

AACE International Recommended Practice No. 43R-08

**RISK ANALYSIS AND CONTINGENCY DETERMINATION
USING PARAMETRIC ESTIMATING – EXAMPLE MODELS AS
APPLIED FOR THE PROCESS INDUSTRIES**

TCM Framework: 7.6 – Risk Management

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January 26, 2009

INTRODUCTION

Scope

This recommended practice (RP) is an addendum to the RP 42R-08 titled *Risk Analysis and Contingency Determination Using Parametric Estimating*. It provides two working (Microsoft Excel®) examples of established, empirically-based process industry models of the type covered by the base RP. The example models are intended as educational and developmental resources; prior to their use for actual risk analysis and contingency estimating, users must study the reference source documentation and calibrate and validate the models against their own experience.

This RP summarizes two landmark empirically-based models; the “Hackney” model, first presented in John Hackney’s 1965 text *Control and Management of Capital Projects* (later expanded on in 1992, and now an AACE publication-reprinted 2002), and the later “RAND” model from 1981 research by Edward Merrow *et al.* for which Mr. Hackney was a consultant. These models posit plausible causal relationships between cost growth (i.e., contingency usage) and various risk systemic drivers such as the levels of development of process and project scope information and the level of process technology. They present similar empirical and quantitative analysis of the reasons for inaccurate estimates of capital costs and provide tools to improve assessment of the commercial prospects of projects at early stages of scope development and/or using advancing technologies. Prior to these models, the literature on the causes of cost growth for process plants provided little consensus about the relative contribution of various risk factors. Therefore, the authors of the source documents measured the factors and statistically assessed their relative influence on cost growth for process plant projects undertaken in North America. The results of their work had a significant impact on the practice of Cost Engineering and the evolution of project management phase-gate scope development systems (i.e., these studies are a basis of AACE’s RP on classification of cost estimates; RP 18R-98).

While this document attempts to summarize the basis of the models, it is highly recommended that users review the source documents before using the tools as a basis for their own study or development. Instructions for using the tools themselves are included in worksheets.

RECOMMENDED PRACTICE

Cautions

Empirical models, until validated with new data or analysis, cannot be assumed directly applicable to projects beyond the scope of those that form their empirical basis. The following describes the general model basis.

Project Types

Both of these models are based on actual project experience on process plant projects undertaken in North America from the 1950s through the 1980s. Process plant projects are characterized by having process mechanical and fabricated equipment at their heart, supported by a variety of structural, piping, electrical, control, and other scope elements. Piping tends to be the most significant cost driver for non-equipment costs. The model basis projects generally included both the process units as well as supporting outside battery limit and off-site components. The project types are common in the oil and gas, petrochemical, chemicals, hydro-metallurgical, power and other industries. The principles apply, but the actual models will be less applicable for projects with either little process equipment (i.e., buildings and

infrastructure) or projects where the equipment or machinery is dominant (e.g., dry processes with little piping, manufacturing, pyro-metallurgy, etc.).

Given that the basic nature of the engineering, procurement and construction business has not changed drastically since the 1980s (not considering market turmoil which was the case in the 1980s as well), it is felt that time has not diminished the value of the models much. **However, users should always validate the models with their own more current data. AACE would appreciate other researchers updating or expanding on the work of these pioneers.**

Data Ranges

There are many variables in these parametric models and the examples show the allowable entry ranges for each. However, users should take great caution in entering most or all of the variable values at their extremes. This would be extrapolating the models outside of the range of the empirical data and extrapolation generally provides poor results. For example, the Hackney model can have a maximum definition rating of 8498; however, it would have been rare for a project to have an overall rating of over 5000. Similarly, if all the variables in the RAND model are entered at their best possible defined rating, the outcome will be negative contingency which is generally not a recommended outcome (unless the base estimate is biased on the conservative side; an important consideration that is not addressed in the model).

Risk Ranges

These models are limited to assessing *systemic* risks or those risks which are driven by characteristics of the company's practices, the plant processes, the project system, and so on. Risks that are "project-specific" and have less commonality in occurrence or impact are not amenable to regression analysis. At early stages of scope definition (e.g., Class 5 or 4 estimates), systemic risks are the dominant drivers of cost growth. When definition is well defined (Class 3 or better), project-specific risks become more dominant and other contingency analysis methods such as range estimating or expected-value approaches are more appropriate. Note that for this RP, risk is defined as *the net impact or effect of uncertainty (threats – opportunities)*.

RAND MODEL

Background

The RAND model resulted from research done under contract with the US Department of Energy (DOE) to study the cost and performance problems on pioneer process plants. The RAND study authors used cost engineering knowledge of the day (such as documented in the Hackney model with its focus on the level of scope definition and the level of technology as major drivers of cost growth) and RAND client input as a starting point for their work. Being more current than the Hackney work and reflecting a more robust statistical sampling and analysis approach, the RAND model is summarized here first.

The RAND study collected planning and cost performance information on actual completed pioneer process plants in North America and used regression analysis techniques to find causal drivers of cost growth. A dataset of 106 estimates from 40 plants were used in the final model. The RAND report presents several models that were statistically significant. The study found that the following project and estimate characteristics were most significantly related to cost growth:

Level of New Technology

It had been observed in industry that unforeseen design, engineering, construction or start up problems occurred when a process plant used commercially unproven technologies. These project problems often require extensive redesign or repair during project execution. The "newness" of technology was conceived in the study as a continuum, ranging from completely standard technologies being

commercially replicated processes, to scale up of a process only demonstrated in a pilot or research facility. The RAND study tested various quantitative measures of this continuum of technology as cost growth drivers. They found that the relative proportion of the total plant cost invested in process steps using commercially unproven technologies had the highest correlation with cost growth. This variable was called PCTNEW.

Impurities

Another industry observation was that the level of technical difficulty encountered during research and development (R&D) and early process development appeared to be correlated with problems experienced in later project design, construction and startup. In particular, cost growth showed an ascending relation with the presence of IMPURITIES (associated with buildups and corrosion) in the feedstocks or process streams, particularly for processes that involve catalysts or extensive recycle.

Project Definition

The amount and quality of project information used as a basis of the estimate was shown to be strongly correlated with cost growth. The measure found to have the best correlation was a combination of the level of engineering definition accomplished prior to the estimate and the average degree of definition of the following four site information elements: on-site and off-site unit configurations (plot plans), soils/hydrology data, environmental, and HSE requirements. A composite variable called PROJECT DEFINITION was constructed by rating the definition of each on a 4 point scale, computing the average value of the four site information variables, and adding level of engineering rating to that average.

Other Variables

While the above variables were dominant, other cost growth drivers were identified and included in the model. These included:

PLANT COMPLEXITY: a count of the number of continuously linked process steps or block units in the plant. When there are more linked process steps, there is more chance of overlooking process issues and problems which tend to cascade and sometimes compound through the process flow.

INCLUSIVENESS: if the base estimate excludes certain costs that tend to happen, more cost growth can be expected. The variable used in the model is the percentage of three commonly needed, but excluded, elements in the base cost estimate, each scored as 1 if included and 0 if not: (e.g., if 1 of 3 items is included, variable is 33.3 percent)

- land purchase/leases/property rentals,
- initial plant inventory/warehouse parts/catalysts,
- pre-operating personnel costs.

R&D: The interaction of the level of technology and project definition was found to add a compounding affect on cost growth. This effect was captured by including the PROJECT DEFINITION variable a second time with a separate coefficient if the process technology was still in R&D phases at the time of the estimate.

Overall

Each variable had an independent and statistically significant effect on the cost growth, could rationally be considered causal, and together accounted for 83 percent of the total variance in the sample dataset cost growth (project-specific risks likely explain much of the residual). The final model takes the following form:

$$\text{COST GROWTH} = a - X1*\text{PCTNEW} - X2*\text{IMPURITY} - X3*\text{COMPLEXITY} + \dots \\ \dots + X4*\text{INCLUSIVENESS} - X5*\text{PROJECT DEFINITION} - X6*\text{PROJECT DEFINITION (if in R\&D)}$$

Where:

a = intercept

X = estimated regression coefficients

COST GROWTH = base estimate (excluding contingency) costs divided by the final actual costs
(normalized for escalation and major scope change)

While most estimators calculate cost growth factors as actual/estimated costs, it was found the inverse has a more normal distribution as appropriate for regression analysis. More information on these variables can be found in the example tool.

The overall model of cost growth is shown graphically in Figure 1 for a typical dataset project for varying levels of project definition. Keep in mind that the cost growth shown here is expressed as of estimate/actual (less cost growth at top of chart) and definition improves with a lower rating (less definition at right of chart).

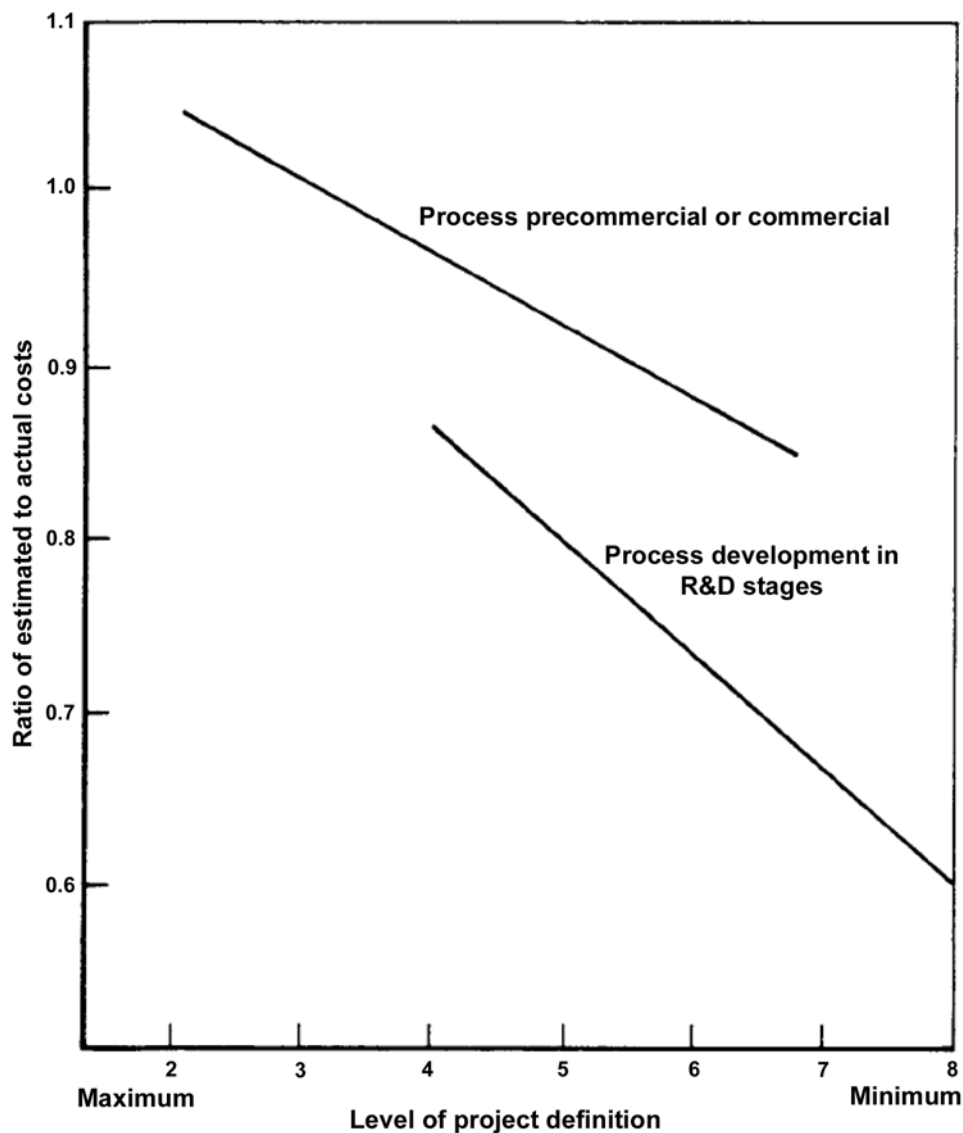


Figure 1. RAND Model of Cost Growth vs. Project Definition
(Used with permission from RAND Corporation)

Range

The RAND model did not provide a specific model for accuracy range. However, users can refer to the methods in recommended practice No. 42R-08, *Risk Analysis and Contingency Determination Using Parametric Estimating* for estimating the range using the concept of contingency as the standard deviation. Another approach used has been to incorporate the RAND model in a Monte Carlo simulation, replace the parameters with distributions with min-max values as shown in the RAND report, and use the resulting outcome as a representation of the range in terms of percentages.

HACKNEY MODEL

Background

John Hackney has been credited as being the first to publish (in 1965) an empirically-based parametric model of cost growth recognizing the significance of the level of project definition and technology as key risk drivers at the time of project funds authorization. Mr. Hackney was a consultant to the later RAND work covered above, and he continued to improve his own methods as he gained more information after the RAND work was published. Cost engineers had long recognized that one of the greatest single risks producing deviations of actual costs from early estimates was the difficulty of anticipating, at the time of the estimate, all of the physical installations, essential features, site and market characteristics, and practices required to accomplish the project. Mr. Hackney, using actual data from his extensive industry experience with owner and contractor companies, developed a systematic way to model the relationship of definition risk and cost growth. This RP reflects his model and definition ratings index circa 1990 as included in the 1992 2nd edition of his text *Control and Management of Capital Projects* (in reprint by AACE, 2002).

The risk drivers included in Mr. Hackney's definition rating scheme is much more extensive than that in the RAND model because not every factor was tested statistically (only the overall resulting ranking was tested). The RAND study model only included items that passed tests of statistical significance for the study dataset. The individual items in the Hackney list are therefore more speculative. However, there is general consensus that if the items in the Hackney list are not well defined for a project, there will be increased risks. The Hackney details add color and understanding to the short list of RAND factors; therefore it was felt that it was of value to provide users with both models to consider. At the bottom line, the two models yield similar cost growth results.

Definition Rating

In order to model the cost growth and its relationship to the state of project definition at the time an estimate is prepared, it is necessary to establish a quantitative rating for the definition status. As an approach to this problem, Mr. Hackney developed a project definition checklist with six principal categories of scope information. These categories, as detailed in the attached spreadsheet model, are summarized as follows (users should always refer to the source text for complete definitions):

General Project Basis

This category originally included three primary elements: product and by-products definition, raw materials definition, and process background definition (i.e., the state of development of the process or newness of process technology which is a major risk driver). In 1990, a category for definition of "utilities and services" was added. Also, an "ownership factor" was added to reflect the tendency for public sector (or mixed ownership) projects to experience more cost growth.

Process Design

This category includes four primary elements: flow balances, major equipment types, material of construction, and who reviewed the design basis. In regards to reviews, it has become more apparent

that team involvement (including operations and construction) in determining and agreeing on the scope is important to reducing risks.

Site Information

This category includes a large number of elements that have to do with defining the site environment and conditions. These include: surveys (including soils), studies of the state of reusable equipment and supports, building, utilities and yard improvements, weather, and status of local regulations. In 1990, items were added or re-weighted to address wind and earthquake conditions, increased emphasis on environmental, health and safety conditions, and review of the site by the construction group.

Engineering Design

This category includes a large number of elements involving the status of basic engineering. These include layouts, line diagrams, equipment, buildings, yard improvements, hazard control, coatings, and review of the engineering by research and operations. In 1990, an item was added for “control centers and computers,” including both hardware and software as these elements became more complex over time. Many other items were modified slightly. Again, emphasis on review of the engineering was increased in weight by adding review by regulatory authorities and construction.

Detailed Design

This category includes a limited number of elements regarding detail drawings and their review. The weight on these items is fairly limited because most of the risk drivers have been addressed before production design begins. As with engineering design, there is increased emphasis on “construction” review because it has been found that difficulties often are uncovered by their review of the detailed drawings.

Field Performance

This factor is a constant for estimates prepared prior to project authorization when no field work has been done. However, Mr. Hackney envisioned that this cost growth model would be reapplied during project execution as part of ongoing risk management. As most of the preceding scope and design definitional risks became null or moot during construction execution, the field performance would represent most of the residual systemic risk.

Figure 2 shows the recommended rundown pattern for reduction of the 50 points for “field performance” as the percentage completion of field labor advances. This provides for a slow rate of reduction early in the construction period and a more rapid rate only during the closing phases of the project. This is to recognize that until the man-loading gets near its peak and more skilled trades join the work, performance will not be well understood and therefore there is a necessity for holding contingency funds for performance in this early period.

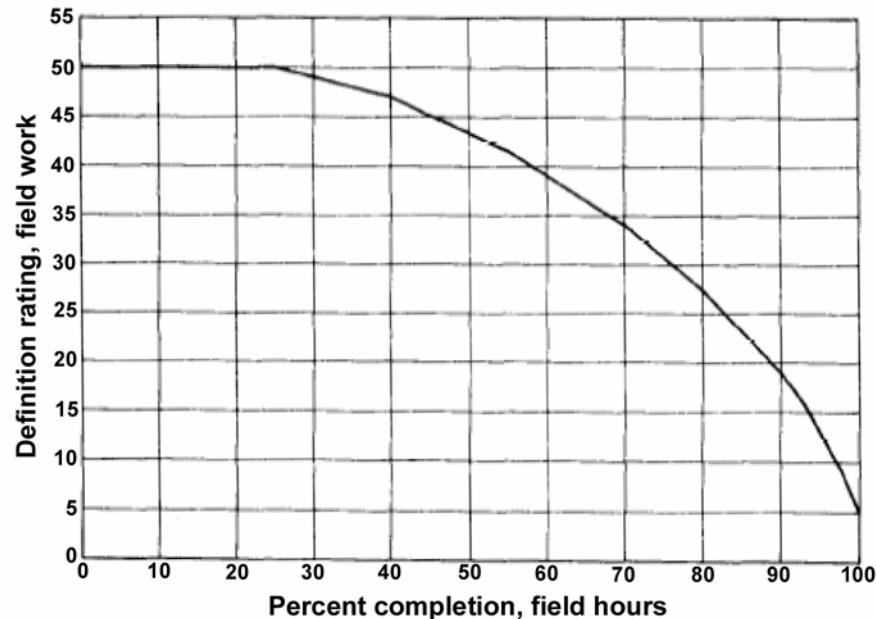


Figure 2. Drawdown of the Field Performance Rating (Hackney)

Rating Each Item

In the ratings checklist, each item was given a maximum weight to indicate the general potential degree of uncertainty produced in the overall project if that particular item is completely unknown or undefined. Complete and full definition, or non-applicability of the item is indicated by zero. Although the assignment of weights is highly subjective, they represent the sort of impact which might be expected if the item in question were completely misjudged. In weighting, highest values are given to items such as process background and raw material information, because lack of definition with respect to such items can have the most serious effects on project cost. Other items such as sanitary sewer design for example-are given low weighting, since, for process projects, they have a relatively minor effect. This weighting is generally consistent with the RAND findings as Mr. Hackney went back and updated his model after the RAND study was released.

When information for an item has not yet been established, the maximum rating is entered on the checklist. If design or other definition work is partially completed, the item's definition rating is proportionately reduced from the maximum value. It has been found by experience that lack of definition of items in the "general project basis" section will produce uncertainties in subsequent design work. Therefore the rating of this section is used, not as an additional item, but to establish a multiplier for the sum of the ratings of the other five sections.

Considerable judgment is involved in using the checklist, and opinions as to rating individual items will differ. However, when reasonably experienced individuals separately rate a job, Mr. Hackney found their rating *score* results can be expected to agree in total within about +/- 10 percent. The definition rating, therefore, can be used as a valuable quantitative indication of the degree to which a project is "pinned down" at a given stage of development. Furthermore, consideration of individual ratings on the detailed checklist brings out those points where lack of definition presents the greatest potential threat. These items can be given priority in further definition of the project.

Basis For Contingency Allowances

Contingency allowances are established in order to compensate for the uncertainties which can be produced by all the factors previously discussed. The most dependable guide in establishing proper

contingency allowances is experience from past projects. To organize and analyze this experience, actual versus estimated cost was tabulated by Mr. Hackney for all estimates for all company projects of record. To bring the data to a common basis, any contingency allowances already in the estimates were eliminated. Corrections were made to compensate for valid overall project scope changes, such as changes in plant capacity or type of product which were made after the estimate was prepared.

When the percentage overruns of estimates is plotted against the definition rating at the time of estimate, the points have considerable scatter, but the dominance of the relationship between definition ratings and overruns is readily apparent. The inescapable conclusion is that estimates made in the very early phases of a project while research and development are in progress and before project definition is complete (and particularly while research and development are in progress) cannot possibly prove highly accurate, because the project estimated is seldom or never the same as the project built although it is within the overall project scope as agreed with business.

The data on Figure 3, which includes information from about 30 projects from several companies in Mr. Hackney's experience, indicates that there is a bias toward underestimating the cost of partially defined projects. On the average, additional requirements are uncovered as the design advances toward complete definition. It is only occasionally that features included in early estimates are found to be unnecessary.

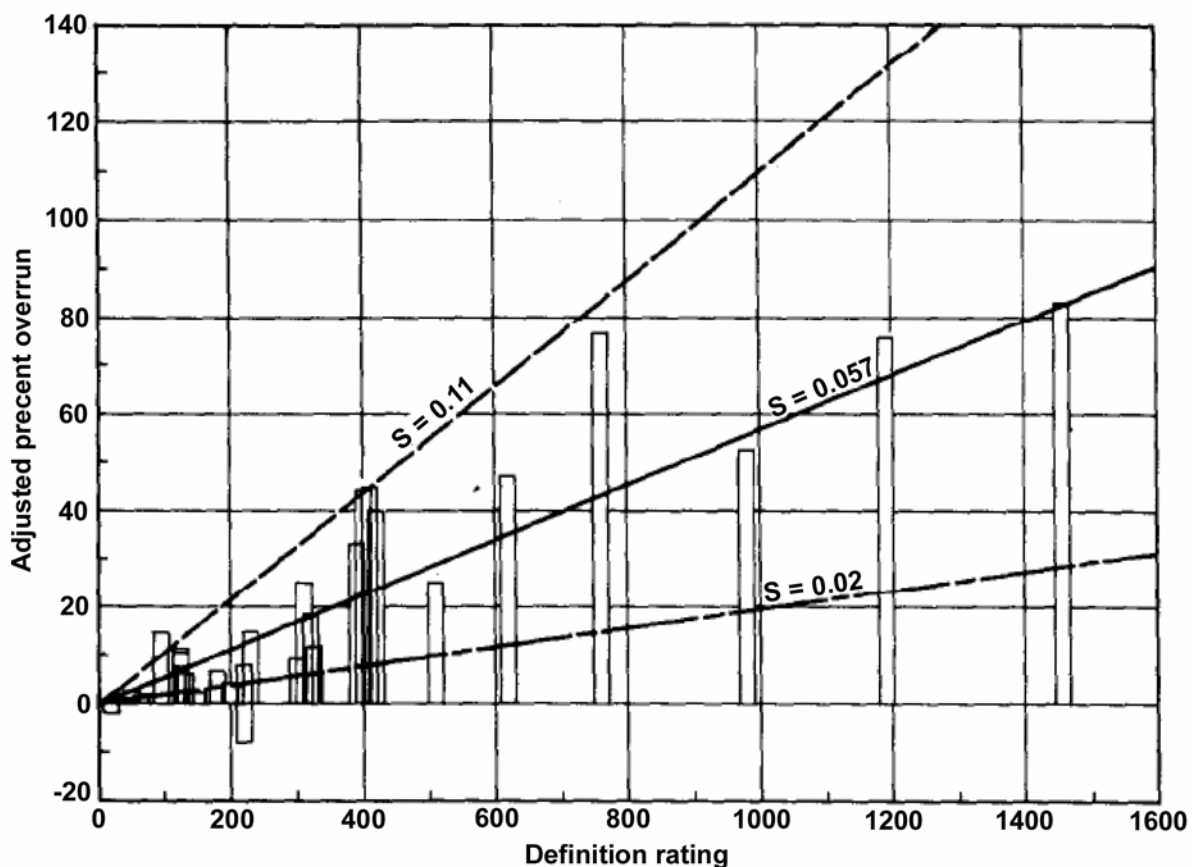


Figure 3. Hackney Model of Cost Growth Versus Definition Rating (Hackney, 1997)

Computing Contingency Allowances

Figure 3 is shows the relationship of cost growth and project definition with the definition rating on the X-axis and adjusted percent overrun or excess of actual costs over bare estimates without contingency

allowances on the Y-axis. Three lines are drawn; the intermediate line represents the slope where half the bartops are below and half above. The upper and lower slope lines represent the 80 percent accuracy range where 10 percent of the bar tops are above the upper slope and 10 percent of the bartops are below the lower slope.

If the value of “S” for the lower slope (0.02) is applied to the definition rating for a project at a given stage of its development, the result is the **allowance for unlisted items**. Very rarely will a contingency less than this be required. If the intermediate value of S (0.057) is applied to the definition rating for a project at a given stage of its development, the result is the **even-chance contingency allowance** percentage which added to the base estimate without contingency allowances, will provide a 50/50 chance of the actual cost overrunning or underrunning the estimate.

The statistical distribution of the historical data can also be confirmed in general terms by comparisons to the findings of the RAND study. Calibration to a corporation’s own data is recommended. The methodology can be utilized with more assurance if it reflects a company’s own experience as well as the experience of others.

Historical Accuracy Range Computation

Mr. Hackney developed range information from his data. For statistical computation, it is desirable to work with normally distributed data. Near-normal distributions are obtained if accuracy ranges are converted from terms of deviation of actual costs from estimates, to deviation of estimates from actual costs (i.e., estimate/actual). When the data is inverted in this way, accuracy ranges about the even-chance or median estimate become “balanced,” that is, the plus side of the range has approximately the same absolute value as the minus side.

To address the fact that in his data, some escalation had occurred from the time of estimate preparation to actual completion, Mr. Hackney adjusted this factor out from the data. The forecasting accuracy correction formula is provided in the attached Hackney tool based on typical escalation rates.

The statistical calculations used by Mr. Hackney are shown in full in the example worksheet. More information will be found in Mr. Hackney’s text and technical papers referenced by this RP. The project cost accuracy range so computed is a balanced, normal range of percentage deviations of even-chance estimates from actual costs. In project work, however, it is customary to think of overruns in terms of percent deviations of actual costs from estimates. To present data in these terms, it is necessary to invert the range of estimate deviations from actual costs to obtain the range of deviations of actual costs from estimates and the tool makes that inversion.

Using the 80 percent confidence or 0.8 range as a measure of estimate accuracy is useful because it is a relatively simple, statistically viable concept that most consider a practical range. One-tenth of the estimates will be outside this range on the high side, and one-tenth on the low side. However, some people prefer to quote results on a standard deviation basis. In that case, the 0.8 range for normally distributed data is a range of 1.28 standard deviations (i.e., the standard deviation of the data can be computed by dividing the 0.8 range values in percent of actual by 1.28). The tool provides ranges in both ways.

Contingency Allowance Alternates

The contingency allowance alternates are computed in the attached spreadsheet as both percents of the base estimate and in millions of dollars. (or the base estimate currency). Currency effects are not included in contingency). The ranges and contingency allowances are provided as follows:

The **estimate with Minimal, 90% Overruns Allowances** can be used as rock-bottom “budget amount” for project cost control as a possible, but not very realistic target as projects of record have been met only

1 time out of 10. Bettering this record can be an objective of the project team, but only when the company culture is not punitive, as the team is unlikely to achieve this objective.

The **estimate with Even Chance, 50% Overruns Allowances** will be the best all-purpose estimate which can be provided until project definition can be improved. Assuming an unbiased management risk appetite, this amount should be submitted for approval by corporate or other spending authorization bodies. The organization responsible for project performance should be authorized to spend up to this amount without referral to the appropriating authority unless there is a scope change.

The **estimate with Not To Exceed, 10% Overruns Allowances** can be used as a practical worst case value during scoping studies and profitability analysis. This upper limit will be exceeded only 1 time out of 10.

CONCLUSIONS

This RP summarizes two industry models for predicting project cost growth and for estimating contingency and accuracy ranges for systemic risks. Both the RAND and Hackney models are based on empirical data and research that has shown that projects authorized on the basis of poor project definition and/or using commercially unproven technologies are biased low. Models of the type covered in this RP can be used to address this bias.

The concepts and models are somewhat complex, so it is imperative that users refer to the source materials before applying these tools. Also, consider their range of applicability. Taken verbatim the tools are excellent for educational purposes, allowing a user to interactively see and gain an understanding of the impacts of various definitional risk factors. Prior to using the tools for actual project contingency estimating, it is recommended that users calibrate the tools for their own project experience.

ATTACHMENTS

For example models, see 43R-08_Models.xls (MS Excel file)

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