

## **APPENDIX E**

### **Corrosion Costing Models**

---

## **E.1 INTRODUCTION**

In order to meet the corrosion management objectives, tools or methodologies have been developed to calculate the cost of corrosion over part of an equipment's or asset's lifetime or over the entire life cycle. Methods that range from cost adding to life-cycle costing and constraint optimization are described in the following sections.

## **E.2 CORROSION COSTING METHOD USED IN THE US DEPARTMENT OF DEFENSE**

### **E.2.1 Background**

- Past corrosion cost studies have had difficulty separating corrosion costs from non-corrosion costs. The DoD has developed a methodology where only direct and auditable costs are calculated and no attempt is made to determine the cost implications of corrosion-induced readiness issues or safety concerns. Accurate cost information was considered by DoD to be extremely useful by itself to facilitate decision making, and it was concluded that decision makers could not use readiness and safety information to judge the cost-benefit tradeoffs on a project-by-project basis; nor could they use this information to measure the scope of the corrosion problem or judge the overall effectiveness of a chosen corrosion mitigation strategy. Thus, when focusing on cost information only, the difficult task of turning non-cost measurements into costs was eliminated, and only the direct cost of corrosion is now being considered. As an added benefit, by just addressing the direct corrosion costs, these costs become transparent and auditable.
- The costing methodology and resulting determination of Return on Investment (ROI) is discussed in the following sections.

### **E.2.2 Corrosion Cost Determination**

#### **E.2.2.1 Assumptions**

Going on the assumption that the direct corrosion costs are sufficient to demonstrate the benefits of corrosion control in a transparent fashion, the following specific cost elements of corrosion are identified:

- Labor hours (e.g., for inspection, repair, and treatment).
- Materials and parts usage.
- Premature replacement of the assets/equipment or its major components.
- Corrosion facilities.
- Training.
- Research, development, testing, and evaluation (RDT&E).

DoD included RDT&E costs, although these costs may occur before a weapon system or facility is placed into operation, because DoD is able to separate expenditures specifically for corrosion from other RDT&E spending.

#### **E.2.2.2 Identifying Corrosion Cost Elements**

Within DoD, maintenance required as a result of corrosion is rarely identified as such in reporting systems. Therefore, it is necessary to develop a list of typical corrosion-related maintenance activities, such as cleaning, sand blasting, and painting.

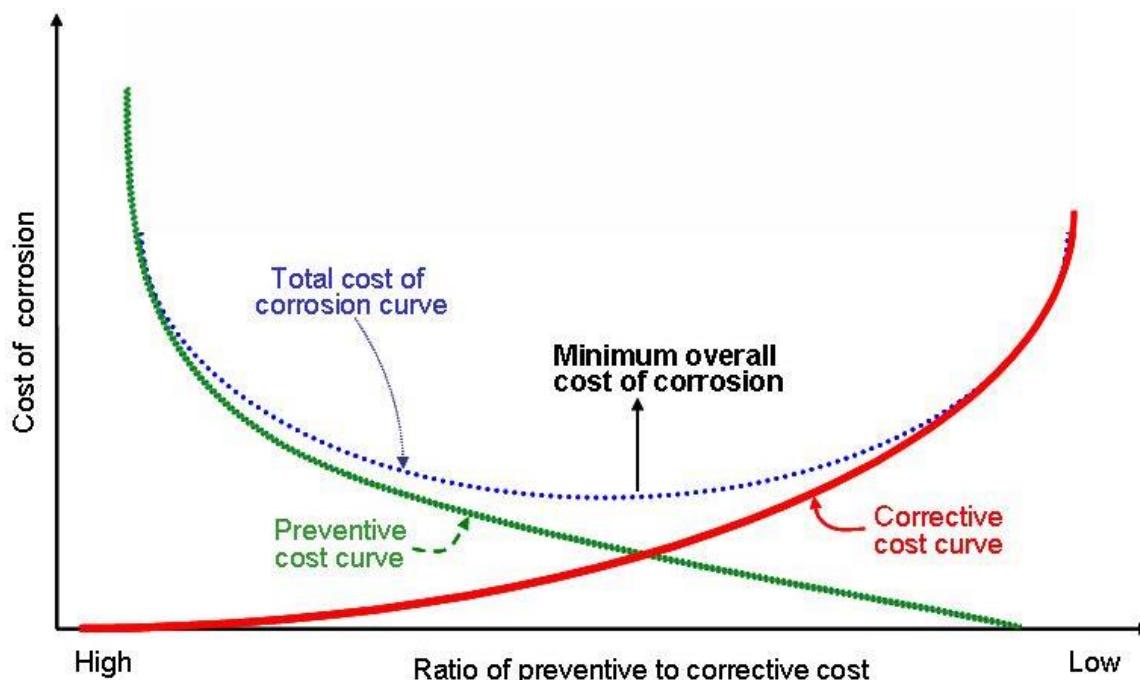
### E.2.2.3 Characterization of Corrosion Costs

The corrosion costs are divided into categories that provide additional insight into the nature of these costs. The two most useful characterizations are corrective and preventive costs:

- Corrective costs are incurred when removing an existing nonconformity or defect. Corrective actions address actual problems.
- Preventive costs involve steps taken to remove the cause of potential non-conformities or defects. Preventive actions address future problems.

From a corrosion management standpoint, it is useful to determine the ratio between corrective costs and preventive costs. Over time, it is usually more expensive to fix a problem than it is to prevent a problem; however, it is also possible to overspend on preventive measures.

Figure E-1 shows that classifying the cost elements into categories helps decision makers to find the proper balance between preventive and corrective expenses to minimize the overall cost of corrosion.



**Figure E-1. Preventive and Corrective Corrosion Cost Curves**

The task of classifying each cost element in the DoD as either preventive or corrective, would be an enormously challenging undertaking using standard methods, which would involve thousands of people trying to classify millions of activities at billions of dollars of cost. The DoD argues that the real value of characterizing costs into preventive and corrective categories is to determine the ratio between the nature of these costs, and that the classification does not require precision. To simplify, the preventive and corrective cost elements are characterized as shown in Table E-1.

**Table E-1. Classification of Corrosion Cost Elements into Preventive or Corrective Natures**

Cost Element	Classification
Labor hours	Corrective or preventive
Materials	Corrective or preventive
Premature replacement	Corrective
Corrosion facilities	Preventive
Training	Preventive
RDT&E	Preventive

The classification of the labor hours and the associated materials as corrective or preventive must be determined on a case-by-case or project-by-project basis, and in order to ensure consistency, DoD classifies direct labor hours and the associated material costs based on the following rules:

- Hours and materials spent repairing and treating corrosion damage, including surface preparation and sandblasting, were classified as corrective costs.
- Hours and materials spent gaining access to equipment that has corrosion damage so that it can be treated are classified as corrective costs.
- Hours spent on maintenance requests and planning for the treatment of corrosion damage are classified as corrective costs.
- Hours and materials spent cleaning, inspecting, painting, and applying corrosion prevention compounds or other coatings are classified as preventive costs.
- Hours spent at a facility built for the purpose of corrosion mitigation (such as a wash facility) are classified as preventive costs.

#### E.2.2.4 Structure and Parts Costs

DoD characterizes corrosion costs as either structure or parts costs. All direct materials and direct labor costs are sorted into one of these two categories. Direct costs can be attributed to a specific system or end item.

Structure and parts are defined as follows:

- Structure is the body frame of the system or end item. It is not normally removable or detachable.

Parts are items that can be removed from the system or end item, and can be ordered separately through government or commercial supply channels.

By segregating direct corrosion costs into structure and parts categories, decision makers can give the design community more precise feedback about the source of corrosion problems.

DoD has a major concern about the effects and costs of aging of weapon systems. The age of a typical weapon system is calculated starting with the year of manufacture of the individual piece of equipment—essentially, the age measures the structural age of the weapon system. The age of a removable part is not tracked, with the exception of major, more expensive components like engines. Separating the corrosion costs related to the structure of the weapon system (which has an age measurement) from the corrosion costs related to removable parts (which do not have an age

measurement) may give further insight into the relationship between structural costs and the effects of aging on weapon systems.

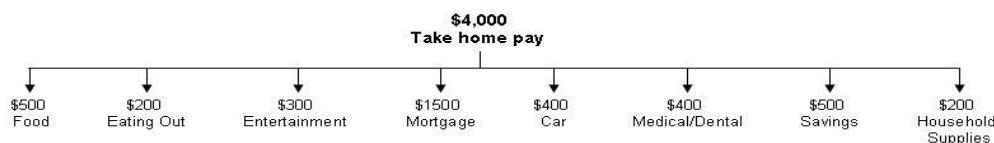
## E.2.3 Corrosion Cost Measurement Methodology

In order to quantify a verifiable cost of corrosion, DoD uses a methodology called the ‘top-down/bottom-up’ approach. In order to explain this methodology, an analogy of a household budget is used.

When analyzing a monthly household budget, it may be of interest to determine how much of this budget is spent on meat. Normally, it would not be possible to determine the amount spent on meat by just looking at the information at hand, i.e. check book logs and credit card records. Even if the expenses are logged diligently, it is highly unlikely that ‘meat’ expenditures could be recorded in their own separate category. This is also the reason that corrosion costs are not easily found – they simply are not identified in maintenance databases in their own category. In order to determine the amount spent on meat, “top-down/bottom-up” analyses are conducted as described in the following sections.

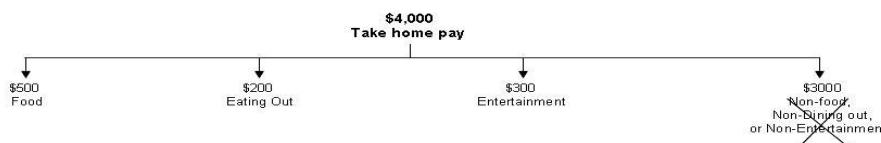
### E.2.3.1. Top-Down Analysis

In this analogy, the top-down portion of the analysis begins with identifying the combined net household monthly income. For illustration purposes, this is \$4000 per month. The next step is to separate this income amount into the major categories of spending that are visible in the check book logs, credit card records and other normal expense recording done in the household. A typical example might be similar to the “cost-tree” diagram shown in Figure E-2.



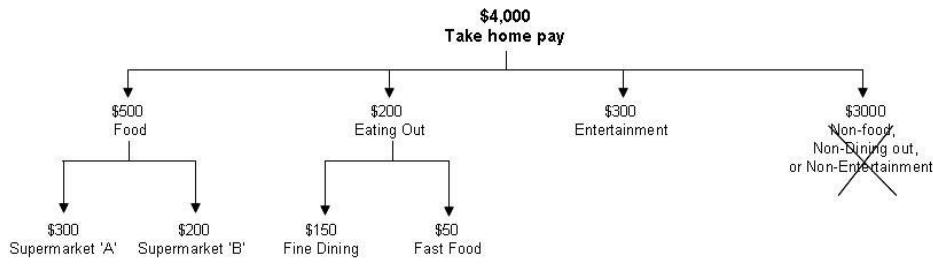
**Figure E-2. Top-down Analysis using Household Budget Example**

Note that the typical categories of spending in the second level of the cost tree account for the entire \$4000 monthly household income. This will always be the case in the top-down portion of the analysis, where each level of the cost tree has to account for the entire spending amount of the level above it. Once the expenses are clearly visible, those categories that could not possibly contain any spending for meat can be eliminated. These categories do not receive any further attention, and the three remaining categories (food, eating out and entertainment) will be focused on. Although the exact amount spent on meat is still unknown, the diagram in Figure E-3 clearly shows that the amount spent on meat cannot exceed \$1,000.



**Figure E-3. Consolidation of Budget Categories Showing those that Potentially Contain Meat.**

The spending within these three categories can be further examined in more detail as shown in Figure E-4.



**Figure E-4. Expansion of Potential Meat Spending in More Detail**

Note how each level of the cost tree below accounts for all the spending in the level above. In the example, this is as far as the top-down analysis can go, although there is still no definitive answer to the question about meat spending. The corrosion cost calculation can now be completed with the 'bottom-up' portion of the analysis.

### E.2.3.2. Bottom-Up Analysis

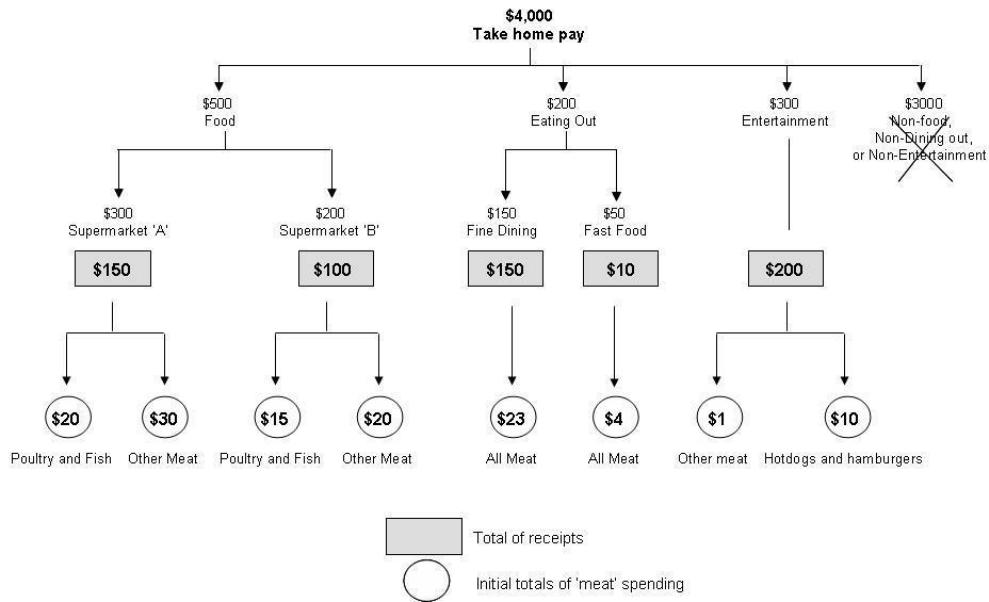
Figure E-4 shows that all spending on meat is contained in the five categories at the lowest level of the cost tree:

- Supermarket 'A'.
- Supermarket 'B'.
- Dining out.
- Fast food.
- Entertainment.

The bottom-up portion of the analysis requires obtaining as many detailed receipts for the spending in each of these five categories as possible. It requires grocery receipts for supermarket 'A' and 'B', restaurant receipts for dining out and fast food spending and receipts for all the entertainment expenses. The methodology does not require every receipt to be obtained but the more of the spending that can be accounted for with the receipts, the more accurate the spending estimates become.

### E.2.3.3. Combined Top-Down/Bottom-Up Analysis

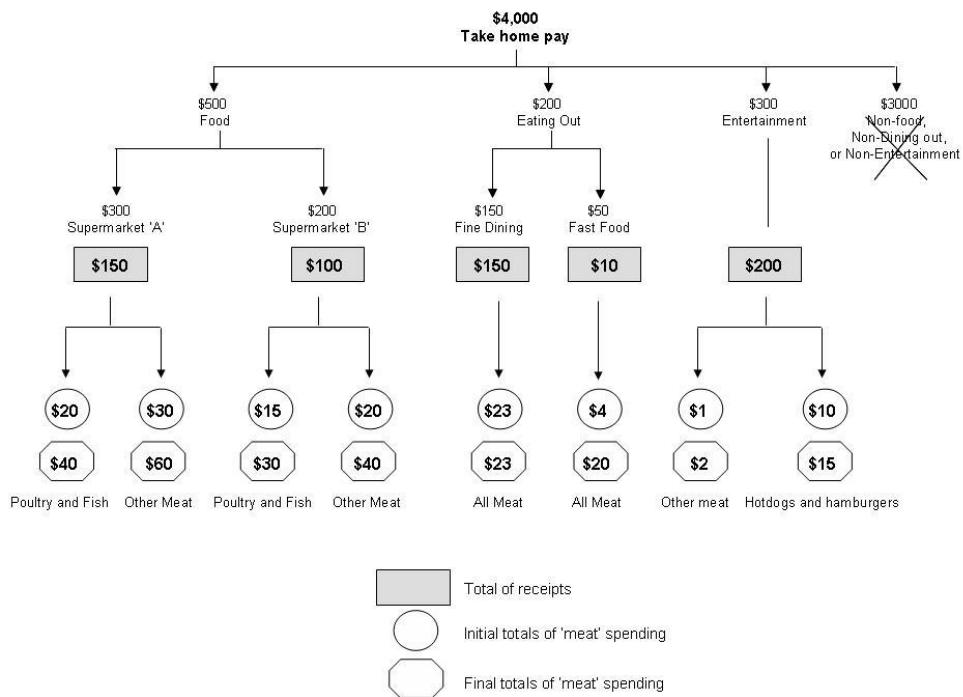
Once all the receipts that can be acquired for the month in question have been obtained, it is possible to determine the answer about how much is spent on meat. The next step is to examine every entry for every grocery receipt and extract the spending on meat. It is also possible at this step to categorize the meat spending by type. For example, categories of meat could include pork, chicken, beef, etc. Figure E-5 shows the analysis to this point.



**Figure E-5. Initial Calculation of Meat Spending**

It is important to not only quantify the amount of spending on meat, but also to calculate the total amount of the receipts for each of the five categories of spending. By comparing the top-down amount for each category (the 'should have' amount) with the total of the receipts for each category (the 'did have' amount), it is possible to identify gaps in the bottom-up data collection, or to re-examine some of the top-down assumptions should the two totals not converge.

Once the calculations have been verified, the final step in the analysis is performed as illustrated in Figure E-6.



**Figure E-6. Final Calculation of Meat Spending**

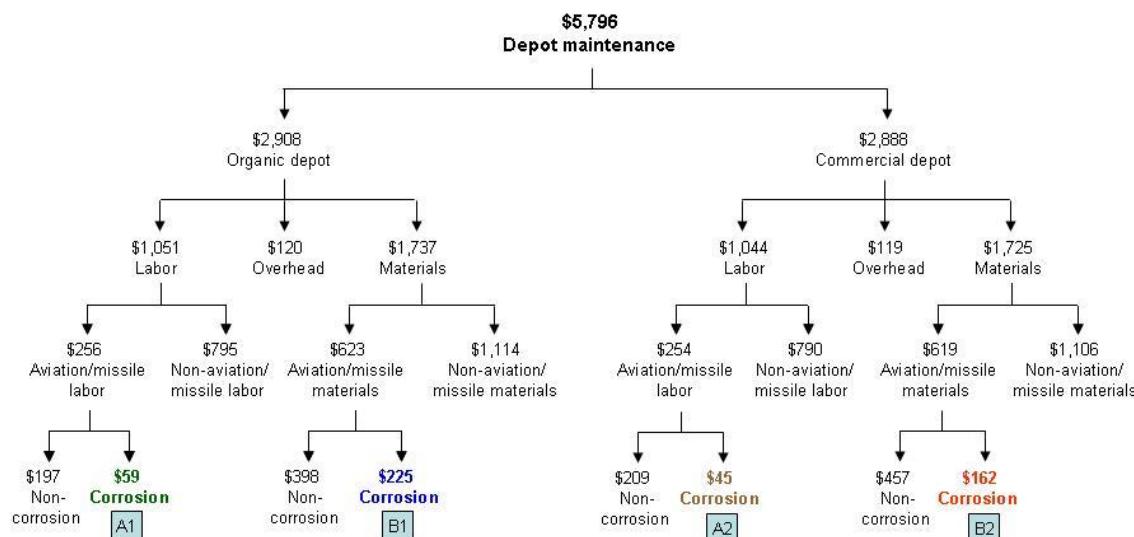
Based on the ratio of obtained receipts (\$150) and the top-down spending at Supermarket 'A' of \$300, the ratio of 1:2 is determined. To compensate for the fact that the obtained receipts (bottom up) account for only 50 percent of the top-down spending amount, the 'poultry and fish' and "other meat" totals are multiplied by two.

The total meat expenditures for poultry and fish from Supermarket 'A' are therefore \$40, and for "other meat", \$60.

Finally, this multiplication is repeated for each spending category in Figure E-6 and determines the total monthly spending on meat to be \$230.

#### E.2.3.4. Application of the Costing Model to Corrosion

The example above is a simplified explanation of determining the cost of corrosion, which can be readily applied to actual cost of corrosion determination, where corrosion takes the place of spending on meat, while the different types of maintenance expenditures are the categories of spending on food. Figure E-7 shows a cost tree from a completed DoD corrosion study.



**Figure E-7. Cost Tree from a DoD Corrosion Cost Study**

The cost diagram in Figure E-7 outlines the spending on corrosion during depot maintenance of a military aircraft<sup>1</sup>. The logic and appearance of this diagram is similar to that of the "meat" example with each lower level of the cost tree summing to the level above it. The real challenge here is to conduct the bottom-up analysis – in essence, extracting the corrosion related costs from the operations and maintenance activities.

Conducting the bottom-up analysis to extract corrosion costs involves millions of maintenance labor, parts and other material supply records. DoD has built a computerized search algorithm that is based on the corrosion activities, subject matter expert input, applicable coding of the maintenance records for corrosion, work center information and any other details contained in the records that would help identify corrosion related work. Once all available bottom-up corrosion data has been acquired and

<sup>1</sup> materiel maintenance requiring major overhaul or a complete rebuilding of parts, assemblies, subassemblies, and end items, including the manufacture of parts, modifications, testing, and reclamation as required. - **Department of Defense Directive 4151.18, Maintenance of Military Materiel, 12 August 1992, Enclosure 2.**

placed into a standard format, the search algorithm is executed, and work records which involve corrosion related work are flagged.

For certain types of corrosion related activities, a percentage is applied based on discussions with the maintenance technicians to determine the final amount of corrosion related work. The flagged records with their labor and materials totals are added to determine the initial totals. Like in the meat example, the final step is to apply the top-down to bottom-up ratio to account for data that was not obtained.

Both the top-down and bottom-up methods by themselves have their flaws. Determining the total cost of an enterprise can be a challenge by itself (in the meat example above, this was the total household income). Starting with an incorrect "all there is" estimate will almost guarantee an incorrect top-down outcome. The results of a well implemented top-down analysis can yield a good estimate of overall costs, but that estimate can lack the detail necessary to pinpoint major cost drivers within the enterprise. The bottom-up method can produce very accurate, auditable information so long as maintenance data collection systems accurately capture all relevant labor and materials costs, identify corrosion-related events, and are used with discipline. If any of these three boundary conditions are missing, corrosion costs are likely to be determined incorrectly, and in most cases, they will be understated. By combining both the top-down and bottom-up methods and determining if the results are approaching each other, the overall method and assumptions can be validated. If the two results initially do not converge showing a large top-down to bottom-up gap, the approach must be corrected in order to prevent erroneous cost information, assumptions, or incomplete data from corrupting the final outcome.

Using the combined top-down/bottom-up cost estimation method yields some significant advantages over other corrosion cost estimation methods:

- In addition to understanding total corrosion cost, the corrosion cost by type of equipment or component (i.e. weapon system) and subcomponent can be determined.
- The costs by level of maintenance and by work center, i.e. who is doing the work, can be understood.
- The method allows DoD to characterize cost by their preventive and corrective natures, as well as by parts and structure. This characterization applies not only to corrosion-flagged records but each of the millions of maintenance records in the bottom-up data.
- The methodology allows subject matter experts to help build the recipe (extract the meat from the receipts), which leads to a high level of ownership of the data once it is finalized.
- Not only corrosion but total maintenance costs can be understood by type, by weapon system. This has shown to be surprisingly useful for maintenance managers at all levels, because there is no central system that compiles complete maintenance cost information by weapon system.

In order to accommodate the anticipated variety of decision makers and data users, DoD designed a corrosion cost data structure that maximizes analysis flexibility, as shown in Figure E-8 below.

Using this data structure, the data can be analyzed under the following work breakdown structure headings:

- Equipment type.

- Age of equipment type.
- Corrective versus preventive costs.
- Depot, field-level, or outside normal reporting costs.
- Structure versus parts cost.
- Material costs.
- Labor costs.

## Data Structure

Aviation Type xxx Age z years	Cost	Percent of total			
Aviation Type 6 Age 5 years	Cost	Percent of total			
Aviation Type 1 Age 12 years	Cost	Percent of total	Labor	Materials	WBS
Corrective corrosion costs					
Preventive corrosion costs					
Depot maintenance corrosion costs					
Field maintenance corrosion costs					
Outside normal reporting costs					
Structure direct corrosion costs					
Parts direct corrosion costs					

Will capture all types of weapon systems

**Figure E-8. Corrosion Cost Data Structure and Methods of Analysis - Work Breakdown Structure (WBS).2**

Any of these WBS data elements can be grouped with another (with the exception of outside normal reporting costs) to create a new analysis category. For example, a data analyst can isolate corrective corrosion costs for field<sup>3</sup> level maintenance materials if desired.

## E.3 LIFE CYCLE COSTING

Life Cycle Costing (LCC) is a commonly used cost evaluation tool that provides a long-term outlook in the expenditures of a facility over its lifetime by examining:

- Capital cost (CAPEX).
- Operating and maintenance cost (OPEX).
- Indirect cost caused by equipment failure.

<sup>2</sup> Work breakdown structure coding determines the weapon subsystem on which work is being performed. We use the work breakdown structure convention established in *DoD Financial Management Regulation*, Volume 6, Chapter 14, Addendum 4, January 1998.

<sup>3</sup> Field level maintenance is more limited in scope than depot maintenance and is normally performed close to the owning units area of operations.

- Material residual value.
- Lost use of asset (i.e., opportunity cost).
- Any other indirect cost, such as damage to people, environment and structures as a result of failure.

The LLC approach makes it possible to compare alternatives by quantifying a long-term outlook and determining the return on investment (ROI).

### **E.3.1 Capital Expense**

Capital Expense (CAPEX) is part of the direct cost incurred during the initial stage the life cycle which includes:

- Design.
  - ◆ Design and selection of corrosion prevention systems.
    - Corrosion protection, such as cathodic protection and coatings/paint.
    - Corrosion mitigation, such as the use of corrosion inhibitors and other chemicals.
    - Corrosion prevention by the use of corrosion resistant materials.
    - Corrosion allowance on non-corrosion resistant materials.
    - Corrosion monitoring systems.
  - ◆ Corrosion experts and engineers who carry out corrosion and materials selection related studies.
  - ◆ Laboratory corrosion tests or other technical assessments.
  - ◆ Techno-economic analysis of alternatives.
- Acquisition of materials of construction and corrosion prevention materials and devices.
- Construction costs.

### **E.3.2 Operational Expense**

Operational Expense (OPEX) is part of the direct cost incurred during the operational stage of the life cycle and includes:

- Corrosion prevention and monitoring.
  - ◆ Corrosion inhibitors and other corrosion control chemicals.
  - ◆ Monitoring probes.
  - ◆ Electric power for dosage point and cathodic protection.
  - ◆ Replacement.
- Technical support.
  - ◆ Personnel for routine maintenance and corrosion control.
  - ◆ Cost of routine maintenance and corrosion control (e.g. painting, NDE, inline inspection for pipelines, cathodic protection).
  - ◆ Specific studies and activities to be carried out to address non-routine corrosion issues.
  - ◆ Emergencies as result of corrosion.

- Additional operating cost as a consequence of a corrosion related incident.
- Insurance against corrosion-related risks.

In some industry sector demobilization, decommissioning, and mothballing, which are the final stage of the life cycle are considered to be part of OPEX.

### **E.3.3 Indirect Expense**

In addition to the direct expense that can be determined by assessing CAPEX and OPEX, indirect expense over the life of a structure or facility must also be considered. The financial losses or penalty charges, which are associated with losing production, because of corrosion related failures, and include the cost of lost revenue and costs associated with lost revenue. Other indirect costs associated with failures include societal cost, environmental cost, and damage to brand and reputation. One way to aggregate these costs and scale them by likelihood of occurrence is through risk assessment.

## **E.4 DETERMINISTIC APPROACH TO LIFE CYCLE COSTING (LCC)**

When optimizing both direct and indirect costs of corrosion in a deterministic approach, it is important to account for benefits and costs of all the options. Such benefit-cost analysis (BCA) determines the net present value of options. In addition, the BCA helps to determine the cost per unit of service, which is, in fact, the highest aggregation of costs and benefits.

If the service level defined within a certain constraint can characterize the benefits, life cycle costing (LCC), which is essentially a cost effectiveness analysis, is equivalent to BCA. If the goal of a cost-effectiveness analysis is to obtain a service level that is equal to the optimal service level under BCA, then the LCC analysis will arrive at the same solution as BCA. LCC is therefore equivalent to a cost-effectiveness framework that seeks to minimize the cost of achieving a specified goal. A well-executed LCC is essentially the cost side of BCA; however, LCC does not seek to address environment and society, but rather minimizes the costs.

LCC analysis in corrosion management can be used to assess corrosion management alternatives. Since LCC analysis is a cost minimization methodology, it is a good method to compare the cost of different options for corrosion management. It determines the annualized equivalent value (from the present discounted value) of each option and compares these with the lowest cost option. Since in this analysis it is assumed that all options meet the same service requirement, the lowest cost option is therefore the most-cost effective option to achieve the service requirement. While LCC is an appropriate method to compare the costs of different options, it simplifies the benefit side by only considering the benefits of the specified service level.

For example, if the required service level is a four-lane bridge designed to last for 60 years, the benefit of the bridge will be very different for one serving 5,000 cars per day than for one serving 50,000 cars per day. An analysis of the former case would probably conclude that a two-lane bridge was sufficient, while an analysis of the latter case would conclude that a six-lane bridge was required.

Structures and facilities are built to serve a desired function. Since there is more than one way to achieve the requirement of the structure, LCC can be used to compare the cost of different options that satisfy the service requirement. It is important to emphasize the LCC approach as illustrated in the following paragraphs:

- Costing of project alternatives cannot be based on their first estimate costs. For example, an uncoated carbon steel pipeline (first option) costs less at construction than a coated carbon steel pipeline (second option); however, the latter option lasts longer. Therefore, for the correct comparison, the construction cost must be annualized over the entire lifetime of the pipeline. A comparison of the two options is therefore based on the annualized value of each.
- It is further incorrect to simply sum up all corrosion related costs that occur during the lifetime of the structure. Continuing the above example, assume that both options have rehabilitation scheduled at two-thirds of their lifetime (year 13 for the unprotected pipeline and year 27 for the protected pipeline). For simplicity, assume that the rehabilitation costs are the same for both options. In the case of simply adding up all costs, the bare carbon steel pipe may look better since its initial cost was lower. However, when the different costs are expressed in an annualized form, rehabilitation of the coated pipe will result in lower costs.

### E.4.1 Current Cost of Corrosion

The current cost of corrosion is defined as the sum of the corrosion related cost of design and construction or manufacturing, the cost of corrosion related maintenance, repair, and rehabilitation, and the cost of depreciation or replacement of structures that have become unusable as a result of corrosion. The current cost of corrosion is the difference between the approach where no consideration is given to corrosion and corrosion control and the current approach. It is calculated by LCC analysis and characterized by the annualized value.

Measurement of the current cost of corrosion is carried out in the following steps:

- Determine the cash flow of corrosion.
- Describe corrosion control practices (materials, actions, and schedule), determine the elements of corrosion cost, and assign cost to all materials and activities that are corrosion related.
- Calculate present discounted value (PDV) of cash flow.
- Calculate annualized value for the PDV.

These steps are discussed in more detail in the following sections.

### E.4.2 Cash Flow

After the corrosion management practices are analyzed, the direct and indirect elements of the corrosion costs are identified. The corrosion cash flow of a structure includes all costs, direct and indirect, that are incurred due to corrosion throughout the entire life cycle of the structure.

### E.4.3 Corrosion Control Practices

**Determine Current Practice.** The current practices to control corrosion vary greatly between the different industry and government sectors that are described in this report (see Sections **Error! Reference source not found.** and **Error! Reference source not found.**). Even within a sector, there are different approaches to design, maintenance, and depreciation of similar facilities or structures. A reasonable approach to determine the total corrosion cost is to extrapolate from a typical corrosion cost to the entire sector.

**Elements of Corrosion.** As discussed previously, corrosion costs can be direct or indirect. Direct costs are defined by the following elements:

- Amount of additional or more expensive material used to prevent corrosion damage multiplied by the (additional) unit price of the material.
- Number of labor hours attributed to corrosion management activities multiplied by the hourly wage.
- Cost of the equipment required as a result of corrosion related activities. In case of leasing the equipment, the number of hours leased multiplied by the hourly lease price.
- Loss of revenue due to lower supply of a good. For example, consider the case of a leaking liquids pipeline. When as a result of the leak the pipe needs to be shut off for repair, the revenue loss due to this interruption in service is accounted for as a cost of corrosion. If the market is such that other organizations in the industry at the same cost can satisfy the demand, then the revenue loss of one organization is the additional revenue gain of another, a transfer within the industry, therefore, not counted as corrosion cost.
- Cost of loss of reliability. Repeated interruption in the supply of a good or a service could lower the reliability of the service to such a level that consumers select an alternative and possibly a more expensive service. For example, if repeated interruption in the supply of natural gas forces consumers to rely on electricity for heating, then the cost of this revenue loss is accounted for as a cost of corrosion for the oil sector, but it is a gain for the electricity sector. If consumers choose other petroleum products as their new energy source for heating, then the cost would be transferred within the oil sector from natural gas to petroleum; therefore, it would not be accounted for as a cost of corrosion for the oil sector.
- Opportunity cost of lost production because an asset is no longer suitable for its purpose.

As previously defined, indirect costs are incurred by others (i.e., not the owner or operator). Examples of indirect costs are:

- The loss of trust in the reliability of product or service delivery by the company.
- increased costs for consumers of the product (lower product supply on the market result in higher cost to consumers).
- lost tax revenues.
- effect on local economy (loss of jobs).
- effect on the natural environment by pollution.
- effect on reputation.

Once a monetary value is assigned to these items, they are included into the cash flow of the corrosion management and treated the same way as all other costs.

#### E.4.4 Present Discounted Value of the Cash Flow

Structures are designed to serve their function for a required period of time, which is referred to as the design service life. More than one option can be utilized to satisfy service level for the required service time. These options, that already satisfy the service requirement, have different lengths of life,

depending on, among other things, design and overall management. Once the cash flow for the whole lifetime is determined, the value of each option for the entire life cycle can be determined. One cash flow cycle (a complete life cycle) of a structure is as follows:

- Year zero.

Direct cost is the total initial investment of constructing a new structure or facility. If there is an old structure, its removal cost is not included. User cost is associated with the construction of a new structure. If there is an old structure, user cost associated with its removal is not included.

- During service.

Direct cost includes all costs associated with maintenance, repair, and rehabilitation. User cost can be generated by worsening conditions of the structure that reduces the level of service by temporary being out of service of the structure during any maintenance, repair, or rehabilitation.

- Last year.

Direct cost includes all cost of structure removal. If the old structure is replaced with a new one, the cost of the new structure is not included. User cost is associated with the removal of the structure. After the removal of the old structure, a new life cycle begins.

All materials and activities that are corrosion related during the lifetime of the structure must be identified, quantified, and valued. Direct costs of the corrosion management activities, or cost to the owner or operator, include material, labor, and equipment costs. When determining their costs, all related activities need to be accounted for. For example, if a corrosion-related maintenance activity on a bridge deck requires traffic maintenance, its cost needs to be included. The price of labor, material, and equipment are assumed to be the same for all design and all corrosion management alternatives.

The corrosion management schedule of the structure determines the direct cost cash flow. In the following sections the calculation of the present value of the cash flow entries is presented.

The initial investment occurs in the "present"; therefore, no discounting is necessary.

Annual maintenance is assumed to be constant throughout the life cycle of the structure. This is the present discounted annual value,  $PDV\{AM\}$ , and is calculated back to the present as follows:

$$PDV\{AM\} = AM * [1 - (1 + i)^{-N}] / I,$$

where

AM = cost of annual maintenance (\$ per year)

N = the length of the structures service life in years

i = interest rate

For the calculation of the present value of activities that grow annually at a constant rate (g), a modified interest rate needs to be calculated by the following formula:

$$i_0 = (i - g) / (1 + g) \text{ and } i > g,$$

where

- $i_0$  = the modified interest rate
- $i$  = interest rate
- $g$  = constant annual growth rate

If the first payment ( $P_1$ ) occurs in year one, the present value of a cash flow that grows annually at a constant rate over  $n$  years is calculated by the following formula:

$$PV\{P\} = [P_1 / (1 + g)] * [1 - (1 + i_0)^{-n}] / i_0$$

$PV\{P\}$  is the present value of a cash flow series that starts at  $P_1$  in year one and grows at a constant rate  $g$  for  $n$  years when interest rates are  $i$ , which are equivalent to the present value of an annuity of  $[P_1 / (1 + g)]$  for  $n$  years when interest rates are  $i_0$ , where  $i_0$  is given by the equation above.

The first payment for repair activities, however, usually does not occur in year one, but, rather, in year  $t$ ; therefore the above formula calculates a value at year ( $t-1$ ) that is equivalent of the cash flow series of repair through  $n$  years. This value needs to be calculated back to year zero of the life cycle to determine the present discounted value of the repair:

$$PDV\{P\} = PV\{P\} * (1 + i)^{-(t-1)}$$

The PV of one-time costs, such as one-time repairs (R), rehabilitation (RH), or removal\_of an old structure (ROS) is calculated as follows:

$$\begin{aligned} PDV\{R\} &= R * (1 + i)^{-t_R} \\ PDV\{RH\} &= RH * (1 + i)^{-t_{RH}} \\ PDV\{ROS\} &= ROS * (1 + i)^{-t_{ROS}}, \text{ where} \end{aligned}$$

R = the cost of the repair

RH = the cost of the rehabilitation

ROS = the cost of removing the old structure

T = the year in which the cost is acquired

The present value (PV) of alternatives is calculated as the sum of the PV of its cash flow:

$$PV = I + PV\{AM, P, R, RH, ROS\}$$

#### E.4.5 Annualized Value of the Cash Flow

In calculating the lifetime cost of alternative corrosion management approaches, the irregular cash flow of the whole lifetime is transformed into an annuity (a constant annual value paid every year) for the same lifetime. The annualized value (AV) of the alternative approach is calculated from the PV by the use of the following formula:

$$AV = PV * i / [1 - (1 + i)^{-N}], \text{ where}$$

N = service life of the structure

The annuity of the initial investment ( $I$ ) made in year zero is determined such that its present discounted value is equal to the present discounted value of its annuity:

$$\sum_{n=1}^N [A\{I\} / (1+r)^n] = PDV\{I\} = PDV[A\{I\}], \text{ where}$$

$A\{I\}$  = annualized value of the capital investment

$A\{CM\}$  = annualized value of all corrosion management costs

$R$  = annual discount rate

$N$  = service year,  $n = 1 \dots N$ ,

$N$  = entire service life

$PDV\{I\}$  = present discounted value of the initial investment

$PDV[A\{I\}]$  = present discounted value of annuity of the initial investment

The actual corrosion management costs throughout the " $n$ " years of the structure's service life will fluctuate. The fluctuating cash flow is replaced with an equivalent uniform cash flow of its annuity. The annuity of the corrosion management yearly cash flow is determined such that the present discounted value of the original cash flow is equal to the present discounted value of the annuity:

$$\sum_{n=1}^N [A\{CM\} / (1+r)^n] = PDV[\{A\{CM\}\}] = PDV\{CM\}, \text{ where}$$

$PDV\{CM\}$  = present discounted value of the original cash flow of corrosion management

$PDV[\{A\{CM\}\}]$  = present discounted value of the uniform cash flow or annuity

The annuity of the original cash flow is then:

$$A = A\{I\} + A\{CM\}$$

This annuity or "annualized cost" is a constant annual value paid every year whose present discounted value is equal to the present discounted value of the irregular cash flow for the whole lifetime of the structure.

In summary, the current cost of corrosion is the sum of the amount spent preventing corrosion at the design and construction phase, the amount spent on maintenance, repair, and rehabilitation to control and correct corrosion (cost of corrosion management), and the amount spent on removing and replacing structures that become unusable due to corrosion (depreciation or cost of replacement).

Measuring the current cost of corrosion requires the following steps:

- Determine the cash flow of corrosion.
  - ◆ Describe corrosion management practice (materials, actions, and schedule), determine the elements of corrosion cost, and assign cost to all materials and activities that are corrosion related.
- Calculate present discounted value (PDV) of cash flow.
- Calculate annualized value for the PDV.

## **E.4.6 Past Trends of Corrosion Management Costs and Benefits**

The current cost of corrosion is merely one point in time that is the result of past trends and developments. If the history of corrosion management practices can be determined, current practices can be placed in perspective. By examining the past, the following questions may be answered:

- Have material options and their costs changed?
- Have corrosion management practices and their costs changed?
- What is the effect of different materials and corrosion management practices on the lifetime of a structure?
- Has the number of failures due to corrosion (incidents, injuries, fatalities, and property damage) changed?
- Has the cost of failures caused by corrosion changed (cost of environmental cleanup, litigation)?

## **E.4.7 Cost Saving through Improvement of Corrosion Management**

Within a specific industry sector there is a range of current practices in dealing with corrosion, from old technology to state-of-the-art. The cost and results of each of these practices are different. While one of the practices achieves the most for its cost, i.e., is the most cost-effective, others could be improved to be more cost-effective. An important question is whether improvement of currently used practices could indeed lower the current cost of corrosion. As better ways are developed to protect against corrosion, the potential for saving will increase.

The goal of corrosion management is to achieve the desired level of service at the least cost, including user costs. Finding the corrosion management program that has the greatest net benefits, including user costs, to society requires an understanding and careful analysis of all the direct and indirect costs involved. Cost benefits could be demonstrated by changing optimal corrosion management and more corrosion resistant materials.

Similar treatment could be performed for other sectors, but because of the complexity of corrosion control and corrosion management issues, there is usually insufficient information available to identify the design-maintenance option with the lowest annual cost, including user costs. However, the results of the surveys and associated interviews for the various industry segments have indicated a wide range of corrosion management practices, suggesting that.

## E.5 RISK BASED APPROACH TO LIFE CYCLE COSTING

### E.5.1 Bayesian Networks

With good design and construction, and diligent corrosion maintenance control, the deterministic LLC approach can be used to decrease the likelihood of corrosion. However, corrosion management can be complex, and hence corrosion related decisions involve a considerable amount of uncertainty. By using a deterministic approach to calculate CAPEX and OPEX, lack of information or poor quality of information may lead to incorrect corrosion cost estimates.

Because of the considerable amount of uncertainties associated with corrosion decisions, deterministic approaches to conduct corrosion LLC may not be accurate. A probabilistic approach provides a means for quantifying these uncertainties and makes the outcomes of options that might otherwise not even be considered transparent. A probabilistic or risk-based approach to LLC enables the following risk questions to be answered:

- What can go wrong?
- How likely is it?
- How does it affect us?

Given by the mathematical expression:

Risk =  $\{S_i, p_i, C_i\}$ , where

$S_i$  = a set of scenarios or threats (what can go wrong?)

$p_i$  = the probability of occurrence (how likely is it?), and

$C_i$  = the consequence (how does it affect us?)

In this definition of risk, for a given system or a design option, there may be a set of scenarios, each with its own pair of probability (frequency) and consequence, which then can be portrayed as a curve of probability vs. consequence, see Figure E-9.

There are two major schools of thought defining risk, the frequentists and the subjectivists (Bayesians). The two schools generally define probability differently. The frequentists' or statistical view of probability is that probability is an objective number that can be approached if a sufficiently large number of controlled observations are made. The relationship between frequency and probability is defined by the well-known Bernoulli's limit theorem:

$$p(|f(x) - p(x)| > \varepsilon) \rightarrow 0 \text{ as } N \rightarrow \infty ,$$

where the frequency,  $f(x)$ , of a population of data approaches the probability,  $p(x)$ , of that same data as the number of trials approaches infinity. Stated another way, frequency is a measurable quantity based on repeated observations, whereas probability represents the degree of belief or confidence in the measured frequency, also referred to as probability of frequency.

The subjectivists on the other hand, refer to probability as simply a degree of belief in an event. This view stems from the idea that not all phenomena can be repeated in a controlled manner to derive statistical distributions. This is especially true of complex systems. Therefore, probability can be assigned to the strength of an expert's belief about an event and then can later be corrected using

repeated observations. This is at the heart of the Bayes theorem and it is often referred to as a belief network.

In reality, the frequentist and subjectivist perspectives can be combined—where possible statistical distributions are derived through the use of mechanistic models that are, in turn, based on experimental data with their associated uncertainties—but we also include direct probability distributions representing the degree of belief of an expert in a given observation. These two streams of probabilities are linked in a Bayesian network that can be updated through laboratory or field observations.

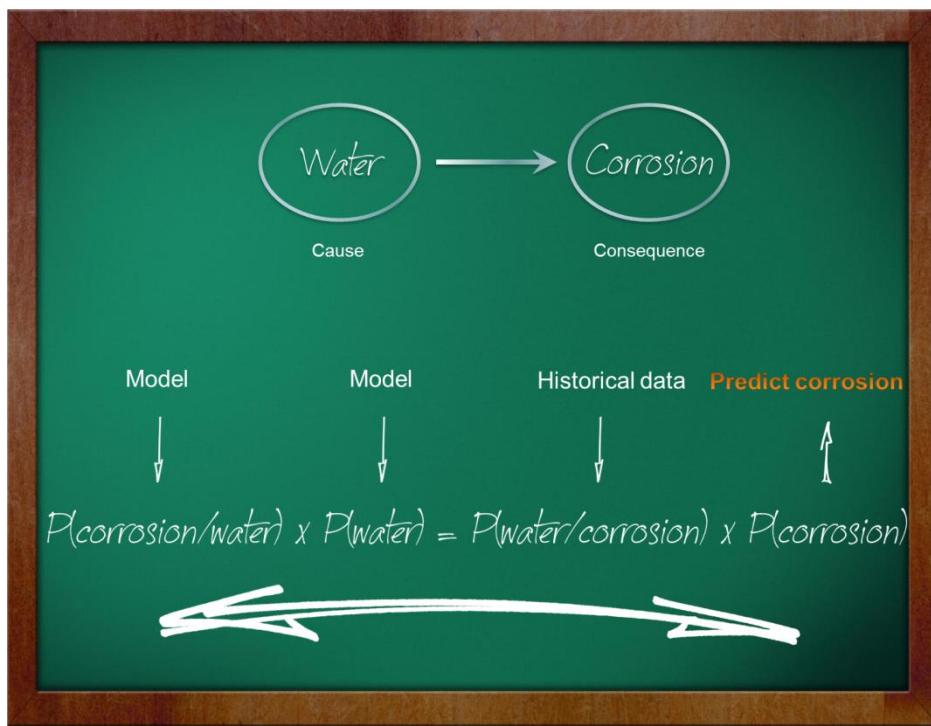
The Bayes theorem states that the posterior probability of an event (i.e., probability of the event after an observation is made) is related to the prior probability of the event (i.e., before the observation is made) through the probability of observing the event and the conditional probability of observation given the event occurred, as given by the following equation:

$$p(A) = p(B) \cdot \frac{p(A|B)}{p(B|A)}, \text{ where}$$

A and B are two causal dependent events,

$P(A)$  and  $P(B)$  their respective probabilities,

$P(A|B)$  the conditional probability of A given B and  $P(B|A)$  the conditional probability of B given A.



**Figure E-9. Simplified Bayesian Network**

This simple but powerful theorem allows us to compute the probability changes every time we obtain a new piece of evidence, data or observation. The use of Bayesian network in the context of risk assessments has several advantages:

- **A Bayesian network does not require a fixed set of inputs and outputs.** Any information can be used by the model even if it is not an input. The more information is added to the network, the less uncertainty in the final probability.
- **A Bayesian network can run forward** (from cause to consequence) **or backward** (from consequence to cause). Any information can be used by the model to update the states of its consequences and the probability of its causes. For example, the model can run forward to calculate possible corrosion threats probability or backward to perform failure analysis.
- **Bayesian networks can estimate future events by combining data and knowledge of the system.** Many future estimates use past inspection data only to forecast future performance. This practice could be compared to driving a car by only looking at the rear-view mirror. To forecast threats, one has to understand the underlying mechanisms of degradation, which are complex and almost never linear. Bayesian networking can consider complex processes, such as the corrosion LLC illustrated below.

## E.5.2 Bayesian Network Approach to Corrosion Life Cycle Costing (LLC)

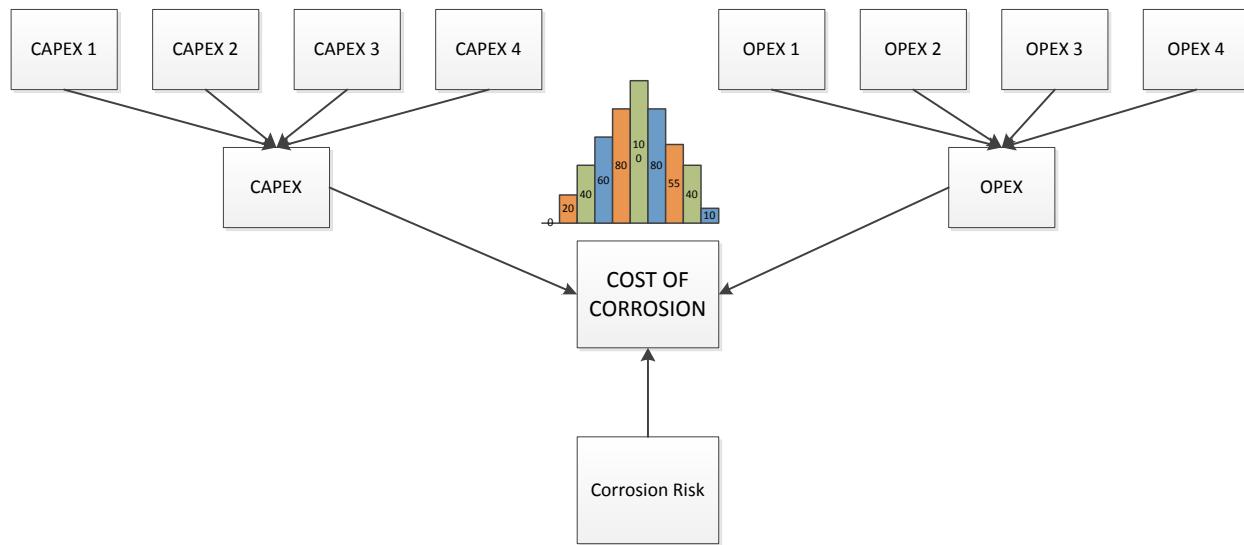
While a Bayesian approach to LCC can quantify the uncertainties in calculating direct and indirect corrosion costs associated with OPEX and CAPEX, there always exists the additional risk of unanticipated corrosion threats. The significant variability in corrosion threats associated with the uncertainties in corrosion mechanisms as well as inspection data, leads to the conclusion that a probabilistic approach (implied in risk assessment), rather than a deterministic approach, is highly desirable. A detailed example of the Bayesian Network approach to determine the cost of corrosion due to the mechanism of corrosion under insulation (CUI) is given Appendix D; CUI is a problem in refineries, petrochemical, chemical plants, etc.

Because of the uncertainties, the probabilistic analysis method chosen must meet a number of challenges:

- The probabilistic analysis should include models that represent various corrosion failure mechanisms.
- The probabilistic method should be able to include different types of uncertainties.
- The probabilistic model must be constructed in a transparent manner so that all assumptions and the logical connections between causes and consequences can be seen.
- The probabilistic model should provide the ability to make decisions even with imperfect or missing data.
- The analysis should have the ability to correct the analyses by observations.
- The results of probabilistic calculations, assuming that they are properly validated, must be presented in a simple visual interface so that decisions can be made more easily and updated based on further observations or remedial actions.

A Bayesian network can meet these challenges. This is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data analysis.

- The model encodes dependencies among all variables, and it readily handles situations where some data entries are missing. Bayesian analyses provide an effective way of reasoning under uncertainty, which is not always intuitive.
- A Bayesian network can be used to learn causal relationships, and hence can be used to gain understanding about a problem domain and to predict the consequences of intervention.
- The model has both causal and probabilistic semantics; it is an ideal representation for combining prior knowledge, which often comes in causal form, and data.
- The model has a principled approach for avoiding the over fitting of data.



**Figure E-10. Cost of Corrosion of an Asset Showing the Three Main Contributors**

The probabilistic approach described above will allow determination of the life cost of equipment/assets with and without corrosion control, and identify cost savings that can be made over the life of equipment or an asset with proper and cost effective corrosion control.

## E.6 CONSTRAINT OPTIMIZATION

A constraint optimization framework is used to determine the optimal corrosion management practice for a specific structure or facility.

Developing the constrained optimization framework takes three major steps:

1. Optimizing expenditures of the structure.
2. Maximizing service level subject to budget constraint.
3. Build constrained optimization model.

In the first step, in optimizing expenditures of the structure, the goal is to find the combination of inputs that produces the outcome at a minimum cost. There is a relationship between the inputs (CM and I) and the output (SL). This relationship is called the production function, which is like a cooking recipe that tells us how to get SL with the use of CM and I. There are many combinations of CM and I that would give us SL. But each of these combinations has a different price. We want to find the combination of CM and I that costs us the least, yet does the job. Maximizing the production function subject to a budget constraint means to determine the most optimal way of using the inputs (CM and I) to produce the requested output (SL). Therefore, in our optimization, we establish the most optimal expenditure ( $AEV\{I\} + AEV\{CM\}$ ) for a given service level ( $SL_0$ ). For example, one may "gold plate" the bridge and have no maintenance or may invest less in the capital, but apply extensive CM program. Both of these options could result in the same service life length, but not for the same life cycle cost. The one with the lower LCC is preferred.

Thus the first step established the relationship between inputs and output (the production function) and optimized production by finding the cheapest combination of inputs to produce *any* levels of output.

In the second step, in maximizing service level subject to budget constraint, the goal is to produce the highest service level with the already optimized two inputs (I and CM) if only limited funds are available. Expressed in analytical terms the maximization of service level subject to budget constraint (all terms are in present value) is as follows:

$$\begin{aligned} \text{Max } SL &= \text{Max } SL(I, CM) - \lambda (I P_I + CM P_{CM} - B) \\ &\quad | I, CM, \lambda \end{aligned}$$

Determining the first order conditions:

$$\begin{aligned} \frac{\partial Y}{\partial I} &= \frac{\partial SL}{\partial I} - \lambda P_I &= 0 \\ \frac{\partial Y}{\partial CM} &= \frac{\partial SL}{\partial CM} - \lambda P_{CM} &= 0 \\ \frac{\partial Y}{\partial \lambda} &= -(I P_I + CM P_{CM} - B) = 0 \end{aligned}$$

from which:

$$\begin{aligned} \frac{\partial SL}{\partial I} &= \lambda P_I \\ \frac{\partial SL}{\partial CM} &= \lambda P_{CM} \end{aligned}$$

therefore:

$$(\frac{\partial SL}{\partial I}) / P_I = (\frac{\partial SL}{\partial CM}) / P_{CM}$$

Executing the calculations determine the optimal I and CM amounts subject to budget constraint.

In the third step, the constrained optimization model is established, with the objective to lowering expenditure. The constraint is an engineering definition to minimize financial input subject to engineering constraint. Or more precisely, minimize the cost of production subject to the service requirements.

$$\text{Min } \alpha \quad | \quad = AEV\{I\} + AEV\{CM\} + \lambda [ SL(AEV\{I\}, AEV\{CM\}) - SL_0 ] \\ | \quad AEV\{I\}, AEV\{CM\}$$

where  $SL_0$  desired service requirement

or the same equation with Present Values

$$\text{Min } \alpha \quad | \quad = PV\{I\} + PV\{CM\} + \lambda [ SL(PV\{I\}, PV\{CM\}) - SL_0 ] \\ | \quad PV\{I\}, PV\{CM\}$$

In summary, the constrained optimization satisfied two constraints: minimizing expenditure and achieving service level, in the following three steps:

1. The first step, optimizing expenditures of the structure, provided that the service level  $SL(PV\{I\}, PV\{CM\})$  is produced by the optimal / most effective combination of inputs. Or in other word, the minimum amount of input ( $PV\{I\}, PV\{CM\}$ ) is used to produce  $SL$ .
2. The second step, maximizing service level subject to budget constraint, provided that the service level used here is achievable given the available budget.
3. Therefore, the third step achieves the required service level (within given budget) by minimizing expenditures (of the optimal combination of inputs).

Calculating the first order conditions (by taking the first derivative to minimize the function) from the equation with present values (FOC's):

$$\begin{aligned} \frac{\partial \alpha}{\partial I} &= 1 + \lambda (\frac{\partial SL}{\partial I}) = 0 \\ \frac{\partial \alpha}{\partial CM} &= 1 + \lambda (\frac{\partial SL}{\partial CM}) = 0 \\ \frac{\partial \alpha}{\partial \lambda} &= SL(I, CM) - SL_0 = 0 \end{aligned}$$

The tradeoff between the initial investment and the corrosion management efforts during service can be written as follows:

$$\frac{\partial SL}{\partial I} = \frac{\partial SL}{\partial CM} \quad \text{when } I \text{ and } CM \text{ are measured in dollars.}$$

The above equilibrium means that the marginal expenditure of corrosion management is equal to the marginal expenditure of building / replacing the structure. (In order to make the statement about the marginal tradeoffs we need to know the time period a structure is expected to be in service.) This equation of marginal tradeoff stands for new and existing structures as well.

- For a new structure the marginal cost of corrosion management for the planned useful life is equal to the marginal cost of building (investing into capital) the structure.
- For an existing structure first the corrosion management options need to be optimized and the optimal practice determined. The marginal cost of this optimal corrosion management for the remaining planned useful life is equal to the marginal cost of replacing the structure  $T$  years from now in the future.

In the final step, externalities are included in the constraint optimization framework. Since determining social cost is not the focus of this report, it is assumed that indirect cost (externalities) can be measured and valued in monetary terms.

$$\text{Min } \alpha \quad | \quad = \text{AEV}\{\text{I}\} + \text{AEV}\{\text{CM}\} + \text{AEV}\{\text{SC}\} + \lambda (\text{SL}[\text{AEV}\{\text{I}\}, \text{AEV}\{\text{CM}\}] - \text{SL}_0) \\ \text{AEV}\{\text{I}\}, \text{AEV}\{\text{CM}\}$$

where: SC = indirect cost of the CM practice analyzed

AEV{SC} annualized value of the indirect cost of CM

Externalities are additional expenses that need to be minimized along with initial investment and corrosion management expenses. Therefore, it is included in the objective function (the first part) of the constrained optimization equation.