Calculating Project Contingencies to Avoid Software Project Failures

Eduardo Miranda and Alain Abran

This article posits that project contingencies should be based on the amount it will take to recover from the underestimation and not on the amount that would have been required had the project been adequately planned right from the beginning. The model proposed takes into account not only the magnitude but also the time at which the underestimation is acknowledged.

There seems to be a general misunderstanding to the effect that a mathematical model cannot be undertaken until every constant and functional relationship is known to high accuracy. This often leads to the omission of admittedly highly significant factors (most of the 'intangible' influences on decisions) because these are unmeasured or unmeasurable. To omit such variables is equivalent to saying that they have zero effect. Probably the only value known to be wrong.

– **Jay Forester, 1961**

Introduction

It is not the same:

- To start a 12 months project or to start a six months' one and later extend it by another six months.
- To start a small product or cut into half a large product during the middle of the project to meet the deadlines.
- To start a project with the right amount of people or to add resources anytime later.

The effort to recover from the underestimation would depend at least on two parameters:

- The magnitude of the underestimation; and
- The time at which the recovery action is initiated.

Mathematically this could be described as:

$$<1>\ Contingency = \iint RecoveryCost(u,t)\, p(t)\, p(u)\, dt\, du$$

Equation <1> above states that contingency funds must equal what it would cost to recover from an underestimation of magnitude *"u"* acknowledged at a time *"t"* by the probability of *"u"* and the probability of *"t"*, that is the probability of experiencing an underestimation of magnitude *"u"* and the probability of acting on it in month *"t"* relative to the start of the project.

By including in the project cost any expected recovery efforts, the following benefits could be realized [1]:

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- Better profitability decisions, by avoiding the winner's curse associated with low cost bids and highly leveraged projects.

- Reduced cost of capital, as budgets could be based on expected risks rather than on worst case scenarios for all the projects.

As shown by Figure 1 contingency funds are used to address the project's residual risk. Specific perils would be addressed using risk mitigation, avoidance or transfer as customary.
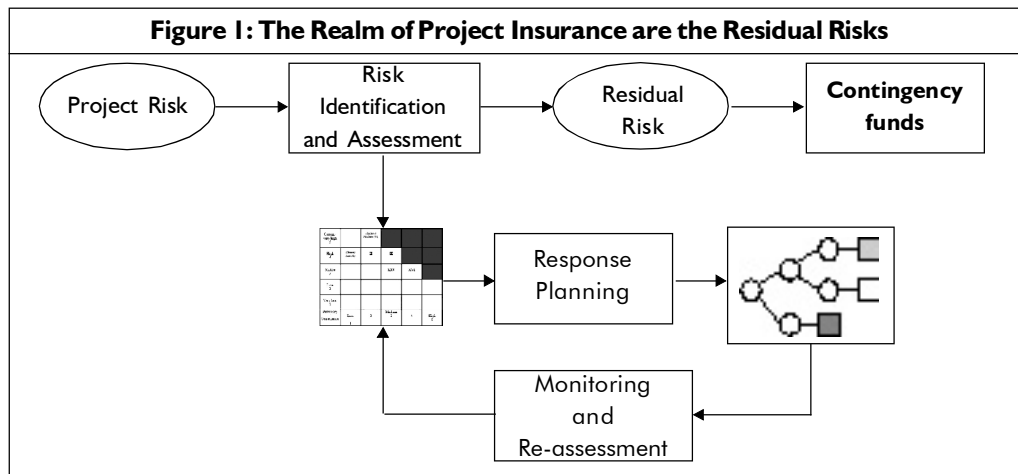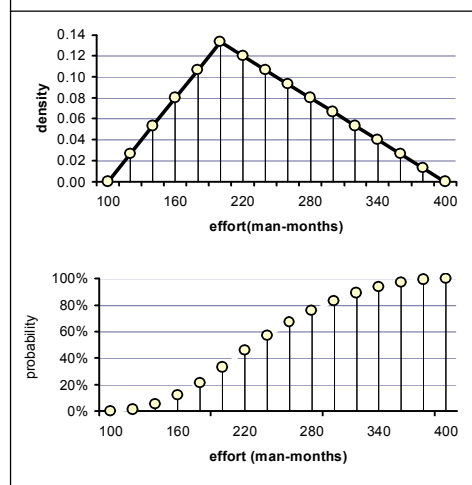
Figure 1: The Realm of Project Insurance are the Residual Risks

Figure 2: Effort Density and Cumulative Distributions

The estimate of a software project is a range of values, (see Figure 2) within which an organization believes it is possible to achieve the objectives of the project with a defined probability. Although other distributions are possible, the reasons for selecting a triangular distribution will be given later.
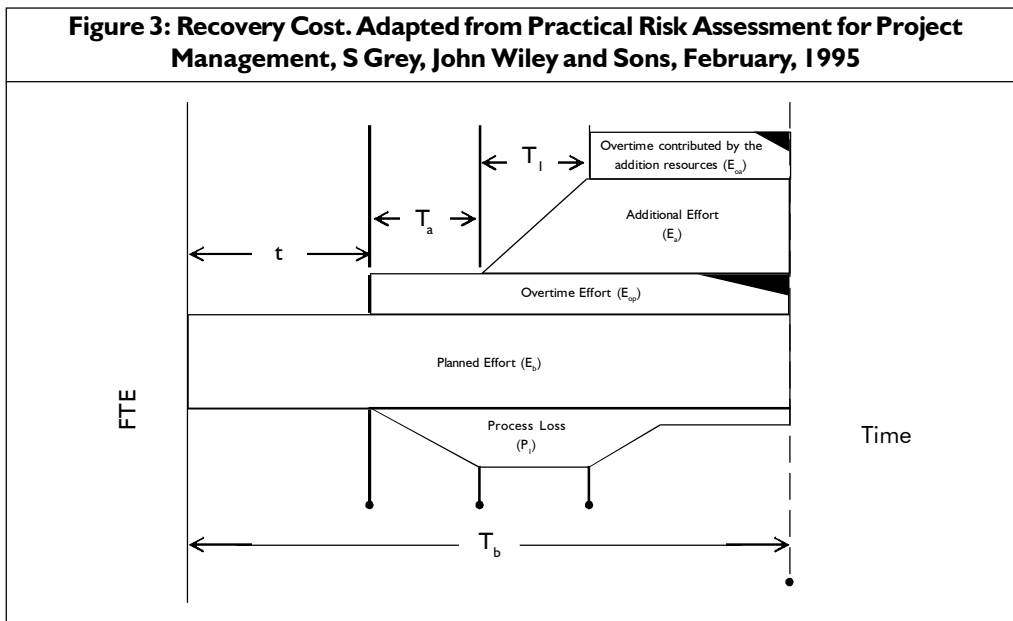
What would happen if the budget allocated to this project is, for example, 180 man-months? What is the probability of finishing within budget? What would be the effort necessary to recover from the underestimation assuming that we don't want to delay the delivery date or cut scope? What would be a fair way to calculate an insurance premium for this project?

From Figure 2, the probability of finishing the project in 180 mm or less, is 20%, so the probability of being overbudget is $(1 - 0.2) \times 100 = 80\%$.

Calculating the Number of Additional Resources

Figure 3 illustrates the effort to makeup in a project under recovery:

- The planned effort (E_b) is the amount of effort originally budgeted for the project, it is the product of the time budgeted (T_b) and the original staff (FTE_b). "t" is the time at which the underestimation is acknowledged and a decision to do something about it finally made.

- The additional effort (E_a) is the effort that will be contributed by the resources brought in to help recover from the delay.

- The sloped left side of the quadrilateral model the fact that there will be a certain time (T_l) before the new staff becomes fully productive.

- "T_a" is the mean time since the decision to bring in new people is made and the time at which the new staff arrives.

- The overtime efforts (E_{op} & E_{oa}) are contributed through overtime by both, the original and the additional resources. Overtime efforts are affected by fatigue as modeled by the dark triangles on upper right corners.

Figure 3: Recovery Cost. Adapted from Practical Risk Assessment for Project Management, S Grey, John Wiley and Sons, February, 1995

- The process loss (P_l) includes all the extra effort: Ramp-up, coaching and communication overhead imposed in the original staff by newcomers.

Mathematically, the effort required to recover from an underestimation (u) would be equal to the effort that could be contributed through the overtime of the original staff (E_{op}), plus the effort of those brought into help (E_a) and the overtime of the newcomers (E_{oa}), less the effort necessary to compensate for the losses during process (P_l).

<2> $u = E_a + E_{op} + E_{oa} - P_l$

Effort, whether from the original or the additional staff of the project, would be calculated as the product of Full-Time-Equivalent (*FTE*) resources and the period (*T*) on which those resources are applied to the project. Other efforts, like for example the losses due to the need to further decompose the work, communication overhead, the initial tutoring of new project members and the extra integration effort, would follow the same general form $(E = FTE \times T)$ but will be multiplied by co-efficients designed to quantify the concepts.[1]

The effort contributed by the additional staff would be then:

<3> $$E_a = FTE_a \times (T_b - t - T_a) - \frac{FTE_a T_l}{2}$$

The term $\dfrac{FTE_a T_l}{2}$ accounts for the learning effort of the new staff.

The effort available through overtime is modeled as percentage of the overall available effort less a productivity loss due to fatigue arising at a time "*Lag*" after the decision to utilize overtime is made:

<4> $$E_{op} = C_o FTE_b \left[T_b - t - \frac{C_d \left(T_b - t - Lag\right)^2}{2} \right]$$

<5> $$E_{oa} = C_o FTE_a \left[T_b - t - T_a - T_l - \frac{C_d \left(T_b - t - T_a - T_l - Lag\right)^2}{2} \right]$$

The process losses will be modeled as:

<6> $$P_l = \frac{C_r \times FTE_a \times T_l}{2} + \frac{C_c \times FTE_a \times T_l}{2} + \frac{C_i \times FTE_a \left(FTE_a + 2 \times FTE_p - Teams\right)\left(T_b - t - T_a\right)}{2 \times Teams}$$

The constants $C_r, C_c \ \& \ C_i$ stand for the ramp-up, coaching and interaction factors. Justification for these choices will be provided in Section 4.

Substituting the terms $E_a, E_{op,}, E_{oa} \ \& \ P_l$ in equation <2> by <3, 4, 5 & 6> we obtain:

<7>
$$FTE_a^2 \left[\frac{C_i \left(t + T_a - T_b\right)}{2 Teams} \right]$$

$$+ \frac{FTE_a}{2 Teams} \left[-Teams \left[\begin{matrix} 2\,t + 2T_a + T_l + C_c\,T_l + C_r\,T_l + 2\,C_o\left(t + T_a + T_l - T_b\right) \\ + C_d\,C_o\left(lag + t + T_a + T_l - T_b\right)^2 - 2T_b \end{matrix} \right] + C_i\left(2\,FTE_b - Teams\right)\left(t + T_a - T_b\right) \right]$$

$$- \frac{FTE_b \left[2C_o t + C_d C_o \left(lag + t - T_b\right)^2 - 2\left(1 + C_o\right)T_b \right]}{2} - u = 0$$

Equation is an equation of second degree for which general solution is:

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[1] Other forms are possible at the expense of more complicated expressions based, perhaps, on hypothesed parameters reason why any anticipated accuracy gain must be carefully assessed against the added

$$FTE_a = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$
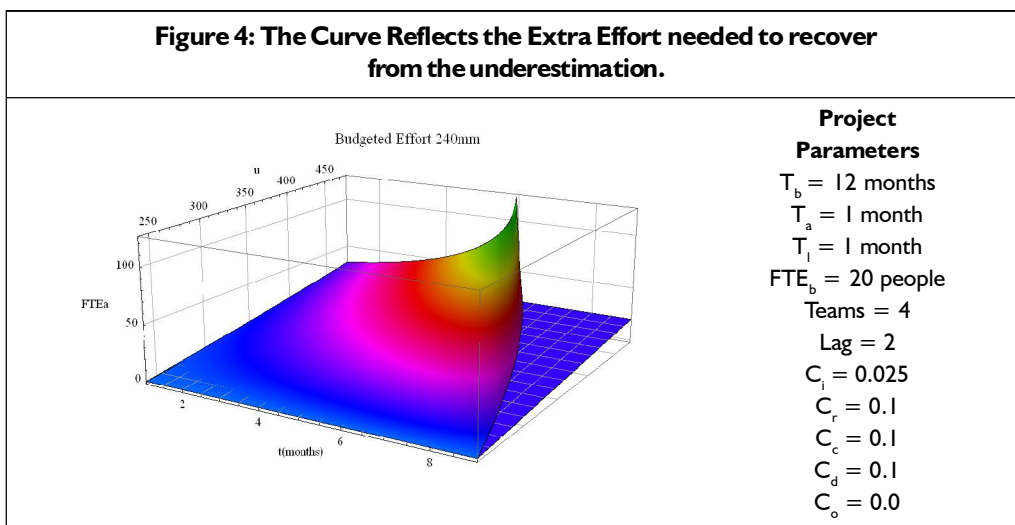
So by renaming

$$a = \frac{C_i\left(t + T_a - T_b\right)}{2\,Teams}$$

$$b(t) = \left[\frac{-Teams\left[\begin{array}{c} 2t + 2T_a + T_l + C_c\,T_l + C_r\,T_l + 2\,C_o\left(t + T_a + T_l - T_b\right) \\ + C_d\,C_o\left(lag + t + T_a + T_l - T_b\right)^2 - 2T_b \end{array}\right] + C_i\left(2\,FTE_b - Teams\right)\left(t + T_a - T_b\right)}{2\,Teams}\right]$$

$$c(u,t) = \frac{FTE_b\left[2C_o t + C_d C_o\left(lag + t - T_b\right)^2 - 2\left(1 + C_o\right)T_b\right]}{2} - u$$

We obtain:

$$<8>\ FTE_a\left(t,u\right) = \frac{-b(t) + \sqrt{b(t)^2 - 4a(t)c(u,t)}}{2a(t)}$$

This is the number of additional resources, (see Figure 4) required to maintain a predefined schedule as a function of an underestimation on the original effort planned for the project and the time at which it is acknowledged. The curve reflects the extra effort needed to recover from the underestimation. Right back upper corner is the region that motivated Brooks' famous admonition that adding a person to a late project makes it later. Lower plane shows effort if originally planned.

Figure 4: The Curve Reflects the Extra Effort needed to recover from the underestimation.

Budgeted Effort 240mm

Project Parameters
T_b = 12 months
T_a = 1 month
T_l = 1 month
FTE_b = 20 people
Teams = 4
Lag = 2
C_i = 0.025
C_r = 0.1
C_c = 0.1
C_d = 0.1
C_o = 0.0

The function is valid only if additional resources are required, that is the underestimation is greater than the effort that can be provided through the use of overtime alone and if the decision to bring the additional resources is made on time. If the losses, for example due to high $C_r, C_c, \& C_i$ values, are greater than the effort that could be generated in the remaining time $(T_b–t–T_a)$ the equation has no real solution, the solution is an imaginary number and indication that under the circumstances it would be impossible to maintain the schedule no matter how many people you add.

Calculating the Cost of Recovery

The cost of recovery comprises the cost incurred through the overtime of the original staff and the cost, if needed, additional resources and their overtime. Sometimes the additional staff should be considered at a different rate as they are temporary. The parameter in equation refers to the proportion of consultants or temporary workers employed in the project.

$$<9> \quad Recovery\,(u,t) = \begin{cases} R_o\left(u - T_b FTE_b\right) & if\ \ u \le FTE_b\left[T_b + C_o\left(T_b - t\right)\right] \\[2em] \begin{aligned} &R_o C_o \times FTE_b\left(T_b - t\right) \\ &+ \left[\left(1 - temp\right)R_n + temp \times R_t\right] \times FTE_a\left(u,t\right)\left(T_b - t - T_a\right) \\ &+ \left[\left(1 - temp\right)R_o + temp \times R_t\right] \times C_o \times FTE_a\left(u,t\right) \times \left(T_b - t - T_a - T_l\right) \end{aligned} & otherwise \end{cases}$$

$$R_n = \text{Normal Rate}$$
$$R_o = \text{Overtime Rate}$$
$$temp = \text{Proportion of temporary personnel to be employed}$$
$$R_t = \text{Temporary personnel rate}$$

Losses during Process

The addition of unplanned resources midway through project will result in one or more of the following:

- Need to breakdown the work on additional segments so that it can be allocated to the newcomers.

- Need to coach the new staff.

- Additional integration work.

- Additional coordination effort.

The additional work is captured by equation <6> above. The first two terms of the equation:
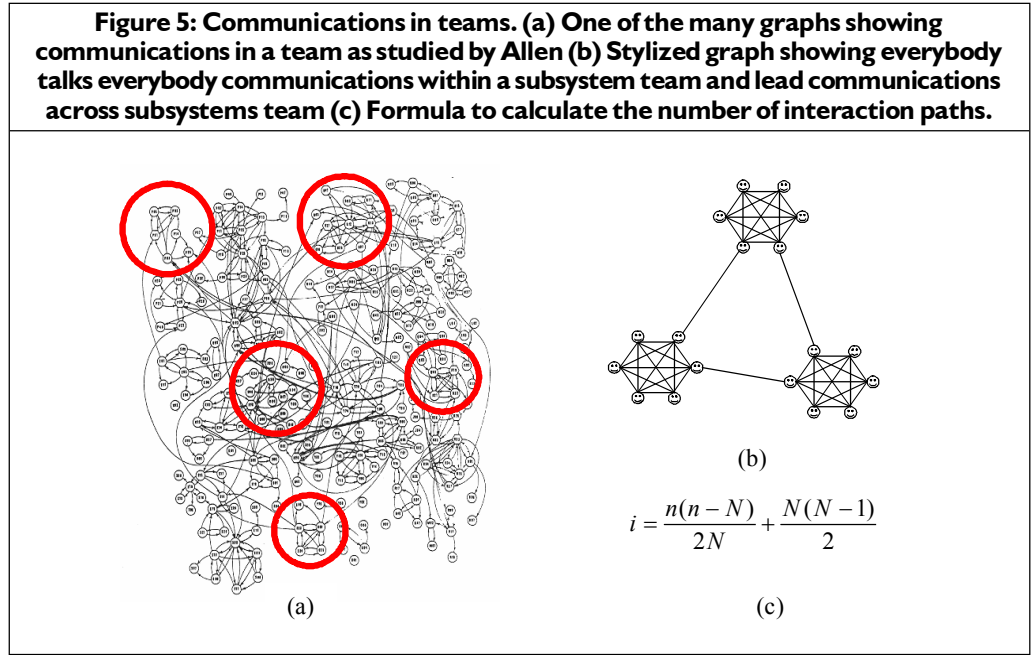
$$\frac{C_r \times FTE_a \times T_l}{2} \ \& \ \frac{C_c \times FTE_a \times T_l}{2}$$

Model the ramp-up process leading to the incorporation of the newcomers and the effort spent by the original staff coaching them. Both efforts are modeled as triangular areas.

The third term:

$$\frac{C_i \times FTE_a \left(FTE_a + 2 \times FTE_p - Teams \right)\left(T_b - t - T_a \right)}{2 \times Teams}$$

Models the extra effort spent coordinating the activities of the extended team and while a full discussion of the formula it is out of the scope of this article it is based on the findings of Thomas Allen[2], see (Figure 5a) and in a previous work by Miranda[3].

Figure 5: Communications in teams. (a) One of the many graphs showing communications in a team as studied by Allen (b) Stylized graph showing everybody talks everybody communications within a subsystem team and lead communications across subsystems team (c) Formula to calculate the number of interaction paths.

(a)

(b)

$$i = \frac{n(n-N)}{2N} + \frac{N(N-1)}{2}$$

(c)

An easy way to establish the value of the constant "Ci" is to look at the ratio of team leaders to team members in the project and to use this number as the overhead factor. Usually, this number will be in the range of 1 to 10 to 1 to 4. So Ci would be in the range of 0.1 to 0.25.

## Probability of Underestimation

Since the actual probability density distribution function for the duration of the project is unknown, the choice of a simple triangular distribution is a sensible one. Its right skew, (see Figure 2) captures the fact that while there is a limited number of things that can contribute to make the project easier and these are usually discounted at the beginning of the project, the number of things that can go wrong is virtually unlimited. Equation <10> below gives the cumulative probabilities for a triangular distribution.

$$<10> \quad F\left(u\right) = \begin{cases} 0 & \text{if} \quad u \leq u_{min} \\[2mm] \dfrac{\left(u - u_{min}\right)^2}{\left(u_{max} - u_{min}\right)\left(u_{ml} - u_{min}\right)} & \text{if} \quad u_{min} < u \leq u_{ml} \\[2mm] 1 - \dfrac{\left(u_{max} - u\right)^2}{\left(u_{max} - u_{min}\right)\left(u_{max} - u_{ml}\right)} & \text{if} \quad u_{ml} < u < u_{max} \\[2mm] 1 & \text{if} \quad u \geq u_{max} \end{cases}$$

Probability of Acknowledging the Underestimation on a Given Month

Wishful thinking[4], inaction inertia[5] and the fact that is easier to recognize an underestimation later rather than earlier in a project suggest making the probability of acknowledging an underestimation of magnitude "u" proportional to the time "t", that is the later in the project the higher the probability (see Figure 6).

Figure 6: The y-axis is the ratio of the actual remaining duration over the current estimated remaining duration and is plotted as a function of relative time for each project at each week. "This is almost certainly a result of the project manager holding on to a deadline in hopes that a miracle will occur and the software will release. Finally, the day of reckoning occurs, with no miracle in sight. In the extreme case, the ratio is a divide-by-zero as the deadline arrives, but significant work remains; at this point, the project estimate is usually reset. In many cases, this cycle repeats until the software releases." *Todd Little, Schedule Estimation and Uncertainty Surrounding the Cone of Uncertainty, IEEE Software, May/June 2006*

$$p(t) = \frac{t}{\sum_{i=1}^{T_b - T_a - T_l - 1} i}$$
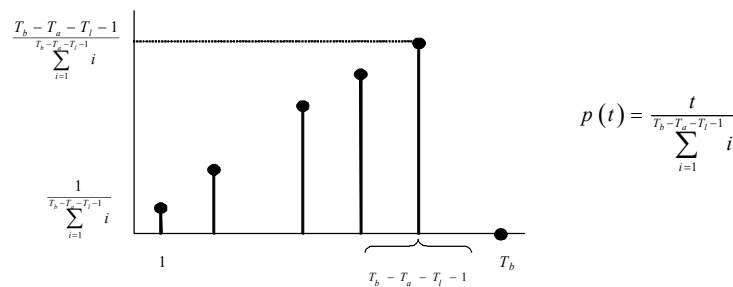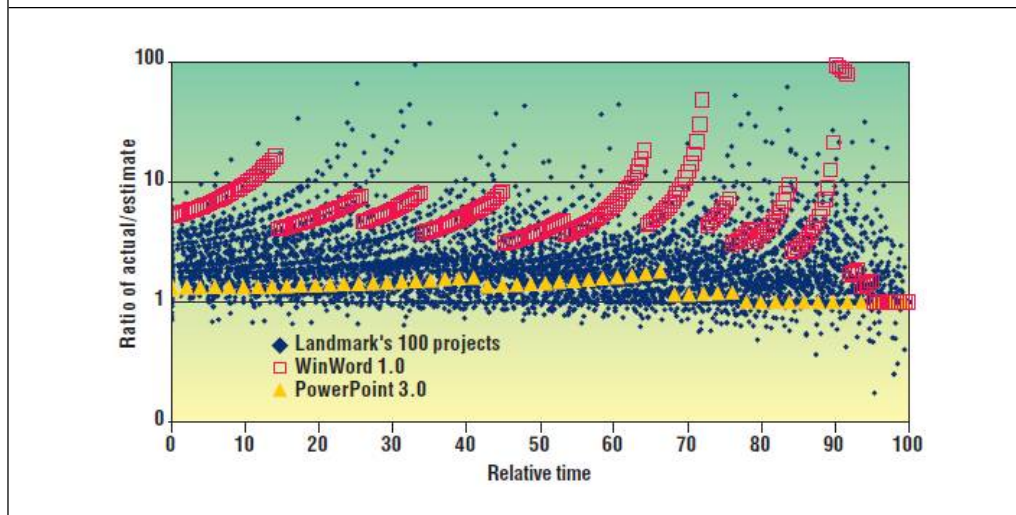
The probability function does not extend up to T_b as one must account for the time to recruit and the time to learn and for at least one month to do some work.

Other possibilities for the probability function would include the use of Bayesian probabilities to model the effect of the underestimation, e.g., larger underestimations will be easier to notice than smaller ones, but this treatment is outside the scope of the present work.

Calculating Contingencies

Equation <1> establishes the level of contingency funds at the expected value of the recovery cost.

Although the integral could be resolved analytically, the resulting expression is complicated because of the piece-wise continuity of the two triangular probability density distributions and the need to decompose the function to consider whether the project could be recovered through the use of overtime alone or if additional resources need to be added. In consequence the integral will be approximated by a sum of its parts as per the algorithm below.

1. For $budget = u_{min}$ To u_{max}

    $FTE_b = budget / T_b$

    $\delta = 1$ This is the integration step

    1.1. For $u = budget$ to u_{max} Step

    1.1.1. For $t = 1$ To $\left(T_p - T_a - T_l - 1\right)$

    1.1.2. If $u - budget \leq C_o \times FTE_b\left(T_b - t\right)$ then - Could the project be recovered with overtime alone?

    $ValidRecoveryCost = R_o\left(u - budget\right)$

    1.1.3. Else

    1.1.3.1.   If $b\left(t\right)^2 - 4a\left(t\right)c\left(u,t\right) > 0$ then - Can we recover? If not, and for calculation purposes the algorithm will use the last valid calculation

    $ValidRecoveryCost = RecoveryCost\left(u,t\right)$

    1.1.3.2.   End if

    1.1.4. End if

    1.1.5. $Contingency = Contingency + ValidRecoveryCost \times p\left(t\right) \times \left[F\left(u\right) - F\left(u - \delta\right)\right]$
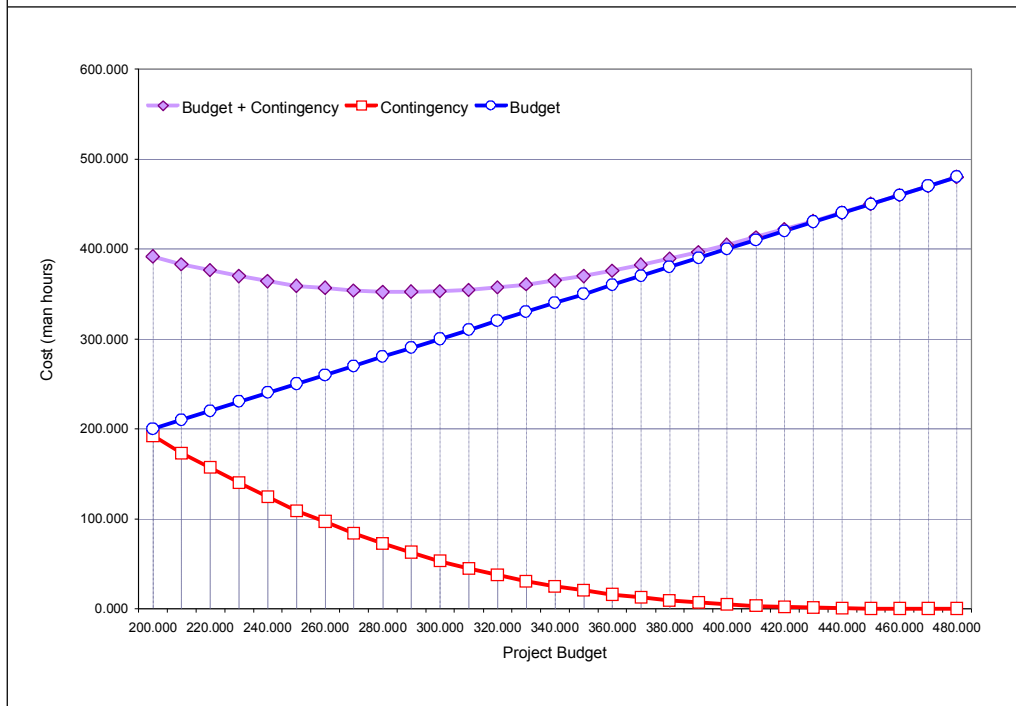
    1.1.6. Next t

    1.2. Next u

    $Contingency = 0$

2. Next $budget$

Figure 7:
Sample Outputs from the Contingency Calculation Algorithm

Conclusion

The models for calculating the cost required to recover from an effort underestimation typically include the magnitude of the underestimation. In this paper, we have presented a more comprehensive model that also takes into account the probabilities of acknowledging an underestimation at any time through the life of the project, as well as the losses during the process.

Our model begins with the recognition that the contingency funds must equal the cost of recovery from an underestimation of magnitude u acknowledged at a time t by the probability of u and the probability of t, that is, the probability of experiencing an underestimation of magnitude u and the probability of acting on it in month t relative to the start of the project. This model takes into consideration in particular the losses due to overtime inefficiencies until the complement of staff becomes efficient, the time to acquire the new resources and their learning curves, as well as the inefficiencies due to the increase in communication costs resulting from a greater number of staff working to overcome the underestimation.