Management System for Repair, Evaluation, Maintenance, and Rehabilitation of Inland Water Transportation Facilities

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Development of a management system for the maintenance and rehabilitation of locks on the inland waterways is described; the concepts and procedures apply to other facilities as well. The design of the management system is based on a life-cycle analysis of the performance and costs of facilities as affected by Repair, Evaluation, Maintenance, and Rehabilitation (REMR) policy. Life-cycle analyses of facilities require a new approach to looking at the performance of a facility and the factors that influence costs throughout its service life. This approach is referred to as "demand responsive" because maintenance, repair, rehabilitation, and reconstruction are viewed as responses to the demand for repair or renewal of a facility. Treating demand-responsive activities requires that the estimates of future resource requirements for and costs of maintaining facilities not simply be extrapolated from past trends; they must instead be based on predictions of structural and operational deficiencies caused by use, environment, and age. The concepts involved in applying life-cycle costing to analyses of REMR policy are discussed. Example models of facility performance for lock gates, walls, and mechanical equipment are developed; this performance is related to the costs and the impacts of different REMR policies; and building these models within a prototype version of a PC-based management system is discussed. The prototype REMR management system is then applied in several examples to demonstrate the application of demand-responsive maintenance concepts to realistic problems, to illustrate management system features and procedures, and to interpret system results.

The work described in this paper has been sponsored by the U.S. Army's Construction Engineering Research Laboratory (CERL) as part of the Army's Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program. The REMR program responds to a growing need to keep civil works under the jurisdiction of the U.S. Army Corps of Engineers in safe, working condition. The rationale for the REMR program is supported by statistics indicating the growing importance of maintenance, repair, and rehabilitation compared with new construction. For example, operations and maintenance (O&M) have consumed rapidly increasing shares of total Corps appropriations for civil works in recent years, as the data in Table 1 (*1*) indicate.

TABLE 1 PERCENTAGES OF CIVIL WORKS APPROPRIATIONS DEVOTED TO OPERATIONS AND MAINTENANCE VERSUS NEW CONSTRUCTION (*1*)

Year	O&M (%)	Construction (%)
1967	16	79
1970	24	66
1977	28	65
1980	35	56
1983 (estimated)	40	46
1985 (projected)	50	

The objective of this research is to develop a management system for the evaluation, maintenance, repair, and rehabilitation of civil works under the jurisdiction of the Corps of Engineers. The management system is built on the following premises:

1. REMR activities need to be seen in their economic, as well as technical, dimensions. Consequences of REMR policy alternatives (to the Corps as well as to industry) must be reduced to an economic basis for comparison.
2. Trade-offs among evaluation, maintenance, repair, and rehabilitation over time need to be accounted for.
3. Trade-offs in distributing or allocating resources among competing needs throughout a network of facilities also need to be considered.
4. In addition to the need for economic relationships in Item 1, there are questions of distribution (e.g., to whom do the costs and benefits of the REMR program accrue?) and of the influence of noneconomic decision criteria (e.g., defense needs) on the selection of the most appropriate REMR alternatives.

To scale the Corps' diverse and extensive system of projects to more manageable proportions, the current research is limited to one class of inland waterway structures: navigation locks. This approach allows exploration and development of the engineering, economic, technological, and management principles and relationships needed to address facility maintenance and rehabilitation for this type of structure. (It should be noted that locks throughout the country have significantly different dimensions, capacities, and structural and operational features.) When the applicable concepts, principles, analytic methods, and computer software have been developed and demonstrated

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for locks, they can be extended and adapted to other civil works within the Corps' inventory.

LIFE-CYCLE COSTING

The Corps of Engineers has had long experience in applying economic principles to engineering decisions. Calculations of benefits versus costs have been routinely applied to the evaluation of water projects for many years. These procedures extend projections of project costs and benefits through an analysis period and, by comparing the discounted totals of various alternatives, identify the economically most efficient project option or decision. As applied to the analysis of REMR projects, life-cycle costing of existing facilities considers the total costs of evaluation, maintenance, repair, rehabilitation, reconstruction, operation, use, and (in special cases) abandonment of a facility through its service life.

Demand-Responsive Approach

The implementation of life-cycle analyses of facilities required a new approach to looking at the performance of a facility and the factors that influence costs throughout its service life. This approach is called "demand responsive" because maintenance, rehabilitation, and reconstruction are viewed as responses to the demand for repair or renewal of the facility. This demand for work arises through both a physical dimension (the condition of the facility, reflecting the quality of initial design and construction; the accumulation of wear and damage from the combined effects of traffic loads, environment, and age; and corrections due to past repairs) and a policy dimension (standards of initial design and construction and the level of maintenance, repair, rehabilitation, or reconstruction to be performed, expressed through quality standards). Furthermore, because the prediction of facility condition is central to the demand-responsive approach, the impacts, as well as the costs, of alternative investment policies can be computed.

Treating REMR actions as demand-responsive activities requires that two additional elements be introduced within existing planning and management models. The first is that estimates of future resource requirements and costs cannot be extrapolated solely from past trends because these data reflect past policies and practices. Instead, the estimates must be based on predictions of structural and operational deficiencies caused by use, environment, and age as affected by future REMR policy. The second is that new relationships must be identified between the as-maintained state of the civil facility and the impacts on both the Corps and industry (the users of the facility) to provide a measure of the benefits (or disbenefits) of each policy at the costs computed. Organization of these ideas within a unified structure is shown in Figure 1.

Applications

The analytical procedures needed to implement the management structure in Figure 1 have been organized within simulation models and closed-form optimization procedures, both of which have been used to address different types of investment decisions in the transportation field. The development of simulation models is described elsewhere (*2, 3*), and the mathematical optimization procedures are presented by Fernandez-Larranaga (*4*). These tools have been applied to a diverse set of problems encompassing optimization of investments (*5–7*), evaluation of alternative investment programs (*8, 9*), allocation of scarce resources among competing activities (*10*), predicting impacts of deferred maintenance (*11*), and financing maintenance and rehabilitation (*12, 13*). Recently the optimization approach of Fernandez-Larranaga (*4*) was refined to develop simplified models and engineering curves for use by engineers in the field (*14*). Thus the demand-responsive approach provides a powerful framework for addressing decisions in facility life-cycle management, and it can be applied to a number of problems in facility investment and maintenance.

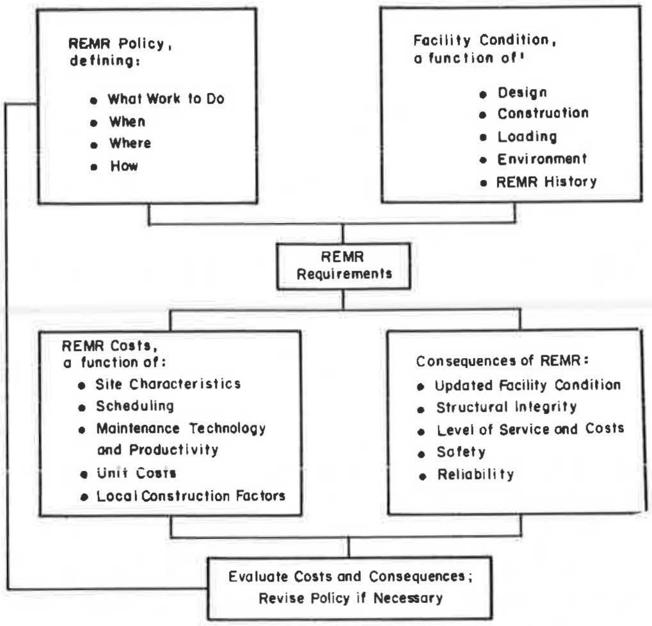

FIGURE 1 Approach to REMR planning and management.

Analyzing Life-Cycle Cost Streams

Cost streams (for both agency costs and user costs) are shown schematically for two facility strategies in Figure 2. It is assumed that traffic and environmental factors are identical in both cases but that initial facility design and subsequent performance differ in response to capital investment and maintenance policy.

These differences are evident in the respective streams of agency costs and user costs. Strategy 1 in Figure 2 entails higher agency costs for construction, maintenance, and rehabilitation but lower costs of facility usage; Strategy 2 presents the opposite pattern, with lower agency costs but higher user costs. The first strategy may be interpreted, for example, as that for a facility built and maintained to high standards to ensure premium service throughout its life. The second strategy may then be interpreted as one for a conventional facility maintained adequately but not exceptionally.

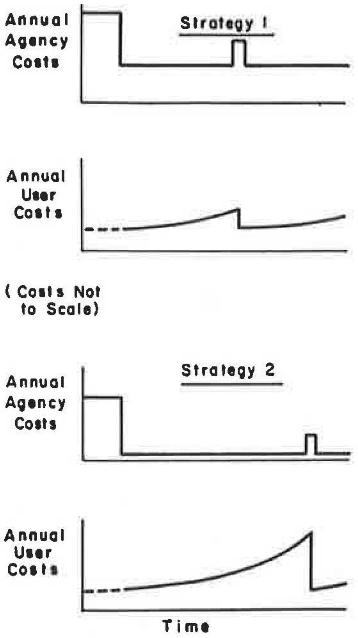

FIGURE 2 Schematic cost streams for two REMR policies.

From an agency perspective, Strategy 2 is the lower-cost alternative and perhaps would be preferred. From a total cost viewpoint, however, the savings in agency costs in moving from Strategy 1 to Strategy 2 are offset by the increase in user costs. Therefore it cannot be said a priori that one strategy is better than another; that determination depends on the relative total costs of the two options and the discount rate at which they are analyzed.

The analysis of total costs can be summarized as follows. Each of the cost streams in Figure 2 would be discounted to compute present costs. Present agency costs and present user costs would be summed in each strategy to yield net present total costs. The respective net present total costs would then be compared to identify the alternative that has the lowest total discounted costs; that alternative is the preferred option.

Evaluation of Results

The total discounted costs of a set of REMR policy options may be compared to identify the best policy, with or without budget constraints. To illustrate how this is done, assume that the benefits can be reduced to monetary terms and thus compared directly with costs. Furthermore, assume that instead of investigating only two policies, as shown in Figure 2, several policies are actually tested using a simulation model.

The results of each policy may be organized in ascending order of costs to the agency owning the facility. Because impacts or consequences of REMR policy are also in monetary terms (in this example), they can be plotted on the same graph with costs for each policy. If REMR policies are sensibly defined and efficiently carried out, more expensive policies (to the agency) should yield more advantageous impacts (i.e., greater reductions in costs associated, say, with safety, travel time, or trip reliability), which leads to the diagram in Figure 3.

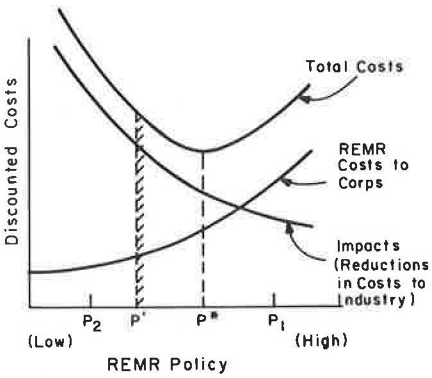

FIGURE 3 Conceptual determination of the optimal REMR policy.

Identification of the most advantageous policy now becomes a question of minimizing total transport-related costs for the network configuration and traffic specified. In the absence of budget constraints, the appropriate policy is shown in Figure 3 as P* because total costs (REMR costs to the agency plus costs associated with impacts of REMR activities) are minimized at this point. If a budget constraint is imposed, the best policy that can be funded lies to the left of P* (i.e., at P′). The relationships used to assess REMR requirements and costs, based on the principles of life-cycle costing used in the management system, are described in the following section.

PREDICTING REMR REQUIREMENTS, COSTS, AND IMPACTS FOR LOCKS

Analytic Requirements

The prediction of REMR requirements and costs according to the life-cycle framework developed in the previous section is based on the following analytic models and data:

1. Definition of measures of condition of the facility;
2. Models to predict the deterioration in condition over time, as functions of initial design and construction standards, facility age, traffic use, operating environment, and other causal factors;
3. Statements of REMR policy, expressed as quality standards defining what work is to take place, when, and where;
4. Sets of REMR activities, defining the technology to be used to correct or prevent deterioration, and the amount or quality of the improvement to be gained; and
5. Models to predict the costs and the impacts of these REMR alternatives.

Preliminary analytic models for Items 1–5 have been developed for navigation locks and are described with their results in the following subsections.

Facility Condition

Research to develop and quantify condition indices as performance measures is proceeding concurrently with this research. Therefore, how these indices must be structured to serve the objectives of a REMR management system is discussed here. It is also assumed that the measures characterize facility performance adequately and can be obtained through currently available technology for inspection and monitoring.

Furthermore, future facility condition is subject to uncertainty due to imperfect knowledge of the processes of deterioration; imperfect means of inspection, monitoring, and evaluation; and the resultant risk of unanticipated failure (such as the catastrophic failure of a supporting element). Therefore the indices used to measure facility condition in this paper have a probabilistic or stochastic dimension expressed either (a) by the mean (or expected value) of condition at some future time and the standard deviation of that estimate or (b) by the probability of failure of a lock component at some future time.

The probabilistic or stochastic aspect of facility condition is shown in Figure 4. The distribution in the upper graph in Figure 4 is based on better levels of evaluation and maintenance presumed to be applied through time T, and the distribution in the lower graph derives from a lesser policy (e.g., less frequent, or lower-quality, maintenance). For purposes of this explanation, the two cases have been constructed so that the means of the distributions at time T are the same, so that the deterioration curve follows the same path in both examples in Figure 4. The effect of the maintenance policies is then seen in the variance or standard deviations of the respective distributions, with the lesser maintenance policy presumed to result in a higher standard deviation. Essentially this means that less maintenance (or less inspection, evaluation, routine repair, etc.) of a facility leads to a loss in the reliability of its future condition.

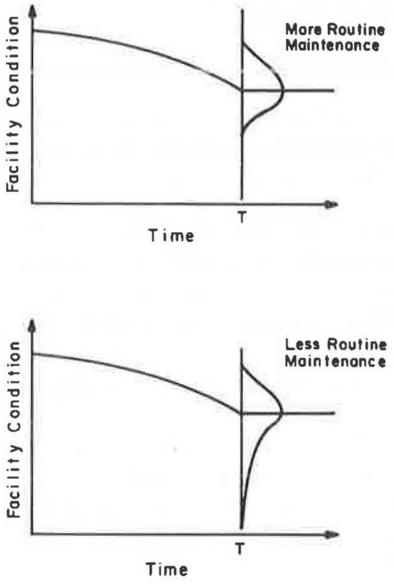

FIGURE 4 Effect of routine maintenance on reliability of facility condition.

Because locks comprise different structural and operational features, separate indices can be defined for each of these major components. There is the option of either working with this set (or vector) of condition indices or combining them (according to some empirically established formula) to compute a single overall index for the lock. In this phase of the study, the problem of expressing the condition of the lock is decomposed into separate predictions for three major components: gates, walls, and mechanical equipment.

The following measures of facility condition are used in this preliminary analysis:

- Expected value of the gate condition index,
- Standard deviation of the gate condition index,
- Expected value of the wall condition index,
- Standard deviation of the wall condition index, and
- Probability of failure of mechanical equipment.

These measures recognize the variability inherent in measures of condition (as shown in Figure 4) and the different physical and operational characteristics of several components of locks. In the examples that follow, lock gates and walls will be used to illustrate the types of preliminary relationships developed for the management system, with the understanding that analogous models have been developed for mechanical equipment. These models are intended for use only in the prototype version of the management system; the deterioration and cost models will be validated and calibrated in the field before they are included in a production version of the management system.

Deterioration Models

Three basic forms of deterioration models have been developed. The first predicts the expected values (i.e., the means) of the gate or wall condition indices. The second estimates the standard deviations of these indices over time. The third computes the probability of failure of mechanical equipment. Preliminary analytic expressions for each of these models are presented hereafter.

Expected Value of Condition Index

At this preliminary stage in the research, time has been assumed to be a surrogate for several factors that affect lock damage and deterioration: quality of design and initial construction (or of subsequent reconstruction or major rehabilitation), type and extent of lock usage, aging and time-dependent changes in material properties, and environmental effects (temperature, water intrusion, chemical attack, etc.). Subsequent research may shed light on the respective contributions of these factors to declines in the conditions of lock gates and walls and on how they can be best represented analytically. For the time being, a simple time-related function will suffice to illustrate schematically the role of deterioration functions in the REMR management system.

The expected value of the condition index for gates and walls is given by

$$CI(t) = CI_0 - a_1 \exp(b_1 \cdot t^{0.5}) \qquad (1)$$

where

$CI(t)$ = condition index of the gate or wall in year t,
CI_0 = initial condition index, and
a_1 and b_1 = coefficients.

Standard Deviation of Condition Index

The standard deviation of the condition index is assumed to vary with time, the policy governing routine maintenance and evaluation, and the performance of repair and rehabilitation activities. This relationship is structured as a Markov process in which the standard deviation of the condition index in any given time period is assumed to be a function solely of the standard deviation in the preceding time period and the level of REMR activities performed in year *t*:

$$\begin{aligned} \sigma(t) &= \sigma[t-1]\delta \quad \text{for } t \geq 1 \\ &= \sigma_0 \quad \text{for } t = 0 \end{aligned} \tag{2}$$

where

$\sigma(t)$ = the standard deviation of the condition index for gates or walls in year t;
δ = a variable that reflects the change in standard deviation of condition as a function of REMR activities, where $\delta > 1$; and
σ_0 = the standard deviation of the condition index in year 0.

Additional comments on the ways in which REMR activities interact to influence this relationship will be given shortly.

Effects of REMR Activities

In an analytic sense, REMR activities affect not only the values of specific variables (e.g., δ in Equation 2) but also the way in which Equations 1 and 2 must be interpreted. The reason is that activities such as repair or rehabilitation create discontinuities or steps in the deterioration functions. Thus, although the basic concepts underlying the present approach to deterioration are reflected in Equations 1 and 2, some refinements are needed to account for changes due to past REMR activities. Also, the interpretation of σ in Equation 2 needs to be more fully discussed. These extensions are covered in the following paragraphs.

Repair and Rehabilitation One major consideration in all REMR deterioration models is the effects of discontinuities in the relationship between condition and time. These discontinuities are due to activities like repair and rehabilitation, which produce an immediate and significant increase in the facility's condition index. Analytically this is important because it represents an interruption in the historical deterioration trend. The way this problem is handled in the preliminary models for locks is shown in Figure 5.

The curve in Figure 5 is a plot of the deterioration function for the mean condition index over time as given by Equation 1. The curve is interrupted by repair or rehabilitation at time *T*. (Whether repair or rehabilitation, and whether minor or major, would be indicated by the extent of improvement in the mean condition index.) The question is: What is the rate of deterioration after the repair or rehabilitation? The assumption made for both of these activities is that the rate of deterioration is uniquely coupled with the value of the condition index itself. This is shown graphically in Figure 5 in which the slope of the deterioration curve after repair or rehabilitation is equal to the slope of the curve at that same value of condition index (*CI*) before repair or rehabilitation.

This assumption is based on a concept of "equivalent facility age," which is the time between initial construction (or reconstruction or complete rehabilitation) and the time at which the condition index first intersects the reference value *CI*. In Figure 5, the equivalent age is denoted by *m*. In effect this says that the repair or rehabilitation performed at time *T* restores the facility to the condition it enjoyed at an earlier time *m*. The slope of the deterioration curve (from Equation 1) would be given by

$$-a_1 \cdot b_1 \cdot 0.5 \exp\,(b_1 \cdot m^{-0.5}) \tag{3}$$

where the constants are as defined for Equation 1. Equation 1 itself can now be generalized as follows:

$$CI(t) = CI_0 - a_1 \exp\,(b_1 \cdot m^{0.5}) \tag{4}$$

where *m* now denotes the (equivalent) age of the facility (i.e., the time since the last new construction, reconstruction, or major rehabilitation). Note that the expected value of facility

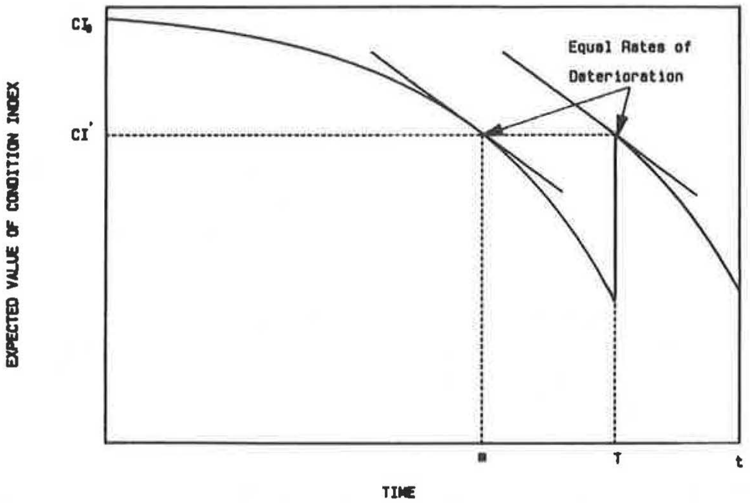

FIGURE 5 Effect of repair or rehabilitation on facility condition.

condition represented by Equation 4 captures the effects of only those REMR activities that change the magnitude of the condition index (i.e., repair and rehabilitation). It does not directly reflect the impacts of routine maintenance or evaluation. These latter activities, together with repair and rehabilitation, are reflected in the computation of the standard deviation of condition index over time in Equation 2, specifically through the variable δ.

Routine Maintenance If in some time interval there is no rehabilitation or repair, and policies governing routine maintenance and evaluation remain constant, then the variable δ likewise remains constant (and greater than 1). When routine maintenance varies, δ is a quadratic function of the difference between actual and maximum routine maintenance as given by

$$\delta = a_5 + b_5 \, [\text{Max(Routine)} - \text{Routine}\,(t)]^2 \qquad (5)$$

where

a_5 and b_5 = constants,
Max(Routine) = a value representing the maximum level of routine maintenance effort, and
Routine(t) = the routine maintenance policy in year t.

Major rehabilitations restore the standard deviation of the condition index to its original value σ_0. Minor rehabilitations or repairs are assumed to reduce the standard deviation by some proportion.

Equations 2 and 5 represent, albeit in a limited but nevertheless important way, the interactions among the different REMR activities in influencing facility performance and cost. This is a characteristic of the demand-responsive approach and is important to the ability of management to assess trade-offs among different REMR policies.

Agency Costs

The cost models for routine maintenance and evaluation, lock operations, major and minor rehabilitation, and repair are based on analysis of existing data [Chapters 3 and 5 of Markow et al. (*15*) provide detail on how past cost data were used to estimate cost and deterioration model parameters]. However, two new analytic features have been introduced in accordance with concepts presented earlier: (a) REMR policies have been included specifically as variables affecting the demand for work, and hence its cost, and (b) the role of uncertainty has been explicitly recognized.

Scheduled Repair or Rehabilitation Costs

Rehabilitation costs are assumed to be proportional to an increasing linear function of the amount of improvement achieved [Section 5.2 of Markow et al. (*15*) provides justification for the linear assumption]. The relationships are as follows:

$$S\_Cost(t) = 0 \quad \text{if neither minor nor major rehabilitation is done in year } t$$

$$S\_Cost(t) = \begin{cases} a_6 + b_6 \cdot \Delta & \text{if } \Delta \le \Delta_{\max} \\ a_6' + b_6' \cdot \Delta & \text{if } \Delta > \Delta_{\max} \end{cases} \qquad (6)$$

where

$S\_Cost(t)$ = scheduled maintenance cost for gates or walls in year t;
a_6, b_6, a_6', b_6' = coefficients;
Δ = the amount of condition index improvement in year t; and
$\Delta_{\max}$ = the maximum amount of condition index improvement that can be achieved by minor rehabilitation.

Unscheduled Repair or Rehabilitation Costs

Unscheduled repairs or rehabilitations occur when the condition index is allowed to fall below a minimum standard or the mechanical equipment unexpectedly fails. For gates or walls, the expected value and standard deviation of the condition indices are known. Therefore, if the predicted value of the condition index is assumed to be normally distributed, the probability of the condition index's falling below the condition standard can be estimated and the expected cost of repair computed as follows:

$$US\_Cost(t) = inc\_prob \cdot us\_maint\_cost \qquad (7)$$

where

$US\_Cost(t)$ = the expected value of the unscheduled gate/wall repair or rehabilitation cost in year t;
inc_prob = the incremental probability of the gate/wall condition index falling below the minimum condition index standard in year t, where the increment is computed as the difference in the probability of failure in year t compared with year $t - 1$; and
us_maint_cost = the expected value of unscheduled minor rehabilitation or repair cost for gate/wall in any year.

Routine Maintenance Cost

The model of routine maintenance costs (including facility evaluation but excluding annual operating costs) is the sum of quadratic functions of the level of routine maintenance given by

$$\begin{aligned} Routine\_Maint\_Cost(t) = {} & a_8 + b_8 \cdot [G\_routine(t)]^2 \\ & + c_8 + d_8 \cdot [W\_routine(t)]^2 \\ & + e_8 + f_8 \cdot (M\_routine)^2 \end{aligned} \qquad (8)$$

where

$Routine\_Maint\_Cost(t)$ = routine maintenance cost in year t;

$a_8, b_8, c_8, d_8, e_8, f_8$ = coefficients;
$G\_routine(t)$ = routine maintenance policy for gates in year t;
$W\_routine(t)$ = routine maintenance policy for walls in year t; and
$M\_routine$ = average routine maintenance policy for mechanical equipment for the entire planning horizon.

Lock operating costs are not included here unless they can be shown to be sensitive to REMR policy.

Lock Damage Costs

Repair or rehabilitation costs due to motor vessel damage are based on the average annual damage cost because the probability of damage is assumed to be a Poisson process. A preliminary value of $15,320 per incident is used as the damage cost in the prototype management system.

Traffic Growth

Traffic volume determines both the usage of the lock (affecting REMR requirements and costs) and the impacts of lock performance as affected by REMR policy. Given the long service lives of lock facilities, it is unrealistic to expect that traffic growth can extend uniformly throughout the entire analysis period. Therefore, some growth rate may be specified for a limited number of years only; traffic will then become asymptotic to some maximum anticipated volume. The relationship used to represent traffic growth is

$$T_t = A - B \exp(-c \cdot t) \tag{9}$$

where

T_t = annual traffic in tows in year t,
A = $(1 + \text{growth rate}/100)^{\text{growth years}} \cdot$ growth start,
B = A − growth start, and
c = 0.20 (coefficient).

Growth rate is the rate of annual traffic growth in percentage; growth years is the number of years that the given growth rate is to be used; and growth start is the yearly traffic in year 0 (barges/year).

Impacts on Waterway Users

In general, REMR activities performed on locks may result in reduced shipping costs to users because of more efficient and safer performance of locks and reductions in unexpected breakdowns (although scheduled downtime may increase somewhat). Components of user (or industry) costs relevant to REMR performance include the delay cost associated with waiting in queues and lock servicing, cost incurred during facility downtime, traffic mode diversion cost, and safety and reliability cost. To illustrate these models, the delay cost model is described.

If the condition of a lock were poor, the performance of the lock would also be expected to be poor (i.e., the average service rate of the lock would be low or the standard deviation of the service time would be high, or both). As a result, traffic going through the lock would encounter longer delays. The relationship between the average service rate of the lock and the condition of the three components of the lock is captured as follows:

$$\mu(t) = \mu 0 \left| \frac{\exp\{a_3\,[Mfail(t) - 0.50]\}}{1 + \exp\{a_3\,[Mfail(t) - 0.50]\}} \right|$$
$$\times\ 1/\big(1 + \exp\{b_3\,[GCI(t) - 5.0]\}\big)$$
$$\times \big(1 + \exp\{c_3\,[WCI(t) - 5.0]\}\big) \tag{10}$$

where

$\mu(t)$ = the expected service rate of the lock in year t,
$\mu 0$ = the service rate of the lock in year 0,
a_3, b_3, and c_3 = coefficients,
$Mfail(t)$ = the mechanical device probability of failure in year t,
$GCI(t)$ = the lock gate condition index in year t, and
$WCI(t)$ = the lock wall condition index in year t.

When the average service rate and the variance in service time have been quantified, queueing theory models are used to compute the traffic delays at locks. The use of the queueing models has been common in Corps project evaluation, and a review of the existing queueing theory approaches used to compute the delays at locks appears elsewhere (*15*, Chapter 4). Whereas queueing models used by the Corps have assumed two adjacent locks to be independent of each other, new models have been developed to account for the interdependencies between adjacent locks upstream or downstream in affecting barge arrivals, delays, and departures. Thus, in a limited way, these models can account for "network" effects due to REMR work at nearby locks as well as at the lock in question. Total queueing delays computed by these models are translated into total delay costs.

Within anticipated ranges of facility condition, the effect of an REMR activity would be some improvement in the performance of an existing lock. The effect of this change in facility condition on traffic mode diversion is therefore assumed to be insignificant. Also, because there are no standard procedures for computing safety and reliability costs, such costs and benefits are not included in the management system at the present time.

Total Cost Tallies

When all of the cost items have been computed, the agency costs and user costs are totaled by summing the following items annually through the analysis horizon: the costs of both scheduled and unscheduled rehabilitation, repair, and routine maintenance of lock gates, walls, and mechanical equipment; the costs of damage to the locks by barges; and user costs due to facility downtime and to delay in the queue and during lock cycling. These annual costs are then discounted and summed for the entire analysis period.

Case Study of REMR Policies

A case study of six example REMR policies was developed to demonstrate the capabilities of the prototype management system. The six policies are given in Table 2 and range from lower-cost, lower-standard policies (beginning with Policy 1) to higher-cost, higher-standard policies (concluding with Policy 6). The higher standards reflect more frequent and more extensive REMR work performed on the facility than do the lower-standard policies. The six policies were run successively using the model; results are summarized in the cost curves in Figure 6.

The results of the case study in Figure 6 are a discrete analog to the conceptual results shown in Figure 3. For example, the least-cost solution, Policy 2, corresponds to the optimal policy P* in Figure 3. In the absence of other, noneconomic considerations, Policy 2 would therefore be the recommended REMR policy in this example. Furthermore, the trends of the individual cost curves in Figure 6 help in understanding the trade-offs among cost components leading to this result.

For example, the policies in Figure 6 are ordered such that the standards of REMR increase from left to right. Discounted agency costs likewise increase with increasing policy standards, as suggested conceptually in Figure 3. Furthermore, with more frequent and more extensive REMR work under the higher policies, average lock condition and service rate also improve, reducing the average delay per tow. The impact of this improved facility condition on user costs is somewhat more complicated, however, because a number of competing trends are at work.

User costs are relatively high for lower REMR policies because of the resulting poorer lock condition and its adverse impacts on lock cycling time and associated delays and queues. Furthermore, with the lower levels of evaluation and routine maintenance, there is a higher expected frequency of unscheduled downtime for maintenance and repairs. As the REMR policy improves, so do lock condition, service time, and delays to industry, as suggested conceptually in Figure 3. Indeed, this trend is borne out by the case study results in Figure 6, particularly if Policies 1–5 are compared. However, although unscheduled downtime in Figure 6 decreases from Policy 1 to Policy 6, scheduled downtime increases because of the greater amount of work called for by the higher REMR policies.

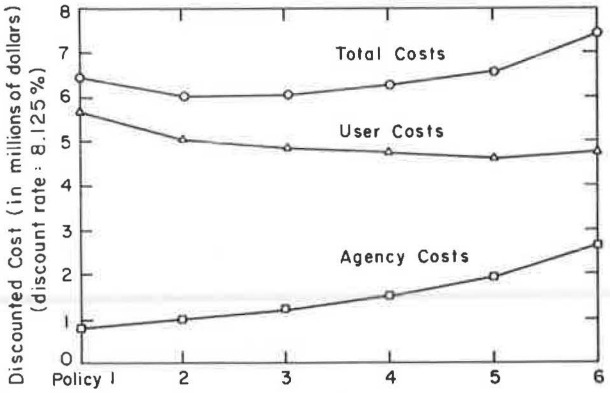

FIGURE 6 Results of case study.

At some point a limit is reached, beyond which any additional REMR work begins to interfere with lock traffic in an uneconomical way. For this case study, this trade-off is illustrated by the comparison of Policies 5 and 6 in Figure 6, at which interval the discounted user costs begin to rise, in addition to the already increasing agency costs of the higher-standard policies. The implication of these trends is that although Policy 2 is optimal, any further improvements in policy are not economically warranted: not only will incrementally higher standards cost the Corps more, they will, at some point, also delay traffic with no compensating benefit.

This comparison of competing policies (Figure 6) serves to illustrate the basic ideas and procedures involved. More important, it provides a practical example of the application of demand-responsive concepts of life-cycle costing and how these concepts can be applied in a practical way to REMR management of civil works.

CONCLUSION

The objective of this research program has been to design, develop, and illustrate a computerized package to assist districts, divisions, and the Office of the Chief of Engineers of the Corps of Engineers in the management of REMR programs for civil works. The REMR management system is based on the

TABLE 2 REMR POLICIES TESTED IN CASE STUDY

	Policy					
Item	1	2	3	4	5	6
Lock gates						
Minimum condition standard	2.1	4.1	5.4	6.7	7.6	8.8
Major rehabilitation interval (years)	49	45	40	35	30	25
Repair interval (years)	35	30	25	20	15	10
Routine maintenance level (0–10)	3	4	5	6	7	8
Repair ΔCI	0.45	0.45	0.45	0.45	0.45	0.45
Lock walls						
Minimum condition standard	7.7	8.0	8.4	8.7	8.9	9.2
Major rehabilitation interval (years)	49	45	40	35	30	25
Repair interval (years)	35	30	25	20	15	10
Routine maintenance level (0–10)	3	4	5	6	7	8
Repair ΔCI	0.2	0.2	0.2	0.2	0.2	0.2

concepts of life-cycle costing of civil facilities and demand-responsive analyses of repair, evaluation, maintenance, and rehabilitation. The research has comprised several tasks involving (a) formulation of concepts needed to manage programs of facility repair, evaluation, maintenance, and rehabilitation; (b) integration of management elements within a framework of facility life-cycle costing; (c) review of information on the frequency and costs of REMR performance and development of preliminary models of facility condition and costs; and (d) incorporation of these predictive models within a prototype REMR management system, illustration of its use, and interpretation of its results.

Results of the research to date indicate several areas in which further studies need to be made in future stages of this work. Among the more prominent topics requiring investigation are (a) a much better understanding of the mechanisms of deterioration and the role of REMR activities in correcting or preventing distress, (b) determination of appropriate condition indices at the facility level, (c) relationships quantifying the costs and impacts (or consequences) of alternative REMR policies, and (d) mathematical procedures to yield optimal REMR policies.

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