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**OHIO RIVER NAVIGATION INVESTMENT MODEL:
REQUIREMENTS AND MODEL DESIGN**

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ABSTRACT

Oak Ridge National Laboratory is assisting the U.S. Army Corps of Engineers in improving its economic analysis procedures for evaluation of inland waterway investment projects along the Ohio River System. This paper describes the context and design of an integrated approach to calculating the system-wide benefits from alternative combinations of lock and channel improvements, providing an ability to project the cost savings from proposed waterway improvements in capacity and reliability for up to fifty years into the future. The design contains an in-depth treatment of the levels of risk and uncertainty associated with different multi-year lock and channel improvement plans, including the uncertainty that results from a high degree of interaction between the many different waterway system components.

Key words: inland waterways economic analysis

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) is working with the U.S. Army Corps of Engineers to develop the Ohio River Navigation Investment Model (ORNIM), which will extend and update the procedures used within the Corps Lakes and Rivers Division (LRD) to evaluate the economic feasibility of proposed inland navigation improvement projects. Division planners and economists already have at their disposal a suite of models, built around a project and systems simulation approach, that was developed in the mid-1970s and has been continuously used and modified over the past twenty years. ORNIM will build upon this legacy and add new capabilities to:

- analyze projects within a systems context;
- incorporate risk and uncertainty associated with project performance and economics; and
- allocate funds among expenditure categories of maintenance, rehabilitation, and new construction.

In the course of developing this new and expanded modeling system, ORNL will also assist LRD in reengineering its navigation project analysis system to take advantage of current and next generation computing hardware and software capabilities. The initial use of ORNIM will be to support the currently ongoing Ohio River Main Stem Systems Study, with eventual application to the entire Ohio River System.

The paper is organized as follows. Section 2 provides a statement of the ORNIM objectives and requirements. Section 3 goes over, in abbreviated fashion, the existing analytical base, i.e., the LRD legacy models. With this as the backdrop, Section 4 looks at several alternative approaches to developing ORNIM, and Section 5 covers ORNL's selected ORNIM structure and development plan. Section 6 concludes the paper with a summary of the ORNIM development schedule.

2. OBJECTIVES AND REQUIREMENTS

This section discusses the objectives to be achieved by ORNIM and the resulting system requirements.

2.1 ORNIM Objectives

The near-term objective is to extend the Corps' modeling capabilities to address the benefits of new construction, major rehabilitation, and major maintenance for all nineteen navigation lock and dam sites on the Ohio River mainstem. In the follow-on phase of model development, the capabilities of the modeling systems will be extended to the entire Ohio River Navigation System.

The model also will be capable of identifying an optimal investment strategy from an identified set of new construction, major rehabilitation, and major maintenance projects/policies, and given that the Corps will be subject to yearly or multi-year budget constraints.

2.2 System Requirements

The modeling system to be constructed must satisfy both specific requirements for decision makers (the business perspective), and specific requirements for analysts within the Corps who will use and maintain the system (the analysis perspective). From the business perspective, ORNIM must: (1) be credible with analysts and decision makers within and outside of the Corps; (2) be responsive to relevant policy issues and questions; (3) produce results that are reproducible, reliable, and reusable; and (4) produce results that can be communicated in a way that facilitates decision making.

From an analysis perspective the modeling system must: (1) have capabilities for system-wide analysis; (2) incorporate risk and uncertainty with respect to commodity demand forecasts, land and river transportation rates, and system reliability; (3) include detail to adequately represent the Ohio River System; (4) execute within a reasonable processing time; (5) be compatible with existing and/or projected capabilities of Corps staff to run and support the model (the Corps will not rely on outside support for system execution or routine maintenance); (6) generate reports that are policy relevant and consistent with legal and other requirements placed upon the Corps; and (7) be compatible with required inputs and needs of other analysis systems within the Corps, such as environmental analysis.

2.3 The Current Modeling System: A Simple Overview

The Corps currently maintains a modeling system that is used to estimate the expected benefits of new construction projects. The models in use include the Waterway Analysis Model (WAM), the Tow Cost Model, and the Equilibrium Model.

In a typical analysis, the Corps begins with exogenous information on (1) projected shipments of commodities that will occur over time within the Ohio River System, (2) projected rates and accessorial (e.g., pick-up and delivery) charges for both river and competing land modes of transportation, and (3) information about the transportation capacity of the Ohio River System. (Overland modes are assumed to have no capacity constraints, and neither land nor river rates are a function of commodity traffic.) As represented in Figure 1, the Corps estimates the capacity of a particular lock and the entire system for both with-project and without-project conditions. The with-project conditions reflect the projected new capabilities of the river system given that the project in question is completed as envisioned. These various exogenous inputs are used within the current modeling system (comprising WAM, Tow Cost, and Equilibrium) to estimate the net benefits of the river system with and without the construction project in question.

Figure 1. Current LRD Modeling System.

The models are exercised in an iterative fashion, balancing waterway delay costs (which increase with tow traffic) against the cost of shipping by an alternative mode, to arrive at equilibrium traffic levels. The addition of new capacity to the Ohio River System results in two types of benefits: (1) reduced delays, and therefore reduced delay costs, for commodities that were shipped by river prior to the addition of the new capacity, and (2) the benefits of additional river tons, derived as the difference in the cost to the shipper of the waterway movement as compared with the overland movement.

2.4 Moving Toward The Near-Term Objective

In the near term, ORNIM will extend the current modeling system in four primary ways. First, the system will be capable of modeling all nineteen locks and dams along the Ohio River mainstem. Second, the new system will account for risk in transportation rates and commodity forecasts. That is, these important inputs will be treated as random variables rather than as constants, and their variability will be incorporated explicitly into the analysis. Third, the new system will be capable of estimating the benefits of major maintenance and rehabilitation, as well as new construction. Fourth, the outputs of the new system will be consistent with the needs of other Corps analysis activities, such as environmental analysis.

Figure 2 gives a simple representation of how these near-term objectives will be met. Note that the benefits of major maintenance will depend on the contribution of those activities to increased physical plant reliability. Major rehabilitation will improve both lock capacity and physical plant reliability. These near-term objectives will be met by integrating and extending the current set of models.

2.5 Moving Toward The Ultimate Objective

In its final version, ORNIM will: (1) be extended to the entire Ohio River System; (2) incorporate uncertainty to account for different futures (i.e., scenario analysis will be used); (3) incorporate Corps budget constraints; and (4) allow for optimization of the net benefits of the Corps' activities across new construction, maintenance, and rehabilitation projects and policies, and across time. (Different scenarios could represent, for example, different demands for coal on the Ohio River System given different assumptions about electric power restructuring.)

Optimization of all the Corps major activities across the entire system poses a significant combinatorial problem (see Section 4.2 below). ORNL foresees the need to identify initially a limited number of new construction, major rehabilitation, and major maintenance projects/policies, and also the need for a reduced form optimization model that will be used in an iterative fashion with the integrated and extended set of current models. The modeling systems' ultimate object is to help analysts identify the optimal investment path in new construction, major rehabilitation, and major maintenance to maximize river system benefits over time, given the Corps' expected multi-year budget constraints.

It is important to note that, like the existing models (see next section), the analytical components of ORNIM will consider only waterway system options. For example, the competing overland modes are assumed to have sufficient capacity to absorb any movements diverted from the waterways, and the origin-destination pattern of the commodity movements remains fixed. For the near term, any such considerations must continue to be handled with ad hoc procedures. Relaxing these limitations could be the object of future ORNIM enhancements.

Figure 2. Near-Term Model Framework.

3. EXISTING ANALYTICAL BASE FOR ORNIM

This section reviews, in abbreviated fashion, the existing analytical base for ORNIM, i.e., the LRD legacy models and related information sources. The design intent is that ORNIM will include and reproduce all of these capabilities.

3.1 The Waterway Analysis Model (WAM)

The Waterway Analysis Model (WAM) simulates the movement of individual tows on the waterway to generate infrastructure performance measures. The model is perhaps the most detailed of the analysis tools used for river system economic assessment. For the purpose of model analysis, the Ohio River system is organized into sub-units, referred to as sectors, and the sectors further segmented into reaches. A reach is a homogenous section of the river with a port,

lock or branch point at either end. A WAM discrete simulation analysis can focus on a single lock and reach (which is its normal mode of use) or the entire river system.

The model data base incorporates detailed descriptions of the major physical components of the waterway, i.e., the locks, lock chambers, and river channels. The simulation is conducted using a detailed characterization of the transportation equipment on the waterway, specifically the towboats and barges. The vessel factors used to compute the speed of a tow on any given reach are the size and draft of the barges and the horsepower of the towboats. An analysis is initiated by defining a set of tows for a specified time horizon, usually a year. The tow list indicates the composition of the tow, the commodity shipped, the origin and destination ports, and time of departure for each tow. The simulation then proceeds to determine the transit time along the river and the time in lockage for each of the tows. The model is realistic enough to include such factors as queueing of vessels at a lock. The mix of vessels includes back hauling empty barges, as well as recreation craft. From an analysis and summarization of all shipments, the model derives annual average measures of system performance.

Given a set of projected tows the simulation model provides a large set of standard performance measures on the waterway system. The model generates data for each lock in the system and provides a summary lock utilization and delay report as well as information on individual lock chambers in the chamber status report. Activity on each of the key points on the river system is summarized in port activity, reach activity, and river bend utilization reports. The system wide use of transportation equipment is summarized in the equipment utilization report. For the purpose of the National Economic Development (NED) benefits analysis the summary report of interest is the lock utilization report which can be used to examine the relationship between total tonnage on the river and the time a typical tow is delayed waiting to transit a lock, i.e., the average delay time.

The lock traffic and delay information is often used to estimate a delay curve, showing how the expected average annual delay changes as the amount of traffic on the river increases. At low volumes, few tows arrive simultaneously at any given lock. As the volume of traffic increases the number of simultaneous demands increases and queues may form as each tow has to wait its turn for lockage. While some variations in delay and tow traffic can be gleaned from an analysis of the historical record, the situations of most interest are often outside the range of past experience. For these cases, a simulation analysis can provide an estimate of the expected delays. Several runs of the WAM model can be used to develop the expected annual delay that a specific lock is likely to experience at various volumes of river traffic. In Figure 3 for example, three WAM runs provide three points on the average delay curve, from which the remainder of the curve can be interpolated. A lock specific relationship can be used to explore the impacts that an increase in tow volumes may have on delays. While this figure shows that infinite lock delays are possible theoretically, the LRD legacy models use procedures to recognize fleet availability constraints, and ORNIM will incorporate similar constraints. In the National Economic Development benefits

Figure 3. Delay Curve Developed from WAM Analysis.

analysis, WAM delay curves are used as inputs to the Tow Cost and Equilibrium models which jointly determine the traffic volume realized out of the projected potential shipments.

3.2 The Tow Cost and Equilibrium Models

The purpose of the Tow Cost Model (TCM) and Equilibrium (EQ) model is to determine which commodities will ship on the waterway in a given year; and the total savings that will be accrued by shipping these commodities on the waterway as compared to the land alternative. The total savings are used to estimate the national economic benefit produced by the waterway.

These coupled models utilize the following input data:

- a list of commodity movements that may be shipped either over land or over water. These movements are expressed in terms of the number of tons of a given commodity that are annually carried between a given origin and destination;

- the average hourly ownership and operating costs for each kind of tow equipment, and the commodity inventory carrying costs;
- the average time required for various tow activities (e.g., loading, unloading, barge pickup, etc);
- the time it takes to transit a lock, weighted over the various types and sizes of tows that will use the lock; and
- the cost of shipping each movement overland.

The calculation of waterway savings requires the determination of intermediate results which include:

- the identification (by EQ) of which movements will ship over the waterway (at a savings compared to the land alternative);
- shipping plans for each movement which specify the types of tows used to carry the movement at each point of the waterway and the number of these tows required each year; and
- the total tonnage shipped through each lock and the corresponding lock delay times.

Figure 4 illustrates the general process by which TCM and EQ perform their calculations. The set of movements that will ship on the waterway, the waterway savings, the shipping plans, annual tonnage carried through each lock and the resulting lock delays are all interdependent. Because of this the TCM/EQ calculations must be carried out in an iterative fashion until their results are consistent. Intermediate items can be held fixed (e.g., the shipping plans) to help the coupled models converge.

At convergence the model produces a self-consistent set of results which include:

- the set of movements that will ship on the waterway (at savings);
- the shipping plans which will be used to carry each movement;
- lock delays resulting from waterway traffic;
- the waterway cost of carrying each movement; and
- the total transportation savings produced by the waterway.

3.3 Engineering Reliability Analysis

A major source of variability to be included in ORNIM is the risk of unsatisfactory performance of a navigation structure. This might be due to any random failure of a critical lock chamber component, such as a gate or valve, which causes the chamber to be put out of service until such time as it can be repaired. Probability of unsatisfactory performance is a function of time, traffic cycles, or both. The Corps is going through a detailed analysis of the physical characteristics and condition of the major lock chamber components in an effort to obtain an engineering assessment

Figure 4. Coupling of Tow Cost and Equilibrium.

of this type of risk. To do this, Corps analysts have identified the major subassemblies that might be subject to corrosion or fatigue failure, and are running service cycle simulations to develop probability of failure estimates. These estimates will be expressed as hazard functions, which specify the probability of unsatisfactory performance of a component in any given year, given that it has survived up to that point in time. As time and traffic cycles build up, of course, the failure probabilities increase.

Of additional interest is the level of severity of a failure (e.g., minor, moderate, or major) and the associated downtime, repair cost, and component reliability following the repair. The Corps engineering reliability analysis team is generating estimates of the probability of each failure state and the ancillary cost and consequence items. The hazard functions and consequence data are the

basic inputs to event trees which can be used in an economic model for maintenance decision making. One such model being developed by the Corps is the Life Cycle Lock Model (LCLM), which will be used to simulate lock closures and their economic consequences over a fifty-year period.

The engineering reliability analysis will be a major input to ORNIM. An issue currently being investigated is how to aggregate the individual component hazard functions into composite functions that will characterize the probability of failure of the lock chamber. Composite functions are needed because it is impractical to treat individual subassemblies at the systems level of analysis, due to the combinatorial problem of evaluating the enormous number of unique system states that would be possible.

3.4 Environmental Impact Models

Currently, assessing the environmental effects of tow traffic on the inland waterways is performed off-line from the simulation modeling and economic analysis, but using river traffic inputs that are derived from the latter. Two ecological models, NAVPAT and QUEPAT, are used to look at the effects of tow traffic on biological habitat suitability. These analyses are project-based, rather than system-wide. They consider the river sections between locks, given changes in the lock locations and sizes and the concomitant changes in the size, composition, speed, and frequency of passage of the tows. The environmental analyses require considerable disaggregation of this data. For example, tows are described by their specific dimensions, horsepower, and propeller speed, and the river cross section is subdivided into twenty cells, for which analyses are conducted over very short time intervals. These environmental models are of fairly recent vintage, and are detailed enough to be compatible with both the existing LRD models and the proposed ORNIM. Consequently, the ORNIM development strategy is to ensure that the environmental models will be able to receive tow traffic data which is at least as detailed as that which is being provided currently.

3.5 Navigation Industry Impacts

A key part of the expanded ORNIM analysis will be data on the impacts of system performance on the barge operators and shippers who use the waterway. Since a primary objective of ORNIM is to assess trade-offs between new capacity and system reliability, information about the costs of unscheduled closures (due to lower system reliability) is crucial. Preliminary discussions have been held with industry representatives on the availability of information on topics such as:

- the impacts of lock closures, especially those extending for more than a few days;
- differential effects of planned and unplanned lock closures;
- operator and shipper actions to prepare for and recover from lock closures;

- navigation project benefits, especially those (such as reliability) that are not captured by present analysis methods; and
- major sources of uncertainty affecting barge demand and river operations.

The industry representatives indicated that at least some data were available on nearly all of these topics. Hence, part of ORNIM development was devoted to meeting with the navigation industry to build up a data base in these areas. Preliminary results verify that this is a complex topic with little organized data available, so additional work on this topic is underway.

3.6 Navigation Analysis Data

There is a rather complex web of data underlying analysis and evaluation of proposed navigation improvement projects. The existing models require inputs on commodity origin-destination flows, river system physical characteristics, the makeup of the towboat and barge fleet, locking times, lock outages, vessel operating costs, and shipping rates for water and alternative mode movements. The entire economic analysis process relies on industry surveys, area economic and demographic profiles, projections of economic conditions, and so on. Finally, the analysis process itself produces numerous intermediate and final data files. Dealing with all of this data in a structured but flexible way is an important aspect of the ORNIM development process. Space precludes further coverage of this topic here.

4. ORNIM DEVELOPMENT STRATEGY

4.1 New Capabilities Required

Comparing the capabilities provided in the existing analytical base with the objectives and requirements for ORNIM that were stated earlier affirms that a number of new or expanded analytical tools are needed. Some of these are:

- (1) An integrated approach to calculating the system-wide benefits of alternative navigation improvements;
- (2) An in-depth treatment of risk and uncertainty associated with multi-year lock and channel improvement plans, including engineering reliability of structures, variability of waterway demand, variability of operating costs and rates, and uncertainty due to unforeseeable changes in government policies and macroeconomic conditions;
- (3) The ability to formulate optimal budget-constrained multi-year investment plans for the entire Ohio River System, featuring trade-offs between maintenance, rehabilitation, and new construction;

- (4) An approach combining detailed simulation of waterway system operations with the use of optimization methods to search through the very large number of possible multi-year investment plans;
- (5) An efficient computing environment, coupling the best features of the existing LRD modeling suite with the latest software and hardware to facilitate cost-effective and timely analyses of policies and plans; and
- (6) A modeling outcomes display system that clearly sets forth for decision makers and the public the expected benefits of the recommended improvement plans, and that clarifies the level of uncertainty of these benefits.

All of this must be delivered in a package that enables reviewers to understand what was done, and that provides traceability of the results.

Table 1 summarizes the capabilities of the existing models. The left side of the table lists the major features that are needed in ORNIM. The right side indicates which features are present in the major existing models, including the WAM, TCM, EQ, and LCLM. As can be seen, the features listed near the bottom of the table are not available in any of the current models.

4.2 Development Alternatives

ORNL looked at four basic approaches that could be followed in developing ORNIM, as follows:

- (1) an extended WAM, that would rely heavily on simulation;
- (2) an extension of the TCM and EQ models;
- (3) an optimization model that would directly seek the best investment plan; and
- (4) a hybrid model combining various elements of the other approaches.

To some extent the first three approaches are all needed to provide the desired features. The main differences in the development approaches are in how much effort is devoted to building each of the new models.

In an extended WAM, nearly everything would be done in the simulation, which would have new modules to capture demand diversion, tow list generation, movement costing, risk functions, and so on. Only the optimization would be done outside of this model, and it would likely be limited to searching over a manually generated set of alternatives, which would necessarily be limited in number. The appeal of this approach is the realism and potential veracity of the simulations. With proper design, the simulation outputs would reveal much about how each plan would perform under traffic. The disadvantages are the significant model development and calibration time, even with modern object-oriented simulation tools, and the tremendous load of detailed

TABLE 1. Existing model features.

Feature	WAM	TCM	EQ	LCLM
Discrete tow movement simulation of locks	✓			
Discrete tow movement simulation of waterways	✓			
Generation of lock delay curves	✓			
Determination of waterway traffic levels	✓	✓		
Determination of shipping plans		✓		
Model hourly cost		✓		
Model demand		✓	✓	
Calculate movement costs		✓	✓	
Balance supply and demand			✓	
Analysis of single projects	✓	✓	✓	✓
Modeling of lock hazards				✓
System modeling of lock hazards				
Model demand variability				
Model hourly cost variability				
Analysis of system-wide project plans				
Analysis of repair and maintenance plans				
Analysis of repair and maintenance policies				
Optimization of system-wide project plans				

input and output data to manage. Computing time would also likely be a constraint. (These disadvantages of WAM are what have led to the use of the TCM/EQ style of analysis.) Alternatively, TCM and EQ could be modified to incorporate most of the new features. WAM would still be used for operational questions and to generate lock delay curves, but everything else, save optimization, would be done in the Extended TCM (ETCM). The advantage, as with the simulation approach, is that everything is familiar, and the work required revolves around developing some new algorithmic formulations and converting everything into an object-oriented language. The disadvantage is that each situation to be analyzed would need to be explicitly input to the model, placing a huge burden on the analysts. In fact, the combinatorics related to the number of runs required blow up quickly, as discussed below.

The main disadvantage of the optimization approach is its ability to deal with conducting a search over the extremely large number of discrete investment plans that need to be considered. For example, a system with nineteen locks, with two chambers at each lock and five possible investment options for each chamber yields 5^{38} investment options per time period, which is approximately 10^{26} , or a number with twenty-six digits to the left of the decimal point. When the uncertainty elements of the problem are considered, the combinatorics explode. Even with clever ways to pare down the analysis set and automate the run generation process, optimization methods offer the only real hope to systematically explore the entire solution set.

As might be expected, a hybrid approach to developing ORNIM offers some of the best of each of the other three approaches. One such parsing of the desired features is indicated in Table 2. The hybrid approach incorporates the WAM, the ETCM, and an optimization model. As can be seen in Table 2, extensive work will be needed on the ETCM. Likewise, a new optimization model must be built. The WAM is expected to be used without significant modification, and reengineering or reprogramming it to take advantage of current generation computing environments will be postponed to a later effort. This is the approach that ORNL is following, and that is presented in detail in the next section.

5. ORNIM SYSTEM DESIGN

This section first presents the overall ORNIM system design, with specific attention to incorporation of the navigation hazard functions and to reengineering an extension of the TCM. This is followed by a presentation of the preliminary design of the optimization model.

5.1 ORNIM System Design

The proposed ORNIM system design, based on the approach recommended in Section 4, provides for many capabilities, including:

- system lock/chamber/component hazard modeling;
- the use of probabilistic input data;
- the generation of probabilistic output data;
- analysis of system-wide project plans;
- optimization of repair, maintenance and project plans; and
- analysis of repair and maintenance policies.

TABLE 2. Hybrid approach.

Feature	WAM	ETCM	Optimizer
Discrete tow movement simulation of locks	✓		
Discrete tow movement simulation of waterways	✓		
Generation of lock delay curves	✓		
Determination of waterway traffic levels		✓	
Determination of shipping plans		✓	
Model hourly cost		✓	✓
Model demand		✓	✓
Calculate movement costs		✓	✓
Balance supply and demand		✓	
Analysis of single projects		✓	
Modeling of lock hazards		✓	
System modeling of lock hazards		✓	
Model demand variability		✓	
Model hourly cost variability		✓	
Model system-wide project plans		✓	✓
Model repair and maintenance plans		✓	✓
Model repair and maintenance policies		✓	
Optimization of system-wide project plans			✓

Figure 5 presents a conceptual overview of a strawman system to implements these capabilities. The figure is a Venn diagram which shows that ORNIM is composed of three main components; the Ohio River Multi-year Investment Model (MIM), the Ohio River Navigation Model (ORNIM) and the Waterway Analysis Model (and successors). The optimizer is a new capability to be developed for ORNIM which is discussed in Section 5.3. The Ohio River Navigation Model is also composed of two parts: the Navigation System Hazard Model and the Waterway Supply and Demand Model. The Navigation System Hazard Model can be thought of as an extension of the LCLM to the entire waterway. The Waterway Supply and Demand Model performs functions similar to those found in the Tow Cost Model and the Equilibrium Model, however these functions are extended to allow for the processing of probabilistic inputs and the generation of

Figure 5. Conceptual Overview of ORNIM.

probabilistic outputs. The Waterway Analysis Model is used to generate a database of lock delay curves which are specific to given tow traffic distributions and tow arrival distributions. These delay curves are, in turn, used to develop (via regression techniques) lock delay functions which are functions of tonnage, arrival distributions, and tow traffic distributions.

5.2 Navigation System Hazard Model

Figure 6 gives an overview of the Navigation System Hazard Model. This model uses and produces waterway event scenarios. These scenarios are defined as a sequence of events which change the state of chambers, chamber components, and locks. The model inputs a Project Plan which is a scenario of planned changes to the state of various locks and chambers. The events

Figure 6. The Navigation System Hazard Model.

contained within the Project Plan are included in every output Waterway Scenario the model produces. The waterway scenarios produced also include unplanned events such as chamber closure events and chamber repair events which are generated by the model. The model uses a time-varying set of state transition probabilities to generate the output scenarios. These transition probabilities are constructed from information contained in the Project Plan, the Policy object, and the chamber component hazard functions.

Currently two approaches are being considered for this model. One is to build a Monte-Carlo simulation and the other is to use an analytic approach. Some experimentation will be required to determine the proper modeling and analysis approach.

The number of possible scenarios is large enough so that they cannot all be investigated. The role of the Navigation System Hazard Model is to identify the most likely waterway scenarios and their probability of occurrence. Each waterway scenario has an associated repair scenario with associated costs. The distribution of the associated waterway and repair scenarios is the output of the model.

5.3. Optimization of Multi-Year Investment Plans

In a later phase of the ORNIM development effort ORNL intends to link the Ohio River Navigation Model (ORNIM) to a multi-year investment model (MIM) that will allocate periodic waterway improvement budgets across a fifty-year, multiple lock and channel infrastructure investment plan. Three types of waterway investments will be allowed to compete for budget constrained funds within this model: (1) investments in operations and maintenance (O&M), (2) investments in rehabilitation of locks or channels, and (3) investments in new lock capacity.

The search for the most suitable model formulation is underway now, so that a candidate optimal investment model can be linked to the navigation model as soon as the latter is ready. This is an important linkage because the best solution to the allocation of multi-year investments is likely to require some iteration between these two models. That is, the lock delay and channel transit time functions for a given distribution of tows will need to be computed for input to the MIM.

Figure 7 shows the type of functional linkage proposed. Inputs to the MIM are (1) data on the waterway network, including the lock and channel structure; (2) data on current system capacities and lock delay curves, for current as well as alternative candidate lock and channel improvements, and (3) current and forecast tow volumes by river reach, in the form of outputs from the navigation model. A number of the challenging technical issues associated with the investment optimization model are discussed below.

Problem Size and Complexity

The level of detail and large number of different variables that need to be included in the problem makes it a challenging computational exercise to derive a waterway investment plan, based on a selection from among all reasonable lock and channel improvements over a fifty-year planning horizon. The basic optimization problem can be stated as follows.

A budget is apportioned by the model between periodic O&M costs, major rehabilitation costs, or the costs of adding new lock capacity. A large set of the model constraints ensure a logical solution to this budget-constrained optimization problem. The constraints ensure that total tow transit times through each lock in each time period are based on the correct state of the lock, and given the current length of time, or age, that a lock has been in its current state. That is, once a lock experiences some kind of improvement, its age, for this new state automatically gets set back to 0. A set of (0,1) decision, or state-transition, variables are used by the model to represent where and when investments are made. A second set of integer accounting variables ensure that a given lock is treated by the model as being in the correct state and age at the right time. Other constraints ensure logical consistency of lock state and age conditions and of their transitions over time. Lengthy lock closures associated with a major rehabilitation or with a lock capacity expansion project can be factored into the time period and lock specific transit times and tied to the appropriate lock states. So can the costs of delaying operation and maintenance work on lock

Figure 7. Overview of Optimization Process.

chambers to the point where the chamber fails, causing lock chamber down time and therefore traffic delay costs while repairs are carried out.

Initial testing of proposed model formulations is taking place using off-the-shelf optimization code and beginning with a subset of the Ohio River lock and channel data. Final model form is likely to require some original software to be written by ORNL, depending to a large extent on how well the different model formulations perform in terms of computational run times. Heuristic search techniques will probably need to be used to reduce the size of the solution space handled by the model. Three candidate solution methodologies are being investigated:

- a. Branch-and-bound,
- b. Lagrangean relaxation, and
- c. Benders decomposition.

Equilibrium Behavior

The effects of delay reductions due to lock improvements on the subsequent waterway traffic volumes also should be accounted for in the model. So should the effects that increases in delay have on these traffic volumes during periods of lock closure for extensive rehabilitation or capacity expansions. Capturing these changes in waterway traffic volumes will require some form of iterative process that must be able to converge on a stable near-optimal solution, (*i.e., a demand-supply equilibrated optimal investment model*). Ideally, the effects of changes in landside carrier haulage rates on diverting potential traffic to or from the waterway system should also be captured, and if possible, incorporated directly within the MIM. A more accurate computation of the net economic benefits of waterway improvements should be the result. Both of these MIM extensions will be explored to determine their plausibility, and a recommendation made to the Corps on whether they appear worthwhile (*i.e., cost-effective and doable within the time frame of the present project*).

Stochastic Optimization

A further extension of the MIM would be the incorporation of stochastic aspects of lock delay, shipper demands, and lock and channel performance functions directly within the MIM formulation. Alternatively, this may need to be handled instead within the Extended Tow Cost-Equilibrium Model formulation. A preliminary exploration of options for inclusion in the MIM will be carried out and a recommendation made to the Corps on whether a further model extension appears worthwhile.

6. ORNIM DEVELOPMENT SCHEDULE

At this writing, the first phase of the model development effort, which will produce a working prototype, is completed. So far, the proposed system design is being followed fairly closely. Significant attention is being given to establishing credible relationships between maintenance policies and the resulting reliability performance of the system. This phase was completed in the Fall of 1997, with a second phase scheduled for completion in the Summer of 1998.

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