Methodology for Planning Efficient Investments on Inland Waterways

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A methodology that addresses the analytic complications associated with making investment planning decisions for inland waterway improvements is presented. The complications include interdependencies between locks, bidirectional traffic, stalls, dual chamber facilities, and budget limitations. The methodology addresses most steps of the investment planning process for locks, namely project evaluation, sequencing, and scheduling.

The national waterway study and other navigation studies identified a need for substantial investment in the waterway infrastructure on the basis of several trends and observations. The first trend is that lock conditions are deteriorating, giving rise to an increase in tow delays. Currently, there are about 100 locks that have exceeded their design life. The second is that traffic levels are consistently increasing for many locks in the system. Also, prospects for increased grain exports are improving. Currency reform, the grain export enhancement program, reduction in worldwide carryover stocks of grain, and other factors have contributed to increases in exports. A third trend is an increase in tow sizes. Whereas this tends to increase overall transport efficiency, large tows must be disassembled into several pieces to move through the chamber and must later be reassembled. The fourth observation is that additional funding sources for major lock rehabilitation projects is not likely. The major sources of funding for such projects are the federal matching share and fuel tax receipts. The federal share of 50 percent and the fuel tax rate of 20 cents beyond 1995 are not likely to increase in the near future.

The trends identified by these studies present interesting but challenging opportunities for developing a more comprehensive methodology for inland waterway planning and operations analysis. The following are the primary analytical needs in developing such a methodology:

1. More reliable forecasting methods,
2. More reliable techniques for predicting delays at locks,
3. Identification and assessment of the benefits of lock rehabilitation, and
4. More efficient techniques for sequencing and scheduling lock improvement projects.

This paper presents an overview of a methodology designed to address many of the analytical needs resulting from trends in conditions, traffic levels, and funding sources for waterway locks. Particular emphasis is placed on satisfying Items 2 and 4 above. The methodology is the product of several research projects conducted over the last 4 years through the Institute for Water Resources and consists of the following components:

1. Exploratory data analysis and characterization of problems,
2. A microsimulation model of waterway traffic and lock operations,
3. Statistically estimated functions ("metamodels") to approximate the results of the simulation model,
4. An algorithm for prioritizing and scheduling proposed lock improvement projects, and
5. A computer program for cash flow analysis for the Inland Waterway Trust Fund.

BACKGROUND

There are numerous analysis tools available to assist in modeling lock operations and investment parameters. These include benefit-cost analysis, mathematical programming, queuing theory, and simulation. There exist some significant works on the application of these tools to waterway problems. However, extensions of the previously available methods were necessary to meet the analytical demands of current U.S. waterway transportation problems.

Determination of Delays at Locks (Analytic Models)

Two single-lock models based on the application of queuing theory have been found for estimating lock delays. DeSalvo and Lave (*1*) represent the lock operation as a simple server queuing process with Poisson distributed arrivals and exponentially distributed service times. However, these assumed distributions do not adequately fit the physical system of locks on waterways (*2*). Wilson (*3*) improved on this model by treating the service processes as general distributions rather than as exponentially distributed, which is far more realistic (*2*). However, this was for single-chamber locks only, and the Poisson arrivals assumption is not realistic for all locks.

Two other deficiencies exist in both of the above models. First, neither accounts for stalls. Stalls cause service interruptions at locks, thus reducing lock capacities or increasing delays. Their occurrence is very difficult to predict. Second,

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both models were developed to analyze delays at a single isolated lock. Since the delays at adjacent locks may be highly interdependent, it is desirable to analyze lock delays for entire systems.

Queuing theory offers some solutions for more general queuing systems [i.e., those beyond Poisson arrivals and exponential service times (M/M/1)]. In special cases combining Poisson arrivals with general service times (M/G/1) and general arrivals with exponential service times (G/M/1), closed-form solutions for the mean waiting time have been obtained (*3*). G/G/1 queues are difficult cases in queuing theory, and the available techniques for handling them are incomplete. Solving G/G/M queues is even more difficult than solving G/G/1 queues. The methods of approximations and bounds have been proposed to solve G/G/M queues (*4*). These can be accurate and efficient under heavy traffic conditions. However, the methods are difficult to extend to the series and networks of queues found in waterways.

Determination of Delays at Locks (Simulation Models)

An early microscopic simulation model to analyze lock delays and tow travel times was developed by Howe et al. (*5*). In that model, service times were based on empirically determined frequency distributions. To avoid some troublesome problems and errors associated with the requirement to balance long-run flows in that model, Carroll and Bronzini (*6*) developed another simulation model. It provided detailed outputs on such variables as tow traffic volumes, delays, processing times, transit times, average and standard deviations of delay and transit times, queue lengths, and lock utilization ratios.

Each of these models simulates waterway operations in detail but requires considerable amounts of data and computer time, which limits their applicability for problems with large networks and numerous combinations of improvement alternatives. They both assume Poisson distributions for tow-trip generation, which is not always realistic. Moreover, service failures ("stalls"), which are very different in frequency and duration from other events and have significant effects on overall transit-time reliability, are not accounted for. Hence a waterway simulation model that explicitly accounts for stalls is desirable for evaluating and scheduling lock improvement projects.

Benefit-Cost Analysis for Interdependent Improvement Projects

The delays at locks have been shown to be interdependent, that is, delays at one lock are related to delays at one or more other locks (*7*). That is because the departure process from one queuing station (e.g., a lock) in a network affects the arrival process at the next queues in that network. Interdependence not only yields difficulties in predicting lock delays but also in conducting benefit-cost analysis. Current methods of benefit-cost analysis are quite satisfactory for analyzing mutually exclusive projects and reasonably satisfactory for independent projects. However, there is a void in analyzing projects that are interdependent.

In evaluating and sequencing mutually exclusive projects, the net present value and benefit-cost ratio methods (*8*) can be used if the benefits and costs are quantifiable and can be accurately assessed over the planning horizon. This is because, in such cases, the benefits and costs of projects are not dependent on the project set selected. When working with independent projects, we can use an integer programming approach, where the objective is to maximize the sum of net present values subject to a set of budget constraints. (*9*).

However, for interdependent projects, the estimates of benefits and costs must be performed simultaneously with project selection. Therefore, it may be necessary to enumerate all possible project combinations when selecting a set of projects and all possible permutations when sequencing a set of projects. However, as a practical matter, complete enumeration becomes infeasible as a method of finding optimal combinations and permutations of projects as the number of projects becomes even modestly large. An alternative to complete enumeration is an augmented integer programming formulation. Such methods are discussed elsewhere (*9*). To capture some of the interdependence, the objective function includes interaction terms for pairs of projects. These terms represent the deviation from linear addition when summing the net present values for two interdependent projects. For example, if Projects A and B are independent, the net present values may be summed linearly:

$$\mathrm{NPV}_{AB} = \mathrm{NPV}_A + \mathrm{NPV}_B \tag{1}$$

Alternatively, for interdependent projects an interaction term is added:

$$\mathrm{NPV}_{AB} = \mathrm{NPV}_A + \mathrm{NPV}_B + d_{AB} \tag{2}$$

There are significant shortcomings with such an approach. First, only paired interactions are represented; depending on the application, three, four, or more projects may be simultaneously dependent. Second, the number of integer variables and interaction terms is excessive. The estimation of interaction terms is quite complex for most applications. Whereas many problems may be smaller than this example, most integer programming algorithms have serious difficulties with problems of this size.

There is a need to formulate the selection and sequencing of interdependent projects in a manner that is not computationally intractable and that does not require excessive estimation of interaction terms. It seems that overcoming these voids requires the development of a method whereby the numerous permutations of possible programs may be efficiently represented and searched (without complete enumeration) and the determination of efficient project implementation schedules.

COMPONENTS OF THE METHODOLOGY

Simulation Model

In light of the many shortcomings and difficulties associated with analytic methods of estimating delays at locks, a simulation model has been developed to analyze tow operations along waterways. The model may be used to determine the relations among delays, tow trips, distributions of generated travel times, and coal consumption and inventories. The model can account for the stochastic effects and seasonal variations and can estimate the following: tow delays at each lock, interarrival and interdeparture time distributions for each lock and for each direction, tow travel times along the waterway, inventory levels and expected stock-out amounts for commodities delivered by waterway, and many other variables of interest to waterway users and operators.

Development of the model was based on the Lock Performance Monitoring System (LPMS) data. The model is event scanning, with four types of events initiating a status update: (*a*) stochastic generation of tow trips; (*b*) tow entrances at locks as determined by arrival times, chamber availability, and chamber assignment discipline; (*c*) the arrival of a tow at its destination; and (*d*) the occurrence of stalls at a chamber.

Several features of this model lend themselves well to waterway operations. The simulation model is microscopic (i.e., it traces the movement of each individual and records its characteristics, including the number of barges, commodity types, speed, origin and destination, travel direction, and arrival time at various points). Any distributions for trip generation, travel speeds, lock service times, and tow size may be handled by the model. These distributions can be specified for each interval in tables or by standard statistical distributions. Tows are allowed to overtake other tows, and the model simulates two-way traffic through common servers and accounts for stalls. The size of waterway systems that the model can handle is limited only by computer and computer capacity. Further, the model has been developed with "dynamic dimensioning" for additional increases in flexibility in modeling various waterway systems.

The main simplifying assumptions in the current version of the simulation model are as follows:

1. The tows maintain a constant size through the entire trip.
2. The service discipline is first-in-first-out, as are operations on the Mississippi and Ohio rivers.
3. The queue storage area is unlimited.
4. The tow speeds are normally distributed and constant for each round-trip.
5. The time intervals between two successive stalls and the stall durations are exponentially distributed.

These assumptions are not seriously restrictive, but they can still be easily modified.

The simulation model consists of five operation routines and one scheduler routine. The operation routines are associated with the five types of events and are invoked by the scheduler. Figure 1 is a chart of the flow of data as dictated by the model.

To check the logic of this simulation model, its results were first compared with theoretical (but well-established) results from queuing theory. The results of the model were then compared with observed data to demonstrate how closely the model represents real systems and verify its ability to simulate the special features of waterways.

A partial validation of the model is possible by comparing the model to theoretical results for the special case of Poisson arrivals and generally distributed service times. The waiting times predicted by the simulation model at a single lock were compared with those obtained from queuing theory for this special case. A validation has been conducted for a variety of volume/capacity (V/C) ratios ranging from 0.0471 to 0.8934. To reduce the variance of the output, each result was obtained by averaging the output from 30 independent simulation runs. To ensure that results were compared for a steady state, each simulation run discarded the first 10,000 tow waiting times and collected the next 12,000 values for computing the average waiting time.

The results, given in Table 1, confirm that the simulated and theoretical average waiting times are extremely close. Such results verify that the overall mechanism of the simulation model is correct. They also show that generally distributed service times are generated satisfactorily in the simulation model. That is reassuring, since the same logic is used to generate generally distributed interarrival times for G/G/1 queues and, ultimately, to develop metamodels for series of G/G/1 queues.

The simulation results were then compared with the observed data at Locks 22, 24, 25, 26, and 27 on the Mississippi River. These locks were selected on the basis of their criticality and available data. The five locks were simulated as an interacting series. Some of the validation results are summarized in Table 2. Each result is averaged from 80 independent simulation runs. Table 2 indicates that the difference between the simulated and observed average waiting times for each lock is within the 95 percent confidence interval based on the *t* test, except at Lock 25. The observed data also show that tows sometimes were kept waiting at Lock 25 even when the chamber was idle. Therefore, no direct comparison of average waiting times at Lock 25 is appropriate.

Metamodel Approximations to Simulation

Each simulation run takes from a few seconds to a few minutes on a personal computer, depending on the values of various parameters. Despite this high level of efficiency, simulation time becomes expensive for evaluating large combinatorial problems such as investment planning. Furthermore, the project combinations may have to be evaluated over several time periods. A metamodeling approach that statistically estimates unknown parameters of equations from simulation results and then uses these equations as substitutes has been developed to overcome the computational requirements of simulation. The main difficulty with this approach is in finding structural forms for the approximating functions that fit the simulation results as well as possible. This was accomplished by queuing theory insofar as possible for these functions.

In this study, a numerical method has been developed for estimating delays through a series of queues. The method decomposes systems of queues into individual queuing stations. The analysis of each queuing station is further decomposed into three modules: arrival processes, departure processes, and delay functions. Arrival processes at a particular lock depend on the departure distributions from the upstream and downstream locks and the intervening speed distributions. Departure processes depend on the interaction among the arrival distributions and service time distributions at one lock. Delay functions relate the waiting times to the arrival

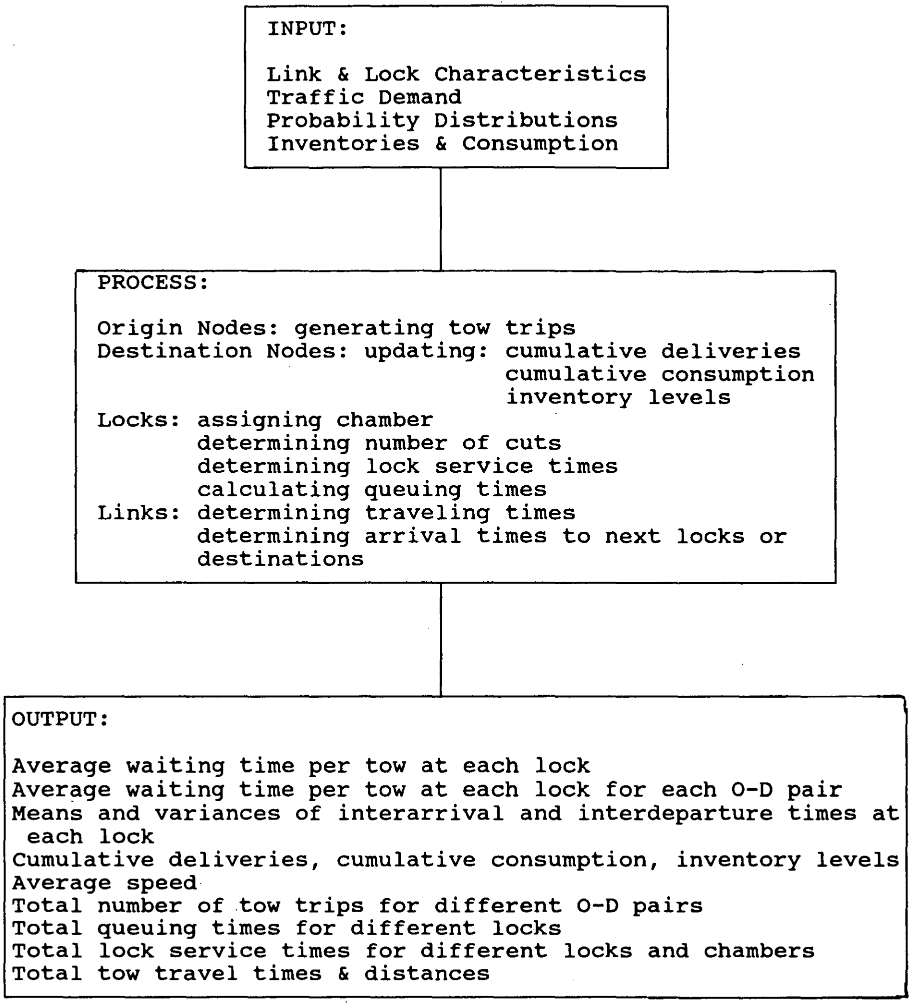

FIGURE 1 Structure and elements of the simulation model.

TABLE 1 Comparison of Theoretical and Simulated Results for a Single Lock Queue (M/G/1)

V/C	T_A*1 Avg (hr)	Var (hr^2)	T_S*2 Avg (hr)	Var (hr^2)	W_{sim}*3 (hr)	W_t*4 (hr)	Devia.*5 (%)
0.893	0.888	0.789	0.793	0.319	4.9516	5.0059	-1.09
0.755	0.888	0.789	0.670	0.227	1.5575	1.5522	0.34
0.566	0.888	0.789	0.503	0.128	0.4926	0.4935	-0.19
0.330	0.888	0.789	0.293	0.044	0.1082	0.1087	-0.46
0.047	0.888	0.789	0.042	0.001	0.00155	0.00156	-0.64

*1 T_A: interarrival times
*2 T_S: service times
*3 W_{sim}: average waiting times from simulation
*4 W_t: average waiting times from queuing theory
*5 Devia.: deviation which is defined as $(W_{sim}-W_t)/W_t*100\%$

and service time distributions. The basic concept of this method is to identify the parameters of the interarrival and interdeparture time distributions for each lock and then estimate the implied waiting times.

To estimate delays in a queuing system, we need to know the means and variances of the interarrival, interdeparture, and service time distributions. For series of G/G/1 queues and bidirectional servers, a difficulty arises in identifying the variances of interarrival and interdeparture times because the interarrival times at each lock depend on departures from both upstream and downstream locks, and the variances of interarrival times cannot be determined from one-directional

TABLE 2 **Comparison of Simulated and Observed Waiting Times**

Lock	W_{sim} *1 (min)	W_{obs} *2 (min)	Difference (min)	95% Confidence Interval
22	4.09	3.73	0.36	3.49
24	6.12	6.36	0.24	6.72
25	4.49	10.94	6.45	–*3
26	119.40	130.99	11.59	60.73
27	36.49	34.43	2.06	23.92

*1 W_{sim}: simulated average waiting times
*2 W_{obs}: observed average waiting times
*3 The comparison is not appropriate.

scans along a series of queues. To overcome such complex interdependence, an iterative scanning procedure is proposed. The core concept is to decompose the system into individual locks and then sequentially analyze each of those locks. At each lock, the two arrivals from both directions are first combined into an overall arrival distribution and then split into two-directional departure distributions.

The algorithm is initiated by scanning along waterways from either direction, sequentially estimating the interarrival and interdeparture time distributions for each lock. Initially assumed values for the variances of interdeparture times from the opposite direction must be provided for the first scan. Then the scanning direction is reversed and the process is repeated, using the interdeparture time distributions for the opposite direction estimated in the previous scan. Alternating directions, the scanning process continues until the relative difference in the preselected convergence criteria stays within preset thresholds through successive iterations. Waiting times at locks can be computed in every iteration (and then used as convergence criteria) or just once after all iterations are completed.

Arrival Processes

The mean and standard deviation of interarrival times are estimated in two steps. First, the means and standard deviations of directional interarrival times at a particular lock are estimated from the interdeparture time distributions of the adjacent locks. If flows are conserved between locks and the V/C ratio is less than 1.0, such relations are represented in Equation 3:

$$\bar{t}_{aji} = \bar{t}_{djk} \qquad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{3}$$

where

$\bar{t}_{aji}$ = the average interarrival time for Direction j and Lock i,
$\bar{t}_{djk}$ = the average interdeparture time for Direction j and Lock k, and
j = direction index (1 = downstream, 2 = upstream).

Because speed variations change headway distributions between locks, Equation 4 was developed to estimate the standard deviation of directional interarrival times at one lock.

$$\sigma_{aji} = \sigma_{djk} + \underset{(0.002)}{0.0251}\ln\left(1 + \frac{D_{ik}\sigma_{vik}}{\mu_{vik}}\right) \qquad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{4}$$

$R^2 = 0.999954 \qquad n = 107 \qquad s_e = 0.0586 \qquad \mu_y = 5.1685$

where

σ_{aji} = standard deviation of interarrival times for Direction j and Lock i,
σ_{djk} = standard deviation of interdeparture times for Direction j and Lock k,
D_{ik} = distance between Locks i and k,
μ_{vik} = average tow speed between Locks i and k,
σ_{vik} = standard deviation of tow speeds between Locks i and k,
j = direction index (1 = downstream, 2 = upstream),
s_e = standard error of dependent variable, and
μ_y = mean of dependent variable.

This suggests that, theoretically, the standard deviation of directional interarrival times should be equal to the standard deviation of directional interdeparture times plus an adjustment factor depending on the speed distribution and distance.

Second, the overall mean and coefficient of variation of interarrival times for this lock are estimated on the basis of coefficient of variation of directional interarrival times.

$$\bar{t}_{Ai} = \frac{\bar{t}_{a1i} * \bar{t}_{a2i}}{\bar{t}_{a1i} + \bar{t}_{a2i}} \tag{5}$$

$$C^2_{Ai} = \underset{(0.027)}{0.179} + \underset{(0.014)}{0.41}\,(C^2_{a1i} + C^2_{a2i}) \tag{6}$$

$R^2 = 0.9188 \qquad n = 79 \qquad s_e = 0.0059 \qquad \mu_y = 0.988$

where

$\bar{t}_{Ai}$ = the average interarrival time at Lock i,
C^2_{Ai} = squared coefficient of variation of interarrival times at Lock i, and
C^2_{aji} = squared coefficient of variation of directional interarrival times for Direction j and Lock i.

In Equation 6 the coefficients of variation of upstream and downstream interarrival times carry the same weight in estimating the overall variance of interarrival times, since the mean directional trip rates are equal.

Departure Process

The departure module estimates the mean and coefficient of variation of interdeparture times. On the basis of the flow conservation law, if capacity is not exceeded, the average directional interdeparture equals the corresponding interarrival time:

$$\bar{t}_{dji} = \bar{t}_{aji} \tag{7}$$

The coefficient of variation of interdeparture time is estimated in two steps. First, the coefficient is estimated for combined two-directional departures. Departure processes with generally distributed arrival and service times are analyzed using Laplace transforms. The following metamodel was eventually developed to bypass the difficulties of determining the variances of the lock idle times:

$$\begin{aligned} C_D^2 &= 0.207 + 0.795\,(1 - \rho + \rho) + (\rho^2 - \rho^2) \\ &= 0.207 + 0.795 = 1.002 \cong 1.0 \end{aligned} \tag{8}$$

Next, the coefficient of variation of directional interdeparture times is estimated. The following metamodel was developed for this purpose:

$$\begin{aligned} C_{dji}^2 &= \underset{(0.0056)}{0.518} + \underset{(0.0068)}{0.491} C_{aji}^2\, C_{Di}^2 \end{aligned} \tag{9}$$

$R^2 = 0.9710$ $n = 158$ $s_e = 0.013$ $\mu_y = 0.9164$

where

C_{dji}^2 = squared coefficient of variation of directional interdeparture times for Direction j and Lock i,
C_{aji}^2 = squared coefficient of variation of directional interarrival times for Direction j and Lock i, and
C_{Di}^2 = squared coefficient of variation of interdeparture times for Direction j and Lock i.

Delay Function

The delay function is intended to estimate the average waiting time at a lock. By applying Marshall's formula for the variance of interdeparture times, an exact solution for the average waiting time, W, was obtained as follows:

$$W = \frac{\sigma_A^2 + 2\sigma_S^2 - \sigma_D^2}{2\bar{t}_A\,(1 - \rho)} \tag{10}$$

where

W = average waiting time,
σ_A^2 = variance of interarrival times,
σ_s^2 = variance of service times,
σ_D^2 = variance of interdeparture times,
$\bar{t}_A$ = average interarrival time, and
ρ = volume to capacity ratio.

In this delay function, the average waiting time increases as the variance of interarrival and service times increases and decreases as the variance of interdeparture times increases. The average waiting time approaches infinity as the V/C ratio approaches 1.0.

Comparison of Simulated and Numerical Results

To validate the numerical method, its results were compared with the results of the previously validated simulation model. Various system configurations were compared, including a relatively large 20-lock system.

The parameter values for this test system (e.g., means and standard deviations of input distributions and distances between locks) were obtained from random number generators, except for traffic volumes, which were assumed to be 10 tows per day in each direction throughout the system. The numerical model estimates aggregate waiting times within 8 percent of those simulated. At individual locks, the percent errors are slightly greater but within 10 percent. In its current form, the modeling approach does not consider possible diversion to other modes on the basis of excessive delay. However, the model might be applied iteratively with a demand reestimation model.

Project Sequencing and Scheduling

Sequencing

Either the simulation model or the metamodels may serve as a project evaluation tool. That is, both are able to provide delay estimates for a system of locks for different combinations of proposed lock improvements (i.e., any measure that physically or effectively increases the capacity of a lock). This is the basis for estimating the benefits associated with such improvements. The choice should be based on a trade-off between precision for complete lock operations (favoring simulation) and computational efficiency (favoring the metamodels). Thus, the metamodels may be used for preliminary screening and the simulation for the final detailed evaluation.

The next step in the investment planning methodology is a technique whereby the permutations of investment sequences may be efficiently searched and a corresponding optimal schedule found. The proposed approach for searching the solution space of possible project permutations represents the solution space in two dimensions and applies a heuristic search algorithm in selecting the preferred sequence. Given a system cost evaluation function for interdependent projects $g(\mathbf{X},\mathbf{Y})$, the selection and sequencing problem may be represented in two-dimensional space. The function $g(\mathbf{X},\mathbf{Y})$ incorporates both benefit and cost factors into a generalized cost while accounting for project interdependencies, where $\mathbf{X}$ is a vector of delay variables and $\mathbf{Y}$ represents a particular combination of projects.

Assuming that each set of projects may be viewed as a system generating a common time-dependent output, a two-dimensional representation is feasible. For the lock rehabilitation problem, the costs associated with a given combination of projects in a given time period t may be written as

$$(SC)_{iY} = C_Y + g\{X[\lambda(t)],Y\}(OC) \tag{11}$$

where C_Y is the total capital cost of construction for the set of projects Y. The term $g\{X[\lambda(t)],Y\}$ represents the delay and corresponds to the functions obtained from some interdependent evaluation (e.g., from a simulation model). OC is the opportunity cost of delay (which may be either a constant or a function of time). Evaluating SC at different levels of output for a combination of projects Y defines a curve with annual system costs SC_Y on the vertical axis and output level λ on the horizontal axis. Repeating for different values of $\mathbf{Y}$ (i.e., different project combinations) produces a family of curves. By always choosing the lowest-cost curve for any given output level λ (i.e., by choosing the "lowest envelope" of the curves in Figure 2), a sequencing and scheduling decision path is defined. Because the output is assumed to be time dependent, the horizontal axis may also represent time periods (e.g., years). Output and time may be linked through a demand function, $\lambda(t)$.

Consider an example with interdependent projects A, B, and C. Figure 2 shows a family of system cost (SC) curves corresponding to the possible combinations of these three projects. Note that in general, combinations involving only one project are preferable (lower SC) for low levels of volume (thus earlier in the horizon stage) and become less preferable as volume increases. Under this representation, one combination is preferred to another at a given output level (or time period) if its corresponding curve lies above the other. (Although the convex and monotonically increasing properties of the curves in Figure 2 are likely to occur for costs with a delay component, they are not a prerequisite for the methodology.)

In the example shown in Figure 2, the selection and sequence of projects is dictated by the lowest "envelope" defined by the curves. This lowest envelope corresponds to the minimization of the time integral of the system cost for feasible expansion paths. Here, all three projects would be accepted if the volume level is expected to eventually exceed Q_2. We see also that the sequence of projects should be A, B, C; this is because Curve A lies below B and C, and AB lies below AC in the relevant regions. Project A is preferred up to volume level Q_1 at the same time Project B should be implemented since Curve AB falls below Curve A. At volume level Q_2, Project C should be added to A and B, thus implementing Combination ABC.

Unfortunately, not all such families of curves can be interpreted as easily as Cases 1 and 2. Consider a second case shown in Figure 3, where Curves A and AB are unchanged but the others are different. Here, Curves AB and AC intersect each other before intersecting Curve ABC. It cannot be stated a priori whether Combination AB or AC should be selected on the expansion path between A and ABC. It is expected that if Area 1 is greater than Area 2, Combination AB is preferred to AC and Project B should precede Project C on the expansion path. Areas 1 and 2 correspond to the difference savings when integrating over Paths A-AB-ABC and A-AC-ABC, respectively.

Scheduling

Under the assumption that the benefits associated with a given combination of projects in some period vary only with the output of the system in that period, the start dates of the projects do not affect the system costs. Thus the SC curves for a project combination depend only on the presence, rather than start times, of particular projects in that combination. The implications in the context of waterways are that the capital cost of construction, operating and maintenance costs, and benefits from reduced delays are not affected by the age of the locks at any given time (i.e., by project start dates) but only by the volume of traffic using the locks. This assumption

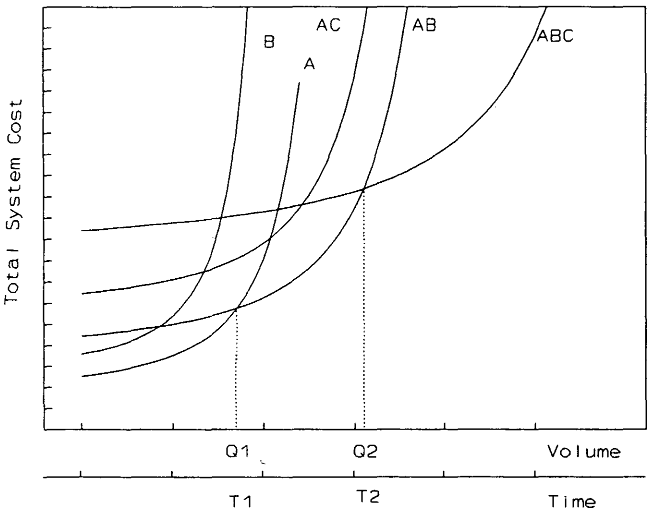

FIGURE 2 System cost for three interdependent projects (Case 1) incorporating a budget constraint.

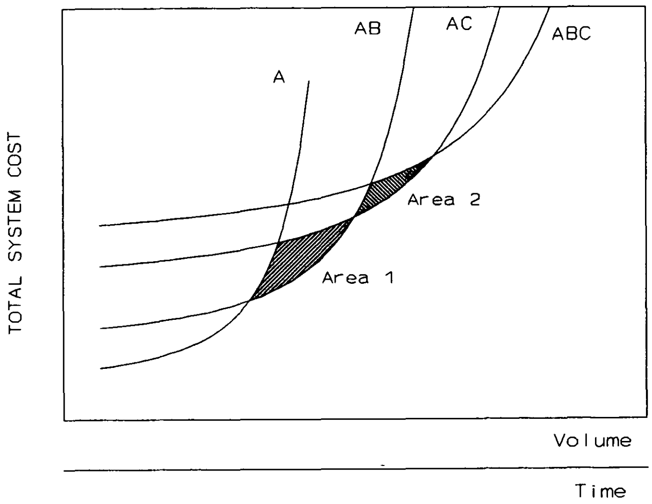

FIGURE 3 System cost for three interdependent projects (Case 2).

is very reasonable for the capital costs but somewhat simplifies the operating and maintenance costs. The assumption is also reasonable for delay benefits, although it neglects the effect of long-term economic changes induced by the presence and performance of waterway investments.

In structuring the budget constraint, it will be assumed that funds not spent in a given period will be available in subsequent periods. Under this assumption, budget limitations have the effect of delaying the earliest feasible start date of a given project combination, just as they limit the earliest start of an individual project. Consider the small example of two projects A and B. In constructing the Curves A, B, and AB, the infeasible portion must not be included. Figure 4 shows that Combination A is not financially feasible until time T_1 corresponding to output Q_1. Combination AB is not feasible until time T_2. The possible expansion paths are then as follows: (*a*) start A at time T_1 and B when Curves A and AB intersect, and (*b*) start B immediately and A when Curves B and AB intersect.

In the validation, systems of four and six locks were used to compare the solution from the algorithm with that obtained through exhaustive enumeration. (Conducting such tests on larger systems is not possible because the optimal solution cannot be determined for comparison with the solution obtained from the sequencing methodology.) In these four- and six-lock experiments the optimal answer was found by the algorithm in 93.3 and 95 percent of the cases. In the suboptimal cases, the cumulative costs were within 1 percent of those of the optimal sequences.

Cash Flow Analysis

The output of sequencing and scheduling algorithm is the order in which the projects are to be implemented and the project start times (i.e., the time when construction is complete and the facility is returned to full operation). Unfortunately, the implementation of construction schedules are not without uncertainties. Often, projects may be delayed because of funding interruptions, technical complications, cost overruns, or other unforeseen conditions. Such delays and overruns can be binding on the Inland Waterway Trust Fund (IWTF). For example, if soil and geological surveys incorrectly assess the type of foundational rock, a project might be interrupted to permit further engineering and design. For this reason, it is helpful to have a methodology for evaluating financial sensitivities to changes in project costs and schedules.

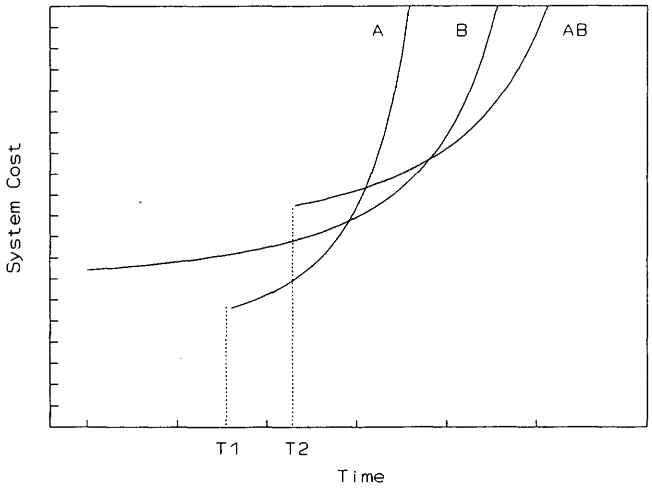

FIGURE 4 Incorporating a budget constraint.

Such a methodology was developed and programmed for the Corps of Engineers to conduct sensitivity analysis of the IWTF with respect to numerous scheduling and budgeting parameters. The primary computational objective behind the methodology is to reveal the resulting trust fund balance profile over a specified planning horizon. The methodology allows for the inclusion of the numerous factors in obtaining the cash flow profile of the IWTF, for example,

1. Project sequence and start dates,
2. Distribution of project costs over the construction period,
3. Duration of the construction period,
4. Length of any project interruptions,
5. Interest rate accrued on unspent sums over the planning horizon,
6. Fuel consumption rates over the planning horizon, and
7. Fuel tax rates over the planning horizon.

The computer program that implements the cash flow analysis consists of four modules and a comprehensive user interface. The scheduling module provides utilities for controlling project-specific parameters such as project start time, construction duration, and interruptions. The expenditure module considers four basic trust fund parameters: distribution, federal matching share, inflation, and base year for discounting. This module provides for three types of expenditure distributions (normal, uniform, and user defined). The revenue module incorporates the fuel tax, fuel consumption, and account interest rates to determine the total revenues available in each time period. The output module provides a summary table of the trust fund balances and a host of graphic utilities and summary statistics. The computer program has been successfully applied to analyze the sensitivity of the trust fund balance to many of the possible uncertainties.

ADDITIONAL APPLICATIONS OF THE METHODOLOGY

Applications that can be envisioned for this entire methodology or for some of its components include the following:

1. Estimation of lock delays under various conditions such as congestion levels, stall patterns, traffic mix, operational improvements, major capacity improvements, and closures for maintenance;
2. Computer evaluation of various lock operating options such as chamber assignment selection for tows, grouping of vessels in chambers, use of helper boats, priorities among vessels, and platooning (m-up-n-down);

3. Investment planning and programming, including selection and timing of new projects and smaller-scale improvements under financial constraints;
4. Improved management decisions for tow operators (e.g., optimizing fleet schedules and operating speeds under various levels of lock congestion and unreliability);
5. Improved management decisions for shippers (e.g., inventory policies, mode choice, and facility location decisions); and
6. Improved demand forecasting based on an improved estimate of future service levels.

Beyond such waterway applications, it appears that the approximation methods for queuing networks may be applied in other types of systems such as road networks, communication networks, manufacturing plants, and parallel computer processors. The algorithm for scheduling interdependent projects should have even wider applicability.

CONCLUSIONS AND EXTENSIONS

A fairly comprehensive methodology has been developed for evaluating and scheduling waterway system improvements. Some of the elements may be separately used in several other important applications. Some relatively complex aspects of the waterway system, such as the interactions among delays at adjacent locks, the effects of relatively rare lock failures on delays, and the effects of reliability and congestion on tow operating decisions and shipper inventory policies can be analyzed with this methodology.

Further research would be desirable in several areas, including the following:

1. Improved microsimulation components to analyze, in greater detail, various lock operating options;
2. Improved metamodels for the approximation of operating characteristics at multiple chamber locks;
3. Hybrid model switching automatically between simulation and metamodels depending on required model sensitivity;
4. New variants of the scheduling algorithm that trade computation time for improved solutions; and
5. Connections to a model that predicts equilibrium demand over time in a multimodal network.

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