Triangulation of Modeling Methodologies for Strategic Decisions in an Inland Waterway Transportation System

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Abstract

We show how optimizing models, computer simulation, and expert opinion were integrated to investigate the potential performance of a waterway navigation system under different scheduling regimes and infrastructure changes. Analytical models are used to derive scheduling rules that balance efficiency against equity. Discrete-event simulation is used to assess system performance under various infrastructural changes (helper boats, expanded locks) and traffic management schemes (such as load leveling, priority scheduling, or self-regulation by the barge industry). Expert opinion is sought to address concerns of stakeholders and shed light on industry reactions to different policy alternatives. We show the importance of triangulation involving different modeling and philosophical approaches in generating relevant information for development of solution strategies.

1. Introduction

The Upper Mississippi River (UMR) navigation system is a major inland waterway transportation artery. It includes a series of 29 lock and dam facilities that enable passage between adjacent pools of a water staircase between St, Louis, Missouri and Minneapolis, Minnesota (Figure 1). Seasonal congestion occurs at a series of five 600-foot locks (numbered 20, 21, 22, 24 and 25) between a pair of 1200-foot locks of much greater service capacity (numbered 19 and 26). At the shorter locks, large barge tows need to be decoupled and winched through the lock in a “double” lockage operation that requires more than triple the time of a standard “single” lockage. In the latter case, a powered vessel with barges fits completely in the lock and the lockage operation involves a single cycling of the lock chamber to change the water level. To deal with the congestion and transportation delays, the U.S. Army Corps of Engineers (USACE) has proposed a major expansion of the five smaller locks to balance their service capacity with that of the larger locks. Doing so will dramatically increase the total throughput capacity in this most congested section of the river. Lock expansion, however, is estimated to cost over $2.4 billion and the project is expected to require more than 20 years to complete [14].

Figure 1. The UMR navigation system

The USACE, urged by the National Academy of Sciences [14], commissioned a series of studies to identify the potential effects of various congestion mitigation measures as alternatives to full-scale lock expansion, or as interim measures that could be employed pending construction of the larger locks. The research included the development of a simulation model for assessing procedures to increase the efficiency with which current resources are utilized. The model may be used, for example, to investigate the possible effects of helper boats to reduce lockage times, to assess the gains achievable from smoothing the arrival patterns of commercial traffic, or to study the impact of requiring all tows to be configured to pass through each lock as a “single” lockage.

In this paper, we describe the use of integer programming and discrete-event simulation to investigate alternative scheduling mechanisms and infrastructure investments. Our work illustrates the advantages and limitations of triangulating analysis with different approaches and the need to consider self-adapting mechanisms of dynamic systems when projecting the performance of systems under stress. Finally, we mention important economic and political considerations that
necessarily influence the solutions chosen by public-sector decision makers. Our experience underscores the value of various forms of methodological triangulation to obtain a complete picture of a complex problem. Only by using a variety of research methods can the problem be explored with sufficient scope and depth to generate the information required for a fully informed decision.

2. Prior research

With discrete event simulation models, investigators have identified the potential of improving performance of inland waterway navigation systems by using alternative scheduling procedures in place of the prevailing practice rooted in first-come first-served principles [2, 4, 6, 10, 11, 12, 13]. Sweeney [9] first studied operations in this section of the UMR with a discrete-event simulation model that had vessels initially enter the river northbound, proceed through the entire sequence of five locks, return later for southbound travel, and continually circulate through the shipping season until they left the system southbound on a final trip at the end of the year. His “replicating simulation” approach dealt with deficiencies of previous studies that used steady-state analyses and it accommodated inter-dependent lockage activities calibrated with historical UMR data. It did not, however, perfectly represent seasonal traffic activity at the locks. Nor did it consider the fact that not all tows make the complete roundtrip without stopping in a pool. Some stop to drop off and take on barges. Of those tows that stop, some reverse direction. Further refinements were needed to represent these intra-system activities.

Smith et al. [7] developed a simulation model to represent UMR operations between locks 20 and 25 (inclusive) with greater realism and to analyze performance under different traffic levels and scheduling regimes. Nonstationary exponential distributions with complementary intensification and thinning mechanisms were used to create the proper mix of random arrivals at each lock according to month of year, day of week and time of day. Vessel itineraries were generated dynamically to reflect time-varying probabilities that tows of different types would continue to the next lock, rather than terminate their voyages in their current pool. Parameters of probability distributions for activity times were adjusted according to tow characteristics (reflected in the type of lockage required) and prevailing river conditions (varying by month of the year). The model was validated by comparing detailed simulated performance with actual performance (including seasonal variation in waiting times at locks and lock utilization) under the range of traffic levels experienced over the past 20 years. The model was then applied to study a variety of scheduling rules and infrastructure changes [8].

In parallel work, Nauss [5] produced an integer programming formulation of this problem and found an optimal clearing schedule for individual UMR lock queues could be derived by complete enumeration (for queues of reasonable length). In the IP solutions, the “most valuable” or “most efficient” vessels are generally placed at the head of the queue. His work reinforced the expectation that efficiencies are gained when vessels are selected in order of their expected lockage times, net of the setup time for the lock. In this model, however, full consideration of the sequence-dependent setup times was not incorporated.

Major conclusions from work to this point were: (1) commercial traffic would have to increase substantially above year 2000 levels before gains from alternative scheduling regimes would be noticeable; (2) with a 20% increase in commercial traffic above year 2000 levels, noticeable efficiencies could be achieved by using alternative scheduling rules with virtually no cost of implementation; and (3) increases of more than 30% in commercial traffic require infrastructural or operational changes to avoid unreasonable delays in peak periods.

3. Efficiency versus equity in scheduling

Scheduling rules geared to maximize efficiency were shown to favor one class of user at some cost to another. Presented with these findings in a meeting arranged by the USACE, representatives of the barge industry asserted that the relevant metric for judging over-all efficiency of the system was the average time that commercial vessels spend waiting at the locks that are encountered in their itineraries. (Neither cargo, nor destination, nor size of tow should alter the severity of a delay). In periods of stress, however, exceptions to FIFO may be (and are) employed to clear backlogs more efficiently. FIFO was seen as a processing sequence that fosters equity; Fastest lockage time (net of setups, involving lock turnbacks if necessary) was seen as the rule that best promoted efficiency.

To cope with the problem of adverse impact on some classes of vessel, we undertook to assess the impact of adding constraints to the scheduling problem that would limit the amount of inequity that an individual vessel could experience in pursuit of over-all system efficiency. We accomplish this by altering the IP model for the deterministic representation of the scheduling problem to limit the maximum delay that a vessel could experience beyond its completion under FIFO processing. We then handle it in the simulation model by shifting a vessel to a higher processing priority every time a corresponding amount of time has been spent queued for the lock. In the following sections, we compare the inferences drawn from the two approaches to the problem.
4. An integer programming (IP) model for sequence-dependent setup times and maximum
displacement beyond FIFO completion times

Lockage times depend on the type of lockage; so do the lock setup times. An “exchange” lockage occurs when a departing vessel in one direction clears the area to allow another vessel traveling in the same direction. Generally, turnbacks are more efficient because the turnback time is less than the time for departing tows to clear the area.

The IP formulation has the form of a “set covering” problem in which each vessel moored upstream or downstream is assigned to a position \( j \) in the lockage sequence. The setup time and the processing time for an operation both depend on the current operation and the sequence. The setup time and the processing time for an operation.

Decision variables are defined as follows:

\[
Z_{jUU} = \begin{cases} 
1 & \text{if lockage } j + I \text{ is an upstream turnback} \\
0 & \text{if not}
\end{cases}
\]
\[
Z_{jDD} = \begin{cases} 
1 & \text{if lockage } j + I \text{ is a downstream turnback} \\
0 & \text{if not}
\end{cases}
\]
\[
Z_{jDU} = \begin{cases} 
1 & \text{if lockage } j + I \text{ is a downstream exchange} \\
0 & \text{if not}
\end{cases}
\]
\[
Z_{jUD} = \begin{cases} 
1 & \text{if lockage } j + I \text{ is an upstream exchange} \\
0 & \text{if not}
\end{cases}
\]
\[
TRD_{ij} = \begin{cases} 
1 & \text{if vessel } i \text{ is lockage } j \\
0 & \text{if not}
\end{cases}
\]
\[
TRU_{ij} = \begin{cases} 
1 & \text{if vessel } i \text{ is lockage } j \\
0 & \text{if not}
\end{cases}
\]

Parameters

\[
EXD_{ij} = \begin{cases} 
1 & \text{if downstream vessel } i \text{ is lockage } j \\
0 & \text{if not}
\end{cases}
\]
\[
EXU_{ij} = \begin{cases} 
1 & \text{if upstream vessel } i \text{ is lockage } j \\
0 & \text{if not}
\end{cases}
\]

To process all vessels at a lock with minimum total time in queue, we minimize \( \sum_{j=1}^{N} ENDLOCK_{j} \) subject to:

\[
N \sum_{j=1}^{N} (TRD_{ij} + EXD_{ij}) = 1 \quad \forall i = 1...N_D \tag{1}
\]
\[
N \sum_{j=1}^{N} (TRU_{ij} + EXU_{ij}) = 1 \quad \forall i = 1...N_U \tag{2}
\]
\[
Z_{jUU} + Z_{jDD} + Z_{jDU} + Z_{jUD} = 1 \quad \forall j = 1,...,N-1 \tag{3}
\]

\[
N \sum_{i=1}^{N_D} tmutr_{i} \times TRU_{ij} \leq ENDLOCK_{j} \tag{4}
\]

\[
ENLOCK_{j+1} + \sum_{i=1}^{N_U} (tmutr_{i} \times TRD_{ij} + tmuex_{i} \times EXD_{ij}) \leq ENDLOCK_{j} \forall j = 1,...,N \tag{5}
\]

\[
N \sum_{i=1}^{N_D} (EXD_{ij} + TRD_{ij}) + N \sum_{i=1}^{N_D} TRD_{ij+1} \leq 1 + Z_{jDD} \quad \forall j = 1,...,N-1 \quad \tag{6}
\]

\[
Z_{jDD} \leq N \sum_{i=1}^{N_U} (EXD_{ij} + TRD_{ij}) \quad \forall j = 1,...,N \quad \tag{7}
\]

\[
Z_{jDD} \leq N \sum_{i=1}^{N_U} TRD_{ij} \quad \forall j = 1,...,N-1 \quad \tag{8}
\]

Constraints (1) and (2) force each downstream and upstream vessel to be locked as a turnback or exchange; (3) force the successive pair of lockages \( j \) and \( j+1 \) to be an upstream or downstream turnback or exchange; (4) starts the process with a turnback for immediate efficiency and initializes the accumulation of lockage times; (5) determine the completion times for succeeding lockages; (6,7,8) define lockage \( j+1 \) as a downstream turnback if and only if a downstream lockage is followed by a downstream turnback lockage. Sets of constraints similar to (6,7,8) are defined for \( Z_{jUU}, Z_{jDU}, \) and
To ensure consistency of lockage combinations for accumulation of related set-up and lockage times. Standard binary constraints are imposed on the 0-1 variables.

To impose the constraints on the maximum displacement that each vessel experiences relative to its completion under a FIFO regime, we determine \( FIFO_D \) and \( FIFO_U \), the times that upstream vessel \( i \) and downstream vessel \( i \) would clear the area under a strictly FIFO sequence. We then add the constraints

\[
\sum_{j=1}^{N} (EXD_{ij} + TRD_{ij}) \leq FIFO_D_i + waitlim
\]

for each downstream vessel \( i \) and a complementary set of constraints for each upstream vessel to prevent displacements greater than \( waitlim \) occurring in the schedule for any vessel. This last set of constraints (9), which impose equity on the solutions by limiting the displacement for any vessel relative to its FIFO service time, are nonlinear. They require special attention in the solution process.

With the IP model, we investigate the consequences of imposing the additional constraints with various values of \( waitlim \) (trading efficiency for equity) and use the results to guide in the development of decision rules for testing in the dynamic environment.

5. Effects of limiting allowable delays when resequencing vessels for efficiency

Efficiencies from scheduling are generated by exploiting differences in lockage times of vessels and differences between setup times for turnbacks and exchanges. We therefore expect the benefits from resequencing to be greater when there are more single-tow vessels in the mix of traffic, which is dominated heavily by double tows. To explore the tradeoffs between efficiency and equity, we solve the IP with different values of \( waitlim \).

We present the results of two sets of 20 problems to represent random combinations of vessels queued for double and single lockages upstream and downstream at peak periods of the year. Recognizing the range of variation in mix of tows requiring double and single lockages, we use 0.9 for the probability that a tow would require a double lockage in the first set of problems and 0.7 for the probability that a tow would require a double lockage in the second set. For each of the 40 problems, we produce a locking sequence:

1. under a purely FIFO regime,
2. using the IP without a limit on \( waitlim \),
3. using the IP with \( waitlim \) set to 480 minutes,
4. using the IP with \( waitlim \) set to 360 minutes.

To solve the nonlinear IP problems (cases 3 and 4), we modified an implicit enumeration procedure demonstrated in [5] to produce an optimal solution for the linear version of the model (case 2) and further employed a heuristic restriction procedure to impose the nonlinear constraints. The implicit enumeration procedure for the linear version (case 2) was validated against solutions using the CPLEX solver (themselves achieved in 2 sec. per problem). For cases 3 and 4 with \( waitlim \) set at 360 and 480 minutes, however, we use the heuristic to produce feasible lower bounds on improvement for the sum of waiting times, without validation against an optimizing algorithm.

Table 1 contains results for an expected 90:10 mix of traffic; Table 2 contains results for an expected 70:30 mix. Under a 90:10 expected traffic mix, average remaining clearing times decreased 0.3% for double tows, 95.8% for single tows and 9.9% over all relative to the FIFO solution when \( waitlim=99999 \). The change in locking sequence favors singles downstream, then singles upstream, then doubles upstream, and finally, doubles downstream. Doubles downstream (the least efficient lockages) suffer extreme delays. Imposing the 480-minute displacement constraint (\( waitlim=480 \)) to mitigate inequity reduces over-all improvement to 8.2%. Imposing a tighter 360-minute displacement constraint reduces the average over-all improvement further to 7.6% for these 20 sample problems.

In the second set of IP solutions (for the 70:30 expected traffic mix), minimum average remaining clearing times increase by 9.3% for double tows, decrease by 85.8% for single tows and are reduced by 20.4% over all (relative to FIFO) when \( waitlim=99999 \). Adding the 480-minute displacement constraint reduces over-all improvement to 19.1%. Adding the 360-minute displacement constraint reduces over-all improvement further to 18.7%. Individual solutions without the displacement constraints revealed that the locking sequence that minimizes total remaining queue time tended to schedule operations so that the sum of set-up and locking time for the next vessel was minimized. Adding the displacement constraints, of course, changes the solution.

In practice, the queue-clearing problem changes with each new arrival or departure and there is random variation in the actual lockage times. Although the integer programming solutions take just 10 seconds or so to generate with the heuristic employed, the USACE and representatives of the barge industry expressed a strong preference for converting the insights from the IP analysis into a set of local scheduling rules that are clearly understood and verifiable by interested parties. To test the impact of alternative decision rules over the course of the shipping season with its greatly varying traffic intensity and traffic mix, we employ a discrete-event simulation model.
### Table 1 – Optimization Results with 10% Probability for Single Tows

<table>
<thead>
<tr>
<th>Tow Configuration</th>
<th>Average Number in Beginning Queue</th>
<th>Av Total Clearing Time FIFO</th>
<th>Av Total Time without Displacement Restriction (pct change in parentheses)</th>
<th>Av Total Time with 480-min. Limit (pct change in parentheses)</th>
<th>Av. Total Time with 360-min. Limit (pct change in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doubles Upstream</td>
<td>8.8</td>
<td>1174.1</td>
<td>580.3 (-50.6)</td>
<td>812.0 (-30.8)</td>
<td>933.7 (-20.5)</td>
</tr>
<tr>
<td>Singles Upstream</td>
<td>1.1</td>
<td>1099.1</td>
<td>61.4 (-94.4)</td>
<td>64.0 (-94.2)</td>
<td>58.8 (-94.6)</td>
</tr>
<tr>
<td>Doubles Downstream</td>
<td>9.15</td>
<td>1055.7</td>
<td>1612.8 (+52.8)</td>
<td>1400.3 (+32.6)</td>
<td>1309.3 (+24.0)</td>
</tr>
<tr>
<td>Singles Downstream</td>
<td>0.95</td>
<td>1047.9</td>
<td>37.4 (-96.4)</td>
<td>33.8 (-96.8)</td>
<td>43.8 (-95.8)</td>
</tr>
<tr>
<td>Doubles total</td>
<td>17.95</td>
<td>1115.5</td>
<td>1111.7 (-0.3)</td>
<td>1131.8 (+1.5)</td>
<td>1140.0 (+2.2)</td>
</tr>
<tr>
<td>Singles total</td>
<td>2.05</td>
<td>1102.1</td>
<td>45.8 (-95.8)</td>
<td>46.0 (-95.8)</td>
<td>46.4 (-95.8)</td>
</tr>
<tr>
<td>All vessels</td>
<td>20</td>
<td>1114.1</td>
<td>1004.2 (-9.9)</td>
<td>1022.5 (-8.2)</td>
<td>1029.8 (-7.6)</td>
</tr>
</tbody>
</table>

### Table 2 – Optimization Results with 30% Probability for Single Tows

<table>
<thead>
<tr>
<th>Tow Configuration</th>
<th>Average Number in Beginning Queue</th>
<th>Av Total Clearing Time FIFO</th>
<th>Av Total Time without Displacement Restriction (pct change in parentheses)</th>
<th>Av Total Time with 480-min. Limit (pct change in parentheses)</th>
<th>Av. Total Time with 360-min. Limit (pct change in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doubles Upstream</td>
<td>6.55</td>
<td>892.0</td>
<td>603.1 (-32.4)</td>
<td>785.3 (-2.0)</td>
<td>853.3 (-4.3)</td>
</tr>
<tr>
<td>Singles Upstream</td>
<td>2.75</td>
<td>808.7</td>
<td>146.1 (-81.9)</td>
<td>145.6 (-82.0)</td>
<td>141.2 (-82.5)</td>
</tr>
<tr>
<td>Doubles Downstream</td>
<td>7</td>
<td>929.5</td>
<td>1347.5 (+45.0)</td>
<td>1210.6 (+30.2)</td>
<td>1162.8 (+25.1)</td>
</tr>
<tr>
<td>Singles Downstream</td>
<td>3.7</td>
<td>873.3</td>
<td>111.6 (-87.2)</td>
<td>112.5 (-87.1)</td>
<td>122.6 (-86.0)</td>
</tr>
<tr>
<td>Doubles total</td>
<td>13.55</td>
<td>913.7</td>
<td>998.7 (+9.3)</td>
<td>1016.0 (+11.2)</td>
<td>1021.2 (+11.8)</td>
</tr>
<tr>
<td>Singles total</td>
<td>6.45</td>
<td>845.0</td>
<td>120.0 (-85.8)</td>
<td>120.7 (-85.7)</td>
<td>121.1 (-85.7)</td>
</tr>
<tr>
<td>All vessels</td>
<td>20</td>
<td>897.9</td>
<td>714.6 (-20.4)</td>
<td>726.3 (-19.1)</td>
<td>729.9 (-18.7)</td>
</tr>
</tbody>
</table>

### 6. Simulation of the stochastic system

Each individual lock’s environment (Figure 2) is modeled as a multi-queue single-server system. The discrete-event simulation model deals with a constantly changing system over the course of the navigation season. It also uses a restricted queue discipline to ensure that maneuvering for the next lockage is physically possible. Arriving commercial vessels and recreation vessels queue separately upstream and downstream at each lock. The next vessel to lock in each class is positioned at an appropriate mooring buoy and cannot be displaced by another. In other words, it will be the next commercial or recreational vessel to lock in the respective direction, regardless of theoretical efficiencies that might, on average, be gained from inserting a tow with different characteristics.

We include traffic for five classes of commercial vessel, differentiated by the barge-tow configurations that determine their locking characteristics:

1. double tows (towboats with enough barges to require locking in two steps), which take an overall average of 117 minutes to process at a lock;
2. jackknife tows (tows that must be partly disconnected with the towboat pivoted at right angles to fit in the locking chamber before the gates are closed), with overall average locking time of 82 minutes;
3. knockout tows (tows for which the towboat must be disconnected from the barges and reconnected after following the barges through the lock), with average of 63 minutes;
4. single tows (that can be locked directly without reconfiguration), averaging 33 minutes;
5. single commercial vessels without barges (e.g., towboats that may be proceeding to the next pool to pick up a tow, or USACE vessels involved in maintaining the UMR navigation system), averaging 24 minutes;

Recreational vessels are much more maneuverable. They are locked individually or in groups. Their lockages average 14 minutes.

Some arrivals are random, while others occur following a pool transit from a previous lock. Different distributions for locking times are employed for each of six classes of vessel, adjusted for whether their movement is upstream or downstream at a particular lock. They are further adjusted for whether the lockage operation is an exchange, turnback or fly (immediate entry with no queue encountered), and finally adjusted for the calendar month in which the lockage occurs.
either (1) to continue to the next lock in the same direction or (2) to proceed to a destination in the current pool at which the vessel will be reconfigured for its next movement upstream or downstream. Simulated vessels that do not proceed directly to the next lock are “terminated” after completing lockage and their subsequent activity is handled by regenerating vessels and tow configurations at random in the respective pools for upstream or downstream travel. With such a structure, we represent the system as the individual lockmasters see it and use only the information that vessels must currently provide on arrival at a lock (i.e., the next step in their itinerary is determined in the succeeding pool). The resulting periodic patterns corresponded extremely well with historical averages (by month, day, and hour of day).

**Activity times.** Much of the variation in vessel activity (lockage and pool transit) times is systematic – caused by differences in sizes and configurations of tows, direction of traffic, type of lockage (fly turnback or exchange) and river conditions. To remove the systematic effects (and allow for different coefficients of variation) before generating random activity times, we partition the data according to type of tow (double, single, singles without barges and recreational) and direction, and construct regression models that give the logarithm of the expected processing time for the particular type of lockage or pool transit. Jackknife lockages and knockout lockages are accommodated by incorporating (0-1) indicator variables in models for single lockages. By partitioning the data and employing the regression model with logarithmic transformations, we produce normally distributed residuals. We therefore employ the corresponding lognormal distributions for activity times and generate them after their precipitating events (selection for lockage or determination that the vessel will next transit the river pool). Designating $T$ as the activity time, $X$ as the vector of explanatory variables, $E(\log(TIME(X)))$ as the expected value of the logarithm of the activity time derived from the partitioned regression of the logarithm of the times against the explanatory variables, and $MSE(X)$ as the mean squared error (residual) of the regression equation, we generate the activity times from lognormal distributions with

$$\text{Mean}(T) = e^{E(\log(TIME(X)))} + MSE(X)/2$$

and

$$\text{Standard deviation (T)} = \sqrt{(e^{2E(\log(TIME(X)))} + MSE(X)) - (e^{MSE(X)} - 1))}.$$  

We also impose a lower bound on activity times (in this study, $T_{0.01}$, the first percentile from historical data for the relevant operation and vessel class). Thus, we use $T = \text{Max(randomly generated time, } T_{0.01})$ for the activity time.

**System interruptions.** Queues may develop as a result of interruptions in service at a lock (termed lock impairments by the USACE). Periods of impaired lock

Figure 2 – Lock Environment (Courtesy USACE)

The model thus:

- accommodates multiple classes of traffic with different arrival patterns, itineraries and service characteristics;
- provides a queuing and processing structure that can dynamically alter service priorities of queued vessels while conforming to physical realities of upstream and downstream traffic movements to and from the locks;
- produces detailed measures of system performance that show the mix of vessel traffic movements and waiting times in the vicinity at each lock at different times of the year;
- facilitates experimentation with alternative sequencing rules under different levels of commercial barge traffic and under different operating characteristics at each lock; and
- enables tests of statistical significance of observed effects on system performance.

**Arrival patterns.** We generate all commercial arrivals upstream at Lock 25 and downstream at Lock 20 as random arrivals using non-stationary exponential distributions, allowing for monthly seasonal variation in vessel traffic. We also employ non-stationary exponential generators for the vessels upstream at Locks 20, 21, 22 and 24 and downstream at Locks 21, 22, 24 and 25 for the traffic that does not proceed directly from the previous lock in the same direction. To impose the other periodic effects, we use intensification and thinning. We generate the commercial arrivals at each lock upstream with arrival rates inflated by the product of factors for hour-of-day and day-of-week effects on system performance.

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operating conditions (caused by adverse river conditions or lock or vessel failures that interfere with lock operations) are imposed randomly and independently at each lock at seasonally varying rates. They are imposed in the model by pre-empting the lock for the duration of the impairment.

Traffic Control at the Locks. A decision is made with each arrival or departure whether to reposition the lock for a new lockage in the same direction (turnback) or to leave it positioned for a vessel queued in the opposite direction (exchange). If there are no vessels queued, the lock is left in its current position, and the next vessel will have no delay (a fly lockage), because the lock chamber can be repositioned, if necessary, during that vessel’s approach. Priority formulae are employed to select the next vessel to lock according to the rule in effect.

The basic scheduling rule that serves as our bench mark takes all vessels in order of their arrival except recreational vessels. Recreational vessels can be locked efficiently (as a group if more than one is queued for service) as quick exchanges among commercial vessels. Our FIFO rule is thus designated FIFORECPRIOR as a reminder that adjustments are made (with all rules) to accommodate recreational lockages amidst the commercial vessels.

At the end of a lockage, we record the vessel number (coded for point of origin and direction), the lockage operation (e.g., 21U for 21 upbound), tow-vessel type, time of arrival, time of start lockage, time of departure, whether the lockage was exchange, turnback or fly, and the vessel priority number. This enables us to identify all points in time at which a change in the system’s state took place and to perform a complete statistical analysis (including dynamic queuing characteristics) with the same type of data as provided by the USACE database of historical waterway activity. The Statistical Analysis System (SAS) is used for this detailed analysis.

7. Simulated performance

In our analysis, recreational lockages occur with priority because their additional maneuverability allows them to be integrated efficiently and USACE policy limits the time that recreational vessels should wait. Solely focusing on efficiency for commercial vessels would have them locked in order of their arrival times. In deploying this rule, the locks are turned back as necessary to serve the vessel that arrived first at the lock from either direction. The dynamic priority shifting is redundant, as each vessel experiences the FIFO sequence.

Solely focusing on efficiency in clearing queues would have vessels selected for lockage according to the expected time required to clear them through the local lock (FLT). In this case, vessels are queued for the mooring buoy in increasing order of their expected lockage times and selected according to whether the next lockage can be completed more quickly with a turnback or exchange.

We give simultaneous consideration to equity and efficiency by shifting vessels to higher priorities if they wait more than a prescribed time interval. With the resulting rule, vessels are ordered within a priority class according to their expected lockage times and the next vessel to be locked is the one that can be locked most quickly unless a competing vessel at a mooring buoy has been shifted to a higher priority class due to an excessive wait. Fastest locking time (considering vessel characteristics and differences in times for turnback or exchange) determines which vessel is selected for lockage if the vessels traveling in opposite directions are in the same priority class. We call this rule FLTX (for fastest locking time with exceptions for vessels with long waits).

To explore the local and system-wide effects of imposing alternative sequencing rules, we analyze the simulated results of one hundred years of waterway activity from January 1 through December 31 with the seasonal effects imposed on traffic levels, lockages and vessel movements as described earlier. An extensive report is generated that summarizes (with monthly and annual statistics) the frequency and duration of impairments at each lock; tow configurations upstream and downstream at each lock; descriptive statistics for activity times (lockage operations and pool-transits); lock utilization; queue sizes and queueing times; and operation types (turnback, exchange and fly lockages) for each tow type (single, double, single ex barge, etc.) in each direction at each lock. We shall highlight some major comparative findings regarding the impact of different scheduling rules.

Using Year 2000 traffic levels as the base case, we performed analysis of variance (ANOVA) on the average times for tows to complete lockage operations under FIFO, FIFORECPRIOR, FLT, FLTX with priority shifts every six hours (360 min.), and FLTX with priority shifts every eight hours (480 min.). With a .01 level of statistical significance for pairwise comparisons, we concluded that average lock transit times (and waiting times) were significantly lower for FIFORECPRIOR than for FIFO and lower for all the FLT variants than for FIFORECPRIOR. Imposing the priority shifting scheme, however, did not significantly change the average times that vessels were tied up at the locks. In other words, adding the constraints to impose equity did not appear to alter significantly the benefits derived from locking with consideration for immediate efficiency. The conclusions were the same when we performed the ANOVA using a logarithmic transformation on lockage times to stabilize variances. At higher levels of traffic, the beneficial effects of FLTX are greater still.
Table 3 reveals how the queueing burden is shifted to vessels with tow configurations that require longer locking times under the FLT variants, but with greater over-all efficiency achieved. It also reveals how FLTX moderates the extreme delays that would otherwise occur for some double tows if FLT were used without priority shifting. The lower median waiting times (and 95th percentiles) for FLT relative to FLTX with 480-minute priority shifting invites speculation that relaxing the priority-shifting period from 360 or 480 minutes may allow for sufficient efficiency over all to "lift all boats", but the ANOVA results, which are determined from the annual averages, were statistically indistinguishable for FLT, FLTX-360 and FLTX-480.

### Table 3 - Medians and 95th Percentiles of Waiting Times for FIFORECPRIO and FLT Variants with Year 2000 Commercial Traffic Plus 20%

<table>
<thead>
<tr>
<th>Vessel-tow Configuration</th>
<th>FIFORECPRIO (benchmark)</th>
<th>FLT</th>
<th>FLTX 480 min</th>
<th>FLTX 360 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>95th</td>
<td>Median</td>
<td>95th</td>
</tr>
<tr>
<td>Double</td>
<td>334</td>
<td>3,772</td>
<td>165</td>
<td>3,688</td>
</tr>
<tr>
<td>Jackknife</td>
<td>378</td>
<td>3,732</td>
<td>116</td>
<td>705</td>
</tr>
<tr>
<td>Knockout</td>
<td>324</td>
<td>3,322</td>
<td>127</td>
<td>716</td>
</tr>
<tr>
<td>Single</td>
<td>296</td>
<td>3,473</td>
<td>106</td>
<td>630</td>
</tr>
<tr>
<td>Single ex Barge</td>
<td>275</td>
<td>3,062</td>
<td>92</td>
<td>573</td>
</tr>
<tr>
<td>Recreational</td>
<td>51</td>
<td>125</td>
<td>49</td>
<td>123</td>
</tr>
</tbody>
</table>

8. System self-adaptation

As a model validation measure, we plotted (Figure 3) the average waiting times for all vessels at the five locks (computed from 100 replications of one year of simulated activity) under commercial traffic intensities that ranged from 20% less than year 2000 levels to 30% more than year 2000 levels under the assumed operating assumptions. The top two curves represent the results under the FIFORECPRIO and FLT rules respectively. (Performance under FLTX-360 or FLTX-480 falls between the two curves but closer to FLT.) We then superimposed the actual average waiting times as determined from the USACE OMNI data for the past 17 years as hollow circles in Figure 3. Note how well these observations agreed with the waiting times inferred from the simulation model, except in the three years when traffic levels were 15% or more above year 2000 levels. Under those traffic levels, the simulation model projected longer waiting times than actually occurred. Investigating the lock operating procedures during those three years, we determined that to deal with the extremely long delays, helper boats were frequently employed in the vicinity of the locks to reduce the times required for locking the vessels. From an analysis of the historical data, we were able to determine that the use of helper boats reduced lockage times by 12.5% on average. Running the model with this adjustment for the use of helper boats eliminated the discrepancy. (See the third curve in Figure 2).

Under high traffic scenarios, helper boats have a much more profound effect on lock queues than altering local lock scheduling practice, but with much higher implementation costs. In subsequent years, incidentally, traffic levels dropped and helper boats are no longer deployed.

The in-depth investigation of historical performance statistics in conjunction with the simulated performance under various scenarios led to an understanding of the self-adaptive mechanisms that came into play when the system was under stress.

9. Operating performance with new 1200-foot locks

The model was next applied to an analysis of the potential performance of the system if new 1200-foot locks were installed as suggested by the USACE. Performance at Locks 20 through 25 with new 1200-foot locks will depend on design characteristics and water flow. We constructed estimates of performance with data from Lock 19 (the 1200-foot lock at the north end of the bottleneck) and Lock 26 (the 1200-foot lock at the south end of the bottleneck). Based on historical distributions of tow types between locks 20 and 25, we classified tows with more than six barges traveling downstream and tows with more than seven barges traveling upstream as “double” lockages. Similarly configured tows are locked more quickly at Lock 26 relative to Lock 19; so queuing times are lower for calibrations based on Lock 26 data.

Regardless of scheduling rule used, waiting times are virtually eliminated with both fast and slow new 1200-foot locks over the full range of traffic scenarios; from 20% less than year 2000 commercial traffic levels to 30% more than year 2000 commercial traffic levels.
10. Discussion and Conclusion

The mathematical programming results were useful in helping to devise scheduling rules that would promote efficient operation in the dynamic environment. They did not, however, provide measures of effectiveness through time for the stochastic behavior of this highly seasonal system. In actual operations, the queue clearing problem changes with each arrival and departure and the actual activity times vary randomly about the expected activity times employed in the optimizing model. Discrete event simulation is necessary to incorporate the stochastic effects. It was clear, from both approaches, however, that mechanisms were needed to foster equity while pursuing operational efficiency. With the IP approach we limited the delay that a vessel could experience beyond its place in a FIFO solution. In the stochastic analysis, we shifted the priority of a vessel each time a designated interval of time had passed.

Relaxing the constraint on the maximum wait that a vessel could experience relative to a FIFO sequence axiomatically allows greater flexibility in searching for a solution to the optimizing formulation (and leads to lower expected average wait times). Altering the allowable displacement from 360 to 480 minutes relative to the FIFO schedule, for example, changed the average reduction in queue-clearing times by a further 0.5 percentage points in the IP solutions for the 20 randomly generated problems (statistically significant using a paired differences test at the .001 level). In the stochastic environment, however, estimates of over-all improvement were considerably muted. Changing the priority-shifting interval from 360 to 480 minutes did not have a statistically distinguishable impact on the average time that vessels spent clearing the locks. It seemed, from the simulation analysis, that for the dynamic system, there would be considerable latitude in setting the priority shifting limit at a negotiated value without having a noticeable impact on system performance.

At year 2000 traffic levels, we do not see material benefits of changing from current industry practice (FIFORECPRIO with negotiated intervention in extreme situations). With a 20% increase in traffic, however, we would recommend consideration of an FLTX scheme, with automatic priority shifting at a negotiated time interval between six and eight hours and possibly a priority reservation scheme with payment for priority passage at a lock. Helper boats can help further to reduce backlogs in peak periods.

At higher traffic levels, infrastructure upgrades are required to reduce queueing times to reasonable levels. Both fixed and variable costs of alternative upgrades vary greatly and they can be imposed in different ways (e.g., general tax levies or user fees). The manner of assessing the costs of infrastructure improvements will affect future system utilization as shippers and barge operators adjust their operations to adjust to the new economic structures. In a companion paper [1], we discuss how the results illustrated in Figure 3 were incorporated into a meta-analysis for assessing, in aggregate, the net economic benefits from adoption of the respective remedial measures and in formulating a possible strategy for undertaking system upgrades to accommodate future growth in traffic.

Questions remain, at intermediate levels of traffic growth; about what would happen if the scheduling rules developed from a local optimization model were replaced with rules that consider conditions at all locks simultaneously. This would require barge operators to divulge more information about their shipping itineraries and to cede control to a less transparent scheduling mechanism. A similar combination of optimization modeling and discrete event simulation may be employed to investigate the potential benefits of scheduling mechanisms geared to system-wide optimization.

The simulation model may be enhanced to incorporate models of system behavior under alternative traffic-regulation mechanisms (e.g., requiring all tows at specified times to be configured for lockage with a single cycle, or payments for priority bookings). Construction of such models should reflect expert opinion from the shipping industry and analysis of historical data from operations such as the Panama Canal, where priority booking has been used for several years. In modeling the impact of an upgraded UMR
infrastructure with user fees, it may be wise to investigate how ferry operators in the English Channel adjusted their fare structures and operations after the Channel Tunnel went into operation. Development of new intermodal shipping terminals and diversion of traffic to competing railroads and trucking lines may occur and interfere with cost recovery on the UMR. Consideration must also be given to the economic and political environments in which the decisions will be made and implemented.

Similar approaches could be used to study other inland water transportation systems such as the rivers, canals and port facilities in Europe. The River Information Services (RIS) systems being developed in the EU [3] could support similar modeling endeavors in pursuit of operational efficiencies. Specifics, of course will differ, because most European river vessels are self-powered, major transportation waterways (e.g., the Rhine) have fewer locks, and more than one commercial vessel may be handled in a single lockage.

In conclusion, we reassert that triangular research designs involving optimization, simulation, statistical modeling, and expert opinion reduce the risk of generating information for decision support that exposes a small part of the proverbial elephant. Optimizing models for snapshots of evolving scheduling problems tend to overestimate the benefits achievable on implementation because only the earlier phases of the solution tend to be implemented. Later parts of the solution get changed as new information becomes available and subsequent stochastic variation adds an additional element of uncertainty. They do, however, provide valuable information for the creation of strategies and decision rules. Simulation alone can be cumbersome in pursuit of optimal decision strategies; yet it can give realistic portrayals of time-varying performance of dynamic systems when the systems are modeled with sufficient realism. Extensive statistical analysis and modeling are required to provide fixed parameters for optimizing models and time-varying or state-driven parameters for simulation models. They are also required for studying the system further in conjunction with model outputs. Finally, expert review and projections are needed to consider short-term and long-term adaptations that may reinforce or undermine the effects of resulting strategic decisions.

11. References