

2.0 Decision Theory Literature Survey

2.1 Introduction

This chapter presents a survey of the decision making literature. This survey is necessarily selective because the body of work is so vast*. We structure this chapter as shown in Figure 2.1. Using this framework, we will locate our work in the prescriptive branch of the tree. We will then highlight the rationale for this positioning, as well as, the salient points of our contributions. But we defer any detailed discussions of our work to the rest of this document.

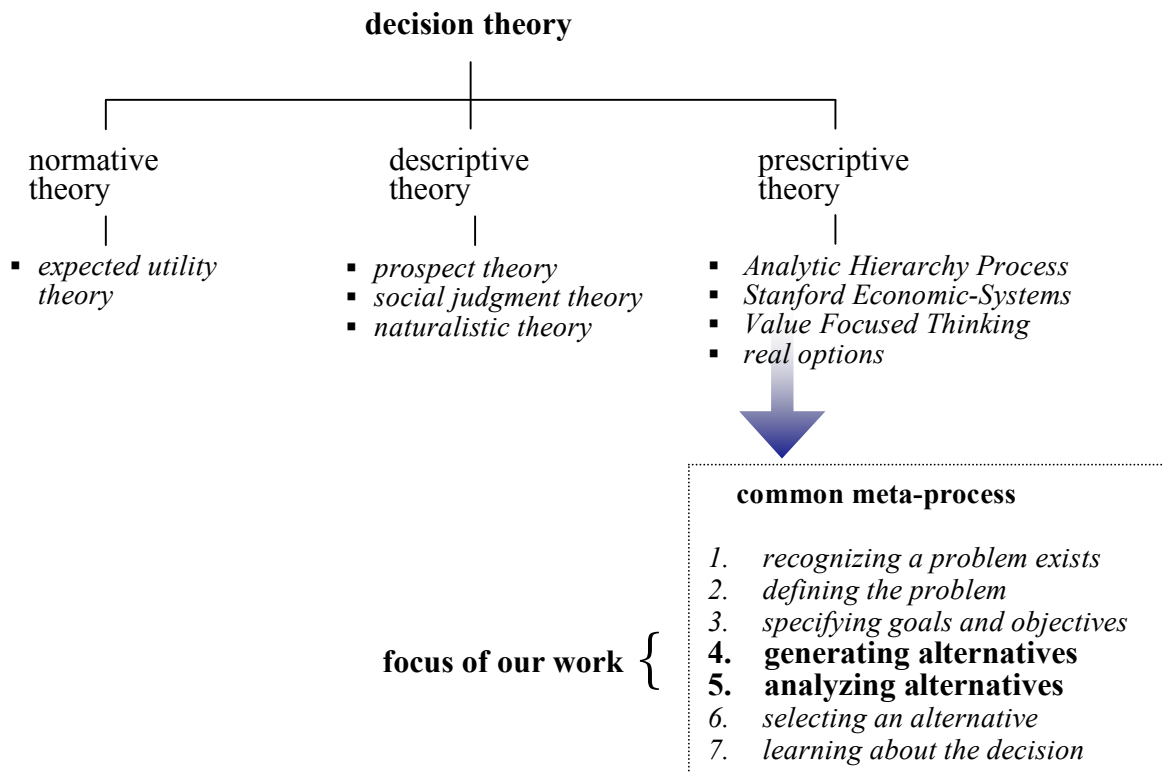


Figure 2.1. Chapter structure in graphical form

Scholars identify three research streams: the normative, descriptive, and prescriptive schools of decision-making. For our survey, we will select key representative work from each of the three streams as shown in each leg of the tree. Following a brief survey

* Edwards and von Winterfeldt (1986) write that “articles related to judgment and decision-making appeared in more than 500 different journals.” Under “decision theory,” Google scholar shows 652,000 citations and Amazon.books shows 207,238 titles.

of the normative and descriptive school, we sketch some apparent new directions in research. In the prescriptive stream, we select four strands of research as exemplars of prescriptive methods. These are shown as the right-hand branch of our tree. We will show that although each prescriptive method is unique, there is a *meta-process* that can represent each prescriptive method. This meta-process is known as the “canonical model” of decision making. Our work belongs in the prescriptive school. And within this school, our work is specifically located in the *construction* phase, i.e. the generation of alternatives, as well as, the analysis phase of the meta- model. This is the *design* phase of the decision process. Design, the subject of identifying and creating alternatives is virtually absent in the decision-making literature. It is generally assumed that alternatives exist, are easily found, or readily constructed. However, Simon (1997a) observes that:

“The classical view of rationality provides no explanation where alternate courses of action originate; it simply presents them as a free gift to the decision markers.”

This void is surprising because synthesis must necessarily precede analysis; analysis that determines the decision maker’s preferences among the alternatives and which culminates in the selection of the one choice to act upon. Analysis has crowded out synthesis. Consistent with our engineering orientation, we will use an engineering approach to specify, design, and analyze alternatives. We have excluded the selection of an alternative, i.e. what is generally considered decision-making, from our work. Our work in this dissertation concentrates on the construction and analysis of alternatives.

2.2 The three schools of decision making

A *decision* is making a choice of what to do and not to do, to produce a satisfactory outcome. (e.g. Baron 1998, Yates et al 2003). A decision is a commitment to action, an irreversible allocation of resources, and an ontological act (Mintzberg 1976, Howard 1983, Chia 1994, March 1997). *Decision theory* is an interdisciplinary field of study to understand decision-making. It is a “palimpsest of intellectual disciplines (Buchanan 2006)”. It draws from mathematics, statistics, economics, psychology, management, and other fields in order to understand, improve, and predict the outcomes of decisions under particular conditions.

The origins of modern decision theory are found in Bernoulli’s (1738) observation that the *subjective value*, i.e. utility, of money diminishes as the total amount of money increases. And to represent this phenomenon of diminishing utility, he proposed a logarithmic function (e.g. Fishburn 1968, Kahneman and Tversky 2000). However, utility remained a qualitative concept until the seminal work of von Neumann and

Morgenstern (1947). They generalized Bernoulli's qualitative concept of utility (which was limited to the outcome of wealth), developed lotteries to measure it, formulated normative axioms, and formalized the combination into an econo-mathematical structure - *utility theory*. Since then, the volume of research in decision making has exploded. Bell, Raiffa, and Tversky (1988) have segmented the contributions in this field into three schools of thought "that identify different issues ... and deem different methods as appropriate (Goldstein and Hogarth 1997)." They are the normative, descriptive, and prescriptive schools of decision making. We follow Keeney (1992) and summarize their salient features in Table 2.1.

Table 2.1. Summary of normative, descriptive, and prescriptive theories

	normative	descriptive	prescriptive
focus	how people should decide with logical consistency	how and why people decide the way they do	help people make good decisions prepare people to decide
criterion	theoretical adequacy	empirical validity	efficacy and usefulness
scope	all decisions	classes of decisions tested	specific decisions for specific problems
theoretical foundations	utility theory axioms	cognitive sciences psychology about beliefs and preferences	normative and descriptive theories decision analysis axioms
operational focus	analysis of alternatives determining preferences	prevention of systematic human errors in inference and decision-making	processes and procedures end-end decision life-cycle
judges	theoretical sages	experimental researchers	applied analysts

2.2.1 Normative Decision Theory

"Rationality is a notoriously difficult concept to understand."

O'Neill

Unlike planetary motion, or charged particles attracting each other, decisions do not occur naturally; they are acts of will (Howard 1992). Therefore, we need norms, rules, and standards. This is the role of normative theory. Normative theory is concerned with the nature of rationality, the logic of decision making, and the optimality of outcomes determined by their utility. Utility is a unitless measure of the desirability or degree of satisfaction of the consequences from courses of action selected by the decision maker (e.g. Baron 2000). Utility assumes the gambling metaphor where only two variables are

relevant: the strength of one's beliefs (probabilities), and the desirability of the outcomes (Goldstein and Hogarth 1997). The expected utility function for a series of outcomes with assigned probabilities takes on the form of a polynomial of the product of the probabilities and outcome utilities (e.g. Keeney and Raiffa 1993, de Neufville 1990). For the outcome $X = \{x_1, x_2, \dots, x_n\}$, their associated utilities $u(x_i)$ and probabilities p_i for $i=1, 2, \dots, n$, the expected utility for this risky situation is

$$u(X) = \sum p_i u(x_i) \text{ where } \sum p_i = 1.$$

In order to construct a utility function over lotteries, there are assumptions that need to be made about preferences. A *preference order* must exist over the outcome set $\{x_i\}$. And the axioms of: completeness, transitivity, continuity, monotonicity, and independence must apply (e.g. de Neufville 1990, Bell, Raiffa, Tversky 1995 edition, Resnik 1987, and Appendix 2.1). The outcomes and their utilities can be single attribute or multiattribute. For a multiattribute objective $\mathbf{X} = \{X_1, X_2, \dots, X_N\}$ and $N \geq 3$, under the assumptions of utility independence, the utility function takes the form:

$$KU(\mathbf{X}) + 1 = \prod (K_k U(X_k) + 1)$$

Where the attributes are independent, the utility function takes the form of a polynomial. A person's choices are *rational*, when the von Neumann and Morgenstern axioms are satisfied by their choice behavior. The axioms establish ideal standards for rational thinking and decision making.

In spite of its mathematical elegance, utility theory is not without crises or critics. Among the early crises were the famous paradoxes of Allais and Ellsberg (Allais 1953, Ellsberg 1961, e.g. Resnick 1987). People prefer certainty to a risky gamble with higher utility. People also have a preference for certainty to an ambiguous gamble with higher utility. Worse yet, preferences are reversed when choices are presented differently (Baron 2000). Howard (1992) retorts that the issue is one of education. Enlighten those that make these errors and they too will become utility maximizers. Others claim that incentives will lower the cost of analysis and improve rationality, but research shows that violations of stochastic dominance are not influenced by incentives (Slovic and Lichtenstein 1983). These paradoxes were the beginning of an accumulation of empirical evidence that people are not consistent utility maximizers or rational in the VNM axiomatic sense. People are at times arational.

A significant critique of classical normative theory was Simon's thesis of bounded rationality (Simon 1997b). Simon's critique strikes normative decision theory at its most fundamental level. Perfect rationality far exceeds people's cognitive capabilities to calculate, to have knowledge about consequences of choice, or to adjudicate among competing goals. Therefore, people *satisfice*, they do not maximize. Bounded rationality is rational choice that takes into consideration people's cognitive limitations. Similarly, March (1988, 1997), a bounded rationalist, observes that all decisions are about making two guesses – a guess about the future consequences of current action and a guess about future sentiments with respect to those consequences (March 1997). These guesses

assume stable and consistent preferences. Kahneman's (2003) experiments cast doubt on these assumptions; they show that decision utility and predicted utility are not the same. Keeney (1992) a strong defender of classical normative theory, identifies *fairness* as an important missing factor in classical utility theory. In general, people are not egotistically single-minded about maximizing utility. For example, many employers do not cut wages during periods of unemployment when it is in their interest to do so (Solow 1980). The absence of equity also poses the question about the "impossibility of interpersonal utility comparisons (Hausman 1995)." Sense of fairness is not uniform. Nor does utility theory address the issues of regret (Eppel et al 1992), which has become an important research agenda for legal scholars (Parisi and Smith 2005).

Experimental evidence is another contributing factor to the paradigmatic crises of normative theory. Psychologists have shown that people consistently depart from the rational normative model of decision making, and not just in experimental situations with colored balls in urns. The research avalanche in this direction can be traced to Tversky and Kahneman's (1974) article in *Science* and subsequent book (Kahneman, Slovic, Tversky 1982) where they report that people have systematic biases. Baron (2000) reports on 53 distinct biases. In light of these research results, Fishoff (1999), Edwards and von Winterfeldt (1986) report on a variety of ways to debias judgments. The analytic power of pure rational choice is not completely supported by experiments and human behavior because it does not address many human cognitive errors as presented by descriptive scholars. The contributions from psychologists to economic theory and decision-making have a high level of legitimacy and acceptance. Simon and Kahneman have both become Nobel laureates. And research in behavioral economics is thriving (e.g. Camerer, Lowenstein, Rabin 2004).

We note that many of the arguments and experiments that critique the normative theory are grounded in descriptions of how decision making actually takes place. Therefore, we now turn our attention to descriptive theory and then consider new research directions in decision making.

2.2.2 Descriptive Decisions Theory

"[let them] satisfy their preferences and let the axioms satisfy themselves."

Samuelson

Descriptive theory concentrates on the question of how and why people make the decisions they do. Simon (e.g. 1997) argues that rational choice imposes impossible standards on people. He argues for satisficing in lieu of maximizing. The Allais and Ellsberg paradoxes illustrate how people violate the norm of expected utility theory (Allais 1952, Ellsberg 1961, and e.g. Baron 2000, Resnick 1987). Experiments by

Kahneman and Tversky's (1974) publication of "judgments under uncertainty: heuristics and biases" reported on three heuristics: representativeness, availability, and anchoring. These heuristics lead to systematic biases, e.g. insensitivity to prior outcomes, sample size, regression to the mean; evaluation of conjunctive and disjunctive events; anchoring; and others. Their paper launched an explosive program of research concentrating on violations of the normative theory of decision making. Edwards and von Winterfeldt (1986) write that the subject of errors in inference and decision making is "large and complex, and the literature is unmanageable." Scholars in this area are known as the "pessimists" (Jungermann 1986, Doherty 2003)." For our work, the bias of overconfidence is very important (Chapter 9 of this dissertation). Lichtenstein and Fishoff (1977) pioneered work in overconfidence (also e.g. Lichstein, Fischhoff and Phillips 1999). They found that people who were 65 to 70% confident were correct only 50% of the time. Nevertheless, there are methods that can reduce overconfidence (e.g. Koriat, Lichstein, Fishoff 1980, Griffin, Dunning, Ross 1990). In spite of, or possibly because of, the "pessimistic" critiques of the normative school, descriptive efforts have produced many models of psychological representations of decision making. Two of the most prominent are: Prospect Theory (Kahneman and Tversky 2000) and Social Judgment Theory (e.g. Hammond, Stewart, Brehmer, Steinmann 1986).

Prospect Theory

Prospect theory is similar to expected-utility theory in that it retains the basic construct that decisions are made as a result of the product of "something like utility" and something like "subject probability" (Baron 2000). The something like utility is a value function of gains and losses. The central idea of Prospect Theory (Kahneman and Tversky 2000) is that we think of *value* as *changes* in gains or losses relative to a reference point (Figure 2.2).

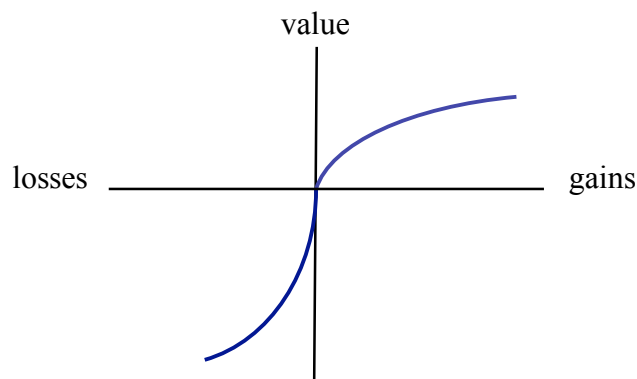


Figure 2.2. Hypothetical value function using prospect theoretic representation.

The carriers of value are changes in wealth or welfare, rather than their magnitude from which the cardinal utility is established. In prospect theory, the issue is not utility, but changes in *value*. The value function treats losses as more serious than equivalent gains. It is convex for losses and concave for gains. This is intuitively appealing, we prefer gains to losses. But if we consider the invariance principle of normative decision theory, this principle is easily violated in Prospect Theory. Invariance requires that preferences remain unchanged on the manner in which they are described. In prospect theory the gains and losses are relative to a reference point. A change in the reference point can change the magnitude of the change in gains or losses, which in turn result in different changes in the value function that induces different decisions. Invariance, absolutely necessary in normative theory and intuitively appealing, is not always psychologically feasible. In business, the current asset base of the firm (the status quo) is usually taken as the reference point for strategic corporate investments. But the status quo can be posed as a loss if one considers opportunity costs and therefore a decision maker may be lead to consider favorably a modest investment for a modest result as a gain. Framing matters.

The second key idea of prospect theory is that we distort probabilities. Instead of multiplying value by its subjective probability, a decision weight (which is a function of that probability) is used. This is the so-called π function. (Figure 2.3) The values of the subjective probability p are underweighed relative to $p=1.0$ by the π function. And the values of p are overweighed relative to $p=0.0$. In other words, people are most sensitive to changes in probability near the boundaries of impossibility ($p=0$) and certainty ($p=1$). This helps explain why people buy insurance - the decision is weighed near the origin. And why people prefer a certainty of a lower utility than a gamble of higher expected utility. This decision is weighed near the upper right-hand corner. The latter is called the “certainty effect” e.g. Baron (2000). This effect produces unrational decisions (e.g. Baron 2000, de Neufville and Delquié 1988, McCord and de Neufville 1983).

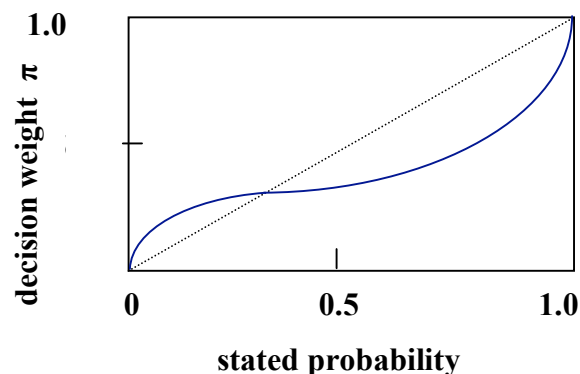


Figure 2.3. A hypothetical weighing function under prospect theory.

In summary, prospect theory is descriptive. It identifies discrepancies in the expected utility approach and proposes an approach to better predict actual behavior. Prospect theory is a contribution from psychology to the classical domain of economics.

Social Judgment Theory

Another contribution from psychology to decision theory is Social Judgment Theory (SJT) (e.g. Hammond, Stewart, Brehmer, Steinmann 1986). SJT derives from Brunswick’s observation that the decision maker decodes the environment via the mediation of cues. It assumes that a person is aware of the presence of the cues and aggregates them with processes that can be represented in the “same” way as on the environmental side. Unlike utility theory or prospect theory, the future context does not play a central role in SJT. Why is this social theory? Because different individuals, for example experts, faced with the same situation will pick different cues or integrate them differently (Yates, Veinott, Palatano 2003). The SJT descriptive model (lens model) is shown in Figure 2.4*. The left-hand side (LHS) is the environment; the right-hand side (RHS) is the judgment side where the decision maker is interpreting the cues, $\{X_i\}$, from the environment. The ability of the decision maker to predict the world is completely determined by how well the world can be predicted from the cues, how consistently the person uses the available data Y_s , and how well the person understands the world G, C . These ideas can be modeled analytically.

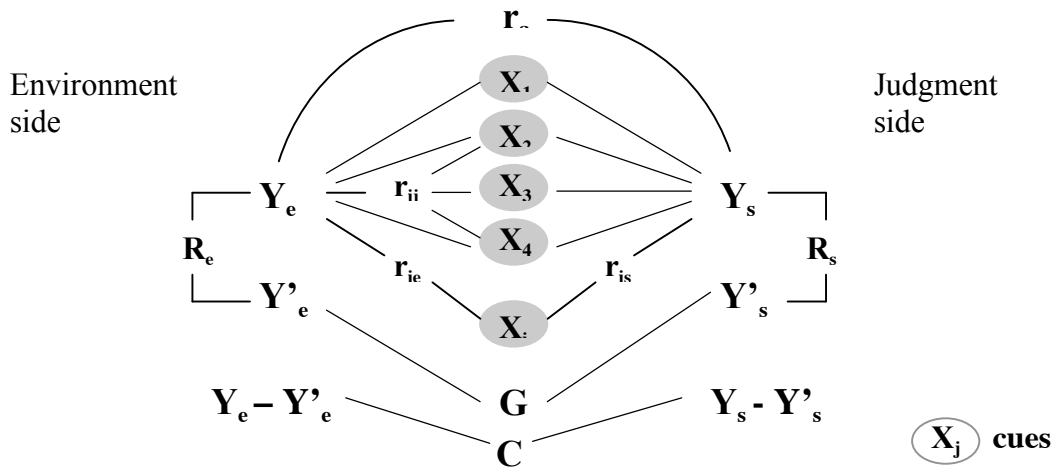


Figure 2.4. The lens model of Social Judgment Theory.

The system used to capture the aggregation process is typically multiple regression. We have a set of observations, Y_s . We also have ex post information on the true state Y_e . The statistic r_a , the correlation between the person’s responses and the ecological criterion values, reflects correspondence with the environment. $R_s \leq 1.0$ is the degree to

* This description is adapted from Doherty 2003.

which the person's judgment is predictable using a linear additive model. The cue utilization coefficients r_{is} ought to match the ecological validities r_{ie} through correlations. G is the correlation between the predicted values of the two linear models. G represents the validity of the person's knowledge of the environment. C is the same between the residuals of both models, and reflects the extent to which the unmodeled aspects of the person's knowledge match the unmodeled aspects of the environmental side. Achievement is represented by

$$r_a = R_e * R_s * G + C[(1 - R_e^2) * (1 - R_s^2)]^{1/2}$$

A person's ability to predict the world is completely determined by how well the world can be predicted from the available data R_e , how consistently the person uses the available data R_s , and how well the person understands the world, G and C . We note the similarity of this model with Ashby's (1957) Law of Requisite Variety from complex systems theory. It states that the complexity of environmental outcomes must be matched by the complexity of the system so that it can respond effectively. In order for the system to be effective in its environment, it must be of similar and consistent complexity as the environment that is producing the outcomes.

Naturalistic Decision Making

We must bring up another strand in the descriptive school, the Naturalistic Decision Making school. Members of this strand reject the classical notions of utility maximizing and economic rationality; they opt for descriptive realism (e.g. Gigerenzer and Selten* 2001, Klein 1989, 1999, 2001, Pliske and Klein 2003). Gigerenzer (2001) writes that "optimization is an attractive fiction." Instead, for decision making he offers an "adaptive toolbox," a set of "fast and frugal" heuristics comprised of search rules, stopping rules, and decision rules. Klein's work describes decision making in exceptional situations which are characterized by high time pressure, context rich settings, and volatile conditions. Klein studies experienced professionals with domain expertise and strong cognitive skills, such as, firefighters, front line combat officers, economics professors, and the like. He finds that they are capable of "mental simulations," that is "building a sequence of snapshots to play out and to observe what occurs (Klein 1999)." They rely on just a few factors – "rarely more than three ... [and] a mental simulation [that] can be completed in approximately six steps (Klein 1999)." For us this is an important result, for we will combine this finding with other similar research findings for our work.

2.2.3 Research-Directions

We have seen how paradoxes and the landmark experiments of Kahneman and Tversky, present evidence that people arrive at decisions that are not consistent with normative

* Selten is also a Nobel laureate.

theory. These paradoxes and experiments are descriptive. The Naturalistic strand of research describes how professionals under situations of extreme pressure and volatile conditions make decisions, it presents a picture that is different from normative theory. Zechhauser's (1986) articulates the debate between normative and descriptive theorists with three insightful axioms and three practical corollaries. They are paraphrased below because they capture the spirit of the research directions in decision theory.

Axiom 1. For any tenet of rational choice, the behavioralists can produce a counterexample in the laboratory.

Axiom 2. For any "violation" of rational behavior, the rationalists will reconstruct a rational explanation.

Axiom 3. Elegant formulations will be developed by both sides, frequently addressing the same points, but freedom in model building will result in different conclusions.

Corollary 1. The behaviorists should focus their laboratory experiments on important real world problems.

Corollary 2. The rationalists should define the domains of economics where they can demonstrate evidence that supports their view.

Corollary 3. Choice of competing and/or conflicting formulations should be decided on predictive consistency with real world observations.

Bernoulli (1738) is credited with the qualitative concept of utility. Von Neumann and Morgenstern (1947) took this concept, formalized it, and build a system of thought for rational decision making. Recent research is looking more deeply at the fundamentals, e.g. what is utility? Is it in our interest to maximize utility? What are the deep mental and psychological processes for decision making and how do they work? Kahneman (2003) distinguishes between *experience utility* and *decision utility*. Experience utility will differ on how and when it is measured, as it is experienced or retrospectively. Experimental findings reveal that recall is imperfect and easily manipulated. We interpret this as another kind of bias. These findings go to the heart of the assumptions of normative theory: that individuals have accurate knowledge of their own preferences and that their utility is not affected by the anticipation of future events. Schooler, Ariely, and Lowenstein (2003) argue that people suffer from inherent inabilities to optimize their own level of utility. They find that deliberate efforts to maximize utility may lead individuals to engage in non-utility maximizing behaviors. They suggest that "utility maximization is an imperfect representation of human behavior, regardless of one's definition of utility (Schooler, Ariely, and Lowenstein 2003)." The cognitive processes for decision making appears to be more sophisticated than merely optimizing utility. Bracha (2004) suggests a framework that involves two internal accounting processes, a rational account and a mental account. A choice is the result of intrapersonal moves that results in a Nash equilibrium. This game theoretic approach is also adopted by Borodner and Prelec (2003) where they model utility maximization as a self signaling-game involving two kinds of utility: outcome utility and diagnostic utility. *Neuroeconomics* is

a new research strand. It seeks to understand decision processes at a physiological level (e.g. Camerer, Lowenstein, and Prelec 2005). It seeks to use technology like MRI to understand which areas of the brain are used in decision making. McCabe, Smith and Chorvat (2005) found that people that cooperate and do not cooperate have different patterns of brain activity. The evidence suggests that different mechanisms were at work for the same problem. The legal scholars appear very active in study of irrational behavior to understand the issues of reciprocity, retaliation and their implications on judicial punishment (Parisi and Smith 2005).

2.2.4 Prescriptive Decision Making

“decision analysis will not solve a decision problem, nor is it intended to. Its purpose is to produce insight and promote creativity to help decision makers make better decisions.”

Keeney

Prescriptive decision theory is concerned with the practical application of normative and descriptive decision theory in real world settings. *Decision analysis* is the body of knowledge, methods, and practices, based on the principles of decision theory, to achieve a social goal – to help people and organizations make better decisions (Howard 1983) and to act more wisely in the presence of uncertainties (Edwards and von Winterfeldt 1986). Decision analysis is a science for the “formalization of common sense for decision problems, which are far too complex for informal use of common sense (Keeney 1982).” Decision analysis includes also the design of alternative choices – the task of “... logical balancing of the factors that influence a decision ... these factors might be technical, economic, environmental, or competitive; but they could be also legal or medical or any other kind of factor that affects whether the decision is a good one (Howard 1983).” Howard (1983) notes that “there is no such thing as a final or complete analysis; there is only an economic analysis given the resources available.” Decision analysis is, therefore, boundedly rational. “The overall aim of decision analysis is insight, not numbers (Howard 2004; 184).

A comprehensive survey of decision analysis and their applications can be found in Keefer, Kirwood, and Corner (2004). We will limit our coverage to four prescriptive methods: AHP (Saaty 1986, 1988); Ron Howard’s method, published by Strategic Decisions Group (SDG) representing the Stanford University school of decision analysis (Howard and Matheson 2004); Keeney’s Value Focused Thinking (Keeney 1992b), and real options (Brach 2003, Adner and Levinthal 2004).

We begin with AHP. It is distinctive, it does not use utility theory. Instead it uses “importance” as the criterion for decisions. It is an exemplar of a prescriptive approach that departs from the norm of using utility theory. In contrast, Howard’s method adheres

rigorously to the normative rules of normative expected utility theory. As such that is an exemplar of a normative approach. Keeney’s Value Focused Thinking is also utility theory based. And Keeney has defined and specified comprehensive and pragmatic processes that strengthen the usually “soft” managerial approaches to the specification of objectives and to the creation of alternatives. As such it is an exemplar of an analytically rigorous and simultaneously managerially pragmatic prescriptive method. Real options is discussed because it a new trend in decision analysis. Table 2.2 presents a summary of the four descriptive methods. More detail is presented in the paragraphs that follow.

Table 2.2 Summary of four descriptive methods

	AHP	Stanford	Value Focused Thinking	real options
preference based on	importance	utility	utility	monetary value.
units	unitless	utils	utils	monetary units
foundations	Ratio scale of pairwise comparisons.	Expected utility theory.	Expected utility and multiattribute utility theory.	Temporal resolution of uncertainty.
principles	Linear ordering by importance.	Rigorous use of normative axioms of utility theory.	Pragmatic use of normative axioms of utility theory.	Sequential temporal flexibility.
distinctive processes / analyses	Factors hierarchy. Matrix -pairwise comparisons No statistics.	Deterministic system representation. Utility function construction.	Specification of values and objectives. Guidelines for alternatives.	Options thinking-abandon, stage, defer, grow, scale, switch.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a prescriptive method predicated on three principles for decision problem solving: decomposition, comparative judgments, and synthesis of priorities (Saaty 1986). The decomposition principle calls for a hierarchical structure to specify all the elemental pieces of the problem. The comparative judgment principle calls for pairwise comparisons using a ratio scale to determine the relative priorities within each level of the hierarchy. The principle of synthesis of priorities is applied as follows (Forman and Gass 2001):

- (1) given $i=1,2,\dots,m$ objectives, determine their respective weights w_i ,
- (2) for each objective i , compare the $j=1,2,\dots,n$ alternatives and determine their weights w_{ij} wrt objective i , and
- (3) determine the final alternative weights (priorities) W_j wrt all the objective by $W_j = w_{1j}w_1 + w_{2j}w_2 + \dots + w_{mj}w_m$. The alternatives are then ordered by the W_j .

AHP is widely used as an alternative to expected utility theory for decision making (Forman and Gass 2001). Forman and Gass (2001) report that over 1000 articles and about 100 doctoral dissertations have been published. But concerns have been raised about AHP. Intransitivity and rank reversal are two violations of normative axioms that can occur in AHP (e.g. Dyer 1990, Belton and Gear 1984). AHP’s approach of pairwise comparison conflates the magnitude and weight of a comparison in a ratio scale in a similar way that the Taguchi method’s signal-to-noise ratio conflates location and dispersion effects. Saaty (2000) and Forman and Gass (2001) retort that rank reversal in closed systems is expected and even desirable when new information is introduced. Consistent with the pragmatics of a prescriptive approach to decision-making, they write “There is no one basic rational decision model. The decision framework hinges on the rules and axioms the DM [decision maker] thinks are appropriate (Forman and Gass 2001).” As a defense, Saaty (1990) quotes McCord and de Neufville (1983b): “Many practicing decision analysts remember only dimly its axiomatic foundation the axioms, though superficially attractive, are, in some way, insufficient ... the conclusion is that the justification of the practical use of expected utility decision analysis as it is known today is weak.”

Stanford Normative School

“Decision analysis” was coined by Howard (1966). His approach to decision analysis is predicated on two premises. One is an inviolate set of normative axioms and the other is his prescriptive method to decision analysis. Collectively these form his canons of the “old time religion” (Appendix 2.2) and position others as “heathens, heretics, or cults (Howard 1992).” His methodology takes the form of an iterative procedure he calls the Decision Analysis Cycle (Figure 2.5) comprised of three phases, which either terminates the process or drives an iteration (Howard 2004). Numerous applications from various industries are reported in Howard (2004).

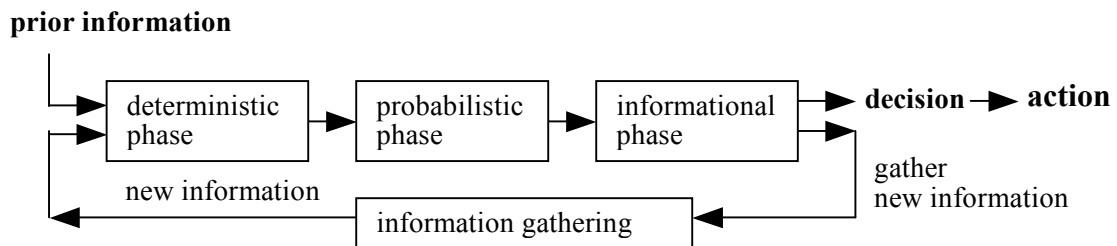


Figure 2.5. Howard’s Decision Analysis Cycle.

The first phase (deterministic) is concerned with the structure of the problem. The decision variables are defined and their relationships characterized in formal models. Then values are assigned to possible outcomes. The importance of each decision variable is measured using sensitivity analysis, and at this stage without any

consideration of uncertainty. Experience with the method suggests *that “only a few of the many variables under initial consideration are crucial”* ... (von Staël 1976, 137).”

Uncertainty is explicitly incorporated in the second phase (probabilistic) by assigning probabilities to the important variables, which are represented in a decision tree. Since the tree is likely to be very bushy, “back of the envelope calculations” are used to simplify it (von Staël 1976). The probabilities are elicited from the decision makers directly or from trusted associates to whom this judgment is delegated. The outcomes at each end of the tree are determined directly or through simulation. The cumulative probability distribution for the outcome is then obtained. Then the decision maker’s attitude toward risk is taken into account. This can be determined through a lottery process. A utility function is then encoded. The best alternative solution in the face of uncertainty is the called certainty equivalent. Sensitivity to different variable’s probabilities is performed.

The third (informational) phase is when the results of the first two phases are reviewed to determine whether more information is required; if so the process is repeated. The cost of obtaining additional information is traded-off against the potential gain in performance of the decision.

Value Focused Thinking

The prescriptive approach of Keeney’s (1992b) Value Focused Thinking (VFT) shifts the emphasis of decision making from the analysis of alternatives to “values”. In VFT, values are what decision makers “really care about” (Keeney 1994). The emphasis on values originates in the potential risks of anchoring and framing (Kahneman and Tversky 2000). Avoid anchoring on a narrowly defined problem that will preclude creative thinking. Instead, anchor on values and frame the decision situation as an opportunity. The assumption is that opportunities lead to more meaningful alternatives to attain the desired values. The theoretical assumptions of VFT are found in expected utility theory and multiattribute utility theory (Keeney and Raiffa 1999) and axioms from normative decision theory (Keeney 1982, 1992b). However, we note that Keeney is more liberal than Howard, Keeney is prepared to consider a suboptimal decision if it is more fair (equitable) (Keeney 1992a). He writes that “the evaluation process and the selection of an alternative can then be explicitly based on an analysis relying on *any** established evaluation methodology (Keeney 1992b).” Adapting from Keeney (1992b), the operational highlights of the VFT method is illustrated below (Figure 2.6), where the arrows mean “lead to.”

What is distinctive is that this method has specified an iterative phase at the front-end where the values of the decision-maker are thoroughly specified prior to the analysis of

* italics are mine.

alternatives. The goal of this phase is to avoid solving the wrong problem and to identify a creative set of alternatives. These steps avoid many of the biases identified in descriptive decision theory, such as, framing, availability, saliency and the like. Keeney (1992b) observes that the most effective way to define objectives and values is to work with the stakeholders. He offers ten techniques for identifying objectives and nine desirable properties for fundamental objectives. Having an initial set of objectives is a prerequisite to creating alternatives. Creativity is the most desirable characteristic for alternatives and VFT presents 17 ways to generate alternatives (Keeney 1992). Keeney's book VFT (1992b) discusses 113 applications.

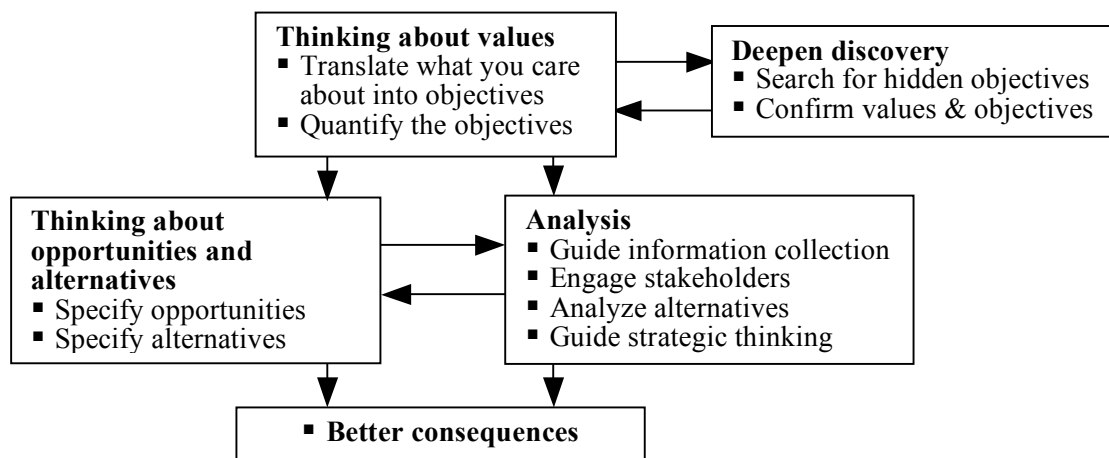


Figure 2.6. Operational architecture of the Value Focused Thinking process.

Real Options

Myers (1977) is credited with coining the term *real options*. An *option* is a right, but not an obligation, to take action, such as buying (call option) or selling (put option) a specified asset in the future at a designated price (e.g. Amram, Kulatilaka 1999). Options have value because the holder of the option has the opportunity to profit from price volatility while simultaneously limiting downside risk. Options give its holder an asymmetric advantage. Real options deal with real assets, not financial instruments that can be traded in exchanges (e.g. Barnett 2005) in efficient markets. Holders of an option have at their command a repertoire of six types of actions: to defer, abandon, switch, expand/contract, grow, or stage (Trigeorgis 1996). Unlike traditional techniques like discounted cash flow, real options is a flexible method of making investments. A real option is not subject to a one-time evaluation, but a sequence of evaluations over the course of the life-cycle of a project. This flexibility to postpone decisions until some of the exogenous uncertainty is resolved, also reduces risk. The Black-Scholes equation is a financial tour-de-force (e.g. Brealey and Myers 2002) and it is inextricably linked with options. But its use in real options has limitations. Returns in the Black-Scholes

equation must be log normal; and it is assumed that there is an efficient market for unlimited trading. For securities, the value of the asset is observable through pricing in an efficient market, for real options the value of the asset is still evolving (Brach 2003). Fortunately, there are many techniques for valuation (e.g. Neeley and de Neufville 2001, Luehrman 1998a, Luehrman 1998b, Copeland and Tufano 2004). However, the managerial implications for real options remain non trivial. It requires substantially more management attention to monitor and to act on the flexibility of the method (Adner and Levinthal 2004). “The value of the real option lies in exploiting it when conditions are right (de Neufville 2001).” Barnett (2005) finds that discipline and decisiveness required to abandon a project are demanding and rare traits in executive management. We see many applications using real options (e.g. Faulkner 1996; Brach 2003; Luehrman 1998a; Fichman, Keil, Tiwana 2005).

De Neufville (2001) presents a three phase process for real options analysis in systems planning and design. It is comprised of discovery, selection, and monitoring. Discovery is a multidisciplinary activity. It entails objectives setting and identifying opportunities. The selection phase is analytic intensive to calculate the value of the options in order to select the best one. Monitoring is the process to determine when the conditions are right to take action. Copeland and Tufano (2004) concentrate on the selection phase and present a procedure using binomial trees. Luehrman (1998a, 1998b) present an elegant and more sophisticated analytic procedure to create a partitioned options-landscape. The landscape identifies six courses of action: invest now, maybe now, probably later, maybe later, probably never, and never. These choices are based on financial metrics. Barnett (2005) presents a framework for managing real options. It is somewhat generic and not directly actionable. We adapt de Neufville’s three phase approach and combine it with Trigeorgis (1998) repertoire of six actions to illustrate a prescriptive decision process for real options (Figure 2.7).

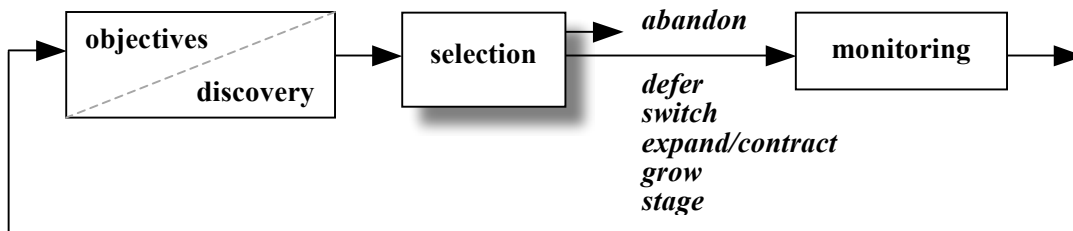


Figure 2.7. Active management of real options

In summary, real options represents a newer direction in decision analysis. It is distinctive; it avoids the limitations of discounted cash flow investment approach. The method is based on sequential incremental decision making to make temporal resolution of uncertainty work. This makes decision making more flexible.

2.3 The canonical normal form.

“We assume that the decision maker’s problem has been identified and viable action alternatives are prespecified.”
Keeney and Raiffa

Although each prescriptive method is unique, we argue that they are all instantiations of the “canonical paradigm” of decision making (Bell, Raiffa, Tversky 1988, 18). This model is widely adopted in the literature in various forms (e.g. Bazerman 2000, March 1997, Simon 1997, Keeney 1994, Hammond, Stewart, et al 1986). The canonical paradigm posits that the decision making is comprised of seven steps:

1. recognition that a problem or an opportunity exists
2. defining the problem or opportunity
3. specifying goals and objectives
4. generating alternatives
5. analyzing alternatives
6. selecting an alternative
7. learning about the decision.

The Scientific Method is an instantiation of the canonical paradigm. Biologists, chemists, and physicists routinely perform experiments that bear little resemblance to each other, but their methods align consistently with the scientific method. The scientific method is a meta-process for doing science. The Engineering Method (Seering 2003) is also an instantiation of the canonical paradigm. Electrical, mechanical, and aeronautical engineers build artifacts that are quite distinct from each other, but their methods are isomorphic to the engineering method. In this same way, each of the prescriptive methods we have described in previous sections, although uniquely distinctive, aligns consistently with the canonical model. The canonical model is a meta-process for decision analysis.

Simon (1997a) writes that:

“The classical view of rationality provides no explanation where alternate courses of action originate; it simply presents them as a free gift to the decision markers.” And,

“the lengthy and crucial processes of generating alternatives, which include all the processes that we ordinarily designate by the word ‘design,’ are left out of the SEU account of economic choice.”

The research on this crucial design phase of decision making (step 4 of the canonical paradigm) is not emphasized in the decision-making literature. But its importance is recognized, e.g. “the identification of new options is even more important and necessary than anchoring firmly on analysis and evaluation as goals of the analysis (Thomas and

Samson 1987).” Alexander (1979) presents case studies of design of alternatives and finds that there is a tendency to truncate the repertoire of alternatives prematurely in the overall process. He concludes that “alternatives design is a stage in the decision process whose neglect is unjustified ... (Alexander 1979).” Arbel and Tong (1982) prescribe the use of AHP as a means to identify the most important variables that affect the objectives of a decision for creating alternatives. But they fall short of providing an actionable construction process for alternatives. Ylmaz (1997) argues for a constructive approach to create alternatives and presents a way to do so using explicitly identified decision factors and their range of responses. His construction requires full-factorial information, which makes the construction process complicated.

This thin presence in design of alternatives is also discernable in our prescriptive exemplars (Table 2.3).

Table 2.3. Summary comparison

	AHP	Stanford	VFT	real options	us
1 Detection of problem/opportunity	○	○	○	○	○
2 Definition of the problem	○	○	⊙	○	⊙
3 Specify objectives	⊙	○	●	⊙	⊙
4 Creating alternatives	⊙	⊙	⊙	●	●
5 Analysis of alternatives	●	●	●	●	●
6 Select alternatives	●	●	●	●	⊙
7 Learning, communicating	○	○	○	⊙	○

- assumed doable
- ⊙ guidelines provided
- generic alternatives defined
- explicit prescriptions

Given a set of alternatives, AHP offers guidelines for creating a hierarchy of decision factors. AHP assumes that the alternatives are known, but what are unknown are the weights of the factors that will enter into the selection of an alternative. By building a hierarchy of the decision factors, the objective, factors, the alternatives are linked through the hierarchy. Using the relative importance of the factors, the AHP method identifies the alternative that satisfies the most important factors. In Stanford’s method, through sensitivity analysis one finds the variables that have the highest impact on the output. Using those variables, we are directed to create creative alternatives, but we are not presented with explicit means to construct alternatives. With the alternatives at hand, utility theory is used to identify the best one. Value Focused Thinking makes creating alternatives the centerpiece of the method and it presents a comprehensive approach to objectives specification. Objectives are used to guide the creation of alternatives. To

create alternatives, 17 very useful guidelines are presented. We are told that “the mind is the sole source of alternatives” and therefore creativity is important. Although we are given a comprehensive set of guidelines and many examples of alternatives from a wide range of applications, Value Focused Thinking does not offer a construction mechanism for the creation of alternatives. At the core, real-options is about two things: sequential incremental decisions, and temporal resolution of uncertainties as time progresses so that the valuation and selection of alternatives are more certain. Like other prescriptive methods it assumes that alternatives can be analyzed rigorously following the procedures of their method. What is distinctive about the real options method is that has a predefined set of generic alternatives (e.g. Trigeorgis 1998, Luerhman 1998a). For example, see Figure 2.7.

This void in research in step 4 of the canonical model, the construction of alternatives, is unexpected. Prescriptive methods are the engineering of decision making; and construction of alternatives is the *design* phase of the canonical paradigm. It is generally assumed that alternatives exist, are easily found, or readily constructed. These assumptions are surprising because synthesis must necessarily precede analysis; analysis that determines the decision maker’s preferences among the alternatives and which culminates in the selection of the one choice to act upon. Analysis has crowded out synthesis. This is like the apocryphal basketball team that that only shoots free throws at every practice (Seering 2003). The assumption being that “the rest of the game is a straightforward extension of making free throws and can best be learned by experience in a game situation (Seering 2003).” Our work will not assume that alternatives are present and ready for analysis. We will use engineering methods of DOE for the construction of alternatives and for the analyses of alternative solutions under uncertainty. These are the subjects of this dissertation and we will try to show that our work is distinctive because:

- We provide an explicit construction mechanism for alternatives creation.
- Alternatives are constructed using variables that are under managerial control and those that are external to management control and are therefore uncontrollable.
- Alternatives span the entire solution space.
- The analysis of alternatives does not require exhaustive analysis of every possible alternative, but is able to predict the value of the maximum outcome.
- The analysis does not require the subjective translation from natural units (e.g. profit, safety, ...) into subjective utility or judgments of “importance” as in AHP. All the analyses are performed in their natural units.
- In the face of uncertainty, we can construct a robust decision (e.g. Taguchi, Chowdury, Taguchi 2000). This is a proactive approach whereby we can construct an alternative that will satisfice under conditions that are unpredictable over the entire space of uncertainty.

The goal of decision analysis is concerned with helping people make better decisions, we must ask: What is a good decision? This is the subject of the next section.

2.4 What is a good decision?

“We can never prove that someone who appeals to astrology is acting in any way inferior to what we are proposing. It is up to you to decide whose advice you would seek.”
Howard

There is no consensus on the definition of a good decision. We will review representative positions on this issue and then present Howard’s criteria of a good decision, which is the one we will adapt for our work.

Those that favor the normative school of decision-making draw a sharp distinction between a good decision and a good outcome (e.g. Howard 1983, Baron 1988). Any decision that adheres to rational procedures and the axioms of normative theory is considered a good decision (Appendix 2.1). To them, the actual outcome is not a valid evaluative factor because any decision can produce bad results given the stochastic nature of the events (e.g. Hazelrigg 1996). We adopt this position. The emphasis on axioms and rigorous rules of thought characterize the practitioners of the “old time religion (Howard 1992)” of decision making. (Appendix 2.2 shows the canons of the old time religion.) In contrast, scholars from the descriptive school report on experiments where people do consider good results, missed opportunities, difficulty, and other factors as important categories of decision quality (Yates et al. 2003). Research in behavioral decision making shows a more complicated picture about the mental processes of decision making than single minded “utility” maximization (e.g. Kahneman 2003, Schooler, Ariely, and Lowenstein 2003, Stamer 2004).

Those of the prescriptive school are more pragmatic and embrace bounded rationality. Edwards (1992) presents proverbs for descriptive theory although he calls them “assumptions and principles” (Appendix 2.4). Keeney (1992b) writes that the problem should guide the analysis and the choice of axioms. And for selecting axioms, he offers the following guidelines. (Table 2.4)

Table 2.4 Objectives of axiom selection for decision analysis

Objectives of axioms for decision analysis
<p>Provide the foundation for a quality analysis address the problem complexities explicitly provide a logically sound foundation for analysis provide for a practical analysis be open for evaluation and appraisal</p>

And to bring insight into the decision and maximize the quality of an analysis, he specifies a set of objectives for the practice of decision analysis (Table 2.5). Unlike many from the descriptive school, “good outcomes” is noticeably absent.

Table 2.5 Objectives of decision analysis quality

Objectives of decision analysis
Provide insight for the decision create excellent alternatives understand what and why various alternatives are best communicate insights
Minimize effort necessary time utilized cost incurred
Contribute to the field of decision analysis
Maximize professional interest enjoy the analysis learn from the analysis

In summary, to those from the normative school, a good decision has coherence and invariance with the axioms of utility theory. Moreover, given the unpredictability of future events, the quality of a decision is completely decoupled from outcomes. To those who favor descriptive theories, outcomes and other behavioral variables are important factors that determine decision quality. Their argument is buttressed by empirical evidence. Those in the prescriptive camp are boundedly rational, the specific problem guides the selection of axioms, and insights that are useful to the client are the key determinants of decision quality.

Edwards (1992) reports on an informal survey he took at a prestigious conference. His survey showed an overwhelming agreement that expected utility theory is the appropriate normative standard for decision making under uncertainty. The same group also showed an overwhelming agreement that experimental evidence shows that expected utility theory does not fully describe the behavior of decision makers. Tversky and Kahneman (2000) summarize work from scholars that show that dominance and invariance are essential and that selective relaxation of other axioms is possible. This lends force to Keeney’s (1992b) pragmatic objectives for prescriptive decision analysis and axioms selection.

Howard’s Criteria of a Good Decision

Howard (2001) identifies six criteria to determine decision quality. They are:

1. **A committed decision-maker.** By definition a decision is a commitment to action, of making a choice of what to do and what not to do (Section 2.2 of this chapter). A decision does not exist without a principal who is ready to take action and reallocate resources for more attractive outcomes.
2. **A right frame.** A decision frame is “the decision maker’s conception of the acts, outcomes, and contingencies associated with a particular choice. (Tversky and Kahneman 1981)”. Framing is the process of specifying the boundaries of the decision situation. The frame determines what is considered relevant and what is irrelevant in the decision analysis.
3. **Right alternatives.** Step 4 of the canonical model is the process of generating alternatives. Howard states that this is the “most creative part of the decision analysis procedure (Howard 1983).” His test of a creative alternative is one that “suggests the defect in present alternatives that new alternatives might remedy.”
4. **Right information.** Information is a body of facts and/or knowledge that will improve the probability that the DM’s preferred choice will lead to a more desirable outcome (e.g. Hazelrigg 1996).
5. **Clear Preferences.** Howard’s desiderata in Appendix 2.2 summarize what he means by “clear preferences.”
6. **Right decision procedures.** This means adherence to the desiderata of Appendix 2.2 and consistent with the axioms of Appendix 2.1. Having the right decision procedure also means following “good engineering practice” for the synthesis of new alternatives prior to analysis of alternatives. .

We will use these criteria to evaluate the decision quality of our field experiments. Note that the outcome of the decision is not a criterion of decision quality. We agree with this position, any decision can produce bad results given the stochastic nature of the events (e.g. Hazelrigg 1996). Howard (1992) cogently articulates this position ...

“Everyone wants good rather than bad, more rather than less – the question is how we get there. The only thing you can control is the decision and how you go about making that decision. That is the key.”

Appendix 2.1 The Utility Theory Axioms

A *lottery, or gamble*, is central to utility theory. A lottery is a list of ordered pairs $\{(x_1, p_1), (x_2, p_2), \dots, (x_n, p_n)\}$ where x_i is an outcome, and p_i is the probability of occurrence for that event.

completeness.

For any two lotteries g and g' , either $g \succeq g'$ or $g' \succeq g$.

i.e. given any two gambles, one is always preferred over the other, or they are indifferent.

transitivity.

For any 3 lotteries, g , g' , and g'' , then if $g \succeq g'$ and $g' \succeq g''$, then $g \succeq g''$.

i.e. preferences are transitive.

continuity.

If $g \succeq g' \succeq g''$, then there exists α, β in $(0,1) \ni: \alpha g + (1-\alpha)g'' \succeq g' \succeq \beta g + (1-\beta)g''$.

i.e. the Archimedean property holds, a gamble can be represented as a weighted average of the extremes.

monotonicity.

Given (x_1, p_1) and (x_1, p_2) with $p_1 > p_2$, then (x_1, p_1) is preferred over (x_1, p_2) .

i.e. for a given outcome, the lottery that assigns higher probability will be preferred.

independence (substitution).

If x and y are two indifferent outcomes, $x \sim y$, then $xp + z(1-p) \sim yp + (1-p)z$.

i.e. indifference between two outcomes also means indifference between two lotteries with equal probabilities, if the lotteries are identical. i.e. two identical lotteries can be substituted for each other.

Appendix 2.2 Desiderata of Normative Decision Theory

Normative decision theory's strongest evangelist is Howard from Stanford. He puts forward the canons of "old time religion" as the principles of normative decision making. These are summarized by Eppel et al (1992) as shown below.

Desiderata of Normative Decisions
<p>Essential properties</p> <hr style="border-top: 1px dashed black;"/> <ul style="list-style-type: none"> applicable to any decision must prefer deal with higher probability of better prospect indifferent between deals with same probabilities of same prospects invariance principles <ul style="list-style-type: none"> reversing order of uncertain distinctions should not change any decision order of receiving any information should not change any decision "sure thing" principle is satisfied independence of immaterial alternatives new alternatives cannot make an existing alternative less attractive clairvoyance cannot make decision situation less attractive sequential consistency, i.e. at this time, choices are consistent equivalence of normal and extensive forms
<p>Essential properties about prospects</p> <hr style="border-top: 1px dashed black;"/> <ul style="list-style-type: none"> no money pump possibilities certain equivalence of deals exist value of new alternative must be non-negative value of clairvoyance exists and is zero or positive no materiality of sunk costs no willingness to pay to avoid regret stochastic dominance is satisfied
<p>Practical considerations</p> <hr style="border-top: 1px dashed black;"/> <ul style="list-style-type: none"> individual evaluation of prospect is possible tree rollback is possible

Appendix 2.3. Keeney's Axiomatic Foundations of Decision Analysis

Keeney articulates 4 sets of axioms of decision analysis (Keeney 1992b) as below:

Axiom 1

Generation of Alternatives. At least two alternatives can be specified.

Identification of Consequences. Possible consequences of each alternative can be identified.

Axiom 2

Quantification of Judgment. The relative likelihoods (i.e. probabilities) of each possible consequence that could result from each alternative can be specified.

Axiom 3

Quantification of Preferences. The relative desirability (i.e. utility) for all possible consequences of any alternative can be specified.

Axiom 4

Comparison of alternatives. If two alternatives would each result in the same two possible consequences, the alternative yielding the higher chance of the preferred consequence is preferred.

Transitivity of Preferences. If one alternative is preferred to a second alternative and if the second alternative is preferred to a third alternative, then the first alternative is preferred to the third alternative.

Substitution of consequences. If an alternative is modified by replacing one of its consequences with a set of consequences and associated probabilities (i.e. lottery) that is indifferent to the consequence being replaced, then the original and the modified alternatives should be indifferent.”

Appendix 2.4. Foundations of descriptive theory (Edwards 1992)

The following are direct quotes from Edwards (1992) except for our comments in parentheses and italics.

“Assumptions

1. People do not maximize expected utility, but come close.
2. There is only one innate behavioral pattern: they prefer more of desirable outcomes and less of undesirable outcomes. These judgments are made as a result of present analysis and past learning.
3. It is better to make good decisions than bad ones. Not everyone makes good decisions.
4. In decision making, people will summon from memory principles distilled from precept, experience, and analysis.”

“Principles

Guidance from analysis

1. more of a good outcome is better than less
2. less of a bad outcome is better than more
3. anything that can happen will happen
(we interpret this to mean that outcomes are uncertain.)

Guidance from Learning

4. good decisions require variation of behavior (e.g. be creative)
5. good decisions require stereotypical behavior (e.g. be thorough, don't play around)
6. all values are fungible
7. good decisions are made by good decision makers based on good intuitions
8. risk aversion is wise. “look before your leap.”

Guidance from experience

9. good decisions frequently, but not always, lead to good outcomes
10. bad decisions never lead to good outcomes
(we interpret this to mean that poorly formulated problem statements and, ad-hoc decision analyses are unlikely to produce relatively good outcomes even in favorable conditions.)
11. the merit of a good decision is continuous in its inputs
12. it is far better to be lucky than wise”
(we interpret this to mean that the stochastic nature of future events may surprise the decision maker with a favorable outcome. We are certain Edwards is not suggesting that we depend on luck as the basis for decision making.)