorporation of scheduled and unscheduled outages and associated shipper response.

The purpose of this document is to define the overall framework for NaSS, describe the individual models/tools that are components of the NaSS suite and discuss key technical issues that are important to the understanding of proposed NaSS models. This document is not an introductory presentation on lock or waterway modeling, rather it is designed to present and consolidate the findings and discussions of the PDT; as such, the intended audience is expected to be familiar with prior waterway and lock modeling work within the USACE. This document was prepared by Richard Males, based on extensive interaction with the PDT. Portions of this document were written by or extracted/revised from documents and presentations prepared by Mark Lisney, Shiaau-Lir Wang and Paul Schonfeld.

Section 2
Executive Summary
2.1 Prior Work

The design of the suite, and the models within the suite, draws heavily upon experience with previously developed USACE models and applications, including the basin-level models WAM, ORNIM, and NavSym; and single lock model representations WAM, LCLM and LockSym. This existing set of available models has been used with success in research and USACE planning studies to date. The investment optimization model SIMOPT developed by the University of Maryland to explore genetic algorithm (GA) optimization in conjunction with waterway simulation has also been an informing example. The existing body of knowledge and experience is quite solid with respect to:

- Understanding of the lockage process, and how to model detailed accounting of vessel times within a lockage under a variety of lock operating policies and given chamber interference characteristics;
- Techniques for structuring object-oriented data-driven navigation simulation models with graphical user interfaces (GUI);
- Methods for integrating optimization and simulation modeling.

However, a review of the available models suggested that a number of important features could be handled in an improved fashion. In particular, improvements are desired in the areas of:

- Insuring that system effects in a waterway are properly accounted for;
- Incorporating reliability estimates of locks and lock components directly into the simulation analysis;
- Adding a representation of shipper short term responses to delays and outages in the modeling;
- Adding a representation of shipper long-term response (mode choice) to increased congestion and decreased reliability of the waterway (i.e., increase in transportation rate and time);
- Adding the ability to simulate several new queue service policies and traffic management schemes;
- Making the analysis more driven by commodity flows (consistent with NETS analysis approaches);
- Incorporating equipment constraints;
- Simulating barge pick-up, drop-off and re-fleeting practices.

Some of these features are available, to a greater or lesser degree, in existing or current model development efforts, but the integration of all of them in a basin-level simulation model has yet to be accomplished. Thus, much of the design effort has been oriented towards exploring these issues and determining how they can best be implemented.

2.2 General Model Characteristics

The intent of the NaSS suite of models is to provide data-driven, transparent, non-proprietary, peer-reviewed and USACE-certified models for application by USACE engineers and planners in inland navigation studies and research. Each model is expected to have a modern GUI for ease of use and data development.

Data-driven models are those in which particular situations are defined, not in the programming code, but by the data that is provided for the model. In this fashion, a single model can serve a wide variety of problems and locations. Transparency means that the inner workings of the model are clearly shown through documentation, visualization and animation, and detailed outputs. The models are to be non-proprietary—they should not require the purchase of commercial software to be run. Models are expected to have passed internal and external review processes and the forthcoming USACE planning model certification processes.

Model architecture will be based on the use of a GUI, data stored in a database, and computational kernels that read and write the database, with the GUI acting as the "control center." At present, each model is anticipated to be separate, but eventually the expectation is that they will be joined in a common user interface. The models will be designed for the Wintel (MS Windows™) platform. Programming languages and approaches will be object-oriented, using the Microsoft .NET™ framework. It is anticipated that the primary programming languages will be C++ and C#, and the database will be Microsoft Access™.

A "spiral development approach" is proposed for each model and for the NaSS suite as a whole. Models are expected to evolve over time, from initial proof of concept, to prototype, to beta testing using a real field study as a test bed, to a fielded "Version 1.0" model with documentation and training, and to subsequent versions as user needs dictate. This spiral development approach has been used successfully by IWR tool developers in the past.

2.3 Elements of the NaSS Model Suite

The NaSS Model Suite is proposed to consist of the models/analysis tools shown in Table 1.

A corollary tool that is currently under development, the Inland Navigation Animation Module (INAM), a visualization package for LPMS data, can also be considered as part of the NaSS suite, and is expected to evolve along with the visualization component of the System Network Model.

TABLE 1
ELEMENTS OF NaSS MODEL SUITE

Model/Tool	*Description/Purpose*
Simulation and/or Optimization Models	
System Network Model	Monte Carlo simulation model of generation and movement of tows and other vessels through the locks and reaches of a system-wide waterway network (or a portion thereof).
Investment Optimization	Develop optimal investment plans at waterway and lock level given budget constraints, using a GA optimization in conjunction with the System Network simulation as the evaluation model.
Auxiliary Tools	
Data Analyzer	Extract, summarize, display (report and graphics) information from LPMS, WCSC, OMNI.
Results Analyzer	Extract, summarize, display (report and graphics) outputs from NaSS models.
Data Pre-processor	Pre-process data from LPMS, WCSC, OMNI for use with System Network Model.

Although the term "model" is used in the descriptions above and throughout this document, the design of each model may also contain sub-models to perform specific well-defined functions (such as converting commodity demand to trips, or transforming optimization data from the Investment Optimization Model for use as input to the System Network model).

In addition, it is proposed that development of proof of concept models be initiated to explore technologies and issues related to:

- Use of agent-based modeling techniques to examine shipper responses;
- More detailed modeling of how tow configurations are actually assembled and change through a trip on a waterway, as barges are picked up and dropped off.

Each model in the NaSS suite should be usable in a stand-alone fashion, and each model is expected to evolve over time with new features and capabilities. However, much of the design intent is that the models be used in concert with one another within a planning study. The Investment Optimization model is intimately tied to the System Network Model, using results from runs of the System Network Model as the basis for optimizing investments. Some of the possible inter-relationships are shown in Figure 1.

Initially, the interactions and communications between the models will be accomplished through interchange of data (through files or use of common databases). As the specific needs for interaction/communication become clearer over time, a closer binding of interacting models through programmatic means is anticipated.

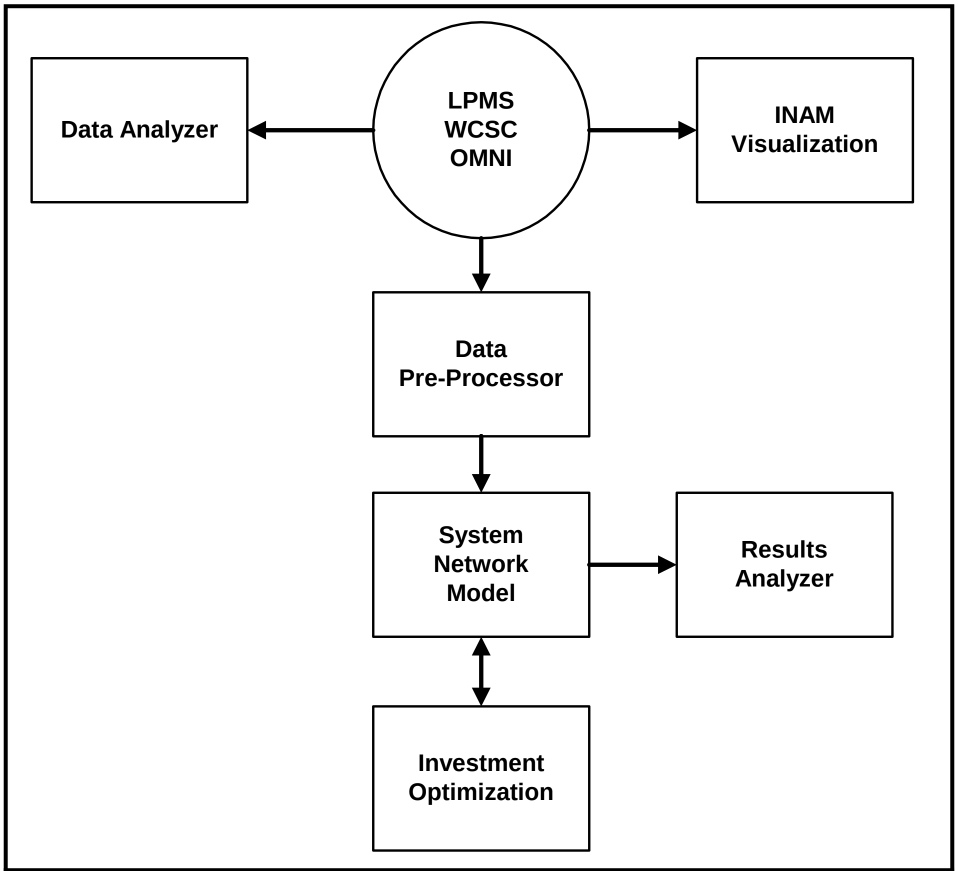


FIGURE 1
COMPONENTS OF THE NaSS SUITE

2.4 Model Features

2.4.1 System Network Model

The System Network Model is a discrete event life cycle Monte Carlo simulation model that will generate shipments between ports based on commodity movements, move vessels through a waterway system of reaches and locks, take into account possible re-fleeting occurring at designated locations and incorporate shipper response to unscheduled outages. It is designed to handle a multi-reach, multi-lock segment of a waterway that should logically be analyzed as a unit or for which system effects at a lock of interest are important. It will incorporate complex representations of both lock reliability and lockage behavior or, at user option, use a simple representation of a lock with limited service time distributions and lockage policies, such that, within the system, some locks may be represented in a complex (detailed) fashion and others with a simplified representation, at the discretion of the user. Lock chambers will be represented as sets of components, with associated state-based reliabilities and failure modes. The model will be suitable for examination of alternative repair and rehabilitation policies, as well as for analysis of alternative lockage policies and traffic management systems, and provision of features such as mooring cells. The model will be capable of representing a single lock if desired.

Key features of this model will include:

- Commodity-driven analysis, in which the specification of commodity demands between ports in the network is the primary driving force for vessel (tow) movements;
- Responsiveness of shipments to outages and delays (shipper response);
- Incorporation of probabilistic reliability of lock chambers;
- Conservation of equipment;
- Complex or simple lock representation.

The System Network Model is designed to answer questions such as:

- What is the overall system performance of a waterway network under different operating, demand load and reliability conditions?
- What delays and costs are expected based on lock reliability issues?
- How effective are alternative lockage policies at reducing delays and delay costs?
- What is the impact of a traffic management system?
- What combinations of lockage policies are preferable under various circumstances?
- What is the lock and shipper response to unplanned outages?
- What delays and diversions are anticipated under different maintenance, rehab and operational scenarios?
- What is the probabilistic nature of lock chamber downtime and closure, based on component-level reliability (for use with the System Network Model)?
- How does any single lock improvement project affect delays at other locks?

2.4.2 Investment Optimization Model

The approach taken by the University of Maryland-developed SIMOPT model, in which optimization through a GA is combined with running of a simulation model of a waterway, is proposed for the Investment Optimization Model. The SIMOPT model demonstrated that this combined optimization/simulation approach is feasible. Under the SIMOPT approach, GA is used to specify promising combinations of investments. Each such combination of investments is then run through the simulation model to determine how the system performs under that particular investment plan. The results of the simulation model for each set of investments proposed by the GA are then returned to the GA for evaluation, with the GA developing a new set of investments for further testing by simulation. (The GA approach develops the new set of investments through an analogy to chromosomal division and mutation, hence the name). The iterative process between the GA and simulation model ends when no (or only small) further improvement in the performance of investment sets is found in successive iterations. The approach is shown schematically in Figure 2.

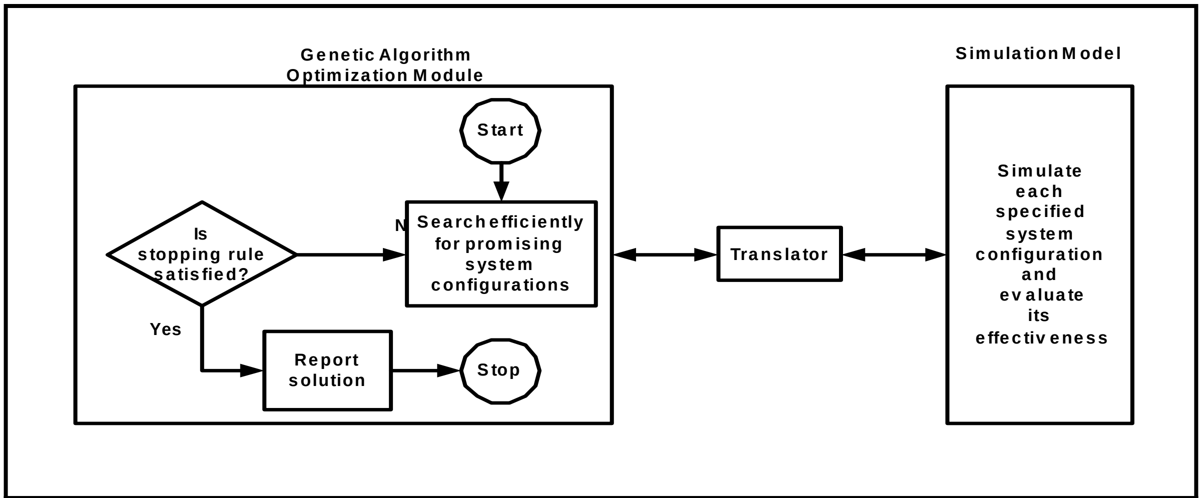


FIGURE 2
GENETIC ALGORITHM INVESTMENT OPTIMIZATION

As shown in Figure 2, the investment optimization model is actually a combination of three elements:

- The GA optimization
- A simulation model (e.g., a system network model)
- A "translator" that translates GA outputs into more detailed simulation model inputs reflecting changes after projects are implemented

The investment optimization model is designed to answer such questions as:

- What is the best use of available funds in terms of improvements at a single lock?
- What is the proper scheduling and choice of investment decisions on a waterway system?
- How do existing USACE budgeting choices compare with "optimal choices?"

It should be noted that investment, in this context, consists of Operations and Maintenance (O&M) investments that can change project reliability, and project investments, which can change both reliability and project capacity (e.g., additional lock chamber, larger lock chamber). The optimization will need to consider the possibility of both types of investments.

2.5 Graphical User Interface

"Transparency" has been noted as important to the philosophy of model design, allowing users and analysts to easily explore (and hopefully understand) the workings of the model and the underlying data. Key to such transparency is a solid, intuitive user interface. The models discussed herein contain a great deal of data, with complex hierarchical data inter-relationships.

It is a difficult but essential task to render this information in a form that clarifies these interrelationships, and assists the user in creating, viewing and editing the needed data.

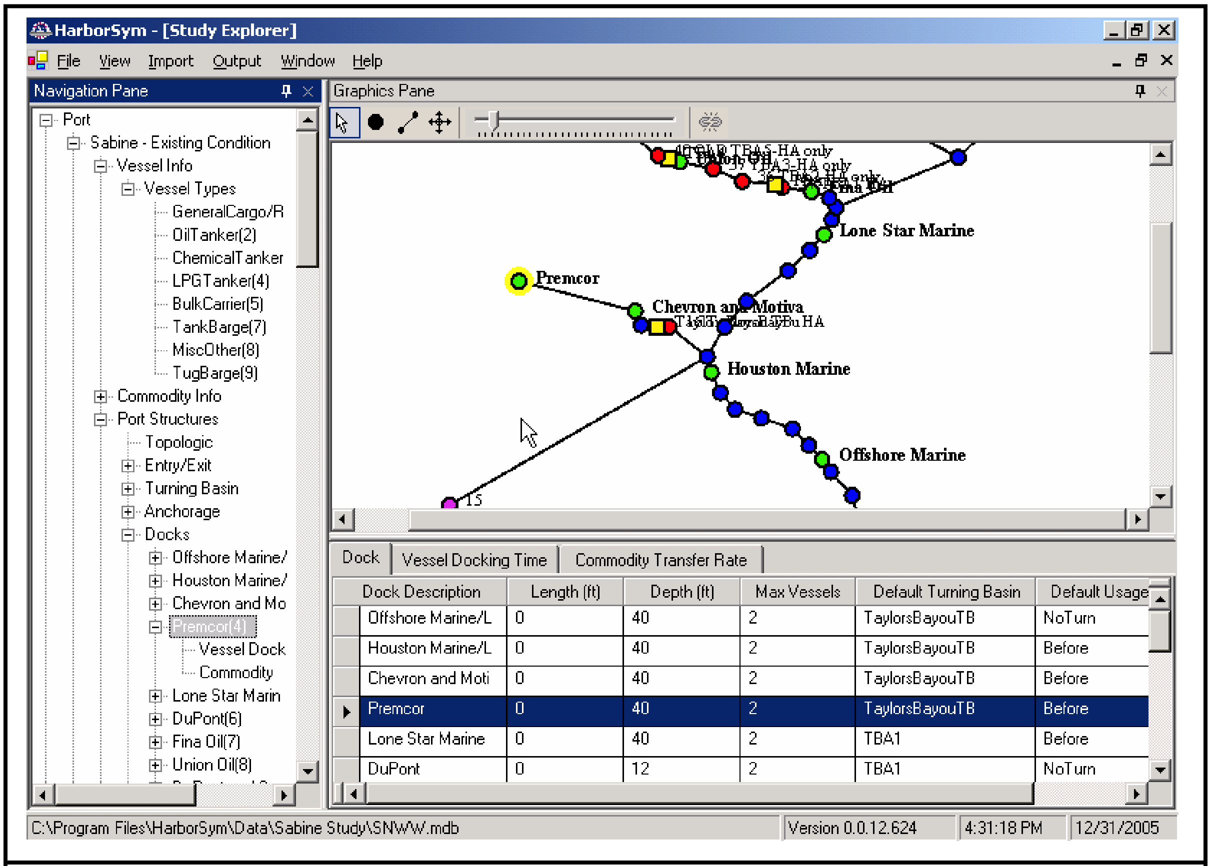
A "three-pane" GUI has been used successfully in other models in this regard (HarborSym, LockSym), and is proposed as the basis for the GUI to be used for most of the models within the NaSS suite, in particular the System Network Model. The three pane approach contains the following basic elements:

1. A top-level menu that allows standard selection of features;
2. A tree-structured "explorer" pane that shows the hierarchical connections between the elements of the system, and that allows for rapid access to each element and to certain operations on that element;
3. A graphics pane, that presents an appropriate graphical view of the element that is being created, edited or examined, allowing for graphical user interaction (e.g., drawing a network, locating nodes, selecting reaches, etc.);
4. A data grid pane, that provides a spreadsheet-like interface to data about the selected element.

Information presented in each of the three panes is coordinated automatically—selection of an element in the explorer pane will result in the appropriate graphical view of that element in the graphics pane and display of the associated data in the data grid pane.

A screen capture of the three-pane GUI architecture, as implemented in HarborSym, is shown in Figure 3. As noted above, GUI implementation for the various models of the NaSS suite is expected to be similar, adapted to the specific needs of each particular model/application.

Also consistent with prior usage in other models, additional graphical user interaction is expected to be available to users during simulation or "post-processing" animation, allowing user selection of options for display, and the ability to highlight an element, for example a tow, and obtain detailed information about that tow (origin, destination, commodities carried, route, etc.).



Dock Description	Length (ft)	Depth (ft)	Max Vessels	Default Turning Basin	Default Usage
Offshore Marine/L	0	40	2	TaylorsBayouTB	NoTurn
Houston Marine/L	0	40	2	TaylorsBayouTB	Before
Chevron and Moti	0	40	2	TaylorsBayouTB	Before
Premcor	0	40	2	TaylorsBayouTB	Before
Lone Star Marine	0	40	2	TBA1	Before
DuPont	0	12	2	TBA1	NoTurn

FIGURE 3
EXAMPLE 3-PANE GUI (FROM HARBORSYM)

2.6 NaSS as a Component of NETS

The NaSS models are designed to be used within the overall framework of other NETS models. The NETS initiative recognizes the complex interactions that exist between commodity demands, shippers, consumers and transporters. This dynamic interaction results in modal choices by shippers based (in part) on cost and congestion of the transport links, which in turn, has an impact on the quantity shipped. This is a spatially-distributed problem (transportation exists because of supply and demand in different locations), and the resultant distribution of actual shipments at any given moment is, in economic terms, a spatial equilibrium. NETS has defined a rough 3-tier modeling hierarchy in which, at the top tier, a global forecasting model of supply and demand results in large scale trade patterns, which then define regional commodity supply and demand patterns, which are in turn routed in tier 2 (via a regional routing model) through a multi-modal transportation network that defines the specific traffic expected on a particular waterway. Analysis of congestion and other issues on the waterway given the knowledge of the traffic is then the domain of tier 3 microscopic system models that examine specific vessel movements and facility behavior on waterways, at locks and in harbors. This is shown schematically in Figure 4, (taken from Southworth, 2005).

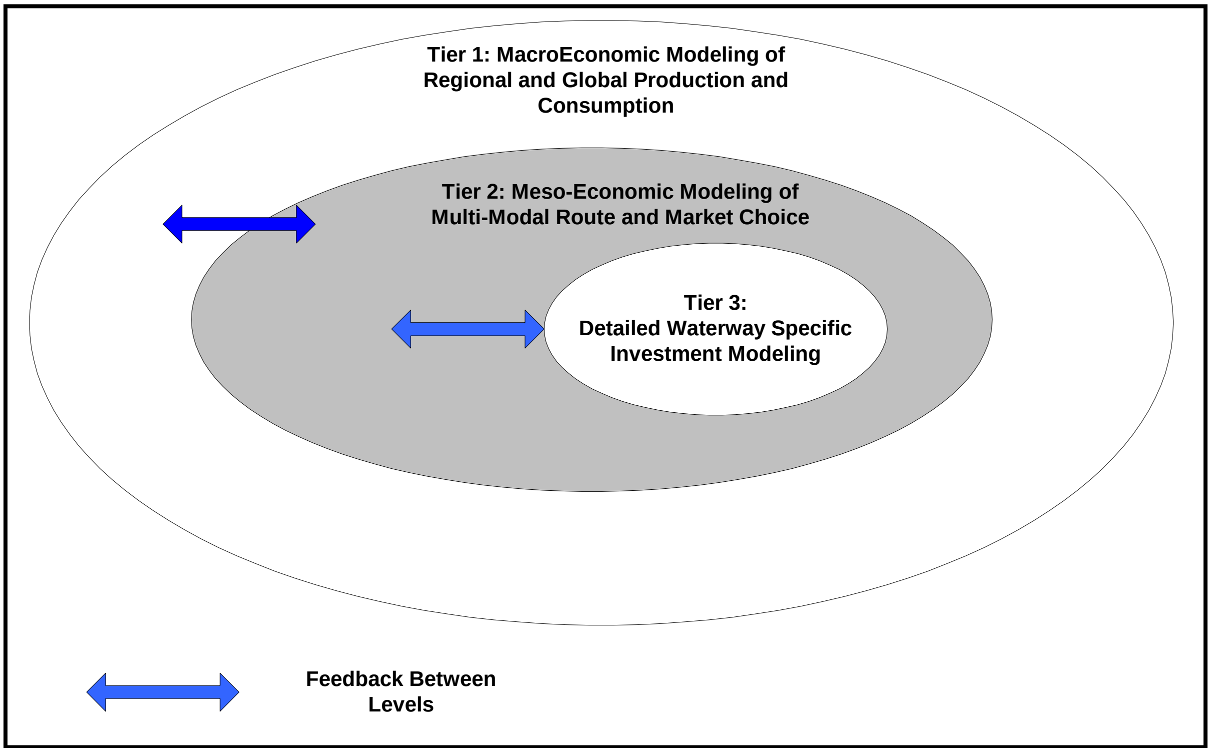


FIGURE 4
NETS 3-TIER MODELING HIERARCHY (AFTER SOUTHWORTH, 2005)

The NaSS models are oriented quite specifically towards analysis of vessel movements on the reaches and locks of the inland waterway system, and on the behavior of individual locks and/or lock systems themselves—the System Network Model falls within the NETS category of microscopic system models. The System Network Model anticipates input from other NETS tools that define general spatially-distributed commodity demands and forecasts. The System Network Model is not a spatial equilibrium model. Rather, the proposed usage is interactive with the regional routing models, which are spatial equilibrium models that incorporate shipper response to congestion. That is, a proposed set of commodity demands will be run through the System Network Model to obtain congestion information (much as WAM is now used to provide quantity-delay curves to ORNIM). This congestion information can then be used with the NETS regional routing models, in an iterative fashion, to obtain a balanced set of commodity demands and transit costs. [The situation is actually somewhat more complex, in that shipper response to congestion is to be incorporated within the System Network Model, as well as within the Regional Routing Model.] These proposed usage relationships are shown schematically in Figure 5. A good deal of further exploration will be needed to establish and define these interactions and feedbacks in more detail, in particular as the System Network Model is a life cycle model, in which congestion is expected to change over time, with corresponding changes in shipment patterns, while the higher level models are static or annual models.

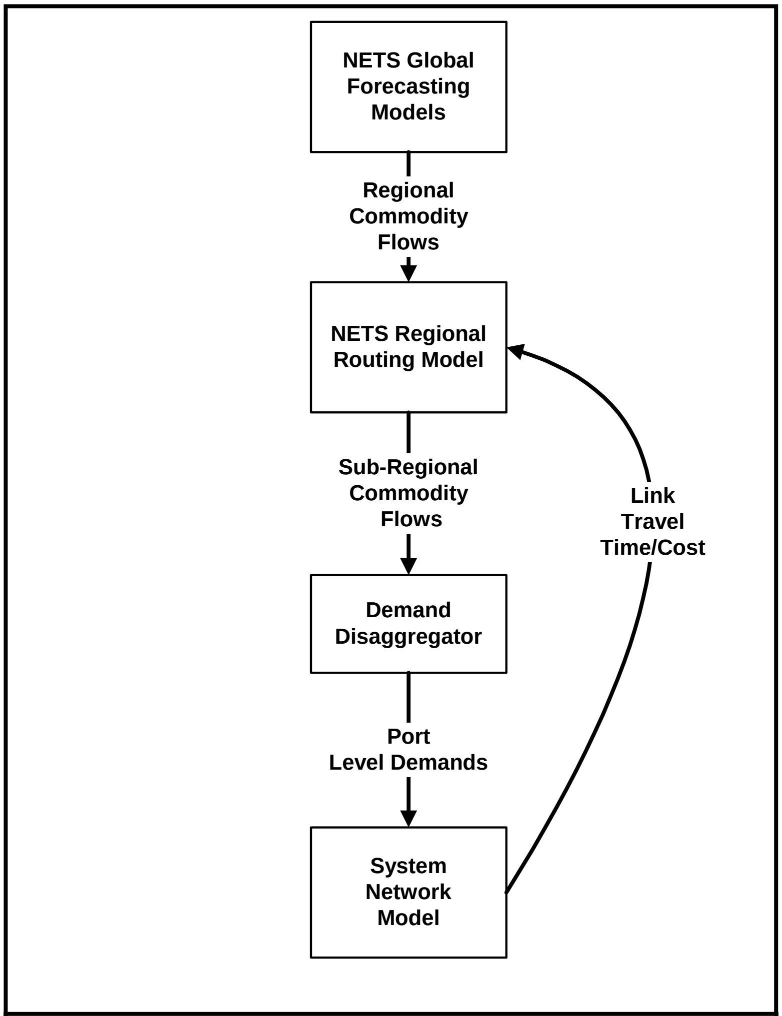


FIGURE 5
SYSTEM NETWORK MODEL AS A COMPONENT OF NETS

2.7 Model Boundaries

It is essential to bound the problems that each model addresses, and to understand the nature of these bounds. For the waterway system, our understanding of the interactions and complexities is far greater than our ability to represent those complexities within models. Accordingly, reasonable and appropriate simplifications must be made.

The System Network Model is expected to be driven by forecast commodity demands (export and import) at ports along the waterway (Origin-Destination-Commodity [O-D-C] values) with additional supplemental information describing recreational traffic, together with a description of the available fleet. In addition, it will be possible to specify traffic throughout the system directly, either as a "shipment list" or from statistics. Traffic will be developed as a set of potential trips, based on the unconstrained O-D-C commodity transport demands and equipment availability. It is clear that delays and closures of the waterway have an impact upon the amount of commodity shipped on the waterway—in fact, understanding that impact is a major component of the NETS initiative. Congestion and/or outages may lead to shipper responses that result in the original input O-D-C quantities not being satisfied, that is, the actual trips (output of the model) are not equivalent to the potential trips needed to carry the input O-D-C demand. This will require a re-estimation of the input O-D-C quantities, using the regional routing model together with the congestion and reliability-related outputs of the System Network Model, until such time as the two models are in balance.

2.8 Recommended Next Steps

The following initiatives can be undertaken in the near future:

- Proceed on the detailed specification, design and implementation of the Data Analyzer and Preprocessor:
    - Review of current and future plans for database schemas for LPMS, OMNI, and WCSC information
    - Review current methodologies for data extraction and pre-processing used for WAM, ORNIM;
    - Review work conducted by Mark Lisney on data quality;
    - Review design of NaSS for data requirements;
    - Review LPMS animation capabilities and insights gained about LPMS data during development of the LPMS INAM animation;
    - Develop a design document for the Data Analyzer, based on the above;
    - Implement the prototypes based on design.
- Develop proof of concept/prototype models as follows:
    - Single lock prototype—detailed lock behavior on a single lock, to explore issues of internal geometry representation, lockage policies and data needs;
    - System network model prototype with highly simplified lock—to resolve issues relating to specification and generation of commodity driven movements, conservation of equipment, movement of empties, non-tree networks and re-fleeting, with simplified or no lock behavior; Emphasis needs to be placed on the routing, shipment creation, re-fleeting, conservation of equipment, data structures and movements. At a later time, addition of shipper response to scheduled and unscheduled outages to the network behavior prototype using willingness-to-wait (WTW) and Wilson-Train modal choice concepts should be added;
    - Agent-based proof of concept and prototype—specifically to examine shipper response to scheduled/unscheduled outages and long-term congestion, in the agent context.

The development of the above proof of concept models should allow for the next stage of spiral development, an initial prototype for the System Network Model, including the following features:

- Multi-lock (maybe 2 or 3) network with limited alternate paths (loops)
- Multi-chamber
- Interference at locks
- Re-fleeting
- Generation of vessel movements by direct shipment list specification
- Complex vessel movement description
- Lockage policies: first to arrive, N-up/N-down
- Component-based reliability
- Shipper response, including initial implementation of Wilson-Train approach to modal choice
- Detailed lockage time components and movement geometry
- Modeling each cut
- Equipment conservation and movement of empties
- Scheduled outages
- Determination of vessel operating costs, waterway infrastructure O&M, repair and rehabilitation costs
- GUI implementation

The first prototype should have sufficient capability to allow it to be used (or used with some modification) in a test bed study, when one is available and also to be used in conjunction with the development of the GA optimization tool. This is clearly an ambitious goal for the first prototype, but, given the extensive work that already has been done by members of the development team, it should be reachable.

Once the initial prototype system network model is in place, it is suggested that a brief design document be prepared defining the relationships between the system network model and the investment optimization model, to be followed by a prototype investment optimization model.

Following upon the completion of the first prototype, a proof of concept of the commodity-driven movement generation and statistically-driven movement generation should be developed, using either the first prototype or the network behavior prototype.

In order to carry out the above efforts, it will be necessary to select appropriate test cases/test beds to insure that real-world issues and data are being considered.

The Investment Optimization model development and Results Analyzer should follow the implementation of the prototype System Network Model. Further design, in particular of the translator component, will be necessary as the inputs to the System Network Model are better defined through the prototype.

2.9 Issues

While the current document attempts a description of many of the features of the proposed models, many additional design decisions will need to be made during the prototype development efforts. It is intended that the current document be updated with "design memos" as these decisions are explored/made.

Because the design of NaSS is being done while other components of NETS are still in ongoing development, in particular the Regional Routing Model, many of the issues of model interaction will need to be re-visited. This same issue applies to use of the Investment Optimization Model with the System Network Model, which cannot be properly designed until the full characteristics of the data description for the System Network Model are clear.

There is a great deal of expectation that the Wilson-Train model [Wilson, 2004] of shipper response will play a vital role within the System Network Model. This model is still evolving, as further work is being done on the Columbia River system, and clarification of how the model might be used to represent shipper response to unscheduled outages, as well as for long-term congestion issues, needs to be undertaken. This should be done in the near future, prior to development of the second stage prototype for the System Network Model that will incorporate such shipper response.

The remainder of this document provides more detail on the design of the System Network and Investment Optimization Models.

Section 3
General Framework of the System Network Model

This general framework of the system model describes:

- How the system is described as a network, from a data and spatial point of view;
- How a lock is described;
- What the elements of a lockage are;
- What is moving on the network, i.e., the vessels/tows and their commodities and origins/destinations;
- How these movements are specified as shipments;
- How these shipments are affected by channel characteristics, such as width, depth and curvature;
- How lock service reliability is handled;
- How shipper response to lock service reliability (scheduled and unscheduled outages) is handled;
- How conservation of equipment and movement of empties are handled.

These items are inter-related. Thus, the definition of a lock and the description of what is moving on the waterway, is related to the elements of a lockage. This is, unfortunately, necessarily complicated. Note that, at least at this point in the discussion, there is no concept of a "simplified" system as yet. If we are ever going to need a detailed description of a system and lockages, we must know how to describe it at the appropriate level of granularity. Once that description has been developed, we can seek simplifications where appropriate. This is preferable to working up from a simple representation to a more complex representation. Accordingly, the following discussion is pitched at the maximum level of detail that is expected to be used within the network model.

3.1 Terminology

There is no universally accepted and consistent set of terms that is applied relative to waterway entities, either in common usage or in the world of modeling. The following is an attempted starting point for definitions that can be used going forward in the modeling. Undoubtedly, changes will be needed, in particular as the object orientation of the model effort evolves.

1. Definition of Entities that Traverse the Waterway
    a. Vessels/Watercraft

A craft intended for navigation on water; A general term referring to all types of watercraft including ships, barges, tugs, yachts and small boats, whether powered or non-powered. Essentially, it is anything that floats and carries a commodity and/or passengers or pushes something that carries a commodity. Vessel attributes include size, type (a taxonomy will need to be developed), identifier, LPMS type, etc. Currently defined LPMS Vessel Types are shown in Table 2.

TABLE 2
LPMS VESSEL TYPES

C	Dry Cargo Vessel
E	Liquid Cargo Vessel
F	Fishing Vessel
G	Federal Government Vessel
J	Dredge Vessel
K	Crewboat Vessel
M	Non-Cargo Vessel
N	Government-Nonfederal Vessel
P	Passenger Boat or Ferry
R	Recreational Vessel
T	Tow or Tug Boat
U	Federal Government Contractor Vessel
Z	Other

i. Powered Vessels—a vessel intended for navigation that moves on the waterway under its own power. This includes towboats, recreational craft, passenger craft, ferries, etc.;

  (1) Tow Boat—a specialized power vessel with a flat bow used to move barges (occasionally referred to [improperly] as a tug, which has a pointed bow). Towboats are classified primarily based on horsepower.

  (2) Tug Boat—a specialized power vessel with a pointed bow used to move integrated barges and assist other powered vessels in maneuvering in tight areas.

  (3) Light Boat—a towboat with no barges.

  (4) Ship/Self-Propelled Commodity Carrier (SPCC)—a single powered vessel that is transporting a commodity, such as a tanker, fishing vessel, etc.

ii. Unpowered Vessels

  (1) Barges—a heavy, non-self-propelled vessel used to transport goods. Each barge is of a specific type (tank, open hopper, covered hopper, etc.) and dimensions and has a known commodity capacity for a given commodity. [A separate set of information will provide the correspondence between barge type and commodity that can be carried by that barge type]. We may wish to consider barge classes within types, where classes are a size-based definition, with

associated maximum commodity capacity by commodity and class. Barge cost information is provided for barge types of open hopper, covered hopper, deck, self-unloader, tank, pressure tank, steel tank, and chemical tank and for various sizes (horsepower) of towboats in: http://www.usace.army.mil/inet/functions/cw/cecwp/cecwp_temp/egm051.pdf

(2) Integrated Barge—a barge that is notched for the pointed bow of a tug

b. Groups of Vessels that move as a unit:

   i. Tow—one towboat with one or more barges (individually loaded or empty)

   ii. Flotilla—two or more configured vessels capable of self-propulsion—a flotilla can be a tow, but also may include other combinations, including multiple powered vessels. Note that LPMS defines a flotilla as: "A tow with barges; or for reporting purposes a self-propelled vessel that is carrying a commodity for subsequent sale (i.e., ship, fishing vessel)."

2. Definition of the Waterway

The waterway is represented as a link/node network, which may contain loops.

a. Reach/Link—a contiguous section of the waterway on which vessels travel, that can largely be represented by common physical characteristics and within which tows/SPCCs do not discharge or accept commodities and do not reconfigure. Transit rules and vessel speeds are defined at the reach level. Reaches are bounded by a single upstream and single downstream node.

b. Node—a terminal point of reaches, dividing reaches physically and logically. Nodes consist of a variety of types, including ports, re-fleeting points, topologic nodes and terminus nodes (entry/exit from the system).

c. Port—nodes at which vessel trips originate and end, and where commodities may be loaded/unloaded. A port is the model representation/aggregation of one or more real world docks. Tow and barge reservoirs can exist at a port.

d. Re-fleeting point—a node at which tows can change configuration, changing the number of barges and/or the towboat.

e. Lock/Lock Reach—an area of the network, represented as a specialized reach, through which vessel movement is metered through one or more lock chambers. A lock reach has internal geometry that specifies the location of approach points, gate wait points, etc.

3. Definition of Commodity Movements

Commodity movements are characterized by:

- origin port
- destination port
- commodity type
- quantity
- time frame (e.g., annual, seasonal or individual shipment)

a. Annual Movement—an O-D-C quantity, defined on an annual total basis

b. Seasonal Movement—an O-D-C quantity, defined on a specified seasonal basis. The sum of all seasonal O-D-C movements should be equal to the annual quantity for that O-D-C.

c. Trip—a departure and arrival of a powered vessel or tow or SPCC from a given origin to one or more destinations. Trips with multiple destinations are said to consist of multiple Legs. (Leg 1 from origin to first destination, leg 2 from first destination to second destination, etc.)

d. Shipment—an individual O-D-C quantity transported on a single trip by a tow or SPCC. Note that, under this definition, a tow moving on the waterway may contain multiple shipments (e.g., coal between two docks, grain between two other docks).

e. Movement Shipping Plan—trip leg to trip leg definition of tow-size and towboat horsepower characteristics for a defined movement. This plan applies to all generated shipments (i.e., trips).

f. Dedicated Movement/Dedicated Shipment—an O-D-C shipment made by a single tow/SPCC on a single trip from a single origin to a single destination, where the same barges or SPCC will return empty to the origin in a backhaul shipment.

3.2 Overview

This section summarizes the overall approach and framework for the system network model. More detail and discussion is provided in subsequent sections.

1. Architecture: The model is an event-driven detailed Monte Carlo life cycle simulation of a waterway network, or portion thereof. A GUI provides user interaction, while a relational database (MS Access™) stores the necessary input and output data and an animation module displays vessel travels through the system.

2. System Representation: The basin is described as a reach (link)-node network, with reaches separating nodes. The network is largely tree-structured, although some local loops are allowed. Four types of nodes are proposed: port, re-fleeting point, terminus and topological (which includes junctions). Locks are proposed to be represented as a reach (or possibly as a set of reaches). Transit rules are defined at the reach level, as are transit speeds (which are also defined by tow/horsepower).

3. Lock Reach Internal Geometry: A lock reach has internal geometry describing a spatial extent, from approach point to approach point. Gate wait points, chamber sill locations and

chamber mooring bits are defined between the approach points, in the upstream and downstream direction. Locks can have 1 or 2 chambers.

4. Lockage Description: A lockage tracks each vessel, and individual cuts of tows, through each chamber of each lock. For a complex lock representation, approach, entry, chambering, exit and chamber turnback times are accounted for under conditions of single and multiple cut for fly, exchange and turnback situations. Interference between chambers may exist in multiple chamber situations (gate and approach interference). [For a simple lock representation, total service time distributions are provided for fly, exchange and turnback.]

5. Lockage Policies: Lockage policies are assumed to have complete knowledge of everything within the lock domain, i.e., the type/size of each vessel in each queue, for some designated period of time into the future. Lockage policies need to be adaptive, i.e., to be able to change as queue sizes and other factors dictate. A proposed set of lockage policies to be implemented initially includes: first to arrive; N-up/M-down (with a "trigger" when the queue length exceeds a given value); setting tow priority based on expected service times; shortest processing time first; recreational vessel schedules and rules; limiting a chamber to single cut tows only; limiting a chamber to a specified direction; and forcing recreational craft into a certain chamber at dual chamber locks.

6. Vessel Movement: Vessels move on the network, from node to node, along reaches (and through lock reaches). A powered vessel may or may not have barges associated with it—if so, it is a tow (or flotilla). A powered vessel without barges (SPCC) may also carry commodities. If a powered vessel does not have barges, it can be a lightboat, a recreational craft or a vessel of type "Other" such as passenger or government vessel. Barges can be added or subtracted from a tow at a port or re-fleeting point. A tow can be permanently re-configured at a re-fleeting point and temporarily re-configured to enter a lock. Otherwise, it moves on the waterway in a standard traveling configuration (e.g., the number and array of barges with the power vessel) at a data-determined speed in each reach.

7. Movement Specification: Vessel and tow movements are specified at the basin level, in one of three ways:

   a. as seasonal origin port-destination port-commodity movements, from which vessel/tow movements are derived;

   b. as seasonal origin port-destination port vessel movement statistics, by vessel/tow type, from which individual vessel movements are developed;

   c. as a detailed manifest of complete vessel/tow shipments (in order to use historical data within the model)

8. Conservation of Equipment and Movement of Empties: "Reservoirs" of equipment (barges and power vessels) are defined at the port (and possibly the pool) level and populated initially. As trips are required, equipment is taken from the pool reservoir. As trips terminate at a port, they deposit the power vessel and barges at the port reservoir. No trip is ever prevented from moving by virtue of lack of equipment in the reservoir—rather, equipment needed to serve the trip is generated and then becomes available as if it had been

in the initial reservoir. Such generated equipment is recorded through the simulation and can be used for calibration of the initial reservoirs. Certain types of origin-destination trips will imply backhaul of empties, thus automatically creating a backhaul trip at the completion of the original trip (dedicated shipment). Other trips will deposit empties in the reservoir without generating a backhaul. A separate process needs to be developed to account for light vessel movement and movement of empties to ports where they are needed for equipment conservation. This process is expected to be explored in a proof-of-concept examination. We will need to consider how equipment reservoirs are re-stocked if and when that becomes necessary, and whether simple decision rules are applied or a more complex optimized restocking decision is done within the simulation. At present, there is no intent to distinguish among different tow operating companies, but that possibility should be kept in mind for future development.

9. Reliability: Reliability is handled through lock chamber level definition of components with associated event-driven (age and/or cycles) reliability functions. Components change state in response to events and performance of a chamber is a function of the state of the components. Thus, unscheduled outages are determined internal to the model, as opposed to external closure schedules. Major and minor maintenance activities are represented in the model by internal rules that create scheduled events. Unscheduled minor events, such as weather, accidents, and other minor closure events, are created internal to the model based on rules and/or statistical/historical data.

10. Shipper Response: Shipper response to scheduled and unscheduled outages is based on the development of a set of seasonal "potential shipments," i.e., shipments that would take place in the absence of outage. Shippers are assumed to have advance knowledge of scheduled outages, thus they can adjust the potential shipments by shipping prior to the closure, shipping after the closure, diverting the shipment to another mode or shipping as scheduled and accepting the anticipated delay. Shippers only have knowledge of unscheduled outages from the moment that they occur, allowing for changes to shipments that have not started and diversions for shipments already on the waterway. The Train-Wilson probabilistic approach to determining shipper response is suggested as the method of determining how any given shipment behaves in response to scheduled outages and long-term conditions on the waterway (cost, time and reliability). This will require, for each shipment, estimates of the cost and time of the shipment, as well as some metric that defines reliability of the system. This will require further analysis to explore how this can work in the context of the simulation model and how to develop the needed data. Response to unscheduled closures will initially be based on "WTW, willingness-to-shift (WTS), willingness-to-divert (WTD)" concepts, based on the expected duration of the unscheduled outage.

11. Cost-Benefit Considerations: The System Network Model will track operating costs of vessels (based on horsepower for power vessels and barge type for unpowered vessels), time of vessels in the system (categorized by time spent in reaches, time at docks and various elements of time spent in the lockage process). Appropriate costs will be assigned to each of the time elements (e.g., maneuvering versus line-haul fuel consumption rates). Repair and rehabilitation costs will be tracked, at the system, lock, lock chamber and component levels. It will be desirable to track fuel consumption of vessels, based on their

status (transiting reaches, at dock, etc.) for environmental and cost purposes, with possible future consideration given to optimization of speeds. Cost of shipper response to scheduled and unscheduled outages will be developed, include possible alternative mode costs, as well as costs associated with delay, diversion and demurrage.

3.3 System Representation

The system is represented as a node-link network. The network is expected to be largely tree-structured, although some loops may exist. Each link is a reach, representing a portion of the waterway (between nodes) on which vessels travel. Nodes are expected to be referenced to a river mile indexing system, as well as by geodetic coordinates (latitude/longitude or northing/easting). Upstream and downstream nodes are defined based on direction of water flow, where possible, or by a set convention (e.g., for GIWW).

The following node types are considered:

- Topologic nodes—serving only as start and end points of reaches
- Port/dock nodes—serve as origin/destination of commodity and/or vessel movements;
- Terminus nodes—serve as entrance/exit points to the portion of the network under study (e.g., boundary nodes);
- Re-fleeting Points—locations at which a tow can be reorganized into a different configuration with a different towboat. These can be co-located with a port node, to allow for representation of re-fleeting at a port;

All reaches are connections between a pair of nodes. The following link/reach types are considered:

- Open Channel—a reach without a lock; a segment of the waterway where vessels can move subject only to transit rules, i.e., without any physical barrier to movement;
- Locks—while a lock is typically represented as a node, within the NaSS design, it has internal geometry such that the entire description of the important areas relating to a lock could extend over perhaps 2-4 miles. As such, it is proposed that a lock be treated as a particular type of reach (as is done in NavSym). This is a key question for implementation considerations and there are advantages and disadvantages in both methods of representation. The remainder of the discussion will assume that a lock is represented as an extended area (lock reach), but this may be revisited during implementation to change to a nodal representation, as the design concepts are not heavily dependent upon the ultimate choice of implementation.

Vessels will travel on a designated route from origin port to destination port. In a purely tree-structured network (or portion thereof), there is a unique route from an origin to a destination. Where alternative routes are possible (in a network with loops), it will be necessary to determine which route is chosen. This can be done initially (at time of generation of the trip) or adaptively as a vessel observes congestion and chooses an alternative route. Some aspects of route choice may be deterministic (e.g., hazardous cargo travels on one route, normal cargo another), some may be probabilistic (x% of O-D-C trips take Route A, y% take Route B). Further examination of how to handle route choice is needed, with particular reference to how important this problem is in any given waterway.

Powered vessels can incur time at port nodes (for loading and unloading, and for tow configuration), re-fleeting points (for re-configuration and change of tow), and at locks (for passage through the queue and lock). It is assumed that vessels do not incur any time when traversing a topologic node, unless they must wait before entering the next reach, due to transit rules.

Reaches may have additional descriptive attributes assigned. In addition, vessel speed is associated with individual reaches, that is, vessels may travel at different speeds in different reaches, as specified by input data. All reaches may be subject to congestion and transit rules (in WAM, only bends are areas where transit rules exist). Transit restrictions in a reach are defined by rules associated with the reach, e.g., no overtaking, no meeting, single vessel reach, one-way traffic, etc., as is done in NavSym.

Regions can also be defined, e.g., pools, governmental jurisdictions, port hinterlands, etc., by associating nodes and reaches of the network with such regions. There should, in general, be a port within each pool (in order to provide an origin and destination for recreational vessels transiting a lock), but this need not be a hard and fast requirement. “Terminus” ports are also needed to serve as sources and sinks at system boundaries as shown in Figure 6.

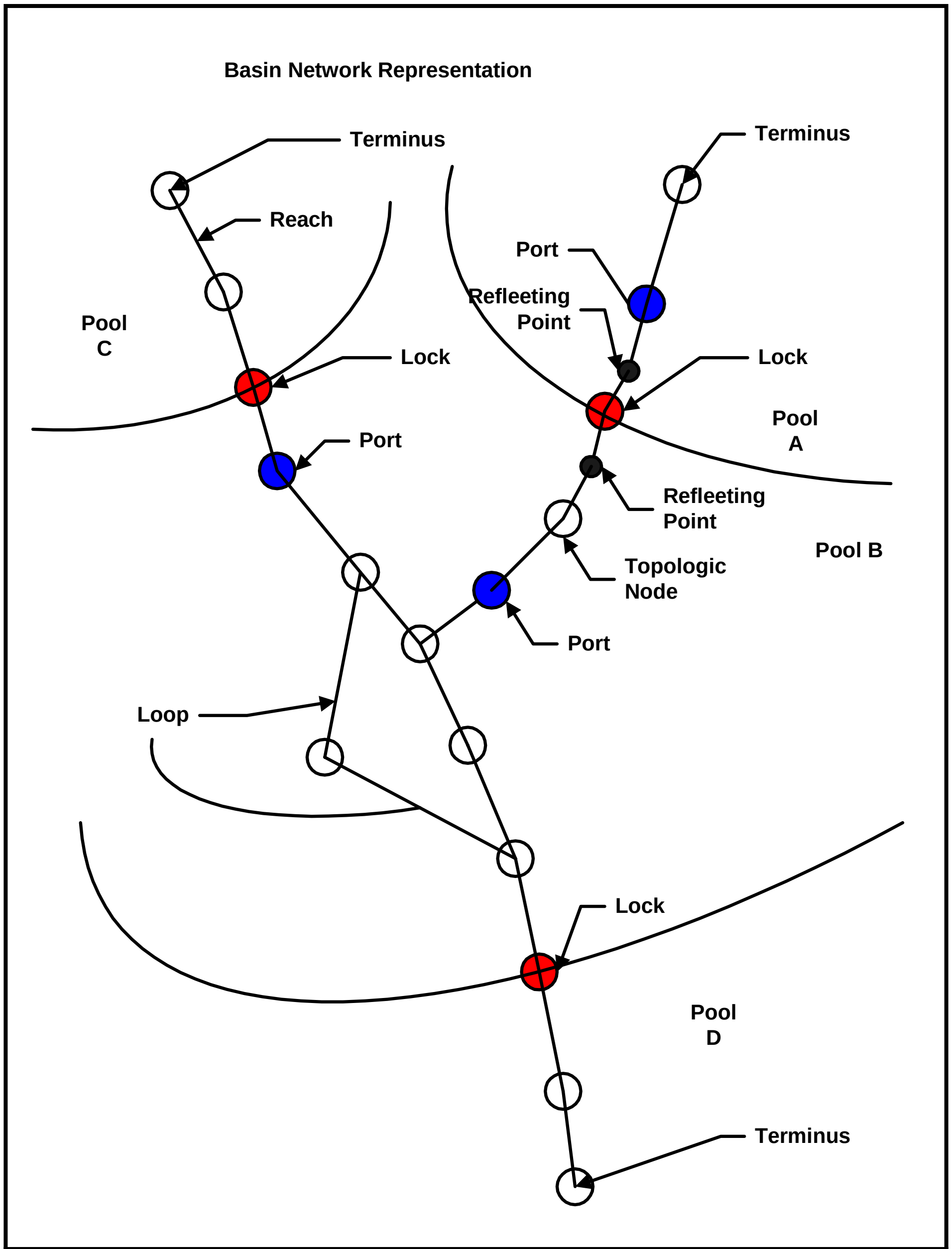


FIGURE 6
SYSTEM REPRESENTATION

3.4 Spatial Representation

There is some complexity to the issue of spatial representation of the system. Spatial representation can be coordinate-based (e.g., latitude/longitude of a port), but it can also be attribute-based, i.e., Reach A is in Pool 23, State of Kentucky, Region A. (A reach may also cross regional/governmental boundaries, but should not be in more than a single pool). Regions will likely be important in association of ports with hinterlands, and this association should be made explicit by assigning nodes to hinterland regions.

It is also normal to associate locations in a river system with a "river mile index," but the ordering/indexing/reference system may vary from river to river or agency. Further, certain data collection systems may not provide accurate recording of river mile data. A lock separates two pools, so it is not really "in" one pool or the other.

It will be advisable to maintain a robust and flexible methodology for spatial associations with the elements of the network. In addition, the network itself may change during a life cycle simulation—locks may be eliminated at a specified time in the life cycle, and new ones brought on line, or reaches opened/closed. This is discussed in more detail below.

A river reach between nodes should have a defined length and width, but the "real world" reach will have varying width and will be a curve, rather than a straight line between the nodes. Nodes in general are thought of as 0-dimensional objects and reaches as essentially one-dimensional (with a width attribute) but we need to be able to represent a lock with internal geometric structure in order to be able to handle such things as interference and proper accounting for the travel times associated with the elements of a lockage.

Thus, three forms of representation are needed for the basic elements:

1. A "GIS"-oriented format, where detailed representation of the path of a reach is available. Depending upon the degree of visualization ultimately desired, this representation can vary (Figure 7).

   Note that, for each representation, we can consider constant width and depth along the reach or variable width and depth. It is proposed that, at least initially, a separate polyline representation of a reach be storable and that reach width and depth be assumed constant between nodes. It is recognized that width/depth can change seasonally and in response to droughts/floods, but at present there is no intent to include time variability in channel representation.

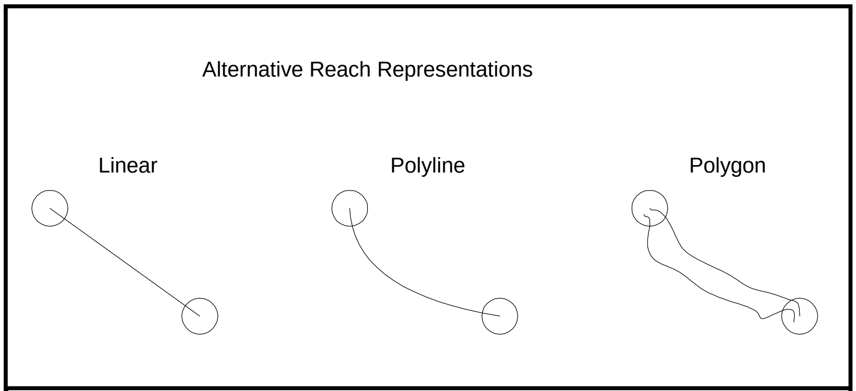


FIGURE 7
ALTERNATIVE REACH SPATIAL REPRESENTATIONS

2. A "model"-oriented format, where the dimensions of reaches and locks needed for the internal modeling of transit times and rule restrictions are maintained.

3. An "attribute" format, where the appropriate associations to external locational references are maintained.

It is desirable to have a good geographic representation of the system, using standard geographic coordinates, in particular latitude and longitude. For purposes of display and animation, a Cartesian coordinate system is necessary. Generally, for small areas (e.g., a single State), a State Plane Coordinate system or UTM zone is used. Because the representation of a basin may cover a large area of the U.S., it may span multiple state plane coordinate or UTM zones. Accordingly, an alternative Cartesian representation is needed. ORNL, in their spatial representation of a multi-modal network that will be used within NETS for the regional routing model, has addressed and resolved this problem on a global scale and we should attempt consistency with their approach. ORNL uses an Albers projection for this purpose [Peterson, 2000].

Because of the distortions introduced by the choice of any Cartesian coordinate transformation (from latitude/longitude) over a large area, and the requirement that vessels travel along the river, rather than "as the crow flies," it will be necessary to independently specify distances for reaches, that is, the length of a reach as calculated by the linear distance between nodes is not usable for modeling. Fortunately, river mile indexing systems do provide linear measures along the channel.

3.5 Network Changes Over Time

Certain proposed improvements can result in a change to the network geometry and topology over time, for example through replacement and/or relocation of a lock or dredging of a new channel. This is a somewhat difficult situation to model. It is proposed, where such changes are possible, that the initial network incorporate all such possible changes, that is, any future configuration changes are represented in the node-link network. Then, as the model runs through a life cycle, locks or reaches can be activated and de-activated to insure that, at any given point in the life cycle, the network representation corresponds to the changes that have been introduced. Determination of the appropriate timing of some of these changes is the province of the investment optimization model. Such capability should be designed in from the beginning in the system network prototype and given an early test to explore feasibility and issues.

3.6 Lock Internal Geometry

A lock is considered to be a specialized reach with important internal geometry of the lock being contained within the lock reach. As well, there is the concept of a *lock domain*, that is, a geographic area over which knowledge of vessel movements is important. The lock domain will extend over adjacent reaches, possibly to the next upstream/downstream locks (or beyond), such that lockage policies and traffic management systems can take into account activities within the domain.

Movement of vessels through a lock consists of four stages (approach, entry, chambering, exit) with three conditions of approach and exit (fly, turnback, exchange). This is shown in Figure 8. The times associated with these stages are, in general, derivable from LPMS data, although it must be noted that ambiguities in data recording within LPMS (e.g., the exact position used to record the end of a turnback exit) require that certain assumptions be made for consistency. The four-stage/three-condition definition of the lockage process allows for simulation of differing

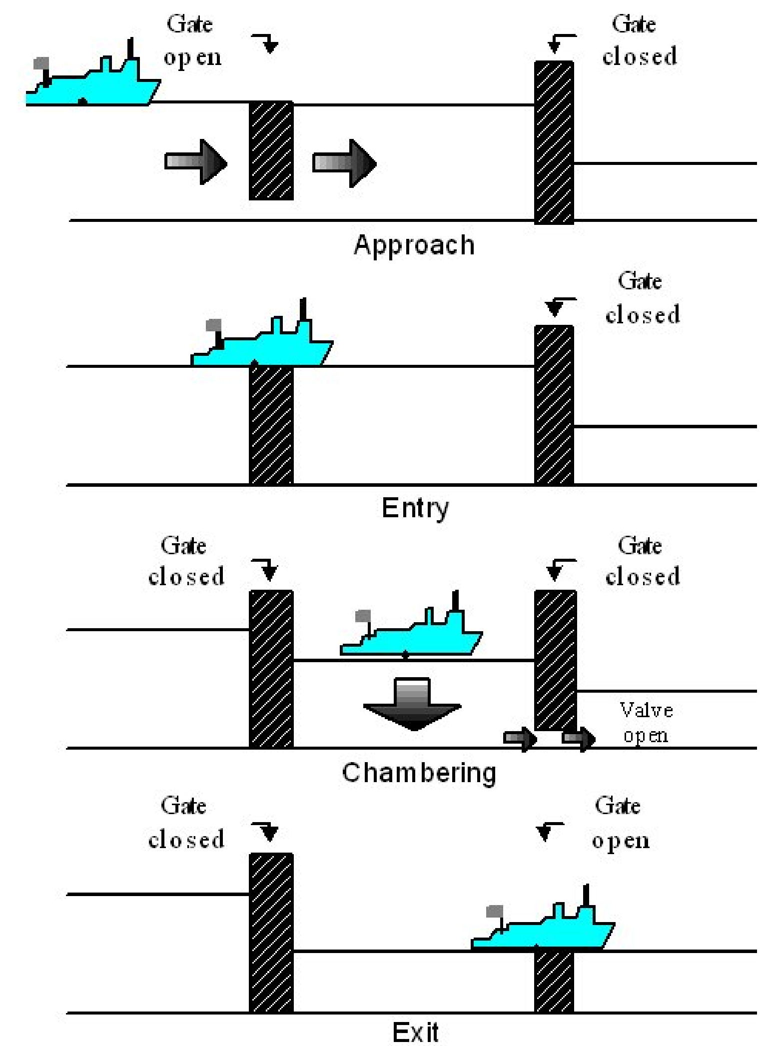


FIGURE 8
ELEMENTS OF LOCKAGE PROCESS

lockage policies, self-help, etc., as opposed to treating a lockage as a single time distribution. This definition is described in more detail later in this document.

The role of interference is discussed and illustrated in the Wang/Tao/Schonfeld draft design document (RevisedKernelDesignDraftNASS.5.16.05.doc), from which portions of the following material are extracted. Figure 9 gives an example of an Approach Interference.

When a tow is in the approach area, either approaching or exiting a chamber, another tow cannot occupy that approach area to approach or exit the other chamber.

Gate area interference, shown in Figure 10, may occur when a tow, or part of a tow, is waiting near the gates of a lock chamber. Whether interference occurs depends upon the configuration of the lock and the length of the waiting tow. Gate area interference can prevent another tow

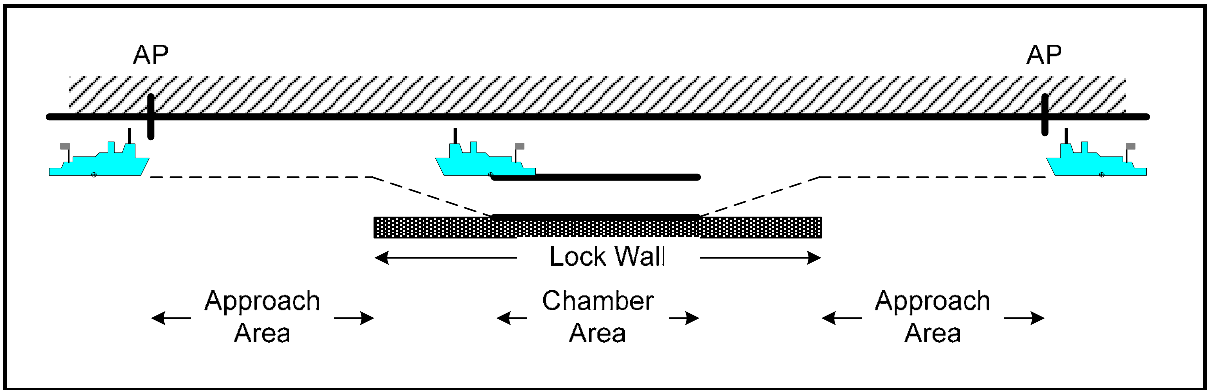


FIGURE 9
APPROACH INTERFERENCE

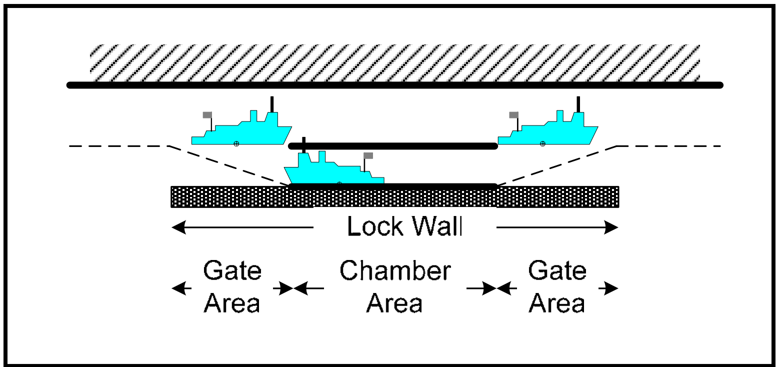


FIGURE 10
GATE AREA INTERFERENCE

from approaching the other chamber, extracting a cut from the other chamber or exiting the other chamber.

For purposes of simulation, it is necessary to associate this with a description of the location of a vessel within the internal geometry of a lock. It is necessary to provide such a description to understand how these four time increments are specified exactly, and how they relate to movements of a vessel.

The internal extent of the lock reach is taken to be from the “upstream” approach point to the “downstream” approach point, which defines the minimal extent of the lock domain for that particular lock. This concept of a lock domain needs to be somewhat flexible, to incorporate extended queues, such as might exist with traffic management systems such as appointment systems and speed control. Depending upon the lockage policy, the concept of a “virtual queue” that extends well upstream and downstream of the lock, beyond the extent of the physical queue, may be needed, to allow for intelligent/optimizing decisions relative to lockages.

Approach points for a lock are designated locations, indicated by markers on the shore. For purposes of simulation, it is necessary to define upstream and downstream locations within the lock reach that are referred to as “gate area wait points.” These locations are important in the definition of turnback entries and exits and in analysis of cross-chamber interference at a 2-chamber lock. It is understood that these are not exact, defined locations in the real world—in the model representation, however, it is necessary to assign these locations, as a known distance from the upstream and downstream gates.

The relevant geometry points within the lock are shown in Figure 11.

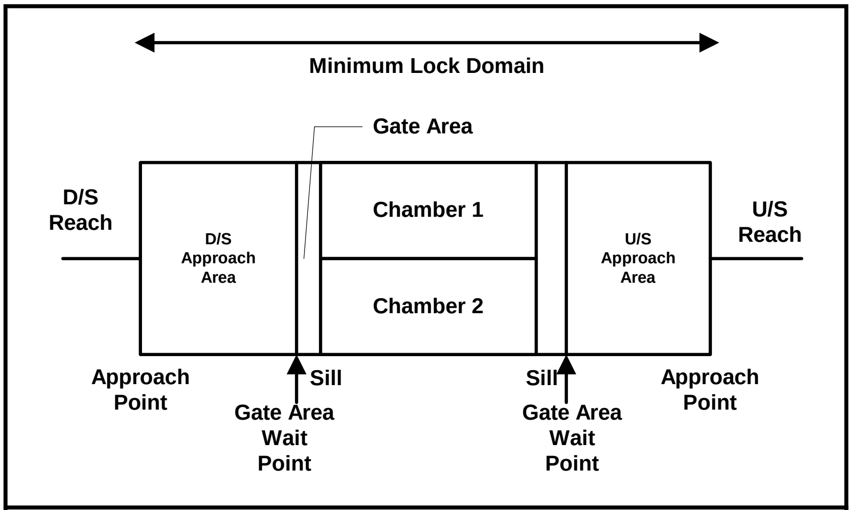


FIGURE 11
LOCK INTERNAL GEOMETRY POINTS

Approach point: point at which a vessel arriving at the lock enters the lock reach, i.e., comes under control of the lockage policy in effect (If queues are long, an arriving vessel may come under the control of the lockage policy a mile or more from the approach point); point at which a vessel exiting the lock leaves control of the lock. A vessel passing the approach point on entry to the lock is in the approach phase of its lockage for fly and exchange approaches and in the pre-approach phase for turnback approaches. Likewise, for fly and exchange exits, a vessel occupies the approach area until its exit is complete. For turnback exits, the exit is complete after the stern passes the gate area wait point. A turnback exit occupies the approach area during a post-exit phase.

Gate Area Wait Point: a location that represents the point at which the bow of the vessel waits to begin a turnback approach. The vessel will wait at this point until the lock is ready for entry. For vessels making turnback approaches, the time required to move from the approach point to the gate area wait point is called the pre-approach time. A vessel waiting in the gate area can cause gate area interference in a multi-chamber lock.

Approach area: The area between the approach point and the gate area wait point. A vessel in this area can cause approach area interference in a multi-chamber lock.

Sill: the point at which a lockage (or cut) entry starts.

3.7 Lockage Processing

From the perspective of a vessel about to enter the lock:

Conditions:

> Fly—the lock is idle, the lock gates are open and available for a passage in the direction of travel and the vessel directly enters the chamber.
>
> Exchange—the exiting vessel is traveling in the opposite direction of the approaching vessel. The lock gates are left open, and the approaching vessel begins its approach when the exiting and approaching vessels are abreast.
>
> Turnback—the lock gates are closed in the direction of travel, because a vessel moving in the same direction is already in the chamber and the chamber must be turned back before the gates can open.

Vessels move through a lock in stages consisting of four time increments:

- Approach—movement from the approach point or gate wait point to bow over sill;
- Entry—entry into the chamber, time required from bow over sill to when the gates begin to close;
- Chambering—time from closing of the lock gates to opening of the gates on the other end of the chamber;
- Exit—exit from the chamber, time required to reach the gate wait point or approach point on the exiting end of the chamber.

Given this, the description of the movements of a single cut within the lock domain can be characterized as shown in Table 3.

The physical representations of an approach under different conditions within the model are represented schematically as shown in Figure 12. The situation for an exit is completely analogous, with a turnback exit consisting of an intermediate movement from the chamber to the gate wait point and thence to the opposite approach point.

It is very important to note that this definition of geometry and movement is necessary to determine when approach and gate areas are clear or blocked, for purposes of determining delay due to multi-chamber interference. It is further complicated for gate area interference in that the length of vessel waiting at the gate wait point determines whether interference occurs.

TABLE 3
ELEMENTS OF LOCKAGE

	Fly	**Exchange**	**Turnback**	**Notes**
Approach	From approach point to bow over sill	From approach point to bow over sill	1) Pre-approach From approach point to gate area wait point 2) Approach (as measured in LPMS) from gate wait point to Bow over sill	Turnback approach is done in two stages: PreApproach, the vessel moves to the closed gates, Approach, the vessel moves from the wait point to bow over sill. Consequently, approach times for turnback are much shorter (typically) than approach times for fly/exchange
Entry	From bow over sill to tied up on lock wall, gates can close	From bow over sill to tied up on lock wall, gates can close	From bow over sill to tied up on lock wall, gates can close	Incorporates time necessary to break the cut (times should be longer for first cut of 2-cut tow than for last cut)
Chambering	closing of gates to opening of gates	closing of gates to opening of gates	closing of gates to opening of gates	Time independent of type, dependent upon head difference
Exit	From gates open to passing of opposite direction approach point	From gates open to passing of opposite direction approach point	1) From gates open to clearing the gates (taken as gate wait point); 2) Post-Exit, from gate wait point to opposite direction approach point	May incorporate time necessary to re-make a tow (first cut not removed from area or pulled far down the wall) (may be longer for 2nd cut of 2-cut tow) Turnback exit in two stages – move to gate wait point, then from there to approach point (post-exit)

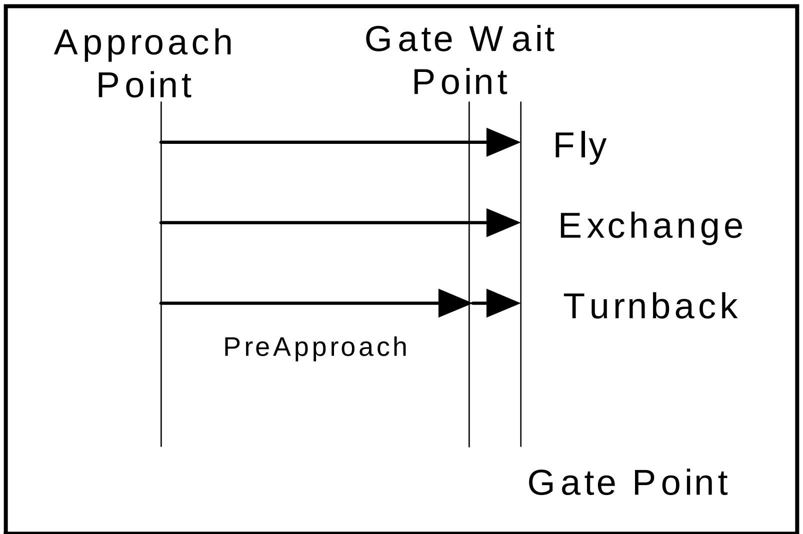


FIGURE 12
APPROACH MOVEMENTS

3.7.1 Components of Lockage Processing

The basic concept of lockage processing is that a vessel will arrive at the approach point, with all facts about the vessel known. A lockage policy will then be applied, determining if/where the vessel enters the queue and what happens next (i.e., what vessel from what position in the queue is processed through which chamber). Once the lockage policy has determined the next vessel to be processed, it is passed through the various stages of lockage, with the condition (fly, exchange, turnback) determined by the model itself. A good deal of responsibility within the simulation is thus placed upon the lockage policy at the lock. Thus, choices are isolated to the lockage policy object, which can interrogate queues and perhaps make use of additional information (e.g., projected arrivals at the lock, willingness/capability of different vessel classes to use the auxiliary chamber, etc.) to set the timing and condition of each lockage.

The simulation model will need to account for all of the time that a vessel encounters as it moves from origin to destination. This includes time loading at the origin port and unloading at the destination port, time moving through reaches, time waiting for processing at locks and for transit through constrained/congested reaches and time spent in re-fleeting activities. It is important to include all of these times for purposes of understanding and validation of the model, as well as for animation/visualization. It will also be necessary to estimate how such times will change in future scenarios. Examination of LPMS data [Lisney, 2005] has demonstrated the importance of certain types of internal times during lockages, for example interference at multi-chamber locks. Reducing interference can reduce total delay at a lock. Thus, it is necessary to define the components of lockage time for a vessel passing through the lock domain and be able to associate management measures with changes in these time elements. Some of these time elements will be generated by the simulation model itself, e.g., time waiting for interference to clear, while others (entry time, chambering time, approach time) will require a lookup into a database.

At this point, we have defined the internal geometry of the lock, and the stages and conditions of movement of a vessel within the lock. For each chamber, the chamber length and width, and the upstream and downstream critical lengths for each chamber for gate interference are all known. The distance from the approach point to the gate wait point, and from the gate wait point to the gate (sill) are also known. The interference conditions that are to be checked for this particular lock (e.g., upstream approach, upstream gate, downstream approach, downstream gate) are also defined.

The model will treat any vessel (tow, recreational boat, government vessel, etc.) in a similar fashion—it arrives at the lock, is put it into the queue, the lockage policy in effect at the lock examines the queues to determine which vessel gets handled next and which chamber(s) it goes to. Each vessel will be assigned a unique category (e.g., tow, recreational vessel, light boat and others) in order to provide information that can be used in lockage policies and in determining whether or not the vessel can cause or is affected by interference. A single queue for each of the upstream and downstream directions is currently proposed. Separate queues by vessel type (tows, government vessels, recreational vessels) have also been suggested. This is a subject for future discussion, but is primarily an implementation issue. Times of the vessel from arrival, to start of lockage, to individual lockage elements (as described in more detail below) are determined for the vessel. The vessel object will record all the times/time increments it sees as it passes through its route, e.g., time entering each reach, time arriving at lock, time ready to start lockage, etc. Thus, at the end of the passage, every time element of interest is known and can be recorded and summed statistically, either by vessel class or lock/reach level, or both.

For purposes of discussion, the vessel will be considered to be a tow, as this is the most complex situation.

On arrival, it is assumed that we know the “traveling configuration” of the tow, the number of barges, commodities carried and horsepower of towboat. Standard configurations for travel will need to be defined based on number of barges. When a tow is generated, it will be placed into one of the standard configurations. The tow (in particular a single cut tow) can temporarily re-configure at a lock to the “lockage configuration” (e.g., jackknife, setover, knockout) that will allow it to most easily transit the lock and permanently reconfigure at a re-fleeting point (i.e., change traveling configuration).

At the time of arrival, the traveling configuration, dimensions of the lock chambers and status of queues are known. The first effort is then to determine the needed number of cuts in each chamber and any required re-configuration into a lockage configuration. Statistics may be available to describe the proportion of single cut tows that configure to jackknife, knockout or setover, or this may be determined directly based on the lock dimensions and the traveling configuration. More discussion and research are needed, especially since the proportions may change with lockage policies and future lock design characteristics. Reconfiguration time needs to be accounted for if it is not already incorporated in approach or entry time statistics. It would be preferable, from a modeling point of view, to have reconfiguration time as separately identifiable.

Vessel at Arrival Point

Record current time as Arrival Time, trigger examination (by lockage policy) of queue, chamber status, to determine which vessel is next selected for service and from which queue [note that other events, such as the completion of a lockage, could similarly trigger a re-examination of the queues]. Vessel stays in queue until selected for service, record Exit Queue Time = Start of Lockage Time

If a single cut tow is reconfigured (to a jackknife, setover, etc.), this will most likely show up as impact of entry and exit times. Accounting for reconfiguration time needs to be explored in more detail during model development.

Start of Lockage

The number of cuts, chamber to be used, condition of entry, whether turnback is needed, are known based on the "decisions" of the lockage policy at the time the vessel is selected for service.

We may also know, at this point, if we are putting any other vessels into the same chamber (another tow, recreational boat, light boat). This is a decision of the lockage policy. A method of determining the time that is associated with adding additional vessels into a chamber is needed and should be explored in more detail during model development.

If interference is possible at the lock, it will be necessary to check approach and gate area interference. On any single lockage, two types of interference (approach or gate) may apply. For example, Tow 1 may be approaching one chamber in the same direction as the tow that is checking interference (Tow 2). Tow 1 will likely prevent Tow 2 from approaching its chamber. If Tow1 is making a pre-approach, it will wait at the gates until the chamber is turned back and the gates are open. While it is sitting at the gate, it may also cause gate area interference that prevents Tow 2 from approaching. In this case, Tow 2 was held up by both approach and gate area interference.

Approach area interference is determined based on calculation of whether a vessel leaving or approaching the other chamber is in the approach area. If a vessel is in the approach area, then the time at which the vessel leaves the approach area is recorded. The difference between this time and the start of lockage time or start of pre-approach time is the Approach Interference Wait Time. Similarly, gate interference is checked based on the known length of the cut that may be waiting at the gate and the critical interference length that is recorded for the lock. The difference between start of lockage or start of pre-approach and time at which the gate area is clear is the Gate Interference Wait Time.

Start Approach Time

The Start Approach time = Start of Lockage Time + Approach Interference Wait Time + Gate Interference Wait Time (where either or both Approach Interference and Gate Interference Wait Times may be positive, if interference occurs or 0).

A start approach event is created at the start approach time.

The Approach Time is determined based on lookup into probability distributions stored in the database. It is proposed that these distributions be stored as cumulative distributions, generated by the pre-processor/data analyzer as derived from LPMS data. This is in distinction to storing a parametric distribution (normal, triangular, etc.), and has the advantage of being completely general, such that empirical data can be used directly without fitting to a parametric distribution. Whichever method is adopted for storing the distribution, the approach times will vary by:

1. Lock
2. Chamber
3. Vessel class
4. Cut #
5. Type of approach (fly, exchange, turnback, pre-approach)
6. Direction (upstream, downstream)
7. Lockage assistance type (e.g., none, tow haulage, self-help, etc.)

[Note: the model must also be able to switch between processing times during the simulation, as conditions change. For example, during normal operations on the Upper Mississippi, tow haulage units are used, leading to one set of distributions. At highly congested periods, the industry may decide to switch to self-help to relieve the congestion, then return to tow haulage when congestion clears. This capability should be designed into the prototype (at minimum in the data structure design) and needs to be incorporated for all other lockage time components. The methods of triggering a change in the distribution, e.g., from tow haulage to self-help and back again, will need further examination and consideration as to whether they are deterministic (i.e., based on reaching a certain queue size), or probabilistic.]

For a turnback approach, as discussed above, a "pre-approach" time will need to be developed, because the recorded LPMS approach times start at the gate wait point and pre-approach is not directly available. This can be done statistically by subtracting the distribution of turnback approach times from the distribution of fly approach times for a chamber. This should be done as part of the pre-processor effort, i.e., pre-approach distributions should be available as data, rather than estimated within the model.

For turnback approaches, the pre-approach can begin anytime after the previous vessel starts its entry. Note that this means that the determination of the next vessel to be locked under a turnback situation must be made starting at the end of the approach of the previous vessel. Interference can affect pre-approaches the same way it can affect fly and exchange approaches.

Once the approach time is determined, an "end approach" event can be created at the end of fly and exchange approaches. For turnback approaches, an end pre-approach time is created to represent the time a vessel ends its pre-approach. The actual approach cannot begin until the chamber is turned back (the end of chamber turnback event triggers the start of approach). Then the end of approach can be scheduled. For fly and exchange approaches, the end of approach event frees the approach area for use by other vessels. For turnback approaches, the end of pre-approach event frees the approach area, and sets a length of vessel at the gate area. The start of the turnback approach frees the gate area. Note that recreation vessels, lightboats, passenger vessels and government vessels do not cause nor are they affected by interference.

Start Entry

A "start cut entry" event is created at the end of approach time (+.0001). For purposes of calculating interference, the length of the tow at the gate will be set to zero for a single cut tow or to the length of the tow minus the length of the cut in the chamber, for a multi-cut tow. At some point in model development, it will be desirable to consider in detail how the chamber is packed with barges, which will provide information on the length of the cut in the chamber, for purposes of determining interference. As a first attempt, the model will assume that the tow length is reduced by the length of the chamber each time an entry is made.

The entry time duration for the cut (time from bow over sill to tied on lock wall) is determined. This is a lookup into a distribution for the lock chamber, similar to that for an approach, and with the lookup parameters:

1. Lock
2. Chamber
3. Vessel class
4. Cut #
5. Direction
6. Lockage assistance type

Note that the term "cut" is used generically here, a straight single would be considered a 1-cut tow. Note also that entry time should not vary by fly, turnback or exchange.

Create "end cut entry" event at start cut entry time + entry time duration.

At this time, it may be possible to add other vessels (tows, recreation, lightboats) to the chamber. This will be a determination of the lockage policy. Appropriate time (Added Vessel Time) must be accrued in adding these vessels. Note, other vessels can only be added to straight single lockages. They can not be added to a tow that has reconfigured or has multiple cuts. Tows pushing hazardous commodities cannot participate in multi-vessel lockages.

Start Chambering

Chambering can start once the cut and any added vessels are in the chamber (End Cut Entry + Added Vessel Time)

The chambering time itself (time to fill/empty the chamber) should be independent of the contents of the chamber and may be considered a function of:

1. Lock
2. Chamber
3. Chamber condition
4. Head differential
5. Filling or Emptying

At this stage of development, it is probably too complex to deal with head differential as a continuous variable, due to the unknown times at which head differential will change. If this level of complexity is desired, further examination will be required.

It may, however, be important to take into account chamber condition for chambering time. A valve that is not operational can cause a chamber to fill or empty at half speed. We can add a "performance penalty" to chambering time based on chamber component states, as is done in LockSym, to get a total chambering time. This approach will be discussed further under component reliability.

In existing practice, gates have been modeled as a "work- don't work" item [Lisney, personal communication]. They are not like valves where a valve can be inoperable, but the chamber can still operate. If the gates don't work, the chamber is shut down. However, it seems at least plausible that gates could be in a condition such that opening/closing them more slowly than normal might be advisable. A decision should, in general, be made on the value of including performance penalties that are assigned to specific aspects of the lockage cycle, taking into consideration all components. This would be data-driven, by breaking down the performance penalty associated with each component/state into the elements that are assigned to the lockage cycle components. For example, gate movement time penalties would be assigned to the chambering (gate movement is included in the chambering time in LPMS).

Cut Ready For Exit

The Cut Ready For Exit Time = End Cut Entry Time + Chambering Time. This initiates the cut exit event.

Cut Exit

A single cut tow that is ready for exit may be subject to approach or gate area interference from another chamber. For multiple cut tows, an extracted cut may cause interference, such that a tow in the other chamber cannot exit that chamber. Accordingly, it will be necessary to include logic to insure that the cut extract will wait and to insure that the model does not get into a deadlock situation due to interference (nothing can move). The extracted cut may, however, prevent future activities at the other chamber. The waiting times associated with these interferences needs to be determined, as for the case of approach and added to the actual cut exit, e.g.,

Cut Exit Time = Cut Ready For Exit + Cut Exit Approach Interference Wait + Cut Exit Gate Interference Wait.

At the cut exit time, the exit time duration is determined, similar to the approach time, through a lookup to a distribution, again based on:

1. Lock
2. Chamber
3. Vessel class
4. Cut #
5. Type of approach (fly, exchange, turnback, post-exit)
6. Direction (upstream, downstream)
7. Lockage assistance type

Recall that the post-exit time is analogous to the pre-approach time for a turnback exit, in order to represent the time from the movement away from the gate to the far approach point and should similarly be derivable from fly and turnback exit data in LPMS. Note that the impact of direction of travel and current flow on this time estimation may need to be taken into account.

The exit time duration will determine the times when the approach area is occupied on exit (for the purpose of interference) from the point of an entering vessel. Note that, on the exiting end of a chamber, the gate area is set busy only for multi-cut lockages. Also note that for multiple cut tows, the chamber must be turned back before the next cut can start its approach. It should be noted that in many cases, recreational vessels and light boats are allowed to lock through on the turnback operation between cuts.

The time when the vessel finally crosses the approach point on exit is then recorded.

If the next vessel lockage is a turnback, the Chamber Turnback Time is determined in the same manner as chambering time is determined. The chamber turnback begins at the end of the exit, which is also the beginning of the post-exit. Recreational vessels and light boats may be allowed to lock through during the chamber turnback operation.

The overall process repeats. We need to keep track of individual cuts and total vessel movement, so we need to know when we have completed processing all of the cuts of a vessel.

3.8 Vessel Movement Description

3.8.1 What Moves on the Waterway?

As noted previously, it is proposed that all vessels moving on the waterway (tows, recreational vessels, government boats, passenger vessels, etc.) have the same generic description, with differences characterized by data. Thus, the essential unit of movement consists of a power vessel with zero or more barges. We will also make provision for power vessels that can carry cargo without separate barges, e.g., an ocean-going barge, tanker, etc.

A vessel is characterized by:

- Vessel type (e.g., towboat, passenger vessel, recreational, etc.)
- Horsepower (if a powered vessel)
- Operating costs (in motion and while waiting)

- Commodity type carried (if power vessel can carry commodity)
- Commodity quantity carried (if power vessel can carry commodity)
- Length
- Beam
- Name or other unique identifier

Some of these facts may be structured as derived from the type, e.g., horsepower, operating costs, commodity type/quantity and possibly length/beam could all be determined by power vessel type.

NOTE: HarborSym maintains a list of the distinct vessels that are available to the simulation. This may be advisable within NaSS, providing a list of the equipment resources, which might prove useful when considering "conservation of equipment" issues. This should be primarily applicable to tow boats; recording each recreational vessel is problematic.

A tow consists of a towboat with one or more barges. On the Lower Mississippi, tows of upwards of 50 barges are possible. http://oldriverbillzumwalt.members.ktis.net/barges.htm.

We have the option of dealing with individual barges or dealing with the barges as a group (e.g., five tank barges). A structure as described below allows for handling in either manner. Note that this level of detail is expected to be useful in allocating commodities to movements and trips, and in dealing with equipment resource limitations. Note also that standardized names/types exist and should be applied:
http://www.iwr.usace.army.mil/ndc/data/dictionary/ddvess.htm

A tow is defined as shown in Table 4.

TABLE 4
ELEMENTS DESCRIBING A TOW

Entity	Number of Units	Type	Commodity
Power Vessel	1	Tug	N/A
Barge	5	Tank Barge 1	Oil
Barge	5	Tank Barge 2	Empty

This describes a tow of 10 barges, 5 of which are Tank Barge 1 carrying oil and the other 5 are Tank Barge 2, empty. Each barge is characterized by type, and each type is characterized by length, beam and physical type (hopper, tank, etc.). At present, barges are assumed to be either fully loaded or empty. It may also be desirable to be able to reference the value of commodity carried, for possible use in some lockage policies that might take into account high-value cargo.

Barge physical dimensions are defined in relation to barge type (see http://www.ingrambarge.com/additional/Ingram_Draft_Registers.pdf for an example of information in this regard see Table 5).

TABLE 5
EXAMPLE BARGE TYPE AND PHYSICAL CHARACTERISTICS DEFINITION

Barge Type	Length	Beam	Light Draft	TPI
Covered	195	35	1' 7"	17
Hopper	200	35	1' 4"	18.21

The quantity of commodity on each barge can be determined in an indirect manner, based on the assumption that each barge is either completely loaded or empty. Separately, we will maintain a list of commodities, and a relationship between barge type, commodity and quantity of commodity as shown in Table 6.

TABLE 6
COMMODITY CAPACITY - BARGE TYPE RELATIONSHIP

Barge Type	Commodity	Quantity
Tank Barge 1	Oil	4160 barrels
Tank Barge 2	Oil	5000 barrels

Note that uniform capacity measures need to be established for commodities, consistent with how commodity forecasts are defined and including standard commodity codes:

- Commodity
- Description
- Standard code
- Unit of measure (generally tons, other where appropriate)

This relational data structure allows us to define a tow as a combination of a power vessel and barges, with barge types, dimensions and commodity quantities known.

3.8.2 Vessel Movement (Shipment) Description

Now that we have defined and have a method of characterizing what is moving on the waterway (essentially a power vessel plus zero r more individual barges), we need to define how the movement of this entity is described, e.g., from where to where. At this point, a key decision is whether or not a tow can contain barges that originate/terminate at different ports (i.e., a trip with multiple legs). In the most general case, we would want this capability, so that tows could start at an initial origin, pick up and drop off barges at intermediate ports and proceed to a final destination. If we wish to maintain this, then the data structure for a tow needs to be revised as shown in Table 7 to add origin and destination ports, as well as the order in which ports are visited:

TABLE 7
DATA STRUCTURE FOR TOW WITH MULTIPLE PORTS

Entity	Number of Units	Type	Origin Port	Destination Port	Commodity	Order of Visit
Power Vessel	1	Tug			N/A	N/A
Barge	5	Tank Barge 1	1	2	Oil	1
Barge	5	Tank Barge 2	1	3	Empty	2

For purposes of calculating things like demurrage charges, we may also wish to consider adding a delivery date (or maximum number of days after embarkation) beyond which such charges would accrue.

3.8.2.1 Re-fleeting

At this point, it is worthwhile to discuss re-fleeting, because it is relevant to movement description. As proposed, re-fleeting points are locations in the network at which tows re-configure, as at the mouth of the Kanawha on the Ohio River, where, for example, 15 barge tows are re-fleeted to 5 barge tows for trips on the Kanawha and vice-versa as shown in Table 8. Commodities are not proposed to be imported/exported at a re-fleeting point, commodity transfers take place only at ports. [This is an implementation simplification, to separate out the re-fleeting functionality in a separate object.] The function of a re-fleeting point is solely to re-configure and re-size tows and possibly change power vessels. Just as the responsibility of deciding what happens at a lock is given over to the lockage policy at that lock, responsibility for re-fleeting is given to the re-fleeting point. That is, the re-fleeting point must know what to do with an arriving tow of 5 coal barges moving downstream, or conversely with an arriving tow of 15 barges moving upstream. Consider a re-fleeting point at the mouth of the Kanawha (numbers and ports are made up). Then knowledge of how to re-fleet can be provided in data, roughly as follows (additional information may prove to be necessary)

TABLE 8
RE-FLEETING DEFINITION

Inbound Tow Size	Action	Destination Port	Outbound Tow Size	Outbound Power Vessel Type	Re-fleeting Policy Group
15 (coming upstream on Ohio River)	Divide into smaller tows	Nitro	5	Small Tug	A
5	Assemble Larger Tow	Cincinnati	15	Large Tug	B

The re-fleeting point acts as a storage facility for equipment. If a 15-barge tow arrives bound for Nitro, the re-fleeting point knows that it needs to make up three 5-barge tows using small tugs, while conversely, 5-barge tows coming down the Kanawha river are to be assembled into a single 15-barge tow. Depending upon whether we wish to have the model wait on equipment availability or not, the re-fleeting point would store the arriving equipment until such time as the needed outgoing equipment was there, that is, a 15-barge tow could not start until the required outbound power vessel type and 15 barges were available.

If different entities (i.e., barge companies) have different re-fleeting policies, then this could also be captured in data by naming the set of policies in the above table that refer to a particular group of users, and, in the analysis below, referring to the named set at a re-fleeting point as an additional data item within the movement description.

3.8.2.2 Enhanced Movement Description with Re-fleeting

Assuming that re-fleeting is an integral part of the simulation, then we need to add information about re-fleeting to our movement description as described in Table 9.

TABLE 9
ENHANCED TOW DEFINITION WITH RE-FLEETING

Entity	Number of Units	Type	Origin Port	Re-fleeting Point	Re-fleeting Policy Group	Destination Port	Commodity	Order of Visit
Power Vessel	1	Tug					N/A	N/A
Barge	5	TankBarge1	Port 1	N/A	B	Port 2	Oil	2
Barge	5	TankBarge2	Port 1	RP 2	A	Port 3	Empty	1

That is, the 5 Tank Barge 2 barges are first dropped at re-fleeting Point 2, where they are re-assembled according to the Policy A rules for that re-fleeting point for the destination port 3. Note that if the entire tow is destined for a re-fleeting point, then the power vessel becomes part of the equipment inventory for that point, otherwise it continues (as in the case above) with the 5 Tank Barge 1 barges to Port 2.

3.9 Generation of Vessel Movements

The above describes what moves on the waterway, and how it is transformed at re-fleeting points. The description allows for tracking of equipment (at minimum counting barges by type at ports). Complete specification of a vessel movement, for the purpose of simulation, requires that the initial time/date of the movement (i.e., the movement away from the first port) be specified. Thus, a time/date must be added to the above specification. Generation of vessel movements, then, involves:

1. Determining the tow configuration that moves from a given initial port;
2. Determining the time at which that movement takes place.

Accordingly, we need to supplement our description of a movement with a date/time that represents the departure time from an initial port. We can do this in a relational fashion by assigning an ID to a vessel movement (as described above), and then putting a time on that movement as shown in Table 10.

This approach allows for a method of describing routine shipments, say coal to an electric plant, that occur on a regular schedule.

TABLE 10
MOVEMENT ID AND DATE RELATIONSHIP

Movement ID	Movement Date
1234	12/10/2005 14:01
1234	1/15/2006 13:00

Note that this approach does not, at present, allow us to describe or generate movements that start at a port, and then proceed to another port and pick up additional barges. That is, under the currently proposed generation structure, a movement starts at a single port, with a set of barges that may be destined for multiple ports. This may be a reasonable simplification, but further discussion is required to assess the need for handling more complex movements.

Three methods of generating vessel movements are proposed:

1. By Direct Shipment List Specification
2. By Generic Movement Statistics
3. By Commodity Demand

All three methods can be combined to generate the total set of movements that can be generated. The first method will allow for entry of historical movements, development of a consistent set of test data and delineation of complex movements. The second method is useful for creating movements based on known movement statistics, where the satisfaction of a set of commodity demands is of lesser interest. This could be the case when investigating rehabilitation proposals at a single lock, where it is necessary to develop “loadings” of the lock, but where the specific commodities are not important. Finally, the commodity demand approach allows for driving the simulation by commodity demands, consistent with the NETS framework.

3.9.1 Life Cycle Modeling

Two key issues in life cycle modeling are: specification of the change in shipments over time, and change in the network over time. A proposed method for handling network change has been described previously. While other factors may change over a 50-year period (nature of the fleet, for example), the representation of long-term change in shipments has been seen as somewhat complex, because shipments may change over time in terms of vessel type, commodity, quantity and O/D pair. Accomplishing this in a data-driven fashion has not been simple and the incorporation of general growth multipliers that would apply over the life cycle has not been satisfactory. The proposed solution to this is to pre-specify all vessel types and configurations that might come on line in the future (e.g., if larger locks are built) with a time frame of associated availability and to associate a growth curve with each shipment representation (generic movement statistics or commodity demands).

A set of “growth” curves can be defined and stored, giving the value of a multiplier over time. For example, the following curve represents a 3 percent annual growth over a 50 year life cycle as shown in Figure 13.

By allowing the user to create and store named curves giving a multiplier to be applied in any given year of the life cycle, a great deal of flexibility can be achieved—curves can represent growth or decline, or can represent a sudden change, growth and/or decay as shown in Figure 14.

These named curves are then associated with the shipment specifications, as described below. The use of named curves allows the same growth pattern to be easily applied to a number of different specifications, simplifying user input. Note that the direct shipment list specification does not require the use of growth curves, as any desired pattern of future shipments can be incorporated.

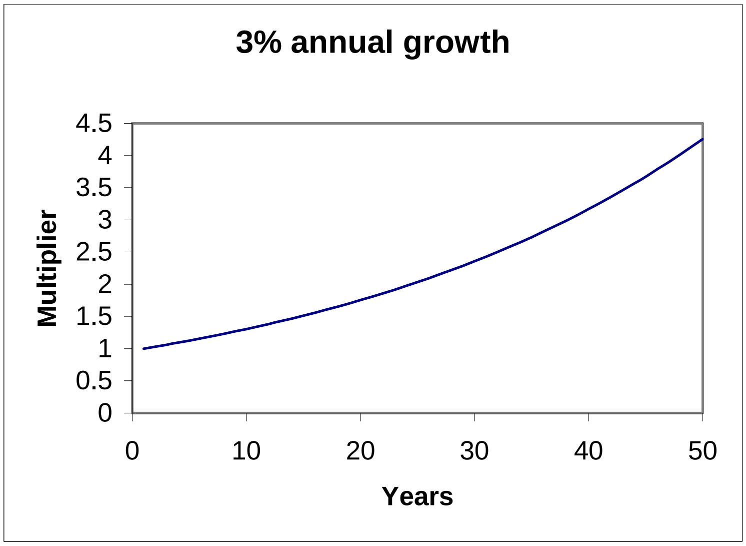


FIGURE 13
EXAMPLE GROWTH CURVE = 3 PERCENT ANNUAL RATE

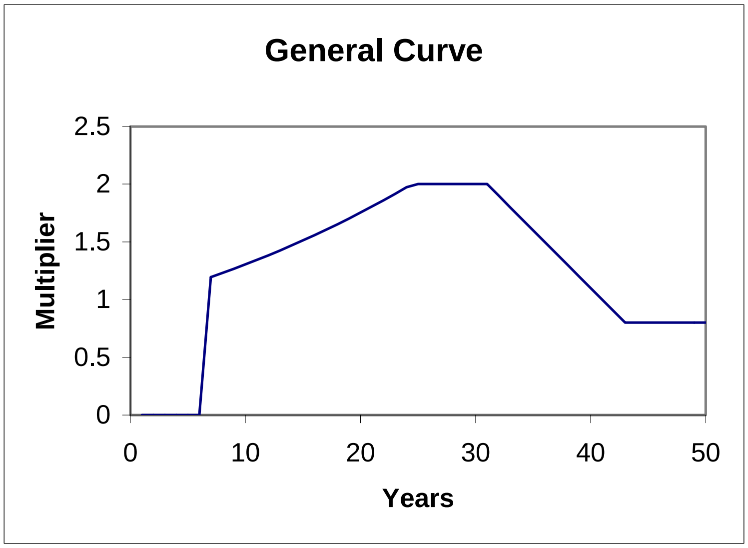


FIGURE 14
EXAMPLE TRAFFIC GROWTH/DECLINE CURVE - USER DEFINED

3.9.1.1 Direct Shipment List Specification

A shipment list, developed from historic data, is used to describe the movement. The GUI will be responsible for taking an external specification of shipments in a standard format (most likely as a spreadsheet) and placing it into the relational framework of the simulation, as is currently done in HarborSym with deep draft vessel calls. One key advantage of implementing the direct shipment list is that it will allow work to proceed on model development without needing to deal immediately with the issues of statistical or commodity-driven generation. It will also allow for testing of more complex shipments than are likely to be generated by the other proposed methods.

3.9.1.2 Generic Movement Statistics

Generic movement statistics are useful for describing vessel movements around a single lock or limited set of locks, where large-scale commodity movements are not the primary focus. Statistics-based movements will also be needed for situations such as movement of recreational vessels and other vessel types.

When considering generation based on movement statistics, the issues of temporal variation must be addressed. There is no question that commodity movements on the waterway are seasonal in nature, depending upon growing seasons and seasonal energy demand, as well as seasonal river conditions. While we may consider commercial traffic to be a 24 hour-a-day operation, recreational vessels exhibit diurnal as well as seasonal variation and day-of-week variation (e.g., higher usage on summer weekends during the daylight hours).

In general, the model will allow user specification of seasons as start and end dates, e.g., season 1 from January 1 through January 15, season 2 from January 16 through January 31, etc. There is no requirement that seasons be of equal length. A reasonable maximum number of seasons should be considered, but this maximum number should be sufficient to capture the variability that is present.

Once seasons have been defined, statistical distributions of vessel trips by type between ports can be defined. Current practice has been to define trip statistics by a mean and standard deviation of trips within the period, which leads to the generation of a specific number of trips in the period, which are then assigned to specific times within the period, in a two-step process. Various alternatives for specifying the distribution of number of trips are possible (normal, triangular, complete cdf, etc.). Whether the method of specifying a distribution should be user-selectable or fixed needs discussion/examination. Assuming, for now, that a normal distribution of number of trips is applied, the generic statistics are defined in Table 11.

TABLE 11
GENERIC TRIP STATISTICS

Season	Vessel Type	Tow Size	Commodity	Origin Port	Destination Port	Mean # of trips in season	SD # of Trips in Season	Life Cycle Curve Spec	Within Season Variability Method
1	Tank1	5	Oil	A	B	25	12	2 % growth	flat
1	Tank1	15	Oil	B	C	13	10	General Curve	flat
1	Hopper1	10	Grain	A	B	19	8	Level	flat
1	Rec	1	People	A	C	300	80	4 % growth	summer rec

Provision is made for associating generic commodity types with movements, if desired to maintain the overall structure of the model that tracks commodities as well as vessel movements.

The above approach will generate tows of uniform contents (i.e., all barges of same type carrying same commodity) and destination.

As noted above, distribution of vessel movements over time once the number of movements in a season is determined is done in a second process. It is proposed that, when specifying information for the season, a "within-season variability methodology" be specified. This methodology can then be associated with data, such as a probability distribution of movements as a function of days in the season, coupled with a diurnal distribution. For example, if 325 recreational vessels are to be generated in season 1, then the "summer recreation" methodology would first contain a distribution allowing for assignment of each of the 325 vessels to a day in the season, and a second step would assign times within each day, again based on an input distribution. A flat methodology would point to a flat distribution for days within season (equi-probable on any day) and a flat time distribution (equi-probable any time). Because of the clear differences in weekday and weekend traffic for recreational vessels and the fact of a life cycle model (which incorporates leap years) it will be necessary to insure that assignment can be made to specific days of the week (e.g., Saturday, Sunday).

Re-fleeting needs to be handled. Either the movement specification statistics can be augmented with a definition of the re-fleeting point that must be used between the origin and destination, or a separate specification that looks at each generated movement and determines whether re-fleeting is appropriate can be used. This latter may be more general for use with commodity-driven movements. In such a case, the specification of re-fleeting would identify the re-fleeting point associated with movements between ports, based on tow size as shown in Table 12.

TABLE 12
RE-FLEETING POINTS BASED ON TOW SIZE

Vessel Type	Tow Size	Origin Port	Destination Port	Re-fleeting Point
Tank1	5	A	B	N/A
Tank1	15	B	C	RP 1
Hopper1	10	A	B	RP 2

3.9.1.3 Commodity Demand Driven Statistics

In this situation, rather than specifying vessel movements, the same seasonal concept is used to specify port-to-port O-D-C quantities needed. Again, using a normal distribution as an example (without requiring that a normal distribution be the only available, or even the preferred, distribution) and allowing the mean to vary according to a curve (if need be, the standard deviation could also be varied by curve, if we want to get to the level of complexity of greater variability expected in out-years) as shown in Table 13.

TABLE 13
COMMODITY O-D STATISTICS WITH GROWTH

Season	Commodity	Origin Port	Destination Port	Mean Quantity	SD Quantity	Life Cycle Curve Spec
1	Oil	A	B	40000	3000	1.5% growth
1	Oil	B	C	80000	7000	2 % growth
1	Grain	A	B	120000	9000	3 % growth
1	People	A	C	300	80	4 % growth

We have previously discussed description of the standard units that are associated with commodities. Converting commodity demand into vessel movements requires knowledge of the tow that will be carrying the movement. The HarborSym Vessel Allocator fleet forecast algorithm for deep draft vessels first determines a fleet of vessels based on statistics by vessel class and then attempts to satisfy commodity demand by loading vessels according to a user-defined priority. A similar approach can be used here. The user specifies the available fleet, in terms of tows of a given type of barge and separately (again as noted above) provides information on which barge types can handle which commodities, and in which quantity. Then a fleet specification is developed (possibly by pool or possibly global to the basin) that defines the tows that should be used to load commodities. If we are considering life cycle modeling, then we need to specify the time frame during which a fleet specification is available, in order to allow representation of change in available fleet as shown in Table 14.

TABLE 14
METHOD FOR REPRESENTING CHANGE IN AVAILABLE FLEET

Season	Barge Type	Tow Size	Number of Tows Available	Priority	Start Availability Date	End Availability Date
1	Tank 1	15	20	1	1/1/2001	12/31/2010
1	Tank 1	5	40	2	1/1/2001	12/31/2005

This specification indicates that there are 20 Tank 1-15 barge tows available for loading in season 1 in 2001 through 2010 and that they should be used to satisfy commodity demand prior to loading the 5 barge tows that are available in 2001 through 2005. We can consider other data structures that would define seasonal availability and change in quantity over the years, but the basic idea is to provide a data-driven method of defining the fleet specification available to the algorithm in each season of any year.

The algorithm then attempts to load tows according to this priority, in essence creating information similar to that generated by the generic statistics method, that is, number of tows of a given type carrying a given commodity between two ports. Assignment of times can then proceed as in the generic statistics approach.

It is suggested that a separate proof of concept of this commodity-driven approach be developed, building on the work done in the HarborSym Vessel Allocation procedure, as the above sketch of the procedure certainly can use more detail. It will also be desirable to review the Tow Cost Model algorithms for generating the most cost effective tow size, given the available tow horsepower.

3.10 Lockage Policies

In the above discussion, a good deal of responsibility has been assigned to the role of the lockage policy in determining what is to be done next when a vessel arrives. Wang and Schonfeld [May 2005] discuss lockage policies as follows:

Different locking policies have been applied in previously developed simulation models. NavSym employed three policies: longest queue, FIFO (First In First Out) and N-Up N-Down. WAM also modeled three policies: FIFO, N-Up N-Down and one-way (for locks with twin chambers). In addition to FIFO, Wang considered issues of priority and fairness with SPT (Shortest Processing Time) and FSPT (Fairer SPT) alternatives. The proposed model should incorporate the operational policies included in the previous models, especially in WAM. Based on the conditions at the locks, the model should also be able to change policies during the simulation run. Other operational alternatives will be considered in future model development, including:

1. *Assignment of tows to multiple chambers*
2. *Priorities and mixing rules for commercial and recreational traffic*
3. *Priorities based on relative service times, time values for tows and their contents and relative lateness*
4. *Fairness objectives and constraints*
5. *Maximum saving control*
6. *Speed control*
7. *Integrated control of adjacent locks*
8. *Alternating platoons of variable size (M-up and N-down)*
9. *Appointment and reservation systems*
10. *Tow cutting and reassembly considerations*
11. *Chamber packing*
12. *Chamber packing with tow cutting*

13. *Auxiliary ("helper") towboats at congested locks*

14. *Water conservation considerations*

15. *Favoring barges or vessels that have incorporated technologies that reduce processing times, such as more efficient coupling-decoupling systems for multi-cut lockages*

Lockage policies are lock-specific and, as noted above, need to be adaptive to queue lengths. A lockage policy is assumed to have complete knowledge of everything within the lock domain, i.e., the type/size of each vessel in each queue, recalling that, as noted above, the lock domain size may be somewhat elastic to allow extended knowledge and projections of arrivals. We can also allow the lock policy to have information on what is traveling in the reaches adjacent to the lock, such that, if the lock is empty, it can be turned in the direction of the next approaching vessel, if desired. Further, the lock policy should have information about congestion at adjacent locks, so that it could favor movement of vessels towards an uncongested adjacent lock, rather than adding more vessels to an already congested adjacent lock.

Note that we have already proposed a very detailed granularity for vessel generation, in particular daily/diurnal variations, in order to handle recreational vessels. Recreational lockage schedules are defined and change seasonally, as shown in Table 15.

TABLE 15
EXAMPLE RECREATIONAL LOCKAGE SCHEDULES

Annual Seasonal Recreational Vessel Lockage Schedule
for the Period 15 May 2005 through 15 September 2005

Navigation Lock	Bonneville	The Dales	John Day
River Mile	145	191	216
Upstream Lockage Times	9:00 a.m.	9:00 a.m.	9:00 a.m.
	12:01 p.m.	12:01 p.m.	12:01 p.m.
	3:00 p.m.	3:00 p.m.	3:00 p.m.
	6:00 p.m.	6:00 p.m.	6:00 p.m.
	9:00 p.m.	**9:00 p.m.**	**9:00 p.m.**
Downstream Lockage Times	*9:30 a.m.*	*9:30 a.m.*	*9:30 a.m.*
	12:30 p.m.	**12:30 p.m.**	**12:30 p.m.**
	3:30 p.m.	**3:30 p.m.**	**3:30 p.m.**
	6:30 p.m.	**6:30 p.m.**	**6:30 p.m.**
	9:30 p.m.	**9:30 p.m.**	**9:30 p.m.**

http://www.nwp.usace.army.mil/pa/news/shownews.asp?rn=05-128

Thus, the lockage policy data at each lock should be able to reflect this type of information.

It is suggested that the initial implementation (prototype) use a subset of possible lockage policies, but incorporate, at minimum:

1. First to arrive
2. N_up/m down (with "trigger" when queue length exceeds a given value)
3. Priority based on tow service times
4. Recreational vessel schedules and rules

5. Limiting a chamber to single cut tows only
6. Forcing recreational craft into a certain chamber at dual chamber locks

Other policies can be added over time.

NOTE: It is recognized that this is not a really adequate description of design for the lockage policy, in terms of "how to do it." There does not, however, appear to be any insurmountable conceptual problem in designing/prototyping a functional lockage policy. Additional discussion on this subject can be deferred to the prototype development effort.

3.11 Conservation of Equipment and Movement of Empties

The need for modeling limited equipment resources and movement of empties has been recognized for some time, but has been seen as a difficult task in the context of a simulation model. A methodology is proposed below that can serve as a start on the problem, but it is recognized that this will need further exploration through a proof-of-concept model.

3.11.1 Equipment Reservoirs

A specification of available equipment—counts of power vessels and barges, by type—is referred to as an equipment reservoir. This information is maintained for each port and must be set initially by the user. We can also consider the possibility of regional equipment reservoirs, specified at a higher level rather than the port level, for ease of initial data specification. In this case, port reservoirs would initially be empty and would be filled from the regional reservoir on the first movements in the simulation. Such regional reservoirs might roughly correspond to pools, but may also take into account ports in different pools. A definition of the ports that can be serviced by a regional reservoir will be necessary.

Reservoir "levels" (i.e., counts of power vessels and barges, by type) will be tracked over time at the port (and regional if they are used) reservoirs.

Vessel movement specifications, generated as noted above, contain information on the power vessel and barges. Note also that "empty" is a possible commodity, allowing for direct specification of movement of empties, although, as discussed below, it is proposed that the model also be able to internally generate movements of empties as backhauls, as well as movement of light vessels and empties deliveries to ports in need.

The process of tracking power vessels and barges proceeds as follows:

1. If there is nothing at the port reservoir, an appropriate power vessel and number of barges are drawn from the pool equipment reservoir (or designated nearby ports) when a trip is initiated. This reduces the number of barges and power vessels available at the pool reservoir (or adjacent ports). We will assume that, at the start of the simulation, vessels/barges from the regional level "equipment reservoir" are immediately re-positioned to the port. If there is nothing at the pool or regional reservoir, the trip is still initiated, but an equipment deficit is recorded, and the vessel and barges are tagged as "generated." They then become available throughout the simulation, but will carry the "generated" tag, so that, at the end of the simulation, we can count how many vessels/barges have been generated at each pool/port.

2. At the end of the trip, the power vessel and barges are deposited in the port reservoir at the destination port. At this point, full barges are converted to empty if they were not initially empty. Data-driven unloading times per barge, by barge and commodity type, can be specified. The barges from a trip will become available only when all have been unloaded, e.g., if we have a 6-barge tow with each barge requiring 10 minutes to unload, then all 6 would become available at the port reservoir 60 minutes after arrival.

3.11.1.1 Generation of Movements of Empties

Empties can be moved as either backhauls associated with a delivery as might typically be the case for petroleum and chemical barges in dedicated shipments, or in a more ad hoc fashion where empties might be collected and delivered to a point of need, but not associated with a particular movement. Also, as noted above, “empty” can be treated as a commodity and specified directly, such that generated shipments include O-D pairs for the “empty” commodity.

For the case of backhauls, the definition of a trip can be supplemented with an indicator of whether or not it is a dedicated shipment, apparently as done in the tow cost model, in which case every O-D-C that is dedicated will generate a corresponding D-O empty trip, initiating after some unloading time for the O-D-C trip.

The issue of ad hoc movements is more complex, and likely will require further examination, but the proposed approach allows for some interesting possibilities in this regard. We wish to move light vessels and empties that have been deposited at a port to locations where they are needed. The key issue in internal generation of such movements is where to send the equipment. Given that we know, beforehand, all of the planned O-D-C trips, this can be used to provide information as to equipment positioning needs. An initial, calibration phase of the model could be run without ad hoc movements, which would then generate excesses and deficits in the reservoirs. The initial allocation of equipment and dedication factors would be adjusted. Another run would be made and excesses and deficits would again be reevaluated. When the optimal initial allocation and dedication factors are found, the model could then be run in production mode. In production mode, if a port needs a piece of equipment, it will look to the nearest port. If the port needs a towboat, and one is available at the next port, a check would be made to see whether the towboat should take some barges with it when it moves. If so, it will take some barges. This might require some form of “global” intelligence to apply heuristics to the needed movements. In any case, it will be necessary to look carefully at how any simplified decision rules about equipment movements actually behave—in general, this will be a fruitful area for further examination at a later time.

3.12 Reliability

Reliability considerations are proposed to be handled using component states and state transitions, as is currently done in LockSym. Under this approach, at minimum one component is assigned to each chamber. The component can be in one of a number of states, with transitions between the states defined probabilistically, based on “component state transition functions.” A full discussion of the approach (which also incorporates a discussion of how shipper response is handled) is found in draft documentation for LockSym [Males, 2004]. The following are edited extracts from that document

3.12.1 Component-Based Lock Representation

A lock is represented as a hierarchy, as shown in Figure 15, consisting of a lock, composed of one or two chambers (main and auxiliary). Each chamber is composed of one or more components. There is no particular physical definition or behavior associated with a component—it is an abstract general concept. A component is simply something that can fail and whose current status participates in determining the overall performance of the lock. This concept allows the modeling effort to focus on the specific components of interest for the rehabilitation examination. A component can occupy one or more states and each state can have one or more failure modes. Each component has an associated value of "age" and "cycles," that is incremented as the simulation proceeds and that can be re-set by a component repair or rehab.

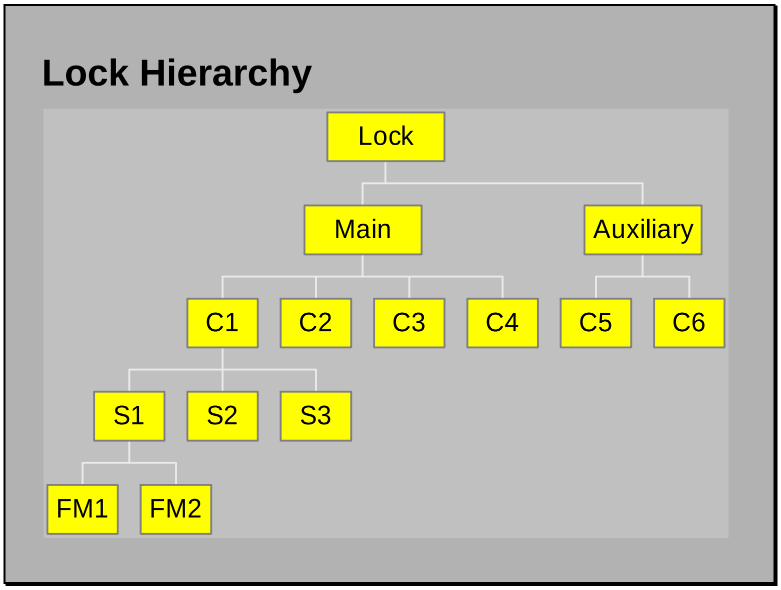


FIGURE 15
LOCK HIERARCHY FOR COMPONENT-BASED RELIABILITY

3.12.1.1 Component States

In order to make data handling and modeling feasible, the concept of component states is used. Each component can occupy, at any given time, one of a set of user-defined states specific to that component. A miter gate, for example, might be in one of three possible states—excellent, poor and non-operational. A guidewall might be in one of four possible states—very good, medium, poor and highly degraded. States are user-defined. Each component can then transition between its available states. The probability of moving to another state is a function of the current state. This is generally referred to as a Markov system or Markov process.

3.12.1.2 State Transitions and Associated Events

The driving force for moving a component from one state to another state can be either the passage of time or the cycling of the lock (e.g., simply opening or closing of the gates), with or without a vessel. Thus, over time, a gate can corrode. It can fail due to stresses associated with repeated opening and closing. A barge can collide with the gate, causing major or minor damage.

The model abstracts this idea to define events under which a component can undergo a particular state transition:

- Time—a regular passage of time, in some user-specified constant period (number of hours);
- Cycling—a cycling of the lock, where no damaging collision is possible (either because there are no vessels at the lock during the cycle or because damage would be negligible—if a rowboat hits the miter gate, the miter gate will not be damaged);
- Lockage of a Vessel (heavy vessel)—i.e., an event where a damaging collision is possible.

State Change Probabilities

In order to define probabilities associated with a change in state of a component, *State transition probability curves* are associated with the component for each of the event types and failure modes that are expected. These curves are typically referred to as PUP (probability of unacceptable performance) functions as shown in Figure 16.

It is understood that such a function should properly be defined as a 3-dimensional function (or family of curves) in terms of both age and cycles—clearly, an older gate that has undergone more operating cycles should be more susceptible to failure than a newer gate with the same number of cycles. However, this level of complexity was determined to be well beyond the existing availability of hazard function data. Accordingly, PUP functions are defined either as age or cycle-based.

Recall that, for each component, the age and number of cycles are known (and continuously updated during the simulation). Thus, at any given time, when an event takes place that may cause a state transition, it is possible to determine, by curve lookup, the associated current probability of that state transition.

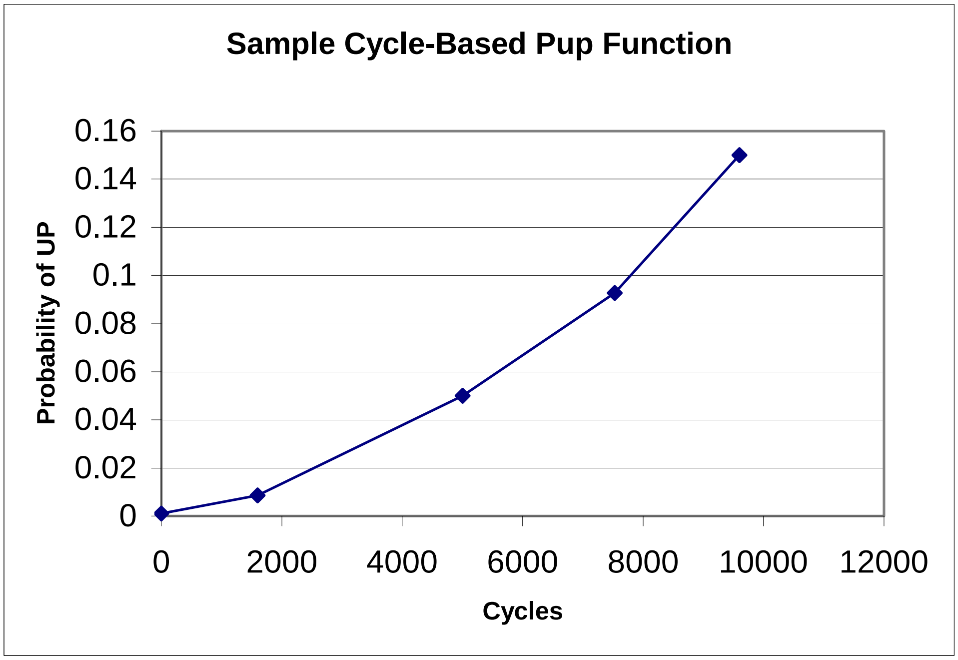


FIGURE 16
CYCLE-BASED PROBABILITY OF UNACCEPTABLE PERFORMANCE FUNCTION

3.12.1.3 Failure Modes and Repairs

For each component state, it is possible to have multiple failure modes, with different probabilities of occurrence. When an event that can trigger a state transition takes place, the current values of the point probabilities of each failure mode are determined from the associated lookups into the PUP functions (based on current component age or cycles). These probabilities are arrayed cumulatively on a probability line, a random number is generated, and the determination is made if there is a failure, and, if so, which failure mode should be selected.

For each failure mode, a repair cost and duration are defined. The repair for a given failure can involve changes to more than the component that underwent failure. For example, if a gate fails, then the electrical system component can also be replaced. The user defines all the component repairs associated with each failure mode. Each such component repair involves setting the current state for that component and revising the current age and cycle.

If the particular failure mode is activated, then the chamber is out of service for the duration period and the associated cost is added to the economic analysis. At the end of the repair, the component states, ages and cycles are re-set to the user-defined values. The post-repair state can be the same as the current state or it can be different. For example, a minor repair can simply consume time and dollar resources, without making a significant enough performance change to move to a different component state.

The resetting of age and cycles associated with a repair can be either absolute or relative. If the values for post-repair age and cycle are positive, then the component's current values are set to these values. If, however, either of the values is negative, then the change is made relative to the current value. For example, if the current age of a component that is being repaired is 25 years, and the user entered value post-repair is 10, then the age is reset to 10 years. However, if the entered value is –5, then the post-repair age becomes 20 (25-5).

3.12.1.4 Scheduled Outage

A scheduled outage is a user-defined period in which the lock chamber is down for maintenance. The user can set a scheduled outage as either a one time or an annual recurring event, with a start date and duration. There are no component state transitions associated with scheduled outages.

3.12.1.5 Scheduled Rehabilitation

A rehabilitation (rehab) is a scheduled outage at the end of which component state changes (or age/cycle changes) take place. Rehabilitation events take place at user-defined times, with specified costs and outage durations, and associated component rehabs, exactly analogous to component repairs in that a new post-rehab state, age and cycle are specified. Each set of rehab events is grouped into a rehab plan that can be activated when the simulation is run. Thus, multiple rehab plans (alternatives) consisting of different combinations of component rehabs can be stored and tested.

It is suggested that this approach be used for each lock/chamber, handling the level of detail through data. That is, at minimum each chamber at a lock is represented by a single component. Some locks, e.g., a lock at which a rehab study is being done, would be represented by more components, with more states and failure modes. A "simple" component for another lock might have two states, a single failure mode and a single associated repair.

3.12.1.6 Performance Penalties

The concept of a performance penalty is used to relate the state of the components to the performance (in terms of time spent serving vessels) of a chamber. In LockSym, each component state is associated with a performance penalty in hours, with a minimum of zero. At any given time, the total performance penalty that is added to the lockage time is calculated as the sum of the individual state-based performance penalties, given the state that each component is occupying. Within LockSym, this is a single number, added to the lock delay. For NaSS, the performance penalty is proposed to be probabilistic and should be associated with a particular stage of locking (e.g., approach, entry, chambering or exit). Thus, a component representing a set of valves would apply the performance penalty to the chambering or chamber turnback stage, as would the gate performance penalties. This will allow a closer coupling of the performance penalties to a physically-based description of the system and can easily be data-driven as shown in Table 15.

TABLE 16
STATE BASED PERFORMANCE METRICS

Component	State	Mean Performance Penalty Metric	SD Performance Penalty Metric	Metric Usage	Applied To
Valve	Good	0.0	0.0	% multiplier	Chambering
Valve	Poor	.25	.06	% multiplier	Entrance/Exit
Upstream Wall	Poor	0.1	.03	minutes added	Approach
Gate	Poor	20.	5.0	minutes added	Chambering

Different abstract components that are related to real physical components (valves, gates) will have different metrics and methodologies for assigning the associated performance penalties. Valve performance penalty should be specified as a given percent of the chambering or chamber turnback time. For a lock with two filling and two emptying valves, if a filling valve goes out, the filling time is doubled. This doubling is applied to the randomly drawn time. Gate performance penalties can be expressed as minutes added.

It is certainly recognized that performance degradation should properly be a function of the combined state of the components, rather than a simple addition of performance penalties, as is currently proposed.

3.13 Shipper Response

Shipper response refers to the choices that waterway shippers have in response to changes in cost, time and reliability of moving on the waterway. Shippers can continue their planned shipments (accepting the delays, increased costs and decreased reliability), change destination, change mode (not ship on the waterway, or use truck to get to another port of export) and/or delay the shipment until a later time (when the scheduled or unscheduled outage has finished) in response to congestion and outages. This is a heavily-studied issue within NETS. In particular, the Wilson-Train model [Wilson, 2004] uses a "stated preference revealed choice" survey methodology and provides a logit model that gives the probability of a shipper selecting one of the available shipment choices based on measures of reliability, time and cost.

The LockSym approach is less sophisticated, relying on deterministic concepts of WTW, WTS and WTD, as described below. A synthesis of the two approaches is expected to be used within NaSS. Further discussion about appropriate implementation of the Wilson-Train model is required, as noted previously.

3.13.1 Potential Movements

Following the approach developed for LockSym, vessel movements are those generated as discussed above, in the absence of outages. Recall that this is a set of time-based movements from an origin port to destination ports, assuming that the locks on the route are in operating condition. This initially-generated set of movements is referred to as "potential movements," in that it can then be modified by shipper response. The model will then record the actual movements that take place. Thus, shipper response is seen as transforming the potential movements into a set of current movements.

At the start of each season, the potential movements are generated, under the assumption that locks are operating and scheduled outages are known. Once the potential movements are available, the response to outages can be applied.

The following is extracted from LockSym Draft Documentation [Males, 2004] and refers to a single lock:

"The feedback between outages and vessel behavior is represented by the "response to outage" system. Vessels that have been generated by the potential trips system enter the respective upstream and downstream potential trips lists, with assigned arrival times. As the simulation proceeds, when an arrival time is reached, the vessel is extracted from the potential arrivals list and placed in the corresponding arrival queue for the lock. Thus, all vessels that have been generated are either in the potential trips list or are in the lock queue. The potential trip list is then processed based on knowledge of scheduled outages, to create a "revised trip list," which in turn is used to drive the simulation.

When scheduled outages are present (regularly scheduled outages or rehabs), the potential arrival list is scanned, immediately after generation, to determine the preference behavior of each individual vessel, based on its WTW, WTS or WTD. Waiting implies that the vessel will accept the delay; diverting removes the vessel from the potential list and the waterway; and shifting changes the scheduled arrival time of the vessel onto the waterway. This behavior is defined and assigned at the vessel class level, by definition of the "WTW" and "WTS" times.

Each vessel in the potential trip list is placed into one of a set of categories, based on algorithms that take into account the projected vessel arrival at the lock, the start and end of the scheduled outage and behavioral preferences that are associated with the vessel class. For each vessel in the potential trip list, the following are taken as the possibilities:

1. *U (Unaffected)*
   Vessel is unaffected by the scheduled outage and arrives at the lock at the same time as originally scheduled.

2. *W (Wait)*
   Vessel is affected by the scheduled outage, but shipper preferences are to accept the additional wait time, so vessel arrives at the lock at the same time as originally scheduled.

3. *D (Divert)*
   Shipper preference is to not initiate the shipment on the waterway. At present, no distinction is made between a shift in mode and a decision not to ship at all.

4. *S (Shift in Time)*
   Shipper preference is to delay the shipment to a later time, but maintain it on the waterway. Note: within the NaSS model, the possibility of the shipper accelerating the shipment to an earlier time should also be considered.

Thus, the processing of the potential trip list involves assigning vessels to each of the four categories. Vessels that are diverted are removed from the potential trip list; vessels that are unaffected or wait are unchanged; and vessels that shift in time have a revised arrival time. In the case of diversion or shift, it is necessary to account for the added cost of the activity, at present by adding a fixed cost defined at the vessel class level.

The categorization into the various categories is handled by assigning, to each vessel class, a time span associated with "WTW" and "WTS" time spans. It is assumed that WTS is greater than WTW. Thus, a vessel with a WTW of 5 days and a WTS of 7 days will accept the wait for any outage that would cause a delay of no more than 5 days. [Note that this does not include time spent waiting in the queue at the lock]. If the outage is such that the arrival time will be between 5 and 7 days after start of the outage, then the vessel will shift. If the outage will delay the arrival by more than 7 days, then the vessel will divert. This is shown schematically in Figure 17, for the case of a scheduled outage.

Trips for the period are shown as short vertical arrows. The two outer large arrows delimit the start and end of the scheduled outage, while the inner arrows show the critical times associated with WTW and WTS. Vessels are thus assigned to the Unaffected, Wait, Shift and Divert categories based on where they fall on the time line. [Recall that WTW and WTS are vessel class specific, so different vessels at the same position on the time line may be categorized differently].

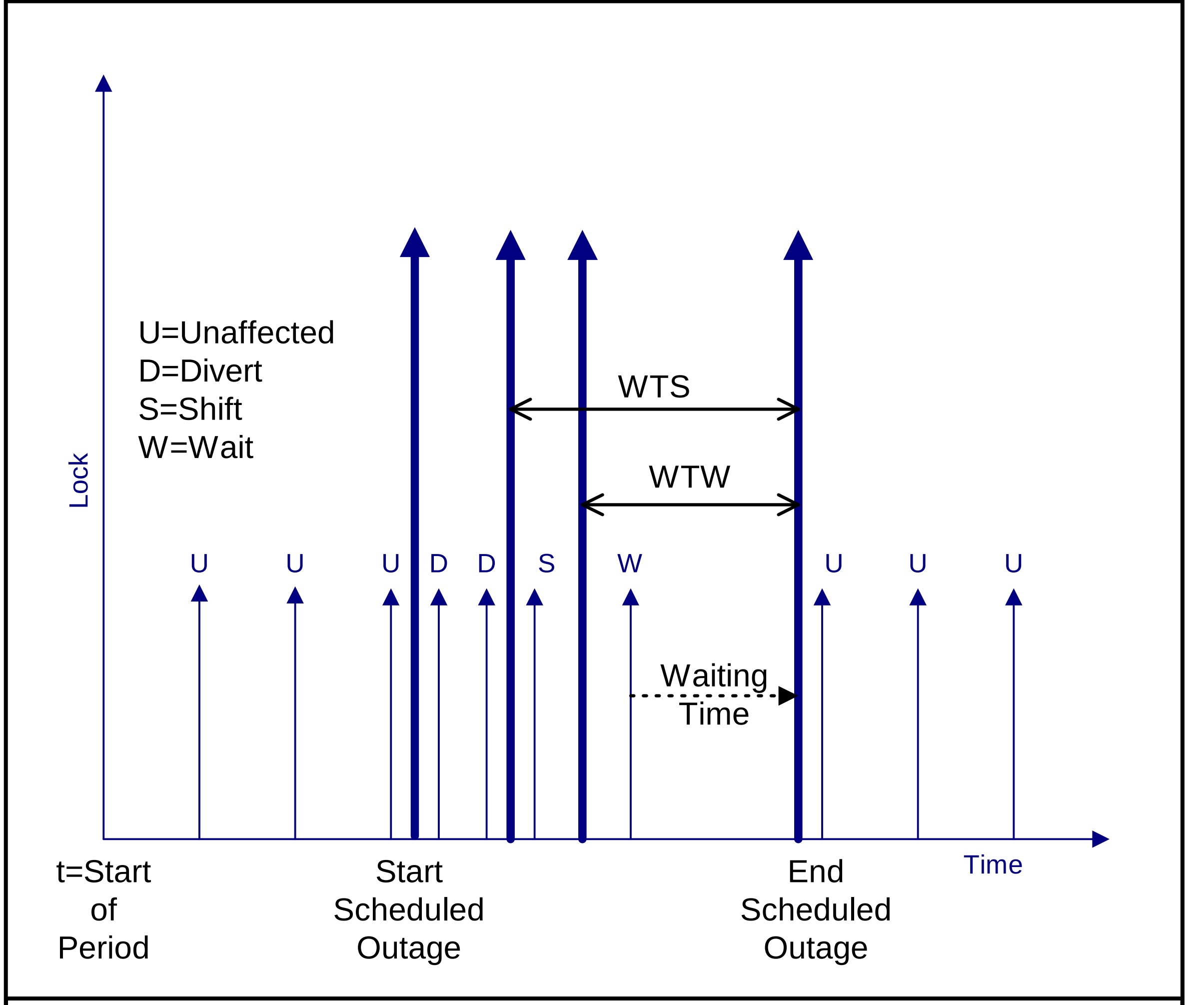


FIGURE 17
WILLINGNESS-TO-SHIFT, WAIT, DIVERT ON UNSCHEDULED OUTAGE

Unscheduled Outages

The revised trip list is used to drive the simulation. When an unscheduled outage (failure) takes place, due to the manner in which the simulation is constructed, the duration of the outage is immediately known. Once an unscheduled outage event takes place, both the potential trip list and the list of vessels on the waterway waiting to be locked are re-examined. Thus, for all those vessels that have not yet initiated trips on the waterway, the situation is the same as for a scheduled outage, i.e., the options are to wait, shift or divert. The primary difference is for those vessels that are already in the waterway en route to the lock – the only options these vessels have are to wait or to terminate the trip (offload cargo, turn around). At present, we are not considering the possibility of termination of an already initiated trip.

Data Specification at Vessel Class Level

In order to support this approach, the following four data items are specified at the vessel class level, for both scheduled and unscheduled outages (it is assumed that shipper preferences and costs may change if there is foreknowledge, as for the case of scheduled outage), for a total of 8 data items describing shipper preference behavior:

- Willingness-to-Wait Time
- Willingness-to-Shift Time
- Diversion Cost
- Shift Cost
- Shift-In-Time

Vessels that are confronted with an outage may have the option of shifting their departure time to a later date, to avoid the outage. (As discussed previously, the possibility of shifting to an earlier date exists for a scheduled outage, but this option will not be explored at this time). The true shift time would likely be the result of contractual agreements, with some kind of economic optimization performed on the part of the shipper. The currently implemented method of handling the shift in time is to distribute the shifted vessels randomly over a window of time starting when the lock is back in service and of the same length as the WTS. The objective is to avoid jamming too many vessels into the time immediately upon return of the lock to service. Other options are possible for assigning the new shifted time and this issue deserves more examination."

In order to handle a multiple lock situation, it will be necessary to have an estimate, for each potential trip, of arrival time at each lock. For example, if a shipment needs to pass through two locks to get to a lock that has an unscheduled outage that has started before the shipment moves on the waterway, it will be necessary to estimate the travel time to the earlier locks and the delay at each lock, to determine the time at which the movement gets to the lock with the outage. If arrival is well after the outage is expected to terminate, then the trip may initiate, otherwise shift or diversion might be expected. Also, if the Wilson-Train approach is to be applied, similar estimates of time and cost will be needed. A method of continuously calculating system "reliability" will need to be developed and factored into the Wilson-Train analysis during the simulation.

In order to achieve a synthesis of the deterministic approach outlined above and Wilson-Train, the Wilson-Train model would be used to determine a threshold probability of a given shipment diverting off the waterway. Each shipment would be tested probabilistically (i.e., a random number would be generated) against the threshold. If the vessel diverts, a cost is assessed. If it stays on the waterway, then waiting and shifting in time are possible, which, for now, should be handled deterministically.

NOTE: looping networks, where alternate routes are possible, should be considered as one of the options, in particular if the alternate route avoids a delay. This possibility should be kept in mind during prototype implementation, but not necessarily implemented in the first stage of prototype development.

Section 4
Investment Optimization Model

The proposed system network model is a simulation model, designed to predict waterway performance given inputs describing the system. That is, individual improvement projects for the waterway, e.g., lock chamber expansion and reliability improvement measures (major rehab, maintenance) are defined and the model is run under those conditions. The system network model in and of itself does not provide information as to the best set of such improvements. Simulation models are typically used to evaluate with/without project conditions, thus the particular set of project conditions must be pre-specified to the model. When there are a large number of alternative projects or timing options for projects, as would be the case in analyzing a system of locks, it is not obvious which set of combinations should be tested through the simulation model.

The selection of "best" options from a large set of combinations is typically the realm of optimization modeling. Optimization models seek to maximize an objective function, which is usually some measure that is related to the outputs that a given set of inputs will produce, subject to constraints. Thus, it is necessary to be able to transform the inputs (in the case of a navigation system, the choice and timing of investments in improvements) into some output measures, such as delay costs or net present benefits. This transformation is referred to as an evaluation function, which may be in the form of a simple equation or a more complex model. Numerical optimization models typically require that the evaluation function be repeatedly calculated and use various methods to search over the input space, that is, to select sets of inputs for evaluation, in an attempt to find the optimal input set. In general, it is not possible to evaluate all combinations of possible inputs (complete enumeration), as this is too costly in terms of computation time. Thus, optimization models require: (a) a search strategy to limit the inputs that are tested; and (b) an evaluation function that gives a value of the objective function for the input being tested.

When complex optimization problems are considered and when the number of input variables becomes large, two factors must be considered in a solution strategy:

1. Determination of the single "best" or optimum solution may be computationally difficult, as compared to finding near-optimal or "very good" solutions;

2. It may be difficult or impossible to develop closed-form evaluation functions; thus, a complex simulation model is needed to serve as the evaluation function.

Under these circumstances, the idea of using a simulation model as an evaluation function in conjunction with a near-optimizing search strategy represents a possible solution path. Under this framework, the search strategy defines inputs to the simulation model. The output of the simulation model is a measure of "goodness" or "fitness" of each solution and is used to inform the search for another set of inputs for testing. One such approach that has been demonstrated successfully in this context is that of GA. In particular, the University of Maryland team has developed the SimOpt model [Wang, Schonfeld, 2005] that demonstrates the feasibility of using a GA search strategy in conjunction with a river system simulation, under simplified conditions of possible investments at locks.

The GA (http://en.wikipedia.org/wiki/Genetic_algorithm) approach to optimization uses a particular search strategy that is an analog to reproduction in evolutionary biology. A "chromosome" is used to encode a set of inputs or candidate solutions, which are then evaluated for "fitness" by an evaluation function. An initial, random set of chromosomes provides the first generation of possible solutions. The chromosomes with the highest levels of fitness in the 1st generation are then modified and tested as the second generation, with fitness of each such chromosome again evaluated. This process continues through successive generations until changes in fitness of the best chromosome fall below some threshold level, that is, until there is no further significant improvement from generation to generation.

The process can be summarized roughly as follows:

1. Create initial solution(s)
   a. develop an initial set of chromosomes (first generation) that represent inputs to the simulation model
2. Evaluate those solution(s) using the simulation model
   a. run the simulation model to obtain output (fitness) measures
3. Apply the search algorithm to generate new solution(s) by evaluating previous solution(s) and determining new search directions
   a. select the better individual solutions from the previous generation (based on fitness) for genetic refinement
   b. create new solutions (next generation) by using crossover, mutation and other genetic operators upon the previous generation to create new chromosomes
   c. evaluate new solutions with simulation model
   d. replace some or all previous solutions in new population
4. Check the termination rule
   a. Have enough iterations been completed?
   b. Have enough solutions been evaluated?
   c. Have the search results stayed unchanged for certain number of generations?
   d. Have the search results improved by less than X% over the previous N generations?

   If the termination rule is satisfied, terminate the process and report results. Otherwise, go to step 3.

Such heuristic search algorithms applied in large-scale combinatorial optimization usually do not guarantee an absolute global optimum, but only a near optimal solution.

The difference between the global optimum and a near optimal solution is usually insignificant, considering the uncertainties in inputs and in functional relations.

4.1.1 Genetic Algorithm—Simulation Architecture

In view of the above framework, the Investment Optimization model must communicate with the simulation model. A chromosome is a representation of the investment choices that can be made in the simulation model. However, there is not necessarily a direct correspondence between these investment choices and the form of input used by the system network model. Accordingly, a "translator" module is proposed that can take as input the chromosomal definition used in the GA optimization and translate this into inputs for the simulation model as shown in Figure 18. Similarly, it may be advisable to have the translator module convert the outputs available from the simulation model into a single fitness value that can be used within the optimization, rather than requiring that this be done within the GA code. In this manner, the GA code can be isolated to conducting the search and creating new generations, with the translator changing as the simulation model is modified.

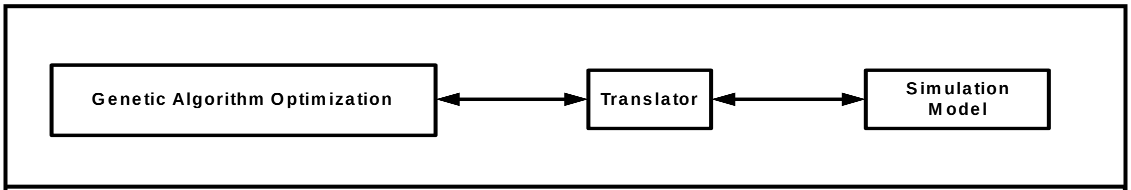


FIGURE 18
TRANSLATOR - SIMULATION MODEL

4.1.2 Project Sequencing Problem

In a sequencing problem, such as the traveling salesman problem (TSP), (http://en.wikipedia.org/wiki/Traveling_salesman_problem) each node in a network must be visited once. The project sequencing problem is similar to the TSP and mainly concerns the relative order of the nodes, i.e., each node's relative and absolute position. A waterway network configuration includes locks, reaches and ports. Candidate improvement projects for some congested locks are proposed for capacity expansion. If the project size is lumpy rather than continuous at any project location, the solution space is increased by a factor of

$$\prod_{i=1}^{n} P_i$$

where Pi is the number of possible projects at lock *i*. The project scheduling problem will then consider more permutations.

Two major aspects of a GA must be considered here: solution encoding and genetic operators. In both of these a solution is represented by an integer sequence in which each number appears only once.

4.1.2.1 Solution Encoding

Traditionally, a path representation (permutation representation or order representation) seems the most natural representation. The chromosome is defined by a string in which the desired projects are listed according to the order of their implementation. An example is shown in Figure 19.

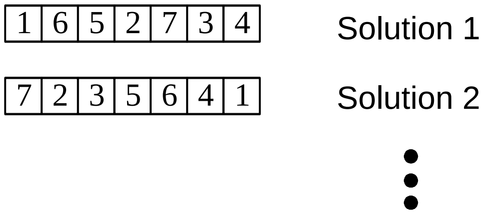


FIGURE 19
SOLUTION ENCODING FOR GA

4.1.2.2 Genetic Operators

If the traditional one-point crossover operator is used, it is seen that the path representation may lead to an infeasible solution, in which some nodes are visited twice and some nodes are skipped (as indicated in following figure). Therefore, some repaired crossover operators used in TSP should be employed to avoid illegal offspring in the project sequencing/scheduling problem.

Most crossover operators are established as two-point or multi-point crossover. Generally, a permutation representation will yield illegal offspring in the sense that some projects may be missed and some projects may be duplicated (as shown in the Figure 20). Thus a repairing procedure of making each number shown only once in a sequence is embedded to resolve the illegitimacy.

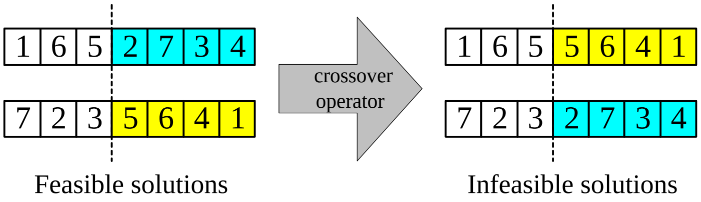


FIGURE 20
GA CROSSOVER WITH INFEASIBLE SOLUTIONS

Recently, several crossover operators have been proposed for the path representation, such as partial-mapped crossover (PMX), order crossover (OX), position-based crossover (PBX), order-based crossover (OBX) and edge recombination crossover (ERX). Those operators have served as standard operators for solving the sequencing problem. For the mutation operators, it is relatively easy to introduce a small change within a single chromosome, such as an insertion mutation (IM), reciprocal exchange mutation (EM) and inversion mutation (VM).

4.1.3 Inputs of Project Information

The proposed lock improvement projects are intended to improve the capacity, service time and reliability at locks. From historical data, service time distributions can be developed for the existing locks. For locks after improvement projects, it is more difficult to estimate the service time distributions. Besides, if an improvement project adds a parallel chamber and transforms a single-chamber lock to a double-chamber lock, the lockage behavior will be changed, e.g., in regarding chamber bias and lock interference, as well as service time distributions. Therefore, it is important to consider how project information will be specified and translated into proper inputs for simulation and optimization models.

For any single project, there should be a structure which may contain the following information:

- Project index (from 1 to N projects)
- Lock location (lock ID, each lock may have more than one project alternatives)
- Number of chambers
- Estimated construction cost
- Expected annual maintenance cost
- Construction time
- Capacity expansion ratio (after project improvements) or new service time distributions
- Capacity reduction ratio (during project construction time) or temporary service time distributions or lock outages related to construction.

4.1.4 Project Scheduling

As funds become available over time and assuming that funding is not sufficient at any time during the simulated analysis period to implement all justifiable projects, the project sequence automatically determines the implementation time for each project. Each project in the sequence is then implemented as soon as the funding stream allows it. Hence, with a constrained budget over time, the optimal project sequence uniquely determines the optimal project schedules.

4.4.5 Single Project vs. Multiple Projects at Single Location

As implemented in SIMOPT, the simplest case allows at most one project at each lock location. However, it should be possible to have multiple alternatives at particular lock locations, including projects which supplement or fully replace previous ones. In such cases we must sequence projects, not locations. If multiple projects are implemented at the same location, their costs are not independent and those interrelated costs must be estimated for various timing alternatives.

4.4.6 Construction Time and Capacity Reduction

The SIMOPT's simplifying assumptions in solving the project selection/sequencing/scheduling problem is that lock capacity increases instantaneously after a lock improvement project is completed. It does not yet consider project construction time or any possible capacity reduction during the construction period. However, if the lock capacity is temporarily reduced, possibly down to zero, we must consider how to model the demand reaction to the abnormal delays during construction.

4.4.7 Computation Efficiency

Combining two stochastic processes of simulation and GA optimization requires considerable computation time. Since simulation is used for evaluating each generated project sequence and several simulation runs over the analysis period are required to reliably evaluate each solution (i.e., each system improvement schedule), considerable time is required for the optimization process. We should also try to check whether any newly generated solutions are similar to previously evaluated solutions, in order to avoid re-simulating them.

In general, the various constraints (e.g., on available budgets, precedence and complementarity among projects, regional distribution of projects) that may be relevant in investment scheduling problems should be checked before candidate solutions generated by the optimization algorithm are subjected to lengthy simulation. Thus any "infeasible" solutions, i.e., solutions that violate any constraints, should be rejected before being simulated. If the problem becomes more constrained, the number of feasible solutions decreases and the total time required for the search should also decrease.

4.4.8 Other Genetic Algorithm Operators

In addition to standard GA operators, we should seek to develop some "smart" GA operators that specifically exploit our problem structure. For example, since traffic in a waterway network is restricted by some geometric relations, some improvement projects for adjacent locks could be considered jointly, for example if certain implementation sequences are known in advance to be desirable.

Section 5

Discussion

The above is a rough sketch of the essential concepts of the primary models proposed for the NaSS suite: the system network model and the investment optimization model.

The guiding principles were:

- Data-driven approach
- Consistency in handling each element of behavior
- Maintaining capabilities found in existing models

This is clearly a very ambitious task, in no small measure because our understanding of the complexities of the problem is much greater than our ability to model all of those complexities.

Further discussion is obviously merited, in particular as to whether the whole concept hangs together or falls of its own weight and whether there are glaring flaws in the approach. At this point, however, it is suggested that work start in the near future on the various proof of concept/prototype developments, together with selection of a test data area (note that test data is not considered to be the same as a test bed, which is a real application for a project). Only by getting into the real issues through developing and demonstrating models and data structures will the possibilities, problems and limitations be revealed.

The initial efforts should be oriented towards exploring the questions that seem difficult at this point, in particular multi-path networks, conservation of equipment and re-fleeting, to see if the conceptual design proposed is adequate. The Upper Ohio might serve to provide initial test data for the prototype—there is a good deal of experience on the part of the development team with this area and the associated data.

Section 6
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