COATING MAINTENANCE OPTIMIZATION FOR STEEL PENSTOCKS

by

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Abstract

Two methods for minimizing coating maintenance costs for steel penstocks are presented in this thesis. The first method performs a life-cycle cost analysis using equivalent annual costs to compare the three maintenance strategies: touch-up, overcoat, and, strip and re-coat. The strategy with the lowest annual costs is considered to be optimal. The second method uses a dynamic programming approach to obtain the minimum costs resulting from a sequence of rehabilitation choices.

A computer application, Penstock Maintenance Program (PMP), was developed based on the two optimization procedures. It was intended for this program to serve as a practical tool to minimize the yearly costs of penstock coating maintenance. The program was therefore developed on a platform which is both accessible and familiar. An on-line help feature has also been provided to ease the use of the program.

In addition to performing the two optimization procedures, PMP allows the user to enter trial sequences of rehabilitation strategies to compare equivalent annual costs. Interval calculations have also been implemented to handle imprecisely defined cost data.

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Acknowledgments

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1. Introduction

Disastrous penstock failures are becoming more frequent at hydroelectric stations, particularly in the past 15 years with older facilities. Historically, more deaths have occurred due to penstock failures than dam failures [Stutsman, 1996]. It is therefore necessary to establish cost-effective programs to prevent penstock failure. Penstocks, of course, are pressurized, closed water conduits used for conducting water from the water surface to a power house where electricity is generated.

One of the main reasons for the failure of steel penstocks is the corrosion of the base metal, resulting in a loss of structural integrity. Consequently, the control of ongoing corrosion becomes important in prolonging structure serviceability. Although corrosion cannot be prevented, it can be controlled by preventive maintenance. The application of rehabilitation activities can extend the service life of a penstock. Therefore, analysis techniques such as life-cycle cost analysis or dynamic programming can be used to aid decision making in creating rehabilitation strategies.

A research project between B.C. Hydro and the University of British Columbia was conducted to incorporate two methods for minimizing the costs of a penstock coating maintenance program into a computer application. This may aid in scheduling rehabilitation activities on a timely, cost-effective basis.

1.1 Objectives

One objective of this research is to provide a brief description of coating maintenance for steel penstocks. Two methods of minimizing the annual costs for the coating maintenance will be explored. The first method is a life cycle cost analysis using each of the three maintenance strategies: touch-up, over-coat, and re-coat. The second method involves a dynamic programming approach to minimize costs.

The primary objective, however, is to create a tool to aid the decision making process for coating maintenance. This tool, in the form of a computer model, will incorporate the two methods described above in attempting to develop a coating maintenance policy. Alternatively, it could be used to calculate the costs for a specific maintenance policy.

1.2 Literature Review

The need for developing penstock safety programs have been previously identified [Stustman, 1996]. Maintenance painting programs are an important part of any safety program. In fact, many researchers are now using computer applications as tools for developing painting maintenance policies [Cunningham, 1994; Smith, 1995]. In addition to serving as information bases, computers have the ability to perform high numbers of calculations quickly. This is useful when performing life-cycle cost analyses or using dynamic programming approaches to minimizing costs. Research has been done using these methodologies to minimize coating maintenance costs for bridges [Weyers, 1988; Tam, 1994]. Some of the ideas from these previous sources are incorporated into the coating optimization analysis for steel penstocks.

2. Penstock Coating Maintenance

The primary goal of maintenance coating programs is the visual and physical preservation of the steel penstocks by preventing metal loss. This is achieved by using quality coating systems, and performing coating maintenance on a timely basis. The coating controls metal loss and corrosion by forming a physical barrier and preventing the elements from reaching the steel.

The following sections describe various defects that may occur, and the rehabilitation strategies used to correct these defects.

2.1 Types of Failure

Numerous failure modes and defects related to painted structures are possible. Factors that contribute to coating failures include the service environment, the type and application of the coating system, age, chemical exposure, and physical impact. Some of the types of coating failures are described in the following paragraphs.

Blistering is a common defect that can result in early failure on the coating system. They can result from a wide variety of causes. Often, they are filled with a liquid or gas. Blisters can occur at the metal / coating interface or between coating layers. Blisters continue to provide corrosion protection until they are broken.

Undercoating refers to corrosion occurring beneath the coating system. This type of failure usually occurs at breaks in the coating system. It is usually caused by poor adhesion.

Pinpoint Rusting refers to rust breakthrough on the coating surface. It could be caused by inadequate coating thickness or can be caused by aging and the natural degradation of the coating itself.

Delamination failure is caused by inadequate adhesion of a coating system. It can also indicate improper choice of coating materials. Delamination occurs when a coating peels off of its substrate.

Other defects in coating systems include flaking, scaling, chalking, and checking. These are surface defects resulting from stresses in the coating during curing and aging. These failures also contribute to the early failure of coating systems.

2.2 Maintenance Strategies

Three types of maintenance activities are used to maintain the coating systems for steel penstocks. These activities could be compared or combined to provide cost-effective coating maintenance programs. The three rehabilitation methods are: Touch-Up, Over-Coat, and Re-Coat. The other alternative to these three maintenance activities is the "do-nothing" alternative. Of course, this alternative requires that the penstock be replaced once corrosion has reduced its load carrying capacity below the minimum acceptable.

2.2.1 Touch-Up (or Spot Repair)

Touch-Up is used where only a few localized failures are occurring. The use of Touch-Up maintenance implies that the intact, sound coating is retained. The existing coating where there is localized failure is removed, and a new system is applied. Touch-Up maintenance is effective because corrosion is not uniform on the whole penstock, and rehabilitating only the corroded areas will require less effort and reduce the cost of maintenance. This is true when there is only a few areas which require rehabilitation.

2.2.2 Over-Coat

Over-Coating is used where the existing coating system can withstand the application of additional coats. The advantage of a full coat is that it corrects localized deficiencies that may not be visible during inspection, or may not be feasible for Touch-Up maintenance. Over-coating involves removing the existing coating where there are defects, cleaning the intact paint, and applying a new coating over the entire structure. The use of Over-Coating delays the eventual complete removal of the underlying coatings. This may be advantageous due to the high costs associated with the removal, containment, and disposal of the older coatings. The disadvantage of Over-Coat maintenance is that the new coating may fail prematurely due to incomplete compatibility with the existing coating system.

2.2.3 Re-Coat

Re-Coat involves a complete removal of all existing coatings on the penstock until bare metal is reached. A new coating system is then applied to the entire penstock. The costs associated with Re-Coat may be high due to the costs of removing, containing and disposing of the old coating systems. Generally, Re-Coating is used when Over-Coating options are more expensive or are too risky. Re-Coating of the entire structure may also be necessary if the existing coating system has deteriorated substantially. Additionally, Re-Coating may be the only option for some coating systems that could not be spot-repaired or over-coated.

3. Coating Optimization Procedures

Two methods are described for minimizing the annual costs related to the coating maintenance of steel penstocks. The first method compares the equivalent annual costs of using each strategy at regular intervals. The second method allows the three maintenance strategies to be combined in any order to achieve a minimal equivalent annual cost. Both of the methods are dependent on the simulation of coating deterioration.

3.1 Coating Deterioration Simulation

Quantifying coating system deterioration and establishing deterioration patterns are difficult tasks to perform accurately. Although guidelines exist for evaluating the degree of deterioration and corrosion, they are difficult to apply in the assessment of real structures. Since the evaluation of corrosion is visual, they are often subjective at best. Visual records such as successive photos from monitoring programs are best used with corrosion scales to minimize any discrepancies. Table 3.1 shows a ten point rated scale and description of rust grades as published in the ASTM D610 standard "Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces". PMP uses this scale to describe the *degree* of coating deterioration.

Table 3-1: Corrosion Performance Rating ASTM D610

Rust Grade	Description
10	no rusting or less than 0.01 % of surface rusted
9	minute rusting, less than 0.03 % of surface rusted
8	few isolated rust spots, less than 0.1 % of surface rusted
7	less than 0.3 % of surface rusted
6	extensive rust spots bust less than 1 % of surface rusted
5	rusting to the extent of 3 % of surface rusted
4	rusting to the extent of 10 % of surface rusted
3	approximately one sixth of the surface rusted
2	approximately one third of the surface rusted
1	approximately one half of the surface rusted
0	approximately 100 % of surface rusted

The *rate* of coating deterioration used in PMP is modeled after deterioration curves published in the Structural Steel Coating Manual from the Ontario Ministry of Transportation. Three different deterioration functions are given, depending on the environment type: marine, industrial, or rural. PMP approximates each of the three deterioration functions with two linear functions. This can be justified since the deterioration functions are already linear beyond the 0.1 - 0.3% rust level. Furthermore, linear functions are easier to model and interpret than high order polynomials. Figure 3.1 shows the deterioration functions used in PMP. PMP also accepts user defined rates of deterioration.

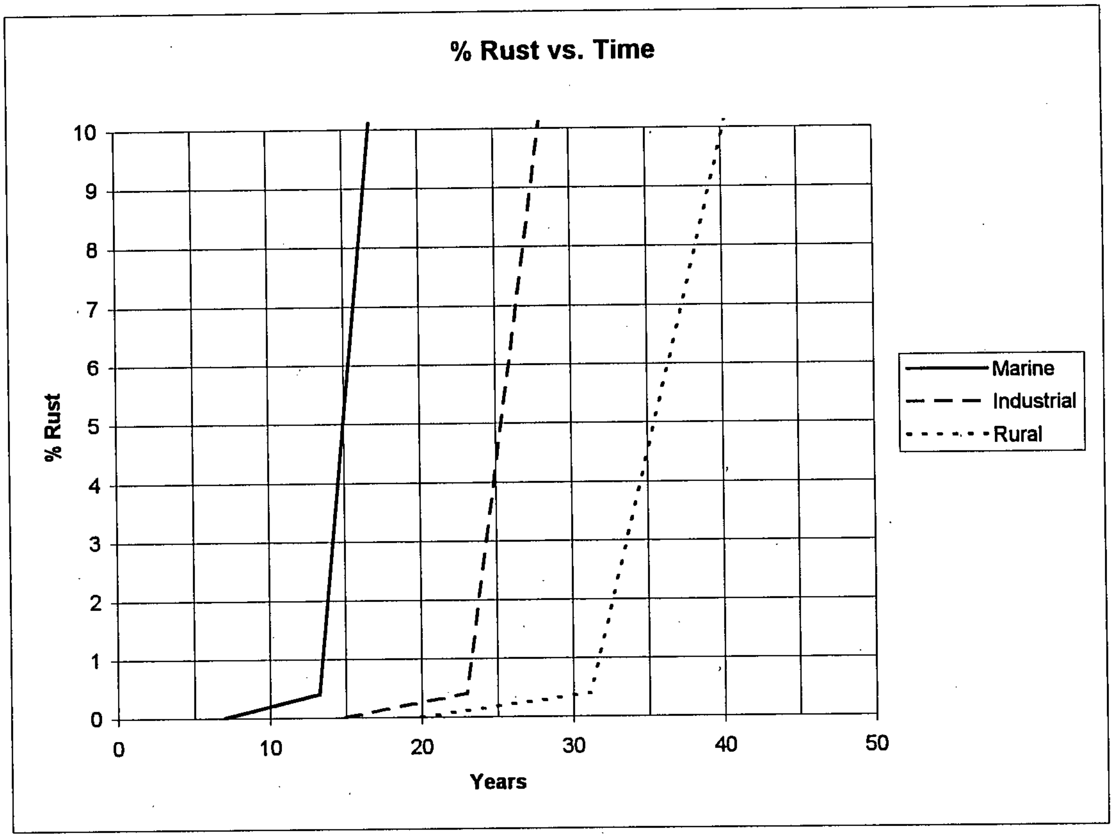

Figure 3-1: Coating Deterioration Functions Used in PMP

3.2 Equivalent Annual Cost Comparison

Comparing the equivalent annual cost of performing each maintenance strategy at different time intervals is a simple approach to minimizing coating costs. This method assumes that only one maintenance strategy will be used at equal time intervals for the design life of the penstock. The results of this analysis shows the minimal costs and the optimal time intervals to perform rehabilitation activities for each strategy. An interval of a maximum and minimum annual cost are associated with each time interval. The true annual cost is bound within the cost interval, the magnitude of which depends only on the precision of the cost data. The following procedure explains the cost calculation.

1. At time j, the degree of rusting, *%Rj*, on the penstock can be calculated from the deterioration curve. This step assumes that at time 0, there is no rusting and the condition rating of the penstock is 10.

2. The percentage of rusted area, *%ARj*, is adjusted for the type of maintenance strategy. This is accomplished by multiplying *%Rj* by a curve factor for the appropriate strategy. The curve factors are used to account for the differences in deterioration rates when different maintenance strategies are used. They are also meant to offset the assumption that the penstock coating is in a new condition after any maintenance activity when in fact this is true only for strip and re-coat operations.

3. The condition at time j, *Cj*, is determined from the ASTM D610 standards. If the condition is not within the condition limits for the strategy as defined by the user, then another time interval is tried.

4. The percentage of area for which maintenance is required, *AMj*(%) is entered by the user in the input module of PMP. This percentage depends on the condition *Cj*. The actual area for which maintenance is required is calculated using the following formula:

$$AMj = AMj(\%) \text{ x surface area of penstock section}$$

5. Costs for performing each strategy include surface preparation costs, coating costs, and fixed mobilization costs. The cost for performing the maintenance at time j, *Costj*, depends on the maintenance strategy. For touch-up, only the rusted areas require surface preparation and coating application. The coating is typically applied with brush application. For over-coating, the whole surface requires coating. Strip and re-coat activities requires surface preparation and coating of the entire penstock. Coatings are

applied with spray applications for both Over-coat and Re-coat strategies. The costs for each strategy are calculated using cost intervals. The costs for each strategy are as follow:

For Touch-Up:

$Costj = AMj$ x (cost_s + cost_c) + cost_sm + cost_cm

where:

cost_s	=	the unit rate for surface preparation for condition *Cj*
cost_c	=	the unit rate for brush application of coating
cost_sm	=	the mobilization cost for surface preparation for condition *Cj*
cost_cm	=	the mobilization cost for brush application of coating

For Over-Coat:

$Costj = AMj$ x cost_s + Area x cost_c + cost_sm + cost_cm

where:

cost_s	=	the unit rate for surface preparation for condition *Cj*
cost_c	=	the unit rate for spray application of coating
cost_sm	=	the mobilization cost for surface preparation for condition *Cj*
cost_cm	=	the mobilization cost for spray application of coating
Area	=	the total surface area of penstock

For Re-Coat:

$Costj$ = Area x (cost_s + cost_c) + cost_sm + cost_cm

where:

cost_s	=	the unit rate for surface preparation for condition *Cj*
cost_c	=	the unit rate for spray application of coating
cost_sm	=	the mobilization cost for surface preparation for condition *Cj*
cost_cm	=	the mobilization cost for spray application of coating
Area	=	the total surface area of penstock

6. The costs at every year j, $Costj$, are then discounted to an equivalent annual cost, $EACj$, using the discount rate r.

$$EACj = Costj \times \frac{r}{(1+r)^j - 1}$$

3.3 Dynamic Programming Approach

Comparing equivalent annual costs for each strategy separately provides useful information for the user. However, it may not provide the most cost-effective sequence of strategies. Dynamic programming is therefore used to determine the optimal sequence of coating maintenance activities using any combination of the three rehabilitation strategies. Dynamic programming is an optimization technique used to maximize or minimize the sum of values resulting from a sequence of decisions, while minimizing computational efforts. It obtains solutions by working backward from the end of a problem toward the beginning, breaking up a large multi-decision problem into a series of smaller single decision problems.

Formulating the rehabilitation scheduling into a dynamic programming framework will be discussed, and an example will be used to illustrate the concepts.

3.3.1 Formulation

The dynamic programming framework consists of *stages* and *states*. The stage variable represents nodes in a path where decisions may be made. This concept is used to allow decisions to be ordered. The state variable describes the conditions which may exist at every stage. In PMP, the stages refer to time increments representing each year for the length of the analysis, while the condition rating of the penstock at each stage is represented by the state variable. Figure 3.2 shows a representation of the dynamic programming framework used by PMP.

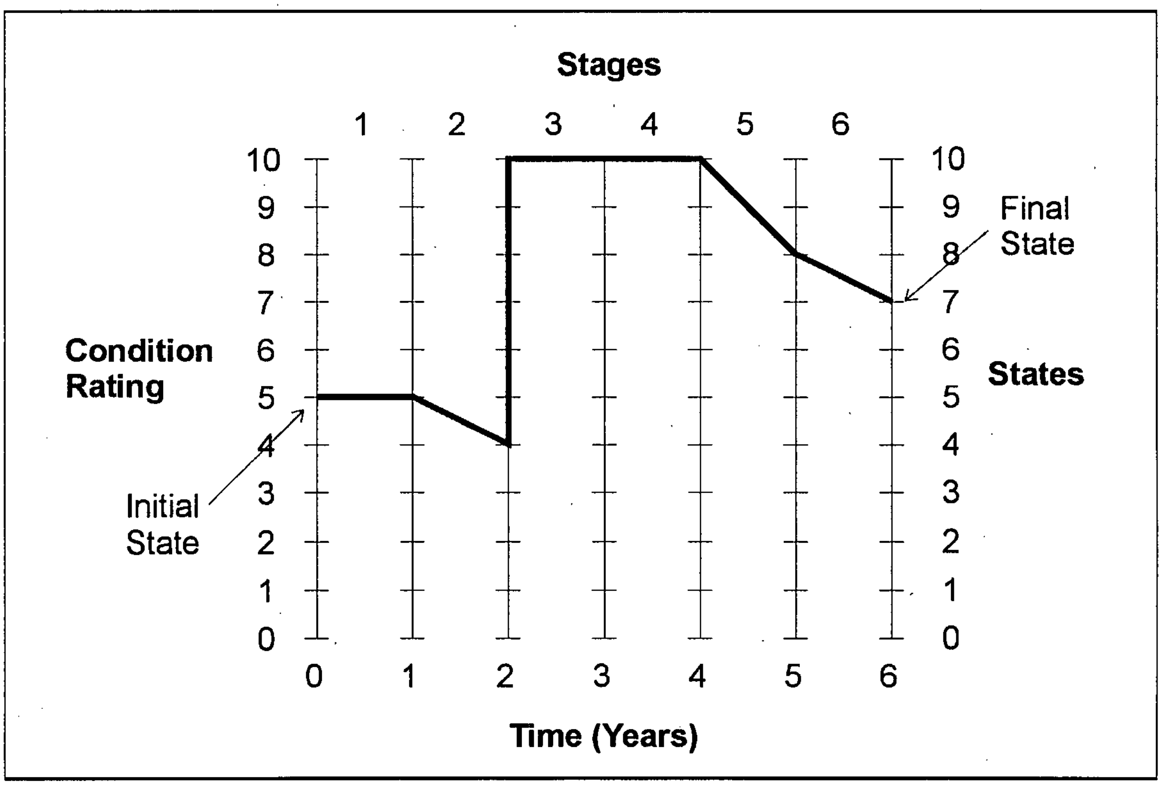

Figure 3-2: Dynamic Programming Framework

At all stage and state combinations which are feasible, a decision *dns* from a set of possible decisions must be chosen. This decision describes how the state at the current stage is transformed into the state at the next stage. This state transformation function depends only on the current stage *n*, state *s*, and decision *dns*. It is described by the formula:

$$s' = t(dns, s, n).$$

In PMP, the set of possible decisions include Touch-Up, Over-Coat, Re-Coat, and do nothing. The choice of any rehabilitation method returns the condition rating (transforms the state) to a value of ten for the same stage.

There is a return or cost corresponding to each decision. The return function is denoted as g(dns,s,n).

The solution of the problem is obtained by finding the optimal or lowest cost sequence of decision choices over all stages. The optimal decision at each stage and state is found using the recursive equation:

$$f_n(s) = \min\,[g(dns,s,n) + f_{n+1}(s')]$$

This function describes the return or cost for the current period, and the cumulative cost for the state under consideration at the previous state. Note that the recursive function for the following stages, $f_{n+1}(s')$, must be known before the current function, $f_n(s)$, can be quantified.

3.3.2 Illustrative Example

Using the dynamic programming approach as described previously, the optimal, or lowest average cost sequence of rehabilitation strategies will be obtained for a simplified set of conditions. In this example, the required condition rating of the penstock at the end of 9 years is six, and there is a minimum acceptable condition rating of five. To simplify the example, all costs for maintenance activities are fictitious and remain in time zero dollars. In PMP, all maintenance costs are discounted to account for the time value of money. Figure 3.3 shows the layout of the feasible region of the problem in a dynamic programming framework.

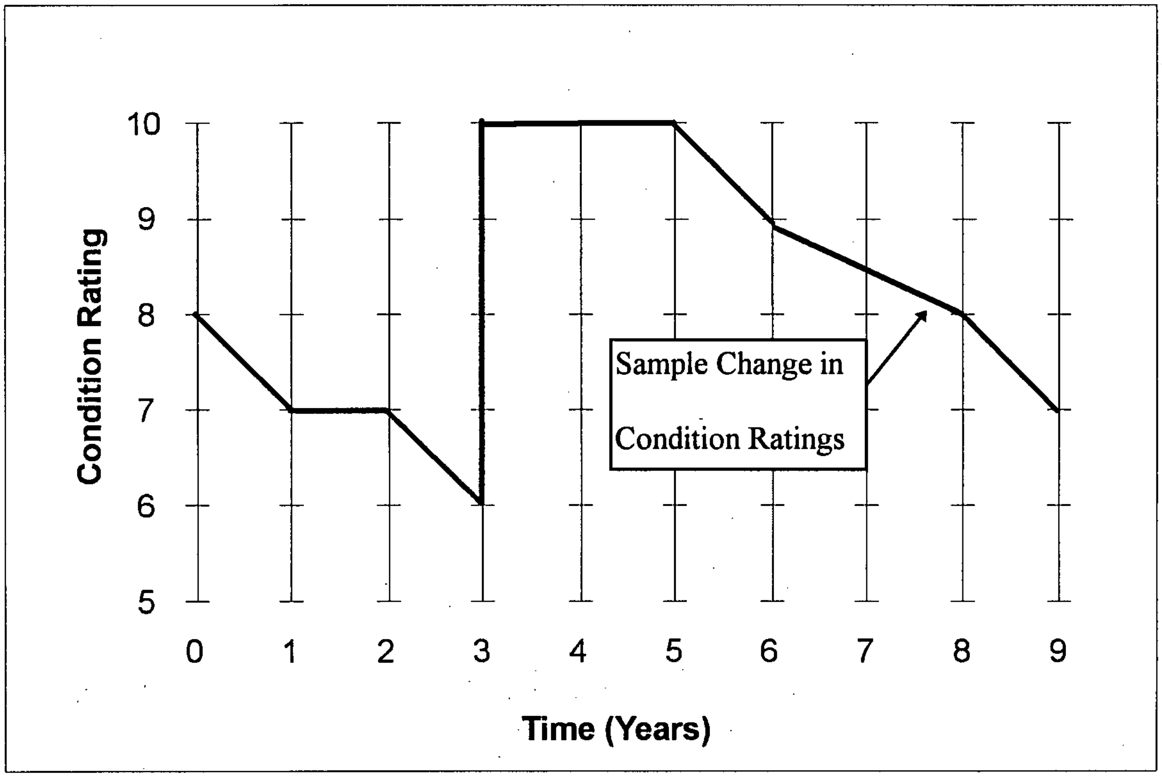

Figure 3-3: Feasible Region for Illustrative Example

The number of decisions at each stage and state are limited by functional constraints. The decrease in condition rating from one stage to the next is governed by the deterioration of the coating system and the previous maintenance activity. A possible set of deterioration functions for the three maintenance strategies is shown in Figure 3.4.

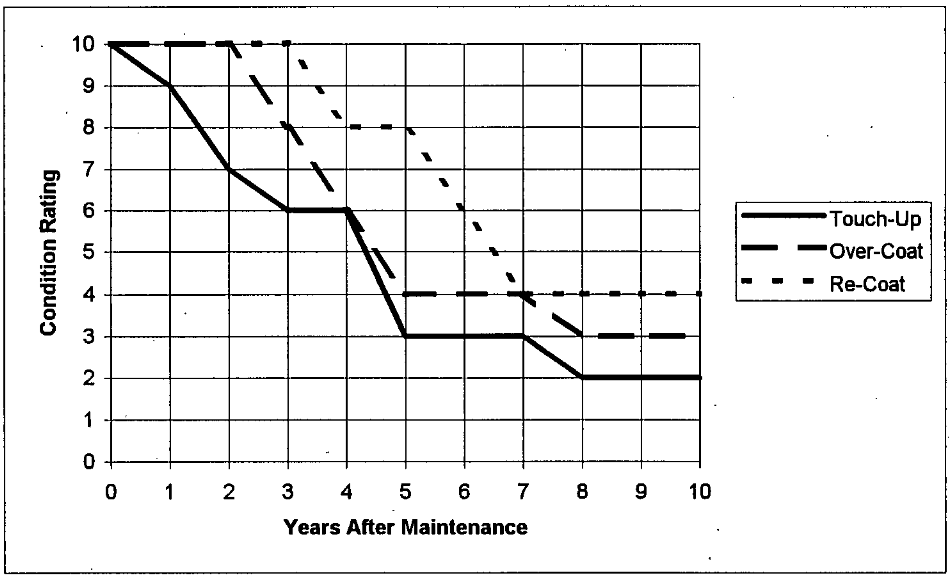

Figure 3-4: Deterioration Functions for Illustrative Example

Table 3.2 summarizes the data presented in Figure 3.4. The table shows the condition rating of the penstock for the years after a certain rehabilitation strategy. For example, the penstock will have a condition rating of six, four years following an Over-Coat. The shaded regions indicate the condition rating interval for which each maintenance strategy is acceptable. The costs are the total average costs for performing the rehabilitation activity. This represents the stage return function previously discussed, and are only tabulated for the conditions that fall within the condition limits for each strategy. Note that for this example, it is not necessary to perform maintenance when the penstock has a rating of eight or higher.

Table 3-2: Deterioration Functions and Costs for Illustrative Example

Condition Rating	Touch-Up		Over-Coat		Re-Coat	
	Years	Cost	Years	Cost	Years	Cost
10	0		0,1,2		0,1,2,3	
9	1					
8			3		4,5	
7	2	$10				
6	3,4	$20	4	$100	6	
5				$200		$1000
4	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
3	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
2	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
1	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
0	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible

Notes
1. Years column represent number of years after maintenance to reach condition in condition rating column
2. Costs column shows total cost of performing maintenance at the condition rating indicated
3. Shaded regions indicate condition interval where each strategy is allowed

The optimization procedure begins at the required condition at the end of the analysis (end of stage nine, state six). This is represented by point A in Figure 3.5. Point A could be achieved if Touch-Up was performed 3 or 4 years previously, Over-Coat was performed 4 years previously, or Re-Coat was performed 6 years previously (see Table 3.2 or Figure 3.4). The deterioration of the coating system is represented by straight lines to simplify the figure, as only the end points are important.

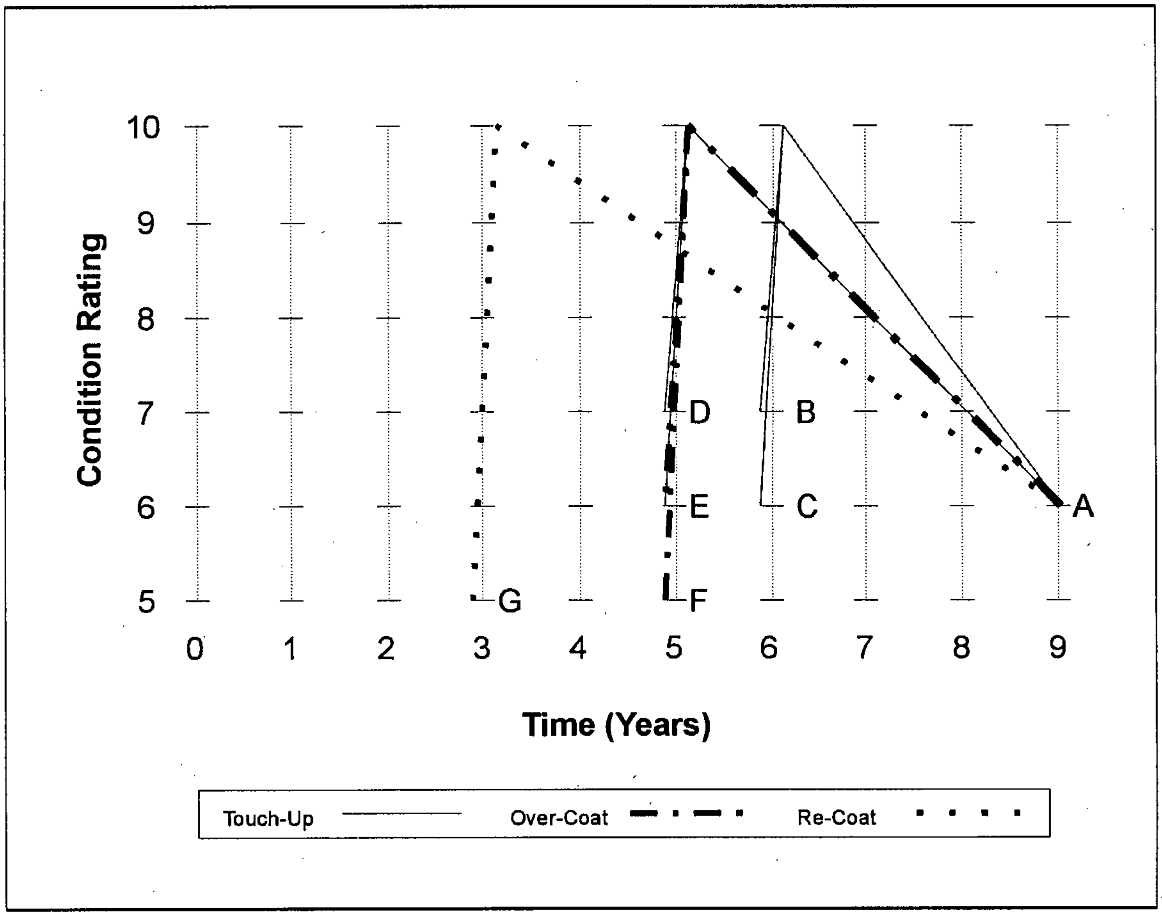

Figure 3-5: Feasible Maintenance Activities to Reach Desired Condition A

For each year that a possible strategy has been identified (years 3, 5, and 6), the allowable states for each strategy are cross-referenced with Table 3.2. For example, it is possible to over-coat the penstock in year 5 to reach point A. The penstock condition rating must be 4 or 5 in order for over-coating to occur. This is represented by points E and F. Points B to G in Figure 3.5 represent other allowable states for performing each strategy at the feasible stages.

This process is continued for points B through G. In this example, only the allowable strategies that reach point E are analyzed. This is shown in Figure 3.6. In PMP, the process of tracing possible paths of the penstock condition is continued for all possible nodes until stage zero is reached.

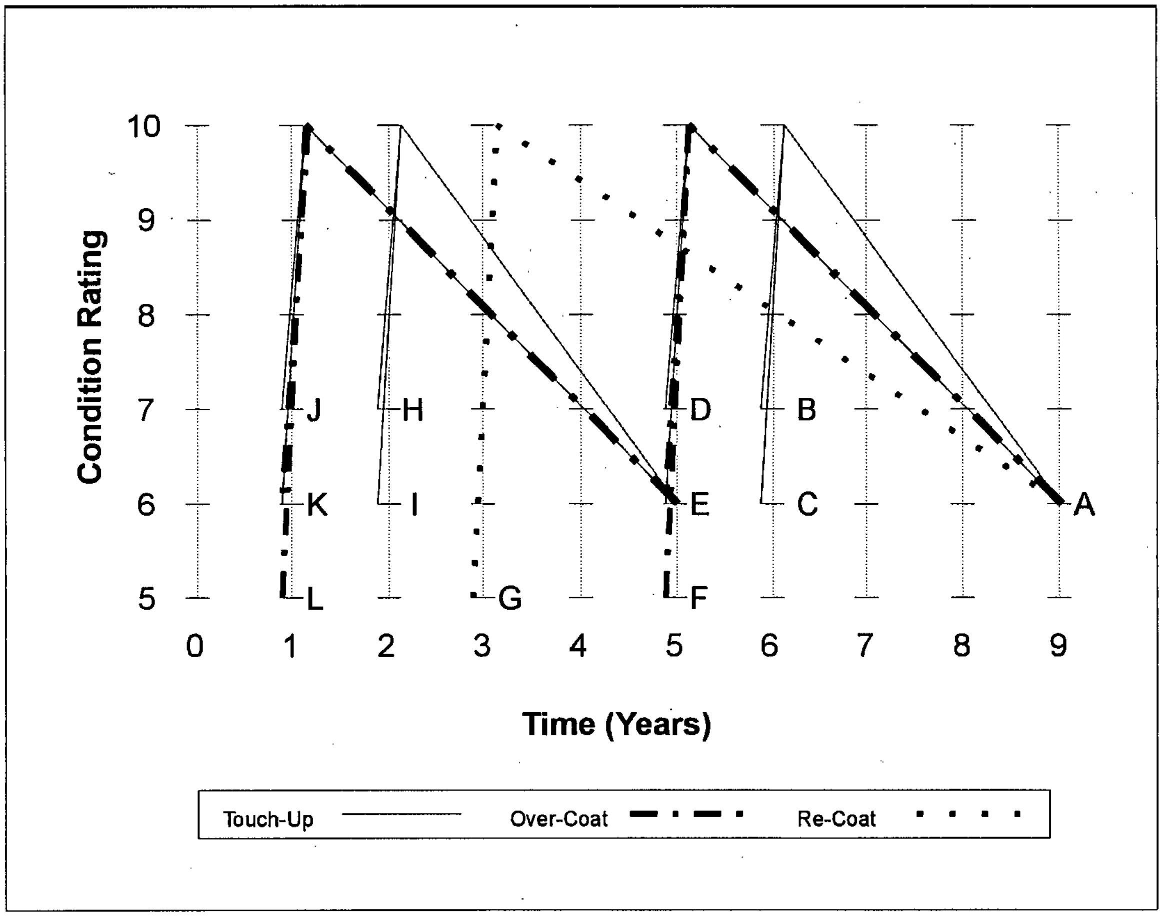

Figure 3-6: Feasible Maintenance Activities to Reach Desired Condition E

Until now, only the feasible paths to reach the desired end condition are analyzed. The recursive formula is used at each of the identified nodes to tabulate and minimize costs, as well as outline the optimal or lowest cost path. The optimal sequence of rehabilitation strategies could be traced using the recursive formula. Table 3.3 shows a tabulation of the costs calculated using the recursive function for each of the feasible stage/state nodes. Also shown are the possible rehabilitation methods for each node. These are the lowest costs for the rehabilitation methods required to reach point A. For example, the lowest cost to reach point A from Year 1, State 6 is $40. Costs shown italicized represent lowest costs for each stage/state. Figure 3.7 shows details of how the costs are calculated for points E and K.

Table 3-3: Tabulation of Lowest Costs for Feasible Nodes

Cond Rate	**Year**									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
10										
9										
8										
7		*T $30*	*T $30*			*T $10*	*T $10*			
6		*T $40* O $120	*T $40*			*T $20* O $100	*T $20*			
5		*O $220*		*R $1000*		*O $200*				

Note: T = Touch-Up, O = Over-Coat, R = Re-Coat

Point E: $$\$20 = \min \begin{bmatrix} \$20 \\ \$100 \end{bmatrix} + \$0$$

Point K: $$\$40 = \min \begin{bmatrix} \$20 \\ \$100 \end{bmatrix} + \$20$$

$$f_n(s) = \min [\, g(dns,s,n) + f_{n+1}(s') \,]$$

Figure 3-7: Evaluation of Cumulative Return Function

The lowest costs from each of the feasible nodes that reach point A are now known. To determine the optimal strategy for this example, the deterioration function of the present coating is projected onto the dynamic programming framework. This is seen in Figure 3.8. Figure 3.8 shows that a maintenance schedule can be implemented in years 1, 2, 3, or 5, or from points J, I, G, or F respectively. From Table 3.3, the cheapest alternative would be to implement a strategy starting year 1 at point J, and the most expensive alternative would be to re-coat at year 5, or point F. The cheapest alternative involves Touch-Up maintenance in year 1 (\$10) and Touch-Up maintenance in year 5 (\$20).

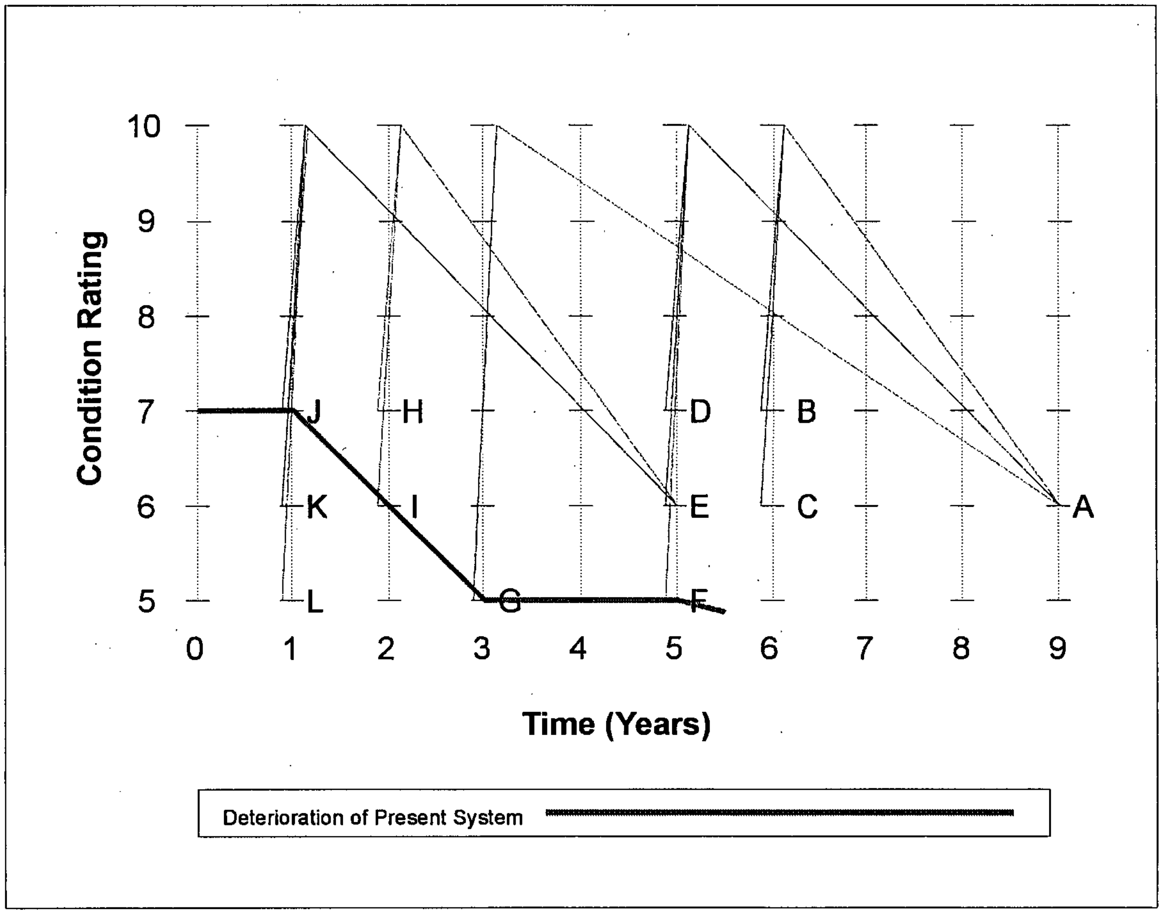

Figure 3-8: Projection of Present Deterioration Function

3.4 *Model Assumptions and Limitations*

Various assumptions were used in the coating deterioration simulation and the cost minimization modules as described above. Three main types of assumptions are identified: those used for the simulation of coating deterioration, those used in the optimization procedures, and general assumptions regarding the penstock and coating condition. However, some of the assumptions may fit in more than one category.

Several assumptions are made in the simulation of coating deterioration. Firstly, quantifying the condition of the existing coating can be very difficult due to the variety of defects. Only visible corrosion defects (percentage of rust) are used to rate the coating condition. The deterioration of the coating itself is assumed to follow fixed paths, and does not take into account the probabilistic behavior due to variability in quality control, environmental conditions, or other factors that affect coating performance. Deterioration functions are also assumed to be similar for each type of strategy, differing only by the use of 'curve factors' or multipliers as explained previously. The use of multipliers are also explained in more detail in the next section. Finally, deterioration is assumed to occur uniformly over the entire surface of the structure.

One of the main assumption in modeling of the optimization procedures is that only the same type of coating system, or a coating system with similar deterioration characteristics, is always used. Different combinations of coating systems cannot be accommodated in the current model. Another assumption is that the condition of the penstock is restored to its original condition after any rehabilitation method, although this is only true for strip and re-coat operations.

The condition of the penstock itself is assumed not to be an issue, and no structural considerations are incorporated into the model. It is also assumed that there is reasonable adhesion between all coating systems. The thickness of the coating system is also not modeled. Finally, to ensure that coating maintenance is not performed over excessively thick coatings or coatings with poor or degraded adhesion, the maximum age of the underlying substrate is limited before a new complete strip and re-coat is required.

4. Penstock Maintenance Program

A computer application, PMP, was developed using the ideas from the previous section. PMP is intended to be a tool to aid the engineer in developing a cost-effective coating maintenance program. Ease of use and accessibility are primary objectives for the application, therefore PMP has been developed for use on a PC based computer running Microsoft Windows 95. This operating system sets the application in a familiar working environment. Results from PMP can also be transferred to other Windows applications such as spreadsheets or word processors. A description of the files required to run PMP are listed in Appendix A.

Numeric data in PMP are dimensionless. The user is supposed to use a consistent set of units. However, the unit of time is always years.

PMP consists of one main set of tabbed pages as shown in Figure 4.1. Specifically, there are five tabbed pages, one page each for: *Input, Results, Strategy Calculator, Reference,* and *General Information*. The *Input* page allows the user to enter values for various calculation parameters. The *Results* page shows the details of calculations for the two optimization procedures. Trial sequences of rehabilitation methods could be entered for economic comparison in the *Strategy Calculator* page. The *Reference* page is used as an information base showing details of past jobs. The *General Information* page shows some background and usage information. Figure 4.2 shows a schematic representation of the program, its modules, and calculations.

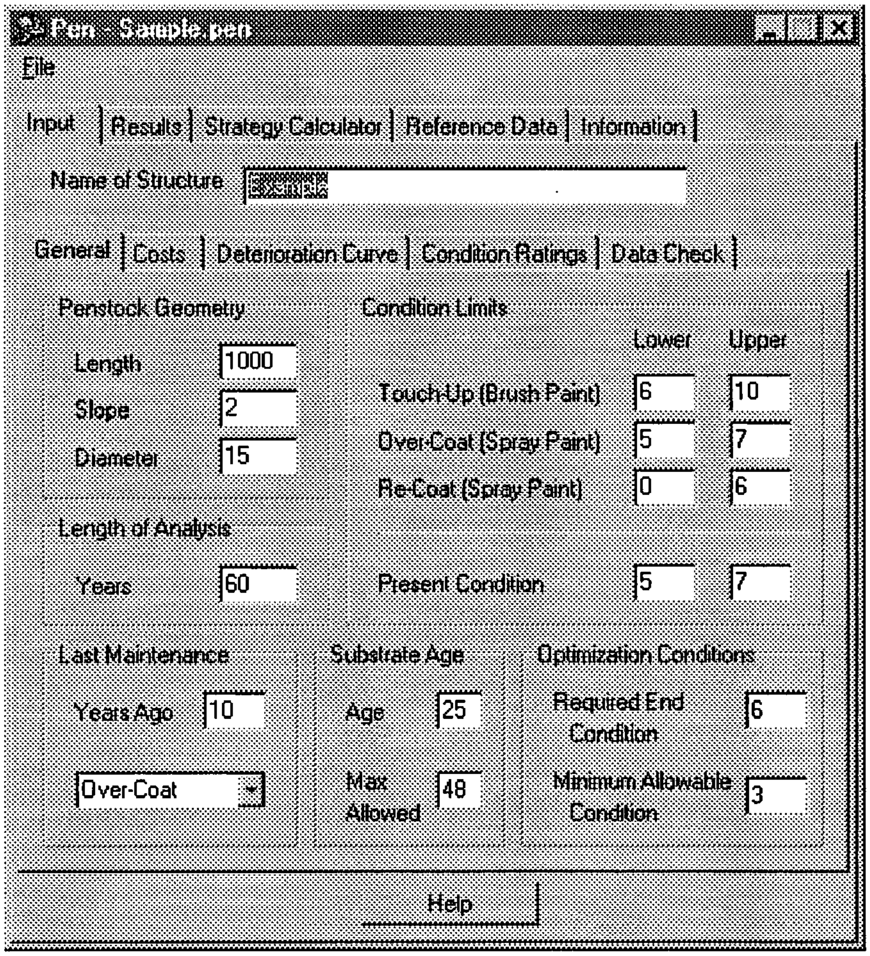

Figure 4-1: PMP User Interface

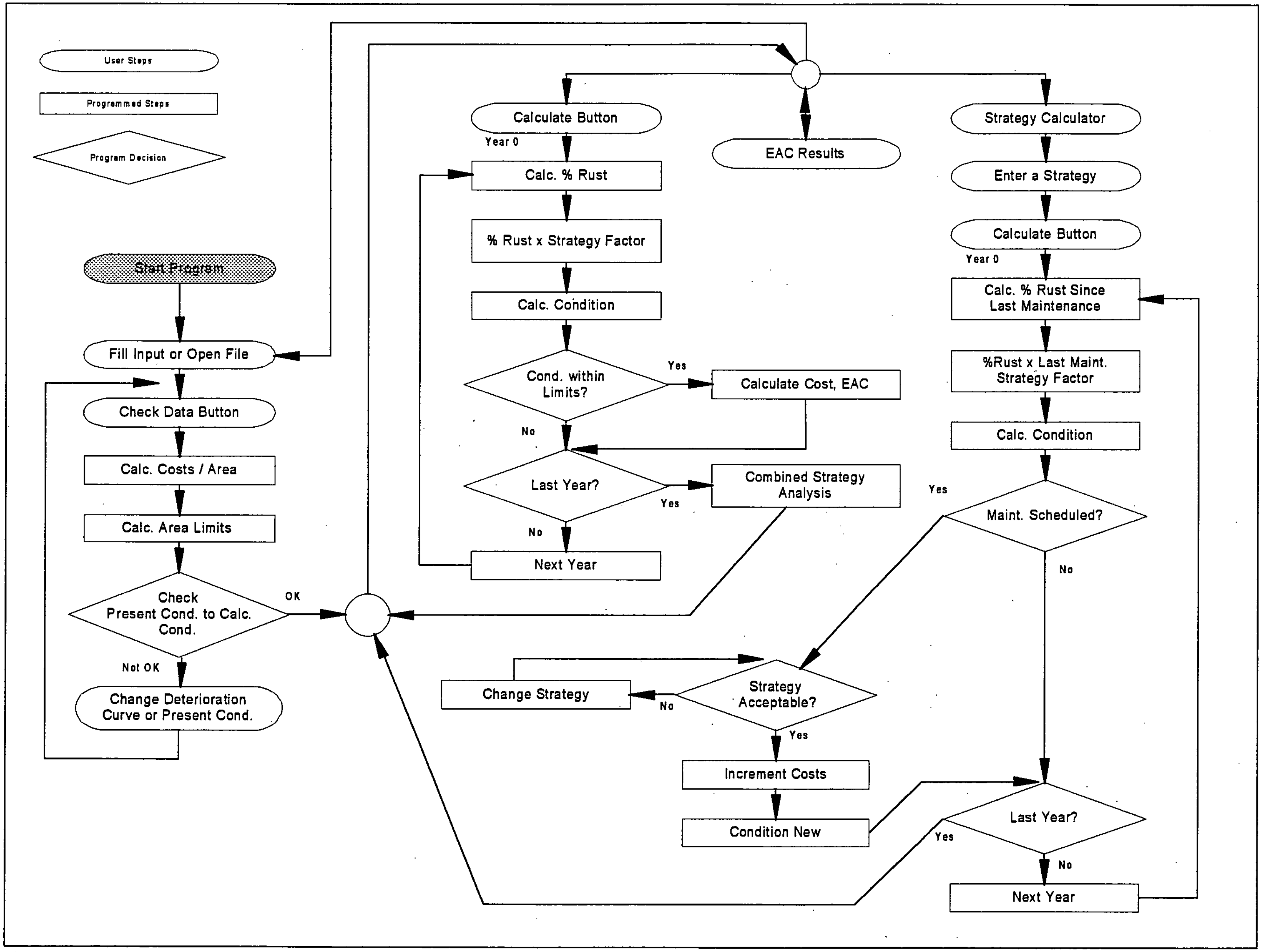

Figure 4-2: Flow Diagram of PMP

4.1 Input

The *Input* page is used to enter and change key calculation parameters. The *Input* page contains a sub-set of five tabbed pages, also shown in Figure 4.1. There is one page each for: *General Parameters, Cost Data, Deterioration Curve, Condition Ratings,* and *Data Check*.

Other components of the *Input* page include a field for naming the project and a page-sensitive help function. The name of the structure can be entered to identify the project. The *Help* button at the bottom of the page opens a window containing variable descriptions and useful comments. The variables and comments correspond to the Input Page that was showing when the Help button is pressed.

4.1.1 General

The *General* input screen is also shown in Figure 4.1. This page is used to enter miscellaneous data required for the analysis. The variables are described below.

The *Penstock Geometry* box contains three variables for the length, slope, and diameter of the penstock section. The *Length of Analysis* box sets the number of years to carry out the analysis.

The data from the *Last Maintenance* box is used to calculate a present condition. This is compared with the observed present condition entered in the *Condition Limits* box. The user is warned of any discrepancies. The number of years since the last strip and re-coat operation is required to determine the age of the underlying substrate. The maximum age of the underlying substrate limits the number of years before another strip and re-coat operation must be performed.

The *Condition Limits* box allows the user to adjust upper and lower condition limits for each of the three maintenance strategies. These bounds are used to constrain the three strategies to the conditions which they are most efficient. Variables for the observed penstock condition are also required.

The required condition at the end of the analysis and the minimum acceptable condition specified in the *Optimization Conditions* box are used in the dynamic programming optimization module. The required condition constrains the condition in the final year of the analysis, while the minimum acceptable condition ensures that the condition remains above an acceptable standard.

4.1.2 Costs

The *Costs* page contains variables which provide financial information to perform the optimization analyses. This includes surface preparation costs, coating costs, mobilization costs and the discount rate used. Costs are entered as a maximum and minimum cost interval, thus allowing for imprecisely defined costs data. Figure 4.3 shows the *Costs* page.

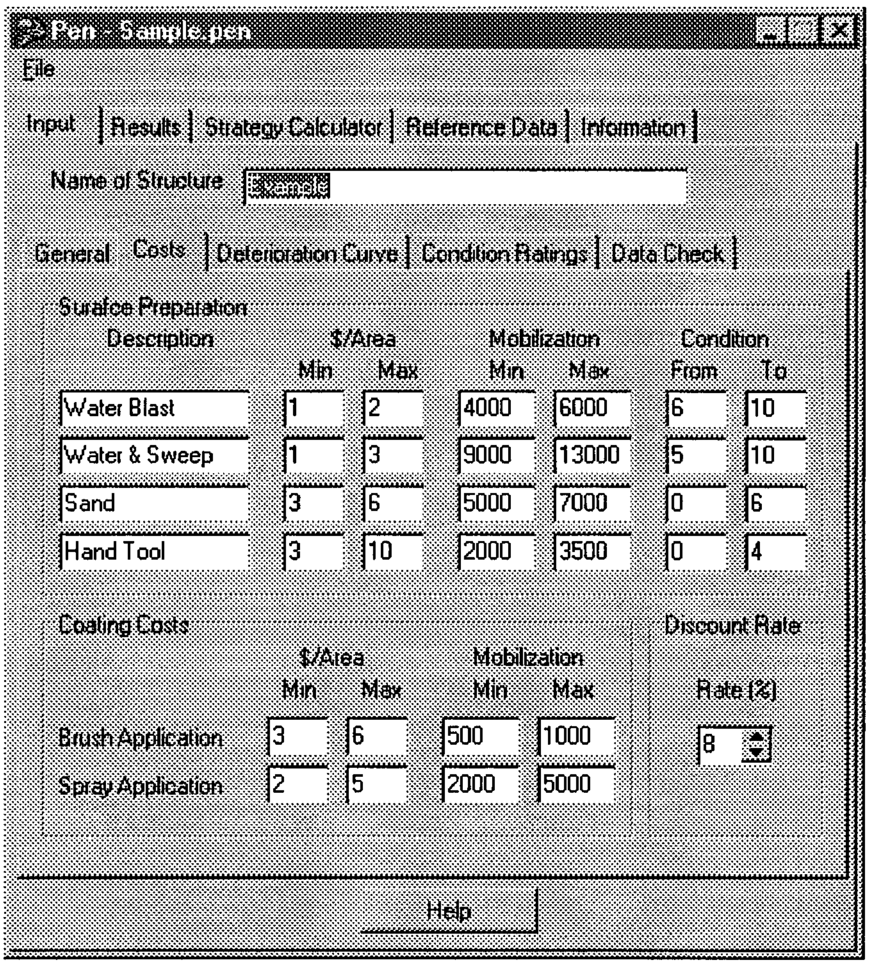

Figure 4-3: Costs Input Module

The Surface Preparation Costs allow the user to enter up to four different preparation methods, their associated unit rates, and the condition limits to which they are applicable. Mobilization and de-mobilization costs can also be entered for surface preparation operations.

Coating system costs are divided into two methods of coating application: brush application and spray application. Typically, brush application is used for touch-up maintenance only, while spray application is used for both over-coat and re-coat maintenance. The unit cost for the coating system includes the cost of the coating system, labour, and any other costs that are necessary in the application of the coating system. Mobilization and de-mobilization of equipment and crew is again entered separately.

The discount rate is used to compare the cost of different maintenance strategies in current day dollars. Discounted cash flow analysis is important because it allows for the determination of the time-value of money [Riggs, 1986]. For example, P dollars invested today accumulates interest at rate i and is worth $P(1+i)^n$ at the end of n years. Similarly, P dollars spent n years from now must be discounted by $1/(1+i)^n$ to determine the equivalent amount of money today.

4.1.3 Deterioration Curve

The *Deterioration Curve* page provides options for simulating the deterioration of the coating system. This is shown in Figure 4.4. Three different deterioration functions are built into the program: moderate, severe, and slow deterioration. The user can choose one of the pre-defined deterioration functions or can input a custom deterioration function for specific projects. The deterioration curves are specified by entering values for the percentage of rust per year. Pressing the *Plot* button will plot the deterioration curves and highlight the selected one.

The curve factors are used as multipliers to the selected deterioration function. These factors account for the differences in deterioration rates when different maintenance strategies are used to apply the same coating system. For example, performing touch-up maintenance on a coating system will not last as long as performing a strip and re-coat maintenance with the same coating system. The curve factor for Touch-Up would therefore be greater than that for Re-Coat. The simulation of rusting on the penstock is accomplished by determining the percentage of rust from the selected deterioration curve and multiplying this by the appropriate curve factor for the maintenance strategy.

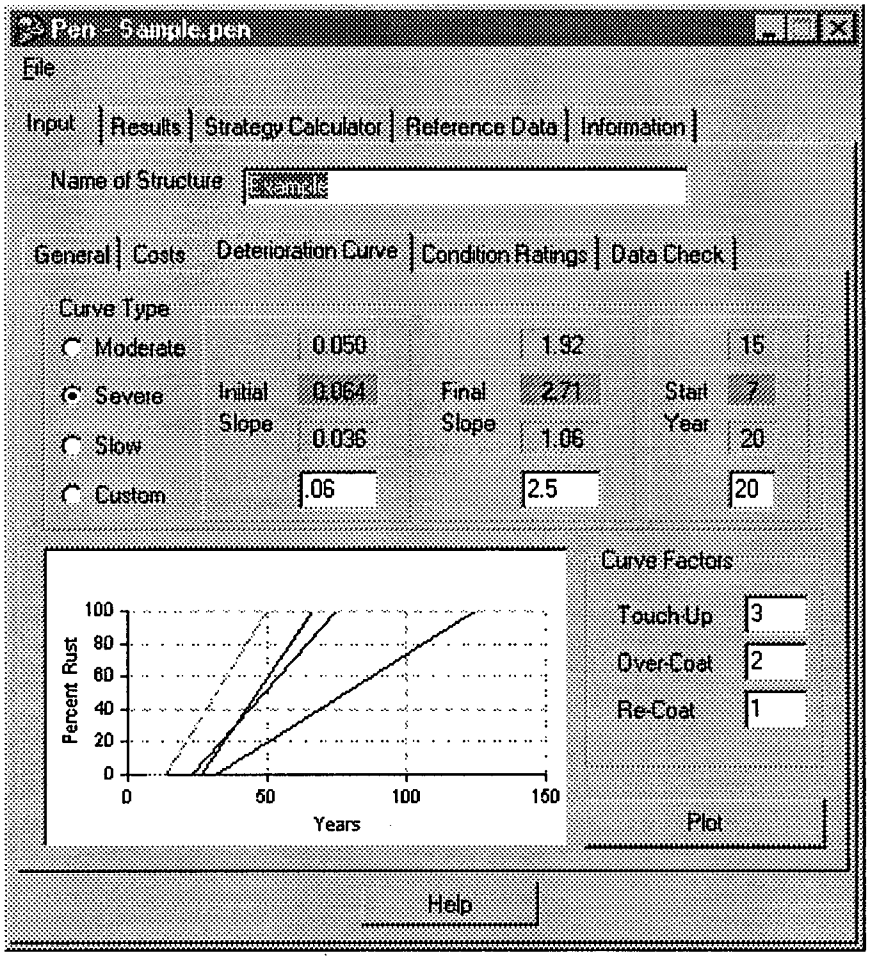

Figure 4-4: Deterioration Simulation Page

4.1.4 Condition Ratings

The *Condition Ratings* page as shown in Figure 4.5 displays the description of the corrosion performance scale from the ASTM D610 standards. The required area for maintenance is related to the condition when maintenance is required. It can be adjusted in the *Condition Ratings* page.

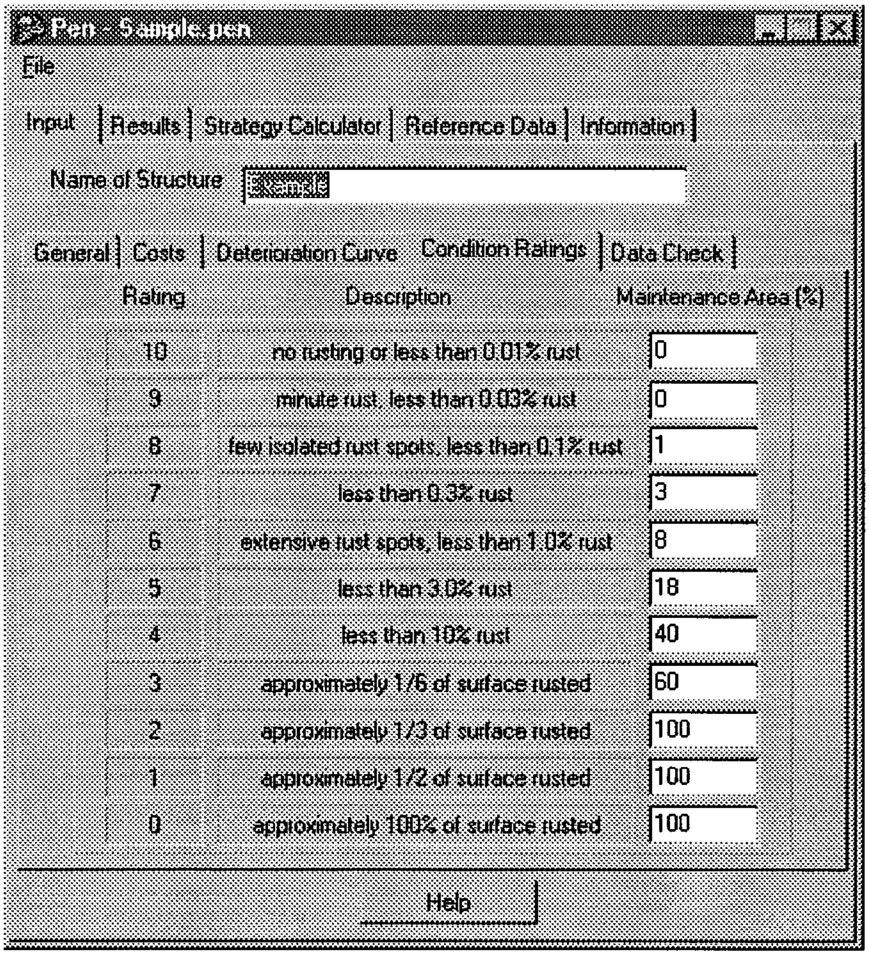

Figure 4-5: Condition Ratings and Maintenance Areas

4.1.5 Data Check

Figure 4.6 shows the *Data Check* page. This page is used to check the input values for errors, and to check whether the input values make sense. Data checking occurs after the *Check Data* button is depressed. PMP first checks that data has been entered into all numeric and text boxes, and that the data is correctly formatted. To check if the input values makes sense, PMP calculates a unit cost table for the three maintenance strategies and for the different surface preparation methods. Area limits for each strategy are also calculated. It is up to the user to verify that these numbers make sense before continuing. Whenever any of the input parameters are changed, the *Check Data* button must be used to ensure that the changes go through the checking procedures. Depressing the *Calculate* key starts the cost optimization procedures.

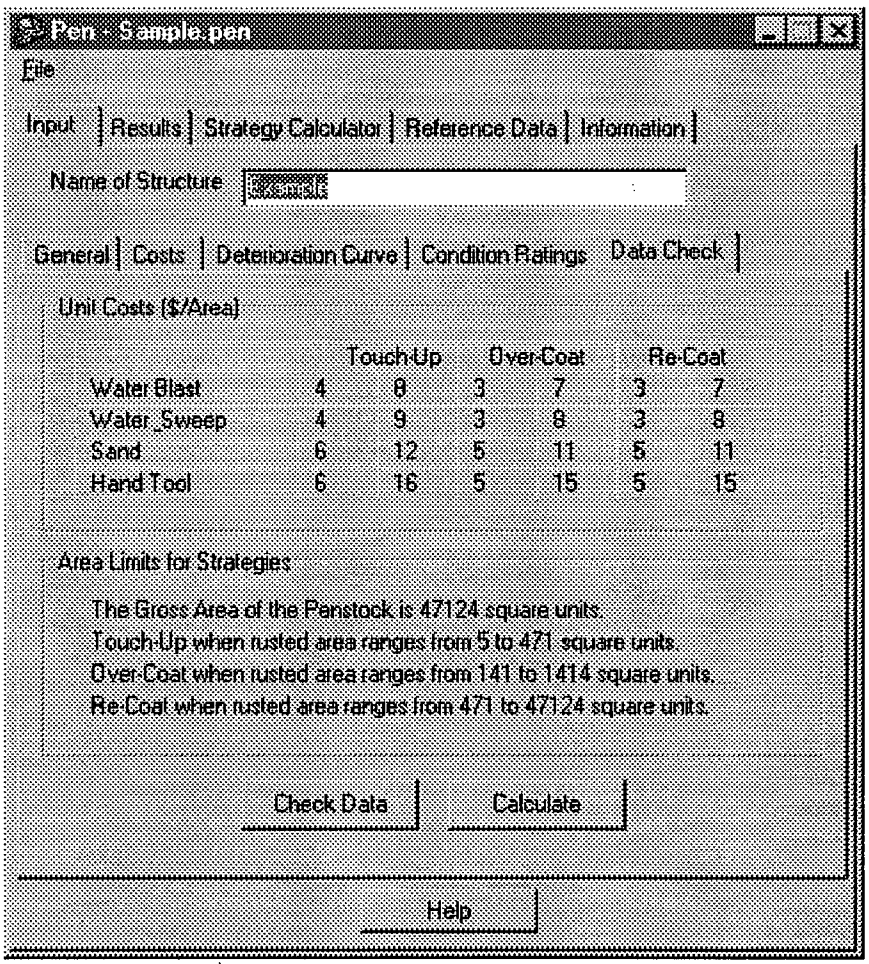

Figure 4-6: Check Data Page

4.2 Results

The *Results* page shows the results of the life-cycle cost analysis and for the dynamic programming optimization analysis. The *Results* page contains a sub-set of four tabbed pages. This is shown in Figure 4.7. There is one page each *for Touch-Up, Over-Coat, Re-Coat,* and *Combined.*

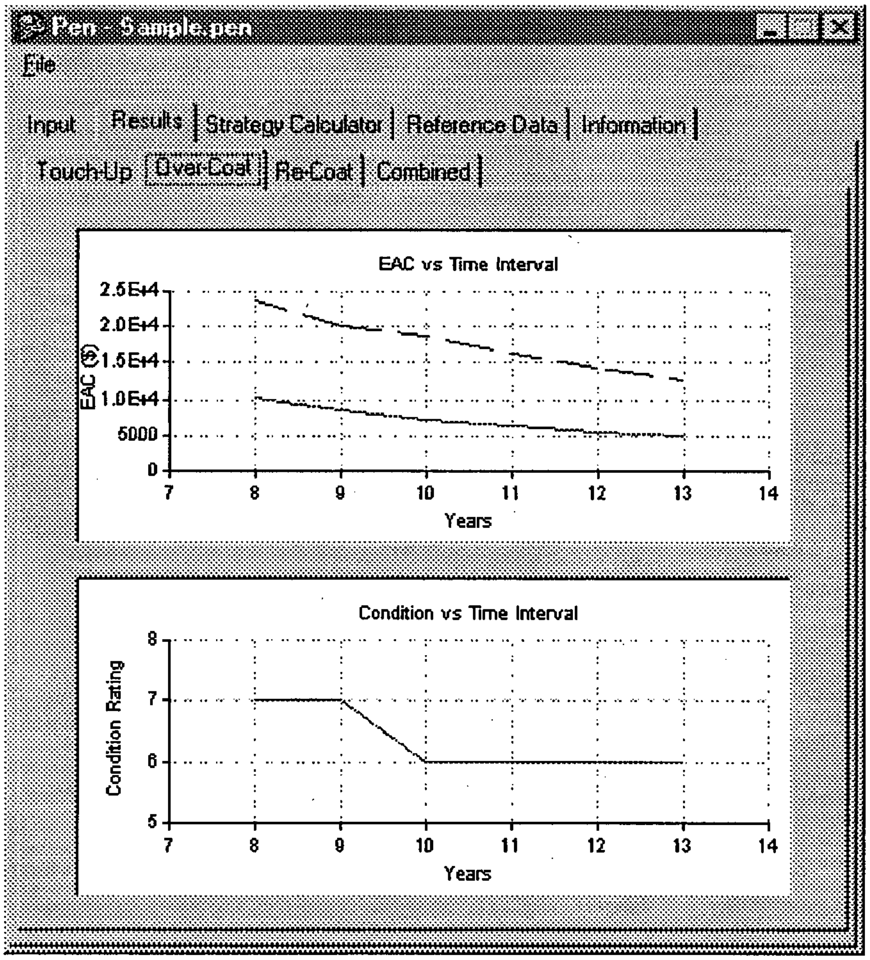

Figure 4-7: Life-Cycle Cost Analysis Results

4.2.1 Touch-Up, Over-Coat, and Re-Coat

Results from the life-cycle cost analysis for the three maintenance strategies could be seen in the *Touch-Up, Over-Coat,* and *Re-Coat pages*. The *Over-Coat* page is shown in Figure 4.7. Each page contains two graphs. The first graph shows the EAC of the strategy plotted for different time intervals. There are two points for each time interval, representing a maximum and a minimum annual cost for performing the maintenance at that particular time interval. The true annual cost is bounded by the minimum and maximum cost interval. Equivalent annual costs are only calculated for the time intervals in which the calculated condition of the penstock falls within the condition limits defined for each strategy. The calculated conditions for each time interval are shown in the second graph.

4.2.2 Combined

The *Combined* page shows the results of the dynamic programming analysis which minimizes the annual costs for a sequence of rehabilitation strategies. Any of the three maintenance strategies can be combined in any order to produce a cost-effective schedule of maintenance activities. There are three sections in the *Combined* page: *Strategy Cost, Condition Rating*, and *Activity Schedule*. This is shown if Figure 4.8.

The strategy cost is shown in the *Cost of Strategy* box. Two dollar amounts represent the minimum and maximum equivalent annual cost interval for the sequence of maintenance activities shown in the *Activity Schedule* box. The *Activity Schedule* box shows the optimal sequence of rehabilitation activities and the year the maintenance activity is to be performed. The condition of the penstock as a result of performing the sequence of maintenance activities is plotted for the length of the analysis.

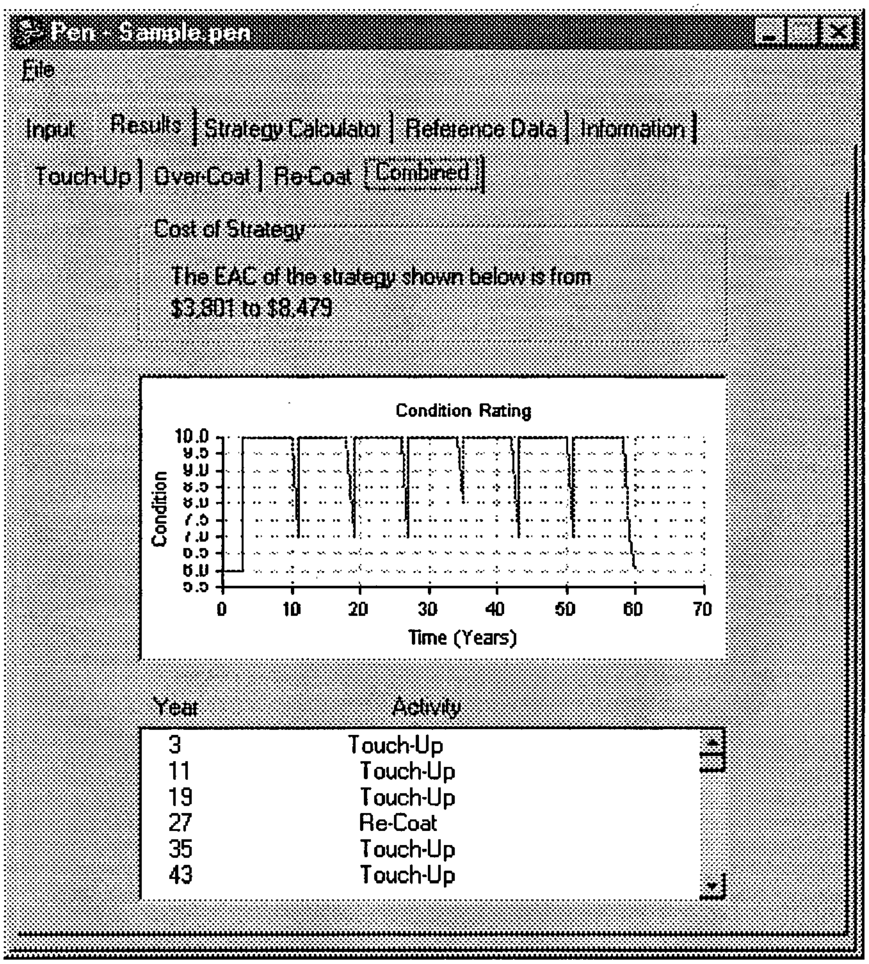

Figure 4-8: Dynamic Programming Results

4.3 Strategy Calculator

The *Strategy Calculator* page allows the user to enter trial sequences of rehabilitation strategies. The equivalent annual cost of the sequence of maintenance activities is calculated, as well as the resulting penstock condition for the length of the analysis. There is a sub-set of two tabbed pages in the *Strategy Calculator*. Figure 4.9 shows the *Strategy Input* page of the *Strategy Calculator*. A *Results* page is the other page contained in the *Strategy Calculator*.

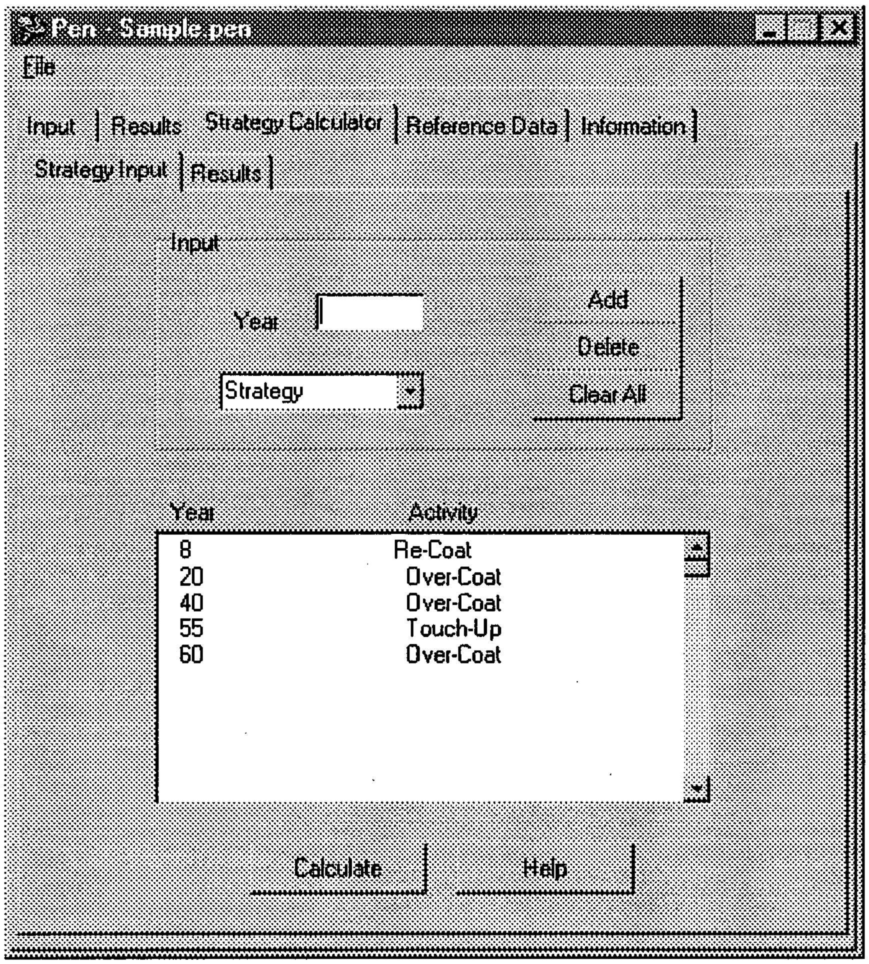

Figure 4-9: Strategy Calculator Input

4.3.1 Strategy Input

The *Strategy Input* page is used to enter a sequence of rehabilitation activities. The page is divided into two sections, an *Input* box and an *Activity Schedule* box. The *Input* box is used to enter single maintenance activities. A year and a maintenance strategy are required. When the *Add* button is pressed, the strategy is automatically entered into the *Activity Schedule* box. Similarly, pressing the *Delete* button when a year and a maintenance strategy are entered deletes the activity from the *Activity Schedule* box. Pressing the *Clear All* button deletes all the scheduled maintenance activities. The *Input* box checks the data for erroneous entries such as input errors or duplicate entries before the maintenance activity is echoed in the *Activity Schedule* box. The user is notified of any errors.

When a trial sequence of maintenance activities has been entered, the *Calculate* button must be pressed. PMP will then check the sequence of activities for errors. The calculated condition of the penstock must be between the upper and lower condition limits for the scheduled strategy. If the penstock condition is not within the upper and lower condition limits of the scheduled activity, then PMP will choose another strategy with conditions limits that encompass the calculated condition. The number of years since the last strip and re-coat activity is also checked. The user is notified of any errors.

4.3.2 Results

Figure 4.10 shows the *Results* page of the *Strategy Calculator*. The *Results* page of the *Strategy Calculator* is very similar in appearance to the *Combined Results* page. The *Results* page of the *Strategy Calculator* is also divided into three sections: a strategy cost, the calculated conditions, and an activity schedule.

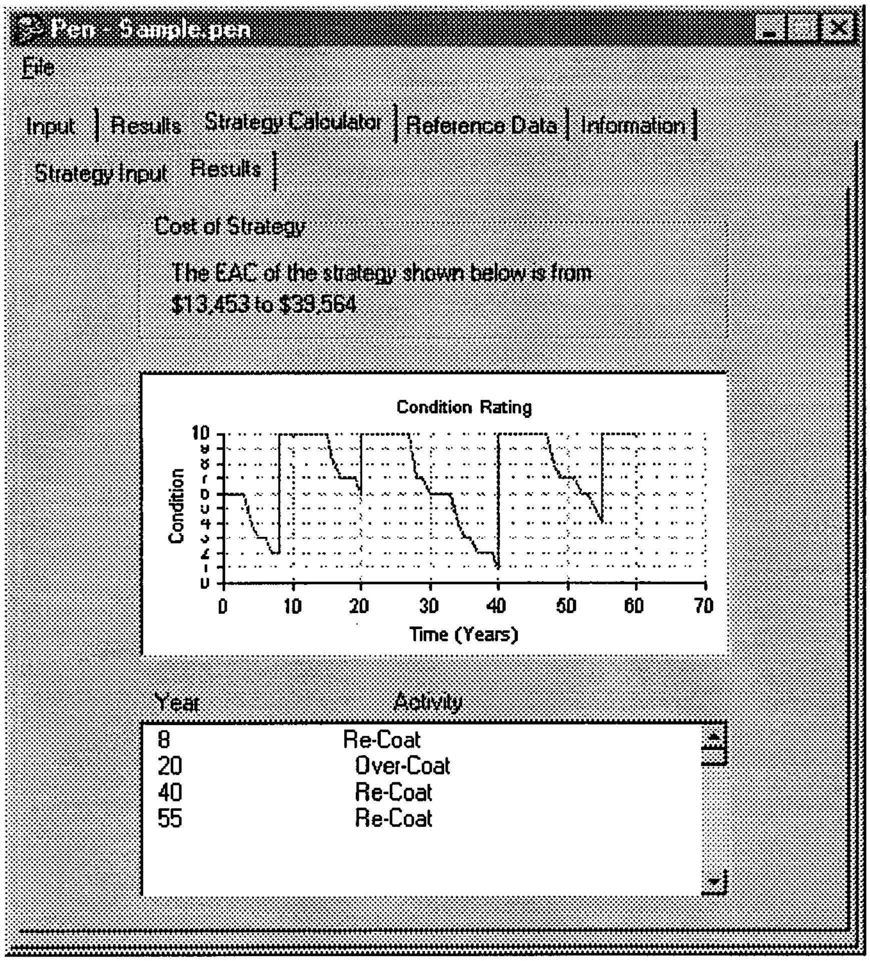

Figure 4-10: Strategy Calculator Results

The strategy cost is shown in the *Cost of Strategy* box. The dollar amounts represent the minimum and maximum equivalent annual costs for the sequence of maintenance activities shown in the *Activity Schedule* box. The *Activity Schedule* box contains the trial sequence of maintenance activities, with any changes that may have occurred during error checking. The condition of the penstock as a result of performing the sequence of maintenance activities is plotted for the length of the analysis.

5. Summary and Conclusions

Penstock coating deterioration has been modeled in a computer program (PMP) which can be used as a tool for decision making on coating maintenance policies. This model uses two routines to determine the optimal timing and method of penstock coating rehabilitation. The first routine uses a life-cycle cost analysis to compare the equivalent annual costs for each of the three maintenance strategies: touch-up, over-coat, and re-coat. The second routine determines the lowest cost combination of rehabilitation strategies and ensures that the coating reaches a specified condition at the end of the analysis. This method uses a dynamic programming approach to find the optimal solution. Alternatively, the computer model can be used to calculate the annual costs for a specific maintenance policy.

Based on preliminary results using PMP, Touch-Up maintenance seems to have the lowest annual costs, and Re-Coat maintenance seems to have the highest annual costs. The lowest cost maintenance may be to perform Touch-Up maintenance at short intervals. These conclusions must be validated by developing deterioration functions specific to each penstock, as well as refining financial data. Preliminary analyses were performed using only data from expert estimates.

6. Future Developments

This thesis represents the preliminary steps towards the cost optimization of coating maintenance scheduling for steel penstocks. The two techniques used to estimate annual costs should be investigated for further refinement to more accurately model the behavior of penstock coatings.

Two major assumptions in the optimization techniques should be examined. The first is that for the same coating type, the deterioration rate for the different application methods differ only by the deterioration curve factors. The second assumption is that after any rehabilitation method, the condition of the penstock returns to a 'new' condition.

As well as refining the optimization techniques, better information is needed to improve on the estimates. This can be accomplished by collecting, monitoring, and analyzing field data, and setting up an information base which may be tied into the computer model. Specifically, information bases are required to refine cost data and coating deterioration functions. The effects of each rehabilitation strategy on coating deterioration should be investigated. Additionally, the effects of adhesion on coating performance, and the change in adhesion with time must also be considered. The use of different coatings and coating compatibility may also be incorporated into the model.

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Appendix A: Program Files

PMP was developed using Borland Delphi version 2.0 for Windows 95. Table A.1 shows the files required for running and maintaining PMP. Delphi version 2.0 or higher would be required to make any changes to PMP.

File Name	Description
pen.exe	Executable program application file
trial.pen	Sample data file
delphi / pen.dpr	Delphi project file
delphi / pen.res	Windows resource file
delphi / penstock.dcu	Delphi compiled unit
delphi / penstock.dfm	Delphi form unit
delphi / penstock.pas	Delphi pascal unit, source code

Table A-1: Program Files for PMP

All the files listed in Table A.1 are saved on a disk labeled "Penstock Maintenance Program".