DECISION ANALYSIS IN COST ENGINEERING

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Decision analysis (DA) and other operations research (OR) techniques came into prominence during and immediately after WWII. Mathematicians, who previously held little respect, assisted the war effort with military planning and other decisions to optimize resources. DA—where probabilities are involved—is a subset of OR.[1]

Ron Howard of Stanford University coined "decision analysis" in 1964, so in 2014, the DA discipline celebrated its 50th anniversary.

What does DA offer the cost professional?

1. More accurate estimates and forecasts for decision making.
2. Logical tools for project risk management.
3. Clarity of judgments and calculations about uncertainty.

This article presents the key features of the DA tools and process. Probability is the language of uncertainty. The fundamental concepts and methods should be understood and used by all cost professionals and allied professionals. Interest within AACE International is evidenced by various elements of Total Cost Management Framework, Recommended Practices, and the new Decision and Risk Management Professional certification.

INTRODUCTION

DA is perhaps the most important management tool since the invention of the organization hierarchy.

DA provides tools and techniques to explicitly recognize risks and uncertainties project feasibility studies, design optimization, and other forecasts. What was leading-edge analysis technology in the 1960s has been routinely taught in university business schools since the 1970s. Though the technology continues to advance, the methodology is proven and well developed. DA has now become mainstream practice. It is embodied in today's headline stories about *predictive analytics* and *data mining*.[2] Small decision problems can be solved with back-of-the-envelope calculations. For more-substantial problems, low- to moderate-cost PC and cloud-based software are making the techniques easily accessible.

Risks and uncertainties often significantly impact value, cost and schedule. DA provides the only logical, consistent way to incorporate judgments about risks and uncertainties into an analysis.

The foundation concept is expected value.

DA focuses on helping decision makers choose wisely under conditions of risk and uncertainty. It is a blend of statistics, systems theory, psychology, and management science/OR. The cornerstone is the *expected value* (EV) [3]

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[1] See "Operations Research" and "Decision Analysis" articles at Wikipedia.org.

[2] A Google search on 11-Apr-2015: "Analytics" brought up more than 600M hits.

[3] Unfortunately, "EV" is also the abbreviation for *earned value*.

concept. An *EV* is, simply, a probability-weighted average outcome. This is detailed later.

As with many inventions, money was the incentive to developing probability theory. Humans have played games of chance since at least 5000 B.C. The initial formalization of probability is often attributed interest in gaming and a letter-writing exchange between Blaise Pascal and Pierre de Fermat, probably in 1654.

DA techniques are now popular in business and engineering curriculums. Unfortunately, people who study DA in college often forget the classroom experience when they enter the real world. Many adult learners experience some delight in become reacquainted with DA. There was some purpose for that statistics class, after all. After developing competence in making conventional, non-probabilistic projections, DA offers a step-improvement in forecast model quality.

What Characterizes DA?

Probability is the language of uncertainty.

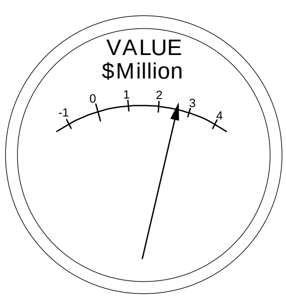
Probabilities and probability distributions are the formal, unambiguous language of uncertainty. The three distinguishing features of a decision analysis are:

1. Capturing judgments about risks and uncertainty as probability distributions
2. Having a single value measure for decision policy. This may be an *objective function* comprised of several decision metrics. Most often in business, the measure is *net present value, NPV*. –and–
3. Putting (1) and (2) together to calculate expected value (*EV*). Alternatives are ranked by their *EV*s.

The workhorse tools for calculating *EV*s are *decision trees* and *Monte Carlo simulation* (simulation).

Type Problems

Having a way to measure value under uncertainty—symbolized by a *value meter*—provides a means to solve three types of problems:



1. **Ranking alternatives** and picking the best one. This is what comes to mind when people think of decision making.
2. **Optimizing.** Finding the best chose of one or more decision variables. For example, finding the optimal bid about in an auction (whether offering to buy or sell). This is really the same as (1) except there may be several decision variables and each has two to perhaps infinite choices.
3. **Appraising.** Assessing the value of an asset, risk, or opportunity. While not a decision itself, the value often drives the decision.

DA helps answer questions such as:

- What is the optimal design capacity for the plant?
- What is our optimal bid? What is the probability of winning the contract? And, if we do win, what is the EV Profit?

- How much contingency should we put into the estimate so that we have a 90% confidence of making a profit?
- What is the Project Completion Date with a 90% confidence?

Decision Policy Measures Value

There are three key areas representing the decision maker's attitudes or *preferences*:

Decision policy is about preferences.

- Preferences for different *objectives*. In business, the overriding concern is usually maximizing shareholder value. For this situation, the objective is to maximize value measured in dollars or other currency. Decisions in the public and non-profit sectors are often more difficult because of competing and conflicting objectives. [4]
- *Time* preference. *Present value* (PV) discounting is the well-accepted approach to recognize the time value. Usually, the objective is about money, though discounting can be used on any metric where there is a time preference. *Net present value* (*NPV*) is the PV of future net cash flow. The most objective discount rate is the company's marginal, after-tax cost of capital. Whether or not cashflow projections include inflation should be matched in the choice of PV discount rate.
- *Risk* preference. Most often, the risk profiles of various alternatives are compared intuitively by the decision maker. Alternatively, the corporate risk policy can be succinctly and completely represented by a utility function.

Good Decisions versus Good Outcomes

One of DA's key tenets is distinguishing good decisions versus good outcomes. A *good outcome* is when the decision maker or organization is better off than before.

A *good decision* is one that is consistent with the attitudes (including values and beliefs) of the decision maker and all of the information available at the time.

EXPECTED VALUE

As mentioned earlier, EV is the foundation concept of DA. An *EV* is not "the value we expect." Rather, this "expected" adjective comes from the *mathematical expectation* concept.

The principal calculations in decision analysis

EV is the *mean* or probability-weighted average of a probability distribution. It is the unbiased and best single-value to represent a distribution. In DA, each alternative is simplified to a single value, its *EV*. Then the decision is simply to choose the alternative with the best *EV*.

Value optimization is typically to maximize *expected monetary value*, *EMV*, which is EV *NPV*. With cost problems, the objective is typically to minimize EV PV Cost.

[4] For objectives other than *NPV* maximization, non-monetary measures may be expressed in monetary equivalents. This is the easiest way to handle multi-criteria decision making.

The meaning of "expected cost" must be clear. To help ensure clear communication that this refers to an EV calculation, the author recommends calling this "Expected Value Cost." The corresponding notation is "EV Cost" or "E(Cost)."

It is important that everyone involved understands context whether EV Cost this is pre- or post-tax, inflated or not, and discounted or not.

There are two principal EV calculation methods: *decision tree analysis* and *simulation*. Each method has its advantages and disadvantages. Often, it is useful to use both methods on different parts of an analysis. Project risk assessment and analysis of alternative actions is typically done with decision trees. Probabilistic (*stochastic*) project schedule modeling requires simulation.

Model Context and Output

The feasibility model, **Figure 1**, should be a permanent feature of a project's documentation. It should reflect the current scope definition and general plan. The model should be updated for new information and project developments as they unfold. A sub-model is a high level project schedule and cost model. When the delivered project becomes an asset placed in service, then the updated feasibility model becomes part of the enterprise portfolio model.

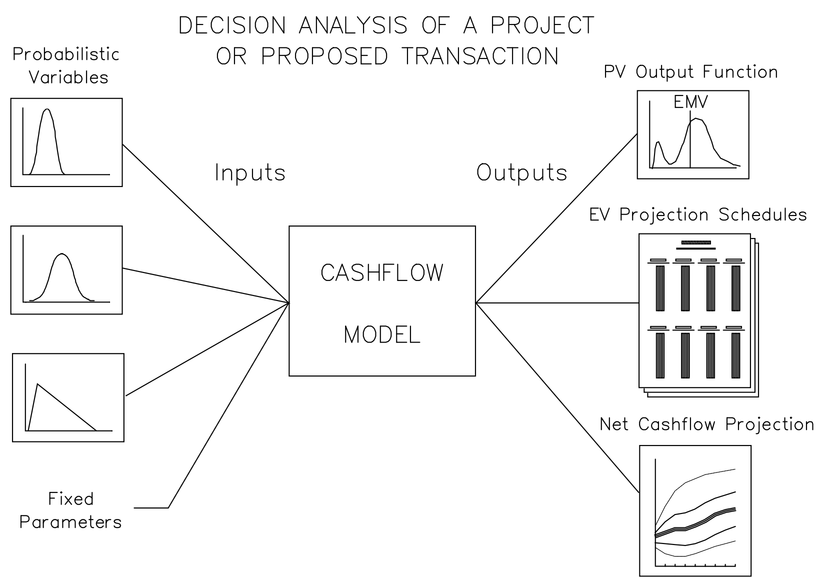


Figure 1. Project Feasibility Forecast Model. A deterministic net cash flow model is at the core. With even a single distribution input, the outcome will be a distribution (as in **Figure 2**).

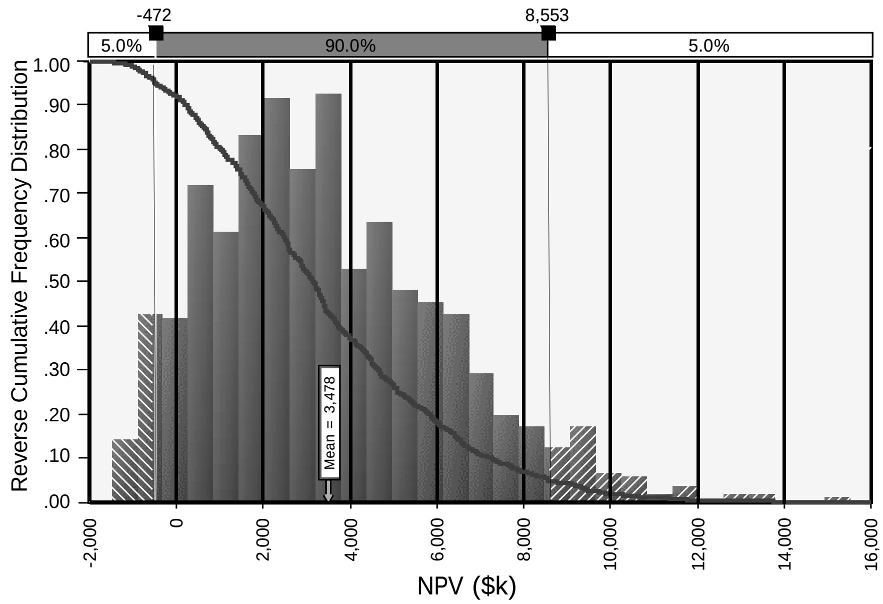


Figure 2. Cumulative Frequency Distribution (and frequency histogram). With the cumulative curve, one can directly read confidence levels or intervals. Shown is the "cumulative greater-than" or "exceedance" form of the curve which is popular when expressing an *NPV* or other value distribution. The complement cumulative curve—ramping up left-to-right—is more common when looking at distributions of schedule and cost. This is a modified chart produced by @RISK.

DECISION TREE ANALYSIS

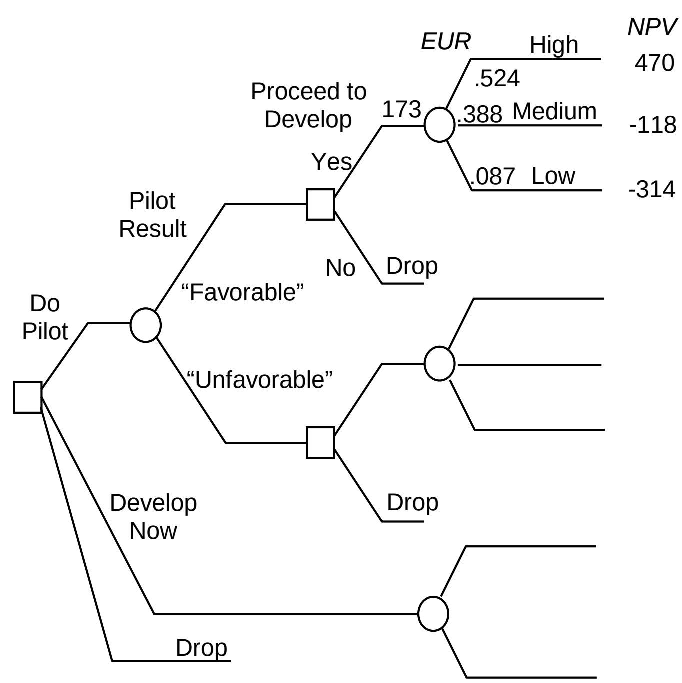


Figure 3a. Schematic Decision Tree. The probabilities and outcome values are shown only for the upper-right chance node. This is to evaluate doing a pilot flood on an oil field. *EUR* is the Estimated Ultimate Recovery. Amounts are in $million.

Decision trees, such as **Figure 3a**, provide a graphical template for *EV* calculations. Decision trees are solved using this discrete *EV* formula at every chance node (represents a risk or uncertainty event):

$$EV = \sum_{i=1}^{N} x_i \ \mathrm{P}(x_i)$$

where x_i is the outcome value

$\mathrm{P}(x_i)$ is the probability of outcome x_i

N is the number of possible outcomes

Here is an example *chance node* representing the Estimated Oil Recovery node in the **Figure 3a**:

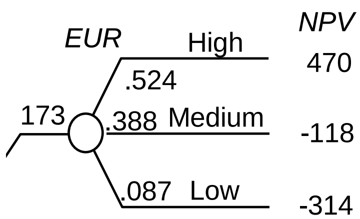


Figure 3b. Chance node with EV calculation.
EMV at the *EUR* node = .524(470) + .388(-118) + .087(-314) = $173M

A decision tree is a graphical template for calculating *EV*s. Trees are most often drawn in chronological sequence, left-to-right.

Working backward, right-to-left, *EV*s at the root decision node are solved by back-calculating the tree:

- Replacing chance nodes with their *EV*s,
- Replacing decision nodes with the *EV* of the best alternative branch.

Working backward is necessary so as to know what alternative to choose at decision nodes.

Strengths

- The tree diagram clarifies the decision problem as a graphic. The diagram clearly shows all important decision elements:
    - Contingencies (outcomes of chance events)
    - Decisions and alternatives
    - Logical sequence of decision points and chance events.
- One can often solve decision trees by hand.
- Decision trees can easily handle evaluations involving low-probability events, such as risk of a hazardous spill or loss of life.

- Trees are best for "value of information problems" having subsequent decision points after more information is revealed.

Weaknesses

- One must reasonably represent all possibilities by a finite number of paths through the tree.
  - This limits the practical number of random variables (chance events and decisions) that can be accommodated.
  - Discrete approximations must replace judgments as continuous probability distributions; thus, some detail is lost.
  - The analyst is limited in the representation of uncertain timespread events, such as for prices and inflation, to a few scenarios.
- An output probability distribution (similar to **Figure 2**) is usually not obtained, only the *EV*. However, with extra effort or software, the outcome distribution can be charted from outcomes and their joint probabilities.
- Branch and outcome values must be value measures (*NPV* works, though, for example, Internal Rate of Return (*IRR*) does not).
- Probabilities must be assessed or calculated for all chance event outcomes.

MONTE CARLO SIMULATION

Simulation approximate an integral equation for the *EV* of a continuous variable:

$$EV = \int_{-\infty}^{\infty} x \, \mathrm{f}(x) dx$$

where f(x) is a probability density function

Monte Carlo simulation offers a simple way to do some complex calculus.

Don't be alarmed by the integral. Even the best mathematicians can seldom solve this directly except for simple distributions. Instead, the approximate the *EV* is solved with simulation using this formula:

$$EV \approx \frac{\sum_{i=1}^{n} NPV}{n}$$

where *NPV* is the outcome, or another value measure

n is the number of trials in the simulation run

Simulation allows us to replace single-value inputs into any model or formula with probability distributions. In effect, simulation provides the means to propagate distributions through the model calculations.

By generating possible futures (realizations) for a project or other system—hundreds or many thousands of times—simulation provides good approximations to the model's outcome *EV*s, probabilities, and forecasts.

Strengths

- A simulation model is a straightforward extension to the conventional, deterministic model (Cashflow Model component in **Figure 1**). Fundamentally, the analyst just substitutes probability distributions for single-point input variables.[5]
- The normal simulation output is a frequency distribution (such as **Figure 2**), displaying the full range of possibilities and approximating the true probability density function. Timespread variables, such as a commodity price, can be modeled in rich detail.
- The distributions can be captured for any meaningful output variables (unlike decision trees that work only with value measures).
- One can model risks and uncertainties in as much detail as desired. There is little cost to additional random variables. All possible eventualities can be modeled in whatever detail is necessary. Simulation is better than decision trees for dynamically modeling system contingencies, such as strikes and breakdowns. Portfolio problems have a multitude of possibilities and are easily represented.
- One can represent continuous probability distributions directly, without discretizing to n-level estimates.
- Complex problems are sometimes easier because conditional probabilities can be calculated automatically by the sampling process.

Weaknesses

- The result is not algorithmically precise. The confidence of a sample mean in approximating the true *EV* may require a very large number of trials. Very large models requiring many trials to converge can be time-consuming and expensive to run.
- Low-probability events are seen rarely in the simulation and, thus, are represented poorly. This exacerbates the problem in the prior point.
- The decision structure is less obvious. Lucidly presenting the model logic depends on the documentation skills of the analyst.
- It less straightforward to revise probability distributions based upon later information. Thus, value of information problems are more difficult.

[5] While somehow representing correlations among variables.

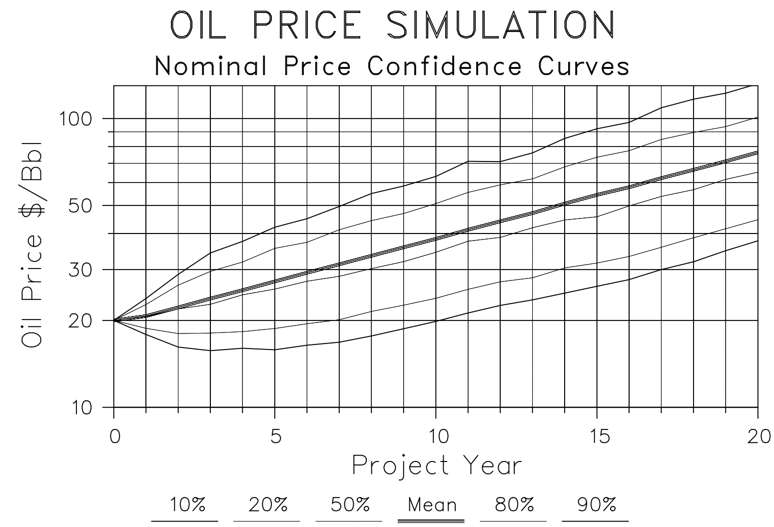


Figure 4. Confidence Curves for a Timespread Variable. As example, there is an 80% chance that the oil price at any particular time will lie between the two outermost bands. (At the time of this 1993 analysis, oil was about $20 per barrel.)

TREE OR SIMULATION?

Many people are unaware that decision trees and Monte Carlo simulation are essentially equivalent methods. Either can be used to calculate *EV*s and outcome distribution curves (recall **Figure 2**).

The choice of calculation method depends on the situation, and many evaluations can benefit from using both at appropriate stages. The following outlines summarize the key differences, strengths, and weaknesses of each technique:

Trees are usually the method of choice when:

- There are low probability risk events, say, less than .02.
- There are subsequent decision points (options), when more information will be available (value of information problems).

Simulation is usually preferred when:

- There are many important risks and uncertainties.
- The problem is to optimize one or more continuous decision variables (e.g., competitive bidding)

There are other management science techniques which, while outside mainstream DA, are very useful aids to decision making. For perspective, it's worth noting the best known of these:

- Critical path method (CPM)
- Linear Programming (LP), genetic algorithms, and other optimization methods
- System dynamics
- Regression, cluster analysis, and other methods in data analytics

- Artificial intelligence, including expert systems and neural networks.

DECISION ANALYSIS APPROACH

Decision analysis is a straightforward, structured process. Here is an abbreviated outline of the typical steps:

1. Frame the problem: What decision is to be made? If there is no decision policy, determine the objective(s) and what criteria will be used to make the decision. What are the decision alternatives? What risks and uncertainties affect outcome value? A structural decision model will clarify the decision problem.
2. Develop a deterministic cashflow to calculate outcome values for each pathway through decisions and chance events. A *deterministic model* is a conventional model where every input parameter is a determined, single-point estimate. Typically, developing this model is the majority of the analysis work. Cost and project professionals are typically the people most involved with developing these models. Accountants may be needed to describe tax calculations, and other disciplines may be called upon for their special expertise.
3. Elicit judgments about key uncertain variables in the form of probability distributions. Use sensitivity analysis to identify which inputs and model parameters significantly impact project value. Sensitivity analysis helps prioritize variables on which to spend more time with SMEs and in obtaining additional information.
4. Substitute the probability distributions into the model (see figure 1) and solve for outcome distributions and *EV*s. Use a decision tree or simulation as the *EV* calculation technique. In simple situations, a *payoff table* will suffice. Many problems employ both decision trees and simulation for different parts of the analysis.
5. Choose the best alternative or combination of decision variables.

WHY COST PROFESSIONALS SHOULD USE THESE METHODS

Most cost professionals work to provide information for others to use. Professionals in any discipline work to master one or more processes. Applying a proven process is a hallmark of professionalism. For professionals in information-providing jobs—that is readers—their work product is analysis.

Credible Analysis

A *credible analysis* is one suited to the purpose at hand. A credible analysis features:

Objectivity is the foremost characteristic of a credible analysis.

- Objectivity, meaning free from unintentional bias. Value is measures value in a way that matches the organization's objective(s)[6]

[6] Decision policy may have an intentional bias, such as *conservatism* prescribed by the organization's risk policy.

- Integrity of the model and calculations, that it reflects the stated assumptions and performs as represented
- Adequate disclosure and communication
- The basis for the analysis is usually a *credible model* that has been:
  - *Validated*: its specifications have been accepted as being reasonably representative of reality; and
  - *Verified*: that it performs according to specifications.

Credible analysis requires explicitly recognizing all important risks and uncertainties in the project forecast. The following sections describe the key features and benefits of using DA. The techniques have universal application.

Benefits of Using DA

Wrapping up, following are some key benefits to cost professionals

1. More accurate estimates

Cost professionals have always dealt with risk and uncertainty when planning, scheduling, and evaluating. A good decision analysis model faithfully and completely represents professional judgments about uncertainty in the form of probability distributions. This model then provides the best way to calculate a forecast. Resulting probability distributions provide the logical means to express uncertainty and to establish any contingency amount.

When uncertainties are significant, a credible evaluation can be achieved only by using these techniques. In addition to characterizing risks, estimation and other types of forecasts are more accurate. Using probability distributions through the calculations corrects for a sometimes-significant error in conventional analysis.

It is interesting and prudent to compare two value approaches:

1. Base case analysis. This is a deterministic model solved using the best single-point estimates, i.e., *EV*s, for input values. When money is the measure, then *NPV* is the value.
2. A probabilistic (stochastic) model solved with probability distribution inputs. When money is the measure and the decision maker is neutral about risk, then *EMV* is the value.

Stochastic variance is the value *correction* realized when migrating from deterministic to stochastic analysis

Stochastic variance is the difference between (1) the conventional (without probabilities) analysis (*NPV*) and (2) the value obtained using decision analysis (*EMV*). The difference can be substantial. Stochastic variance should be a line item on a variance analysis report.

2. Project Risks Management is Natural

With DA tools, project risk management is logical and straightforward. Quantitative (probability) replaces qualitative. Contingency amounts and time buffers are among the decision variables that can solved for with computer optimization. Identifying inputs to a feasibility model and/or identifying tasks in the work breakdown structure are important to modeling.

It is natural to start thinking about what actions might be available to improve the risk (probability) and uncertainty (impact).

In project scope and planning, there are an array of decision variables to optimize. Though projects can sometimes be optimized individually, the context should always consider the portfolio.

3. Clarity in Expression and Communication about Uncertainty

When focusing on a single uncertainty, a probability distribution completely captures an SME’s judgment about that variable. The SME will also be asked to describe how the variable relates to other model features. Even if distributions are not used in the calculations, just thinking about the distribution shape, range, and parameters will often provide a much better single value.

Calculation outputs, such as project value, cost, and completion time, are typically presented as distributions. The forecast will always be wrong. The decision maker deserves to have the best estimate as well as a description of uncertainty in that value. Outcome distributions provide this information.

A project presentation is incomplete without DA:

- The decision maker or other audience rightfully expects an appropriate and well-executed process behind the analysis or plan.
- The model is indefensible unless judgments about uncertainty are quantified and incorporated in the model.
- A thoughtful, well-crafted decision policy is the basis for measuring value.

DA fosters better communication between decision makers, managers, subject matter experts (SMEs), planners, model builders, and other stakeholders.

Decision analysis is gaining popularity due to increasing business intensity, having more people trained in the methods, and the proliferation of applicable and easy-to-use software. Many people are surprised to discover, or rediscover, the power and simplicity of the EV concept.

At first, some might think DA is too complicated. Actually, the foundation concepts are very straightforward. Our youth can and should learn these methods in high school or before. The Decision Education Foundation’s mission is “Improving the lives of young people by empowering them with effective decision skills.” They provide courses for educators, administrators, advisors, counselors, and mentors.

Decision DA is as much a matter of attitude and philosophy as it is a collection of calculation tools. The keys to successful application are being committed to good analysis and ensuring that everyone understands the basic concepts. This is not rocket science, merely good practice.

Further Reading

Clemen, Robert T., and Terence Reilly, 1997, *Making Hard Decisions: An Introduction to Decision Analysis, 2nd ed.*, Duxbury Press, Boston, 664 p.

A leading textbook for college instruction. Clemen and Reilly wrote a 2004 version for use with Palisade Corp.'s DecisionTools® Suite.

Hertz, David B., 1979, "Risk Analysis in Capital Investment," *Harvard Business Review*, v. 57, n. 5, Sept.-Oct., p. 169-81. (an earlier version appeared in the Jan.-Feb., 1964, issue).

An early, classic article of the application of simulation to business decisions. Still relevant except for his choice of decision criterion.

Howard, Ronald A., and Abbas, Ali E., 2015, *Foundations of Decision Analysis*, Prentice Hall.

Despite some unconventional notation and terminology, this may become a leading college textbook.

Newendorp, Paul D., and Schuyler, John, 2015, *Decision Analysis for Petroleum Exploration, 3.0 Edition*, Planning Press, ~580 p.

This has a petroleum industry emphasis, though offering universal techniques. Written as a reference handbook, this is the authors' most complete compilation of DA tools and techniques.

Schuyler, John, 2001, *Risk and Decision Analysis in Projects, 2nd edition*, Project Management Institute, Upper Darby, PA, USA, 259 p.

Based upon an 18-part tutorial series in *PM Network*. A third edition is planned for 2015.

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