Paper 83 – "Development of Utility Functions and Aspiration Levels for Multi-Purpose Inland Navigation Projects"

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ABSTRACT: Many navigation projects in the United States Inland Marine Transportation System (IMTS) are composed of projects that have multiple purposes as part of their successful operation. The U.S. Army Corps of Engineers (USACE) inland navigation projects are primarily utilized for their navigation benefits but these structures provide other critical USACE mission requirements such as flood control, hydropower, water supply, recreation and environmental benefits. With the ever increasing age and deterioration of the USACE IMTS and increasing usage, there is a strong need to prioritize investments and make robust funding decisions over the entire portfolio of inland navigation projects. These decisions must reflect the benefits or value contributed by each of the critical purposes that a project provides to maintain a sufficient utility above currently established aspiration levels for USACE projects.

As part of the USACE Asset Management Program, a methodology that encompasses utility functions for multi-purpose projects is currently under development and being piloted at piloted at several USACE inland navigation facilities. The use of utility functions over multiple critical mission areas allows for a simple scale of comparing the value of the structure to meet the minimum mission requirements through defined aspiration levels. The utility functions under development focus on the current operational condition assessment (OCA) for system level components at USACE facilities. The OCA ranking combined with system level fault trees develop the availability or utility at the system or project level to meet a minimum requirement of operational reliability required. The presentation will focus on the utility function methodology and how that can be applied to any multi-purpose project and a complete demonstration of the utility functions will be highlighted for USACE inland navigation projects.

1 INTRODUCTION

The United States Inland Marine Transportation System (IMTS) has over 220 lock and dam facilities that are aging well beyond their original design lives. This aging infrastructure has been maintained by the US Army Corps of Engineers (USACE) using both routine maintenance (i.e., preventative and recurring maintenance) and non-routine maintenance (i.e., component renewal (major rehabilitation) and corrective maintenance (fix as fails)). However, with the continual leveling off in maintenance funds and increasing age and deterioration of these structures, USACE is developing an asset management (AM) program to address the needs of current and future life-cycle management of its assets across all business lines.

As part of this effort, the AM program is collecting Operational Condition Assessment (OCA) data on many of their assets for use in the prioritization of investment decisions for the limited maintenance and major rehabilitation funding. The OCA data is now being utilized to develop a baseline probability of failure for all IMTS components. These baseline probabilities will continually be updated with each future OCA using Bayesian techniques.

With all this baseline data for age, condition and probability of failure, the ability to model each lock and dam facility down to subsystem levels using fault tree analysis (FTA) is highly feasible. In addition, this robustness of the FTA model will assist in parsing the components into their contribution to the various business lines at a project site. This detail permits the use of utility functions and aspiration levels to be applied to examine that these systems are meeting tolerable operating levels at each project site. This gives tremendous visibility as to which subsystems and components are leading to the lower utility values and operational risk for each project across the IMTS.

2 OPERATIONAL CONDITION ASSESSMENT (OCA) and PROBABILITY OF FAILURES FOR IMTS

2.1 *Mapping of OCA Ratings to Weibull Parameters to Estimate Probability of Failure*

Operational Condition Assessment (OCA) were started on IMTS project around 2010 and many projects are currently undergoing their second rounds of OCA ratings. The current OCA navigation hierarchy has over 4000 unique components in the asset list. Ellsworth and Patev (2015) show this asset hierarchy, down to the "subsystem" level is shown in the left pane and the Component and Sub-Component level in the adjacent panes. Generically, the asset hierarchy for OCA components is as follows:

- Feature
  - System
    - Sub-system
      - Component
        - Sub-component

Each project requires an initial build of the OCA hierarchy to capture multiple system and subsystems found at project sites. Once this baseline and consistent hierarchies are completed, a team will assess the operation condition using the rating scales shown in Figure 1. The assessment procedure for OCA has both QC and QA processes to insure a consistent and repeatable value for condition.

CONDITION RATING		DEFINITION
A	EXCELLENT	1) Has not failed AND 2) does not have critical design flaw AND 3) no documented or observed deficiencies based on available data or studies AND 4) does not show signs of normal wear
B	GOOD	1) Has not failed AND 2) does not have critical design flaw AND 3) no documented or observed significant deficiencies based on available data or studies AND 4) deficiencies do not impact performance or safety. Best condition rating allowed if component shows signs of normal wear.
C	POOR	1) Has not failed AND 2) does not have critical design flaw AND 3) no documented or observed significant deficiencies based on available data, studies, or observed project performance issue AND 4) deficiencies do impact performance or safety.
D	INADEQUATE	1) Has not failed AND 2) does not have critical design flaw AND 3) has documented or observed significant deficiencies based on available data, studies, or has an observed project performance issue AND 4) does not violate law, failure is not imminent before next OCA, has not experienced closure/loss of service due to current condition in recent history, and no critical life safety concern exists.
F	FAILING OR FAILED	1) Has failed OR 2) has critical design flaw OR 3) has documented or observed significant deficiencies based on available data, studies, or has an observed project performance issue AND one or more of the following is true; violates law, failure is imminent before next OCA, has experienced closure/loss of service due to current condition in recent history, or critical life safety concern exists.

Figure 1 Rating Scale for Operation Condition Assessment

However, since the form of a condition rating is an "A" through "F" there needed to be a means of estimating the probability of failure from the OCA data. The relationship between the OCA Condition and an estimate of the probability of failure [P(f)] is critical to developing the concept of utility functions. For this, first an approach, and state-of-the-practice and state-of-the-art models and methods were developed to map OCA ratings to a P(f).

2.2 *Mapping of OCA Ratings to Weibull Parameters to Estimate Probability of Failure*

The approach was based on Expert Opinion Elicitation (EOE). EOE is a common practice to develop failure probabilities when there is a lack of failure information available, as is the case in the Corps. It is also used by industry and government agencies and has been in use in the Corps for nearly 20 years and is codified in Engineering Pamphlet (EP) 1130-2-500 and Engineering Circular (EC) 1110-2-6062.

The USACE has developed an Expert-Opinion Elicitation methodology that is a variation of Delphi Method discussed by Dalkey and Helmer [1]. The EOE process was incorporated into USACE risk protocol in the late 1990's and was developed to assist in producing best estimate probabilities for very complex engineering problems.

The current process utilizes an undisclosed (blind) vote with a two-response elicitation process. EOE is a formal (protocol), heuristic (through discussion) process of obtaining information or answers to specific questions called issues. Heuristics are internal frames of reference used by individuals and groups to inform judgment when no firm data are available. These issues can be addressed by a set of pre-defined questions to obtain the failure rates or probabilities, and failure consequences of civil works components or structures. However, this process, if not controlled properly, does bring in motivational and cognitive biases to results. These have to be examined both during and after the elicitation is performed.

The first applications of EOE were for USACE navigation projects but it is now being applied to estimate probabilities on Flood Risk Management projects (dam safety, levee safety and hurricane protection systems). Since the indoctrination of the EOE process into the USACE, the method has been successfully calibrated to predict both good and poor field performance of both navigation and flood risk management structures.

The USACE Risk Management Center facilitated USACE Subject Matter Experts and Regional Technical Specialists to estimate the median cumulative distribution function (CDF) that defines the probability of failure for all baseline curves over time. This was conducted for 31 different component categories that covered the spectrum of the IMTS inventory.

The second step in this process is the estimation of the Weibull Distribution parameters for each category. The Weibull Distribution is a very commonly used life distribution since it is very versatile in modeling many different types of failure distributions from exponential to normal. The median data from each EOE was processed real-time for the SME/RTS to process and critique the resulting Weibull Distribution parameters for characteristic life or B63.2 life (α) and shape parameter (β). Once agreement was reached by the expert panel the values for these Weibull parameters were finalized and processed to represent the baseline Weibull CDF for each component category. Figure 2 shows a typical Weibull curve based on the EOE results.

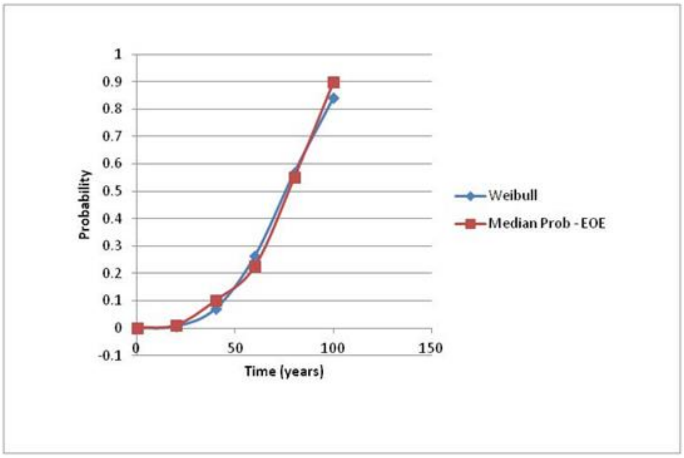

Figure 2 Example of Weibull Curve

The third and critical step is mapping the baseline Weibull Distribution function to the condition states for each baseline curve. This is estimated using the Maximum Likelihood Estimator (MLE) of the Weibull CDF. The MLE processing of the CDF shows where the points of inflection (slope is equal to zero) are over time and hence a resulting change of condition (e.g., A to B, B to C, etc…). The initial conditions for the MLE are tied to the Mean-Time-To-Failure (MTTF) for the Weibull Distribution of the C to D condition transition. Figure 3 shows the MLE for a typical component curve. This estimative mapping process is considered state-of-the-practice for both technical merit and mathematical soundness. The final mapping of condition to Weibull CDF is shown in Figure 4.

As additional OCA field inspection data is collected, the baseline Weibull Distributions estimated in Step 2 to be continuously updated through a Bayesian likelihood function process. These updated Weibull Distributions and their parameters will then modify the MLE in Step 3 for the mapping of new condition states with time. As additional field data is collected over the next few years, this estimative process will become very stable and a tolerable level of convergence should be obtained. This will result in well-defined Weibull Distributions and parameters for all component categories that will be useful for determining risk for USACE inland navigation projects.

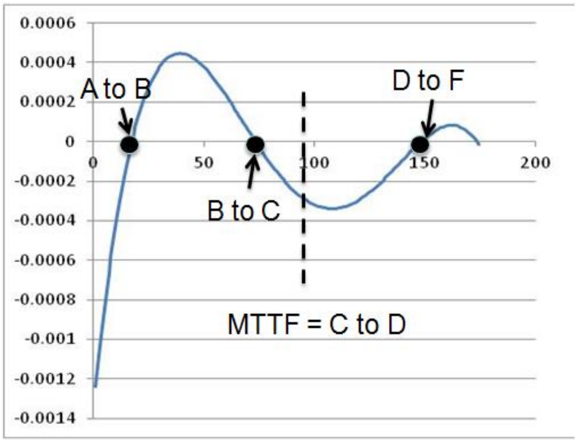

Figure 3 Maximum Likelihood Estimator for Weibull Function relating to OCA rating

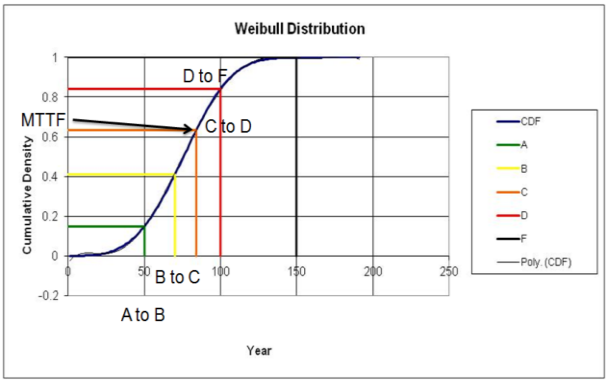

Figure 4 Mapping of Condition to Weibull CDF

2.3 Identification of Critical and Non-Critical Items List for ITMS Components

Patev and Putcha (2005) define the concepts of critical item lists (CIL) and non-critical item lists non-CIL. These account for the importance and redundancy of each component in the entire system such that the top level of analysis accounts properly for the criticality of each of the components in the system. This becomes very important in the utility theory since it is imperative that the value of each component or subsystem is rated based on its criticality to the total utility of the project.

A "critical" asset, or component, is defined in ISO 55000, "Asset Management," as "having potential to significantly impact on the achievement of the organization's objectives. If the failure of a component would cause a one day or longer unscheduled unavailability, it is by definition "mission critical." This is not to minimize impacts of unavailabilities less than a day in duration, but rather to focus on the much more impactful longer durations.

Criticality of Failure Mode	**Classification of Failure Mode**	**Weight (W_i)**
1/1	CIL (Critical Items List)	0.99
1R2	CIL (because it could result in loss of gate)	0.9
1R3	CIL or non-CIL	0.7
1Rn (n>3)	CIL or non-CIL	$0.7^{(n-2)}$
2/2	CIL	0.01
2R3	CIL or non-CIL	0.001
2Rn (n>3)	CIL or non-CIL	$0.001^{(n-2)}$
3/3	Non-CIL	0.001

Table 1 – Critical and Non Critical Items List (Patev and Putcha, 2005)

3 DEVELOPMENT OF UTILITY FUNCTIONS FOR IMTS MULTI-USE PROJECTS

3.1 *Background on Utility Concepts*

The development of utility theory dates back to the early 1700's with Daniel Bernoulli and Gabriel Kramer who are credited with the formal evolution of utility theory. The term utility was axiomized in 1944 by John Von Neumann and Oskar Morgenstern whose book on the theory of games and economic behavior is the backbone of modern microeconomics.

Utility can be defined as the desirability of preference that individuals or societies have for a given outcome. Utility functions are very simple in concept and can account for independence, dependence, conditional, and scaling as well as time effects. Utility mathematics are commonly termed Multi-Attribute

Utility Theory (MAUT) in which the utility is a function of both scaling factors and weights and attribute utility functions. References on MAUT and utility theory is made to Keeney and Raiffa (1971) and Keeney (1980)

Example of the attribute functions X_1 to X_3 are shown in Figure 5 below. The desirable states or preference is where the value of utility is unity. However, the value of preferences may not always be unity. This may be due to legal or other mandatory constraints or the preferences are developed and formulated for a problem by using a facilitator in discussions with experts that can define their preferences for the utility function.

In addition, utility functions can be both increasing utility and decreasing functions. They can also be convex or concave with illustrates if the utility defined by these experts is risk adverse or risk prone. The shapes of differing utility curves is shown in Figure 6

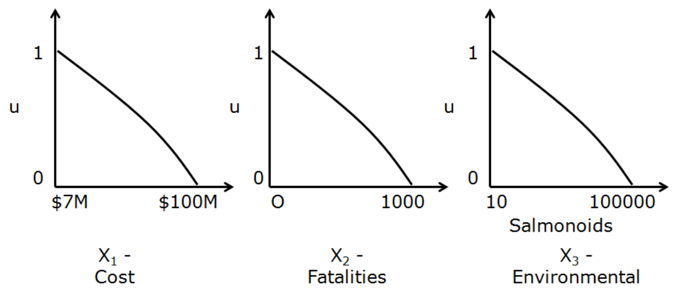

Figure 5 – Example of Utility Functions

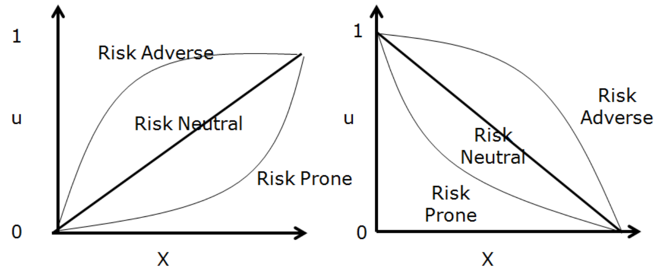

Figure 6 – Varying Shapes of Utility Functions

Another important concept in utility theory is the aspiration level. This is the level in which we can define the level of success or failure of a system. For example, if the goal of an IMTS system is to maintain 95 percent availability of the system then this could be the aspiration level required for a high use lock and dam project. A lower use project may require a lower aspiration level based on the acceptance of a lower availability level. A typical plot of utility and aspiration is shown in Figure 7.

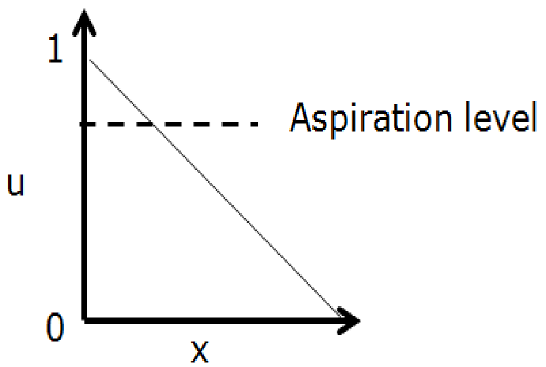

Figure 7 Utility and Aspiration Levels

3.2 *Development of System Fault Trees for IMTS Components and Systems*

As part of the Operational Risk Assessment and Utility Function process, system fault trees are developed from the top level down to components at each project. These fault trees are then populated with their condition rating and then their probability of failure for each component to give the availability and reliability of the top gate

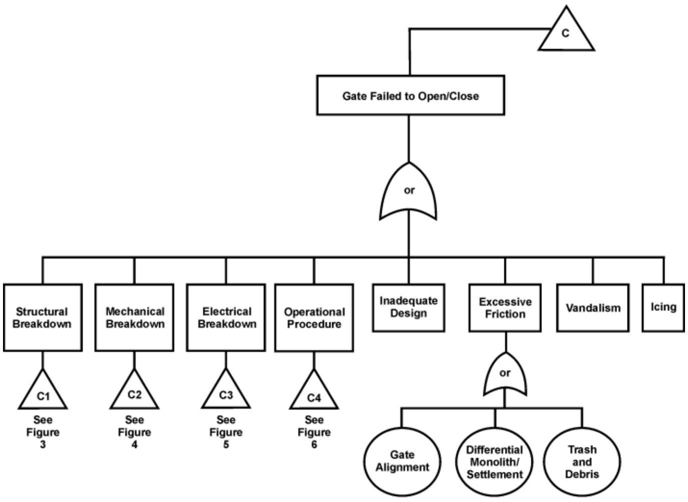

Figure 8 – Example Fault Tree for Dam Gate (Patev and Putcha 2005)

These fault trees and criticality (defined in section 2.3) are combined to determine the availability and reliability of the dam to function on demand. If all the equipment in the fault tree is in “A” condition then the expected utility will be 1.0. If all the conditions are in the D or F condition then the expected utility will be closer to 0. Therefore, as components in the system start to degrade and the condition starts to decline, the utility value starts to move away from 1.0 toward another system state over time. This degradation creates a lower performance level which may cause traffic disruptions and delays. The system state will eventually dip below the aspiration level for the project and indicate that there is required corrective maintenance or component renewal. This relationship is shown in Figure 9.

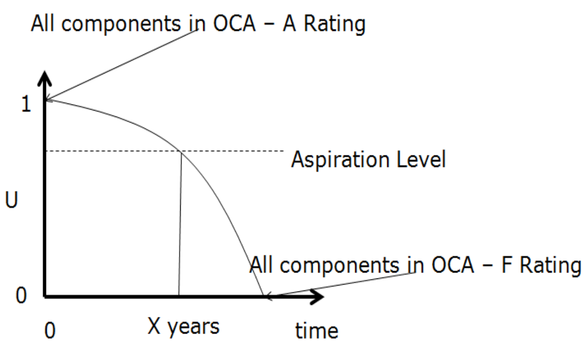

Figure 9 – Availability and Aspiration Level Over Time for a IMTS project

3.3 Utility Applied to Multi-Use Projects

With the development of the project component list and the fault trees, each component can be linked specifically to its utilization under various business lines. For example, a dam gate may be tied to navigation, flood control, water supply, environmental flows and hydroelectric power. USACE had many multi-use projects that may have a primary mission but with many important secondary missions as well.

Since utility functions are not agnostic to any business line, the use of fault trees can filter out the components that are used for the successful operation of each business line. This will greatly assist our decisions with knowing if the overall investment in a single component or system has an effect on the utility level for one, two or more business lines. A schematic from a project with hydropower (HYD), flood risk management (dam gates) and environmental flows (sluice gates) is show in Figure 10. This is a very valuable concept in trying to optimize the investment benefits under limited funding constraints.

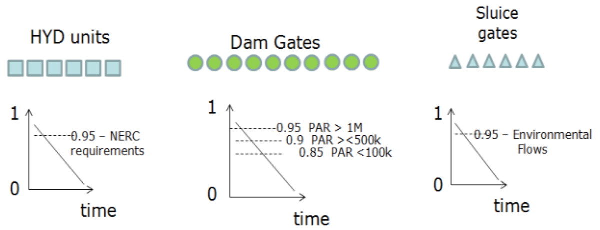

Figure 10 Schematic of Utility Across Business Lines for a Project

In addition, differing aspiration levels for each business lines can be established as well as cross business utility functions and total project aspiration levels. This is shown in Figure 11 where there are four business lines with their respective aspiration levels in red. Therefore, Figure 11 shows that we are still above aspiration levels for Flood Risk Management (FRM) and Environmental Flows (ENV), at aspiration level for Navigation (NAV) and below aspiration level for Hydropower (HYD). The fixing of HYD components could possible increase some of the other utilities such as FRM or NAV.

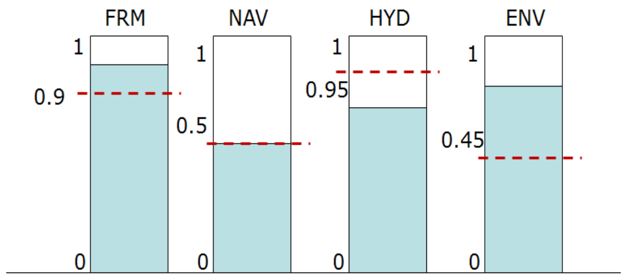

Figure 11 Differing Aspiration Levels for Business Lines

The application of utility theory is widely beneficial to the USACE IMTS as well as the entire USACE portfolio of assets across all business lines. The USACE Asset Management Program is currently in the process of developing and applying the utility methodology across six multi-use projects to define the requirements for future application in the AM business process.

4 CONCLUSIONS

The use and application of OCA, fault trees analysis and utility functions to the USACE IMTS will greatly assist with the USACE investment decision now and in the future. The ability to show how an infrastructure investment affects the entire project from a multi-use perspective is very critical to both improving performance and reliability on the aging infrastructure. The application of this method to the entire USACE portfolio will greatly assist with investment decisions now and in the future

REFERENCES

Dalkey, N. and Helmer O., An Experimental Application of the Delphi Method to the Use of Experts. United States Air Force Project Rand. The Project Rand. Santa Monica, CA 1962.

Ellsworth, D and Patev, R. "Risk Exposure and Informing Life Cycle Investment Strategies Across the U.S Inland Marine Transportation System" SMART RIVERS 2015, Buenos Aires, Argentina.

Keeney, R and Raiffa, H. "Decisions with Multiple Objectives: Preferences and Tradeoffs". Wiley and Sons 1976.

Keeney, R. "Siting Energy Facilities", Academic Press. 1980.

Patev, R and Putcha, C. "Methodology for Risk Analysis of Dam Gates and Associated Operating Equipment Using Fault Tree Analysis", ERDC Report TR-05-3. 2005.

USACE Engineering Pamphlet (EP) 1130-2-500.

USACE Engineering Circular (EC) 1110-2-6062.

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