DISSERTATION

A RISK-BASED DECISION-MAKING HEURISTIC FOR ENGINEERING DESIGN IN PRODUCT DEVELOPMENT

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ROBERT B. MALE ENTITLED "A RISK-BASED DECISION-MAKING HEURISTIC FOR ENGINEERING DESIGN IN PRODUCT DEVELOPMENT" BE ACCEPTED AS FULFILLING IN PARTIAL REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

A RISK-BASED DECISION-MAKING HEURISTIC FOR ENGINEERING DESIGN IN PRODUCT DEVELOPMENT

The process of engineering design requires making decisions. This dissertation involves dealing with risks inherent in engineering design from a process and decision-making perspective. Engineering decision-making transpires through a number of different decision constructs – experiential, scientific, expected value, optimization, and intuitive aggregation for instance - but they all need to take into account the element of risk. Engineering risk uses both qualitative and quantitative methods to deal with such areas as safety, probability, and cost benefit analysis. The risk in question for this method is project development risk rather than societal risk. This paper introduces the Risk-adjusted Value Ratio (RAVR) heuristic as a decision-making tool that combines elements of cost-benefit analysis with elements of traditional Expected Value for risk tempering design decisions. The methodology defines the ratio in terms of expected benefits to expected costs. This ratio is used as a stand-alone evaluation tool between alternatives, as a sensitivity analysis tool, or as a driver for decision-making when using an optimization strategy. It can be used both quantitatively and qualitatively. The RAVR heuristic is shown to accommodate all decision-maker risk preference levels except for risk-seeking, where traditional Expected Value decision-making provides only risk-neutral results. Case studies are provided which demonstrate the RAVR heuristic's various uses as well as its strengths and weaknesses.

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I am grateful to GE Appliances and Waterpik Technologies, the two companies where I have worked, whose education policies have allowed me to fund my academic endeavors as a benefit of my employment. It has been a great training ground and test-bed for many of my ideas. It has also allowed me to pursue my own interests, even though it has taken longer to focus my efforts and caused more heartburn for my advisor and my family.

I am grateful to my parents who have always been supportive of my education. I am especially grateful for my wife, Laura, and my children in their support of me through

these many years. Part-time doctoral work takes time away from many family activities, and their understanding and support, even through their own personal trials, has been a true blessing. I can only hope that my successful completion will have a future positive impact on their lives.

AUTOBIOGRAPHY

Robert B. Male was born in Akron, Summit County, Ohio, on November 19, 1960. He graduated from Cuyahoga Falls High School with honors in June 1979. He attended Brigham Young University from 1979 to 1987, taking a 2-year leave to serve as a missionary for the Church of Jesus Christ of Latter-day Saints in the Pusan Korea Mission from 1980 to 1982. He graduated *summa cum laude* from BYU with a BSME in 1986 and completed an MSME in 1987. He served as Vice President of the A.S.M.E. chapter at BYU in 1986, and has remained a member ever since. He went to work in industry - first with GE Appliances and subsequently with Teledyne WaterPik, now Waterpik Technologies. During his tenure at GE, he was involved in training engineers for corporate excellence, at which point he began Ph.D. work through Purdue University (1992). In the meantime, he obtained a Professional Engineers license in 1992 (Kentucky) and became certified as a New Product Development Professional (NPDP) through the Product Development Management Association (PDMA) in 2000. His career has included all aspects and phases of product development, and he is the holder of numerous patents. His research interests have been in understanding and improving the product development process, especially through decision-making. He received his Doctor of Philosophy in the area of Mechanical Engineering in Spring 2004, under the direction of Dr. P. Fitzhorn, Dr. J. Labadie, Dr. H. Sakurai, and Dr. W. Troxell. He was married to the former Laura Standing in 1985, and has four children.

DEDICATION

I dedicate this effort to my father, Edwin K. Male, Jr., because I have always enjoyed making him proud of me. I also dedicate this to my grandmother, Mildred O'Hara Ward, who continues to live so young, even though she is 98, because of her marvelous worldview and adaptability. I dedicate this to my children – Nathan, Scott, Shannon, and Lydia. They have sacrificed “daddy” time often, but still help me keep my priorities straight. And last, and most of all, I dedicate this to my wonderful wife, Laura. She has always understood my thirst for learning and has encouraged me even at a sacrifice to herself. I love you eternally, Laura.

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1.0 Introduction

This dissertation develops a model that is a representation of the decision-making that occurs within the complex product development process as a concept is fleshed out into a real, manufacturable artifact. The model suggests a method for decision-making, whose origin comes from observations within the engineering development environment of small and major consumer products companies. From comparison of processes that the author has participated in and through discussions with other design professionals from other industries, this model and its method of application appears to have a reasonable fit wherever products are developed.

It has been the experience of many engineers that decision-making is one of the most frustrating aspects of engineering design. Many different decision strategies are invoked to frame problems, determine priorities, gather relevant data, and flesh out alternatives. The process of ranking alternatives in a rational manner seems to be followed until the end of the process, where a supportable and executable alternative must be chosen. Then the process appears to break down from the systematic, "rational" approach as intangibles of the design alternatives begin to be discussed. Often the engineer feels as if there isn't complete enough evidence to support a decision yet. Often the ranking doesn't always follow the engineer's perspective of what the "best choice" should be. Whether the original ranking method supports the final choice appears to make little difference as the alternatives are tweaked with these intangibles, and a plan becomes "rationalized" in the mind of the decision-maker.

When one is involved with engineering design processes and is responsible for the decisions and resulting execution, one begins to understand that the "rationalization process" of the intangibles involves more than gut-level choosing; it is infusing the alternatives with risk data. This "risk tempering" of alternatives makes sense in the context of time-based and capital-based project decisions found in engineering development processes. "Risk tempering" also appears to take into account the risk preference of the decision-maker as well as his or her subjective risk assessment. The context and risk parameters involve a scope broader than the engineering discipline alone.

Consequently, creating a decision model that includes risk is an effort to codify a decision process that is typically done intuitively and subconsciously, rather than explicitly, in the engineering development environment. This abstraction starts with an understanding that any time one wants to really probe into a problem and understand its relationships, the relations become so complex and interconnected that capturing this complexity and making it applicable to all situations is virtually impossible, given finite time and resources. So Pareto's rule will be followed here, shooting to capture the 20 percent of the relationship that has 80 percent of the effect. This will be done in classic terms – simplifying assumptions will be used where appropriate to eliminate the complexity and facilitate understandability. In all cases, it must be understood that this is a model. Its intent is to generate an abstraction that mimics the real world to a degree that valid and useful actions and decisions can be made. It is an attempt to understand and define the decision-making process that occurs during development, fraught with all of its ambiguities and uncertainties. The intent is to guide by providing context and structure for a "risk-tempered" decision, provide a framework to prepare for decision-making, and provide rationale as to why decisions are made that don't seem to follow classical engineering processes.

The objective is to develop a *descriptive* model of the decision-making process, including risk in the product development environment from an engineering design perspective, although the model is decidedly multi-disciplinary in nature. The model – once realized, understood, and validated – then can be used in the *prescriptive* sense. In other words, once the model is understood and trusted, it can be used as a process to guide future decision-making in a conscious sense, with the user recognizing inputs and factors to the decision at hand. With this understanding, the process can then be manipulated consciously to provide better decisions, or at least a better understanding to the factors behind decisions that drive a specific development project.

1.1 Problem

The premise of this work is that design and development is an environment ripe for engineering and multidisciplinary decision-making. It is a critical piece of the development process that is often overlooked for improvement when one tries to create efficiency. Decision-making tends to be a bottleneck in engineering for a number of reasons. Some of the problems for engineers related to decision-making in this environment are determining:

1. The type of decision methodology to be used as an overall strategy in design,
2. The type of decision methodology to be used in specific cases or at specific stages of the development process,
3. A proper and effective way to deal with risk,
4. The appropriate stopping point in a design or when the design is good enough.

These issues will each be explored during the development of this model.

1.2 Opportunity

As a result of research in design theory and methodology involving product development processes, engineering decision-making, and risk quantification and mitigation; and through efforts to apply these principles in practice, there is perceived an opportunity to put forth:

1. A principal model to create structure for engineering decision-making that will permit engineers to make intelligent, compatible decisions within the multi-disciplinary arena of product development,
2. A risk model that works within the framework of the principal model that allows risk prioritization of objectives and can adjust for the decision-maker's risk preference,
3. A demonstration of how the combination model works together to give direction to engineers and project teams in their decision-making.

This combination model will be established in context of current product development process practice, and, as an outcome will be an adjunct to current and traditional decision-making practices.

2.0 Topical Review in Engineering Decision-making

To develop a descriptive model of risk-based decision-making in design, one must realize that many design decisions focus on the absolute facts and calculations of the specific archetype models that exist as artifacts of that process. While this is a focal point of most decision-making, the risk portion is, in fact, multi-criteria and multi-disciplinary in nature. Understanding how to incorporate risk in a way that describes how it appears to be done in actual product development requires a better understanding of the existing study and practice today. To put risk-based decision-making into proper perspective, one must explore three areas in the literature – the engineering design and product development process, decision-making in engineering design, and risk analysis in decision-making.

2.1 Engineering Design and the Product Development Process

From the time the modern research lab was instituted by Thomas Edison, the modern corporation has sought processes to improve the chances of success and improve the efficiency of the product development effort. Asimow [1] was the first quoted in this area of engineering design. He presented a general outline of the phases of design for a product as shown in Figure 2.1. Asimow's primary interest was in the primary design

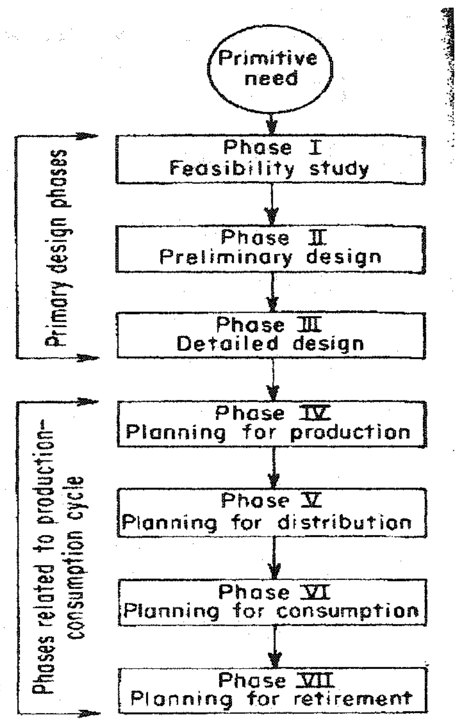

FIG. 3.1 The Phases of a Complete Project.

Figure 2.1 Phases of a Product Development Project [1]

phases themselves, but he realized that there were a number of phases downstream to the regular engineering design phases that these primary phases would affect. This work was done prior to the popularization of concurrent engineering, so the progression is shown as a serial process with no evidence of the complex interrelationships between processes that are associated with concurrent engineering today.

Other methods were developed to fill the chasm between the theoretical selection model and the actual work that must occur to facilitate it. The oft cited source for pragmatic engineering design is the Pahl and Beitz method (see figure 2.2) [2] with its rigorous and detailed evaluations. This method breaks down design into a process with progressive stages of development and decision-making. The design is first systematically defined, then conceptualized, embodied, and then detailed. In this process, systems are decomposed into subsystems and then further into component parts. The specifications are correlated with the component part functions. Then, conceptual design is exercised to determine the appropriate embodiment of each component to produce the most valuable configuration. The Pahl and Beitz process represents the messiness involved with product development through iterations and recursions as well as the complexity in information design requires. However, it stops at the design portion of the development cycle, where the outcome of the work is essentially the drawing packet that describes the artifact.

While the Pahl and Beitz method shows the generally accepted structure for the design process, others have seen weaknesses, omissions, or special cases to this theory that through specific modifications could be easily resolved. Most modifications are minor, but the significant ones include the need for a product implementation step and the need for a product that befits the manufacturing and organizational capabilities available.

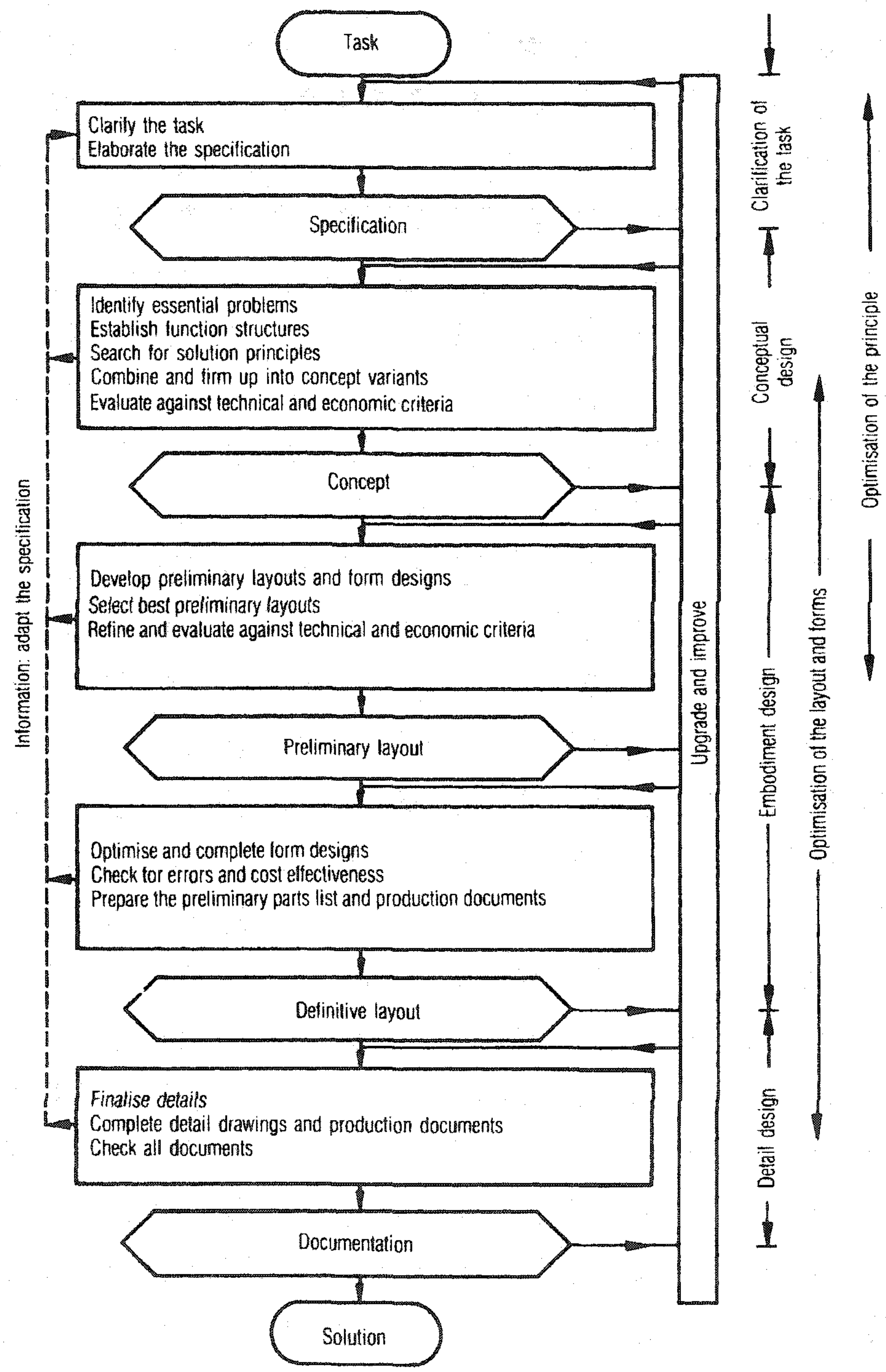

Figure 2.2 Steps of the Pahl and Beitz Engineering Design Process [2]

The processes that will be explored include:

Stage-Gate
Integrated Product and Process Development (IPPD)
Concurrent Engineering (CE)
Value Analysis (VA)
Total Quality Development using Quality Function Deployment (QFD)
Decision-based Design (DBD)

<u>Stage Gate</u> – This approach defines milestones at critical junctures in the product development process, where product viability and risk should be assessed at a management level.[3] See Figure 2.3. This method looks similar to Asimow's phases

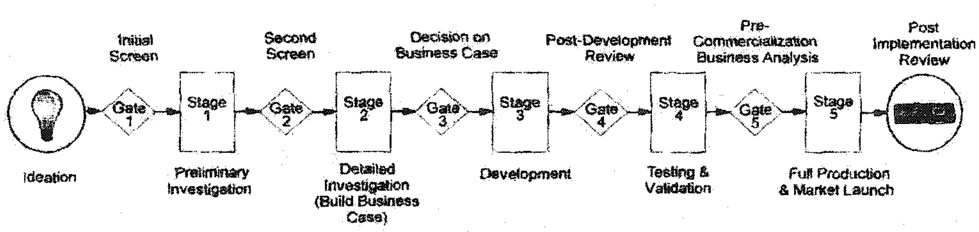

Figure 2.3 Stage-Gate Process for Product Development [3]

approach with a further contribution in that it is recognized that the phases have to pass through a decision step to actually control and facilitate movement onward to the next phase. This control structure allows for creativity and risk-taking to a certain level, but also seeks to keep a close watch on the progress of a development effort. The goal here is to monitor the process just close enough to make sure the effort stays on track in terms of the key factors of development. The addition of this method is to formalize the steps, based on individual company circumstance, and to instill discipline in the process through managerial oversight.

<u>Integrated Product and Process Development (IPPD)</u> – This methodology focuses on eliminating a sequential development effort, where the specification is written; passed to engineering for development, testing, and documenting; then a design passed to manufacturing for the development of the process. The goal here is to bring the process development and product development into a parallel effort, with the communication requisite to achieve a highly produceable design that can occur at a more rapid pace due to less iterations. It is imperative that a cross-functional team works together and deals with the trade-offs of the needs of both product and process. This is exhibited in the IPPD trade-off diagram shown in Figure 2.4 below. [4]

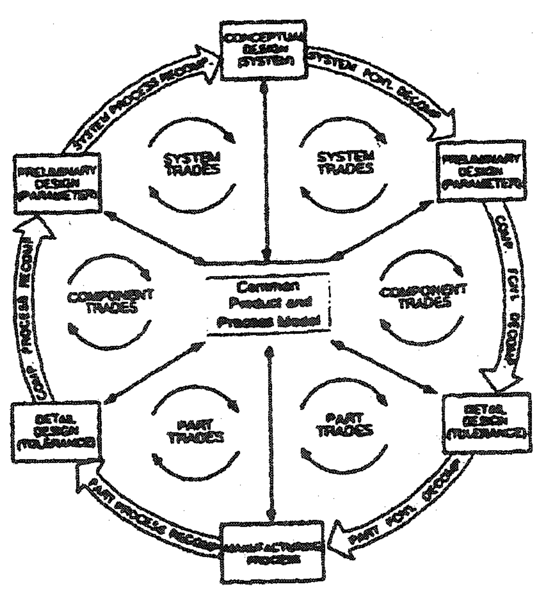

Figure 2.4 IPPD Trade-off Process [4]

The diagram represents the web of interaction and communication between the various stages of the product development phases from an informational standpoint rather than a sequential one. The trade-offs shown exist between the detail levels of the design and manufacturing process, and they must be balanced, usually through compromise, to provide a design that is both functional and manufacturable.

Concurrent Engineering (CE) – This is similar to IPPD and is often used interchangeably with IPPD. One difference is that CE deals with a larger cross-functional team and all the needs of the product. The key is the communication network established and managed so the pitfalls of sequential engineering can be avoided. (See Figure 2.5.)[5]

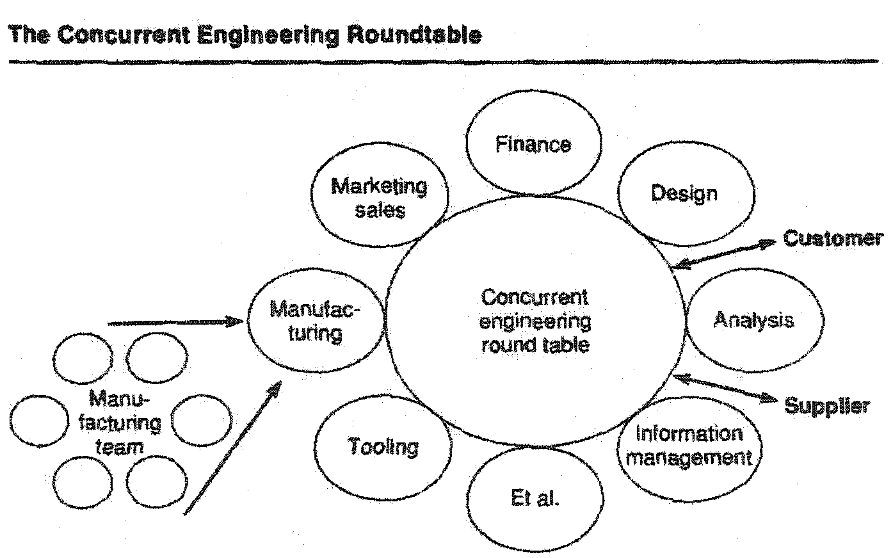

Figure 2.5 Concurrent Engineering Structure Diagram [5]

The advantage of Concurrent Engineering is that many more aspects of the overall picture are brought to light in the early stages of design. Rather than waiting until later stages of development to deal with trade-offs, they are dealt with concurrently. However, sorting through the magnitude increase in up-front criteria and information can be overwhelming. Consequently, the communication channels established must be monitored and managed so that only pertinent (i.e. relevant and dependent) information is communicated.

<u>Value Analysis (VA)</u> – Value Engineering was developed in the 1950's by the General Electric Corporation. It is a systematic and logical approach to improving existing products. It uses a function logic approach (i.e. a hierarchy of functions that provide benefits) and is a process oriented (and very exhaustive) method. The basic premise of Value Analysis is that the cost is proportionate to the function provided [6]. This proportion has been reinterpreted (through application) to where functions represent benefits, and they can be expressed as the ratio

$$Value = \frac{Benefit}{Cost} \qquad \text{Eq. 2.1}$$

The key technique of Value Engineering is to decompose a product into sub-systems and then decompose subsystems into their components. At the component level, functional benefits with associated costs can be assigned. Then the values can be aggregated to show the value of that sub-system. When the benefits are ascertained, the costs are allocated in a logical proportion to that benefit. Typically the Value Engineer looks for costs that are out of line with the functional benefit provided by each of the components. In other words, the goal at each of the levels of the decomposition of the product is to increase the value ratio, or increase benefits and decrease costs. Values that seem inappropriate are targeted for improvement. This is usually accomplished in the creative phase of the Value Engineering process. Common outcomes in this phase are to combine or eliminate low-value parts, or identify and cost-reduce others.

Total Quality Design using Quality Function Deployment (QFD) – This is an offshoot of the Total Quality Management (TQM) movement from the late 1990's [7]. It focuses on the use of the Extended Quality Function Deployment (EQFD) method. EQFD is a graphical method of presenting the multitude of relevant design information to facilitate the overall development process (See figure 2.6.) This method uses the concept

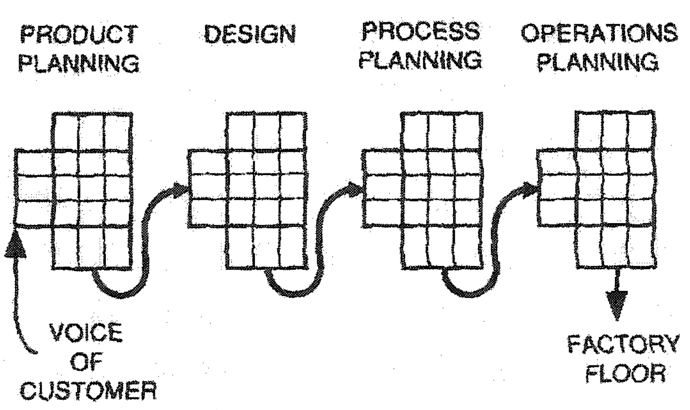

Figure 2.6 Enhanced Quality Function Deployment Diagram [7]

of determining the match between customer requirements in the customers' words and the development team's specifications in technical language. This model is extended using the terminology from Suh's Axiomatic Design methodology [8]. Customer language (VC) is converted to Fundamental Requirements (FR) in the Product Planning matrix. Then Fundamental Requirements are converted in the Design matrix to Design Parameters (DP); Design Parameters are converted in Process planning to Feature Characteristics (FC); and Feature Characteristics are converted in the Operations planning matrix into specifications called Process Controls (PC). This rigorous method is used to prioritize customer features and benefits (VC) and translate them into Process Controls to insure a quality implementation of that benefit. Thus there becomes a link between what is tracked and what the customer receives. Through the development of the QFD matrices, much of design work must occur with direction given only in terms of focusing on the attributes that offer the most value (and thus the highest perceived quality) to the consumer. Completion of the matrices gives priorities and understanding to the important aspects of the design that then offers direction in the development (and decision) process.

All of these methods are designed to improve efficiency in the design process. They look at ways to define the right criteria, communicate between interrelated groups, choose alternatives that meet multi-criteria needs, better define decision points to help keep projects on track, and better define performance measurements and evaluation techniques to provide meaningful measurements related to product success. Most of these processes recommend specific decision methods. However, each technique allows room for decision techniques that can be tailored to the situation. Thus they can still be effectively implemented using many different decision processes.

2.2 Decision-making in Engineering Design - Understanding the Engineer's Decision Process

In general, the act of design requires a multitude of decisions. The designer is responsible to make something of some order and/or usefulness out of chaos. The influence of design is broad, from reshaping nature through landscaping, from creating living spaces through architecture, from creating devices to augment our lives through engineering, or even creating art, news, advertising, or media to influence our thought. All of these things contain design, yet they are all very different activities. The common thread in the design process of all these fields can be stated thus:

> [Design means] *the making of decisions* about size, shape, arrangement, material, fabrication technique, color, and finish, that establish how an object is made. The object can be a city or town, a building, a vehicle, a tool or any other object, a book, an advertisement or a stage set. *Designers are people who make such decisions*, although they will, most often, have some other name describing their specialized concern: architect, engineer, town planner or, possibly, craftsman. [9] (italics added for emphasis)

Allen B. Rosenstein, in an earlier era of product development, also described engineering design as "an iterative decision-making process [10]." As was shown in the section concerning design processes, where there were many different ways to go about developing products, there are also many different techniques and strategies by which an engineer might make decisions. This dissertation will look at those different strategies (or constructs) which fall into the realm of rational models.

2.2.1 Decision-making Constructs

In the development of engineering as a profession through the ages, multiple decision techniques have come about. These have foundations in a relatively few number of constructs, or general strategies for coming to a decision. These constructs include:

Sufficiency
Experiential or Recipe
Scientific Method
Expected Value
Optimization
Intuitive Aggregation

Each of these constructs is described below, along with some of their representative techniques.

Sufficiency – This construct is so ubiquitous that it is easily overlooked as a decision method. It constitutes the determination of whether a design or action is complete or accurate enough to engender enough confidence in the decision-maker to move on to the next activity. Meeting specifications is a sufficiency activity – as is a production qualification process. Often there is not a deterministic answer to the query whether something is correct because of the stochastic nature of testing, etc. Extensive design time and effort is expended in ensuring that the team thoroughly defines, explores and analyzes the problems to produce accurate results. While exerting effort to produce all necessary and sufficient evidence to gain the confidence in one's decision, it is often the understanding of one's inability to be completely thorough that leads, in part, to the uncertainty associated with the calculation of design risks. While no formal methods will be explored in this dissertation, it is noted that in the use of the other decision-making constructs, Sufficiency methods are often used to test and validate conclusions.

Experiential (Recipe) – This construct is one of the earliest forms of decision-making. As craftsmen developed their art, [11] they used cut-and-try methods for developing products to meet their customers' needs. Over time and a number of iterations, they became familiar with the "best practices" for how things should work. This information was often passed along through apprentices and labor guilds, and these practices became hard-and-fast rules for how things should be done. Typically, this construct is used by identifying situations that appear similar and adopting (and adapting) the solution for the new situation from the original situation. Some common engineering decision systems are shown in Table 2.1 below, which follow the Experiential Decision-making construct.

Table 2.1 Decision-making Techniques of the Experiential Construct

Decision-making Construct: ***Experiential (Recipe)***			
Examples – Title	**Description**	**Originator and Time (Ref)**	
DFx	Combination of rules of thumb and best practices in a number of fields, including assembly, manufacturing, recycling, etc.	Bralla (many)	1980s[12]
AI/Knowledge Based Systems	Use of Experts' knowledge in a computer search scheme to make decisions based on a novice's inputs	Turing, Newell, Simon	1960s [13]
TRIZ/TIPS	Knowledge based system that uses fundamental solution techniques gleaned from trends noticed in patents	Altshuller	1990s [14]
Design Guides	Plastics, Machinist Handbooks, Apprenticeships, Guilds, etc	Various sources	Ancient
Boiler Plating	Use of previous work or definitions created in previous design efforts (usually occurs in specifications and on blueprints)	Various Sources	Ancient

<u>Scientific Method</u> – About the Aristotelian era, "engineers" began looking at the world of cause and effect associated with natural phenomena and the principles involved in estimating what these relationships were. Subsequently, the craft of making things began to incorporate this type of thinking, where inventions used principles of physics and properties inherent to the phenomena in ways that created useful tools and devices. The scientific method of decision-making involves understanding the underlying cause and effect relationships within a situation and setting the independent variables to achieve a specific outcome [11]. In general, all of engineering science is based on this construct. Some common, specific engineering decision systems are shown in Table 2.2 below which follow the Scientific Method decision-making construct.

Table 2.2 Decision-making Techniques of the Scientific Construct

Decision-making Construct: *Scientific Method*			
Examples – Title	**Description**	**Originator and Time (Ref)**	
Taguchi/DOE	Use of statistical methods to develop response surfaces. Determine cause and effect, sensitivity to variation	Taguchi, Juran, Deming	1950s [15]
Conjoint Analysis	Response surface technique used to deal with subjective data, usually people's opinions concerning the importance of features in a product	Luce, Tukey	1960s [16]
Kaizen	Uses many of the statistical tools and root cause work to ID issues and their driving	Japan productivity council, Juran, Deming	1950s 1980US [17]
K&T Root Cause	Determines the fundamental driver of a problem and then pursues a corrective action	Kepner and Tregoe	1965 [18]

Expected Value – This decision construct came about as a mathematical construct in the 16th century, when a mathematician created a method to help wealthy people make choices in games of chance [19]. It became a highly used method in the late 1940's when it was linked with utility by von Neumann and Morgenstern [20]. This methodology employs the use of probability of an event multiplied by its outcome to give an expected outcome. It is essentially a weighting principle where outcomes are weighted by their probabilities. This type of decision-making has been adapted to many engineering decision situations. Table 2.3 shows that there are many common decision strategies that follow this construct.

Table 2.3 Decision-making Techniques of the Expected Value Construct

Decision-making Construct: *Expected Value or Utility*			
Examples – Title	**Description**	**Originator and Time (Ref)**	
Value Analysis	Assigns a value to each function a part performs	GE	~1950 [6]
QFD	Weighted Value matrix	Mitsubishi Heavy Industries Kobe Shipyards	~1972 [7, 12]
Pugh	Relative matrix method where alternatives are judged against a baseline concept with respect to specific parts of the design spec. Best concept has highest score	Stuart Pugh	1978 [21]
Subjective Weights	Similar to Pugh method, but each specification is given a priority weight, which is multiplied by the score of that spec. This biases the summation	Kepner – Trego	1960s [18]
Multi Attribute Utility Theory	Concept where overall Utility is combination of many sub goals	Keeney, Raiffa	1976 [22]
Multi Criteria Decision Making	Concept alternative comparison		
Pahl & Beitz	Subjective weights method that converts requirements into weighted fractions of the whole specification. Uses a numeric scale for scoring all attributes (whether objective or subjective)	Pahl and Beitz	1981 [2]
Forced Ranking	Marketing tool uses exhaustive pair-wise comparison to score and rank alternatives. Usually used to set weights or priorities	Unknown	Unknown
Analytical Hierarchy Process	A weighting procedure for criteria similar to the Forced Ranking method, with the difference that instead of one or the other in a pair-wise comparison, there can be a magnitude difference	Saaty	1970s [23]
Game Theory	The idea of probability and chance plays in setting weights on requirements in a decision	Von Neumann and Morgenstern	1944 [20]
Decision trees	Laying out multistep decisions into possible alternatives and their probability. Traversing each path using summation of products leads to an overall Value	Raiffa	1968 [24]
Dominic	A Pugh-like relative matrix method with an additional step that hierarchically ranks subjectively weighted satisfaction of criteria	Dixon et al.	1986 [25]
Electre	MCDM system with ability to deal with varying utility functions and vague data	Vincke	1986 [26]
Promethee	MCDM system with ability to deal with varying utility functions and vague data	Brans, Vincke	1985 [27]

Optimization – This method is an adaptation of the scientific method that has become such a powerful tool that it has transcended its origins. Earliest origins of this method started with Newton, LaGrange, and Cauchy [28]. Newton, of course, developed the Calculus and the ideas of a limit, maxima, and minima of functions. LaGrange was the first to deal with constrained functions, and Cauchy was the first to perform a steepest descent minimization of an unconstrained function. Further development wasn't substantial until the 1950's, when digital computers began to proliferate. When Kuhn and Tucker [29] developed a set of criteria to determine the necessary and sufficient conditions for an optimal solution (best choice), this method began to grow in interest and technique.

Optimization is a hybrid method that combines the idea of a measure of merit (Expected Value) with the Scientific Method [28]. If one can develop equations that define the cause and effect relationships of a phenomenon, then by using numerical techniques one can drive the independent variables to set points that yield a desirable outcome in an automated way. Beyond the mechanics of goal-seeking, optimization establishes a mindset that each situation is an opportunity to make something better by using a systematic, convergent approach. Common examples of this construct are shown in Table 2.4.

Table 2.4 Decision-making Techniques of the Optimization Construct

Decision-making Construct: ***Optimization (Hybrid of SM and EV)***			
Examples – Title	**Description**	**Originator and Time (Ref)**	
Genetic Algorithms	Brute force scientific theory along with Expected Value concept (survival of the fittest)	Holland	1992 [30]
Satisficing	Terminology for just meeting the minimum standards (constraints) in an optimization problem	Herbert Simon	1947 [31]
Linear Programming (SIMPLEX)	Use of objective (goal) and constraint functions. Linear mathematical goal seeking	Dantzig	1947 [28, 32]
Non-linear optimization	Use of objective (goal) and constraint functions. Use of sophisticated nonlinear mathematical goal seeking	Rosen, Zoutendijk	~1961[28, 32]
Goal Programming	Method of optimization where constraints are relaxed and the objective function is built to minimize deviation from target values for the constraints	Lee	1970's [33]

Intuitive Aggregation – This technique is often called gut-feel decision-making. Due to the high dimensionality of most problems, the complexity of the data and evaluation required can be daunting to most decision-makers. Oftentimes the situation is so complex that understanding what the factors are that drive the decision can be lost. Intuitive Aggregation is a theory that realizes humans have a limited capacity to deal with complexity, and so it seeks to reduce problems to the essence of the decision. Another name for this is bounded rationality[34]. One chooses the three or four factors that one believes are driving the results and focuses efforts on discerning the results of those factors alone. Often this is done informally or subconsciously, so this is perceived as making a gut-level decision. Formal methods are few, but references to the documentation of this construct are provided in Table 2.5.

Table 2.5 Decision-making Techniques of the Intuitive Aggregation Construct

Decision-making Construct: *Intuitive Aggregation*			
Examples – Title	**Description**	**Originator and Time (Ref)**	
Druckerian	Data is no better than opinions. So the decision-maker should collect good opinions, figure out what he/she think is right, test the validity of the assumptions and then make that the decision	Peter Drucker	~1940 [35, 36]
Delphi (modified)	Expert opinions are solicited since accumulating hard data might be impossible or not cost effective. Opinions are compiled into one joint opinion and then modified until a consensus is reached among the viewpoints	RAND Corp.	Late 1950s ([37, 38]
Bounded Rationality	The decision is stripped the essential and significant variables and choices are made based on those only	Simon	1947 [39]

The final decision constructs considered for engineering decision-making are hybrids of the above. These are two or more of the above constructs combined to aid the decision-maker. Optimization is a good example of a hybrid construct. However, it is used so extensively that is dealt with separately. The Boothroyd/Dewhust method of Design for Assembly and Part Count Reduction (DFA/PCR) is another useful example of a hybrid method [40]. They use the experiential nature of best practices in the assembly arena and combine that with a scoring method (cause and effect or scientific construct) so a design can be made and scored according to its potential assembly process. Changes can be evaluated on a standard scale so improvement can be measured in the design phase. By combining an Experiential Construct with a choice and result model, this hybrid construct has proved useful in directing design direction and decisions to improve manufacturability.

Further Considerations

Decision-making in general is based on many external factors too, still with the desire to make rational or right decisions given the alternatives. There are many outside factors that affect decision-making, which will be mentioned here but will not be dealt with in the model put forth. These factors will be assumed to be under control, but they can and do have an impact in the final decision, which can change what would be termed a rational decision into one that might be considered biased. These factors include but are not limited to:

Framing – perspective by which a problem is set up. Depending on the position of a problem statement it might be easily resolved or completely intractable

Biases – preconceived notions as to how decisions should be made regardless of the data available

Anchoring –bias focused on extreme points exhibited in previous results rather than on current data or the general body of data as a whole

Lemming approach – blindly following a course of action without considering data available

Politics - using personal or organizational relationships to drive decisions rather than pertinent data [41, 42]

Factors such as these can be argued to cause the decision-making process to become irrational. However, in many cases they affect rational decision-making by influencing the subjective weighting of factors and perception of probabilities that are the foundation of many rational decision constructs. The model presented will not include these factors but can surely be influenced by them.

2.2.2 Reconciling the Development Process with Decision-making

In the design and development arena, engineers can, and will, use many if not all of the constructs described here. Experiential constructs are used often to create quick and effective design solutions by "borrowing" from another's strategy for a similar problem. Fundamental scientific theory is used as a basis for exploiting new phenomena or even predicting dynamics or initial sizing of a system. Expected value is often used as a weighted decision process, as exemplified below, to perform concept selection. And often, intuitive aggregation constructs are used as designers familiar with the situation quickly choose options based on a few key indicators. This is done as their intuition is tapping into subconsciously held assumptions and structures of interactivity of the system.

Just as researchers have looked at the engineering design process in an effort to develop the field of design theory and methodology, they have also looked at the decision-making problem. This investigation is made not necessarily in terms of the individual decision constructs, but in terms of a strategy of decision-making for the whole process of engineering design. Asimow not only defined the phases of engineering design, he also put forth the fundamental view of engineering decision-making known as a decision matrix.

Asimow's methodology [1] is to look at the objectives in terms of criteria (C_i), and then evaluate (V) the possible design alternatives (A_j) with respect to each of those criteria as shown in the matrix below

$$\begin{array}{c|cccc} & A_1 & . & . & A_n \\ \hline C_1 & V_{11} & . & . & V_{1n} \\ . & . & . & & . \\ . & . & & . & . \\ . & . & & . & . \\ C_m & V_{m1} & . & . & V_{mn} \end{array} \qquad \text{Eq. 2.2}$$

As each of the criteria is evaluated, the alternative (A_j) that has the subset of ratings that is highest would be the best choice for the design. He realized the challenge of physical realizability with these choices and dealt with uncertainty separately from his matrix. He developed a mathematical formula to represent the confidence level (L) of physical realizability that exists and is used in the development domain to drive decision-making. The formula is

$$L = f\left[E_n X_B \left(\frac{dE}{dX}\right)_0\right] \qquad \text{Eq. 2.3}$$

where

L = confidence level on a probability scale from 0 to 1.

E = Amount of favorable evidence in decibels

X = current expenditure in dollars

X_B = allowed budget in dollars

$(dE/dX)_0$ = Initial rate of increase in favorable evidence with expenditure

In this case X_B represents the budget in time and capital. So the equation shows that the probability of success is usually the product of current favorable evidence, expenditure, and the rate at which the evidence is improving with that expenditure of money. It has a common sense feel to it, even though it is impractical at any one time to actually calculate this probability. Often in the real world, engineers will estimate their own confidence in solving the problem, and then managers will estimate whether they want to spend the time and money to get it the rest of the way there. In other words, it's done on gut-feel!

Starr [43] recognized this uncertainty of development, but he dealt with the decision matrix not in whether a result might be achievable, but whether the result might be desired or fit the actual operating environment. Consequently, Starr's decision matrix looks like the following:

$$\begin{array}{c|cccc} & p_1 & \cdot & \cdot & \cdot & p_n \\ & N_1 & \cdot & \cdot & \cdot & N_n \\ \hline S_1 & O_{11} & \cdot & \cdot & \cdot & O_{1n} \\ \cdot & \cdot & \cdot & & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & & \cdot & \cdot \\ S_m & O_{m1} & \cdot & \cdot & \cdot & O_{mn} \end{array}$$

Eq. 2.4

Starr extended this model to include weightings for each of the states of nature (p_i). The possible strategies (S_j) were compared to the states of nature (N_i) which reulted in some measurable outcome. The weightings could be used to adjust the effect that outcome might have on a particular Measure of Performance (MOP) used to select a strategy. Starr proposed many measures of performance that could be used. The Expected Value MOP is written as

$$E(V_j) = \sum_{i=1}^{m} p_i O_{ji}$$

Eq. 2.5

Starr realized that averaging the value (he used the word utility) using the EV formula didn't always give results that were most desired. It's akin to designing a product that tries to meet everyone's needs. These products tend to do a lot of things badly instead of one thing well. Consequently, other MOPs that were proposed are

> Equal Likelihood Criterion – if one is not sure of the weights, make them all the same

Pessimistic Criterion – pick the worst outcome for each of the strategies and then pick the strategy with the highest outcome of the worst

Optimistic Criterion – Pick the best outcome of each strategy and then pick the strategy with the highest outcome of the best

Partial Optimist Criterion – pick the best and worst outcomes of each strategy, weight the best with α and the worst with $1-\alpha$ and combine. ($0<\alpha<1$). Choose the strategy with the highest combined score

Minimum Regret Criterion – regret is about the opportunity lost if one picks incorrectly. Pick the strategy whose outcome has the smallest difference from the worst case of all other outcomes

All of these choice criteria look at the decision with an imputed risk. This risk will be discussed in the next section.

Starr's and Asimow's decision matrices tended to show decisions in a static sense, although Asimow dealt with time in his realizability equation (Equation 2.2). Raiffa [24] developed decision trees that use a situation similar to Starr's, except that now multiple decisions can be strung together with alternate states of nature to choose a value (utility) that will instruct the decision-maker on the path to take. Figure 2.7 shows how this decision tree is laid out, and accordingly, Equation 2.5 above can be used to evaluate each of the branches. Then the EV or other criterion can be used to make a choice. Again, this type of structure allows one to look through a number of steps in time and make decisions, but for design decision-making, this is untenable. The problem lies in the number of possible alternatives, outcomes, and number of time steps that one might go

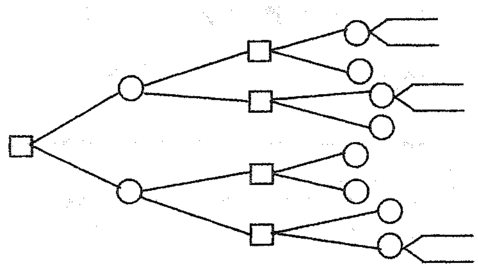

Figure 2.7 Decision Tree diagram

through in the design process. The enumeration of all the branches on a design tree can become unwieldy! The best one can do with this technique is to settle for one or two time steps into the future with a truncated problem (remember Bounded Rationality!).

Tribus [44] provided a decision plan that deals more effectively with time. He uses Baye's theorem to deal with the changes in probability of an event based on the acquisition of new information. By definition a decision has the following elements:

Indications, $\mathbf{I}_i$ – Problem data or information
Actions, $\mathbf{A}_i$ – Alternatives or solutions to a problem
Outcomes, $\mathbf{O}_i$ – Consequences of the Actions
New Information, **X** – Things learned from additional work

Similar to Starr's method, Tribus uses the Actions (in Starr's model strategies) and Outcomes (equivalent between the two) to calculate value. However, this value can be adjusted for time as new information comes to light. The value equation is then written as

$$Value = \sum U_i p(U_{ij} \mid X) \quad \text{where} \quad U_i = (I_k A_j O_i) \qquad \text{Eq. 2.8}$$

This summation is similar to the value accrued when using decision trees, and, again, is based on an Expected Value construct. The importance of this method in light of a product development decision-making process is the fact that the value can be improved (or the opposite) by further effort and work. Tribus displays how this might work in a diagram (see Figure 2.8). It shows a recursive nature to the process, where prior

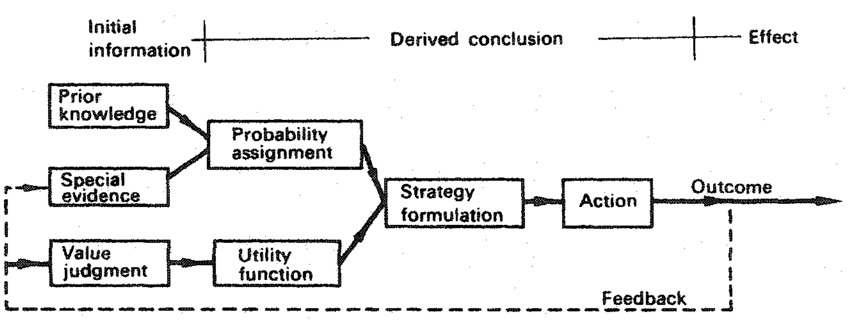

Figure 2.8 Diagram for Decision Problems [43]

knowledge is mixed with current evidence and value judgment to create a set of actions, indications, and outcomes by which to choose. Once the desired outcomes are chosen, it is then left to chance, but the information goes back into the cycle to provide special evidence for the next round of decision-making. The key issue, still, is knowing when there is enough evidence to make the final decision that ends the recursive loop and allows the design to be finished.

If design is viewed in an abstract context, it can be displayed using the Knowledge Paradox [45] (see Figure 2.9.) The Knowledge Paradox shows two curves: one curve –

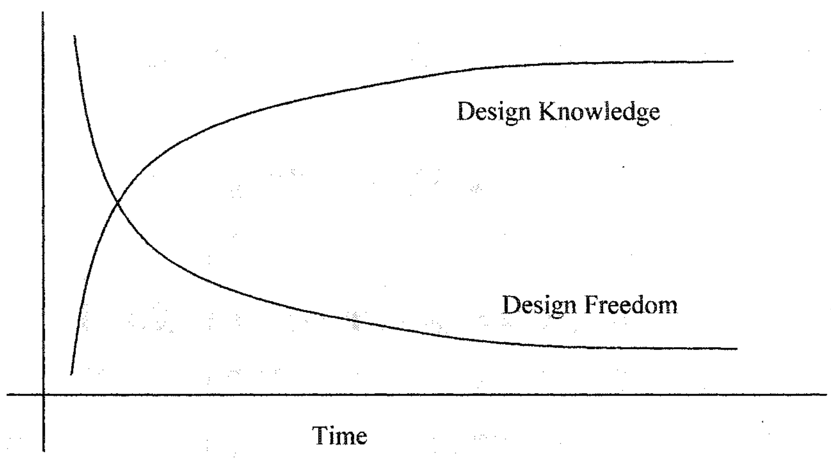

Figure 2.9 Knowledge Paradox [44]

the design freedom curve – starts high and curves down significantly over time (the x axis), the other curve – the knowledge curve – starts low and curves up higher and higher as time proceeds. The Y axis scale is unimportant, as is the specific shape of each of the curves. What this representation shows is that in the design environment, as one's knowledge increases, the ability to make decisions with that knowledge decreases. As decisions are made, design freedom decreases. Typically, the lament that "If I only knew then what I know now…", that somehow a more correct choice could have been selected. However, in light of Tribus's model, one might say the higher the knowledge, the more narrowed the choices become because one gets closer and closer to the final solution. If one looks at the Design Freedom Curve alone, it can be recognized that to finish a design, the design freedom must decrease. In fact, the faster and more monotonic the decrease, the faster the development is completed. Of course the key is to make right decisions so that the design efforts constrain the design variables to a set that results in a successful product. But a method to encourage convergence in a steepest descent decision-making manner would be ideal to promote efficient design processes. This decision-making strategy would fall under the construct of Optimization.

Engineers are comfortable with idea that all product development can fall into an optimization style problem. This is helpful because it structures thought and effort in a way that fits the engineers' credo. They love to tinker with things and make them better than before. This is optimization in a nutshell. They will maximize some benefit and minimize some cost by setting the design parameters, gaining knowledge from their choices, then resetting the parameters to move efficiently through design space to a better outcome. Consequently, the model shown above resonates with engineers, and the process of development proceeds forward with an eye on that model (or one similar to it).

In fact, the Decision Based Design (DBD) methodology that is developing through the National Science Foundation effort is based on an optimization construct. It was introduced by Hazelrigg [46] as a common framework model to structure engineering effort and decision focus. This model was exercised by Shupe [47] and is shown in Figure 2.10. The model shows a process that ultimately has optimization at its

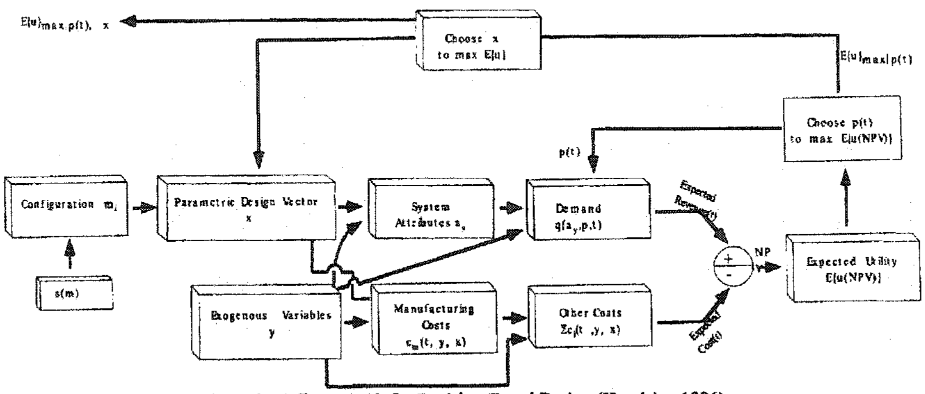

Figure 3: A Framework for Decision-Based Design (Hazelrigg 1996)

Based on Position Paper: Optimization in Decision-Based Design, *DBD Workshop*, Orlando, Florida, April 1997.

Figure 2.10. Decision-based Design Model [46]

core. This model will be discussed later as the starting point for this dissertation's risk-based decision-making model. This decision-making model is versatile in that it can fit with any chosen product development process model, whether it be traditional Pahl and Beitz, Stage-gate, Concurrent Engineering, IPPD, TQM, Axiomatic design, or QFD. The reason it fits is that it provides a method to keep track of overall goals and direction of development. Consequently, this thesis will use an optimization decision-making construct as the basis for the risk model development because it can provide overall strategic direction for product development decision-making, while allowing room for other decision-making constructs and methods to be used in interim and subsystem level decisions.

2.3 Risk Analysis in Decision-making

Engineering decision-making is rarely made under the conditions of certainty. Since engineers design, construct and make decisions based on models of reality, there is never a condition of complete certainty. This introduces risk into all systems. Since the decision-making model of this thesis will deal with risk, the goal of this section is to understand how others have dealt with the risk in the design process.

Risk analysis in engineering design takes on a number of dimensions. Since engineering design is a practice involved in developing products that are for use by others, there is always a concern for safety of the devices so designed. This risk is considered to be societal risk. This is not the focus of decision-making risk in this work. This dissertation will focus on internal risks to the development team. These risks generally include what Crossland [48] refers to as cost-project risk and technical risk that are associated with the environment of an engineering development project. This type of decision-making often involves the use of Quantitative Risk Analysis (QRA) methods. This is the focus of the review in this section.

QRA uses numerical measures of risk impact or probability to drive decisions to acceptable measures. These measures usually are financial, but might also be measured by a performance variable, such as the reduction in risk impact. Crossland [48] uses a cost-benefit analysis that evaluates the full product life-cycle costs and deals with risk prioritization and uncertainty modeling in selecting design alternatives. Aven [49] and

Hauger et al.[50] deal with risk as a cost-benefit analysis, each with a series of parameter uncertainties and consequential impacts.

A special embodiment of QRA that is used extensively in engineering design is Expected Value methods. Engineering development risk was first outlined by Asimow [1] and Starr [43] in their early works on engineering design. They pointed out that there is an element of uncertainty in the design process; whether one could say for certain that what they proposed to develop could really be done. In Asimow's and Starr's work, their fundamental decision construct was Expected Value. Starr, however, pointed out that Expected Value did not always give the most desired answer and specified a number of alternate decision strategies to deal with various concerns of the decision-maker (see Section 2.2.2). Asimow dealt with risk separately with a certainty equation that could be evaluated to determine whether the effort was warranted or not (see Equation 2.3). This incorporated monetary impact into the decision.

Others have done work in decision making along the lines of Expected Value, and have determined, as Starr had, that Expected Value doesn't cover all rational methods of making decisions when probabilities are involved. While Expected Value came from the 16^{th} century, it wasn't until von Neumann and Morgenstern [20] developed the axiomatic approach in their seminal work on game theory that EV became more widely used. The axioms include concepts such as independence of choices, relative ranking, transitivity, and so forth. There are many paradoxes, such as the St.Petersburg Paradox, Arrow's intransitivity theorem, Ellesburg Paradox, and the Allais Paradox, which display cases where straight EV breaks down [51]. Others have done work, such as Kahneman and

Tversky [52, 53] and Holt and Laury[54, 55], to measure and understand the general distribution of decision-making differences between EV and decision-makers with varying degrees of risk tolerance. Holt and Laury's work offers a positive way to identify varying degrees of risk preference exhibited by decision-makers in the decision process, so their work will be employed in Section 4 as a method to exercise and validate the risk-based model that will be presented as this dissertation's thesis.

Other than Expected Value, there are a number of methods that have been explored for engineering design. Duan [56] covers the quantitative analysis by using statistical decision theory coupled with Taguchi Robust Design concepts to model risk. This is accomplished by assigning a risk value to the deviation from the desired value (hopefully the mean or target value) and works well with Taguchi's[15] concept of lost value. This method might drive a single design alternative to a better measure of goodness (or a design with less risk) and focuses on a small set of parameters within a limited scope of the engineering design problem rather than a larger, multidisciplinary situation.

Eschenbach [57], on the other hand, focuses strictly on cost and time as risk measures. He looks at sensitivity analysis, initially using traditional deterministic financial models, and then re-evaluating these models to include probabilistic terms. These results are then compared to those given through techniques such as simulation, scenarios, and range estimating. This method tends to stay on the business side of the development effort, rather than extending into the detail of the engineering domain. Often in engineering design, traditional decision-making techniques start with a decision made under certainty conditions. Then the solution is exercised by exploring the model's sensitivity. The sensitivity analysis points out where the model is most susceptible to changes. Uncertainty is then infused into the model at the most sensitive areas to determine whether these "uncontrolled" deviations might affect the outcome. Often this sensitivity analysis is really uncertainty analysis, and the deviation in results is considered the risk. Dealing with this uncertainty and risk is often delegated to those who have cultivated good engineering judgment.

Jia and Dyer [58, 59] approach quantitative analysis from the standpoint of creating a risk-value model based on a converted expected utility of normalized lotteries with zero-expected values. It is an interpretation of utility functions that deals with the risk variable that can account for a host of special cases, which straight EV formulas cannot resolve. However, it still deals with the complex (and obtuse) method of synthesizing utility functions to incorporate risk into the decision. Utility functions are typically difficult models to develop and interpret, and they offer solutions with low clarity into the key drivers of the decision. Consequently, utility models are rarely used in engineering design.

There is some research available in using QRA methods as a driver to the design development process. Some risk analysis is in terms of engineering research and development decision-making as shown by Thomas [60]. He uses Value Analysis along with a probability function to define the value of a choice. The probability function is exercised using Monte Carlo simulation to develop a probability distribution of value for decision-making comparison. Coldrick et al. [61] develops a composite decision method by combining qualitative scoring, risk analysis and financial considerations. MacKay [62] also uses a simplified EV choice system where the probabilities are adjusted by a risk tolerance factor to evaluate choices for project portfolio development. All three of these methods are used to develop point decisions in the selection of development portfolios. So their application is similar to ordinary methods of QRA as discussed above.

Larson and Cheng, on the other hand, both cover risk analysis within and throughout a product development process. Larson [63] uses IDEF3 modeling techniques (formalized process mapping) of the design process with probabilities exhibited on alternate process paths that are the result of decisions. This allows the team to decompose the complex decision process inherent in a concurrent (multi-disciplinary) environment and provides a measurement of the risk through aggregation of probabilities along a process path for a corresponding decision set. Cheng [64] focuses on the use of stochastic dynamic programming algorithms and sets up the problem as a Markov decision process. This uses single period sub-problems, which then set up a two-stage stochastic problem with an iterative loop. While Cheng is able to demonstrate that he can propagate to Pareto Optimal solution sets, he laments that scalability is limited, which immediately becomes an issue with any non-trivial engineering design problem.

Numerous researchers have looked at issues and special challenges trying to use risk analysis in the design environment. Redmill's [65] issue with risk analysis is that, from an engineering sense, it is almost universally accepted that risk can be objectively measured. This tends to hide or downplay the assumptions that are being made and upon which the decisions are based in the decision-making process. There is often qualitative risk that is not accounted for because of these implicit assumptions, which then causes errors in the magnitude of risk severity. This is an area of concern for any type of decision-making in engineering, whether it is risk-influenced or not. Problems are always simplified so that models can be easily constructed, exercised, and evaluated. QRA methods are the same, and it is the decision-maker's responsibility to insure the model deals with all the pertinent information.

Kaplan [66] argues that QRA can only be useful if it is trustable – based solidly and logically on all relevant evidence available. That means that risk must be derived from data using Baye's theorem. This method contains a useful concept similar to Tribus's work [44], that engineering design probabilities can be estimated by evidence of things that have happened as part of the design history. In Tribus's development, he showed that certainty could be modified over time, and used that evolving probability to steer design decisions (see Section 2.2.2).

Haimes [67] looks at decision-making in large hierarchical multi-objective frameworks. The issues that appear include coordination between objectives and hierarchical levels; the risk of extreme events and their tendency to skew decision-making and impact analysis; or the real effect that a probabilistic event might have. All of these issues play heavily in the arena of engineering development. Engineering design has one set of objectives in the product development process that must be coordinated appropriately within the context of a multi-disciplinary (and hence multi-objective) team. Even engineering designs that are not of a trivial nature must deal with multi-objective weightings. Impacts and weightings of risks will be important here. William's concern is the use of distributed decision-making that's a result of empowerment in the workforce. This is a product of team members making individual decisions that don't sufficiently account for the interactions with other needs in the multi-disciplinary team. While he advocates "accommodation" as a risk management technique, it appears that a concurrent engineering team using an information framework (where design interactions are made explicit) and an aggregate risk function, as will be presented in this paper, might resolve this issue.

Risk prioritization is another issue of concern in developing helpful risk analyses. Restrepo, Ramanan, and Stematis all use a risk significance assessment to focus efforts in minimizing risk. Restrepo's method [68] is concerned with turning qualitative data into pseudo-quantitative date through "risk binning," or grouping risks into events or situations that are similar to historical events where risks are understood. Stematis [69] and Ramanan [70] propose a scalar approach to classify and create quantitative assessments of risk by relative rank. These risks are combined in cost-benefit analyses to assign resources for corrective action. The value of risk prioritization in the engineering environment is opportunity to allocate scarce resources to the issues where they can have the biggest impact. In the decision-making sense, knowing the risks with the biggest impact can also steer the design process towards a situation where there is less risk.

At this point, it is important to make distinctions between uncertainty and risk and their relevance in engineering design. Often in design, there is a general assumption that risk and uncertainty are equivalent. In practice, they are not. Whereas risk and uncertainty deal with the probability of an event occurring, the impact of that event is where there is a difference. Uncertainty merely states that there is a potential for things to not work as expected. This could be associated with the correctness (or failure) of a design, an understanding of usage environment or user behavior, or even the uncertainty of the probability itself. But it definitely can be expressed as a probability. In the Expected Value theory, uncertainty is a multiplicative factor with a value to determine overall utility. It is another factor to help calculate the best Expected Value.

Risk, on the other hand, is a way of looking at uncertainty that exposes the good and the bad consequences of a decision. An event might be fairly uncertain, but it might still be of low risk. An example of this principle comes from a common occurrence in injection molding. There might be a high uncertainty as to the final dimensions of a part, because of the molding process. However, if the part and its accompanying assembly is designed correctly, the risk of missing the exact dimensions might be low. In other words, the result of inaccurate dimensions might be inconsequential. This relationship can be expressed as

$$Risk = \Pr(occurrence) * impact \qquad \text{Eq. 2.11}$$

In this case, according to Equation 2.11, the probability of occurrence might be high, but the adverse impact so small the expected risk is small. On the other hand, the probability for an event might be low, say for instance, a catastrophic failure in an electrical product, but the risk of failure might be so high as to cause the decision-maker to decide against that option because the risk is too high. So risk combines the consequence with the uncertainty to provide a value for consideration, while uncertainty is completely neutral. Because of this, risk and uncertainty, and how they are dealt with in the decision making process, is critical to many of the different process descriptions in QRA.

In Amendola's description [71]of the risk process, there are three stages in defining risk:

1. Evaluating the probability and impact of a situation
2. Evaluating the benefits and costs
3. Setting priorities so that the greatest benefits can be achieved at the lowest possible cost.

As stated before, the type of risk to be dealt with in the product development environment is internal risk, where benefits and costs are associated with the product's development as experienced by the development group. Except where the product might have adverse effects on the outside world (which will then spawn a traditional risk analysis), the risks dealt with here typically are ones that create a success or failure in the product development effort (or with respect to customer satisfaction). This paper will use the definition of success and failure as whether a satisfactory number of objectives in the business plan have been met. The definition of a product development business plan is that it establishes a package of benefits to deliver to customers and an acceptable investment and timing to implement those benefits, which will result in an acceptable return on that product. It will also outline other criteria as well to take advantage of that business's specific capabilities. The business plan or project plan thus establishes the baseline risk assumed when a product development effort is undertaken. The risk-based decision method will be dealing with this type of risk, or deviations from this already accepted level of business risk.

While Amendola's stages fit for societal risk factors, they also can be adapted to internal risk. A product development example would be with Product Failure Modes and Effects Analysis (FMEA). Probability and impact are used in Stematis's approach [69] in defining FMEAs. A risk priority number (RPN) is established for each possible failure, which is defined as a cause, its probability of occurrence, its severity of impact, and its likelihood of detection at various stages of development. The probability of occurrence is a scaled value that represents (from 1 to 10) how likely an occurrence of this failure is. The severity of impact is also scaled and reflects small annoyances (0-2) to major loss of function (6-8) to major threats to health or well-being (9-10). Finally, the likelihood of detection is also a scaled number (1-10) in that one can find and eliminate the problem early (in design – 0-2) or in subsequent testing (3-6), in online production verification (7-8) or in shipping or customer use (9-10). The scaled numbers from each of these evaluations are then multiplied together to give the RPN. This is used to prioritize the problem-solving efforts on a component level in the development process. It creates a default cost benefit analysis by organizing the RPNs in descending order.

Most cases of risk analysis in engineering systems and product development are on a higher level than a component FMEA. They require an evaluation of the cost and benefits with more factors of interest to the group. The management team often does this because the decisions and risks tend to be cross-functional in nature. Again Amendola's process stages can help structure this problem. The technical or engineering responsibility is associated with defining the events and their probabilities. The management responsibility is typically to determine the costs and benefits to these "risks," and make appropriate decisions to maximize the result to the benefit of the firm. This is not saying that the same individual cannot be responsible for both the technical and management aspects of the situation.

Since this thesis will look at risk in light of the optimization construct of decision-making, it is also imperative to explain that this methodology does not mimic stochastic programming as mentioned earlier in Cheng's work [64]. Like his method, stochastic programming [28] uses the uncertainty of design variables in the optimization process. It is a technique that is tied to the mean and variation of design variables, whereby the objective function is adjusted to account for the variation, which results in a distribution of probable objective results. This is done by inserting elegant, but complicated mathematical formulas into optimization algorithms. Or due to computing power available today, is alternately simulated by Monte Carlo methods and then optimized using response surface methodologies. While stochastic programming will help to give the result with a distribution of what the probable end values might be, it does not include a provision to identify or deal with the impact of that variation. The proposed method is not stochastic programming, but could be used as an adjunct to stochastic programming to provide a means to make a value judgment on the impact of this spread.

3.0 Modeling the Engineer's Decision Process with Respect to Internal Risk

Engineering design and development can use optimization methods as a strategy for decision-making. This strategy offers the team a way to outline the objectives and critical constraints of a problem and then deal with the key parameters that drive the solution towards the goals, regardless of other decision-making constructs that might be employed for the interim decisions. In the end though, there are three issues that confront engineers as decision-makers:

1. It is difficult to determine the probability of success for a decision alternative's outcome
2. It is difficult to determine the impact of this uncertainty on the design as a whole
3. Based on the uncertainty of design and its potential impact, it is a challenge to decide when the development of a design is good enough, rather than to have it drag on. (Optimization algorithms tend to be exhaustive!)

The by-products of these issues are that engineers tend to be overly risk-averse and delay decisions too long waiting for the optimal or "safe" outcome. But this outcome might not be safe at all in the larger development context. Higher-level decision-makers tend to get involved and cut the decision short, or make what engineers would deem "irrational choices" based on the perspective of the typical optimization method. Many times these choices are called "satisficing" or taking something that is "good enough" instead of optimal. [31]The challenge is to know what constitutes "good enough" for the design situation at hand. An ideal case would be able to pick the optimal "good enough" solution in the process rather than arbitrarily choosing a solution. The method proposed will offer a solution to this "optimal satisficing" problem by infusing optimization with risk-based analysis.

3.1 Risk Heuristic Basis and Assumptions

As discussed in Section 2.3, risk analysis fundamentally deals with the following issues – the probability of an event and its impact, usually expressed as a cost. The situation in engineering design risk is that the decision-maker must deal with multiple risks (i.e. more than one risk driver) and multiple forms of risk (i.e. different objectives). Consequently, the risk analysis becomes multi-objective in nature (See Haimes.[67]) The challenge is then building decision priorities and evaluating risk in a way that is acceptable to all interested parties. There is not only this complication, but the interested parties might also perceive the risk (either the probability of the event or societal cost of the impact) differently.

Again, the goal of this dissertation is to build a model of risk-based decision-making. The issues and complications of these risk analyses are detailed in section 2.3 from others' research. They are fertile areas to pursue further study and refinement of this first-order effort, but will be ignored for the time being in order to focus on the fundamental method. Therefore, some simplifying assumptions that will be used will include:

1. Probabilities of event occurrence will be single values rather than fuzzy sets or distributions
2. Cost will be determinate rather than a distribution
3. The priorities of the different objectives are predetermined rather than subject for debate in the risk analysis
4. Each of the above terms is realistically quantifiable

In establishing these simplifying assumptions, the risk model will then be made of three components:

1. Risk weighting factor for a specific, prioritized project objective
2. Probability of the occurrence of the risk event
3. Impact of the risk event

Component two and three can be represented by the FMEA approach presented by Stematis [69]. The multiplicative effect will be followed based on his work. This is also the same as Equation 2.11. This equation is quite similar to the Expected Value equation, Equation 2.5. The only difference between the two is that Equation 2.5 is written as an aggregation of many probability terms. Equation 2.11 can be written in the same way; thus, the risk model that is the basis for this work draws from the mathematics of the Expected Value construct. Expected Value is the approach known to many engineers, so it will be the starting point for this method. It will also be developed in the context of an optimization construct, because this gives the decision-making process a time-based, directional, and converging strategy to provide impetus and timeliness to the process. Both of these constructs provide useful principles and techniques that are exploited here; but the proposed method also involves a distillation of observations made by the way risk is dealt with in engineering design settings along with development of the theory of risk-adjusted value.

The resultant model is a mathematical formulation that represents a heuristic process involving interactions of the variables associated with the risk-based method. The proposed method is a heuristic method because it is not a direct theoretical extension of the Expected Value or Optimization constructs, but only uses some of those principles. Consequently, the method will often be referred to as the heuristic to remind the reader of this loose relationship to existing constructs. The term model will be used to represent the mathematical notation of the heuristic method or circumstances when the method is being applied to a specific situation.

3.2 General Optimization Model and the Value Objective

Given that the heuristic will talk about rational decision-making using an optimization construct, it is instructive to look at the pieces of an optimization problem and how they are related. This method can then be used and adapted to deal with decision-making in various situations and circumstances. The components of a decision have been shown in Asimow's and Starr's work [1, 43] and, in general, include:

- Objective, O – Key decision metric or Outcome
- Criteria, C – Constraining and defining information
- Alternatives (or Strategies), A – Actual representations of choice candidates
- Scoring evaluation, V – Evaluations of the alternatives with respect to the criteria
- Weighting factor, p – Prioritizing factor to bias the valuation result according to various importance criteria such as probabilities of success or customer desirability. (This paper will use the terms w and y to represent probability factors and the term a to represent independent weighting factors in subsequent equations.)
- Simplifying assumptions – Important but often unstated conditions which define the scope and applicability of the model

These factors can be employed into a standard optimization problem format. The Objective is usually written as a function

$$O = f(\mathbf{X}) \qquad \text{Eq. 3.1}$$

where one wants to optimize the objective O. If the problem is a minimization (say if the Objective O was a cost) then the problem would be:

$$\text{Find } \mathbf{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \cdot \\ x_n \end{Bmatrix} \text{ which minimizes } f(\mathbf{X}) \text{ or } Minimize[f(\mathbf{X})] \qquad \text{Eq. 3.2}$$

This minimization typically has associated constraining functions that the Objective function is subject to:

$$\begin{aligned} g_j(\mathbf{X}) &\leq \mathbf{0}, j = 1,2,\ldots,m \\ l_j(\mathbf{X}) &= \mathbf{0}, j = 1,2,\ldots,p \end{aligned} \qquad \text{Eq. 3.3}$$

$\mathbf{X}$ in this case is the current design vector that has a dimension of n. If one were to be able to plot the objective function O for all possible combinations of the n-dimensional design vector, an n-dimensional response surface would result. The functions g and l are boundaries that would limit the feasible choices available on this large response surface. If it were possible to produce this graph, choosing a design would be straightforward. However, it would be extremely time-consuming to generate all the data for many designs that would only add uninteresting definition to the response surface (i.e. areas of undesirable outcomes). Consequently, mathematical principles such as Newton's gradient concept coupled with Cauchy's steepest descent strategy direct the solver on a path that leads to interesting solutions more efficiently. The process of determining the gradient and moving in an efficient path requires generating interim solutions, and then requires testing the solution for possible next steps with regards to the objective function. Interim solutions can be thought of as design alternatives and defined as

$$A_i \equiv \mathbf{X}_i \qquad \text{Eq. 3.4}$$

In the real world of design and development, early alternatives or strategies, A, might be compared simultaneously with each other to narrow to a single concept or determine a design direction. In the latter stages of development, this step-wise approach will focus on the refinement of a single alternative. In product development, the optimization is often set up as a maximization problem as well, which takes on a form similar to Equations 3.2 and 3.3, and can be written as

$$\begin{aligned} &Maximize[f(\mathbf{X})] \\ &\text{s.t.} \\ &\quad g_j(\mathbf{X}) \geq \mathbf{0}, j = 1,2,\ldots,m \\ &\quad l_j(\mathbf{X}) = \mathbf{0},\ \ j = 1,2,\ldots,p \end{aligned} \qquad \text{Eq. 3.5}$$

Often in product development a simple mathematical model cannot solve the real problem. The functions might not be continuous or smooth if they are mathematical; moreover, they might not be easily defined or even deterministic formulas in the first place. Consequently, mathematical optimization has a limited range of usefulness in the development environment as a direct construct for problem solving. Rather than explore the depths of optimization theory to define and solve these mixed problems (a daunting task that many others have expended much effort upon), this thesis will use the principles of optimization search and limit the mathematical rigor of its actual execution.

3.3 Determining Base Model for Optimization Measure of Performance

In Decision-based Design (DBD), found in Shupe [47] and diagrammed by Hazelrigg (see Figure 2.10)[46], his model for development optimizing has a simplified objective function of

$$Maximize(Value) = Max\left[NPV(Revenues - Costs)\right] \qquad \text{Eq. 3.6}$$

This objective function is written in terms of the value of income generation. This model puts forth a general optimization problem that is broader than the engineering discipline and extends thinking and effort to the broader multi-disciplinary environment of product development. Although this optimization deals with quantitative numbers, it is general enough in scope that it can allow different decision-making constructs to be used at sub-levels of development and various stages. In this case, it is important to note that this optimization most likely occurs, not by direct evaluation of the derivatives of the objective function, but by systematic improvement resulting from focus on the goal. This general equation also offers enough structure for engineering to deal both with the optimization of benefits, by their link to increasing revenues, and control of costs. For simplification purposes, the constraints equations will be dropped during further development of the model. Note that there is an implied assumption here that all business constraints are being met, at some sublevel of work, of this overriding performance objective.

While Equation 3.6 is written in terms of increase in profit, the model of this dissertation will use a different measure of value. Rather than optimize on a strict summation equation, the heuristic is based on the value analysis paradigm presented by Thomas [60], which is to make decisions based on a value ratio, where the ratio is expressed as

$$Value = \frac{Benefits}{Costs} \qquad \text{Eq. 3.7}$$

This can be incorporated into an optimization model and written as

$$Maximize(Value) = \frac{Max(Benefits)}{Min(Costs)} \qquad \text{Eq. 3.8}$$

Maximizing value according to Equation 3.8 offers many benefits. First of all, it is an efficiency ratio in terms of how well one is doing to make benefits for the amount of money being spent. This makes the performance measure scalable to any size business venture, and has more meaning for the decision-maker. Secondly, this model allows for multidisciplinary decision-making and has the overall generality that is present in Equation 3.6.

Using the ratio of Equation 3.8 offers another benefit. During a development effort, the value should monotonically increase or an intervention is indicated (see example later in this section.) At this level of optimization, Pareto optimality (the best one can do when optimizing two conflicting objectives in a multi-objective problem), or Kuhn-Tucker conditions (traditional optimality conditions [29], also see Rao[28]) are less important, and for that matter, extremely hard to determine anyway. Consequently, the ratio turns out to be the basis for a more flexible and simple decision method, and one that can more closely match the way humans make decisions.

3.4 Dealing with Uncertainty in the Value Ratio Equation

Engineers deal with uncertainty every day. But as stated earlier, the optimization techniques they deal with in development are generally built on deterministic formulas. Both Equations 3.6 and 3.8 follow this determinism. A solution is obtained by following the process, then a sensitivity analysis is performed to check the potential for adverse (or positive) effects to the design by inadvertent alterations of the independent variables. This sensitivity analysis is done with much human input and tends to become a skill learned with time and nuance. But neither model really deals with uncertainty of the data nor the risk involved with that uncertainty.

Many engineers and decision-makers see risk as uncertainty and deal with it in classical terms such as von Neumann and Morgenstern's expected value [20]. But decision-makers need to consider an extended definition of risk and uncertainty in design. That could be the one used in Equation 2.11. Again, this refers to the internal risk being dealt with by the multi-disciplinary development team. The example of an FMEA shows assessments of risk, stage of identification and impact scaled from 1-10 and combined by multiplication to help establish priorities in resolving issues in the development environment. If one looks closely, it can be observed that likeliness of occurrence and stage of identification both relate to the probability of an event, while Stage of Identification and Impact both relate to the cost impact of this event. This FMEA approach can be extended to include actual probabilities and actual costs so that Equation 2.11 can be re-written with the combination of these three areas to yield the general cost-of-risk equation

$$E(Cost_{risk})_i = \Pr(event)_i * (Cost_{impact})_i \qquad \text{Eq. 3.9}$$

Thus risk is not just the probability of an event but its expected impact to the system. This equation has the same form as that of Equation 2.5 and is similar to expected value. It defines the **Expected Cost of Risk (ECR)**.

A common injection-molding situation illustrates the concept of ECR well. There might be a high uncertainty as to the final dimensions of all parts, because of the molding process. However, if the part is designed correctly, the risk of missing the exact dimensions might be low. The probability of the event might be very high (wrong dimensions), but the impact of the wrong dimension can be mitigated by designing the part so the dimension is not in the critical tolerance loop. Consequently, the result of inaccurate dimensions can be made inconsequential. In this case, according to Equation 3.9, the probability would be high, but the impact cost is so small that the expected cost-of-risk is small. On the other hand, the probability for an event might be low, say for instance, a catastrophic failure in an electrical product, but the risk of failure might be so high as to cause the decision-maker to decide against that option because the cost-of-risk is too high. Risk combines the consequence with the uncertainty to provide a value for consideration, while uncertainty alone is completely neutral.

Now return to Equation 3.7 from Thomas. His thesis is that there is uncertainty in the numbers in the value equation, and this uncertainty needs to be incorporated into the decision process. So he re-writes Equation 3.7 as

$$Value = \frac{Benefits}{Costs} * \Pr(success) \qquad \text{Eq. 3.10}$$

where the probabilities of both the benefits and the costs are incorporated into a decision. Thomas's use of this equation was to determine comparison values between business opportunities in portfolio management. However, the same principle can be applied to the decision process in design decision-making. It is worth noting at this point that probabilities shown in Equation 3.10 can apply either to the numerator or denominator, or both. In fact, many of the probabilities of incurring a benefit (which would be an expected value) are also the same probabilities that are tied to a potential cost of that benefit. By using Equations 2.5 and 3.9 and substituting them into Equation 3.10, the result is

$$Value = \frac{Benefits}{Costs} \Rightarrow \frac{\sum \Pr(event) * Benefits(event)}{\sum \Pr(event) * Costs(event)} \qquad \text{Eq. 3.11}$$

In more mathematical notation Equation 3.11 becomes

$$V_R(A_k) = \frac{\sum_{i=1}^{n} w_i B_i}{\sum_{j=1}^{m} y_j C_j} \qquad \text{Eq. 3.12}$$

where the Value ratio, V_R, is the ratio of the sum of the expected benefits (with probabilities, w, and benefits, B) over the sum the expected costs (with probabilities y and costs, C). The counters n and m represent the dimensions of the benefits and costs terms, which might not be the same number. A_k is the design vector that represents the k^{th} design alternative as shown in Equation 3.4. Equation 3.12 is a new definition of value; namely, expected benefits over expected costs, which, for convenience, will be named the **Risk-adjusted Value Ratio (RAVR)**. This is the basic model that will be used to develop an optimization structure and accommodate risk preferences for the design decision-making heuristic of this dissertation.

3.5 Optimizing Based on the Risk-adjusted Value Ratio (Focusing on Expected Cost of Risk)

The next step in the development of the RAVR heuristic is to understand how RAVR can be coupled with optimization to assist the engineering design team in making decisions. While the engineering ideal would be to optimize every product that went out the door, there are mitigating circumstances that diminish that ability. There are many objectives in product development rather than a single objective, and there are many sub-system problems. As one learns in classes on optimization, global optimization is very difficult, if not impossible (without serendipity), and competing objectives are virtually impossible to optimize individually and successfully optimize the whole locally. From a practical standpoint, Pareto's principle states that the last 20 percent of the development will take 80 percent of the time. What this translates to is that a company will spend a lot of resources for the drive from a satisfactory but non-optimal solution to an optimal solution.

Consequently, many design teams drive for a solution that just satisfies the requirements. The term coined for this process is called "satisficing." However, one might find that one could not compete in the marketplace with "me-too" products that merely satisfy the perceived requirements. So the desire to drive to an intermediate point between merely getting in the game with a minimal product and the exhaustive optimization of a product (and possible exhaustion of resources) is strong.

In the design practice there is almost never time to get everything done perfectly, hence is the applicability of the old joke, 'It's time to shoot the engineers and begin production.' In this situation, though, the decision triggers really have to do with trade-offs. These trade-offs are a function of design uncertainty, priorities, and impact cost (see Section 3.1). For example, as the design uncertainty is forced down by the expenditure of learning, schedule cost goes up as the risk of executing the project on time or within the market window goes up. From a mathematical sense, the activity that is occurring in this example follows from equations 3.11 and 3.12. The design team is actually trying to minimize cost-of-risk and maximize benefits simultaneously, and by so doing is trying to create the best value. This effort can be shown by rewriting Equation 3.12 as

$$Max[V_R(A)] = \frac{Max\left[\sum w * B(A)\right]}{Min\left[\sum y * C(A)\right]} \qquad \text{Eq. 3.13}$$

In actuality, what appears to be satisficing on a one-level engineering optimization problem is in essence an optimization of a two-level multidisciplinary problem, where the trade-offs are being balanced to maximize the value to the company. The RAVR model is effective in this situation and allows the multidisciplinary problem trade-offs to be dealt with. This will be demonstrated in the Case Studies Section. All this is done with respect to the uncertainty of information available in the decision-making process.

Another characteristic of this model is that the numerator and denominator optimizations are linked by the fact that they are optimizing the same set of independent variables (A). This requires that the same design strategy (i.e. same design vector values A) be pursued simultaneously both in the maximization of benefits and the minimization of costs. This often causes conflicts and trade-offs because of this dependence, but Equation 3.13 offers a metric by which to make those trade-offs to give the best result (value). However, in many cases, there is a partial independence that can be achieved between the numerator and denominator through techniques used to decompose the design variable vector into subsystems. There might be certain variables that will be significant in the benefits side, while others are significant only on the cost side (such as the selection between similar materials based on price). Often, particularly in product development cases as are shown in Section 5, assumptions are made that hold benefits variables fixed and focus on cost implications.

It should also be noted at this point, to display the most general case of the RAVR heuristic requires that a weighting factor be included to deal with preferences or importance factors in the design process. These factors might include a preference for decisions favoring development speed over technical superiority (or vice versa), or preference for manufacturibility over initial speed of development. In the consumer product industry, product development priorities or objectives usually include the following (in random order, except for safety)

Safety
Technical Superiority (Feature mix)
Development Speed (Speed to market)

Manufacturability

Product Cost

Development Costs (Capital)

Manufacturing Capacity

Quality

These areas involve a multi-disciplinary team with wide ranging concerns and objects. Usually a trade-off matrix is built to establish priorities. Once these priorities are determined they can be added in as weighting factors, *a*, to Equation 3.13 to become

$$Max[V_R(A)] = \frac{Max\left(\sum a_i w_i B_i(A)\right)}{Min\left(\sum a_j y_j C_j(A)\right)} \quad \text{Eq. 3.14}$$

Note that these weighting factors represent the first component of the risk model as set forth in Section 3.1.

Now it is instructive to focus on how the expected cost equation on the bottom of Equation 3.13 drives a normal optimization to a "satisficed" situation. At this point in the theoretical development, Expected Benefits and Expected Cost of Risk are mathematically equivalent, so expected benefits (numerator) will be assumed constant, and the focus will be on the denominator from Equation 3.14. Using the notation for the cost function from Equation 3.2 and making this function an optimization gives

$$\text{Min}(Cost_{risk}) = Min\left\{\sum_{j=1}^{m} a_j y_j C_j(A_k)\right\} \quad \text{Eq. 3.15}$$

Each risk function (j) has a priority weight (a) and a probability weight (y) that relate to costs (C_j) for that situation (A_k) in which there is a development objective. These are the same objectives and priorities mentioned above that are summed to yield the Expected Cost of Risk. The independent variables are represented by k, and it is this parameter (A_k) that is where the minimization occurs although the probability weights (y) are usually a function of the independent variables.

Each of these (and/or any others specified at the beginning of a project) will have some impact on the overall cost of the product to the company. Each has its benefits and risk costs that affect a project. As these costs are accumulated, a composite curve can be formed that represents the overall risk cost of the project, sub-system, or decision. This aggregate cost represents over time the progression of cost-of-risk of a development project.

A simple case is illustrated in Figure 3.1. Curve F1 and F2 represent the Expected Cost of Risk curves for separate development objectives in this example problem. One shows the cost-of-risk decreasing over time. This might represent the decrease in cost-of-risk due to the increase of technology knowledge in a development. As the engineers become more familiar with the product under development, either the probability of a problem decreases, or the problem itself is eliminated. This curve would represent this activity over time. Curve F2 might represent risk increasing over time. Typically, this might be similar to the increase in market risk due to changing market tastes through the

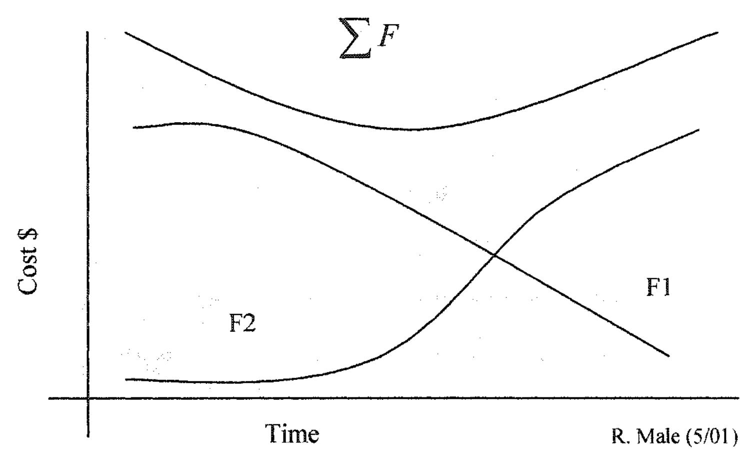

Figure 3.1 Risk Cost Curves and Composite Cost Curve

development phase or increase in risk of missing a market window. The aggregate cost is the summation of these two (or however many objectives are dealt with in the analysis.)

The summation equation looks very similar to graphs seen in economics. The optimal cost point for the project is determined by finding where the gradient of the summation is zero. Theoretically, this is the point where the project operates and where the marginal costs go to zero. This is the low cost point of decision making. If the developer stops on either side of that value, he will spend an incremental amount of money on risk (in this case, returns costs or costs of lost sales.) This can be called the **Marginal Cost of Risk**. It is arguable that all decision-makers in real development environments make decisions this way - to minimize the cost-of-risk, given a set of benefits that they develop for, or try to hit the curve where the Marginal Cost of Risk is low or zero. There are usually more than two functions of risk involved, and oftentimes this calculation of the risk cost is done intuitively, but this minimization of risk cost is consistent with the way the author has seen decisions made.

In actuality, product developers cannot construct these general curves before time, so this optimization on the cost-of-risk follows a different optimization methodology. Similar to stochastic systems, response surface methodology can be employed at a point in time to assess the risk cost and its vector. The difference is that the decision-maker will assess the overall cost-of-risk to see if it has caused the value equation to increase, stay the same, or decrease, and what the general direction of cost is headed. See Figure 3.2.

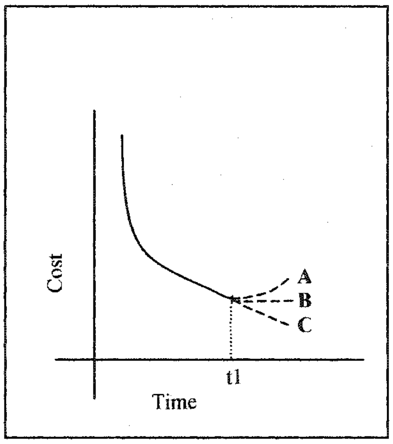

Figure 3.2 Representation of an Aggregate Cost of Risk Curve and Potential Next Steps

Since the actual function is neither well known nor guaranteed to be continuous, the decision-maker will assess at a point in time what his or her actions will be. These actions will not be focused on trying to follow the risk curve directly (as is done in most types of optimization), but will be driven to actions which deal with the development effort as a whole. The decision-maker will try to assess whether at time t1, the project indications for risk cost will follow Curve A, B, or C. Each of these curves represents a data interpretation, which will indicate a different action.

Often the cost curve is looked at exclusively when making decisions on actions to be taken. This is following the implicit assumption that the expected benefits are not changing (e.g. a frozen specification), and so the project is on a path to minimize cost-of-risk alone. However, the benefits side also has some uncertainty associated with it and plays a dynamic part in the Expected Value of a product. So, while the cost curve presents an indicator of risk, this must also be evaluated in the context of the benefits that are being produced. An action matrix of situation types looking at both Expected Cost of Risk and Expected Benefits is shown in Figure 3.3.

Expected Benefits	Increasing (A)	Constant (B)	Decreasing (C)
Increasing / Constant	**I.** Evaluate the RAVR to determine whether the risk is warranted	**II.** Continue the Development Process	
Decreasing	**III.** Stop Development	**IV. Evaluate the RAVR to determine whether the risk is warranted***	
	Expected Cost of Risk		

Figure 3.3. Risk-adjusted Value Ratio Decision Action Matrix (Note: the shaded area (IV) shows a situation which is rarely seen. Usually risk costs increase when benefits are eliminated. However, this situation might be used and evaluated when the risk cost is too high (I) and benefits might be reduced to cause the risk to decrease.

Decision-making with the RAVR heuristic can be done on the macro or the micro scale. This means that it can be used for major milestones or for subsystems development. Since the development process is iterative, this risk cost can be visited often. While benefits are usually specified early on in the development process, the goal of developing them then often follows this reduction of the cost-of-risk. In an overall development optimization, when the marginal cost-of-risk hits zero, it truly is time to shoot the engineers (i.e. stop optimizing the benefits) and begin production (i.e. make the constraining decisions and move on).

In summary, design is driven to create value (increase the benefits of the value function and/or decrease the risk costs) and is constrained by the time-based need to make decisions triggered by the Marginal Cost of Risk. These "satisficed" decisions cause a reformulation of the remaining problem, until all variables are chosen (become constrained) or controlled (as in the case of stochastic variables). While there are a number of ways to come to an end in satisficing design, most notably Pareto Optimality constraints or finding the first feasible solution, the Marginal Cost of Risk approach is novel and unique. It integrates a function representative of the two main factors that affect decision making in the real world, namely time and risk. Because of this, it has the opportunity to shed light on how real decisions are made in cross-disciplinary design. It can offer insight to the decision-maker into what many perceive as a gut-feel decision process.

3.6 Adjusting the Risk-adjusted Value Ratio to Deal with Risk Preferences

Equations 3.6 and 3.13 have shown two methods for decision-making – one that optimizes by maximizing the income (difference between benefits and costs) and one that optimizes by maximizing the value ratio (the efficiency of benefits to costs). While both of these approaches are valid, there are other reasons for the preference of the Risk-adjusted Value Ratio over straight Expected Value. First of all, RAVR mimics real decision-making situations more clearly. While costs to a project are clearly minimized and fit into the difference equation, expected costs (considered risks) are usually dealt with more along the methods displayed in Figures 3.2 and 3.3. Also, the RAVR heuristic represents a new way of perceiving the value of a decision versus the traditional EV (difference method) because it deals with the cost of investment more effectively. When the RAVR equation is adjusted for risk preferences of the decision-maker, it can then deal with anomalies of choice that are displayed by real decision-makers, which the traditional EV method cannot.

When performing a value analysis, the straightforward sum approach is not usually used. Often value is computed using Equation 3.7. This model is often used in business to describe the way consumers might make choices between products. In product decision-making expressed by Thomas [60], this value equation also takes on the uncertainty involved with incomplete information, expressed in Equation 3.10, where the success function was based on the probabilities of being able to realize the benefits and contain the costs. Now this equation can be rewritten by distributing the probability function to affect both the benefits and the costs. The Risk-adjusted Value Ratio again follows as in Equation 3.12, where there are some probabilities, w, that the benefits will be accomplished, and there are some probabilities, y, that certain costs will be incurred. Of course to increase value, either one needs to increase the magnitude of the numerator or decrease the magnitude of the denominator. This will be discussed further later, but first, it is instructive to examine Equation 3.12 more closely and see what its components entail.

Combining Equations 3.10 and 3.12 and looking at the numerator gives

$$Benefits * f(success_b) = \sum_{i=1}^{n} w_i * B_{i:success} \qquad \text{Eq. 3.16}$$

The only difference between Equation 3.16 and the Expected Value Equation 2.5 is that the benefits, B_i, only include the positive values. The negative benefits (negative sums in traditional Expected Value) will be shown in the denominator. If the numerator has the positive outcomes and the probabilities associated with that, the denominator should have the negative outcomes (costs) associated with it. So the denominator can be rewritten in the same form as Equation 3.16 to get

$$Costs * f(success_c) = \sum_{i=1}^{n} y_i * C_{i:risk} \qquad \text{Eq. 3.17}$$

In order to incorporate an adjustment for risk tolerance, a term is added to the cost-of-risk equation that is dependent on choosing an **expected outcome at acceptable risk**, O_e. Observation shows that when people deal with risk, they often establish an acceptable expectation and then try to minimize the negative deviation from that expectation. Because of this expected cost for a situation, a negative deviation will impose a cost-of-risk, while a positive deviation will be considered as incurring no risk cost at all (it goes to the benefits side of the equation.) Choosing an appropriate Expected Outcome, O_e, or Minimum Acceptable Outcome is the key to determining one's risk tolerance or preference. One possible way to define it is to associate it with a return on investment requirement for a situation along with the accompanying opportunity costs. This would be like comparing methods of investment against a standard that might be achieved if the decision-maker left his/her money in that standard and did nothing. This time-value-of-money approach can be shown as

$$O_e \equiv \$benefits @ \text{acceptable risk} = \$investment * (1+i)^n \qquad \text{Eq. 3.18}$$

where i is the interest rate and n is the period of time the money is tied up. This then becomes the baseline expected outcome or expected cost. This means that if a decision-maker received O_e back from an investment, then the investor would have incurred \$0 cost-of-risk. (The investor would be at the acceptable risk preference.)

Using this principle of Expected Outcome at acceptable risk, a portion of Equation 3.15 could then be rewritten to deal with costs to be

$$C_{i:risk}(A_j):\begin{cases} C_i = O_e - O_i \text{ if } O_e > O_i \\ C_i = 0 \text{ if } O_e \leq O_i \end{cases} \qquad \text{Eq. 3.19}$$

This is written so that costs are positive in the final ratio. In explanation, Equation 3.19 states that a cost is incurred (the difference between the actual outcome O_i and the Expected Outcome O_e) when the expected outcome is not quite obtained. If the Expected Outcome is obtained or exceeded, there is no accounted cost. In fact, this will then show up on the benefits side. Note that this is a cost equation based on selection of two positive outcomes, where usually only benefits are considered (such as in the EV case).

Another interpretation of this is possible, and is more in line with the decision-making in a product development environment. The O_e term can be the accepted cost of the project or the approved budget for a development program. Once a project plan is developed and accepted, an investment amount is the expected cost of that plan. Negative deviations from that budget will increase cost-of-risk the same as if an outcome deviates from the expected outcome. Since the cost of projects will not go to zero unless the project plan is rejected, it is possible to set the baseline expected cost at project plan levels and incur unusual risk when the project deviates from the plan. This interpretation would then require the Cost-of-risk equation of Equation 3.19 to be rewritten as

$$C_{i:risk}(A_j):\begin{cases} C_i = O_i - O_e \text{ if } O_e < O_i \\ C_i = 0 \text{ if } O_e \geq O_i \end{cases} \qquad \text{Eq. 3.20}$$

This equation is the method to calculate the Expected Cost of Risk curves in the example shown in Section 3.4.

It is also reiterated, at this point, that there is a tie between the cost side the RAVR equation and the benefits side of the equation in many cases. This is true because a priority function can have either a cost or a benefit associated with it, or both. In one instance, when the incurred cost is higher than the accepted cost, this becomes a cost of risk to the function. On the other hand, if the incurred cost is lower than the expected cost, this then shifts to the benefits side of the equation (and the cost function becomes zero). This is important because it is a shift in the structure of the equation that doesn't occur automatically (at this point) due to the nature of the ratio construct.

At this point, too, it is important to observe that the terms of Equations 3.19 and 3.20 are denominator terms in the RAVR equation. Because the denominator can take on a zero term in some circumstances, this can cause the RAVR calculation to go to infinity. This makes comparisons between less risky alternatives difficult (they might both be infinity) and is not really meaningful in practice. Similar to algorithm techniques in numerical analysis, a small factor ε will be used instead of zero, where

$$0 < \varepsilon << O_e \qquad \text{Eq. 3.21}$$

It keeps the RAVR equation well behaved, which helps keep the results meaningful (since the probability of risk rarely goes to zero) and yet does not bias the answer to the problem. It also allows reasonable evaluations of more than one less risky alternative. This will be demonstrated in Section 4.

Substituting Equations 3.16, 3.19, and 3.21 into Equation 3.12 combines to give a risk preference-adjusted Risk-adjusted Value Ratio (RAVR) written as

$$V_R^*(A_k) = \frac{\sum_{i=1}^{n} w_i * B_{i:success}(A_k)}{\sum_{i=1}^{n} y_i * C_{i:risk}(A_k) : \begin{cases} C_i = O_e - O_i \text{ if } O_e > O_i \\ C_i = \varepsilon \text{ if } O_e \leq O_i \end{cases}} \quad \text{Eq. 3.22}$$

It should be recognized that the RAVR is then the Expected Benefits over the Expected Cost of Risk (ECR), where the expected cost is risk-adjusted by the Expected Outcome, O_e. For product development situations, Equation 3.22 can be modified by substituting Equation 3.19 into the denominator to yield

$$V_R^*(A_k) = \frac{\sum_{i=1}^{n} w_i * B_{i:success}(A_k)}{\sum_{i=1}^{n} y_i * C_{i:risk}(A_k) : \begin{cases} C_i = O_i - O_e \text{ if } O_e < O_i \\ C_i = \varepsilon \text{ if } O_e \geq O_i \end{cases}} \quad \text{Eq. 3.23}$$

This then takes into account the idea of investment of capital and the efficient use of that capital, rather than the lack of consideration as is shown in traditional Expected Value.

A graphic example will illustrate how RAVR and ECR work within an engineering development effort. During the project planning phase, enough information is developed that the initial RAVR function can be established. A function was determined (with a

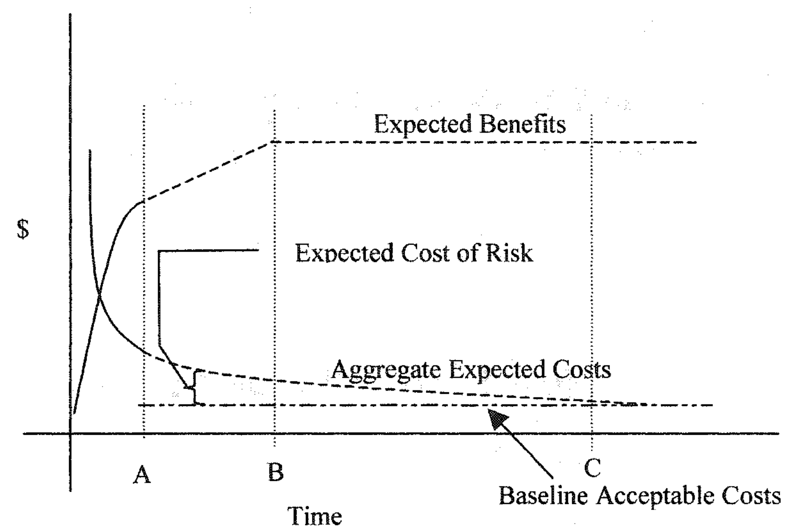

Figure 3.4 Desired Progression of Expected Benefits and Costs within a Product Development Program: A) At Project Plan; B) At Detailed Design Review; C) At Launch

certain level of probability and opportunity to increase confidence) that represents the potential benefits realized when the product is developed for consumers (See Figure 3.4.)

At this stage as well, the expected costs of the project are determined. This is usually with a degree of uncertainty because at this phase (A on the figure) first-order data approximations are used. Now this cost function is at the acceptable cost of risk, because undertaking a project like this is inherently risky. These costs are determined and when the project plan cost, O_e, of the project by which future decisions will be gauged against in the product development plan and is shown as the baseline cost line in Figure 3.4.

During the project planning phase, initial user benefits (the Voice of the Customer – VC – converted to Fundamental Requirements – FR) are also established. The idea is that knowledge about the ways to implement these benefits will increase and a highly manufacturable and functional concept to achieve the user requirements will result. Thus, in a controlled project, the expected benefit will move towards a fixed amount sometime in the project when the specifications are set and the probabilities of providing these benefits reaches a high level. This is shown in Figure 3.4 by the expected benefits curve.

The final curve within Figure 3.4 shows an ideal aggregate expected cost curve. At the beginning of any project, the probability of understanding all the costs is low due to the requisite initial approximation of the data. The expectation is that with time, more will be learned about the situation (i.e. technology, market need, etc.) and the probability will increase that the team can work through and resolve problems of design. This would cause the cost curve to move towards the amount determined as the baseline cost for the project. As the probability of success rises, its complement, the probability of incurring a cost, decreases. As the problems of the design are worked through, extra costs are (hopefully) eliminated by intelligent design. The combination of these two activities is what is anticipated in the design cycle. When their combination is plotted as shown, the

ECR function would then be the difference between the baseline costs and the expected cost. It is shown as the gap between the Aggregate Accepted Costs curve and the Expected Cost curve.

The actual ECR function is an aggregation of functions that will affect the real cost of the product, and these functions don't behave quite as nicely as the ideal case shown. Due to the nature of external forces on the product development project, the composite curve often takes on a different shape. Some of the external factors include market window of opportunity, shifting customers' needs, competitor moves, and so forth. The resulting functions, in this case, will more reflect the reality of the case at hand and will be constructed from assumptions made with respect to this situation. The case studies in Section 5 will illustrate examples of this phenomenon.

4.0 Comparison of Traditional Expected Value (EV) to Risk-adjusted Value Ratio (RAVR)

This section will compare the EV method (Eq. 2.5) with the RAVR heuristic (Eq. 3.22) in terms of complex engineering decision-making with respect to various risk preferences. These are:

Risk-Neutral
Risk-Averse
Risk-Avoiding (Intermediate)
Risk-Seeking
Loss-Avoidance

To compare these two, a risk-preference indicator study developed by Laury and Holt will be used. Equation 3.22 fits the Laury-Holt study [54, 55] better in terms of Expected Outcomes (O_e) rather than the Expected Costs (C_e) represented in Equation 3.23. Consequently, Equation 3.22 will be used to represent RAVR, although the risk modifications displayed in these subsections apply to baseline costs as well as outcomes.

Holt and Laury have explored various risk preferences of decision-makers when faced with hypothetical and real payouts. They developed a choice experiment that was based on the choice sets shown in Table 4.1 below.

Table 4.1 Menu of Choices for Risk Preference Test ([54, 55])

	Option A	**Option B**	**DM's Choice**
Decision 1	$2.00 with probability = 0.1 $1.60 with probability = 0.9	$3.85 with probability = 0.1 $0.10 with probability = 0.9	
Decision 2	$2.00with probability = 0.2 $1.60 with probability = 0.8	$3.85 with probability = 0.2 $0.10 with probability = 0.8	
Decision 3	$2.00with probability = 0.3 $1.60 with probability = 0.7	$3.85 with probability = 0.3 $0.10 with probability = 0.7	
Decision 4	$2.00with probability = 0.4 $1.60 with probability = 0.6	$3.85 with probability = 0.4 $0.10 with probability = 0.6	
Decision 5	$2.00with probability = 0.5 $1.60 with probability = 0.5	$3.85 with probability = 0.5 $0.10 with probability = 0.5	
Decision 6	$2.00with probability = 0.6 $1.60 with probability = 0.4	$3.85 with probability = 0.6 $0.10 with probability = 0.4	
Decision 7	$2.00with probability = 0.7 $1.60 with probability = 0.3	$3.85 with probability = 0.7 $0.10 with probability = 0.3	
Decision 8	$2.00with probability = 0.8 $1.60 with probability = 0.2	$3.85 with probability = 0.8 $0.10 with probability = 0.2	
Decision 9	$2.00with probability = 0.9 $1.60 with probability = 0.1	$3.85 with probability = 0.9 $0.10 with probability = 0.1	
Decision 10	$2.00with probability = 1.0	$3.85 with probability = 1.0	

Laury and Holt used both hypothetical and real pay-out scenarios in this test, as well as varying magnitudes of payout (multiples of the pay-out values shown). The results of this experiment describe in general that decision-makers have variations in risk preferences, and that these preferences can change depending on the magnitude of the decision. Table 4.2 shows the results expected and obtained from the test shown in Table 4.1 that was given to a large sample of individuals. The data from analysis and tests shows that risk-neutral choices dictate the first 4 choices be A and the last 6 choices B. In the risk-averse preference, by contrast, the only time B is chosen is when receiving more than the maximal minimum of $1.60 is a sure thing. The aversion to losing the chance to get a sure $1.60 outweighs the potential for the other gain of $3.85. In the Laury and Holt cases, the coefficient to the choices shows the percentage of people who

Table 4.2 Spectrum of Real DM's Risk Preferences [54]

Decision	Risk Neutral	Risk Averse	People's Choice – Real (1x payout)	People's Choice - Real (90x payout)
1	A	A	A	A
2	A	A	A	A
3	A	A	.95A	A
4	A	A	.82A	A
5	B	A	.7A	.9A
6	B	A	.5A	.8A
7	B	A	.8A	.7A
8	B	A	.9B	.55B
9	B	A	.95B	.6B
10	B	B	B	B

actually chose that alternative. It is noted in the Figure 4.1 below that the choices of many decision-makers tend to fall in between the two extremes,while some decision-makers take on a risk-seeking nature. Aiginger performed a separate survey that supports the

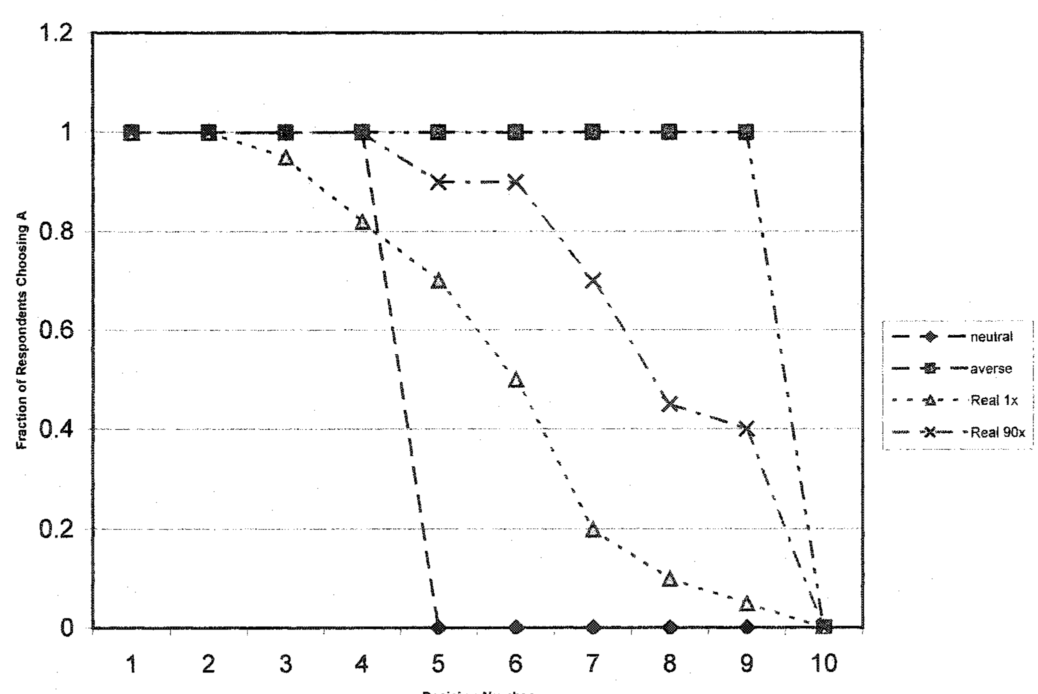

Figure 4.1 Plot of Choice Preferences Shown in Table 4.1

Holt and Laury findings if not the exact numbers. Aiginger's survey [72]showed that for small risks, risk-seekers made up 36 percent and risk-averse decision-makers made up 33 percent with the balance being risk-neutral. On the other hand, for large risks, the risk-averse outnumbered the risk-seekers 53 percent to 12 percent, respectively, with the balance being risk-neutral.

Laury and Holt's work also shows that a certain number of the people will choose a risk-seeking position. But, in general, their results show that a majority of decision-makers tend to move to more risk-averse positions with real pay-outs and even more so when the pay-out potential becomes larger in magnitude. The Laury-Holt data shows that a number of people (60 percent) from this example, even given high pay-outs, tend to choose a less risk-averse position than the extreme risk-averse preference. This will be represented by the intermediate risk or risk-avoiding case.

4.1 Risk-Neutral Case

Using the data from Table 4.1 and calculating the EV and RAVR using Equations 2.5 and 3.18 respectively, Table 4.3 is generated to look at the risk-neutral case. As shown in the table, the Expected Value method essentially follows (and defines) the risk-neutral situation. The RAVR method can also produce results similar to the EV approach. This can only be accomplished by setting the Oe value to maximum payout of $3.85.

Table 4.3 RAVR Compared with Expected Value in Risk-Neutral Case

(O_e = \$3.85, ε=.01)

Decision	EV (A)	EV (B)	Choice (EV)	Risk Neutral		RAVR (A)	RAVR (B)	Choice (RAVR)
1	1.64	.48	A	A		.74	.14	A
2	1.68	.85	A	A		.77	.28	A
3	1.72	1.23	A	A		.81	.47	A
4	1.76	1.60	A	A		.84	.71	A
5	1.8	1.98	B	B		.87	1.05	B
6	1.84	2.35	B	B		.91	1.57	B
7	1.88	2.73	B	B		.95	2.42	B
8	1.92	3.1	B	B		.99	4.13	B
9	1.96	3.48	B	B		1.04	9.26	B
10	2	3.85	B	B		1.08	385	B

However, this is not pragmatic for at least two reasons. First, if the decision-maker can come up with the same answer using either method, it would be smarter to use the easier, simpler method to achieve the results. Second, the strength of the RAVR method is in the fact that it can deal with risk preferences better than the EV (as will be shown in a subsequent section), and allow one to make decisions that fit the real world better than EV. So using RAVR to calculate risk-neutral situations is inefficient from both standpoints.

4.2 Risk-Averse Case (Allais Paradox Example)

It has been shown through the Allais Paradox [73] that maximizing the Expected Value is not always the way that decisions are made in real life. The Allais Paradox is shown in Figure 4.2.

Gamble A	Gamble B
$1 Million Guaranteed	89% Chance of $1 Million 10% Chance of $2.5 million 1% Chance of $0

Gamble 1	Gamble 2
89% Chance of $0 11% chance of $1 Million	90 % Chance of $0 10% Chance of $2.5 Million

Figure 4.2. Allais Paradox Example – Choose 1 of each pair

Many studies ([52-55]et al.) have found that people who make the choice in the first gamble (A vs. B) show a preference for A. If the Expected Values are calculated, Gamble B should win. On the other hand, when the second set of gambles is undertaken (1 vs. 2), the decision-maker will often choose Gamble 2, which does maximize the Expected Value. It was shown that even when this disparity of thought was pointed out, the decision-maker would rarely change his/her position. This paradoxical behavior has been explained away as regret over what is possibly lost. Weber [74] describes this as a satisficing norm, where there is an answer that is good enough (i.e. that provides adequate value). But this explanation again assumes the universal validity of the Expected Value model (Equation 4.1). While this satisficing can occur, having an answer to when something is sufficiently satisficed is opaque and non-informative.

The Allais Paradox can now be revisited with respect to the RAVR heuristic. The problem is shown in Table 4.4 below, along with the calculations of EV, Expected

Table 4.4. Allais Paradox Gamble Analyzed with EV and RAVR Formulas

Gamble	Pr (.89)	Pr (.10)	Pr (.01)	EV	O_e	ECR	RAVR	EV	RA VR	AP
									Choice	
A	$1M	$1M	$1M	$1M	$1M	$100	10000		✓	✓
B	$1M	$2.5M	$0	$1.14M	$1M	$10K	114	✓		
1	$0	$1M	$1M	$110K	$1M	$890K	.123			
2	$0	$2.5M	$0	$250K	$1M	$900K	.277	✓	✓	✓

Outcome (O_e), Expected Cost of Risk (ECR), and then the RAVR calculation. The formulas used for these calculations are Equation 2.5 for the EV (which also doubles as the Expected Benefits portion of the RAVR), the O_e is selected by observation, the ECR is calculated using Equation 3.17 with the substitution of Equation 3.19 and 3.21, and the RAVR is calculated by dividing the Expected Value (Expected Benefit) by the ECR. The calculations show the EV has a higher value for Choice B and Choice 2, which is not the paradoxical behavior exhibited by most decision-makers (see the AP column). As is shown, though, the RAVR does result in the same choices as displayed by the Allais Paradox. Thus, the RAVR should be considered a strong indicator of the way one makes a decision when confronted with a problem laden with probabilities of benefits and risks rather than merely optimizing the Expected Value. The Allais Paradox is a case of having a sure thing as one of the choices. Extremely risk-averse decision-makers will not change their minds from a sure thing, as this paradox demonstrates.

In this case, the paradox shows no investment, so the RAVR is based on the acceptable Expected Outcome, O*e*, which would be $1M. If this system were altered by changing the amount that one must invest, the resulting decision process would change too. For example, if one invests close to $1M, then Gamble A would not look so attractive. A perception of the "hassle" of the transaction might be such that one would need a guaranteed $1.1M return for such efforts to consider this an acceptable risk situation. The Expected Outcome, O_e, of acceptable risk is then $1.1M, and this would change the ECR and RAVR dramatically. One would expect that most engineers would continue to take the choices shown until the Expected Outcome, O_e, became greater than $1M offered.

The results of this section show that RAVR can mimic extreme risk-averse decision-making by setting the acceptable Expected Outcome to the sure bet. It also resolves the Allais Paradox.

4.3 Intermediate Risk-Avoidance Case

As is shown in an earlier section, RAVR used in decision-making can resolve the paradoxical nature of choosing between a risky alternative and one that is more sure – the one where Expected Value alone would take a risk-neutral position. As Holt-Laury study and Aiginger have shown (see Section 4.0), decision-makers don't behave along strictly risk-neutral nor risk-averse tendencies. There is a spectrum of levels that describe the decision-maker's risk tolerance. Some people are risk-neutral, so EV methods work well for their decision analysis tools. But many decision-makers, especially engineering designers, fall between risk-neutral and risk-averse behavior.

The RAVR heuristic can mimic the decision-maker's personal risk preference, which makes it a valuable tool to aid in the decision process. To demonstrate this capability, an example is developed by starting with the same choice conditions of the Holt-Laury experiment above. A set of RAVRs is generated and then compared with the results from Holt and Laury's work shown in Figure 4.1. A table of results from the example is shown below (Table 4.5). The conditions of the RAVR comparison require that an Expected Outcome, O_e, be chosen. Typically this is at a level where the risk of loss is low, which would be the $1.60 level, which is an assured maximal minimum payout in all cases except decision 10. This mimics the risk-averse case discussed above.

Table 4.5 RAVR Results for Varying Values of Oe. (A √ indicates the choice preference)

O_e	$1.60	$1.60	$2.00	$2.00	$2.50	$2.50	$3.00	$3.00	$3.85	$3.85
Decision	VR-A	VR-B	VR-A	VR-B	VR-A	VR-B	VR-A	VR-B	VR-A	VR-B
1	82√	.28	4.56√	.28	1.91√	.22	1.21√	.18	.74√	.14
2	84√	.64	5.25√	.56	2.05√	.44	1.27√	.37	.77√	.28
3	86√	1.1	6.14√	.92	2.21√	.73	1.34√	.61	.81√	.47
4	88√	1.7	7.33√	1.40	2.38√	1.11	1.42√	.92	.84√	.71
5	90√	2.57	9√	2.08	2.57√	1.65	1.5√	1.36	.87	1.05√
6	92√	3.85	11.5√	3.09	2.79√	2.45	1.59	2.02√	.91	1.57√
7	94√	5.99	11.67√	4.78	3.03	3.78√	1.68	3.13√	.95	2.42√
8	96√	10.27	24√	8.16	3.31	6.46√	1.78	5.34√	.99	4.13√
9	98√	23.1	49√	18.29	3.62	14.48√	1.88	11.98√	1.04	9.26√
10	100	385√	200	385√	4	385√	2	385√	1.08	385√

The experiment demonstrates the RAVR method can account for some risk aversion, but not always fall in the realm of extreme risk aversion. Plotting these results (see Figure 4.3) as a comparison with that of Figure 4.1 shows that decision-making preferences

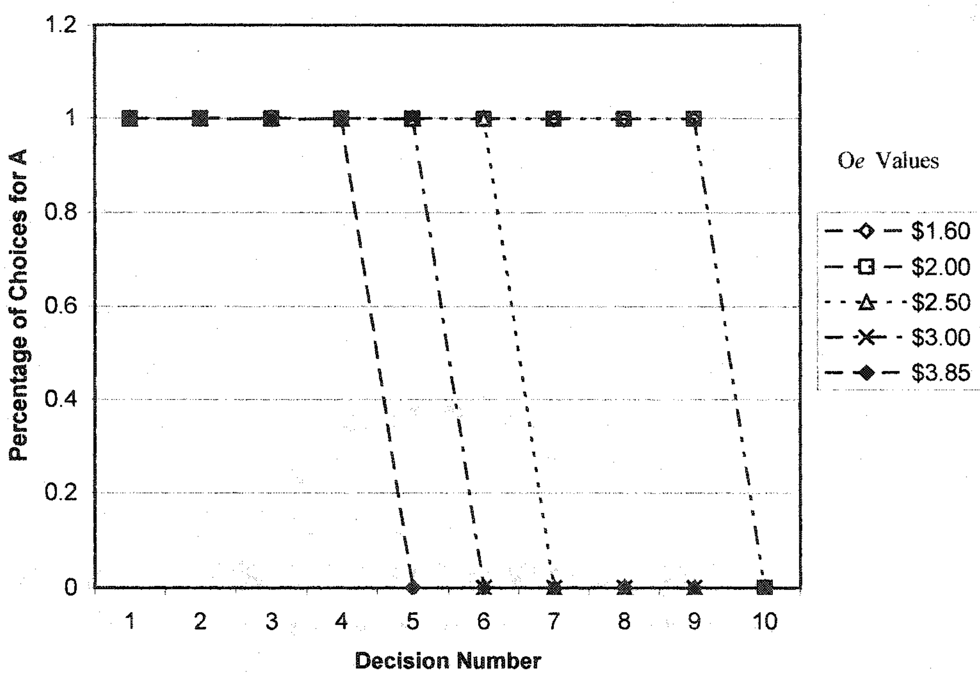

Figure 4.3 Plots of Decision Preferences Using Table 4.5

vary between the risk-neutral Expected Value formula and the extreme risk-averse case of choosing the best "sure thing." There is a means by which the RAVR equation can be modified to accept a factor that tailors the RAVR model to indicate decision preferences the same way a real decision-maker might do so, given their own risk preference or tolerance. The factor would have to be an adjustment of the O_e value itself.

The consideration for setting the O_e could take two paths: to create a factor to multiply the O_e upon when a risk tolerance is determined (similar to taking the Laury-Holt test), or to set the O_e directly. As observed in this choice scenario between A and B, choice A has a narrow band of results (a mere $.40 between the high and low payout), and choice B has a wider band ($3.75 between payout chances). In most engineering situations and often in finance, situations with a wide variation of possible outcomes are considered more risky. Hence, a selection of O_e in the range of the pay-outs of Choice A would be less risky than expected pay-outs in the range of Choice B. Typically, the extreme risk-averse position will be with an O_e chosen such that it matches the largest possible payout in the worst risk case (maximal minimum or Starr's pessimist criterion). This extreme risk case would be evident in the first decision. The risk-averse decision-maker can choose to make $1.60 the acceptable outcome, or the baseline worst-case expectation. But if the decision-maker chooses a higher level of expectation, he or she chooses a higher level of risk tolerance to get the expected amount.

Until an O_e value is chosen above the range of the "sure thing" choice ($1.60-$2.00 range), the RAVR will continue to result in risk-averse decision-making. If an O_e is chosen above the value of the highest payout ($3.85), the RAVR will degenerate into a straight Expected Value calculation and a risk-neutral scenario. But when O_e is selected between $2.00 and $3.85 for this example, decision crossover occurs in the area of intermediate risk-avoidance. Thus, the RAVR model and heuristic can account for the various risk preferences between risk-neutrality up to extreme risk-avoidance. It is left for further study how O_e can be determined for the design situation at hand.

4.4 Risk-Seeking and Loss-Avoidance Cases

The RAVR method for decision-making cannot mimic a pure risk-seeking individual's choice method. That is, one suspects that the risk-seeking engineer is building decisions based on a different risk-benefit model for macro decisions. However, most rational risk-seekers may only take risks where large rewards are possible, and then use methods such as this one to control risks in all other situations. It is felt that the RAVR method establishes a baseline acceptable risk (even for risk-seekers), and that it is sensitive to all other risks outside of this pre-accepted amount.

The next logical step is to determine how this heuristic depicts decisions with respect to losses. Kahnemann and Tversky [52, 53] and Laury and Holt [54] have shown that in the face of losses, some decision-makers tend to be risk-seeking, striving to lose less and taking on more risk to do so. Again, the results from Laury and Holt show that spread through the spectrum are those who are willing to take less risk than others. The spectrum of risk preferences in both the gain and loss domain is shown in Figure 4.4.

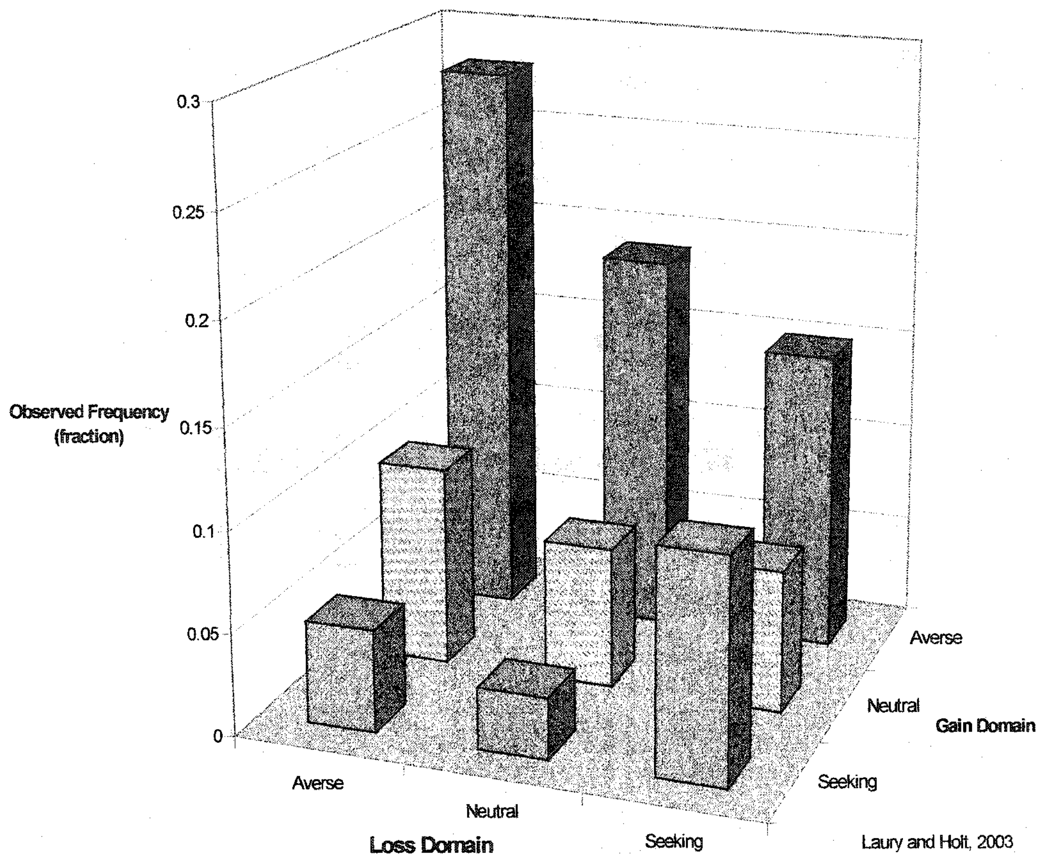

Figure 4.4 Risk Preferences with Real Pay-outs [53]

The RAVR heuristic actually is a gains domain method. It assumes there will be a positive benefit and compares that benefit with the cost incurred to show value efficiency. When one starts dealing with losses, these are direct costs with no benefit associated. Mathematically, this causes the RAVR model to break down. In engineering, one tries to reduce costs by all possible means. This is not a gamble, but an expected benefit with an associated expected cost. The RAVR method does not work with gambling to protect against a future large loss. In reality, this is not the normal model used in product development anyway, but might be used in other engineering decisions that deal with profits and losses from ongoing operations. In engineering design and development, if probability for a benefit goes to zero, or the Risk Cost to generate the benefit goes to 1, then an intervention signal arises (see Fig. 3.3); the decision is usually made to stop development on the effort, and the resources are re-allocated. But once the product is developed and launched, the decision-making during operations might have to deal in the loss domain. The RAVR method will not handle this situation effectively.

Since engineering design and development is focused on bringing new products to fruition, however, they reside on the gains domain side of the spectrum. This allows the RAVR method to be an effective tool for engineering design decision-making.

5.0 Application Case Studies of RAVR

In order to demonstrate the concept of Risk-adjusted Value Ratio, a number of case studies have been developed to evaluate ways the RAVR heuristic can be used in varying situations. The first case study will involve a static, single decision between 2 alternatives. This study will demonstrate the problem setup and use of mathematics to resolve a decision point in a product lifecycle trade-off issue. The second case study involves monitoring RAVR and ECR during a development process. The third case study will show the use of RAVR and ECR monitored throughout the product development cycle and used in multiple related incidents. The case studies are intended to show how different circumstances can drive the RAVR, which will precipitate decision-points and result in actions to drive the development team to a low cost-of-risk point in the design.

NOTE: The case studies used in this paper are instances taken from real situations developing products in companies with which the author has been involved. The respective companies have reviewed them and granted permission for publication.

5.1 Case Study #1: Isolated Decision Evaluation Using RAVR

In this case study, a situation is evaluated that is an isolated decision between a number of alternatives. It is instructive in how to set up and evaluate a decision, whether it is between two alternatives or can represent a choice between two options in a progression of a singular situation over time. Use of the RAVR and the ECR can be used not only for long term direction within a development process, but also for individual decisions between alternatives when there is an issue.

5.1.1 Background: Battery Disposition Decision

The situation is set in the development of a solution to a problem with batteries and the microprocessors that they drive. A high-end toothbrush was developed that was driven and monitored by a microprocessor run by a 2.4VDC NiMH rechargeable battery pack. In the design, development, and implementation phases, a latent issue went undetected. Due to the fact that engineering was constantly working with the models in development, the battery pack never ran down enough to exhibit the weakness in the system that would cause a lot of problems. The issue turned out to be that when the battery ran down far enough, the voltage would drop below the 2.25 VDC threshold where the microprocessor would not have enough juice to keep its "smarts." It would get lost in its subroutines and not be able to figure its way to "home state." The solution was to implement a microprocessor and software reset executed every time the "on" button is pushed. This modification would require 3 months to program, debug, and implement. In the meantime, a more charge stable battery pack was chosen to relieve some of the return problem (product returns were 2 percent due to the reset problem). The battery pack made up a substantial percentage of the cost of the product, so the desire was to find an economical battery source (i.e. low cost). The original batteries were purchased from a low cost vendor, but they turned out to have a 1-3% early failure rate (testing of a small sample size had lead to this rough estimate). They also had slightly higher internal resistance, which caused the batteries to fall below the threshold voltage during the time that they might sit on the store shelf (3-5 months). The more expensive name-brand batteries were more reliable (0.05% failure rate) and didn't fall under the threshold voltage until 36 months. Thus, the battery change was made immediately, and 5000 of the old batteries were quarantined for later disposition when the microprocessor-reset issue was resolved.

5.1.2 Problem Formulation

The resulting decision would be to determine what should be done with the old batteries, given the pending software fix and 5000 old batteries in stock.

The data for the situation:

- The new batteries cost $.40 more per unit
- The original battery packs cost $.83 per unit

- With the new software fix, a cost savings could be realized by balancing out (using up) the original batteries
- The original batteries showed a 1-3% failure rate
- Each returned unit cost the company $100 in return fees, handling and administration

The decision alternatives:

1. Use the microprocessor changes and obtain the cost savings of the old batteries
2. Switch to the processor changes and keep the new battery, scrapping the original batteries and incurring that cost on top of the additional cost of the new battery

5.1.3 Solution Development

The first step of the solution is to start with the RAVR equation. It is repeated here for convenience:

$$V_R^*(A_k) = \frac{\sum_{i=1}^{n} w_i * B_{i:success}(A_k)}{\sum_{i=1}^{n} y_i * C_{i:risk}(A_k) : \begin{cases} C_i = O_e - O_i \text{ if } O_e < O_i \\ C_i = \varepsilon \text{ if } O_e \geq O_i \end{cases}} \qquad \text{(Eq. 3.23)}$$

In both decision alternative 1 and 2, it is noted that the importance weighting is equivalent – that both value equations will deal with the same discipline so that the a_i is the same. Thus this weighting factor will be dropped from the RAVR equation for this example. For instructive purposes, the first step will be to focus on the benefits portion of Equation 3.23. The Expected Benefit of a reliable unit is slightly less on the units with original batteries because the failure rate on batteries (manifest as a unit that won't hold a charge) is lower. The Expected Benefits for each of the alternatives is shown in the calculations of Table 5.1 below.

Table 5.1 Expected Benefits of Battery Decision

Alternative 1	**Benefit**
Use Old Batteries	5000*$.40
Profit On Reliable Unit	.99*5000*$20
Expected Benefit	$101,000

Alternative 2	**Benefit**
Profit On Reliable Unit	.9995*5000*$20
Expected Benefit	$99,950

It is noted that if one looks only at the optimistic side (the benefits), then it is easy to see that balancing out with old product helps the bottom line. However, there is no adjustment for risk taken into account yet.

The next step is to determine the Expected Outcome for this situation. Since it would be desirable to not lose any money at all in this situation, the acceptable cost is $0. It would be hoped that no money would be lost for quality problems as are exhibited here. In other cases, there might be a more pragmatic view that the price of doing business is *X* percent returns (you can't please all of the people all of the time.) So a calculated expected outcome cost would be an amortized payment for all units over the whole population of units (not just these in question). For this problem, however, O_e will be set to $0, because the team doesn't want any return costs. The Expected Cost of Risk will then yield the results in Table 5.2.

Table 5.2 Expected Cost of Risk for Battery Decision

Alternative 1	Cost	Alternative 2	Cost
		Scrap Old Batteries	1.0*5000*$.83
Returns	.01*5000*$100	Returns	.0005*5000*$100
Expected Cost of Risk	$5000	Expected Cost of Risk	$4400

In this case, the Expected Cost of Risk for Alternative 2 is lower than Alternative 1. This shows that there is a higher risk for Alternative 1 that might offset the benefit. In this case study, both the RAVR and the EV will be compared. Calculations are shown in Table 5.3.

Table 5.3 Risk-adjusted Value Ratio and Expected Value Calculations for the Battery Decision

Alternative 1		Alternative 2	
Value Ratio	$101,000/$5000	Value Ratio	$99,950/$4400
RAVR	20.2	RAVR	22.7 √
Expected Value Summation	$101,000-$5000	Expected Value Summation	$99,950-$4400
EV	$96,000 √	EV	$95,550

5.1.4 Solution Review

This shows the difference between the Risk-adjusted Value Ratio and the Expected Value. On an absolute scale, the Expected Value shows that Alternative 1 yields a higher income for the Battery Problem. The RAVR shows the efficiency of the choice. While the EV is a risk-neutral decision process, the RAVR is actually adjusting for risk. As a ratio it offers scalability of results.

In making decisions like this, managers tend to be more risk-averse. The decision-maker started out with the EV method, and noting that the results were close did a sensitivity analysis. The data given revealed that the battery failures could be as high as three percent, which caused the decision-maker to choose Alternative 2. The reason is due to the intangibles, like the loss of goodwill to customers, which is hard to measure. The decision-maker wanted to avoid the extra, unquantifiable risk and, consequently, took a more risk-avoiding position than the neutral EV method. The RAVR model already accounted for the risk of returns and gave the risk-adjusted answer immediately without the extra sensitivity step (although this is still a good idea). So the RAVR heuristic matches the decision-maker's thinking and choice in this study.

5.2 Case Study: RAVR Usage in Product Development Sequence (Single Situation)

This case study will deal with the trends in cost-of-risk and shift in RAVR caused by the ebb and flow associated with product development. While the mechanics of computing the ECR and RAVR will be minimized, this study will focus on how cost, risk and trend data can be translated into RAVR and ECR curves. These curves will then be used to make decisions and compared with the results of the case study.

5.2.1 Project Background: Ozone Disinfecting System Development

A consumer products company sought projects to produce high impact, innovative products for the marketplace that would lead to business growth and impress the stock market to invest in this small firm.

A significant product concept pursued by this company came from the use of a fuel cell technology that generated hydrogen (H_2) by dissociating water and a by-product of ozone (O_3). In many cases, ozone is a problematic substance, but in smaller quantities, it has a germicidal effect, and it decomposes back into oxygen (O_2) once it has done its work. The idea being considered was to infuse the Ozone into water to make a completely safe and residue-free disinfectant. The proposed product could create this solution on-demand as required for cleaning and disinfection. It would be completely safe for children and pets by eliminating the residue that is common with most cleaning solutions based on chlorine bleach or other strong bathroom chemicals, and the chemical disinfecting action would be quicker than that of these other cleaners as well.

The project progressed along the lines of a standard project following a phase gate program similar to the one shown in Figure 2.3. The stages used by this company included

- Technology Scoping and Project Plan Development (Developing FR)
- Conceptual Design – Archetype and Configuration Specification (Converting FR to DP) as well as proof of concept
- Detail design – Meeting all specs at an acceptable quality level and creating the drawing and part DB specifications (Converting DP to PC and QP)
- Implementation – Tooling and Value stream development (Developing system to take raw materials and create PC within QP)
- Pilot Run and Qualification (Testing the Value stream and validating the QP in the finished parameters)
- Launch and commercialization

Developing a project plan that outlined the expectations of product features, product manufacturing and cost, selling price and profitability, a forecast of demand at the investment and product cost targets began the effort. As with all early project plans, there was a lot of risk involved because the numbers were based on many assumptions that would have to be verified and validated as a matter of course during the development of the product. Technical development and scoping proceeded concurrently with training on the fuel cell technology and its incorporation into a system. Also included was the development of the system concept and user controls. From this there was the completion of the product specification, which included the features of the product (control system interface, batch versus continuous flow methodology, permanent cell technology v. replacement, safety levels and performance levels for ozone production). This specification passed the first milestone because of its compatibility with the business plan, and early indications showed a high probability that all performance criteria could be met. This specification is shown in Figure 5.1 below.

Important Technology Performance Characteristics (Fundamental Requirements)

- Infuse ozone to a 50-100 ppm level in 5 minutes
- Prepare 750 ml of water solution to this level per batch
- Be able to operate continuously for 5 cycles
- Provide one-touch convenience for starting a cycle
- Provide for infinite life (full product life of > 5yrs) for the ozone generator cell
- Insure safety from lead contamination from the ozone generator cell

Marketing Characteristics (Fundamental Requirements)

- Provide a kitchen type application for disinfecting that retails for $99
- Provide a number of application vessels for the ozonated water – a carafe and a squirt bottle
- Provide a recharging cartridge (removes impurities from the water prior to ozonation to insure life of ozone cell and optimize the ozonation rate – it basically makes DI water)
- Refills of these will be sold as an adjunct to the main sales – sort of the product's razor blade

Business characteristics (Fundamental Requirements)

- Sell the unit for a retail margin of X %
- Sell the unit wholesale for a margin of > Y% - required to recoup costs of development within an acceptable time period

Figure 5.1 Fundamental Requirements of Ozone Sanitizing Product

There were a number of drivers to the project. During the project plan development, the objectives and priorities were set to determine how the project would proceed and be judged at key decision-making points. Driving priorities for development included

1. Safety – this product will be deemed safe to use (a complete non-issue in the minds of the purchaser) and have assurances of a major testing agency rating
2. Market timing – the product would be delivered in 12 months to coincide with commercialization preparation and with major appliance show announcement opportunities
3. New technology – a new-to-the-world useful tool at a high level of quality would be introduced (consistently will perform to its claims)
4. Cost of the product – will be X and provide the desired margins
5. Manufacturing capability will be at the Z rate to provide the ability to take advantage of a rapidly growing market and a rapid pipeline fill
6. Cost of the project will be Y

The user requirements were established (see Fig. 5.1) and became the baseline package of benefits that were defined as the project targets. The probability of changing these was low and, for the most part, the targets were held consistent during the first two phases (as listed above) and frozen following the conceptual design phase. Most importantly, the project plan outlined some explicit goals, such as target costs, sales prices, expected sales and revenues, which in turn led to expected income and profits. It also established a set of criteria for the product with regards to its adaptation to a home environment, ease of use, and regulatory assurances to give buyers a comfort level with the safety and effectivity of the technology. The plan was also set with an aggressive implementation objective to demonstrate active progress on the company's stated strategy to investors to bring about unique and useful healthcare products to the consumer market. The proof of this would be to capture a large market in this new "residue-less" sanitization technology and grow the business accordingly.

5.2.2 Initial RAVR Development Discussion

For the ozone disinfection product, the most important areas of risk include the technical knowledge function, product cost function, and the project schedule function. The technology being employed in this project is a result of another company's work, so technology transfer will need to occur. The risk of mistakes will be high to begin with, until the technical team gains a certain amount of experience. So early decisions will be quite risky, and as exposure is gained, the risk of decisions will continue to diminish. The resulting knowledge cost-of-risk curve is shown in Figure 5.2 for this situation. Note that this is an estimate.

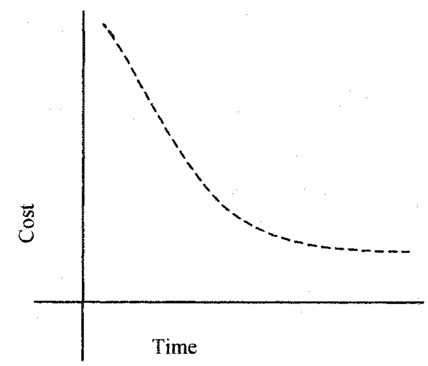

Figure 5.2 Knowledge Expected Cost of Risk Curve

As time increases, it is assumed that the expected cost-of-risk will decrease because a better understanding of implementation will lead to a higher probability of success (or lower probability of mistakes that result in added cost). This is the mirror image to the knowledge curve in the Knowledge Paradox (see Figure 2.9). As more information is gained, the risk of a costly error due to that knowledge is reduced. Note that this curve is a dotted line, because this is an assumption of how the learning curve will affect the project. A solid line would indicate the path traveled, and further dotted lines are estimates as to what will occur in the future.

The probability that the cost of the product will fall into the appropriate range during implementation of the concept is another critical function. While there is a good chance that the design group will be able to target and achieve those costs, common practice shows that to resolve a majority of the minor quality issues near the point of first production, cost is added as fixes are defined and implemented quickly. See Figure 5.3.

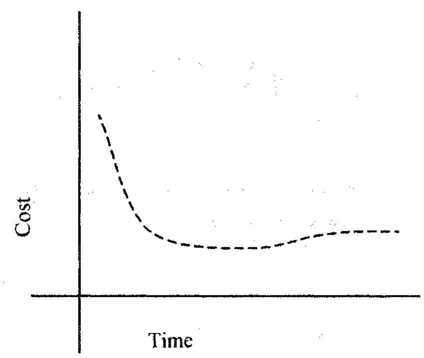

Figure 5.3 Product Cost Expected Cost of Risk Curve

The product cost curve history, which is also estimated, shows that there is a good chance that the probability of cost will decrease over time with an expected slight increase in cost risk close to the implementation of product.

There is a concern about the amount of development time, as an aggressive schedule was specified. In order to hit the market in a twelve-month time window, a design would need to be put together, tested, and validated within a short period. Sales calls to retailers would need to take place at the nine-month mark in order to generate immediate shipments when product was available. For these sales calls to be effective, working prototypes would need to be available, which would push the design team to achieve an effective product embodiment in a short design cycle. The combination of these factors will produce an Expected Cost of Risk curve as shown in Figure 5.4 below.

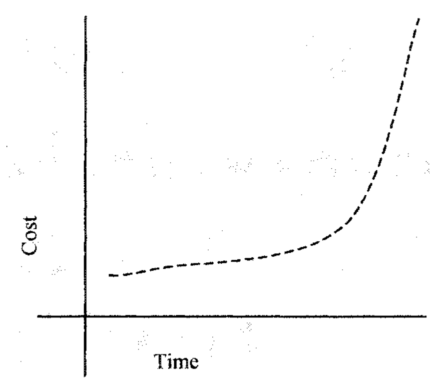

Figure 5.4 Schedule Expected Cost of Risk Curve

Notice that this curve already has an area of increasing risk defined, although it too is an estimate. The Expected Cost of Risk steadily increases through the beginning of the program. This same risk is the one that pushes people to "hurry up and make a decision!" Near the end of the program, especially once commitments are made (e.g. by sales people to retailers), the curve will have a decidedly upward swing, where further delays in the schedule will increase the cost of risk. This might be exhibited in lost sales, expensive "rush" shipping to meet a commitment, penalties for late shipment, or a competitor taking the business (or subsequent business).

While there are other risk curves associated with this case, these three appear to be the critical areas of interest. Based on the information above, the series of curves can be weighted and aggregated to give an aggregate expected cost curve estimate with respect to time that looks more like Figure 5.5. (Compare this with the ideal curve shown in

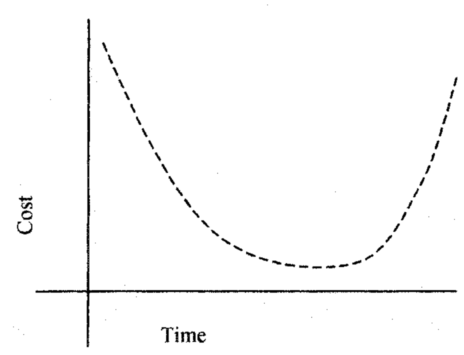

Figure 5.5 Project Aggregate Expected Cost Curve

Figure 3.4)When the Aggregate Cost Function of Figure 5.5 is substituted for the cost function in Figure 3.4, a picture of the project expectations develops (see Figure 5.6.) At the outset of the project, it can be seen that with development time and effort, Expected Benefits will increase (probability will improve that benefits will be realized) and the cost-of-risk for the program will decrease, a condition of increasing value. This stays true up to the point where schedule cost-of-risk begins to influence the curve. Now RAVR will begin to drop, unless the influence of the schedule risk can be abated. Controlling schedule appears then to be the key area to watch to modify this curve and end where desired.

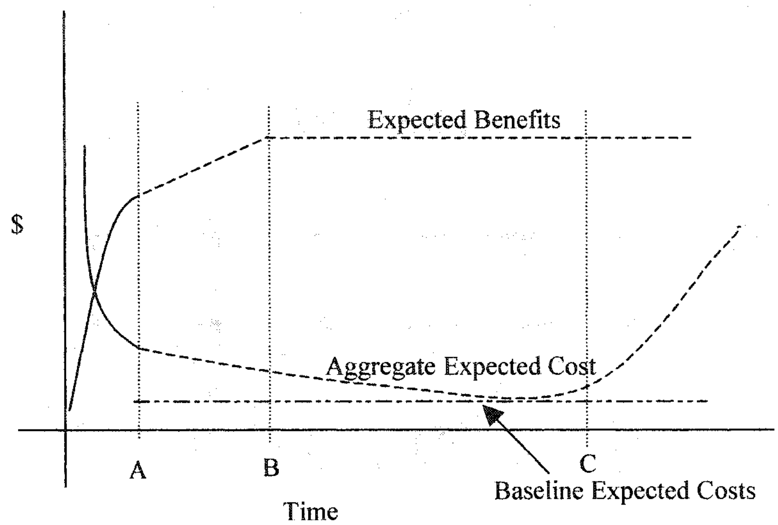

Figure 5.6 Estimated Progression of Expected Benefits and Costs Within Ozone Disinfection Product Project: A) At Project Plan; B) At Detailed Design Review; C) At Launch

Note at this point that all the curves above are estimated based on information available at the time when constructed. In this case study, since the construction of the functions is after the fact, the curves are based on typical project generalities, given the starting information. Much more detail can be added to these curves as the case warrants, but often the decision construct of intuitive aggregation can be used to determine where the critical points are and focus the function development in those areas.

While in most mathematical optimization it is assumed that functions are continuous and most algorithms operate based on this, in the product development project realm this is hardly ever the case. However, in the estimation process, making a broad (and often untrue) assumption that the curves are continuous does little to affect the outcome. It will be the discontinuities in the aggregate function that will be the points of inflection that force the issue of making directional decisions. Of course, in the process of due diligence, the functions oftentimes behave as if they were continuous, because progress and change evolve towards expected outcomes.

At any point in this process when the RAVR function is evaluated, it could show that the value is increasing or decreasing. This could occur at a gate in the stage-gate process, or because a discontinuity develops. The evaluation might show any one of the various combinations of benefits and cost situations displayed in Figure 3.3. When this occurs, the RAVR precipitates a decision at a single point in time, and estimates of the aggregate ECR function and Expected Benefits functions are evaluated as if they are continuous functions for the sake of determining next steps. It is a prognostication that drives the project direction. Whether the function is really continuous or discrete is irrelevant - the optimization method still gives useable direction to the decision at hand based on the assumption of continuity.

5.2.3 Problem Situation: Detailed Design Phase of the Ozone Product

Following the conceptual design review completion, and in the process of detailing the design, it was determined that there were a number of shortcomings that would have to be corrected. Since the design would be a stand-alone kitchen appliance, a pump would need to be added in order to get sufficient flow through the system to infuse water with ozone at a desired rate (as a result of further specifications established in the conceptual phase). Also, due to sizing and ozone generation needs, the system would require a larger power supply, and the electronics which controlled the fuel-cell reaction tended to put off lots of heat, which would require the need to consider forced convection cooling. With the addition of these components to make the unit operate with the level of performance intended, target costs were exceeded by 40%.

Up until this point, the technology was coming to fruition, retailers were showing interest, and the scheduled development appeared to be on-track. Now, proceeding from this point seemed to create more risk and more costs. The schedule would be delayed for a redesign or re-specification of the product to alleviate the costs incurred above, thereby missing the promised market window to retailers; dropping the project would create a vacuum in the credibility of the company; and raising the prices would affect the market share and penetration of the product. The project team was tasked with creating alternatives to respond to this disruption in the positive project progression.

The project team came up with the following options to resolve this situation:

1. Revisit the project scope, modify the concept architecture and project specification
2. Lower performance specification and look for cheaper components
3. Raise the price of the product and re-estimate the sales forecasts and project ROI.
4. Drop the Project

The management team was tasked with picking the best alternative for the company.

5.2.4 RAVR Analysis of Ozone Project

As the project progressed from Point A to Point B in Figure 5.6, things moved along as expected. Consequently, the project followed both the Expected Benefits curve and the Expected Cost of Risk curve as shown. At this point, a product cost discontinuity was discovered! The Product Cost ECR curve abruptly increased so that the aggregate cost-of-risk curve, as shown in Figure 5.7, also increased dramatically, causing the RAVR

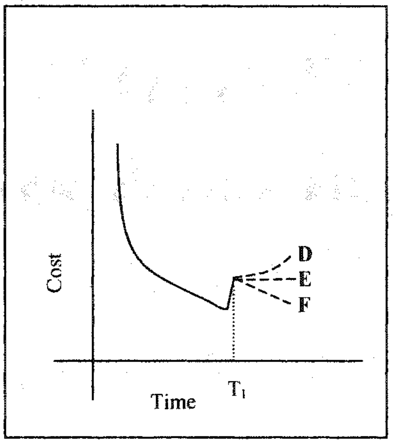

Figure 5.7 Aggregate Cost of Risk Curve For Ozone Sanitizing Product at Critical Point

function to drop. According to the rule of minimizing cost-of-risk, when the ECR starts rising, the project has passed an inflection point and it is time to re-evaluate. A new action must be taken, following the general guidelines shown in Figure 3.3. The goal will be to determine which of the options will lead the project costs in a path associated with D, E, or F on the Aggregate Cost curve of Figure 5.7. Since the proposals for solutions all talk about changes in benefits, the assumption that ECR alone can be dealt with to solve this issue is no longer true. Consequently, both the ECR implications for the options will be explored, as well as the benefits impacts to determine the best RAVR among the options.

In exploring the decision options presented, the following ECR and benefits changes were estimated (refer to Figure 5.7):

1. Revisit project scope, modify the concept – This option could cause the product cost-of-risk to go down, but could also negatively impact the higher priority schedule cost-of-risk since the program is already on a tight timeline. It will probably cause the ECR function to follow Path D. Changing the project scope will most likely cause the benefits function to drop. The RAVR that is calculated from these two situations would exhibit a large decrease from the plan.
2. Lower performance specification and look for cheaper components – This option could lower the product cost risk, but might also run into time constraints and cause schedule risk. The unknown is the probability of procuring cheaper components. Since the magnitude of the required cost reduction is substantial, this is a low probability. At best this option would follow the risk cost similar to Path F that might be slight, but most likely could follow Path E. Relaxing the specification could lower the benefits to the end-user, which might lower the desire to buy and cause the expected benefit to drop. However, being a new-to-the-world type of product, this might not be as severe a drop as anticipated. The RAVR function would show a drop in value but not as severely as in Option 1.
3. Raise the price of the product and re-estimate the Sales Forecasts and project ROI. – This option would assume the current level of risk and follow path E. By raising the price of the product, end-users might not see the value in the product (benefits to price – their cost) as high and thus cause sales (and benefits to the company) to drop. On the other hand, price sensitivity is unknown at this point in the case, so the expected benefit might increase with the price increase. The sales forecast can be dropped, but only to balance out the price increase, leaving the dollar benefits to be a

net zero change. The RAVR for this situation, depending on the resultant change in sales forecast (and consequent *expected* benefits), can be increasing, neutral, or decreasing, depending on the market optimism of the decision-maker.

4. Drop the Project – This option would not follow the path at all – it ends the path. It takes whatever money was spent and that becomes the total cost of the project. It will be under the baseline value of O*e*, but no direct benefits will be realized. The RAVR function would be zero, and is often the choice of last resort when no value can be expected from a finished project. In this situation, the value in some form is still attainable (and is untapped).

Looking at the RAVR estimates for each of the available options, two options - two and three - stand out as viable choices. By lowering the specification and looking for inexpensive components, a reasonable value can be salvaged from the project, although slightly lower than in the original plan. However, with a bit of optimism, it can be seen that Option 3 offers potentially the opportunity of a better value to the company. With the probability of a higher Value Ratio, if numbers were available to calculate, the RAVR would be higher. Consequently, the choice would be to follow Option 3.

5.2.5 Comparison of RAVR to Case Results

The risk resolution at this point in the project became the selling price of the unit (to make a sufficient margin on the product to make a return on the investment). The price would have to rise above the pre-determined "sweet spot" for retail of $99-$129.99. In this case (for a breakthrough product) the decision-maker determined that raising the price offered the best choice for the company. The overriding goal was to have a breakthrough technology that would establish the company in a new market, have large revenue increases, and bring prestige (and stock value) to the company. (Unfortunately, these ulterior motives were not well enumerated in the original product development objectives, and thus, underrepresented in subsequent development of the risk priority functions and their weightings. Consequently these considerations were not available for consideration in the RAVR analysis.) His choice was by business intuition – there were many (including the author) who could not understand this overly "risky" choice.

In this case, the options were given and RAVR was determined (by general reasoning) to select among those options. The RAVR analysis mirrored that of the decision-maker. In hindsight, (and with the help of this analysis), it was shown how appropriate the decision-maker's choice was. It turns out that the RAVR method becomes a good way to organize and aggregate risks. It is much easier to track and account for all design alternatives dealing with risk, and as a prescriptive tool, might be used as a driver to develop more acceptable options to the resolution of a problem. The RAVR function offers a rational method to assess solutions to design issues that can come up in the course of development.

5.3 Case Study #3: Multiple Decision Points in Product Development Using RAVR

This case study presents an extended example where risk control is used for multiple steps in the development process. While in the case study, risk concepts were considered and mitigated during the course of the project, RAVR was not used. This is another post-project study comparing decision-making in the project with what RAVR evaluations might indicate.

5.3.1 Background: Development of a Shower Head

This product example is a showering device developed by a small appliances company. The strategy was to develop a new platform product that could improve the position of the company in its current product line at the high-end of the shower head category. The objectives of the project included the following. The product should

- Fill a high-end position in the product line ($50-75 retail price)
- Be a platform (progenitor of many extensions to satisfy multiple need sets and retail situations)
- Contain high-end features to convey value at that price point
- Be unique

To achieve these objectives, a number of priorities were set to provide for decision-making trade-offs by the project team. These priorities (in order) were

1. Safety – perceived as no risk for the customer and meeting all applicable safety standards for the product category
2. Product quality – best quality and reliability available
3. Product features – full-featured, with real showering options
4. Timing – within schedule and meeting retail commitments

5. Manufacturing Throughput – ability to meet a large volume production schedule
6. Cost – within product cost targets to achieve a good margin on sales
7. Project Cost – within limits to achieve an acceptable payback.

As long as the product development went smoothly, most of the desired features were considered achievable. The need for decision trade-offs would be low. But as the information became more complex, the feature-laden product would require these trade-offs.

The development process consisted of typical steps similar to the Stage-Gate model of Cooper (see Fig 2.3.):

1. Specification phase (Product Requirements or FR)
2. Concept Development
3. Detail Design
4. Implementation
5. Launch

Since this product was to have a large manufacturing throughput requirement and required a strong marketing effort to properly define the product features and position the product correctly in the field, both of these major cross-functional activities were intertwined with the development steps defined above in a concurrent development effort. Marketing and manufacturing team members provided information that helped drive decisions as well as define the criteria and targets that helped define the specification.

During the Specification phase, the cross-functional group spent time in two major activities. The first was using QFD to better define the scope of the development project, using customer feedback data and marketing input as the "Voice of the Customer" information. Through QFD, this information was converted into technical specifications (FRs) and directed the team towards the development of shower modes as the primary manifestation of value in the new product. The team focused on developing the best-in-class shower sprays that covered the main types of showering situations desired by the customer.

Once these product features were identified, the challenge of how to bring them together into a product was tackled. This included converting the marketing manifestation to an industrial design, and describing the technical embodiment that would fit into that design. At this point, the project plan development gave a preliminary accounting of the expected amount of money to be invested on the tooling for value stream development, as well as the time resources of the company workers. Along with this, projected revenues and product costs were included to give an overall idea of the resulting income and expenses the project will incur. This was then used to determine baseline expected Return on Investment (ROI), acceptability of the program risks, of the product development program.

5.3.2 Decision Situation # 1

The project plan was approved and moved on to the conceptual design phase. The most challenging feature turned out to be a special valving arrangement required to improve safety in the product. To prepare for this design challenge, the technical team came up with the following block diagram for the shower head:

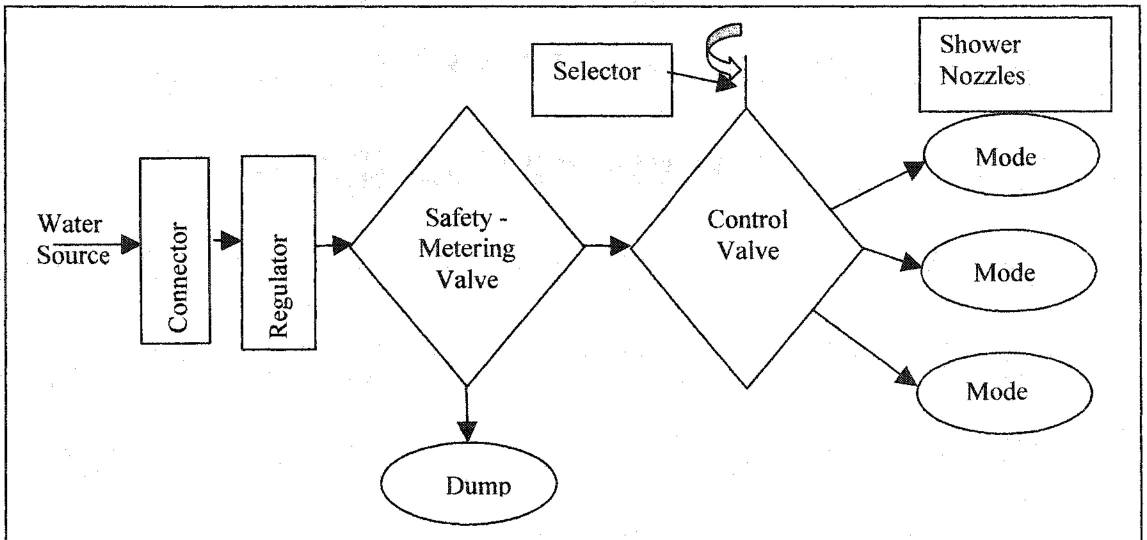

Figure 5.8 Block Diagram of Shower Head Product

From this schema, brainstorming ideas for the valve execution was considered. The concepts were then put in a Pugh's Matrix [21] and evaluated according to the FRs established from the QFD and specification for the valve requirements (see Figure 5.9).

Shower Valve Selection Matrix (Pugh's)

Criteria	A: Radio Button	B: Screw Driven Plate	C: Cam Driven Piccolo Valve	D: Tube Valve	E: Rotating Oring Valve (Flat)	F: Control Plate
Sealing Capability	+	-	+	+	-	Datum
Manufacturability	-	-	0	0	-	
Cost	- -	0	0	-	-	
Mode Options	0	-	+	0	0	
Adapt to Safety Valve	-	+	+	+	0	
Req'd Control Force Under Pressure	+	+	0	+	-	
Reliability	-	-	+	+	-	
Intuitive Interface	+	0	0	0	0	
Score	-4	-2	4	3	-5	0
Rank	5	4	1	2	6	3

Figure 5.9 Example of Pugh's Matrix Selection Process for Shower Head Valve

As the Pugh's Matrix was evaluated, a number of concepts came out as the strong contenders. The trade-offs between the concepts were evaluated and used to try to build stronger top concepts. When this was complete, there were two top concepts that scored relatively well that the team had to choose between. Much discussion went back and forth between the team, and it was felt that the concepts were more closely matched than

Pugh's Selection Matrix showed. Some team members felt that when all was completed, Pugh's Matrix didn't hold enough information to give a clear-cut winner and, therefore, it was a wasted exercise. But it had given enough information to make sure that the team was looking strongly at the most important requirements and considering the impact of the design in all aspects of the development and functional process. Since the cam-driven piccolo valve system was the chief engineer's concept and strongly championed by him, Concept C was chosen.

5.3.3 Decision Situation #2

The next step of the design in the conceptual phase was the proof of concept by prototyping to confirm the concept selection and prepare the team for the challenges of the detail design phase. During this phase, weaknesses in the Piccolo Valving concept started to become apparent. The design didn't have as much space with the industrial design as first thought, and the execution would require some size modifications that might compromise functionality. It was discovered that making the part would also require a complex prototype mold. That made testing prototypes problematic, and thus lowered the confidence in whether the concept was viable. It was felt, however, that the manufacturing challenges could be overcome, and shortly they were, but testing and verification was delayed.

Once the prototype was completed, testing and validation were undertaken as the remainder of the design began to move toward detailed design phase. As the testing occurred, it became apparent that some issues with the valve concept would be difficult to resolve. The prototype showed that the valve mechanism was not able to function with temperature and water pressures that would be seen within the flow channel without "deadheading" (i.e. completely stopping the flow of water). The issue now was whether the design was hopelessly mired in a region of infeasibility. The debate became whether more effort would be effective in overcoming the shortcomings of the current design and whether slight modifications would assist in this.

At this point, the decision-maker lead the team to investigate other alternatives as the project schedule began to slip. Two design alternatives were established:

1. It was determined that due to the size constraints, the valve concept had a dimensional flaw that precluded its proper operation (probability of failure would be very high.) The thought was that by redesign of the basic valve structure (the size of the valve chamber), the valve concept might still work. This would cause the industrial design to be reconsidered and add another six weeks onto an already tight schedule.
2. While timing was lower than product quality on the decision priority list, it was felt that there were other concepts that still would allow a reasonable quality. With many concepts still available in the concept selection matrix, and a close rival in concept scoring, the alternative was to maintain the current size constraints and try a new valve concept.

The team chose Alternative 2. It was felt that a different concept would have a good or better chance of viability, but it would take more time to design and implement. There would be a time trade-off with the Industrial Design iteration needed in Alternative 1. Other concepts for the valve matrix were quickly re-evaluated within the current constraints and even though the cost of the valve was increased, the second ranked concept was validated and implemented.

5.3.4 Decision Situation #3

Due to the extra time required to redesign the valve, the project schedule began to slip. At this point, the team decided to make a trade-off in project objectives to be able to achieve the target project timing. The solution was to incur additional project cost early in the implementation phase to try to pull the project schedule back into line and hopefully hit the product launch target. The team traded money for schedule risk by purchasing a set of prototype valve tools once the new valve design was finalized. These interim tools were smaller and quicker to build than the planned production tool. The prototype tools were not in the original budget, so they were an increase to the cost of the program. However, making prototypes and then using them to go into production caused three effects. First, it caused the manufacturing cost to increase due to extra tooling required for interim use. Second, it caused the piece price of the valve to rise substantially – as much as three times the original estimate. But thirdly, because prototype tools could be completed in eight weeks instead of the 18 weeks that the original tool estimate was for, it would make up parts of the schedule that were lost and decrease the schedule risk substantially. The team was convinced that this was a good trade-off, because the tools would eliminate the high risk to the schedule, and the increase in product cost would be temporary while the production tooling caught up. The expense for the tooling reduced the schedule slip significantly.

5.3.5 RAVR Development for the Shower Head Project

The development of the original RAVR function for this case is very similar to the development shown in Case Study #2. The desired progression of expected benefits and baseline expected costs is represented in Figure 3.4 as before. Again, the aggregate Expected Cost of Risk curve is represented as a continuously decreasing function that proceeds to the baseline cost estimate. But a more realistic ECR curve can be constructed from the data for each of the prioritized objectives.

Figure 5.10 displays the ECR functions that are developed from the data. The highest priority is safety. This function shows that there is a high risk early on in the project that must be resolved. By the time the project proceeds to conceptual design phase, these safety concerns must be resolved. The next two graphs represent the Product Quality ECR function and Product Features ECR function. These functions are very similar in that they are subsets of the Knowledge ECR function. As the design team learns more in

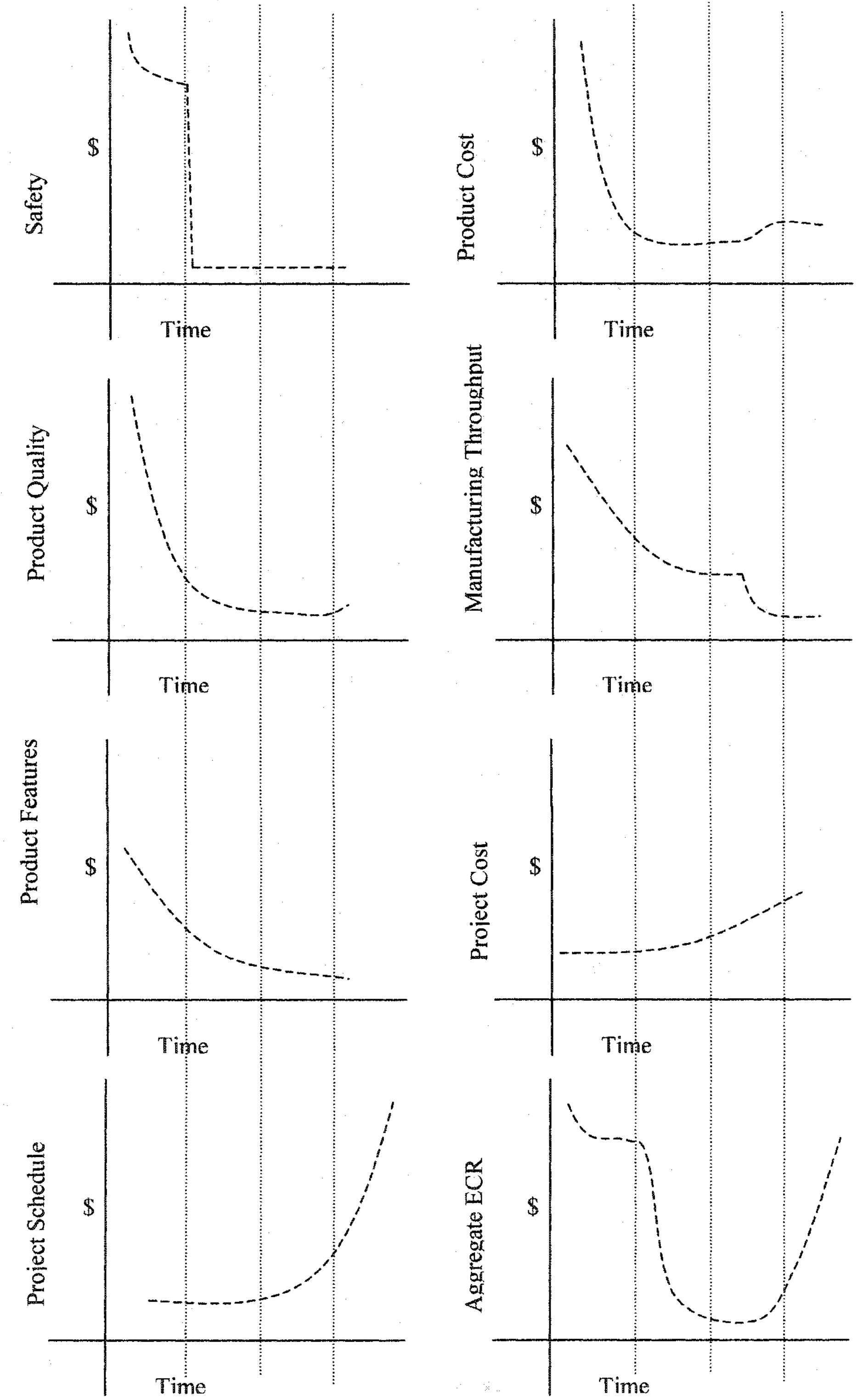

Figure 5.10. ECR Functions for Showerhead Project Example. (1st stage – Concept; 2nd stage – Detail; 3rd stage – Implement; 4th stage – Launch)

the process of the design, better decisions can be utilized, so these functions each show a decreasing ECR over time, similar to Figure 5.2. The functions representing project schedule and product cost are also similar to those of the previous case study. Compare these curves with Figure 5.4 and 5.5 respectively. The rationale behind them is the same.

The final two functions of interest in Figure 5.10 represent the Manufacturing Throughput ECR (the Value Stream Capacity ECR) and the Project Costs ECR. The manufacturing cost-of-risk is high and decreasing as processes are understood, and equipment is designed, built, and tested. Once the equipment is in place and tested at the end of the implementation phase, the cost-of-risk drops significantly. But there is still the training of factory personnel, line balancing and process ramp-up that must occur for the risk costs to completely diminish; thus, this function has a "bench" shape. The project cost function is unique in this case; it is the lowest of the priorities on the objectives list and, consequently, it is compromised more often than the other objectives. For this reason, it steadily increases throughout the project, especially if there is an issue where one of the other objectives has a sharp increase in expected costs.

A representation of the aggregate ECR is the last function plotted to show how one might perceive the risks in the program. Areas that should be monitored will cause the cost-of-risk to rise. This aggregate ECR curve is plotted along with the Expected Benefits function and shown in Figure 5.11. From the outset of the project, the

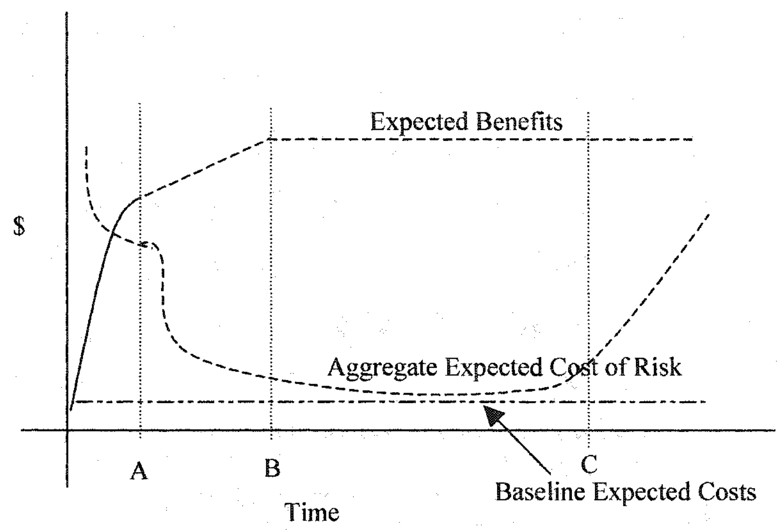

Figure 5.11 Estimated Progression of Expected Benefits and Costs within Showerhead Product Project: A) Conceptual Design Review; B) At Detailed Design Review; C) At Launch

Expected Benefits look stable. This means that the driver of value to the company will be in controlling and minimizing the ECR function.

5.3.6 Using RAVR to Aid in Pugh Matrix Concept Selection (Decision Situation 1)

The question is whether RAVR analysis would have helped in the concept selection method to make a wiser choice. In this analysis, it must be realized that RAVR analysis could act more as a sensitivity analysis adjunct to the Pugh Matrix, rather than replacing it. It should be noted that using a simple method to make the same decision that a more complicated method can do is desirable in the design process. But there is a caution too that the decision method should be rigorous enough to withstand serious crossexamination. In this case, the Pugh Method [21] allowed two concepts to rise to the surface that offered reasonable solutions to the criteria. If the criteria are separated into benefits and costs, a rough RAVR can be established. See Table 5.4.

Table 5.4 Rough RAVR Analysis of Pugh Matrix Concept Selection

Benefits	Concept C	Concept D		**Costs**	Concept C	Concept D
Mode Options	+	0		Sealing Capability	+	+
Intuitive Interface	0	0		Manufacturability	0	0
Control Force Is Low (Ease of Use)	0	+		Reliability	+	+
				Product Cost	0	-
				Adaptability to Safety Valve	+	+
Total Benefits Pts.	1	1		**Total Cost Pts.**	3	2

For a rough value calculation (benefits over costs), the table shows that the benefits (numerator) are equivalent. In the cost side, there is one more good mark for the Concept C (Piccolo Valve), which means that the estimated costs will be higher for Concept D (Tube Valve). With a higher estimated cost and the same benefit, Concept D will have a lower value. Thus, with this rough calculation, Concept C should be chosen.

But this calculation is flawed. There are no proper probability weightings available. Priority weightings of the costs exist, and quick analysis shows that Concept C would still be still the better concept. The flaw in the decision process was the estimation of probability in the ability of the Concept C valve system to seal properly. Probabilities would allow the calculation to be an RAVR analysis rather than a simple value function. Since this was an estimate without a stated probability, it must be assumed that both concepts have the same probability. So the RAVR analysis would not pick up any difference. Since there is no detailed data on the original analysis, it is hard to know how vigorously the probabilities of the estimates were tested. RAVR analysis might assist in this process by making the probability assumptions appear explicitly so that they are not overlooked in the decision-making. In this case as well, it just so happened that the number of risk costs came out the same and the answer was equivalent to the Pugh Matrix. There might be other situations where the cost and benefits are distributed such that this wouldn't be the case. In this case, however, up-front RAVR analysis might have caused the team to focus on the key probability of functionality more closely, helping avoid the project delay or the need for the next decision. However, in this case, the chief engineer's assessment of the risk and probability of success would have probably driven the risk curve as well, so the decision, whether by the team or RAVR, would probably not have changed.

5.3.7 Using RAVR to Aid in Alternative Selection (Decision Situation 2)

Analysis here is similar to the review done in Section 5.2.4. There will be no change in the Expected Benefits, so analysis will focus on the ECR functions and reducing the cost-of-risk to enhance the RAVR. The alternatives are listed below with their critical ECR functions reviewed:

1. Use the current concept (C) and modify the valve housing size. – Considering the ECR functions (see Figure 5.12, Alt. 1), it is evident that the knowledge function has turned up. There is increasing risk in that knowledge says that this option has a higher probability of not functioning. The Product Cost ECR function will also increase with this alternative, because the redesign will add more material and cost. The Project Schedule ECR function will also increase as a step function, because it is known that at least a six-week delay will occur for the redesign. With the functions weighted by priority, the Aggregate ECR Function is developed. It shows that the ECR will increase immediately with this option and then continue to increase. Overall, this option continues on a path of losing value over the life of the project.
2. Change to another concept (possibly D) and keep current dimensional envelope of design. – In this alternative (Fig 5.12, Alt. 2), the same ECR functions apply as in Alternative 1. The Knowledge ECR function starts at the point where the decision is made because no effort has been expended on furthering this concept since the original selection was made. Then it shows a step increase because new exploration on the alternate immediately generates more knowledge risk because

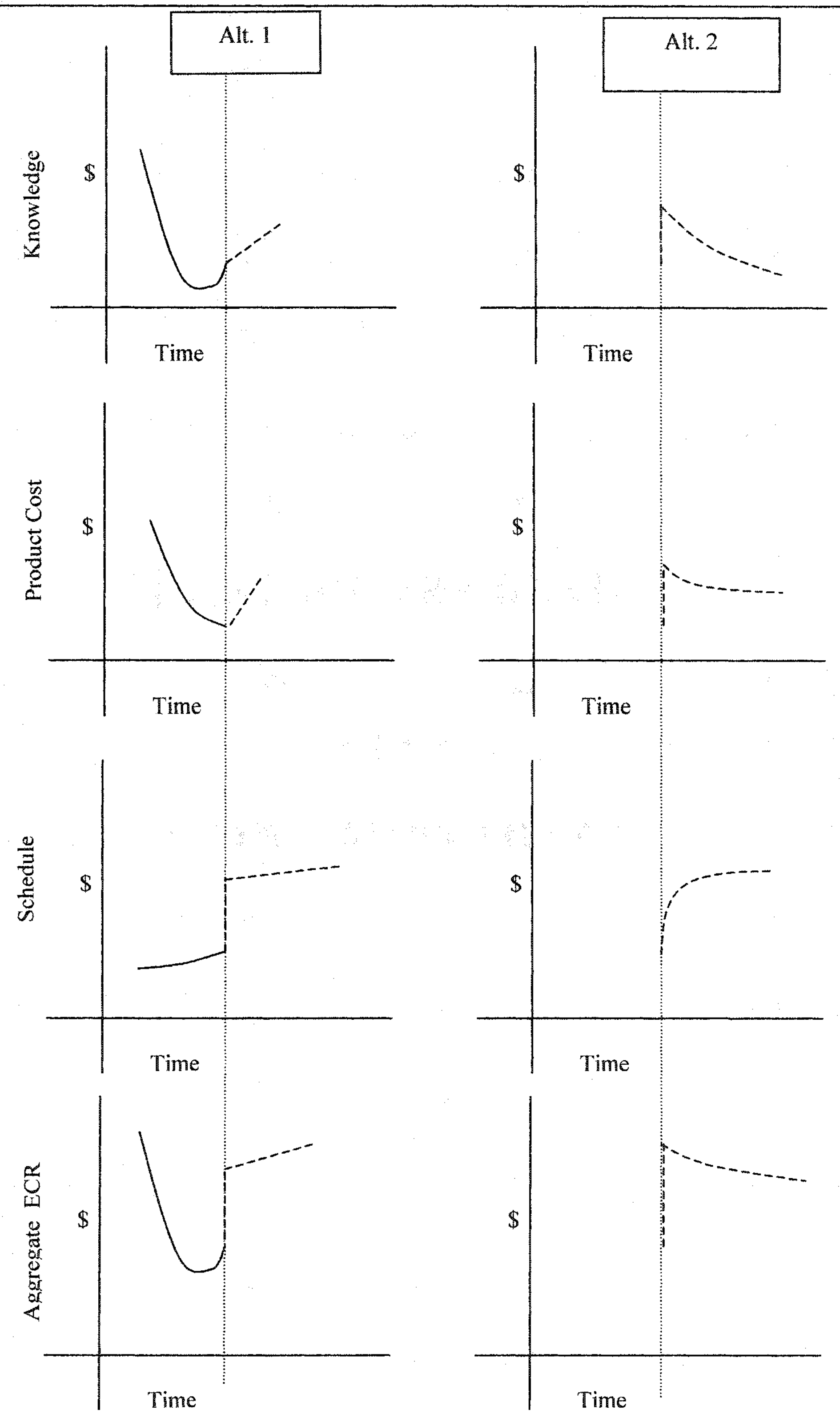

Figure 5.12. ECR Functions for Valve Remediation Decision.

less is known about the concept. Consequently, relearning will cause the Knowledge ECR function to jump up initially before the knowledge will help to lower the cost of risk. It was already determined that the cost of the product would increase with the other valve concepts, so the Product Cost ECR function also shows a step if chosen. Some of the product cost is assumed to be recoverable as the team works on the development, so the ECR function will trend down slightly. The Schedule ECR function will trend upward quickly, because there is a schedule risk associated with restarting a development effort. It will not be immediate, as the Schedule Risk with alternative 1, because it is not known what the delay will be. Some might consider that to be a riskier situation, which might warrant a higher curve, but that is up to the project team to decide. In the Aggregate ECR function, it is shown that the immediate ECR is higher for the second alternative, but it has a chance to trend down and provides a lower cost-of-risk throughout the project.

In the RAVR function, holding the benefits constant, the comparison of Aggregate ECR functions of Alternatives One and Two show that Alternative Two provides a better value. Often the decision is based on the initial risk, which in this case would favor staying with the current alternative and trying to fix it a little longer. But by constructing an RAVR function (using the ECR functions), it can be reasoned out that the project will benefit by higher value long term with the second alternative.

5.3.8 Using RAVR in Cost-of-risk Reduction Planning (Decision Situation 3)

In this situation, alternative 2 has been selected previously and the team is attempting to reduce the cost-of-risk incurred because of the extra time expended in development of the new valve concept. Figure 5.13 shows the ECR functions that are considered for the proposal to improve value. The desire of the team is to trade project cost risk for schedule risk, because project cost risk has a lower priority weighting. The proposal causes the project cost ECR function to take a step, due to the known cost of the prototype tooling. The product cost ECR function will also increase because prototype tooling is simpler and requires more manual steps to create the parts.

Consequently, product cost will increase for a period of time until the production tool is complete. Then the cost will drop again. Even with the two functions creating more risk-cost (cost above the expected baseline cost), the higher priority weighting belongs to the Project schedule ECR function. By prototyping the valve tools and taking them into early production (manufacturing throughput would not be affected), the schedule risk was significantly reduced (by 8 weeks). This resulted in the aggregate ECR function shown, where the project schedule cost-of-risk change dominates and causes the overall ECR to lower and the RAVR to increase. Consequently, the RAVR analysis here would confirm this decision.

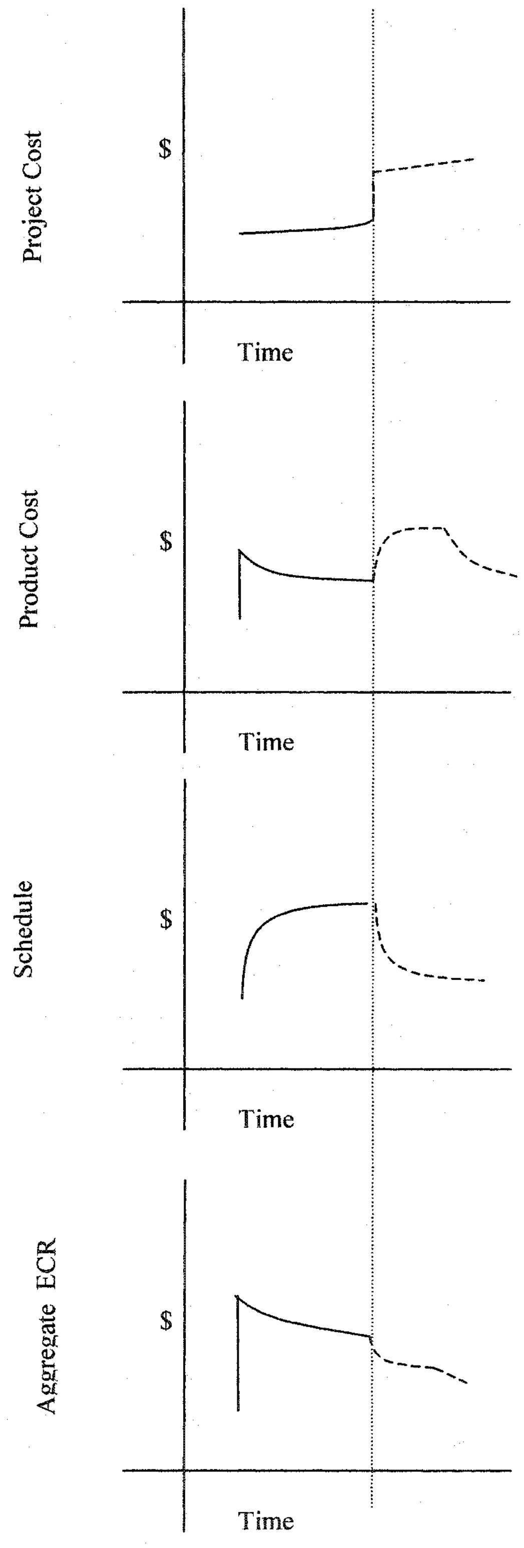

Figure 5.13. ECR Functions for Situation 3 Decision. Valve Remediation Decision.

5.3.9 Showerhead RAVR Analysis Review

Using the RAVR to establish the accepted cost and benefits of the system, the ECR portion of the ratio was used numerous times to control the flow of the project decision-making. This resulted in shifts in direction that produced a better RAVR for the project team as a whole. It is shown that using ECR occurs at 2 different points. One is to recognize that suddenly there is a shift in the Expected Cost or Expected Benefits of the RAVR due to circumstances occurring in the development effort. The second is then predicting where the curves might be going next, based on alternative actions available at the first juncture. Both create actions. The first again becomes an evaluation point where it is understood that some intervening action will need to occur in the development effort. The second is an evaluation of alternatives using the RAVR to help choose the best path for the development effort. Rather than letting the technical criteria dominate the optimization of the product, the development effort then is optimized by allowing the RAVR to be optimized, which ultimately allows for a cross-functional optimization.

In this analysis, it should be noted that in situations two and three, both decisions were not made based on the next projected state of the ECR curve. Instead, the decisions mirrored the decision of the team at the second state past the initial decision point. If straight RAVR or ECR was used in this case, as in the first case study (Section 5.1), different decisions would be made. The difference here shows that sometimes, scenarios are understood further than the next available state. Estimating the RAVR and ECR functions for a series of time-states can be helpful in providing valid and useful decision alternatives.

5.4 Summary of RAVR Analysis in the Case Studies

The case studies have shown where RAVR analysis can be used to aid in making decisions that enhance the value of the product development effort. It was shown how specific calculations can be made to compare two options at a single point in time. The next case study shows how monitoring the RAVR can offer indications of when intervening activities must take place in a project. It also shows the evaluation of all considerations in a risk-based format that can temper the decision-making according to the risk priorities of the project team. The last two case studies show how estimating the RAVR,without the use of actual hard numbers, can risk-temper the decision so that a more informed decision can be made. It is notable that trying to map risk functions beyond the initial decision also gives valuable information. This extended look at the RAVR progression can help decision-makers choose options that might have long term RAVR that might not be immediately available at the decision point.

It should be noted that using RAVR requires the estimation of acceptable costs, likely costs and their probabilities. RAVR analysis fits as an adjunct to many decision methods in that it doesn't actually produce the alternatives. From an optimization standpoint, it does not drive the decision-making. However, its use pushes the decision-maker into a data-rich environment, which provides a credible metric - value - and also offers opportunity extended sensitivity analysis (what ifs). This can occur even with soft, or subjective data, as it provides a way to organize and prioritize the risk elements and impacts in a project decision.

If the RAVR heuristic is used proactively, it can offer ideas of areas to explore for solutions to problems. As was done in the Showerhead case study (Situation #3), when the risk was too high, there was a search for trade-offs to substitute low-impact risk costs for high-impact ones. A structured RAVR analysis that is used throughout a product development effort can point out when these risks are high and lead to areas of focus that can produce these results. From a strategic standpoint, understanding the risks associated with the product development effort and the desire to optimize RAVR are objectives that can steer decision-making in productive directions.

6.0 Concluding Remarks

Risk-adjusted Value Ratio (RAVR) is a unique and novel method that can be used to infuse risk information into the engineering decision-making process in design and product development. It incorporates risk information involving all disciplines of a cross-functional development team. It can also deal with prioritized objectives of the team and the associated risks that are tied to those objectives. RAVR offers a rational metric that is understandable and useful in the design and development environment. It can work as either a quantitative decision method or a qualitative one, but essentially uses quantitative analysis techniques similar to FMEA to deal with subjective risks. It can be used as a stand-alone decision method between choices, as a sensitivity analysis tool, or as a directional indicator within an optimization strategy. RAVR also has the ability to deal with varying degrees of risk-preference from the decision-maker. It therefore is a tool that can match almost any engineering decision-maker's preference, or can be adapted to a team's style and offers useful analysis in making difficult choices.

RAVR's origins are from Expected Value theory, Failure Modes and Effects Analysis, and Value Analysis. And yet, its selective use and combination of portions of these theories along with its matching of decision-making procedures indicated in real product development allow this heuristic to be original in its use and effectiveness. RAVR allows a broader spectrum of risk preferences that EV cannot do alone. It is a cost-benefit analysis technique that uses probabilistic data similar to Expected Value functions, yet incorporates risk in such a way that it can accommodate for an individual's (or group's) specific risk preference level. It also extends the concept of Value Analysis beyond a point decision. In Thomas's case, one was choosing between multiple options to select a portfolio of projects. While RAVR is capable of doing this, it has the power to extend beyond a point decision to look at subsequent events and steer decision-making along the path of effective product development as well.

RAVR is original from the standpoint of tempering each decision with risk. The concept of O_e, of expected benefit (cost) at acceptable risk, is a way of grounding the decision-maker's thinking in terms of relative risk. In engineering design, and product development in general, there is always a requirement that some resources are expended to be able to gain a benefit. Before those resources are used, it is requisite that the decision-maker decides to risk that much (at least) for the effort to begin. Consequently, one can say that a risk-seeking individual has already expended the risk-seeking element of choice on determining to move forward with development based on the established expectations. It is arguable that some people are always risk-seeking in nature, but this seems unlikely. Even a risk-seeking entrepreneur will have to pick battles wisely – taking risks where the opportunities for pay-outs are exceptional, and yet avoiding or mitigating unnecessary risk. RAVR using O_e is based on this fundamental concept. RAVR focuses on the work that limits or reduces the risk to the amount already decided upon. From this standpoint, the risky situation and decision do not need to be dwelled upon; it is now infused within the design decision problem.

Owing to the nature of product development in the cross-functional environment, beyond the early stages of the project, the focus for engineering design is to reduce the cost-of-risk in accomplishing an established set of requirements. RAVR can then be separated into its numerator and denominator terms and appropriate portions of the ratio can be focused on the situation at hand. The original concept of Expected Cost of Risk (ECR) refers to the denominator of RAVR equation and is a strong focus during engineering design. The concept of minimizing the ECR fits with the engineering strategy to optimize design based on a fixed package of benefits – usually an outcome of the specification phase of a project. (The benefits portion of the RAVR is usually the primary responsibility of the commercialization team in improving the probability that the benefits will be valued by the target customer.) As the ECR is optimized, the concept of Marginal Cost of Risk comes into play. Once the Marginal Cost of Risk is zero, then a decision and action must occur to improve the situation further. This Marginal Cost of Risk has other implications as well. Often in development, it is hard to completely optimize a product. The process doesn't allow a true complete optimization to occur because of multi-disciplinary criteria, or even because of the messy process that development is. Consequently, finding a stopping point for the development, often called satisficing, is needed. Using the concept of Marginal Cost of Risk and RAVR, the decision-maker can choose a stopping point based on value development of the product rather than some other arbitrary point. So stopping the development due to a best increase in value is rational and allows for "optimal satisficing," or finding a choice that is good enough that really minimizes the risk of development.

Effectiveness

From the comparisons to Expected Value methods in Section 4 and the case studies from Section 5, RAVR is shown to be an effective tool in the process of making decisions based on risk. In the risk-neutral case, it is shown to give equivalent answers to EV. However, EV is a simpler formula and should most likely be used. It is shown that RAVR offers a wider range of risk preference-based decision results than can EV methods. It cannot effectively deal with risk-seeking behavior, but that is only true in the immediate sense. The RAVR formula already is adjusted for acceptable risk with the O_e term. This acceptable risk can be high or low and is based on the individual. So, in a sense, risk-seeking preferences are tempered into the decision with the RAVR method.

RAVR doesn't always give a desired solution. A case where the Expected Value of the options are the same, but the probabilities and pay-outs vary widely, is problematic. In these situations (similar to a stock value between two companies that is similar, but the range of fluctuation between stock prices over a period shows that one company is wider than the other), depending on the accepted risk chosen, the RAVR will choose the option with the worst case. This is possible because the accepted risk value is set to the lowest term in the most risk-averse case, and the RAVR will show both methods with equivalent value. It cannot distinguish between the two ranges. This can easily be fixed by adjusting the O_e up slightly from the lowest probable value of the options. But this quirk can be problematic if not recognized.

It also has some challenges similar to all methods in being subject to the accuracy of the data that is used for inputs. Because probabilities of risk are often subjective measurements, it might be easy for results to be skewed by a strong-willed team member. Good methods must be established to ground risk and keep relative risks in proper proportions to one another. Another point hidden in the case studies (because they were done in hindsight) was the ability to weight the risks properly. In real time use this might not be quite so straightforward.

Another challenge is the development of the actual action of a satisficed design. The case studies showed where RAVR and ECR could drive to a low cost-of-risk situation as the ideal. When cost-of-risk turns up, there is pressure to take some action. It is not obvious that this situation will occur at a point that is a stopping point in the design. In fact, it most often will occur when an interim situation comes up that is not a good stopping point. However, using the RAVR and ECR consistently will pressure decisions and actions that cause satisficing to occur over the course of a number of steps as the team realizes the extra risk it incurs by extending beyond the lowest cost-of-risk point.

While there are some challenges in implementation, RAVR is an intuitive system can be used either quantitatively or qualitatively. By developing graphs of perceived risk cost as was shown in Section 5, it was possible to develop scenarios for choices that led to important information in the decisions, all without the use of hard numbers. It also allows the combination of all the applicable risks to a multidisciplinary problem, rather than looking at each risk individually, or attempting to develop complicated trade-off schemes.

Finally, RAVR allows the decision-maker to determine value based on the efficiency of benefits and costs generated rather than on sheer quantity. This allows for scalability of the model for all possible projects in an engineering development portfolio. It allows consistent decision-making across the projects, whether it is for a small value improvement design project, or for a new, and break-through product project. This scalability allows RAVR to be an effective decision-making technique for engineering design in product development.

Further Work

At this point, RAVR has been developed more from a descriptive point of view, but has been validated in an after-the-fact manner, also a descriptive point of view. The next steps for this method are to use it in a prescriptive sense. It needs to be incorporated into a project from the beginning in a conscious effort to be used as the decision driver for that project. By using this method in the prescriptive sense, its true value, strengths, and weaknesses can be learned. This will also lead to improvement of the method to better fit situations and foster better decision-making.

Another area of effort would include how to better define the acceptable risk. As shown in the Holt and Laury example in Section 4, people have different risk preferences, probably unconscious of how to define what that risk preference is. A study determining how to gauge a person's risk preference and assisting in choosing an acceptable cost outcome (O_e) at their risk preference would be helpful in effectively exploiting this method.

Using the RAVR in more real world cases will also expose its use to different decision-making methods from different constructs. While RAVR is a combination of EV and Optimization, the question of how it might work with Experiential constructs or other methods shown in the tables in Section 2 would be useful. By extending its exposure, again, the opportunities to understand its strengths and weaknesses are evident. The objective would be to provide a decision-making tool that efficiently helps teams to navigate a project more quickly.

Since this method is tied to optimization and includes a weighting system to account for a team's risk objectives and risk preference levels, a likely challenge is whether RAVR can be incorporated into an artificial intelligence (AI) scheme. This scheme could then assist in or automate the decision-making process in design. A further area of study would be to incorporate RAVR into current AI structures and test its usefulness.

Another area of interest developed as a result of applying this method. As the risk preferences were set and as actual risks were calculated for various projects, it was noted that it is possible for a highly risky situation in one aspect of the design to cause the decision-making to be dominated by that area of the design. This can occur even though it might be a relatively low priority objective in the design. A study on how often this happens (and what kind of consternation is caused on the team) might be interesting. If this situation is spelled out explicitly using the RAVR formula, would a better understanding and acceptance of the decision result? This investigation could lead to further understanding the value of RAVR, or its use could help resolve many sticky decision trade-offs.

It was noted in Case Study 3 that at one point a decision was made based on scenario development rather than on direct analysis of the RAVR (or ECR) at the time. In this case, State 0 was the situation at hand; State 1 was the subsequent situation (where typical RAVR analysis would provide an answer); and State 2 was an area where one could see the situation leading to the eventual result. By developing the multiple state scenarios, a better answer was chosen than if straight RAVR had been determined. This is another area of possible inquiry that is not unique to RAVR. The interest would be in how RAVR analysis might better facilitate that type of information-rich decision-making.

Risk-adjusted Value Ratio is a method that is both unique and novel in the engineering development environment. It is a value-driven method that is sensitive to risk in the development process, and offers decision-making analysis all throughout that process. It can be effective in infusing the problem with risk data and pointing the decision in the direction that is compatible with the decision-maker's risk preference. There are many areas that can be explored further in RAVR to validate its usefulness and extend it into the engineering development environment. But as a decision method, RAVR is shown to be a rational, understandable and useful heuristic for making risk-based decisions in engineering design.

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