RENEWAL & REPLACEMENT FUNDING USING MAINTENANCE STRATEGIES AND PROBABILISTIC ANALYSIS

J.D. Solomon, PE, CRE, CMRP

INTRODUCTION

Infrastructure assets deteriorate with use and time. Renewal work should be performed periodically to maintain the effectiveness and value of an asset. When the asset has reached the end of its functional useful life, it should be replaced. At the heart of any maintenance and reliability program is the effort to preserve and restore the existing system's performance and reliability.

Anticipating future renewal and replacement (R&R) needs to ensure that adequate and timely funding is planned into the capital improvement program (CIP) is an essential component of any maintenance and reliability program. One key aspect is selecting the most appropriate method for developing R&R forecasts. A second equally important but often overlooked aspect is the ability to effectively communicate the methodology and results to decision makers. This paper will address both aspects while putting an emphasis on how to effectively communicate R&R results.

R&R FORECAST METHODOLOGY

Deterministic models use point estimates for each input parameter and from these estimates a single, specific outcome is predicted. Such models are rooted in the theory of determinism, which holds that every outcome event is the result of preceding, or antecedent, events. Some of the many problems associated with forecasts based on this methodology include: the belief that all preceding events can be precisely determined; the failure to account for interdependence among the input events; input events have been accurately measured, interpreted, and reported; and precise models can be developed to capture the relationship of the inputs and output events.

More simply said, the primary problem associated with this approach is its failure to account for uncertainty. It is an oversimplified approach that reduces the applicability and accuracy of the associated forecasts. An equally important ramification is that it normally drives the forecaster to collect as much data as possible, and with a high level of measurement, in order to avoid being considered wrong with the associated prediction of the future. Many organizations waste tremendous amounts of resources collecting data to potentially improve a deterministic forecast while at the same time not gaining any advantage in the decision-making process.

Probabilistic models use statistical distributions associated with input parameters rather than single point estimates. According to ISO 31000[1], the international risk standard, this approach provides a method of taking into account uncertainty on systems in a wide range of situations. It is typically used to evaluate the range of possible outcomes and the relative frequency of the values in that range for quantitative measures of a systems such as cost, duration, throughput, demand and similar measures. According to ISO 31000, it is primarily used either as an uncertainty propagation on conventional analytical model or for probabilistic calculations when analytical techniques do not work. The primary use of a probabilistic approach in the R&R model described herein is primarily related to the former.

Being able to quantitatively address risk and uncertainty is the most obvious benefit for R&R forecasts. However, one advantage that is often not fully appreciated is the ability to use the model in cases where input data is not as perfect as desired by a purely deterministic approach and thereby saving cost by directing limited resources to improve data quality where such data is most critical to the accuracy of the forecast. Such data is classified as highly valued data.

TECHNICAL NATURE OF PROBABILISTIC R&R FORECASTS

The process outlined for R&R forecasts using probabilistic models includes: development of a deterministic model that represents the behavior of the system as closely as possible; performing sensitivity analysis on the deterministic model; develop the probability distribution associated with the uncertainties of each of the inputs; run 10,000 or more simulations and determine statistics such as median values, standards deviations, quartiles, and confidence intervals.[2]

The model outputs can be used to assess either the entire distribution of outcomes (such as the probability of a defined outcome arising) or key measures from the distribution (such as the percent chance that a cost is met or exceeded, or the percent chance that a given total cost will be reached in a given period of time).

Regardless of the manner in which this robust approach can be used, it is statistically based and often applied to complex issues. Some of its limitations include that the accuracy of the solutions depend on the number of scenarios that are analyzed, it relies on being able to determine distributions related to the behavior of the input parameters, and perhaps most importantly the techniques and results can be difficult to communicate.[3]

COMMUNICATION OF R&R MODEL RESULTS

Effective communication of probabilistic analysis is cited by risk and reliability experts as one of the most difficult aspects of any forecast. All types of people, including technical professionals, cannot intuitively understand statistics including the base meaning of probabilities.[4, 5]

A communication plan should be developed before the modeler or analyst attempts to communicate the R&R forecast results to decision makers. This is consistent when attempting to communicate any type of technical data to end users. A basic outline is normally sufficient, and minimum (primary) considerations should include a written description of the target audience, the experience of the audience in the subject matter (here, forecasting and probabilistic methods), key communication objectives, and a list of supporting graphics to communicate the forecast.

Additional considerations depend on the nature of the referenced primary considerations. These include the type of presentation forum, the presenters of the information, the type of graphics, and the format, colors, and word choices of the presentation follow establishing the four key items listed above.

An overarching recommendation is to get the communication as simple as possible. This includes using a finite number of visuals, avoiding detailed explanation of the process and its limitations, and to generally let the receiving audience ask questions to the level to which they want to have understanding.[6]

KEY VISUALS FOR COMMUNICATING R&R FORECASTS

A summary of the five key visual presentations tools that are recommended is as follows:

Time Series Chart of Funding Needs using a Box-and-Whisker Plot

A time series plot displays observations on the y-axis against equally spaced time intervals on the x-axis. For financial analysis, monetary values are represented on the y-axis and time (in years) on the x-axis. The major advantage of time series plots is that they allow the user to evaluate patterns and behavior in forecast data over time.

When performing a probabilistic analysis, the use of a box-and-whisker plot (sometimes called simply a box plot) is used to complement the presentation of the financial data in any given year. More specifically, a box-and-whisker plot is an aerial view of a histogram. The median value synonymous in the presentation with the point forecast associated with a simple deterministic time series plot. Normally the 25th and 75th quartile are depicted as the "box" while the most extreme values, typically the 5th and 95th projections define the ends of the "whiskers."

The box-and-whisker plot allows for a visual representation of the risk associated with the forecast in one graphic. The greater width of the box in any given year implies more uncertainty or potential risk associated with the forecast. Boxes in any given year that are skewed in either direction from the median value also depict the potential for more upside or downside in any given year.

Renewal & Replacement Frequency Table

This table is most useful to O&M staff in understanding the maintenance frequencies that are driving the base model. Renewal events are plotted in yellow and replacement events plotted in green across the entire timeline for each facility. By examining the table, the user can get a feel for the potential for lengthening or contracting R&R frequencies. In the case of multiple facilities, it can be quickly and visually be determined if different R&R strategies are being used at different facilities for the same type of asset or subsystem.

Asset List for Targeted Capital Cycle

The forecast model should provide a list of assets anticipated by the probabilistic analysis for any given time frame, which is most commonly a capital improvement cycle. The use of a probabilistic forecast allows the user to expand (or contract) the subsystems or assets by the relative risk desired, i.e., 50% certainty or 75% certainty over any given time period. This fully captures the power of the probabilistic model by allowing for comparative analysis based on the potential uncertainty around the timing of R&R events, rather than simply a fixed-point estimate of that same timing.

Tornado Diagram

Tornado diagrams are modified versions of a bar chart. They are a classic tool used to communicate the results of a sensitivity analysis; providing end users a quick overview of the critical systems or assets and the relative risk involved with each. For an R&R model, the tornado diagram quickly shows which subsystems and assets create the great risk to the total funding demand over the course of the evaluated lifecycle. Tornado diagrams are also powerful quality control tools relative to the deterministic model prior to performing the probabilistic forecast.

Table of Historical Spending versus Forecasted Funding Needs

Another graphic that is a powerful tool is a summary of historical spending versus future forecasted funding needs based on the probabilistic model. This is summarized for both capital funding and for annual maintenance budgets. Normally this is best shown as a 3-year or 5–year average and it is important to decide on the quartile that will be represented from the probabilistic forecasts.

APPLICATIONS

R&R and Systems Criticality Analysis for Rocky Mount NC

Rocky Mount is a city located in eastern North Carolina. Although it was not formally incorporated until February 28, 1907, the North Carolina community that became the city of Rocky Mount (City) dates from the beginning of the 1800s. The city's population is currently at 57,477. The City's utility department serves approximately 85,000 people within the City of Rocky Mount, Edgecombe County and Nash Counties. It owns and operates over 400 miles of wastewater collection lines, 33 sewer lift stations, and the 21 million gallons per day (MGD) Tar River Regional Wastewater Treatment Plant (WWTP). The City also maintains over 500 miles of water transmission and distribution lines, seven elevated tanks, one ground storage tank, and two water plants, Sunset Water Plant and the Tar River Reservoir Plant, with a combined capacity of 26 MGD**.**

The purpose of the R&R forecast model task development for the City was to build a baseline 20-year R&R model for the water and wastewater plants. Financial estimates of both capital needs and annual maintenance budget needs were to be estimated. The City currently does not have a computerized maintenance management system (CMMS) and did not have a centralized list of assets for each facility.

The development of the forecast model started with a deterministic approach at the asset level and the use of input data such as asset age, condition, replacement value, and useful life. A list of major assets was developed by a CH2M field team based on visual data collection and a number of different spreadsheets and other sources of asset listings. Replacement Asset Values (RAVs) was established by CH2M staff through the use of the City's property appraisal, the 2009 Fixed Asset Registry (FAR), and typical unit cost range for facility replacement based on CH2M data sources and/or input from equipment suppliers.

Building on the validated deterministic models, a probabilistic analysis was performed to incorporate variability and uncertainty by evaluating a range of replacement values and useful life for each asset class. This step assigned probability to a range of projected R&R funding demands. R&R schedules were developed and grouped by process and sub-processes.

The forecast model leverages asset inventory and condition data coupled with expected asset life cycle assumptions and asset replacement values to estimate R&R needs, and allows the funding demand to be summarized at the process and sub-process level. Each treatment facility had approximately 20 processes, between 50-70 sub-processes, and over 1,500 assets.

Annual funding demand projections were averaged for 5-year increments to be consistent with utility capital planning intervals. Annual funding forecasts for R&R needs to be considered carefully in the decision process since asset performance and the exact timing for replacement cannot be easily predicted for all assets that roll up to a holistic R&R funding demand forecast. Assets may last longer or shorter than the assumed useful life and costs for that asset type may vary over time. The probabilistic methodology used for this R&R forecasting effort provided the City with a robust understanding of the magnitude and likelihood of R&R and maintenance funding demands based on the variability and uncertainty related to the input assumptions.

A complete asset list in a single source, such as a CMMS, was not available. Asset inventory information was collected with experienced water and wastewater treatment field engineers. The facility valuation process based on financial records supported the field inventory efforts in terms of helping to validate their relative completeness. Regardless, the model should be revised in the future as input data are updated and refined.

The asset valuation from the field (bottom up) and facility level valuation from financial records (top down) approaches were both used to validate the total asset value of the system as a whole was accurate in the model. The conclusion was that there was agreement within a reasonable range of uncertainty for a first-generation model.

Interview were also conducted with O&M staff the capture the maintenance frequencies with respect to renewal and replacement at the asset type, subsystem, and system levels. Interview were very important in this case since maintenance histories are not being managed in a CMMS. Consistent with best practice, the data collected from the field was validated for general accuracy against standard renewal and replacement ranges from CH2M historical databases.

A sensitivity analysis was performed to determine which subsystems had the greatest variation from base cost. The range presented in the sensitivity analysis results represented the minimum and maximum potential impact derived from the probabilistic forecast with the facility processes ordered from most to least important resulting in a tornado shape.

One primary insight from the sensitivity analysis was that the forecast is very sensitive to high dollar assets and processes with the greatest number of assets classes within it. This is a typical result, and not unexpected, as variations in systems with high value or high variability would have a greater net variation compared to other systems.

Another valuable insight of the sensitivity analysis is gained when comparing to the criticality analysis results that were completed as part of a separate activity. Financial consequences are only one part of a criticality analysis (compliance and public image are among others). The sensitivity analysis within the R&R model illuminated the subsystems with greatest financial risk and helped to provide insights into the degree that costs may (or may not) be driving the evaluation of subsystem criticality. This is also important from focusing more analytical time one understanding the relationship of assets within their own subsystems to help improve (or degrade) overall system reliability.

The probabilistic analysis provided the most valuable insights into the potential timing and locations of the funding needs. This was extremely beneficial since the overall required funding needs were significantly in excess of what the model forecasted in terms of both capital and maintenance budget needs. While this was not unexpected by the staff and this suspicion was indeed a driving force for the R&R model development, understanding the relatively timing, locations, and associated risks and uncertainties were major outcomes.

In summary, the case example from Rocky Mount demonstrates that it is not necessary to have a fully developed asset listing, condition assessment, or even a CMMS in order to doing meaningful R&R assessments. Moreover, because a probabilistic approach address uncertainties related to timing and costs, it provides a realistic picture of risks and the type and locations of more detailed data collection and analysis. This was very important to the City since available funds were limited but the urgency was great.

Renewal & Replacement Forecasting for Muncie, Indiana

The city of Muncie was incorporated in 1865 but the area was first settled in the late 1700s. The population of the city was 70,085 in 2010. Muncie is the home of Ball State University and the Ball Memorial Hospital. Muncie Metropolitan Sewer District (MSD) serves the City of Muncie and the bordering communities. The system consists of 635 miles of separate and combined sewer lines, five sanitary sewer pump stations and one water pollution control facility.

The purpose of the larger project was to develop an asset management plan for the for the system as a whole including infrastructure systems related to the wastewater collection and treatment system, the stormwater collection system, and the flood protection and levee system.

The purpose of R&R forecast model was to provide a 20-year funding forecast for vertical and horizontal assets associated with the wastewater collection and treatment systems, including the combined and separate stormwater collection system. The results of the R&R forecast were intended to be used as a primary tool in an affordability analysis that was to be completed in support of the development of MSDs Integrated Plan (IP) with the Indiana Department of Environmental Management (IDEM) under delegated authority from the United States Environmental Protection Agency (USEPA).

The R&R forecast model was a first-generation model that provided a baseline forecast of R&R and maintenance funding demands. This baseline forecast was based on current MSD practices and available data, and was not intended to optimize those practices based on risk, modified levels of service, and/or maintenance strategies. Subsequent versions of the model will be updated and refined to address these issues as part of the larger asset management program.

As part of the review of the model outputs, it was determined that the R&R forecast results were in part being driven by a number of data uncertainties. There were a number of items of importance for MSD's consideration to support the reduction of the influence of these data uncertainties on the forecast of future R&R funding demand, as well as making the forecast more comprehensive (incorporating assets not included in the baseline R&R forecast). These items included the need to dedicate resources and to develop protocols for a comprehensive asset register, a formal asset hierarchy that reflected the system relationships of individual assets, and a computerized maintenance management system

(CMMS) for documenting how the organization manages, maintains, and operates its facilities.

A number of key insights related to the forecast model and the meaning of the probabilistic analysis results in terms of utilization in the decision process related to financial planning/budget setting activities were meaningful outcomes of the effort.

The first was that the forecasted R&R funding demand is based on the various assets' remaining useful life (from condition assessment, input from MSD subject matter experts, or age information), asset life cycle, asset replacement value, and identified renewal frequency. The variability in funding demand represented for a particular year is directly influenced by the life cycle, replacement value and the translation of the condition score to a percent of remaining useful life for MSD asset near or beyond its assumed life cycle. Therefore, as more data becomes available, the "range" (reflecting the uncertainty in the estimate, as outlined in the previous section) of the box and whisker plots could be expected to be incrementally reduced; however, uncertainty is inherent in asset life cycle estimation, so some degree of variability will always be part of the resulting forecast of R&R needs.

Another key insight was that the boundaries of the forecast (5^{th} and 95^{th} percentile forecasts) are driven by cumulative events that are highly unlikely to occur but are useful in understanding the limits of highest and lowest probabilities. For example, at the 95^{th} percentile forecast, the life cycle of infrastructure is reduced to the lowest expected life cycle, based on assumed life cycle ranges, and costs for replacement are much higher than currently anticipated, based on assumed replacement value ranges. As one moves inward from the boundary of the probabilistic forecast, these scenarios have a higher degree of probability than those scenarios at the edges. Understanding the range and probability of possible funding demands helps in the budget-setting process.

The probabilistic ranges of the forecast are just as important as the values themselves. The variability in annual forecasts provides the insights that the lower end of the forecast (25^{th} percentile) should not be a major focus for budget setting decisions, as the lower end of each year's forecast range has less variability than the upper end, and the consequences for underfunding by focusing on the lower probability scenarios can be significant. With similar logic, the upper end of the forecast (50^{th} to 75^{th} percentile) deserves more attention and discussion; this area has a more variability between years and has a greater potential to impact MSD financial metrics on an annual basis. This end of the variability in the forecast should be where the budget level setting decisions should be made.

Setting budgets for R&R using the median forecast (50^{th} percentile) will provide MSD with a reasonable probability funding demand forecast, but the 50^{th} to 75^{th} percentile forecast range should be evaluated for setting a contingency budget that will mitigate any risk of budget shortfalls for unplanned R&R projects. The analysis results should be considered valid for planning purposes with a strong potential for future refinements as more detailed data is made available.

Similar to the Rocky Mount case example, the Muncie case example demonstrates that it is not necessary to have a fully developed asset listing, condition assessment, or even a CMMS in order to doing meaningful R&R assessments. The Muncie case example also more fully demonstrates the value of the probabilistic forecast in terms of understanding the timing and uncertainties associated with financial decision making. And in the case this consideration was very important in a regulatory negotiation and settlement process.

Renewal & Replacement Forecasting for Orange Water and Sewer Authority

Orange Water and Sewer Authority (OWASA) is a public, non-profit agency that provides water, sewer (wastewater) and reclaimed water services to the Carrboro-Chapel Hill community of North Carolina including the University of North Carolina at Chapel Hill in southern Orange County, North Carolina. OWASA serves about 82,000 people. The agency owns and operates three reservoirs, a 20 MGD Water Treatment Plant (WTP) has a capacity of 20 MGD, 420 miles of raw water, finished water, and water interconnection lines, 338 miles of sanitary sewer and force main lines, and 21 pump stations, a 14.5 MGD Wastewater Treatment Plant (WWTP), and a reclaimed water system.

The case study of OWASA demonstrates the use of the R&R forecast in a comprehensive asset management program for an extremely well managed utility that seeks to further optimize its services and fees. It is a good example of how the model can be used with a fully developed CMMS system and incorporated into a fully developed Capital Improvement Program. It further demonstrates the level of program refinement that the model provides as an enabler of data clean-up, further places where more highly valued information is needed, and incorporated into financial rate setting.

The purpose of the R&R forecast model development for OWASA was to build a baseline 20-year R&R model for the water and wastewater vertical and horizontal assets. The vertical assets R&R models focused on mechanical and electrical equipment, as this is the most relevant to the vertical asset's 20-year R&R forecast (structural elements typically have much longer life cycles). The horizontal asset R&R model included all OWASA owned pipes four inches and greater in size. The model is a first-generation model that provides a baseline forecast of R&R and maintenance funding demands. This baseline forecast is based on current OWASA practices and does not change or optimize those practices based on risk, modified levels of service, and/or maintenance strategies. The model should be revised in the future as input data are refined to optimize the R&R forecasts.

The R&R forecast results indicated that the forecast was in part being driven by asset classes that contain a grouping of a number of assets by asset types. The development of more detailed information on some of these asset classes will provide additional clarity on the asset data that will in turn help to reduce the effect of data uncertainty within the forecast model. For example, at the beginning of the forecasting effort OWASA staff put forth significant effort to identify a number of asset details for valves, actuators, pumps, motors, electrical equipment and mixers. This data included (where appropriate for each asset type): diameter, horsepower, amperage, size classification for generators and switchgear, mixer types and valve types. For five asset classes, there was insufficient data in the CMMS to provide an asset level detail to provide a better gradation of these asset classes and types.

A number of key insights were gained related to the forecast model and the meaning of the probabilistic analysis results. These in turn will be utilized in the decision process related to financial planning/budget setting activities.

Years 1 through 5 appeared to be the most sensitive to the uncertainty related to the life cycle for the major equipment, indicating a large number of replacements – based on age and condition – resulting in a highly variable result. The reality of the Year 1 through 5 data is that the financial model predicts replacements based on the life cycle and does not automatically optimize the replacement schedule based on available funding levels. Adjustments in maintenance strategy could be made to help balance annual funding demands; for example, a pump in poor condition could be prioritized for additional monitoring and maintenance to keep it running for an additional 2 to 3 years to balance funding of R&R.

The lower end of the forecast (25th percentile) should not be a major focus for budget setting decisions, as the lower end of each year's forecast range has less variability than the upper end, and the consequences for underfunding by focusing on the lower probability scenarios can be significant.

The upper end of the forecast (50th to 75th percentile) deserves more attention and discussion; this area has a wide range of variability between years. This end of the variability in the forecast will be where the budget level setting decisions should be made for "normal" or planned R&R funding levels, as well as contingency budgets for emergency or unplanned R&R projects.

Setting budgets for R&R using the median forecast (50th percentile) will provide OWASA with a reasonable probability funding demand forecast, but the 50th to 75th percentile forecast range should be evaluated for setting a contingency budget that will mitigate any risk of budget shortfalls for unplanned R&R projects.

The data and the model should be improved when the model output (R&R forecast) shows significant improvement, in terms of reducing uncertainty in the funding demand values themselves. There is a point where further investments in refining model input data will not change the decisions made with the model outputs (budgeting, maintenance strategies, etc.). A starting point to focus efforts for improving asset data, based on a review of the highest impact asset classes/groupings, was provided.

Considerable work was completed to develop the first-generation R&R forecast. Through the development and clean-up of this information several next steps were taken including restructuring of parts of the CMMS system, refining and developing improved work processes and standard operating procedures (SOPs), and performing an updated criticality analysis. The R&R forecast and subsequent data upgrades also made it possible make significant upgrades to the CIP prioritization process.

The OWASA case example provides an indication of the value of the probabilistic approach in helping a well-managed organization takes its program to even a higher level in terms of reliability and associated funding needs. It demonstrates the power in fully understanding the quantitative risks and associated uncertainties for truly optimizing the decision-making processes at several levels in an organization.

REFERENCES

1. ISO 31000-2009 series, International Organization for Standardization. www.iso.org.

2. Solomon, JD, Sharpe, Adam, and Seachrist, Steven; (2014); The Leading Edge: Gwinnett DWR's Approach to Infrastructure Renewal and Replacement; proceedings from the AWWA ACE Conference.

3. Solomon, JD, and Sharpe, Adam; (2013); Regional Planning Using @RISK, PrecisionTree and Evolver, Part 1: Developing and Applying the Models; proceedings from The Risk Conference.

4. Gigerenzer, Gerd; (2002); Calculated Risks: How to Know When Numbers Deceive You; Simon & Schuster.

5. Kahneman, Daniel; (2011); Thinking, Fast and Slow; Farrar, Straus and Giroux.

6. Solomon, JD, and Sharpe, Adam; (2013); Regional Planning Using @RISK, PrecisionTree and Evolver, Part 2: Communicating to Decision Makers; proceedings from The Risk Conference.

Keywords

Renewal & Replacement; Financial Forecasting; Probabilistic Analysis; Capital Project; Cost Savings; Maintenance Cost; Replacement Asset Value; Maintenance Management

Citation: Proceedings of the 2015 annual conference of the Society of Maintenance and Reliability Professionals (SMRP) in Cincinnati, OH.