PROBABILISTIC MODELING OF TECHNOLOGY DEVELOPMENT FOR USE IN PROJECT PLANNING AND MANAGEMENT

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ABSTRACT

From the dawn of human flight, the use of new technology has been necessary for aircraft to fly faster, further, and higher. That need continues today, making technology development a critical factor in new aerospace systems development. This study introduces some of the detailed formulation behind a process developed to assist the planning and management of a development project for a new technology. The process is based on risk management and uses probabilistic analysis, project network techniques, and Bayesian statistics in order to provide information useful for decision making. The six steps in the process focus on identification and reduction of performance uncertainty, as well as identification of cost and schedule risk and uncertainty. The process introduces some ways in which analysis can interact with expert opinion in order to produce meaningful system-level comparisons of technologies. The iterative nature of the process helps to deal with uncertainty in the technology and outside influences which affect the technology's development.

INTRODUCTION/MOTIVATION

The development of technology is an important part of fielding a new aerospace system, and is a large driver in whether the system meets its cost, schedule, and performance goals. A GAO study on best practices in management of technology development found that insufficient technology development for subsystems of the Comanche helicopter has contributed to the product development project being over budget and behind schedule.[1] As such, an important part of the design and planning process is getting an accurate look at what is required to mature a new technology and the future benefit gained from that technology.

NASA defines technology development as being (italics added for emphasis), "a process of testing and analysis that progressively *reduces the programmatic risk* of selecting that technology for an application and *increases the readiness* of that technology for use in a mission."[2] Reduction of programmatic risk can be seen as a reduction of the risk of a technology being too expensive or not being ready in time to be used for an application. An increase of readiness means a reduction in the uncertainty associated with the technology's performance and a shifting of the performance (as much as possible) towards desirable values.

This reduction in performance uncertainty and shift of performance values is typically performed through planning and carrying out activities such as experiments, analysis, and prototyping. As the development project progresses, the activities get more detailed in focus, and the technology's true performance is determined. These activities, then, are the focus of technology development.

Since the activities that are planned deal with the uncertain performance of a technology, it follows that the programmatics of those activities also have an element of uncertainty. The time and money necessary to complete development activities cannot be known exactly, and the possible ranges of the schedule and budget values can actually be quite large. This introduces the risk of not meeting deadlines or budget limits, an unacceptable situation in today's budget and schedule-conscious environment.

Combining the importance of reduction in performance uncertainty with the resulting cost and schedule risk results in a situation where all three measures must be examined together. This study builds off of earlier work[3] to introduce the details behind a process that could assist in planning and managing a technology development project in order to achieve beneficial levels of performance and performance uncertainty and keep project risks at an acceptable level.

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BACKGROUND

Although risk management and technology analysis are topics of frequent study, previous research has not found any public domain process that combines the two for the reduction of risk and uncertainty in technology development.[3] The next section provides background on the building blocks of such a process, focusing on the modeling of uncertainty, activities, and changes in performance.

Modeling of Uncertainty

Due to the fact that the performance, cost, and schedule of a technology are uncertain, it makes sense for these uncertainties to be modeled in a probabilistic manner. This can be accomplished through representing a technology by key metrics that describe the technology.[4,5] These metrics can then be represented as probability distributions instead of discrete values. The distributions cover a continuous range of metric values and represent the probability that any point in that range might be the true value for the technology. This approach allows the uncertainty to be quantified and propagated from the technology to the system on which it is applied or from the activity level to the project level. Statistical processes and equations can be used to operate on these distributions, allowing for a mathematical formulation to be developed.

One method often used to simulate the use of probability distributions in situations where inputs are typically discrete is Monte Carlo sampling. The basis of this method is a simple, brute-force sampling of the input distributions. Each time samples are taken from the input distributions, the analysis is completed using those sampled values, and then the results are collected. As the number of samples increase, the distributions of the results converge to the correct output distributions.

Modeling of Activities

The activities that are planned to reduce performance uncertainty introduce cost and schedule uncertainty. These activities are the link between cost, time, and performance. In order to model how the choice of activities affects these metric areas (especially cost and schedule) there needs to be a way to model the activities and how they relate within the project. One well-developed method for doing so is *project network analysis*.

Project network analysis is probably best known in the form of the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) developed in the 1950's. Network analysis methods represent a project in a graphical manner through a series of boxes (nodes) and arrows (arcs). In Activity on Arrow (AoA) methods the arcs represent the activities and the nodes help with the flow of information. In Activity on Node (AoN) methods the nodes represent the activities and the arcs are used to show the flow of the process. Both techniques model the order of completion of activities and the possibility of parallel work efforts through visually representing the different paths through the project.[6] For an example of an AoN network, see Figure 1.

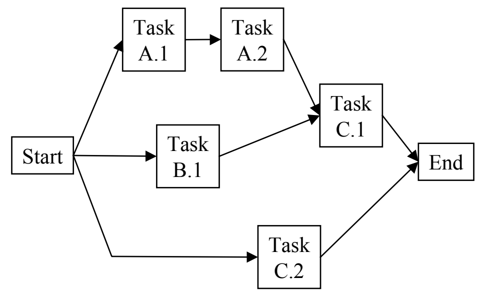

Figure 1: Sample AoN Project Network Diagram

The network representation of the activities in a project allows for simple calculation of cost and time for that project. Earlier network analysis techniques used discrete values, but some more modern techniques can deal with cost, time, and even performance in a probabilistic manner. The Venture Evaluation and Review Technique (VERT)[7] and Visual Slam with AweSim[8] are two more recent computer codes used to perform network analysis. MATLAB's Simulink environment[9] can also be used to perform network analysis. These codes require the user to input distributions for cost and schedule, and then the codes output probabilistic results for the overall project cost and completion time.

One of the typical outputs from network analysis is the critical path of the network. This is the series of activities whose path through the network takes the longest time. The critical path defines the overall schedule for the project, and changes in the activities along this path are the only changes that will affect the overall schedule. When probabilistic analysis is used, the possibility exists for there to be different critical paths, depending on what values are sampled for the different activities. These different critical paths can be tracked, so it is possible to determine the probability for which a given activity lies on the critical path.

Modeling of Change in Performance

Ideally the completion of activities results in a decrease in the performance uncertainty associated with the technology. Different activities will have different results, and it is important to be able to show how the results from an experiment or other activity change the uncertainty for the technology, as well shift the distribution towards (hopefully) better results. One statistical technique that can be used to aid in updating the performance information is Bayesian data analysis.[10,11,12,13]

A part of the broader area of Bayesian statistics, Bayesian data analysis uses Bayes' equation to assist in updating an old understanding of the state of a metric with new information. Bayes' equation can be seen in its simplest form in Equation 1 below.

$$prob(X|E) = \frac{prob(E|X) \cdot prob(X)}{prob(E)} \quad (1)$$

The *prob(X)* term is the initial understanding of the probability, called the *prior*. The *prob(E|X)* term represents the new data, and is often called the *data or likelihood* term. The *posterior*, or updated information, is *prob(X|E)*, and the final term, *prob(E)* is a *normalization* term that is the probability of event E happening. Essentially what this equation says is that the posterior is equal to the prior times the data divided by a normalization constant. While this simple equation holds for discrete probabilities, it can be used for distributions as well.

$$\pi(\theta|x) = \frac{f(x|\theta) \cdot \pi(\theta)}{\int f(x|\theta) \cdot \pi(\theta) d\theta} \quad (2)$$

Equation 2 shows the simplest form used for distributions. In this equation the probabilities of the prior and posterior are represented by $\pi(\theta)$ and $\pi(\theta|x)$ respectively, while the likelihood is represented by $f(x|\theta)$. The normalization term is then related to the product of the prior and likelihood.

Bayesian data analysis uses this central equation to update an old understanding of a probability distribution (the prior) with new data. The application to technology modeling is apparent. As new performance information (in probabilistic form) becomes available from activities that have been completed it is used to update the old information. The posterior resulting from the data of one activity can even become the prior for the next activity. The initial prior might be formed by test data, but is often determined by expert opinion. This is acceptable because Bayesian statistics assumes that distributions are subjective rather than objective. This means that the distributions measure the probability that a given value is correct, as opposed to the frequency of times it was measured to be correct.

Creation of a prior is one of the most difficult, and critical, portions of Bayesian analysis. An improperly formed prior can skew the calculated posterior distribution too heavily towards prior values, and a prior with incorrect values can skew the posterior towards incorrect results. Although there are different ways to create prior distributions, one concept that is of note is the creation of robust priors.[10,11] These are prior distributions that are deliberately broad (have a large variance), or distributions that have thick tails, such as the T distribution (see Figure 2). The benefit of these robust priors is that they have the ability to pass on prior information, but still allow the data distribution to influence the posterior when the prior is far from the true value.

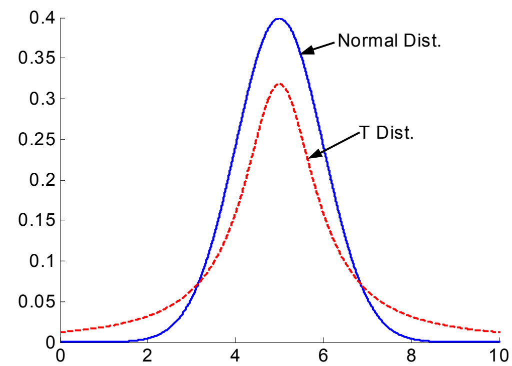

Figure 2: Comparison of Normal and T Distributions (*N*(5,1); *T*(1,5,1))

Bayesian data analysis does have limits, one of which is the concept of *exchangeability*. In Bayes' equation the data and prior distributions must have the same assumptions associated with them. This means that the experiments or analysis that created the distributions must have identical assumptions. Without this comparison of "apples to apples," the equation is not valid.

FORMULATION

Building from the information presented in the background as well as previous study[3], the following is the proposed process for the planning and management of technology development. The sections below will describe the steps shown in Figure 3 and lay out some of the mathematics behind the implementation of the process.

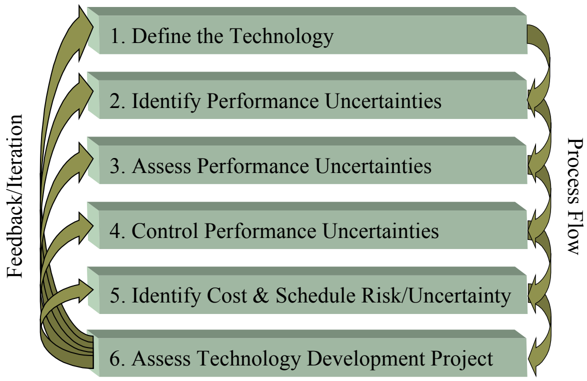

Figure 3: Basic Process for Technology Development Planning and Management

1. Define the Technology

The first step in the process is very straightforward, in order to develop a technology all the information possible should be gathered about the technology. One item of particular interest for the next stages is determining any computer codes that can be used in modeling the technology or the technology's application at the system-level. Another is determining what the goals are for the technology, how it is supposed to affect the system and what measures of effectiveness (also called responses) are used to show the positive or negative effects of the technology. Other information that can be collected is previous development information, the intended application of the technology, and a detailed description of the technology.

2. Identify Performance Uncertainties

This step is focused on determining the areas of performance uncertainty that might need to be reduced. The top-level areas of uncertainty are the technology response metrics. These are metrics which represent the technology's performance at the system level. For example, a structures technology might be represented by its material properties, and an aerodynamic technology might be represented by C_D, C_L, and wing weight. These metrics are the highest level metrics specific to the technology, and typically cannot be controlled directly by the person developing the technology (the *technologist*).

From these metrics the next step is to identify technology level control variables. These are metrics which define the technology and can be modified by the technologist to change the technology's performance. Examples for a structures technology might be the polymer material or treatment temperature. Changes in the values of these metrics will modify the values of the technology response metrics. The relationship between these two levels of metrics can be seen in Figure 4.

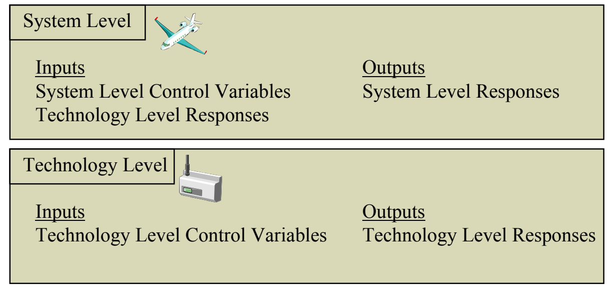

Figure 4: System and Technology Level Metrics

The metrics typically must be identified through expert opinion. Care must be taken to identify all possible technology response metrics and technology level control variables. If a metric is identified and proven to be unimportant in the next step, then little work has been expended. An important metric left unidentified, however, would cripple the development project until it was identified. If the response or control variables can be simulated at the system or technology levels, then the expert can choose inputs to the simulation as metrics for ease of analysis. Metrics can also be identified through a top-down decomposition of the technology.

The next part of this step is to specify the ranges associated with the uncertainty. In order to assess the effects of the uncertainty the ranges over which the metrics vary must be quantified. Ranges should be specified for the technology response metrics and control variables, and will also be gathered from expert opinion. Once the metrics are identified and the ranges set, the uncertainty can be assessed.

3. Assess Performance Uncertainties

At this point the uncertainties must be assessed to determine which are candidates for control through creation of activities. The object of this step is to compare the metric ranges at the system and technology levels to find which metrics have the largest effects on the uncertainty in the technology's performance. These metrics will also be the most capable of shifting the performance in the desired direction. This comparison is difficult, as the metrics' numerical ranges cannot be compared directly. Instead the technologies should be compared by their effect on the system level responses for the applied technology. If they cannot be compared at the system response level, then the effects of the technology level control variables can be compared at the technology response level. Comparison at the level of the system responses is preferable, though, as it allows the effects of the different technology level responses to be rolled up and interact.

If analysis capabilities do not exist, this comparison must be done by expert opinion. This method is adequate, and often used, but there are some shortfalls. Experts might be swayed by biases or unable to properly compare the effects of very complex systems without some sort of assistance.

If analysis capabilities do exist, then this provides an addition to the experts' capability, which can better quantify the interaction between metrics. The metric ranges from step 2 can be used to create a multiple variable linear equation for the responses of interest. The parameter estimates for each metric (the "slope" terms in the linear equation) can then be compared for normalized metric values to determine which parameters have the largest effect on the response. A sample linear equation can be seen in Equation 3, where y is the response of interest, and the x values are metric values for *k* different metrics.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \tag{3}$$

For the regression the parameters β_k are estimated using a least squares fit of the available data as shown in Equation 4 where i is the index for the data point.

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_{1i} + \hat{\beta}_2 x_{2i} + \ldots + \hat{\beta}_k x_{ki} \tag{4}$$

Expressed in matrix form, the equation for the parameter estimates can be seen in Equation 5.[14]

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \tag{5}$$

where

$$\hat{\boldsymbol{\beta}} = \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{pmatrix}, \ \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{21} & \cdots & x_{k1} \\ 1 & x_{12} & x_{22} & \cdots & x_{k2} \\ 1 & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{1n} & x_{2n} & \cdots & x_{kn} \end{bmatrix}, \ \& \ \hat{\mathbf{Y}} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix}$$

For this application, a 2-level Design of Experiments (DOE) is created using the metric ranges defined in step 2. The *y*-values are calculated and then the *x*-values input into the **X** matrix are normalized to equal –1 for the low values of the ranges and +1 for the high values. Since the inputs are normalized the calculated β values can then be compared, the largest values representing the metrics that have the greatest influence on the response *y*. This information can be displayed in histogram form in a Pareto chart as seen below in Figure 5. The next step after identifying the metrics that have the largest effect on the response is to attempt to reduce the range of uncertainty in those metrics and shift their performance towards beneficial values.

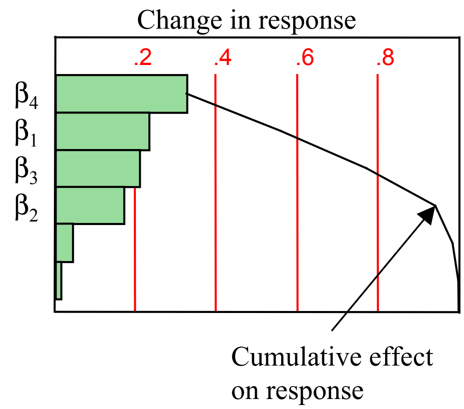

Figure 5: Sample Pareto Chart

4. Control Performance Uncertainties

As stated earlier, unacceptable performance uncertainty is controlled or reduced through the creation of activities such as experiments, analysis, prototypes, etc. Step 3 assessed the metrics to find those areas where uncertainty was having the largest effect on the responses, this step attempts to reduce that uncertainty, as well as explore what can be done to shift the distribution. This step is the least formulaic of the process, there are no set equations or rules to define how the activities should be created. Some guidelines could be given though. It is important to create experiments that have measurable, quantifiable results. In addition, it is useful to create experiments that build off of information gained in previous activities. For areas where uncertainties are very high multiple activities can be created and run in parallel so that one might produce the desired results. In areas where there is little or no analysis capability, experiments can be planned or prototypes created to help to reduce the uncertainty. In these cases the results can also be used to create new analysis methods or validate existing ones. Creation of analysis is also beneficial as it can be used to find the combinations of technology level control variables that create the best performance values.

One important part of this step is the creation of the activity network. Like any project, a technology development project must have a project plan showing how the elements fit together. For this process the project plan will be modeled using a network diagram, so the network can later be modeled using project network analysis. At this stage, the focus of the network diagram is on showing the relationship between different activities: which can be run in parallel, which depend on other activities for inputs, etc. In the next step cost and schedule information will be added to make the network more like a traditional project plan.

5. Identify Cost & Schedule Risk/Uncertainty

In order to look at the cost and schedule risk and uncertainty for the project as a whole, it is necessary to collect cost and time information for each activity. Typically this will be done through expert opinion, with distributions for cost and time being elicited from experts for each activity. This matches the work done in the creation of a typical project plan, except that the data is probabilistic. It is important to note that the cost and time are assumed to be independent. If there is a relationship between the two it can be added without difficulty, but often the two can be considered to be reasonably independent.

Once the cost and time distributions are collected the network can be modeled using a project network analysis code. The network defined in the previous step is used as the structure, and the inputs for the cost and time are added for each activity. When the analysis is performed, a Monte-Carlo-type analysis is typically used to model the system probabilistically. In this situation each distribution is sampled a number of times N, and the results for each sample are represented for the cost by Equation 6, and the time by Equation 7. The results from each sampling iteration are collected and used to form the distributions for the project time and cost.

$$C_i = \sum_{j=1}^{m} c_{ij} \tag{6}$$

$$T_i = \sum_{C.P.} t_{ik} \tag{7}$$

C_i=Total network cost for sample i
c_{ij}=Cost for activity j for sample i
m=Total number of activities
T_i=Total network time for sample i
t_{ik}=Time for activity k for sample i
$C.P.$=Critical path

The results gained from this analysis can be used in a number of ways, which will be mentioned in more detail in the next step. It is of worth, however, to note that if the whole cost or time distribution is not less than budget or schedule limits, then there will be a quantifiable risk of the project going over budget or over schedule. Yearly budget distributions can be calculated if necessary, in order to compare with yearly budget limitations.

6. Assess Technology Development Project

At this point in the process areas of uncertainty have been identified and assessed for their effect on the overall goals for the technology, activities have been chosen to modify the performance and performance uncertainty, those activities have been formed into a network, and the network has been populated with cost and schedule distributions. All of this work provides information that can be used to assess the overall project. This assessment has two phases: the first is an initial review of the project plan while the second is an iterative updating and re-planning of the project. The first phase is primarily programmatic, cost and schedule risks are identified and addressed by reorganizing the network flow and possibly through re-planning activities. The second phase is an iterative process (like a yearly review) that updates performance values, re-examines progress in performance and areas of uncertainty, and re-plans the activities if necessary to address new areas of uncertainty or areas that have not been addressed fully. The combination of these two phases with rigorous metric tracking[15] and technology analysis[16] will result in a well-planned and executed technology development project.

Initial Project Plan Review

As stated, the purpose of the initial project plan review is to take the cost and schedule information gathered in network form and use that information to organize the network. The first step is to look at the overall budget and schedule limits for the development project. When the probabilistic network analysis is performed for the project, distributions showing the cost and schedule uncertainty will be output and can be compared to the overall budget and schedule goals. In the forms of CDFs these distributions can show the risk associated with meeting cost and schedule goals, as shown in Figure 6 and Figure 7.

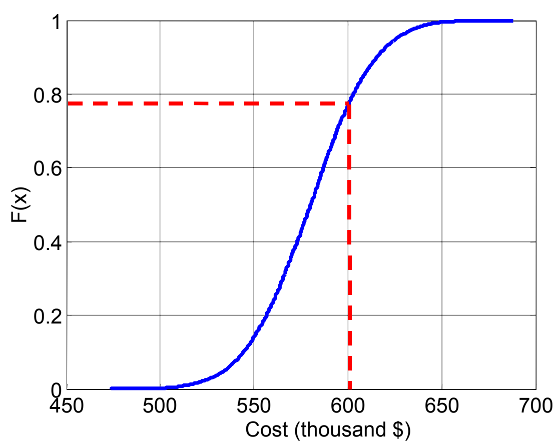

Figure 6: Sample Project Cost CDF

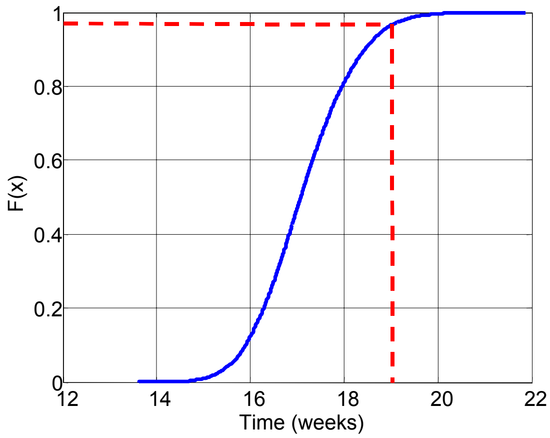

Figure 7: Sample Project Schedule CDF

In Figure 6 the budgetary limit for the project is set at \$600,000. According to the estimates given for the activities in the schedule, this limit has a 78% probability of being met. In Figure 7 the schedule limit is 19 weeks. The probability of meeting this deadline is much greater, at 97%. If the budget limit was shifted to \$650,000 then there would be a 100% chance of coming in under budget. These limits are often non-negotiable, however, and so the technologists and project managers are responsible for deciding if a 22% risk of being over budget is acceptable, or if some of the activities need to be changed. Note that if the cost of changing the project plan would be more than \$50,000, then it would be beneficial to stay with the current plan.

While the overall budget is usually important, another item of importance is the yearly budget. Because the network is not laid out on a timeline, and because uncertainty is inherent in the process, it is difficult to tell from casual observation what the budgetary spending will be for a given year. Just as was plotted for the overall cost, yearly cost distributions can be created to show the likelihood of meeting yearly budget goals, allowing for more detailed arrangement of the activities.

In each of these scenarios if budget or schedule limits cannot be relaxed, the only recourse of the project manager is to adjust the project plan. This can be done in two ways. The first, which addresses the problem of spending too much money in a given year, is to re-arrange the order of the activities in the network. If four activities can be performed in parallel, they can be re-arranged to be performed two at a time, resulting in the same total cost, but less cost at a specific time. Of course, this will affect schedule values.

The second method the project manager has for adjusting the cost and time for the project is to adjust the activities themselves. For cost it is useful to identify the activities that are contributing the most to the overall cost. For schedule overrun, the only way to affect the schedule is to address activities along the critical path. If a reduction in time along the critical path causes another path to be critical, then more than one activity might need to be modified (the probabilistic values showing what elements are likely to be on the critical path can help with this).

Often an experiment or analysis run can be reduced in time and cost by using different procedures or by collecting less data. The key to this is that a reduction in time or cost spent will likely result in greater uncertainty at the end of the activity. This tradeoff is complex, and is best solved through consultation between project personnel and the technologists. This type of re-design is analogous to iterating back to step 4 and re-running thorough steps 4 and 5 of this process.

<u>Iterative Assessment</u>

Due to the inherent uncertainty in the technology and uncertainty in outside factors such as budget levels and political and institutional support for technologies it is important to re-evaluate a technology's development regularly. It is for this reason that the process developed here is an iterative process, there is no way to perfectly plan technology development at the beginning of a project. The iterative portion of this step has two phases: the first is to update the uncertainties for activities that are completed, the second is to iterate through steps 2-6, changing metric ranges and adjusting the project plan as necessary.

Updating Results

Updating the cost and time values for the plan is a very simple process. Activities that have been completed should have discrete values for the cost and time used. These discrete values can be input into the definitions for the activities, thereby reducing the overall cost and time uncertainty. Activities that have been partially completed can have their cost and time distributions altered to reflect the current knowledge about completion cost and time.

Updating the performance is a more difficult process. The typical results from an experiment or analysis run can be considered to still have a degree of uncertainty associated with them due to variability in the results, the error inherent in the code, and uncertainty in input values. Because the results will be uncertain, it is worthwhile to consider the previous understanding of the metric uncertainty in determining the new distribution for the metric. If a detailed full-scale wind tunnel test is done on an aircraft, the results might be considered to be "true" values, but most results should be considered in the Bayesian sense as updates to a useful prior understanding. This requires that a prior should be created to describe the previous understanding and previous results, which can then be updated using the data from the completed activities.

The initial priors for the important metrics should be created using expert opinion based on what is known about the technology or similar technologies. These initial priors should be as robust as possible, as very little is usually known about the technology at this point (see Figure 8). After the first activities are completed those initial priors can be updated with the new data to create posterior distributions. In the cases where the next activity has the same assumptions as the previous one, shown by activities 1 and 2, then that posterior can be used as the prior for the upcoming activity. If the assumptions have changed, then the results from the activities are not exchangeable, and a new prior needs to be created which takes into account the last posterior as well as the change in assumptions. This is best done by a combination of expert opinion and analysis, when the analysis is available and can be used to scale the distribution. The new prior should also be robust, to show that uncertainty has been added to the prior by the change in assumptions (compare $\pi(\theta|x)$ for activity 2 and $\pi(\theta)$ for activity 3).

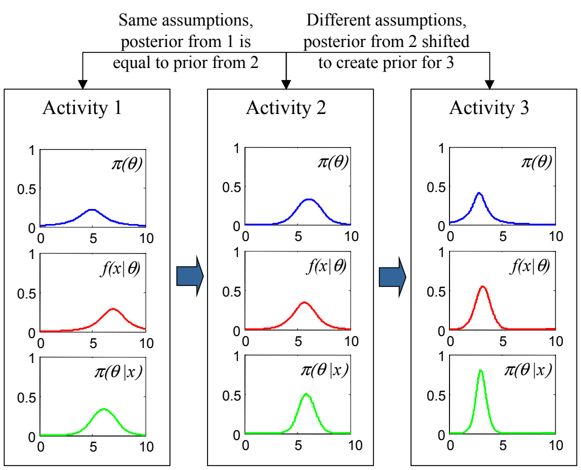

Figure 8: Demonstration of Bayesian Updating

Another issue relating to exchangeability is that experimental results are often not comparable due to the fact that the experiment, analysis, etc was performed on a small scale test article, or using non-operational conditions. This means that the results, though they do show a change in uncertainty, don't necessarily show the change in the uncertainty for a full-scale technology at the system level. Typically results are transformed to the proper level using expert opinion. When possible, though, this should be augmented using analysis capability. If an analysis tool exists that models the physics and can show the change in the results as the assumptions are changed from small-scale to full scale values, then its use by an expert will give more accurate results than using the expert's estimation alone. The results from the small scale analysis can be used to validate an analytical model, and then the physics of the problem represented by the analysis code (run by an expert) can do the transformation (see Figure 9).

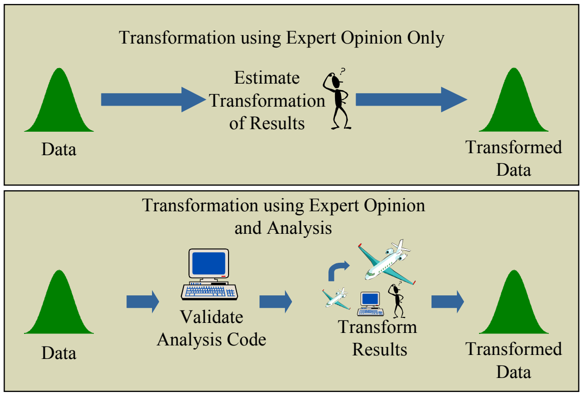

Figure 9: Methods for Making Data Exchangeable

Performing Iteration

Once the cost, time, and performance values have been updated the project should be reassessed by going back to step 2. In areas where the uncertainty has reduced, the ranges can be changed and the analysis in step 3 re-run. Assuming nothing changes drastically the original plan can continue to be followed. However, if the changes in uncertainty cause other metrics to become important, or if existing experiments are not properly reducing uncertainty, then the activities should be modified, or even replaced with new activities. In some cases analysis will show that exploration of different ranges of metric values would be beneficial. Any new or modified activities must be put into the network, given cost and time distributions, and re-analyzed as was done in the initial analysis of step 6. It is this iteration process that allows the project plan to change to adapt to the uncertain environment that is a part of technology development.

CONCLUSIONS AND FUTURE WORK

The process given in this study is focused on assisting the planning and management of a new technology development project. It is based on the need for managing risk and uncertainty for performance, cost, and project schedule. The uncertainties are identified, assessed, and then controlled where necessary to create a usable, feasible technology. Probabilistic methods are used to model uncertainty and pass uncertainty through the different levels of analysis. Project network techniques provide a graphical and analytical framework to link the different activities together and calculate cost and schedule for the project. Bayesian statistics are used to update performance values as results are obtained from completed activities. The whole process is iterative, taking into account the possible changes in the technology, as well as outside influences.

Future work will focus on applying this process to one or more test cases. Test cases will use, or be based off of, real technologies and real development information.

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