A PRAGMATIC VALUE-DRIVEN APPROACH TO DESIGN WITH APPLICATIONS TO ENERGY-CONSCIOUS BUILDINGS

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A PRAGMATIC VALUE-DRIVEN APPROACH TO DESIGN WITH APPLICATIONS TO ENERGY-CONSCIOUS BUILDINGS

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To the alumni of the Georgia Institute of Technology

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LIST OF SYMBOLS

Ω_i	Decision Outcome
π_i	Probability
X	Decision Alternative
L_{vN-M}	von-Neumann-Morgenstern Lottery
u_i	von-Neumann-Morgenstern Utility of Outcome
R	Risk Tolerance Parameter
$\mathrm{Q_i}$	Attribute i of a Decision Outcome
$\mathrm{q_i}$	Value of Attribute i of Decision Outcome
S_i	Set of Strategies Available to Player i
s_i	A Strategy Taken by Player i
Π_A	Artifact-Focused Value
a	Artifact Specification
A	Set of Considered Artifact Specifications
$\mathcal{A}$	Artifact-Focused Design Problem
Π_P	Process-Focused Value
p	Sequence of Process Actions
P	Set of Considered Sequences of Process Actions
$\mathcal{P}$	Process-Focused Design Problem
t_A	Time for Solving a Design Problem
t_P	Duration of a Single Design Process
C_A	Cost of Solving a Design Problem
C_P	Cost of a Design Process
Π_O	Organization-Focused Value

o	Organizational and Incentive Structure
O	Set of Considered Organizational and Incentive Structures
$\mathcal{O}$	Organization-Focused Design Problem
C_O	Cost of Incentives
C_M	Cost of Developing and Optimizing Using a New Model
R_i	Material Property i of a Building Model
f	Model of the Thermal Demand for a Building
σ_*^2	Variance of a Random Variable
ρ	Correlation between Random Variables
θ_{pre}	Pre-Retrofit Uncertainty
θ_{post}	Post-Retrofit Uncertainty
$\theta_{persist}$	Persistent-Retrofit Uncertainty
Y_i	Time Series Variable i
$\phi_{i,j}$	Linear Weight for Variables i at time j
ε_i	Noise Term in Auto-Regressive Model
$\mathit{\Phi}_i$	Row Vector of $\phi_{i,j}$
L	Number of Lags used in an AR Model
M	Number of Seasonal Observations of Y_i
$\mathbf{\Phi}_i$	Matrix of $\mathit{\Phi}_i$ for VAR Model
D_i	Non-normalized Meteorological Data
W	Number of Meteorological Phenomena
λ	Failure Rate per Year
$\bar{r}$	Mean Outage Duration
U	Annual Power Unavailability
EN	Energy Needed

EW	Energy Wasted
EP	Energy Produced
U_E	ESCO's Utility
U_C	Client's Utility
NPV_E	ESCO's Net Present Value
NPV_C	Client's Net Present Value
$\mathrm{EU_E}$	ESCO's Expected Utility
$\mathrm{EU_C}$	Client's Expected Utility
$\mathrm{EV_E}$	ESCO's Expected Value
$\mathrm{EV_C}$	Client's Expected Value
$\mathrm{RP_E}$	ESCO's Risk Premium
$\mathrm{RP_C}$	Trusting Client's Risk Premium
α	Client's Level of Distrust
α_{max}	Client's Maximum Level of Distrust
α_{max}	Client's Minimum Level of Distrust
$\mathrm{S_G}$	Guaranteed Savings
δ_E	ESCO's Discount Rate
δ_E	Client's Discount Rate

LIST OF ABBREVIATIONS

AR	Auto-Regressive
BEM	Building Energy Modeling
CDF	Cumulative Distribution Function
DM	Decision Maker
DMA	Decision Maker Action
DMC	Decision Maker Concern
ECM	Energy Conservation Measure
EPW	Energy Plus Weather File
ESPC	Energy Savings Performance Contract
ESCO	Energy Services Company
EVoI	Expected Value of Information
GURA-W	Georgia Tech Uncertainty and Risk Analysis Workbench
GTSD	Georgia Tech Solar Decathlon House
HDD	Heating Degree Days
IDF	Energy Plus Input Data File
LEED	Leadership in Energy and Environmental Design
LHS	Latin Hypercube Sampling
MAUT	Multi-Attribute Utility Theory
NCPI	Number of Concerns and Properties Included
NDMAI	Number of Decision Maker Actions Included
NPV	Net Present Value
NSAI	Number of Stakeholder Actions Included

NSI	Number of Stakeholders Included
NTDE	Total Number of Decision Elements
PV	Photo-voltaic
SA	Stakeholder Action
SC	Stakeholder Concern
SEP	System / Environmental Property
SMY	Stochastic Meteorological Year
TMY	Typical Meteorological Year
TRY	Test Reference Year
UA	Uncertainty Analysis
UQ	Uncertainty Quantification
VAR	Vector Auto-Regressive
VoI	Value of Information
VDA	Value-Driven Approaches
VDD	Value-Driven Design
vN-M	von Neumann and Morgenstern

SUMMARY

For an enterprise to be successful, operational practices must be well aligned with strategic objectives. Indeed, one would expect every process within an enterprise to be structured to contribute to the overall value of the organization. However, current practice in engineering design treats the design of products and services as fixed practice, seeking only to satisfy requirements on performance and cost. This misalignment between objectives and practice has been shown to be at least part of the cause of the trend of significant cost and schedule overruns. Within the design community, a growing number of researchers have shown interest in extending the value context to include design, such that designers focus on maximizing the 'value' of the product or service, rather than simply satisfying a set of requirements. Thus, by applying a value-driven approach to design, the design community hopes to show that the magnitude of cost and schedule overruns may be reduced, or even eliminated.

However, a criticism of value-driven approaches is that they are difficult to implement, and not sufficiently pragmatic to be used for large scale engineering problems. To begin to reconcile these disparate viewpoints, this dissertation presents research focused on enabling the implementation of value-driven approaches to design in practice at a reasonable cost. It is proposed that the lack of practicality in value-driven approaches is attributable to the lack of well established and verified methods and tools. In order to address this deficiency, this dissertation first presents research focused on developing a better understanding results in a set of characteristics of effective value models to be used within the design process. These characteristics relate not only to axiomatic requirements on value-models to ensure rationality, but also to the specific context of the design of artifacts and the interaction of the artifact with stakeholders.

Then, a conceptual framework is developed as value in design is examined from three perspectives. First, the current state of the art in value-driven approaches to design are related to an artifact-focused perspective of design. Then, a process-focused perspective is utilized to examine the importance of considering the costs of the design process and leads to the finding that it is rational to resort to heuristics during the design process in order to halt an infinite recursion of planning processes. Lastly, an organization-focused perspective provides a basis for examining the value of the structure of incentives and information sharing in organizations. The three perspectives are then applied to derive a set of desired characteristics for a method for specifying value models in design. These characteristics include that the method should be widely applicable to a range of design contexts, repeatable, and utilize gradual refinement to address the cost-benefit tradeoff of added accuracy

A Systematic Method for Developing Value Models (SMDVM) is then proposed to meet these desired characteristics. The method is decomposed into three stages in which the design context is examined iteratively to identify relevant stakeholders, system properties, attributes of concern, and actions that can be taken, relationships between the elements are identified and modeled, and the elements and relationships are refined. A user behavioral pilot study is conducted to evaluate the SMDVM relative to a standard framework for engineering design. Findings from the pilot study support the claim that the SMDVM focuses user effort on more deeply analyzing particular aspects of the design context, but are inconclusive regarding overall effectiveness.

In addition to the specification of a method for developing value models for generic contexts, the dissertation also discusses the development of specialized tools to reduce the costs associated with implementing the method. The application domain explored within this dissertation is the design and retrofit of energy-conscious buildings.

A simulation workbench is developed as a tool to automate the development and analysis of value models for building design and retrofit contexts. The Georgia Tech Uncertainty and Risk Analysis Workbench automates the identification of uncertain parameters, as well as relevant decision elements. The workbench incorporates multiple novel capabilities, including accounting for the "within-batch" variability of material properties, Pre-, Post-, and Persistent retrofit uncertainties, and Stochastic Meteorological Years, which account for uncertainty arising from variability in the weather conditions near a building. The workbench enables architects, engineers, and other practitioners to easily incorporate uncertainty into analyses of building energy consumption, as part of a value-driven approach to design and retrofit.

The developed methods and tools are used to analyze an interesting decision context in the retrofit of buildings under energy savings performance contracts. It is shown how a value-driven approach can be applied pragmatically in order to determine which energy conservation measures a decision maker should propose and the amount of savings which should be guaranteed for those measures. It is also shown how a third party to the contract, such as a local, state, or federal government could utilize such a value-driven approach to determine an incentive structure to encourage stakeholders to pursue higher levels of energy savings.

CHAPTER 1

INTRODUCTION

1.1 What is this research about?

Engineering design is a complex process comprised of several tasks which are usually performed iteratively. Figure 1.1 shows a simple model of a design process in which a designer, given a Problem Description, iteratively refines a design concept to yield a final, selected design. Of particular importance in this process are the activities of *Analysis* and *Evaluation*, as these tasks are responsible for steering the designer towards what is deemed as preferable. *Analysis* is a form of belief elicitation; it is a design action

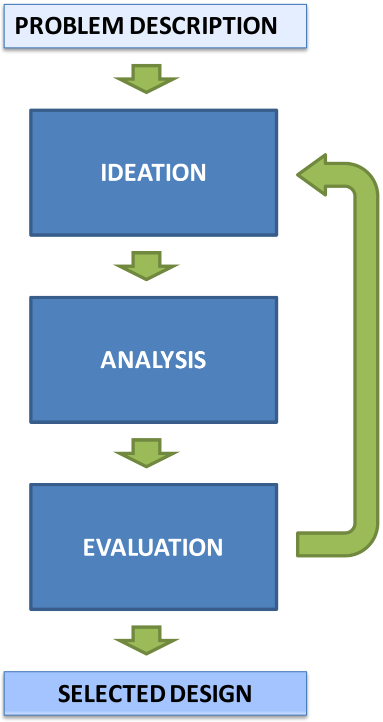

Figure 1.1. A Simple Model of an Iterative Design Process

that the designer believes will yield additional information about a particular design alternative. Finite-Element Modeling, prototyping, marketing, or even back of the envelope calculations are common examples of analyses used in engineering. On the other hand, *Evaluation* is reflective of preference elicitation, as an evaluation is an explicit comparison of the outcomes of the design alternative to the designer's preferences, and is used to determine a measure of effectiveness for the design alternative. This dissertation focuses on the development of models used for Evaluation.

Value-Driven Approaches (VDA)1 take the perspective that design is a purposeful task, by which the designer seeks to develop artifacts that deliver value. From a normative perspective then, a rational designer should attempt to design artifacts that yield the highest value. At a glance, such a statement appears straightforward; available alternatives should be Analyzed, and then Evaluated, and then the most valuable alternative should be selected. In practice however, it can be quite cumbersome to develop an accurate model of what exactly comprises the value to a designer, and equally difficult to solve that model to determine the proper course of action. This dissertation presents research focused on identifying pragmatic resolutions to the difficulty of performing design with a focus on value.

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[1] In this dissertation, the author will use the term "Value-Driven Approaches" when describing the general set of approaches that emphasize the focus on Value in the design process. For example Value-Driven Design (Brown et al., 2009), Value-Focused Design (Marais and Saleh, 2009), Value-Centric Design (Brathwaite and Saleh, 2009), Value-Based Acquisition (Maddox et al., 2013), Decision-Based Engineering Design (Hazelrigg, 1998) etc.

1.2 Gap and Vision

Simplified value models have been developed for consumer products (Taylor, 2012), aerospace engines (Briceno and Mavris, 2005), defense acquisitions (Collopy and Horton, 2002; Weigel and Hastings, 2004), monolithic satellites (Marais and Saleh, 2009), fractionated satellites (Brown et al., 2009), Global Positioning System architectures (Collopy, 2006), and for other domains. However, as is discussed in greater detail in Chapters 2-3, the literature repeats several common issues. Unfortunately, several of the issues have arisen from failure to adhere to the axioms of utility theory, or its resulting theorem. Additional difficulties concern the level of guidance suggested by a given approach; an approach may yield an appropriate model for a specific domain, but may not be relevant for even small deviations outside of this domain. Or, the approach specified may entail developing a value model that captures every insignificant aspect of a design opportunity. In doing so, it is likely that the approach would require so much effort to develop that its cost would exceed the benefit of its use.

A key criticism of these models and the VDA used to develop them is that they are impractical for use for actual engineering design problems due to their high cost of development. In this dissertation, I suggest that this perceived impracticality is the result of a tragic feedback loop, as depicted in Figure 1.2. Because there is little guidance provided in terms of best practices, value modelers follow ad hoc processes, and find it difficult to ensure that they have correctly accounted for their preferences and knowledge. As a result, they may have little to no confidence in the quality of their value models, and attempt to capture any detail imaginable, no matter how insignificant. Such endless refinement drives up the cost and time required to develop such a model,

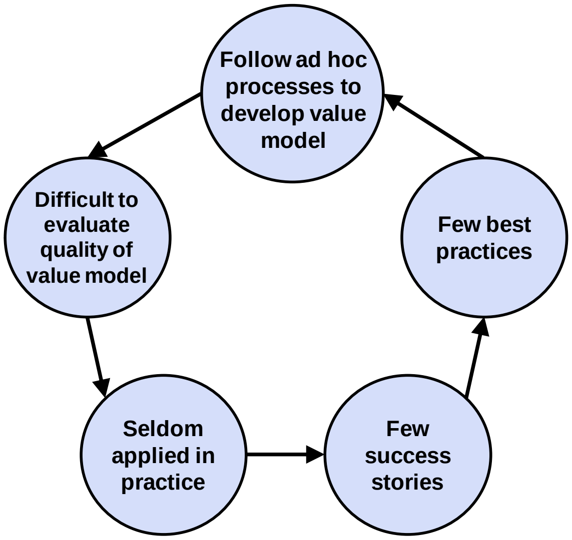

Figure 1.2. Tragic Feedback Loop in the Development and Use of Value-Driven Approaches

meaning that success stories will be few and far between. Ultimately, the loop is completed as the lack of success stories restricts the discovery of promising best practices.

1.3 Research Questions

The tragic feedback loop leads naturally to the Motivating Question for this dissertation:

> **MQ: How can Value-Driven Approaches be made more pragmatic for application in large scale engineering problems?**

Clearly, the motivating question is sufficiently large and complex that it could not be fully addressed within the context of a single dissertation, or even by a single researcher. As such, the motivating question has been decomposed into three targeted research questions that collectively seek to address the intent of the motivating question. Figure 1.3 depicts the decomposition into the topics of the specific research questions,

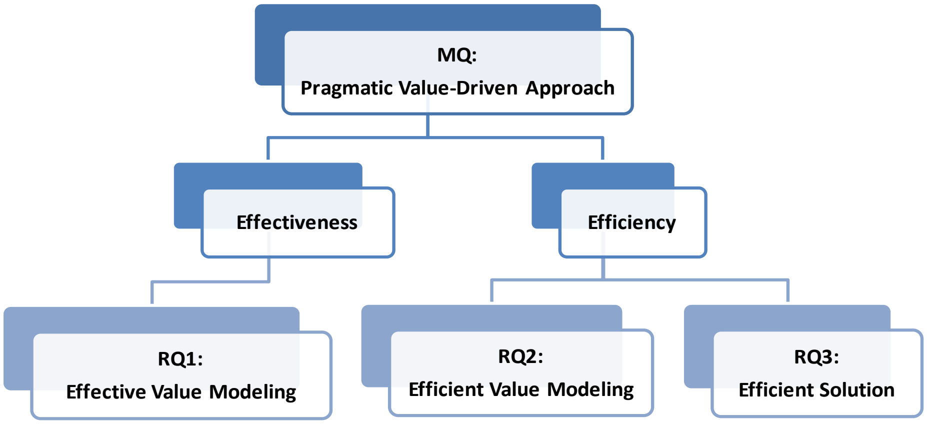

Figure 1.3. Decomposition of Motivating Question into Research Questions

which are further explained in the following sections. The decomposition focuses on the two main aspects of pragmatism: effectiveness and efficiency. Efficiency is further decomposed into two aspects, which pertain to the efficiency of specification and solution of the value model.

If the pragmatism of a value-driven approach is to be compared to that of other approaches, an unambiguous definition of what comprises an effective value-driven approach must first be determined. Research Question 1 will lead to such a definition, by investigating the characteristics of effective value models, as well as the methods used to develop them.

RQ 1: What are the characteristics of an effective approach for developing a value model?

Once a clear specification of a Value-Driven Approach is made, I focus on valuable approximations that reduce the cost of its application. In order to limit the scope to achievable amounts, this research focuses on investigating two of the key areas involved in a Value-Driven Approach: the *Development* and *Solution* of a value model. As such, Research Questions 2 and 3 are:

RQ 2: How can the process of developing a value model for a building performance scenario be made more efficient?

RQ 3: How can the process of solving a value model for a building performance scenario be made more efficient?

1.4 Approach

Due to the difference in focus between the research questions, different approaches are necessary to investigate each. Research Question 1 is focused on the notion of effectiveness, and therefore its investigation relies heavily upon the use of normative theory. On the other hand, Research Questions 2 and 3 emphasize the importance of an efficient design process. As such, the approach for their investigation follows a more empirical process involving the examination of the case study of energy savings performance contracts.

1.4.1 Effective Development through Rationality and a Systematic Approach

I hypothesize that a concise set of characteristics of effective modeling approaches can be determined via examination of the normative theory and literature regarding their usage. Rationality is then the measuring stick by which the effectiveness of value models (and the corresponding methods) can be gauged. As such, the approach to address Research Question 1 is to review the requirements placed on a value model by the normative theories of Utility Theory, Game Theory, Probability Theory. Further characteristics of effective value models are then abstracted from a review of the value modeling literature. Human cognitive limitations have also been shown to impact the design process, and so their impact on the development of value models is investigated as well. Once characteristics of an effective approach are determined, an method that meets these characteristics is proposed, and then evaluated using a pilot study involving a small sample of engineering graduate students.

1.4.2 Efficient Value Model Development through a Systematic Approach and Knowledge Reuse

In addition to the rationality and repeatability offered by a systematic approach to value model specification, such an approach should also provide the benefit of efficiency. By steering a designer's efforts in a directed manner, a systematic approach is expected to provide "good" results, but with reduced development time and cost. Also, through the development of a modeling workbench, it should be possible to reuse knowledge from previous investigations and further drive down the cost of developing value models within the context of the design and retrofit of energy-conscious buildings.

1.4.3 Efficient Solution through Automation and Knowledge Reuse

Provided that the modeling workbench is capable of automating some of the tasks or processes required for simulation, it should also lead to an increasingly efficient solution process as well. Provided that a modeling workbench can be created with sufficient flexibility that the automation does not degrade the effectiveness of the approach, such a workbench can leverage advances in computing technology and repositories of prior knowledge in order to reduce the time required solve complex engineering value models.

1.5 Contributions

As directed by the Motivating Question, the goal of this research is to make Value-Driven Approaches more pragmatic to apply to real world problems. Indeed, the development and solution of a value model constitute a large portion of the effort required for the design process, as acknowledged by Hazelrigg (Hazelrigg, 1998). As such, by making it more efficient to specify and solve value models, the cost of applying value-driven approaches reduces, leading to a shifted frontier in the tradeoff between the fidelity of analyses performed, and the breadth of alternatives which can be considered.

The main contribution of this research is a clarified definition of the characteristics of and a Systematic Method for Developing Value Models. The benefits of such a method are useful beyond the Building Energy Modeling community, but to the systems engineering and design communities at large. The investigation done as part of this research supports designers and researchers by promoting and adding to the relatively young field of Value-Driven Design.

Another key contribution of this research includes an understanding of how this process can be made more efficient by reducing the cost of developing and solving value models. This research should then serve as a first step towards enabling tradeoffs between the fidelity and cost of a value model. This contribution opens a new research topic for consideration, that of how to consider effective and efficient iteration of the value model alongside iterations of the designed artifact.

In the domain of Building Energy Modeling, the investigation of the case study leads to key insights about the impact of Value-Driven Design as a new perspective on the design of buildings. Specifically, the topic of the case study remains a significant open problem; the government is unsure how best to incentivize the retrofit of buildings for energy efficiency (Tweed, 2013). The value-driven approach advocated as part of this research provides a new perspective on this issue, and can be further used to motivate actions, or provide an explanation of why such actions should not be taken. Further, the modeling workbench developed can be useful to the BEM field at large in addressing other problems that require consideration of risk and uncertainty.

1.6 Organization of this Dissertation

The remainder of this dissertation is organized as shown in Figure 1.4. The next chapter presents prior work on the role of value in the design process. Chapter 3 presents research on the desired characteristics of a method for developing effective value models. Chapter 4 then presents a method based upon these characteristics. Chapter 5 presents research on how the method can be applied to the domain of energy-conscious buildings, as well as the development of the modeling workbench focused on making the specification and solution of value models more efficient. Chapter 6 presents an investigation of a case study regarding the value-driven analysis of Energy Savings Performance Contracts (ESPC). Finally, Chapter 7 discusses the research presented in this dissertation, and identifies opportunities for continued research in the field.

Readers interested primarily in the application of a value-driven approach to the design and retrofit of buildings may find it useful to first read §2.1 and §2.2, and then skip to Chapters 5 and 6. The reader can then return to Chapters 2, 3, and 4 as necessary to more deeply investigate the conceptual foundations of value-driven approaches.

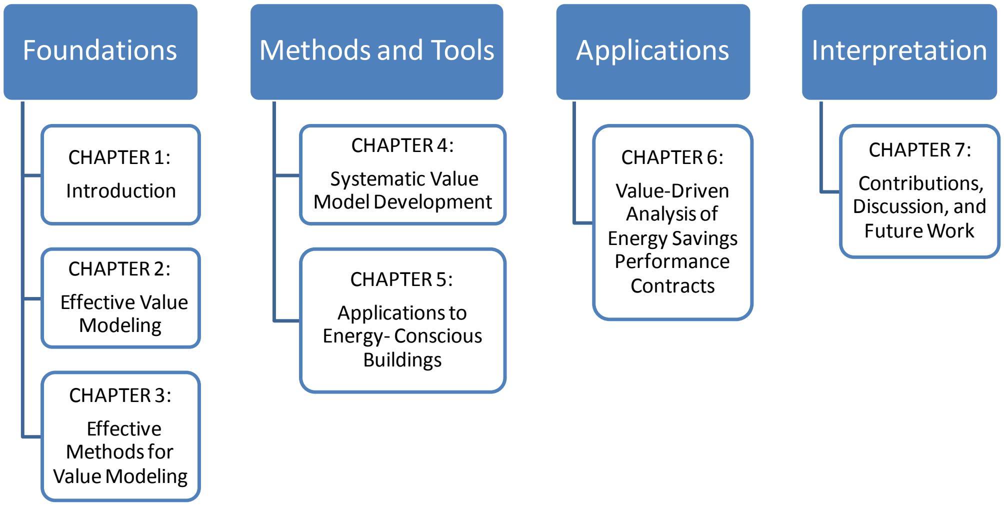

Figure 1.4. Organization of Dissertation

CHAPTER 2

EFFECTIVE VALUE MODELING

2.1 Introduction

In this Chapter, the normative basis for effective value models is investigated. First, normative decision theory and is reviewed and its application to design is reviewed in §2.2. Then, game theory is reviewed as a normative extension to decisions involving multiple stakeholders in §2.3. In §2.4, the normative theories are analyzed to examine the notion of effectiveness with respect to value models for design §2.5 then summarizes the key aspects of the chapter.

2.2 Design, Evaluation, and Decision Theory

The practice of engineering decision-making under uncertainty can be addressed from a normative or a descriptive perspective. A *Descriptive* investigation of decision-making attempts to understand how engineers *actually* make a particular in practice. *Normative* investigations instead try to prescribe how an engineer *should* make decisions. The latter is of greater interest in this research, so that one can better understand how designers *should* act, provided that they desire to rationally maximize their value. Axiomatic Utility Theory provides this normative foundation, and is introduced in the next section.

2.2.1 Axiomatic Utility Theory

An axiomatic theory for making design decisions under uncertainty is provided by Utility Theory. Preferences under uncertainty can be expressed in terms of utilities, the properties of which are outlined by the axioms of the theory. The expected utility theorem then states that the Decision Maker (DM) should select the alternative with the greatest expected utility. The axiomatic foundation of Utility Theory was originally developed by von Neumann and Morgenstern (vN-M) (von Neumann and Morgenstern, 1944) ,with others having developed slightly differing sets of axioms that reach similar results (Berger, 1985; Herstein and Milnor, 1953; Luce and Raiffa, 1957; Marschak, 1950).

The axiomatic foundation imposes simple limitations on the definition of utilities and establishes a definition of the rationality of a DM. However, the axioms do not impose any preferences restrictions, nor do they prescribe what exactly it is that the DM has preferences over. Rather, it is recognized that decision making is a subjective process and the foundation allows for any set of preferences to be modeled so long as they are self consistent; i.e. they cannot account for a DM changing his or her mind on a whim.

2.2.1.1 Axioms

The original axioms as set out by vN-M are reviewed in Table 2.1. The first axiom simply states that the DM has preferences over any possible outcome, and that the DM is capable of expressing that preference. This axiom is necessary to establish that preferences over outcomes exist, such that later axioms can make comparisons between outcomes of differing preference.

The second axiom states that preferences should be transitive. This axiom protects the DM against simple money pumps. For example, if the axiom does not hold, then a DM could logically trade an Apple and $1 to get an Orange. Then he could trade that

Table 2.1. Axioms of von Neumann-Morgenstern Utility Theory

Axiom	**Explanation**
Completeness	For any outcomes (Ω_1, Ω_2) either $\Omega_1 \succ \Omega_2$ OR $\Omega_1 \prec \Omega_2$ OR $\Omega_1 \sim \Omega_2$
Transitivity	For any outcomes $(\Omega_1, \Omega_2, \Omega_3)$ if $\Omega_1 \succ \Omega_2$ AND $\Omega_2 \succ \Omega_3$ THEN $\Omega_1 \succ \Omega_3$
Continuity	For any outcomes $(\Omega_1, \Omega_2, \Omega_3)$ such that $\Omega_1 \succ \Omega_2 \succ \Omega_3$, then for some π_1, $(0 < \pi_1 < 1), \Omega_2 \sim \pi_1 \Omega_1 + (1 - \pi_1)\Omega_3$
Convexity	For any outcomes (Ω_1, Ω_2) such that $\Omega_1 \succ \Omega_2$, then for any π_1, $(0 < \pi_1 < 1), \Omega_1 \succ \pi_1 \Omega_1 + (1 - \pi_1)\Omega_2$
Combining	For any outcomes (Ω_1, Ω_2) , $(0 < \pi_1 < 1, 0 < \pi_2 < 1)$ and $\pi_3 = \pi_1 \pi_2$, $\pi_1(\pi_2 \Omega_1 + (1 - \pi_2)\Omega_2) + (1 - \pi_1)\Omega_2 \sim \pi_3 \Omega_1 + (1 - \pi_3)\Omega_2$

NOTE: $(\Omega_1, \Omega_2, \Omega_3)$ are outcomes. (π_1, π_2, π_3) are probabilities. $\Omega_1 \succ \Omega_2$ indicates that outcome Ω_1 is preferred to outcome Ω_2. $\Omega_1 \sim \Omega_2$ indicates that outcome Ω_1 and Ω_2 are equally preferred.

Orange and $1 to get a Banana. Then he could trade that Banana and $1 to receive the original Orange, losing $3 in the process.

The remaining axioms concern the consideration of vN-M lotteries (see Figure 2.1). In a vN-M lottery, the DM has the option to enter into a lottery with uncertain outcomes $\Omega_1, \dots, \Omega_n$ ranked from most to least desirable, each with a corresponding probability of occurrence $\pi_1, \dots, \pi_n$. The third axiom states that preferences should be continuous over a region: a lottery with two outcomes as possibilities can be reduced to an equivalent certain outcome that is preferred between the two original outcomes. This axiom therefore also assumes that DMs also have preferences for lotteries with uncertain outcomes.

The fourth axiom states that preferences should be convex: if one outcome is preferred to another, an increased chance of receiving it should always be preferred. The fifth axiom states that compound lotteries, or lotteries with a lottery as an outcome, can

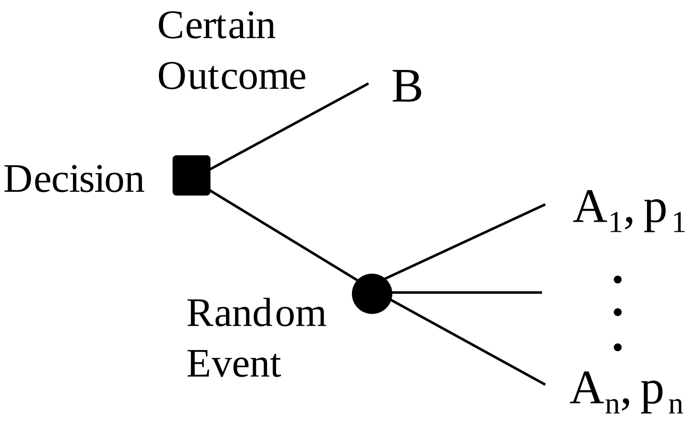

Figure 2.1. An Example of a von Neumann Morgenstern Lottery

be reduced to a single lottery. The Combining axiom is sometimes referred to as the Substitution, or Independence axiom, because it asserts that the evaluation of an outcome is independent of the lottery path in which it was obtained.

2.2.1.2 Expected Utility Theorem

Collectively, these axioms combine to form the basis for a rational decision-making criterion: *Maximize the expectation of utility*. This section presents a expanded version of Hazelrigg's presentation of the proof (Hazelrigg, 2012).

Theorem: The expected utility theorem. Given a pair of alternatives, X' and X'', each with a range of possible outcomes, $\Omega_1, \Omega_2, \ldots, \Omega_r$ and associated probabilities of occurrence, $\pi_1', \pi_2', \ldots, \pi_r'$ and $\pi_1'', \pi_2'', \ldots, \pi_r''$, respectively, the preferred choice is the alternative (with the resulting lottery) that has the highest expected utility.

Proof: From the Completeness Axiom, pair-wise preferences over the potential outcomes must exist. Then, by the Transitivity Axiom, these pair-wise preferences over $\Omega_1, \Omega_2, \ldots, \Omega_r$ can be ordered such that $\Omega_1 \succsim$

$\varOmega_2 \gtrsim \cdots \gtrsim \varOmega_r$ for some specification of $\varOmega_1, \varOmega_2, \ldots, \varOmega_r$. Then, by the Continuity Axiom, each individual outcome $\varOmega_i$ is equally preferred to a lottery $L_i \sim [(u_i, \varOmega_1), (1 - u_i, \varOmega_r)]$ where u_i is the utility of outcome $\varOmega_i$. This results in the net lotteries $L_{vN-M}{}' \sim \begin{bmatrix} \pi_1' \begin{bmatrix} u_1\varOmega_1 \\ (1-u_1)\varOmega_r \end{bmatrix} \\ \pi_2' \begin{bmatrix} u_2\varOmega_1 \\ (1-u_2)\varOmega_r \end{bmatrix} \\ \vdots \\ \pi_r' \begin{bmatrix} u_{\mathrm{r}}\varOmega_1 \\ (1-u_{\mathrm{r}})\varOmega_r \end{bmatrix} \end{bmatrix}$ and $L_{vN-M}{}'' \sim \begin{bmatrix} \pi_1'' \begin{bmatrix} u_1\varOmega_1 \\ (1-u_1)\varOmega_r \end{bmatrix} \\ \pi_2'' \begin{bmatrix} u_2\varOmega_1 \\ (1-u_2)\varOmega_r \end{bmatrix} \\ \vdots \\ \pi_r'' \begin{bmatrix} u_{\mathrm{r}}\varOmega_1 \\ (1-u_{\mathrm{r}})\varOmega_r \end{bmatrix} \end{bmatrix}$. By the Combining Axiom, these can be reduced to $L_{vN-M} \sim \begin{bmatrix} \pi'\ \varOmega_1 \\ 1-\pi'\ \varOmega_{\mathrm{r}} \end{bmatrix}$ and $L_{vN-M}{}'' \sim \begin{bmatrix} \pi''\,\varOmega_1 \\ 1-\pi''\,\varOmega_{\mathrm{r}} \end{bmatrix}$, where $\pi' = \pi_1' u_1 + \pi_2' u_2 + \cdots \pi_r' u_r$ and $\pi'' = \pi_1'' u_1 + \pi_2'' u_2 + \cdots \pi_r'' u_r$. Finally, by the Convexity Axiom, the preferred lottery is that which has the highest probability of receiving the preferred outcome. Because $\varOmega_1 \gtrsim \varOmega_r$, this equates to selecting the lottery with the highest value of π, which is defined as the expected utility.

2.2.2 Objectives, Tradeoffs, and Value

Utility Theory allows for the expression of any preference, provided that it is rational. That is to say that it must be consistent with the axioms presented above. As a result, the DM must still specify about what he or she has a preference; what are the DM's objectives? Following the terminology of (Clemen, 1996) an Objective is "a specific thing that you want to achieve," and is generally stated as (Maximize / Minimize) + (Property) + (Qualifying Phrase). For example, an engineer tuning an engine may desire to *Maximize the EPA rating for fuel economy of the vehicle when operating on the Urban Drive Cycle*.

Objectives can be classified as either *Fundamental* or *Means Objectives. Fundamental Objectives* are important because the DM has a direct preference for the property. *Means Objectives*, on the other hand, are only of interest because they help achieve *Fundamental Objectives.* Depending on whether there is only a single or multiple *Fundamental Objective*, different formulations of utility theory may be appropriate. The next two subsections discuss each of these formulations, as well as the assumptions required for their validity.

2.2.2.1 Single Attribute Utility Theory

Modern utility theory was originally developed for the consideration of decisions with a single attribute (von Neumann and Morgenstern, 1944). The process for using utility theory is quite simple. First, the utility of each potential outcomes is elicited using one of several methods, and then the expected utility for each action is determined. One method for eliciting preference is to ask questions of the form:

> *"Consider a lottery in which participants have a 50% chance of winning nothing, and a 50% of winning $100. You are allowed to either participate in the lottery, or win a guaranteed amount of $50. Would you prefer to accept the guaranteed amount or enter the lottery?"*

The above question is then repeated with different guaranteed amounts until the decision maker is indifferent between the lottery and a guaranteed amount[2]. At this point, since the decision maker is indifferent between the two options, the expected utility of the two options must be the same. For the illustrating example above, assume that a DM's indifference amount is \$35. Then the utility of winning \$35 must equal:

$$E[\mathrm{U}(\$48)] = E[\mathrm{U}(\mathrm{Lottery})] = p(\$0)\mathrm{U}(\$0) + \mathrm{p}(\$100) * \mathrm{U}(\$100) \qquad \textbf{(2.1)}$$

$$\mathrm{U}(\$35) = 0.5 * \mathrm{U}(\$0) + 0.5 * \mathrm{U}(\$100) \qquad \textbf{(2.2)}$$

Because utility is unitless and unique to an affine transform, the $\mathrm{U}(\cdot)$ operator can be defined with two degrees of freedom. Therefore, it can arbitrarily be stated that:

$$\mathrm{U}(\$0) = 0, \mathrm{U}(\$100) = 1 \qquad \textbf{(2.3)}$$

Combining Equations **(2.2)** and **(2.3)**, $\mathrm{U}(\$35)$ is then determined as 0.5. The process can then be repeated for other potential gambles, until the mapping between the attribute and utility is sufficiently refined. An example utility mapping is presented in Figure 2.2.

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[2] An alternate form of preference elicitation asks the decision maker directly for this certainty equivalent.

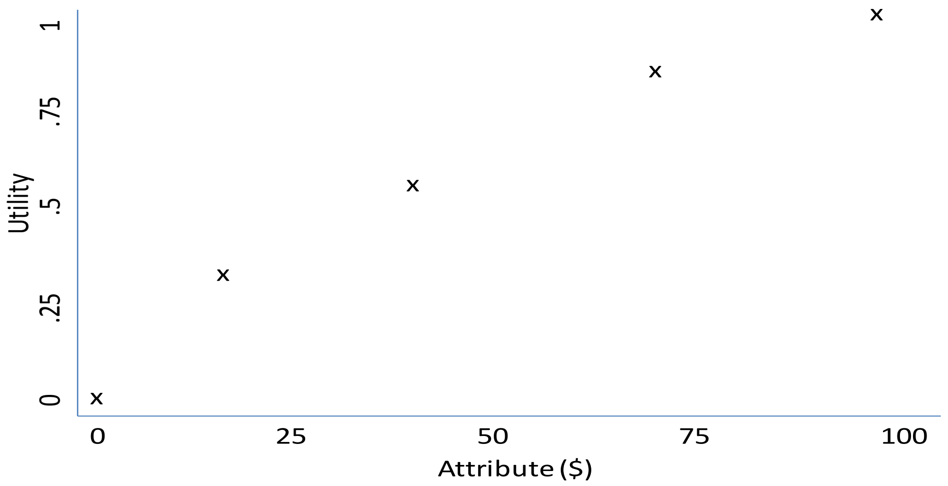

Figure 2.2. Example Mapping between an Attribute and Utility

Given that many decisions involve preferences over attributes that vary continuously (such as profit), it would be impossible to utilize only the approach outlined above. As such, decision makers may define a utility function to perform the mapping from the attribute space to the utility space. While any traditional curve fitting or interpolation technique is technically feasible, care must be taken that the resulting fit be a rational preference ordering and a reasonable abstraction of the decision maker's preference.

Specific to the attribute of worth, several characteristics are so common among different decision makers that they appear to be fundamental (Arrow, 1971; Pratt, 1964). First, it seems logical that utility should increase monotonically with wealth. Second, for positive wealth values, it seems reasonable that the second derivative of wealth be non-positive. The slope should at least not increase with increasing wealth, accounting for the common tendency to be averse to risk. For negative wealth values however, this

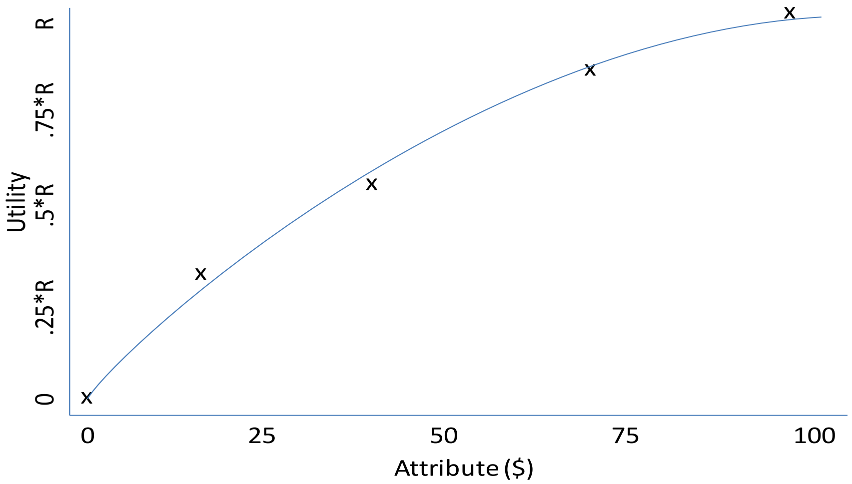

Figure 2.3. Example Mapping between an Attribute and Utility

condition does not always apply, and humans often become risk seeking to avoid a perceived guaranteed loss (Kahneman and Tversky, 1979).

One particular formulation that meets these conditions and has been found to accurately model the attribute utility mapping is to assume that the DM has a risk attitude of constant Risk Tolerance (Howard, 1988) where Risk Tolerance is defined as:

$$\mathrm{R} = -\frac{\mathrm{U}'(\mathrm{wealth})}{\mathrm{U}''(\mathrm{wealth})} \tag{2.4}$$

Under such an assumption, the approximating utility function is defined as:

$$\mathrm{U}(\mathrm{wealth}) = \mathrm{R} \cdot \left(1 - \mathrm{e}^{-\mathrm{wealth}/\mathrm{R}}\right) \tag{2.5}$$

An example fit of the mapping in Figure 2.2 using Equation (2.5) is provided in Figure 2.3. Such a model fit could then be used to evaluate the expected utility of an uncertain prospect, involving the occurrence of any payout. As is shown in Figure 2.3, any curve fitting will result in small discrepancies from the DM's true preference, as no model can ever perfectly capture any phenomenon completely. Provided that these discrepancies are not very large, the assumption can still be valuable as approximation.

2.2.2.2 Multi-Attribute Utility Theory

Whereas utility theory was originally developed for decision-making considering a single attribute, it has since been extended for the consideration of multiple attributes. The foundational work on the subject was conducted by Keeney and Raiffa. In (Keeney and Raiffa, 1993) they show that the principle of *utility independence* is central to the formulation of multi-attribute utility functions. They define Utility Independence as: "[Attribute] Y is *utility independent* of [Attribute] Z when conditional preferences for lotteries on Y given z do not depend on the particular level of z." They further define *mutual utility independence* as the occurrence when Y is *utility independent* of Z, and Z is *utility independent* of Y. The assumption of mutual utility independence is powerful, since it results in a relatively simple formulation of a net utility function, as shown in Equation (**2.6**).

$$u(Y,Z) = C_Y u(Y) + C_Z u(Z) + C_{YZ} u(Y) u(Z) \tag{2.6}$$

The form of Equation (**2.6**) is such that a utility function, as defined in §2.2.2.1 can be defined for each attribute independently. The multi-linear formulation, as shown in Equation (**2.6**) can be extended for an arbitrary number of attributes, as shown in Equation (**2.7)**.

$$u(X) = \frac{1}{C}\left(\prod_{i=1}^{n}[CC_i u_i(X_i) + 1] - 1\right) \tag{2.7}$$

Then, with the form of a multi-attribute utility function thus defined, a set of tradeoffs are made in order to elicit the various weights (C_i) that define a specific function. The tradeoffs elicited take the form similar to

> *"Given a design alternative, with certain attribute levels* $\{Q_1 = q_1, Q_2 = q_2, \ldots, Q_n = q_n\}$ *and a second alternative with certain attribute levels* $\{Q_1 = q'_1, Q_2 = q_2, \ldots, Q_{n-1} = q_{n-1}\}$*, for what value of* $Q_n = q'_n$ *are you indifferent between the two alternatives?"*

If enough of these comparisons are made, then the modeler can solve for the values of the weights (C_i) by setting the net expected utility of the alternatives as equivalent.

The literature is rich with implementation of Multi-Attribute Utility Theory (MAUT). In (Sage, 1977), the author argues that for large scale systems, the presence of multiple attributes necessitates the usage of MAUT to formulate a singular metric for use in optimization.

Given the particular restriction that an additive utility function is appropriate, which is only proper when the various attributes are *Additive Independent*[3],Weber develops an approach to elicit the coefficients of the utility function using fewer elicitation questions in (1985). The resulting net utility function is not precise, but is shown to be strategically similar to the 'true' utility function, if it exists.

Fishburn was instrumental in continued operationalization of MAUT, from investigating an axiomatic basis for additive utility functions (Fishburn and Keeney, 1974), to various non-linear formulations of MAUT (Fishburn, 1989; Fishburn, 1984).

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[3] Keeney and Raiffa define Additive Independence as "Y and Z are additive independent if the paired preference comparison of any two lotteries, defined by two joint probability distributions on YxZ, depends only on their marginal probability distributions." (Keeney and Raiffa, 1993)

Thurston refined and developed a formal method for eliciting the weighting coefficients of a multi-attribute utility function in (Thurston, 1991) and provides case study examples of optimization in the automotive industry.

More recently, MAUT has been utilized in the MIT Engineered Systems Division as part of a framework for evaluating systems with multiple performance attributes when faced with uncertainty in the design, operation, maintenance, and end-of-life stages. For example, Weigel and Hastings model user satisfaction when budgetary uncertainty is present, considering multiple attributes using a MAUT formulation in (Weigel and Hastings, 2004). Ross and Hastings also utilize a MAUT basis as part of their Multi-Attribute Tradespace Exploration toolkit to trade-off performance attributes and "-ilities" such as flexibility, adaptability, scalability, and so on (Ross and Hastings, 2006; Ross and Hastings, 2005).

In (Gurnani and Lewis, 2005) the authors propose an extension of MAUT involving an overlap measure, allowing for a designer's inability to make consistent value-tradeoffs, and therefore specify a consistent and precise value function.

Malak et. al. combine the framework of MAUT with set-based design to enable the consideration of multiple design concepts from an early stage in the design process in (Malak et al., 2008), and present an example considering the conceptual design of power transmissions.

The main criticism of a MAUT approach is that the assumptions of mutual utility independence, or even utility independence, are seldom reasonable (Von Winterfeldt and Fischer, 1975). For example, consider the whether the assumption of utility independence is reasonable for the attributes of Cost, Safety, Flight Range, and Passenger Capacity for a commercial airplane. Assuming a low Cost, high Safety, and medium Flight Range, in a 50/50 gamble between a Passenger Capacity of 100 or 400 persons, a reasonable certainty equivalent may be 200 persons. However, for a low Cost, high Safety, and low Flight Range, the same 50/50 gamble is unlikely to result in the same certainty equivalent of 200 persons, as high capacity is not as valuable for shorter trips since the plane can make the flight route more often. Therefore, the assumption of utility independence does not hold.

2.3 Evaluation with Multiple Decision Makers

Any time multiple decision makers exist, it seems reasonable that each would wish to optimize his or her own utility. However, if their own utility depends on the decisions made by the other decision makers, then often the decision makers will not be able to receive their optimal outcome, and must work with the other decision makers in order to reach a somewhat desired state. In this arrangement, the set of decision makers must decide how to make a common decision.

2.3.1 Aggregation of Preferences and Arrow's Impossibility Theorem

One could imagine then that the preferences of each decision maker could be aggregated somehow, and that aggregation be 'fairly' optimized. However, Arrow showed that no aggregation of preferences for three or more decision makers, when choosing between three or more alternatives, can guarantee that the aggregation meets three reasonable conditions presented in Table 2.2 (Arrow, 1963). Any preference aggregation that ensures Pareto unanimity and that irrelevant outcomes are not selected is necessarily a dictatorship in which a single decision maker's preference set the preferences for the group.

Table 2.2. Desirable Conditions of Preference Aggregations

Condition	**Explanation**
Pareto Unanimity	If every decision maker prefers Ω_1 to Ω_2, then the aggregation should yield that Ω_1 is preferred to Ω_2.
No Dictator	There is no single decision maker with the power that his or her preference of Ω_1 to Ω_2 forces the aggregation to yield that Ω_1 is preferred to Ω_2.
Independence of Irrelevant Outcomes	The aggregation should yield a preference between Ω_1 and Ω_2 that depends only upon the individual decision makers' preferences between Ω_1 and Ω_2, and not upon other (irrelevant) outcomes.

Therefore, Arrow's Impossibility Theorem asserts that no such aggregation of preference can be defined (Arrow, 1963). Utility Theory and Decision Analysis alone are insufficient to prescribe action, and so another basis for decision making with multiple agents is required.

2.3.2 Game Theory as the Basis for Decisions with Multiple Decision Makers

In circumstances where multiple decisions exist, and will be made by different decision makers then each rational decision maker should seek to maximize their expected utility. The complication arises when the outcomes of interest to one decision maker are impacted by another decision maker's actions, and vice-versa. Then, a decision maker cannot identify which action leads to the highest expected utility, without first expressing what actions the other decision makers may take.

In Game Theory, this problem is addressed by considering that rational players will not select actions that are strictly dominated by other actions (Gibbons, 1992). This principle then leads to the identification of sets of strategies for all players that are at least non-dominated. The specifics of how these strategies are identified are beyond the scope of this dissertation, but are discussed in detail in (Gibbons, 1992). In this dissertation, I will focus on the definition of a Nash Equilibrium and its meaning in relation to prescribing action.

2.3.2.1 Definition of Nash Equilibrium

Using the notation of (Gibbons, 1992), an n-player game G consists of potential combinations strategies $\{S_1, S_2, \dots, S_n\}$, where S_i is the set of all strategies available to player i, and the set of result utilities $\{u_1, u_2, \dots, u_n\}$, where u_i is the resultant utility of the outcome to player *i*. Then, the set of strategies $(s_1^*, s_2^*, \dots, s_n^*)$ are a Nash Equilibrium if, for each player i, $u_i(s_i^*, s_{\neg i}^*) \geq u_i(s_i', s_{\neg i}^*)$ for any s_i'. Conceptually, a Nash Equilibrium is a set of actions such that if all players were to take a given action, no player would be able to improve his or her expected utility by changing his or her action alone.

2.3.2.2 Interpreting Nash Equilibria

The definition of a Nash Equilibrium does not preclude the possibility that multiple optimal strategies may exist for a given game. To the contrary, in many situations multiple Nash Equilibria will exist. In such circumstances, it can be difficult to interpret the meaning of a Nash Equilibrium. However, recall that Game Theory only prescribes the rational set of actions that the various decision makers should take (Gibbons, 1992). It does not prescribe which of the set of rational actions should be chosen, as any of such actions could be rationally selected.

Also, sometimes the identified Nash Equilibria may be interesting of an academic nature, but be impossible to actually achieve in practice. For example, if an infinite number of Nash Equilibria exist, such as can occur in games involving decisions over a continuous action space, then it can be quite unlikely that a Nash Equilibrium action will actually be taken, as the likelihood that the various decision makers select the same equilibrium strategy is effectively zero. This reinforces the 'is/ought' dichotomy originally described in §2.2. Game Theory is a *Normative* theory, not *Descriptive*. Therefore, it is not proper to use Game Theory as an explanative basis for how decisions actually *are* made. Investigations should be limited to the exploring how decisions *should be* made.

In the many fields of engineering, decisions often occur in small teams or when stakeholders must agree to work together. Every sufficiently difficult design opportunity will require effort by various stakeholders, and will result in different payoffs to each stakeholder. Often, all parties would be better off they could agree to perform a particular course of action, and then trust in their colleagues to actually follow through with their promises. However, the case is often the exact opposite, as each party is incentivized to deviate from the group in an anguilliform manner. In general, there are two ways to gain trust or cooperation in such games. The first is to change the payoffs for the single game. The second is to transform the game from a one-time game to a repeated game.

2.3.2.2.1 Incentives

Often, players may be able to incentivize other players to change their desired course of action through either side payments or blackmailing. For example, in order to ensure that all players cooperate, one player could offer to bribe the other players to cooperate. However, such side payments tend not to be good long term strategies; early payments can lead to larger demands by other players. Alternatively, players can often blackmail or threaten to penalize other players in means beyond the original game if a desired action is not taken. However, this also can require the blackmailing players to allocate their own scarce resources, and is not always optimal.

2.3.2.2.2 Repeated Games

A complete discussion of repeated games is beyond the scope of this work, the interested reader is directed to (Gibbons, 1992). Here, I will briefly introduce the possibility that by viewing the game as a repetitive game, rather than as a single one-time event, new Nash Equilibria can arise. For example, if a pair of two designers expect to work on a project together again, they may be willing to cooperate, or make concessions on the first stage of a game, knowing that the other player will make the same concessions in the next stage. Therefore, simply changing the perspective on the time horizon can sometimes make it possible to ensure collaboration or teamwork between engineers or stakeholders.

2.3.3 Evaluation and Multiple Decision Makers - Summary

As described in this section, situations often arise when multiple decision makers must collaborate. In these times, Arrow has shown that it is improper to consider the optimization of the 'group' preference, as no such preference exists. Therefore, normative analysis must resort to game theory in order to provide a prescriptive approach forward. This normative theory does not always lead to outcomes that are necessarily the most desired by any decision maker, as each decision maker must account for his or her own preferences, and also those of his collaborators. Specifically within the contexts of design and systems engineering, this concept can have dramatic impacts on the performance and value of a designed system. Therefore, it is often necessary to consider not only the technical, but socio-technical aspects of such a design opportunity.

2.4 Effectiveness in Value Models for Design

Merriam-Webster defines *Effective* as "producing a decided, decisive, or desired effect" (Merriam-Webster, 2004). Previously, it was argued that the purpose of value models is to enable the correct prediction of the value of alternatives such that the value can be optimized. A value model can then be described as effective if it allows the optimization of the decision maker's value.

2.4.1 Value Models in the Literature

The process described in §2.2.2.1 for eliciting preference can be applied to any context, provided that the DM is focused on a single attribute. In many instances, this restriction is quite reasonable and proper. In the design literature, it has been argued that the point of a business is to create and deliver value to its stakeholders (Brathwaite and Saleh, 2009; Hazelrigg, 1998). Specifically, this value is defined in economic terms, resulting in the fundamental objective to maximize the Net Present Value (NPV) of Profit. In the context of such a objective, other attributes of concern can all be addressed as Means Objectives. These Means Objectives can be presented at different level of abstraction, and are likely to be context specific.

For example, Hazelrigg's Framework for Optimal Product Design (see Figure 2.4) offers a particular decomposition of the objectives of the design process that assumes a relatively simple design context (Hazelrigg, 2012). Given the fundamental objective of "maximize the net present value of profit", Hazelrigg proposes three stages of design decisions, and a series of means objectives that apply generically to many product design contexts. First, Profit is decomposed into Costs and Revenues. Revenue is then defined as the product of Demand for a product and its Price. Demand for a product is determined

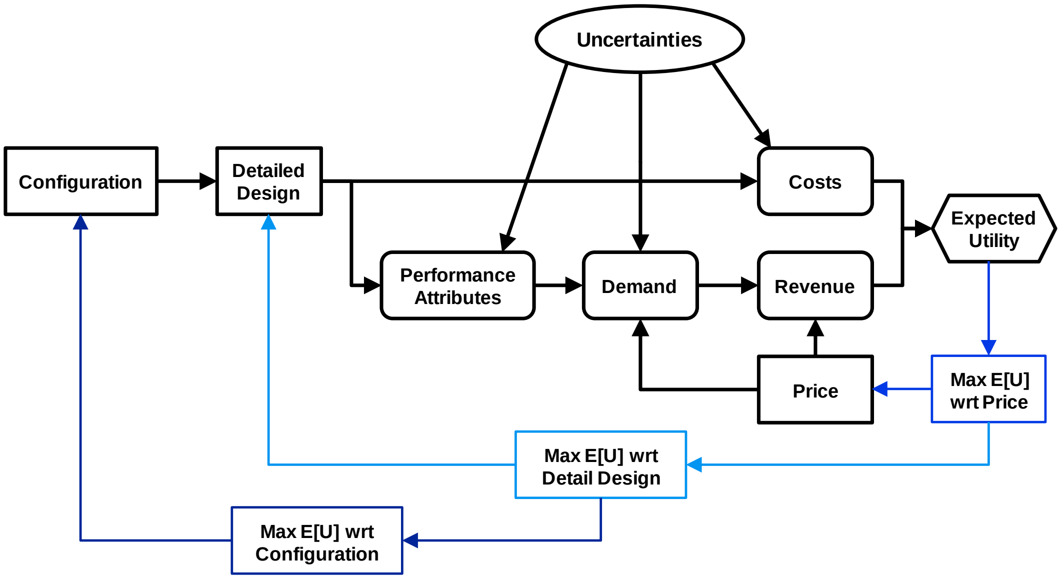

Figure 2.4. Hazelrigg's Framework for Optimal Product Design

****Adapted from Figure 9.2 (Hazelrigg, 2012)***

based on customers' preferences for the defining Performance Attributes of the product. Finally, the Cost and Performance Attributes of the product are determined by the product Configuration and Detailed Design decisions.

Hazelrigg's approach makes several key assumptions about the type of decisions being made. First, it assumes that the artifact being designed is a product for some market. Therefore, this approach cannot address the design of systems meant for the manufacture, transportation, or disposal of other products. Further, it limits the consideration of stakeholders to that of customers, whose only power is whether or not to purchase said product. Any purchasing decision need not happen at the exact same point in time, demand can vary over time within the framework. However, customers do not gain any additional information from early adopters, and therefore the success or failure of a product depends only upon the performance attributes of the product itself, and the pricing strategy under which it is promoted.

The framework implicitly assumes that the individual designer has complete control over the entire product specification, from configuration to pricing. While this may be reasonable for simple products, or even simple systems, many systems are designed beyond the scope of a single designer or even a single team. In fact, for complex systems, or Systems of Systems (Keating et al., 2003) design decisions will be made by entirely separate sets of entities, possibly even with competing objectives. Such a difference has important implications on the form of approach that is reasonable to perform analyses and optimization, as discussed in §2.3.

Collopy has also been instrumental in the development and advancement of Value-Driven Approaches to design. In (Collopy, 1997; Collopy, 1996) he first began to call for formal analysis and evaluation using value as the primary driver for decisions in the design of complex systems. In (Collopy, 2001) he illustrated a "Formal Design Cycle" (see Figure 2.5) that prescribes a generic design process. The Cycle begins with a design concept, specified by particular Design Variables. These Design Variables are then elaborated into a more concrete concept Definition. The defined concept can then be analyzed to predict its properties, or attributes of interest. These properties are then evaluated using a Value Model, which should be used to steer the optimization of the design concept. In (Collopy, 2009), Collopy presents a "Value Model Applied to Design Evaluation," a linearized specification of his Formal Design Cycle, which is similar in form to Hazelrigg's Framework (see Figure 2.6). Design decisions are made about the

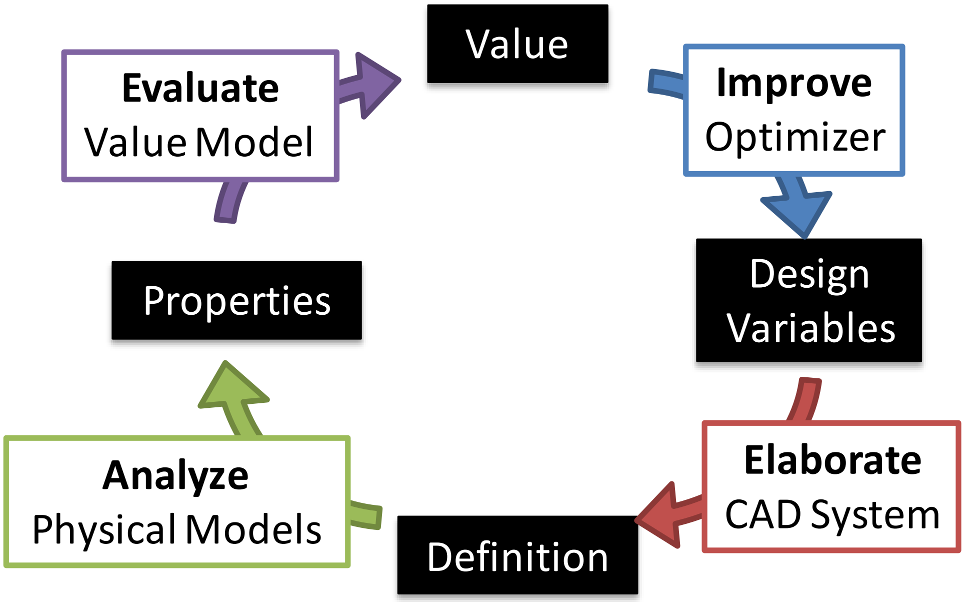

Figure 2.5. Collopy's Formal Design Cycle

**Adapted from (Collopy, 2001)*

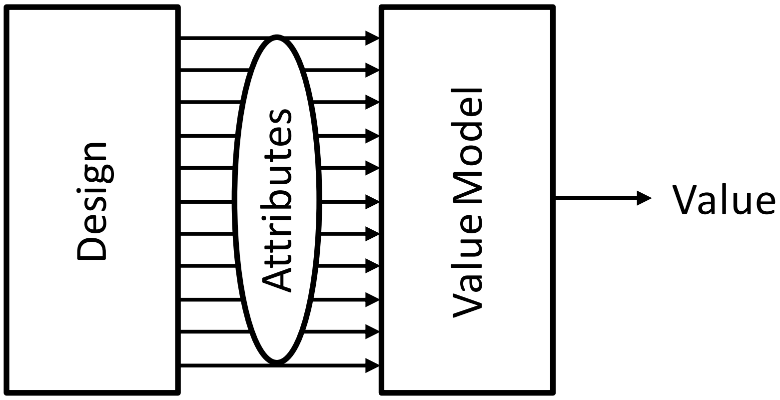

Figure 2.6. Collopy - Value Model Applied to Design Evaluation.

**(Collopy, 2009)*

concept, which will impact the attributes of the system. These attributes are of concern to a decision maker, whose preferences are captured using a value model.

Collopy offers a multitude of perspectives on the definition of value in design, sometimes defining value as that obtained by the acquirer of the system (Collopy and Horton, 2002), the seller of the system (Collopy, 2003), or the surplus (sum of the two) (Collopy, 2001; Collopy, 1997; Collopy, 1996). However, as opposed to Hazelrigg's approach, uncertainty is not a central aspect of Collopy's investigations. Collopy's investigations have continued into the definition and application of value models to new domains such as military/defense (Collopy, 2008) and joint military/civilian aerospace projects (Cheung et al., 2012; Collopy, 2006; Keller and Collopy, 2013).

Other researchers have also investigated the concept of value, including the MIT Engineered Systems Division (Ross, 2003; Ross and Hastings, 2005; Ross et al., 2004). Much of their continued research focused on the value derived from the a system ability to react to uncertain changes: flexibility, changeability, adaptability, and other "-ilities" (Ross and Hastings, 2006; Ross and Rhodes, 2008; Ross et al., 2008; Weigel and Hastings, 2004).

Similarly, Saleh began his research in the valuation of flexibility in satellite design (Saleh et al., 2003) and reliability (Saleh and Marais, 2006). In later work, he advocates the use of a value-centric mindset (Marais and Saleh, 2009; Saleh, 2008) and present a foundation of a value-centric approach. According to Brathwaite and Saleh, (Brathwaite and Saleh, 2008; Brathwaite and Saleh, 2009) the three pillars of value-centric approaches are that 1.) Engineered systems are value delivering entities, 2.) Businesses exist in order to create value for shareholders, and 3.) Value includes information not only about the system, but also about the system's interaction with its surroundings, resulting in a holistic, measurable metric for evaluation. However, the value models created by Saleh and Brathwaite focus primarily only on the narrow topic of satellite design. Further, while their approach accounts for the impact of uncertainty, it utilizes a signal to noise ratio of the expected value divided by its standard deviation, as opposed to a utility theoretic formulation.

Researchers at DARPA investigated novel satellite designs and leveraged a value-driven perspective to argue for their effectiveness (Brown and Eremenko, 2008; Brown and Eremenko, 2006; Brown et al., 2009). By considering the holistic value of fractionated satellites, the authors were able to argue that while the upfront cost was more substantial, they were more than offset by the improved benefits to system reliability and robustness. However, again the approach used focused solely on the design of monolithic and fractionated satellite systems, and lacked a procedural method for application to other domains.

As those in the research community experimented with value-driven approaches, it continued to evolve. Briceno proposed and investigated the impact of a game theoretic perspective of analyzing design of aerospace systems with multiple players (Briceno, 2008; Briceno and Mavris, 2006; Briceno and Mavris, 2005). However, the game theoretic support tool focused mainly upon maximizing individual payouts, without truly considering the payouts and actions of other actors, save for competition.

Wessen and Porter utilize a much less formally specified value-driven perspective, however their approach results in a market-based tool to enable stakeholders to trade resources (Wessen and Porter, 1998). Their approach recognizes that the value derived from a system differs depending on the stakeholder. By explicitly considering the stakeholders' independent value maximizations, the Cassini spacecraft cost growth roughly 1% over specification, with mass actually 3% under budget, as opposed to common trends of 50-100% growth.

Shiau and Michalek also argue that consideration of market systems should fall within the purview of engineering designers in (Shiau and Michalek, 2008). By developing a simple game theoretic model, they identify couplings between various players in simple competition, and note further couplings between the engineering design and marketing decision makers in the scenario as well. Michalek continues his value-focused investigations of optimal product design in (Shiau and Michalek, 2009) and extends to the consideration of consumer choice uncertainty in (Resende et al., 2011).

2.4.2 Common Value Modeling Mistakes and Issues

In (Keeney, 2002), he identifies twelve common mistakes experienced when attempting to perform trade-offs (see Table 2.3). These mistakes focus primarily on attempts to develop 'correct' multi-attribute utility functions, but their lessons are still relevant to a single attribute utility function, in which value is the primary driver of utility. Mistake Five is of primary interest; it explicitly acknowledges that only Fundamental Objectives should be used in making value tradeoffs, and dismisses attempts to tradeoff Means Objectives as invalid.

In addition to the tradeoff mistakes identified by Keeney, value modelers tend to make several other mistakes with respect to developing a model for predicting the value of a system. Table 2.4 shows a list of common issues that have been experienced when designers or researchers have attempted to apply a value-driven perspective. Unfortunately, several of the issues arise from failure to adhere to the axioms of utility theory, or its resulting theorem.

Table 2.3. Common Mistakes in Making Tradeoffs

**Adapted from (Keeney, 2002)*

#	Mistake
1	Failure to understand decision context
2	Lack of Relevant Attributes
3	Inadequate Measures (not Measurable and Comprehensive)
4	Failure to understand Measures
5	Trading off Means Objectives
6	Using Prior Willingness to Trade as indicative of Indifference
7	Attempting to Calculate "Correct" tradeoffs
8	Assessment of Tradeoffs that neglect range of consequences
9	Assessment of Tradeoffs that neglect anchoring
10	Conservative expression of Preferences
11	Using Hard Constraints
12	Failure to Check Consistency

2.4.3 Effective Decision Making

Of primary concern is that the value model should result in a metric that is consistent with von Neumann and Morgenstern's axioms for expected utility theory (recall §2.2.1.1). Of key importance is that that the value model should result in a scalar attribute defining value, and that the decision maker's uncertainty should not be neglected, but should be explicitly accounted for.

Considering the above axioms, several necessary characteristics can already be identified (See Table 2.5). First, a value model must describe the preferences of a single decision maker. To do otherwise denies Arrow's impossibility theorem that multiple agents cannot rationally combine preferences into a single statement of group preference.

Table 2.4. Common Issues Encountered in the Value-Driven Design Literature

Issue		Examples
Value is calculated separately from risk:	How are the risk preferences expressed rational?	(Dubos and Saleh, 2011) (Brown and Eremenko, 2008) (Brathwaite and Saleh, 2008) (Brathwaite and Saleh, 2009)
Value is defined as benefit, separate from cost:	How is a decision made considering two metrics?	(Dubos and Saleh, 2011) (Weigel and Hastings, 2004) (Ross and Hastings, 2005) (Ross and Hastings, 2006) (Ross et al., 2008) (Ross and Rhodes, 2008)
The decision making entity is a group:	How is the preference aggregation rational?	(Collopy, 2006) (Gordijn and Akkermans, 2003) (Brathwaite and Saleh, 2008)
The decision making entity is not identified:	Whose value is being captured?	(Gordijn and Akkermans, 2003) (Ross and Rhodes, 2008)

Second, the model must result in a scalar value metric, as a cardinal ranking is possible only for a single attribute. Next, in accordance with the expected utility theorem, the decision maker's uncertainty about the value metric must be accounted for. Failure to do so results in the inability to calculate the expectation of utility.

2.4.4 Effective Decision Making for Design

The remaining characteristics identified in Table 2.5 refer to practical requirements on a value model. For a company, the driver of utility should be profit. The purpose of a value model is to evaluate a design alternative, and so it must be capable of identifying how the decision maker's actions impact the system of interest. The next logical requirement is that the model should capture how the system and environment impact the events of concern to the decision maker. Finally, the value model should

Table 2.5. Characteristics of Effective Value Models

Characteristic	Explanation
Single DM	Model describes the preferences of a single decision maker
Ranking	Model describes preference using a scalar value metric, allowing a cardinal ranking
Uncertainty	Model describes the beliefs and uncertainty of the decision maker
Risk Preference	Model describes the preferences for outcomes under uncertainty by considering the vN-M utility of the value driver
Rationality	Model prescribes action based on the maximization of the expectation of the vN-M utility.
Driver of Value	The driver of vN-M utility is the net present value of profit for a company, or societal benefit for a non-profit entity
Impact of Actions	Model predicts impacts of design decisions on the system of interest and environment
System Behavior	Model predicts how the system of interest and environment interact to impact outcomes of decision maker's concern
Stakeholder Actions	Model predicts how the potential actions of stakeholders impact the system, environment, and decision maker
Stakeholder Concerns	Model predicts what aspects of the system and environment drive the decision making of stakeholders

capture how other stakeholders impact the decision maker's value by identifying their decisions and the attributes that drive their decision making processes.

2.5 Summary

In economics and decision theory, preferences are expressed using “value,” so that striving for the most preferred outcome can be modeled as maximizing value. Based on simple axioms of rationality, decision theory prescribes how one should go about choosing the most preferred alternative. During the design process, designers are faced with decisions on how to design artifacts that will impact outcomes about which they have preferences. Clearly from this perspective, value maximization is at the core of design—value maximization is what should drive designers. But in order to improve a quantity, it is necessary to be able to measure it, or at least predict the quantity. Value models form this basis for predicting the value of actions; they allow designers to make predictions about the (uncertain) outcomes of a design action, and therefore optimize their value.

CHAPTER 3

EFFECTIVE METHODS FOR VALUE MODELING

3.1 Introduction

Whereas the previous chapter focused on only the effectiveness of a value model, this chapter instead focuses on the effective specification and usage of value models. §3.2 presents a conceptual framework of value in the design process. This conceptual framework is then utilized to evaluate a set of characteristics common to many design processes in §3.3. Then, the conceptual framework is utilized to identify additional characteristics of effective methods for developing value models in §3.4.

3.2 Effectiveness in Value Modeling Methods for Design

There is more to design than just applying decision theory. Before being able to select a design alternative that maximizes value, designers must first identify value opportunities and then generate creative concepts for taking advantage of these opportunities (recall Figure 1.1). Beyond performing these tasks effectively, in this Chapter it is argued that they must also be done *Efficiently*, recognizing the cost of design process as non-insignificant. To support the argument, this section presents a conceptual framework for value in design rooted in normative theories introduced in Chapter 2. The conceptual framework considers decision making not only from the perspective of the artifact, but also of the design process, and of the organizational structure in which humans perform the process. This is different from the traditional focus which was limited to making decisions about the artifact. Broadening the scope to include process and organization leads to several interesting insights into the design process.

3.2.1 Artifact Centric Perspective

When focusing on maximizing the value of the artifact, it is acknowledged that a company derives value primarily from producing an artifact that can be sold for profit. This marks a change from the typical focus of design, in which the engineers seek to create an artifact that meets certain benchmarks on consumer attributes. Instead, the consumers' preferences are only important to help the designers understand what will sell, and at what price. As such, while it is important to create value for the customers in a sustainable business model, the focus is on maximizing the company's value.

3.2.1.1 Value in the Artifact Centric Perspective

From an artifact-focused perspective, a designer is concerned with maximizing the expected utility, $\mathrm{E}[\mathrm{U}(\cdot)]$, of the net present value of profit, π_A, of a given artifact, a, from the set of possible artifacts, A:

$$\mathcal{A}\colon \max_{a\in A} \mathrm{E}[\mathrm{U}(\Pi_A(a))] \tag{3.1}$$

While the conceptual formulation of such an optimization problem is simple, the practical development and implementation is not without difficulties. Hazelrigg (Hazelrigg, 2012) provides a framework to guide engineers through the process, but it remains challenging. As an example, consider the evaluation of a gasoline-electric hybrid vehicle, as described in Figure 3.1. Even for such a simple example, a designer must still perform the following:

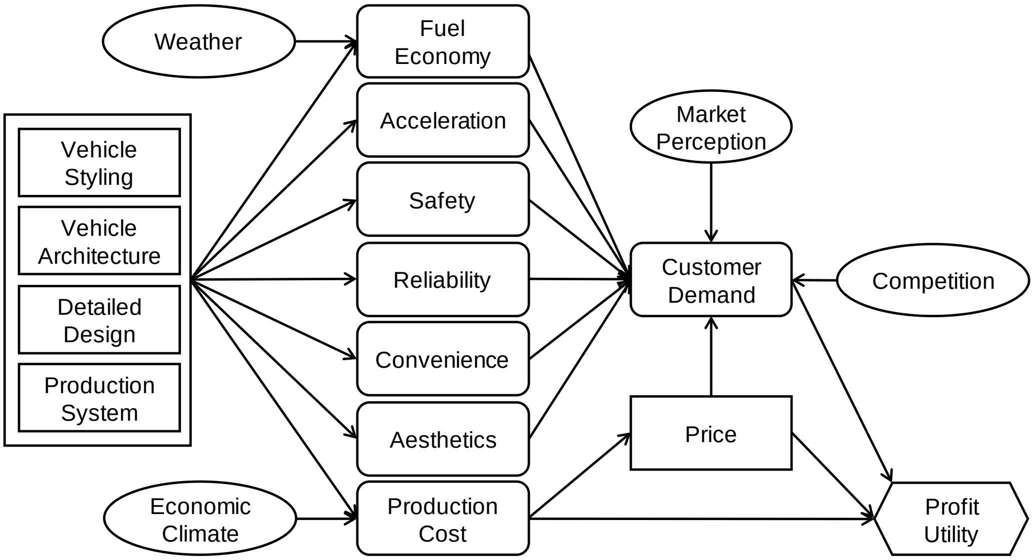

Figure 3.1. Example of a Value-Driven Framework for Evaluation of a Gasoline-Electric Hybrid Vehicle

- Identify which product attributes impact demand
- Create accurate models for demand, including competition
- Create accurate cost models
- Quantify uncertainty for a diverse range of properties
- Perform a nested optimization to determine a pricing strategy
- Consider how the artifact interacts with the enterprise's other product lines
- Consider financial and human resource constraints

Further, the problem becomes even more complicated when there are additional stakeholders, as in the case when the customer is different from the end user, or when retailers, regulators, activists, etc. are involved. Clearly, numerous research challenges remain.

3.2.2 Process Centric Perspective

A decision about an artifact is the implicit outcome of a sequence of decisions made about the design process. A final artifact specification is obtained by generating potential artifacts, and then by then analyzing these alternatives. But there are many possible processes for formulating and solving such a decision problem about the artifact, and designers thus need to decide which possible sequences of process steps to follow.

3.2.2.1 Value in the Process Centric Perspective

A design process has a corresponding value, which includes the artifact value, Π_A, as a function of the artifact but also includes the time used to solve the design problem, $t_A(\mathcal{A})$, and the cost of solving the design problem, $C_A(\mathcal{A})$.

$$\mathcal{A}\colon \max_{a \in A} \mathrm{E}\left[\mathrm{U}\left(\Pi_A\big(a, t_A(\mathcal{A})\big) - C_A(\mathcal{A})\right)\right] \tag{3.2}$$

Note that this problem definition is not a traditional optimization problem due to its self-referential nature—the objective function contains a reference to the optimization problem itself. To be clear, the self reference arises because the framing of the design problem of identifying the optimal alternative impacts the ultimate value to be derived. Therefore, in order to maximize the expected utility of the value, one must optimize the manner in which the original design problem is framed.

To address this self-reference, the design problem can be reformulated from a process-focused perspective. Here, one does not directly specify design alternatives, but rather the actions taken during the design process. The design problem can then be modeled as the following process-focused optimization problem:

$$\mathcal{P}\colon \max_{p \in P} \mathrm{E}[\mathrm{U}(\Pi_P)] = \max_{p \in P} \mathrm{E}\left[\mathrm{U}\left(\Pi_A\big(a(p), t_{\mathrm{P}}(p)\big) - C_P(p)\right)\right] \tag{3.3}$$

Reflecting that a designer chooses a sequence of process actions p from a set of considered actions P, resulting in artifact a. Solving this process-focused decision problem is akin to planning the design process. In the planning stage, designers decide which sequence of design actions to pursue, which computational and human resources to apply, and how much time to allocate to each step. Strictly speaking, the planning stage of p should also be optimized so that it provides the optimal structure for optimizing the process. But then this planning of the planning stage should itself be optimized, and so on. Rather than capturing this infinite recursion as self-reference, these stages are considered to be included in p.

This infinite recursion can be compared to dynamic programming in computer programming. Consider that the artifact, a, is the result of the implemented design process, p_0, which is also the result of planning process p_1, which is the result of planning process p_2, and so on. At each planning process p_i, there are potential sub-processes that could be selected, p_{ij}, each with a corresponding process cost to implement $C_P(p_{ij})$. For completeness, assume that one of these process alternatives is always to "Not Plan," indicating that all previous process steps are also "Not Plan." As opposed to determining the minimum "distance" between two points, the designer is instead interested in maximizing the expected value between start and end of the design process. Consider Figure 3.2, which depicts the design process similarly to the shortest path problem in dynamic programming. At the artifact stage, the 'distance' is the value of the artifact, and then the connections between the nodes are then the cost of implementing the particular planning process.

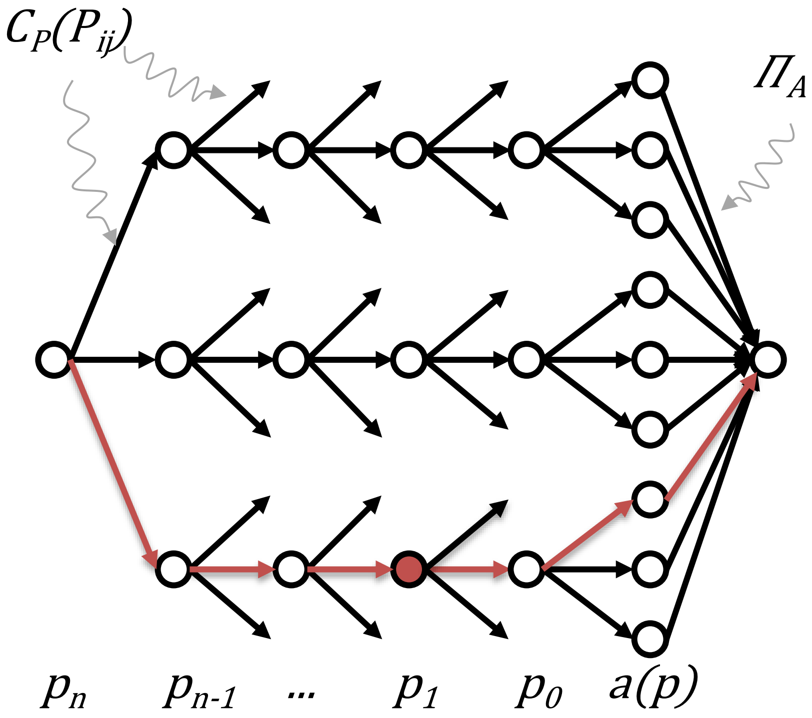

Figure 3.2. Optimal Substructure and the Design Process

This infinite recursion possesses an Optimal Substructure (Cooper and Cooper, 1981; Larson and Casti, 1978) because for any node within the optimal process 'path' the optimal 'sub-path will then be the remainder of the path. That is to say, if the red path in Figure 3.2 were the optimal path, then in planning process p_1, the optimal process to select for the final process would be the center process, and the then the top alternative would be preferred.

The infinite nature of the recursion is broken by recognizing that at some point the cost of further planning is larger than the expected benefit. At that point, it is better to resort to the "Not Plan" planning process, so as to not be subject to the costs of the planning process. Because the "Not Plan" itself can only be the result of the "Not Plan" process, this means that any decisions at this point are not guided by previous optimization. As a result, they must be the result of heuristics—inexpensive rules of thumb that result in a good decision most of the time. Note that these heuristics may occur already at the artifact level, for instance, when a designer restricts the system alternatives being considered to a small number of common system architectures. Such a heuristic is justifiable if past experience indicates that the small set of architectures is almost certainly going to include the most preferred alternative. The heuristics may also occur at the process level, where based on past experience, a designer may choose to describe and analyze a large set of system alternatives at a particular abstraction level, with a particular analysis formalism and at a particular analysis accuracy. The heuristic then pertains to the process: How to represent and analyze a system alternative? Finally, heuristics may also occur one level deeper still, at the level of selecting appropriate planning actions for planning the design process. For large system development efforts, it may be desirable to take the time to plan the development process: What kind of process should one use? How much time should one allow? What are good milestones or go-no-go points? An example of heuristic at this level may be that for a large effort in which new, unproven technologies are considered, a spiral development approach is appropriate because experience has indicated that it provides a relatively low cost approach for maturing the technologies and eliminating the risks associated with them. However, at some point, this recursive planning loop is guaranteed to end because the expense of additional planning exceeds the expected benefits, so that $C_A(\mathcal{P}) \approx C_P(p)$ and $t_A(\mathcal{P}) \approx t_P(p)$, justifying Equation **(3.3)**.

Even when one pragmatically resorts to a heuristic rather than a rigorous solution of a design decision problem, the ultimate objective remains the same: to maximize the overall value, Π_P. This is important to recognize when developing new heuristics (as is the focus of much of the ongoing systems engineering and design research). Whether a particular heuristic is good should be evaluated based on its ability to maximize value. As the global context and the enabling technologies change, it is important to regularly re-evaluate existing heuristics, assess whether the underlying assumptions are still valid, and potentially introduce updated and improved heuristics.

However, conducting this process of reviewing potential heuristics to determine if it is still rational is itself a planning-process, one to determine which process (heuristic) to utilize in the next stage. Therefore, one must be careful to make a distinction between rationally using heuristics, and having a rational heuristic. The former relates to a necessary pragmatism in the design process, and the latter is more of a misnomer. A heuristic itself cannot be "rational" because if there were a justification for the use of heuristic over another, then the heuristic would be merely another process or planning process stage, and therefore should not be classified as a heuristic. Therefore, when individuals refer to the "effectiveness" of one heuristic over another, they are blurring the line between true heuristics and normal process alternatives. This confusion is natural, as the definition of whether two designers would classify a process alternative as a heuristic depends entirely on the experience of the two designers and their capability to develop alternatives to the heuristic. A novice in a particular domain may accept a particular practice as a heuristic, because he or she does not truly understand why the practice is performed, only that it is. An expert, on the other hand, will have an understanding of why the practice is valuable, because he or she will be able to compare the practice to other alternatives.

An example application of planning processes in action regards the evaluation of various methods for guiding the process of ideation. Since value of a process can be a challenging metric to measure or predict, other metrics have been proposed as surrogates. For example, consider the metrics of Novelty, Variety, Quality, and Quantity that Shah et al. propose to evaluate different ideation processes. In (Shah et al., 2003), the authors justify each of these metrics independently, but note in their conclusion that directly adding the metrics together is not likely to form a valuable basis for comparing ideation methods. Still, they have set the stage for a value-driven comparison of ideation methods, by posing a set of reasonable metrics that can now be correlated to value. The ultimate value is likely not just a function of these metrics alone, but also includes a consideration of a number of sociological, psychological, and organizational factors. Design is not performed by automatons in a vacuum; it is performed by cognitively limited humans who interact within a social and cultural context. Therefore, methods that purport to be valuable to a designer should be well aligned with the designer's cognitive abilities, as well as his or her social and cultural norms.

3.2.3 Organization Centric Perspective

From an organization-focused perspective, a decision maker may not make decisions about an artifact directly, but only influence artifact decisions indirectly by delegating decision making to others.

3.2.3.1 Value in the Organization Centric Perspective

As is modeled in Equation (**3.4)**, this decision maker thus designs an organizational structure, o, to encourage others to follow a design process that leads to a valuable artifact:

$$\mathcal{O}\colon \max_{o \in O} \mathrm{E}[\mathrm{U}(\Pi_O)] = \max_{o \in O} \mathrm{E}\left[\mathrm{U}\left(\Pi_A\big(a(p,o), t_P(p,o)\big) - C_O(\mathrm{o})\right)\right] \tag{3.4}$$

where the C_O refers to the costs of the incentives provided to all the stakeholders to whom tasks are delegated. This total cost of the incentives is likely to be higher that than the process cost, $C_P(p)$, in Equation (3.3) due to the additional cost of agency (Laffont and Martimort, 2009). Since, in this model of design multiple decision makers may have the mutual ability to impact each other's payoff, one must rely on game theory (Gibbons, 1992) and mechanism design (Laffont and Martimort, 2009) (specifically, principal-agent theory) as a normative foundation to answer the following pertinent questions:

- How should one assign authority and responsibility?
- How should one exchange information?
- How should one measure performance?
- How should one provide incentives?

Organization-focused decision making plays a particularly important role in the context of system-of-systems engineering (Jamshidi, 2005), in which different portions of the system are designed, owned, or operated by different stakeholders.

When applying game theory to such problems, one would typically assume that it is common knowledge that all players are rational. However, it has been shown that humans often act irrationally (Ariely, 2008). Therefore, if a decision maker believes that other stakeholders may act irrationally (but predictably so) then he or she should account for this. An interesting area of research extends this principle to consider the possibility of our own irrationality when making decisions. If decision-makers want to make good decisions, they should consider that they are subject to biases, and take steps to minimize the effect of such irrationality (Kahneman, 2011; Kahneman and Tversky, 1979). In the end, the goal should be to act as rationally as possible, recognizing internal biases and the likely irrationality of other stakeholders.

3.3 Evaluating Characteristics of Valuable Design Processes

Based on the conceptual framework for value in design identified in the previous section, I now consider five characteristics that are typically encountered in design processes. It is shown that each of these characteristics can be justified from a process-focused or organization-focused perspective, but not necessarily from an artifact-focused perspective.

3.3.1 Gradual Refinement of Artifact Specification

In Figure 3.3, an exhaustive approach for analyzing design alternatives is depicted. In this approach, the decision maker specifies and analyzes the entire set of alternatives in full detail at once, and then selects the most valuable artifact—exhaustive but expensive due to the high cost of both specification and analysis of a large number of alternatives. In Figure 3.4, a different and more common approach is depicted, in which the specification of the alternatives is refined gradually, allowing a designer to choose which branch in the search tree to follow at each step along the way. Rather than choosing from among a set of completely specified alternatives, the designer now chooses which branches of the search tree to explore, while gradually refining the alternative specification.

From an artifact focused-perspective, the exhaustive approach is guaranteed to result in a value that is greater than or equal to the value of the artifact chosen using the approach relying on gradual refinement. The second approach introduces the possibility that the optimal artifact may be pruned during the gradual refinement. However, the

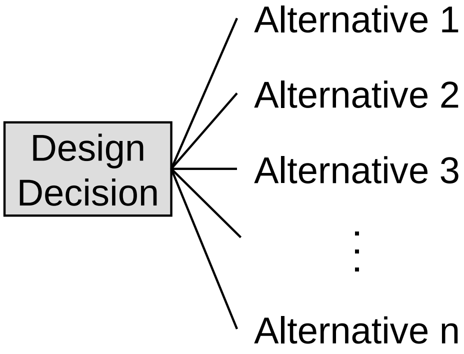

Figure 3.3. A Design Process Involving All at Once Refinement

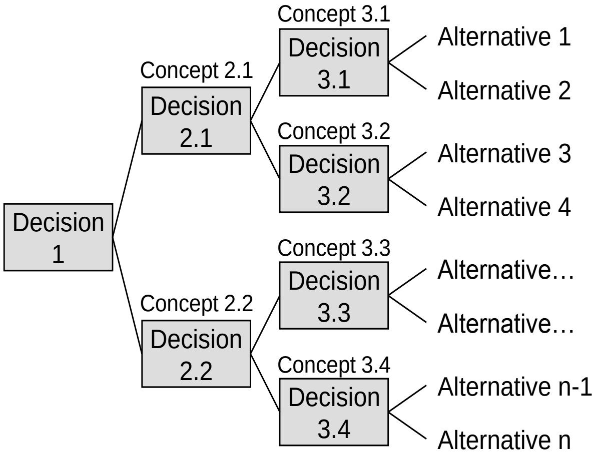

Figure 3.4. A Design Process Involving Gradual Refinement

exhaustive approach includes all artifacts, and is therefore guaranteed to include the artifact that is optimal from the artifact-focused perspective.

However, from a process-focused perspective, the second approach is much more valuable. As expressed in Equation (**3.3)**, besides the artifact value, Π_A, the cost of the design process, C_P, must also be considered. Compared to an all-at-once process, a process of gradual refinement tends to require significantly less time and resources for artifact specification and analysis because fewer alternatives are considered in detail. Thus, as long as the benefits of a shorter, less expensive design process exceed the loss of value associated with potentially suboptimal artifact specification, gradual refinement adds value. A good example of such a fast-moving and time-critical context would be the development of semiconductor manufacturing equipment.

From an artifact-focused perspective, the second approach is suboptimal. At each decision point, a portion of the space of design alternatives is pruned from further consideration, potentially pruning the most preferred artifact alternative.

3.3.2 Gradual Increase in Analysis Accuracy

To compare and select the most valuable alternative, designers use models to make predictions about the future value of artifacts:

$$\Pi_A = f(a) + \varepsilon \tag{3.5}$$

Because the value, Π_A, will be realized at some point in the future, the prediction is inherently uncertain. There are two main sources for this uncertainty: model uncertainty and specification uncertainty. Every model involves abstractions of reality and, therefore, cannot make a perfectly accurate prediction of the future. This *model uncertainty* is illustrated in Equation (**3.5**) by including an uncertainty term, ε. Different models include different abstractions and result in different accuracies. In addition, more accurate models also tend to be more expensive.

Besides model uncertainty, there is uncertainty due to the incompleteness of the artifact specification, a. I call this *specification uncertainty*, noting its similarity to Suh's notion of imaginary complexity (Suh, 2005). Without knowing the additional artifact details that still remain to be specified, the value of the artifact can only be predicted with

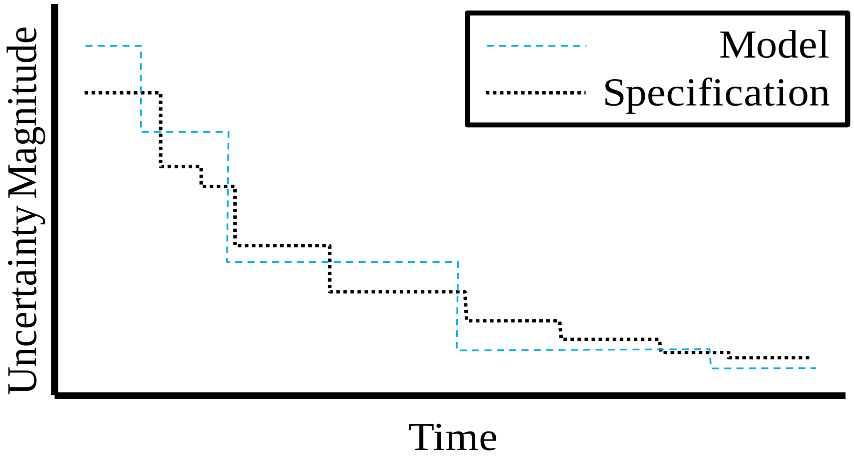

Figure 3.5. Model and Specification Uncertainty Throughout a Design Process

limited accuracy. Assuming that the artifact specification is refined gradually, as discussed in Section 3.3.1, the specification uncertainty also becomes smaller over time, as illustrated conceptually in Figure 3.5.

The two types of uncertainty both impose a bound on the overall accuracy of the value prediction. When the specification uncertainty is large, the overall uncertainty is large also no matter how accurate the model. Similarly, when the model uncertainty is large, the overall uncertainty is large no matter how precisely the artifact is specified.

From an artifact-focused perspective, it is always preferred to perform the most detailed analysis, lest a valuable alternative be mistakenly pruned. However, from a process-focused perspective, when the cost of the analysis is considered as in Equation (**3.4)**, inaccurate and inexpensive models may be more preferable at the early stages of design when the artifact specification still lacks detail.

This means that throughout the design process, the dominant source of uncertainty alternates between the specification and a variety of increasingly accurate and costly models, as shown in Figure 3.5. Initially, the specification's uncertainty dominates all but the most abstract of models. At that time, the cost associated with developing and executing very accurate analysis models is greater than the benefit, so that inaccurate, inexpensive models are used. As the uncertainty in the specification is gradually reduced, more accurate models are preferred because the inaccurate models no longer allow one to distinguish between the good and the best design alternatives. Such tradeoffs between costs and benefits of analysis are studied in value-of-information theory (Howard, 1966; Lawrence, 1999; Thompson and Paredis, 2010).

3.3.3 Delegation of Design Tasks

As discussed in §2.3, a designer, serving as the principal, may delegate design tasks to other individuals, which serve as agents. These agents have their own beliefs and preferences, which are not necessarily aligned with those of the principal. To ensure that these agents take actions according to the principal's beliefs and preferences, the principal needs to communicate what is desired and provide incentives so that if the agents take actions that maximize their own value, they also maximize the principal's value.

From an artifact-focused perspective, whether to delegate or not has no impact, assuming that the principal provides appropriate incentives—either way the same artifact would be chosen. However, as shown in Equation (**3.4)**, from an organization-focused perspective, it would be preferable not to offer incentives as they reduce the principal's value. In addition, time and resources are needed for information exchange between the principal and agents, and in that information exchange, miscommunication can occur, resulting in further reduction in value.

Still, it is often desirable to delegate. Delegation allows for division of labor, and hence specialization, so that design tasks can be performed more efficiently. Additionally, the agents may be more skillful in their specialty, resulting in better artifacts. Finally, the principal may be limited in his output capacity, so that the opportunity cost of personally performing all the design tasks may be higher than the cost of delegation.

In practice, the sum of these benefits often exceeds the cost of incentivizing and informing the agents, so that delegation of design tasks can provide significant value to an organization.

3.3.4 Concurrency of Design Tasks

An additional consequence of delegation is that multiple design tasks can be performed concurrently. From an artifact-focused perspective, concurrency has no impact on the end-result, but from a process-focused perspective, designers are faced again with a tradeoff. On the one hand, if tasks are performed concurrently, information obtained in one design task is not available to the other concurrent design tasks. This can lead to inefficiencies, for instance, because some tasks are performed unnecessarily (Lee and Paredis, 2010), resulting in additional time and costs.

On the other hand, concurrency can provide significant benefits. Because artifact value tends to decrease with time (e.g., due to competition), it is often beneficial to get an artifact to market as soon as possible (Pawar et al., 1994). By performing design tasks concurrently, it is possible to reduce the duration of the design process, resulting in an increase in value. Assuming the expected gains from a shortened design cycle exceed the costs associated with the possible performance of unnecessary work, concurrency is valuable.

3.3.5 Diversity in Teams

In addition to involving multiple designers by delegating separate design tasks, even individual design tasks are often performed by teams. Given the additional cost of labor, it is not directly clear how this practice can be justified from an economic, value-driven perspective. However, a justification can be provided by first considering a psychological and social perspective.

Design involves ideation: ideation of concepts, ideation of systemic consequences, ideation of analysis approaches, etc. These tasks rely on creativity and analogical reasoning. By including individuals with different backgrounds, a wider variety of analogies may be tapped into, resulting ultimately in more valuable concepts. In the literature, diverse groups have been found to be better at complex problem solving tasks (Watson et al., 1993) and more likely to identify novel and valuable concepts (Hoffman and Maier, 1961). Thus, the value of an artifact may be improved by using diverse groups that are capable of ideating more valuable concepts, identifying the systemic consequences of these design concepts more comprehensively, and therefore obtaining better predictions of the value of the design alternatives.

Ultimately, even these psychological and sociological arguments need to be framed in the context of the ultimate goal of design, namely, to maximize value. Provided that the benefits of team diversity arising from an improved artifact and streamlined process exceed the losses due to duplication of effort and the additional cost of communication, it is valuable to use diverse design teams for some of the design tasks.

3.4 Implications for a Method for Developing Effective Value Models

The previous sections have presented a conceptual model of value in design, and then evaluated several common characteristics of design processes. In this section, the focus is more specifically directed towards methods for developing a value model. This investigation yields a concise set characteristics of effective methods for value model specification, which are then utilized to guide the development of the for Developing Value Models that will be introduced in Chapter 4.

3.4.1 Applicability of a Method

The range of applicability of any engineering design tool will depend on the assumptions implicit within. As additional assumptions are imposed, the tool becomes more specialized, and the range diminishes. Similarly, frameworks for applying value-driven approaches to design have made significant assumptions about the structure of the beliefs and preferences of designers in order to specifically address a given context and therefore are only directly applicable within the context. Even for small deviations beyond the original context, the methods may provide little aid or guidance. From a process-focused perspective, a method that only provides guidance in limited contexts is unlikely to be optimal if the designer wishes to consider system alternatives or decisions that do not fit entirely within these contexts. As such, it is desirable that a method be generally applicable to a wider range of design decision contexts.

3.4.2 Precision of a Method

When predicting the value to be derived from an artifact, it is desirable that a method be capable of making precise predictions. This is not to say that a value model should be able to predict value with perfect accuracy; as exposed in §3.3.2, it is often valuable for analysis accuracy to increase gradually. Rather, precision relates to the consistency with which a value prediction is made. If a method is used to determine a prediction of value, then one would expect that if the process were repeated, the same or similar value prediction would result. If the value model cannot make precise, repeatable predictions about value, then uncertainty in the predictive power of the method arises as another source of uncertainty, and becomes intertwined into the already uncertain prediction of value.

3.4.3 Cost of a Method

Considering that the cost of a design process is in general relevant, it is logical that the cost of developing a value model is also important. Therefore, it is unlikely that developing a completely descriptive value model that captures every insignificant aspect of a design opportunity will be optimal. In doing so, it is likely that the approach would require so much effort to develop that its cost would exceed the benefit of its use. Examples in the literature of such processes include (Collopy and Hollingsworth, 2011; Hazelrigg, 1998) among a multitude of others. In §3.3.1 and §3.3.2, it is argued that a process that emphasizes gradual refinement provides a valuable approach to addressing the tradeoff between accuracy and cost. Similarly, an effective method for developing value models should enable the iterative refinement of the value model, until it is sufficiently developed that continued refinement would add less benefit than cost. For gradual refinement to be an explicit feature, the method would need to be capable of not only guiding the identification of potential refinements, but also provide a stopping criterion.

Table 3.1. Desired Characteristics of Effective Method for Developing Value Models

Axiom	Explanation
Result	Method results in an effective value model
Repeatable	Method yields same value model if repeated
Refinement	Method allows a value model to be improved as new information is obtained
Guidance	Method aids users to identify omitted aspects and relationships
Stopping Criterion	Method provides a basis for determining when the refinement is complete.

Based on the consideration of the aspects identified in the previous sections, a concise set of characteristics of an effective method for developing value models is proposed in Table 3.1. In the next Chapter, the characteristics motivate the development of a Systematic Method for Developing Value Models.

3.5 Summary

In this chapter, I have presented a conceptual framework to guide the value-driven design of engineered systems. Starting from the premise that design is a purposeful activity, and that designers should act rationally, in accordance with their preferences. Mathematically this can be modeled as value maximization. Value-maximization is applied from three different perspectives: artifact-, process- and organization-focused. The resulting model of design allows us to explain and justify five common characteristics of design processes, none of which could have been explained based on the purely artifact-focused perspective considered in the value-driven design literature previously.

Maybe the most important conclusion derived in this section is that in terms of value maximization, design is a self-referential optimization problem. From the perspective of value-of-information theory and to break the infinite self-referential recursion, it is necessary to resort to heuristics. For instance, rather than rigorously optimizing a global optimization problem over the space of all possible design actions, heuristics may provide, at low cost, reasonable guidance as to which design actions to perform. From a process perspective, the use of heuristics is almost certainly more valuable than rigorous optimization, which is likely to require more resources than can be justified based on its benefits relative to heuristics.

However, this poses an interesting problem for design and systems engineering research. Given that heuristics are only applicable in the context for which they were derived, they will need to be updated as the context changes. Since the design context changes at an increasingly rapid rate, the design and systems engineering research community will also need to update the heuristics increasingly often. These heuristics span a broad range:

- *Synthesis*—Which architectural patterns are appropriate in the current economic, environmental, socio-political, and technological context?
- *Analysis*—Which mathematical formalism, level of abstraction, and accuracy are appropriate for analyzing the system alternatives, taking into account the current state of the art in numerical algorithms and computing infrastructure?
- *Process*—How much effort should be allocated to concept ideation? Or how much emphasis should be placed on risk management, given the nature of the system being developed?

- *Organization*—Which structure? Hierarchical, matrix, or maybe a decentralized structure based in part on crowd-sourcing?

Given that these heuristics will need to be updated frequently, it is important that the research community develop a methodology for determining which heuristics are most appropriate in a particular context. I argue that normative decision theory should be at the foundation for such a methodology, as is illustrated in the conceptual framework introduced in this work. But in addition, the quality of a heuristic will also need to be assessed based on non-normative theories. For instance, whether a synthesis heuristic is suitable may depend in part on how well aligned the heuristic is with human psychology and with the social and cultural conventions of the designers applying it. Ultimately, the criterion for assessing heuristics should reflect the ultimate objective of design, namely, to maximize value.

CHAPTER 4

SYSTEMATIC VALUE MODEL DEVELOPMENT

4.1 Introduction

In the previous chapter, several characteristics that would be desirable for an effective model specification method were elicited. It was shown that in order to be effective, the method should make an efficient use of resources for the development of the value model, and a set of characteristics were offered describing additional desired properties of such a method. In this chapter, a method is defined and then compared against these criteria and characteristics. To aid in this comparison, current standards in the fields of Systems Engineering, Software Engineering, Engineering Design, and Business Development Models are first reviewed. Then, the Systematic Method for Developing Value Models (SMDVM) is presented and compared to these standards. Lastly, the method's effectiveness (including efficiency) is critically evaluated against the status quo via a cognitive test case involving 35 graduate students taking a course on Modeling and Simulation in Engineering Design.

4.2 Systematic Approaches in the Literature

Outside the value-driven community, researchers and practitioners have long realized the benefits of a systematic approach for evaluating and refining concepts. This section briefly reviews some of the standard approaches in the domains of Systems Engineering, Software Engineering, and Engineering Design. Common between each of these domains is an emphasis on requirements in the design process.

Requirements are constraints that are imposed upon the artifact. Requirements are generally elicited in a process that seeks to identify targets for performance, cost, or other attributes such that if the targets are met, the artifact is likely to be successful. The motivation for requirements is then that one can easily identify minimally acceptable levels of performance and then design an artifact to meet these requirements. Any such artifact that is capable of meeting these requirements is then "acceptable," and are approximately equally preferable. In each domain, the scale and scope of the decision contexts are different, such that different approaches are necessary to guide the requirements elicitation processes in order to result in reasonable requirements.

4.2.1 Systems Engineering

According to the INCOSE handbook, the purpose of requirements definition is to "define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment" (INCOSE, 2011). The process activities identified in the INCOSE Handbook include (INCOSE, 2011):

- *Elicit Stakeholder Requirements* - First identify stakeholders that have an interest in the system throughout its lifecycle, and then determine what the system must accomplish and how well.
- *Define Stakeholder Requirements* - Identify which constraints are imposed by legacy or preceding systems and build scenarios to identify how the product would be used in order to identify requirements that might be otherwise overlooked. Then establish critical levels to meet for each requirement for system success.

♦ *Analyze and Maintain Stakeholder Requirements* - Ensure that the requirements are clear and consistent, and negotiate changes with the stakeholders as necessary. Then document how requirements map to stakeholder objectives.

The above process activities can be expanded to provide additional detailed guidance regarding the implementation, but the core aspects of the process are captured. As opposed to the SMDVM, which is introduced later in this chapter, the INCOSE process focuses on identifying, defining, and analyzing requirements. By focusing on requirements instead of attempting to model value, the INCOSE model accepts the explicit assumption that the systems engineer will be capable not only of identifying the important aspects of concern to the many potential stakeholders, but that the systems engineer will also be able to set proper targets for the design of the system such that the stakeholders will all be satisfied. A further, implicit assumption then neglects the possibilities to make tradeoffs between the properties and attributes constrained by the requirements process. In cases where making tradeoffs between such attributes is sufficiently difficult, or entails significant cost in terms of eliciting the willingness-to-pay for attributes, then such approach may be reasonable. However, the author argues that the decision makers should be enabled to make informed decisions regarding the implicit assumptions they are making.

4.2.2 Software Engineering

In (Bruegge and Dutoit, 2004) Bruegge and Dutoit present the following process of identifying requirements for a software project.

♦ *Identify Actors* - Identify the different types of Users that the system will support.

- *Identify Scenarios* - Observe Users and develop detailed scenarios that describe basic functionality of the system. These scenarios describe concrete examples of how Users may use the system.
- *Identify Use Cases* - Identify the use cases that completely represent the functionality of the system.
- *Refine Use Cases* - Further develop the use cases to declare how the system should react to different states, including errors.
- *Identify Relationships Among Use Cases* - Use cases are consolidated to remove common functionality, ensuring that requirements specifications remain consistent.
- *Identify Non-functional Requirements* - Developers and Users and Clients agree on requirements on the aspects related to how the Users interact with the system, such as performance or documentation.

In software engineering, there are fewer classes of stakeholders that typically need to be addressed, as well as fewer types of interactions that need to be considered. As such, the stage focused on identifying stakeholders can be of limited focus.

Further, in order for the software to function, a complete specification of the system must be made. This is possible for software systems because software is essentially a set of implemented logical statements and therefore its behavior can be predicted very precisely. Hardware, the other hand, resides in the physical domain, which can never be completely specified. As a result, hardware can sometimes function in unexpected manners, while the behavior of software can be more completely controlled.

Therefore, uncertainty needs only to be addressed with respect to the manners in which users and other actors will interact with the software (Herzig et al., 2011). Thus, a successful product can be guaranteed so long all of the use cases are properly identified and addressed.

4.2.3 Engineering Design

Pahl and Beitz describe an iterative approach in which requirements are gradually refined, updated, and adapted as new information is gained during the continued specification of the product (Pahl and Beitz, 1996). Requirements are either identified as *Demands* or *Wishes*, differentiating those requirements that demark a product as "acceptable" from those that describe desirable features. *Demands* are then used as a filter to eliminate poorly performing alternatives, while *Wishes* are addressed during an *Evaluation* of the passing alternatives.

The authors argue that *Wishes* should reflect technical and economic characteristics of the design, and acknowledge that each characteristic may vary in importance. However, the authors note that "During the conceptual phase...weighting is generally not advisable" because information may be easily available. However, they then concede that weighting may be necessary for important attributes. Rather than assigning values and aggregating the multiple attributes into a single attribute via natural comparisons or willingness-to-pay, the authors promote a normalized scoring of performance against the attributes which are then themselves weighted. In effect, the authors advocate a linear approximation of a value model, as introduced later in this chapter. However, the linear weights of the attributes, as well as the scoring against the attributes are both normalized, meaning that natural comparisons cannot be utilized to estimate values for these weights and scores, and experience must be relied upon to produce "reasonable" results. Uncertainty is also addressed in a limited manner, and focuses on information 'gaps' or 'weak spots' rather than probabilistic expressions of belief. Even if these 'weak spots' are addressed probabilistically, preferences for risk cannot be taken into account rationally when the scales have been normalized, weighted, and aggregated into non-natural attributes. Therefore, while the *Wishes* provide an advantage in expressibility of preference over simple statements of requirements, they still fail to provide rational bases for decision making. As a result, they may provide somewhat reasonable guidance only if the preferences over the *Wishes* can be reasonably approximated as linear, and the optimum is robust to selection of attribute weighting.

4.2.4 Business Models and Business Development Processes

The central idea behind business development processes (Hofstrand, 2006), business models (Magretta, 2002), and Frameworks of the Business (Annacchino, 2007) is to model and grow the "long-term value for an organization from customers, markets, and relationships" (Pollack, 2012). In general, this long-term value is defined economically and is gained through "Relationships" with the market. In this regard, business development processes are quite similar to the method described in the next section. Both approaches seek to identify the relevant stakeholders, their concerns and desires, and identify how the decision-maker can interact with the market to provide a product or service and earn portion of the value surplus in doing so. The literature on Business models is rife with successful business model strategies, including the franchise model (Baden-Fuller and Morgan, 2010), the razor and blade model (Osterwalder et al., 2011), focusing on efficient distribution (Baden-Fuller and Morgan, 2010), direct distribution (Morris et al., 2005), and e-business (Bouwman and MacInnes, 2006). The key difference between business development processes, business models, Frameworks of the Business and that of a value-driven approach to design is then the focus of the "artifact" being evaluated.

Magretta's investigation of Business Models (Magretta, 2002) focuses exclusively on the translation of strategic level objectives into operational level processes concerning the distribution of the product to the market.

In (Daas et al., 2013), the authors focus on evaluating "core services" between alternative business models. The Business Model design Module "core service" includes the development of market segmentation and then the specification of pricing and performance goals, which can be expressed as requirements. Again the focus is on the identification of targets for designers to meet, and no guidance is provided on how value could be enhanced if these attribute thresholds could be exceeded.

Annachino' Framework of the Business (Annacchino, 2007) offers a 'system for objective evaluation' of business opportunities. Again, the approach is not directly applied to the design of products or services, but rather is focused on identifying potential market segments for the business to focus upon. However, much of Annacchino's approach could be applied toward the design of products, with a focus on attributes and criteria. Annachino's treatment of criteria is most similar to that of Pahl and Beitz (Pahl and Beitz, 1996) in the previous section, where criteria are weighted by "importance" and then normalized scores against each attribute are utilized to develop a linear approximation of preference. The approach suffers from the same limitations as those identified in the previous section, namely that the linear weighting of criteria will only be accurate reflections of preference within small design ranges, and that the use of normalized dimensions for scoring removes the possibility of making natural comparisons to elicit true preference.

Thus, the literature provides ample analysis of how businesses can be structured to align operational-level objectives regarding the manufacturing, distribution, and sale of products and services with strategic-level goals of maximizing value, However, the scope of the value analysis in practice does not extend to the actual design of the product or services that enable the business to operate and generate value. Rather, "acceptable" target levels for performance, cost, and other metrics are defined, and these targets are then converted into requirements to be delivered to the design team. Rather than utilize such requirements, this research argues that by extending this value-driven context to the product design process, engineers and designers will be better able to optimize against the many the tradeoffs present. However, in order to enable the value-driven design of these products or services, the designers must first be capable of modeling the value to be derived from them. The next section presents a method that describes a systematic approach to developing value models using gradual refinement, such that it can be applied to a wide variety of design decision context in a cost-effective manner.

4.3 A Systematic Method for Developing Value Models (SMDVM)

An outline of the stages and steps of the SMDVM is shown in Figure 4.1. The method is broken down into three major stages, each of which is discussed in greater detail in the following sections. It is acknowledged that other potential decompositions are possible, but this particular decomposition because it enables each task to be clearly

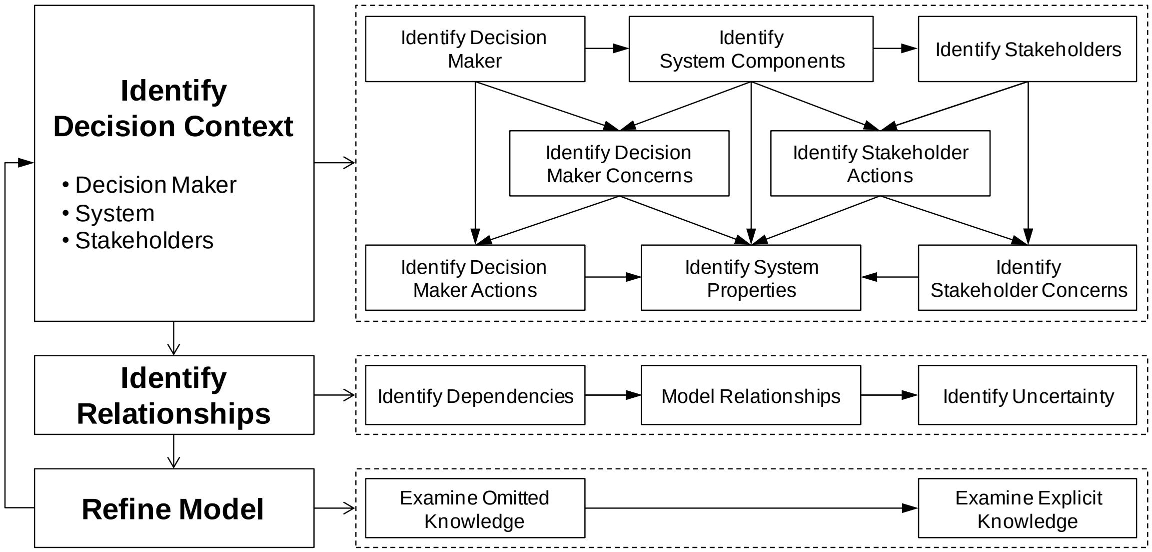

Figure 4.1. Overview of a Systematic Method for Developing Value Models

ordered by the amount of knowledge required. Further explanation and justification for each sub-step is offered in the following sections.

4.3.1 Terminology

In this section, I briefly describe the terminology used throughout the remainder of this section.

♦ *Decision Maker* - An individual entity that possesses the authority to make a decision about the system context, and for whom the value of the resulting system context is being predicted.

♦ *Stakeholder* - Any individual or group of individuals that possess the authority to impact the system, or any of the concerns of the Decision Maker or other Stakeholders.

- *Concern* - Any aspect of the system context that impacts the value of the particular Decision Maker or Stakeholder. Concerns may arise due to affordances granted by liabilities imposed by the system context.
- *Action* - Any decision made by the Decision Maker or Stakeholders that impacts the system context.
- *Property* - Any attribute or characteristic of the system or environment.

4.3.2 Stage 1 – Identify Decision Context

The first stage concerns the identification of the decision maker's objective and potential actions available, as well as the system context and stakeholders. This is done in a series of steps. First, the decision maker is identified unambiguously as the entity that will make the decision, and the fundamental objective is identified. In an enterprise context, this fundamental objective is taken as the net present value of profit. If the system has already been partially specified, it is important to acknowledge and account for these prior decisions. Doing so will also help to identify any potentially relevant stakeholders, as well as the actions they could take that impact either the system or the decision maker's driver of utility. Then, the more focused concerns of the decision maker and stakeholder are identified as elements that are influenced by the system or its environment. The last step is to identify the properties of the system that either affect or are affected by the previously identified concerns and actions.

4.3.2.1 Identify Decision Maker

The purpose for this task is to unambiguously define the decision maker being considered.

1.1 For the decision context being considered, identify the single entity who possesses the necessary decision making authority as the Decision Maker.

If the decision context requires that multiple entities act, select a single entity to analyze as the Decision Maker, first. Then repeat all steps for each other entity separately.

A normative theory for decision making requires that decision authority reside within a single person. Likewise, in the case of multiple decision makers game theory requires that payouts be calculated for each stakeholder for each set of possible actions.

4.3.2.2 Identify Decision Maker Fundamental Objective

The purpose for this task is to unambiguously define the fundamental objective of the decision maker.

1.2 For the Decision Maker, identify the Fundamental Objective by selecting from Table 4.1

Or, begin with an operational-level objective for the system, and continue to ask "Why is that important?" When no further objectives can be identified, the last objective specified is the Fundamental Objective.

It has been shown in Chapter 2 that a single dimensional utility function must exist in order to support a normative theory of decision making. Within the context of a corporation or business, several researchers have argued that the net present value of profit should be this fundamental objective (Brathwaite and Saleh, 2009; Collopy, 1996; Hazelrigg, 1998). For other entities performing design decisions, or that may be stakeholders during the design process, profit may not serve as a suitable fundamental objective. For example, scientific organizations such as the Jet Propulsion Laboratory focus primarily on the scientific value that can be derived from potential exploration projects, while government organizations instead focus on the net benefit to society.

Table 4.1. Example Fundamental Objectives Organized by Type of Entity

Entity	**Fundamental Objective**
Business / For-Profit Venture	Net Present Value of Profit
Government / Non-Profit Organization	Net Present Value of Benefit to Society
Scientific Organization	Net Present Value of Scientific Value

4.3.2.3 Identify System Components

The purpose for this task is to define the current structure of the system under consideration, and serves to further define the decision context.

1.3 Identify the system being evaluated.

Identify any subsystems and components of the system that have already been specified in a structural decomposition.

Identify any functionalities of the system that have already been specified in a functional decomposition.

Decisions are not made in a vacuum, but rather within a decision context that must acknowledge previous decisions and the current state of knowledge. By explicitly identifying the system components and subsystems, the modeler begins to model this context. A structural decomposition identifies the subsystems and components that comprise a system. Early in the design process, artifacts will only be abstractly specified, and so components with well-defined interfaces may not yet be well defined. However, later in the design stage, the components implementing a particular function, or set of functions, will be more fully specified. Knowledge about the particular components that define the system will enable the decision maker to more accurately identify attributes of concern, as well as system properties that drive attributes of concern. Also, depending on the nature of the components decided upon, certain stakeholders may become apparent. For example, certain components may require regulatory approval to be manufactured, installed, sold, or disposed of and therefore these regulatory bodies can be identified. Similarly, a functional decomposition may enable the modeler to more easily identify the Stakeholders that the functions are meant to support. Further, the functions identified may also aid in the identification of Stakeholder Concerns by identifying some of the affordances and liabilities imposed by the system.

In the approaches reviewed in §4.2, Stakeholder identification precedes requirements elicitation, which then motivates the functional decomposition in order to identify a set of sub functions that can then be mapped to structures. The approach followed here reverses this process, due to the difference in focus of the processes. The approaches of §4.2 were focused on refining the concept specification to meet Stakeholder requirements, and so Stakeholder identification must logically precede requirements elicitation which must precede concept specification. However, the focus of the SMDVM is not to impose specifications on a concept, but rather to predict the value of a given concept. Therefore, because it is assumed that a concept is already specified at some level, these steps are reversed.

4.3.2.4 Identify Stakeholders

The purpose for this task is to identify other entities that may or may not have an impact on the decision maker's Fundamental Objective.

1.4 Identify other Stakeholders in the decision making context by determining whether any of the entities in Table 4.2 are relevant.

Or, ask "Does another entity have the ability to directly impact the system or another Stakeholder?"

Then complete steps 1.5 and 1.6 for each such identified Stakeholder.

In order to capture how the other Stakeholders may impact the Decision Maker's utility, it is necessary to first identify the potential Stakeholders. Freeman defines a Stakeholder as "any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 1984). However, as noted by Mitchell et. al. in (Mitchell et al., 1997), many alternate definitions for the term have been offered. They add to the set of definitions by posing three properties of Stakeholders: Power, Legitimacy, and Urgency. They loosely define Power as the capability of an entity to perform actions that impact the decision maker, and Legitimacy as an indication that an entity is affected by the actions of the decision maker. In Mitchell et. al.'s analysis (Mitchell et al., 1997), Urgency deals with the order in which Stakeholder claims should be addressed[4]. They then recognize that "*An entity may [...] have a legitimate claim on the firm, but unless it has either power to enforce its will in the relationship [...] it will not achieve salience for the firm's managers.*" Considering their argument, I agree that only Stakeholders with Power to impact the Decision Maker's utility should be modeled. However, I acknowledge that Power to impact may be directed through another entity,

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[4] Based upon the consideration of their three attributes, Mitchell et. al. derive an ordering by which the Stakeholder concerns should be addressed. As we are primarily concerned with identifying Stakeholders, and will defer selection of optimal action strategies, the concept of Urgency will not be discussed further.

Table 4.2. Common Types of Stakeholders

	Design	**Production**	**Sales and Distribution**	**Operation**	**End-of-Life**
May Impact System	Regulators Developers	Regulators Suppliers	Regulators Distributors	Regulators Maintainers Operators	Regulators Disposers
May Impact Stakeholders	Environment Competitors	Environment	Environment Users Financers Acquirers Competitors Complementers	Environment Users	Environment

such that the Stakeholder may only be able to impact the Decision Maker's utility indirectly.

4.3.2.5 Identify Stakeholder Actions

The purpose for this task is to define the potential actions that a stakeholder may perform, that could have a direct or indirect impact on the decision maker's Fundamental Objective.

1.5 Identify the actions that the Stakeholder may take by asking "How can the Stakeholder directly impact the system or another Stakeholder's Concern?"

As discussed in §4.3.2.4, it is necessary to capture how other Stakeholders may impact the Decision Maker's utility, such that it can be predicted. Because Stakeholders may impact the Decision Maker's utility indirectly, it is necessary to also identify how Stakeholders could impact other Stakeholders. Actions can occur at the present time, or may address a Stakeholder's ability to perform follow up actions once more information is obtained. Because the Stakeholder will have more information as time progresses, dependencies and choice models developed in the second stage are likely to utilize different mappings, and also different uncertainties.

4.3.2.6 Identify Stakeholder Concerns

The purpose for this task is to define the affordances and/or liabilities that may be granted to/imposed upon the stakeholder may perform.

1.6	**Identify the Concerns of the Stakeholder by asking " At the time the Stakeholder's Action may be taken, what affordances or liabilities will the Stakeholder perceive to be granted or imposed by the system or other Stakeholders?**

In a normative model, all entities will seek to maximize their own utility, and so it is necessary to identify the Concerns of each Stakeholder. This will enable the eventual solution of the value model by expressing the Decision Maker's beliefs about the other Stakeholders' preferences.

4.3.2.7 Identify Decision Maker Concerns

The purpose for this task is to decompose the Decision Maker's Fundamental Objective in order to identify the Concerns of the Decision Maker.

1.7	**Identify the Concerns of the Decision Maker by asking "What affordances or liabilities might the system or other Stakeholders grant to or impose upon the decision maker?"** **Or, for a given Concern, decompose it into other Concerns by asking "How could that be achieved?"**

The relationship between the Fundamental Objective and other value model elements is not likely to be direct, but rather through indirect means. As such, elicitation questions in the form of Clemen (Clemen, 1996) are likely to be helpful in decomposing these in a process similar to backward chaining.

4.3.2.8 Identify Decision Maker Actions

The purpose for this task is to define the potential actions that the decision maker may perform, that could have a direct or indirect impact on the decision maker's Fundamental Objective.

1.8 Identify the Actions of the Decision Maker by asking "Does the DM have the ability to directly impact the system, a Decision Maker's Concern, or a Stakeholder Concern?"

The Decision Maker's Actions relate to the usage of the value model. Eventually, the value model will be used to analyze which course of action the Decision Maker should select. Therefore, it is necessary that the value model be capable of relating these Actions to their impact on the Fundamental Objective. This impact can occur directly or indirectly, via the system or Stakeholders.

4.3.2.9 Identify System Properties

The purpose for this task is to identify the aspects of the system and / or environment that may impact the concerns of the stakeholders or the decision maker, or are directly impacted by the actions of the stakeholders or the decision maker.

1.8 Identify the System Properties by asking "Which properties of the system directly affect the identified Stakeholder or Decision Maker Concerns?"

Also, "Which properties of the system are directly impacted by the identified Stakeholder or Decision Maker Actions?"

Systems can be described using an infinite number of properties (Thompson and Paredis, 2010), many which will not be relevant for the analysis of the value of the system. Given that the goal of the method is to develop a effective estimate of the value of the system in an efficient manner, it is necessary to exclude many of these properties. Therefore, this step of the method focuses upon elements that are part of direct

Actions	→	**System, Environment, Concerns**	+	**Uncertainty**
System, Environment	→	**System, Environment, Concerns**	+	**Uncertainty**
Stakeholder Concerns	→	**Stakeholder Concerns, Stakeholder Actions**	+	**Uncertainty**
Decision Maker Concerns	→	**Decision Maker Concerns**		

Figure 4.2. Meaningful Types of Relationships between Value Model Elements

relationships to actions or concerns. In §4.3.3.3, remaining aspects are abstracted as sources of uncertainty, and in §4.3.4.2, the uncertainty is evaluated to determine whether more in depth modeling is proper.

4.3.3 Stage 2 – Model Relationships

The second stage concerns the modeling of relationships between the decision elements identified in the first stage. Four major types of relationships are meaningful to include, as shown in Figure 4.2. The first two types can be viewed as a cause-effect relationship and reflect the modeler's beliefs about the likelihood of an outcome's occurrence. The other types of relationships concern the definition of how concerns aggregate to describe an individual's preferences, and therefore actions. The first three relationships reflect the decision maker's beliefs about external relationships and therefore should include relevant uncertainty. However, it would violate the completeness axiom for the decision maker to express uncertainty in his preference for outcomes. As such, no uncertainty should be included when aggregating the decision maker's attributes of concern.

4.3.3.1 Identify Dependencies

The purpose for this task is to identify which model elements identified in Stage 1 depend on the value of which other value model elements.

2.1.1 Identify the dependencies between decision model elements and each Decision Maker Concern by asking:

Which other Concerns of the DM define the Concern?

Which Stakeholder Actions directly impact the Concern?

Which System Properties directly impact the Concern?

Which Environmental Properties directly impact the Concern?

Which DM Actions directly impact the Concern?

2.1.2 Identify the dependencies between decision model elements and each System / Environmental Property by asking:

Which design alternatives of the DM impact the value of the System Property?

Which Actions by the other Stakeholders impact the value of the System Property?

Which Environmental Properties impact the value of the System Property?

Which System Properties directly impact the value of the System Property?

2.1.3 Identify the dependencies between decision model elements and each Stakeholder Concern by asking:

Which other Concerns of the Stakeholder define the Concern?

Which System Properties directly impact the Concern?

Which Environmental Properties directly impact the Concern?

Which Actions by the DM impact the Concern?

Which Actions by Stakeholders directly impact the Concern?

2.1.3 Identify the dependencies between decision model elements and each Stakeholder Action by asking:

Which of the Stakeholder's Concerns will drive the Stakeholder's decision making?

Due to the diversity of the types of elements identified in the first stage, as well as the multitude of potential dependencies, the process outlined above focuses on identifying the dependencies for each element, one at a time. A comparison to the process can be made to that of an Expert System may use Backwards Chaining to understand the possible influences or causes of some piece of information(Castillo, 1997). Backwards Chaining works on the principle that a query can be proven or disproven by backwards investigation of whether sufficient supporting facts exist (Castillo, 1997). Essentially, given a goal (the decision element), antecedents are identified (other decision elements), and it is then determined whether the antecedent (a directed dependency between the elements) exists.

After this stage, the decision elements and dependencies form a sort of Influence Diagram. An Influence Diagram is a directed, acyclic graph in which the nodes are the decision elements, with the edges representing dependencies or the temporal availability of knowledge (Clemen, 1996). Using Clemen's notation, Influence diagrams contain three types of elements (Choices, Outcomes, and Consequences) and two types of influences (Relevance and Sequence) (Clemen, 1996). Comparing the terminology in this chapter to

Clemen's terminology, only the Decision Maker's Actions would be *Choice*, Uncertainty is equivalent to *Outcomes*, and all other decision elements are *Outcomes*.

This work does not differentiate between *Relevant* and *Sequential Dependencies* as operationalization of either of Clemen's types of dependencies requires some level of both attributes. In order for it to be identified that one Consequence or Property has an influence on another, there must exist some relevance between the two. Further, lest the Arrow of Time be violated, there must also be a Sequential (or even simultaneous) aspect to the relevance.

Note also that in Clemen's decomposition of decision elements, specification of which elements are uncertain is made at the identification stage. This work defers this designation until after the relationships are specified in the next section. The justification for this deferment is that Influence Diagrams themselves do not include a manner for developing the relation between the decision elements, but rather focus on the identification of which relations exist. Unless the relationship between a set of decision elements is modeled, it is impossible to extract which aspects of the relationship will be uncertain. As such, specification of properties as uncertain, as well as quantification of that uncertainty, is deferred until after the relationships are mathematically defined following the procedure in the next section.

4.3.3.2 Model Relationships

The purpose for this task is to define analytical expressions for the dependencies identified in §4.3.3.1.

2.2 Define a model predicting each decision model element by asking "How does the value of the decision element depend on each of the preceding decision elements?"

Almost always, a given system property can be predicted using a multitude of different models. As noted by Hazelrigg in (Hazelrigg, 1999), models are abstractions of reality, and can be specified as *Iconic*, *Analog*, or *Symbolic*. *Iconic Models* are physical productions of the system being designed, often at reduced scales. *Analog Models* rely on similarities between the system being designed and some other similar type of systems to allow predictions of behavior. *Symbolic Models* represent the physical characteristics of the system being designed using symbols and mathematical equations. Each type of model will require different types of resources to develop, and will also predict at different levels of fidelity. Because Symbolic models typically require the least amount of resources to both develop and execute, this method assumes that the modeler will work primarily with them. However, the approach described will still work for other types of models, if found to be sufficiently accurate that their cost is justified in Stage 3.

If the model is used to predict the value of system or environmental property, then the model will generally be physical or statistical in nature. If the model is being used to predict the decision making of a Stakeholder, then a choice model will be utilized. These choice models need not assume rationality on the part of the Stakeholder, and in some occasions may be more accurate if this is the case. When modeling the value of a Concern (Stakeholder or Decision-Maker) the model should describe a "Willingness-to-pay" for the property. These models may be discrete or continuous, depending on whether the property or action exist in the discrete or continuous domains. Models aggregating concerns, on the other hand, are already in the same units, and should be made using natural aggregations.

4.3.3.3 Identify Uncertainty

The purpose for this task is to identify the sources of uncertainty in the relationship between value model elements.

2.3 Identify uncertain aspects in each relationship by asking "What additional information would the DM need to possess in order to know the value of the element with certainty?"

As acknowledged in Table 2.5, it is necessary to capture the Decision Maker's beliefs about the relationships between decision elements. A key aspect is to include a consideration of the uncertainty in the relationships identified in §4.3.3.2. Failure to acknowledge and quantify uncertainty can lead to overconfidence in the accuracy of the prediction, and lead to neglect of risk. The magnitude of risk can drastically impact which decision alternative is the most desired, and may be the dominant driver of expected utility in some situations.

There is likely to be uncertainty in each of the types of relationships. Influences on system and environment properties tend to be physical or statistical in nature, and so uncertainty in these types of models will arise either due to limitations of physical models or the inherent uncertainty of statistical models. Choice models are likely to be uncertain because one can never truly fully understand the decision making tendencies of other individuals, especially when those individuals may or may not be rational. Lastly, the prediction of the valuation of concerns by Stakeholders are likely to be significantly uncertain. Even if detailed interviews with a Stakeholder were possible, the decision-maker could never completely remove uncertainty in how much a Stakeholder actually values an attribute.

With the uncertainty now included in the value model, the former Influence Diagram now more closely resembles a Bayesian network. Bayesian Networks are directed acyclic graphs that relate information in a probabilistic manner via random variables (Witten and Frank, 2005). In a Bayesian Network, any two nodes that are not connected are conditionally independent, indicating that knowledge of one quantity does not imply knowledge about the other property. This is similar to not declaring a dependency between decision elements. If a connection does exist, then conditional independence does not apply, and a dependency does exist. In the analogy to a Bayesian Network, each consequent decision element's prior distribution is uninformed, such that the posterior distribution following any analysis is the conditional distribution, or the probability distribution predicted by the model of the relationship specified in the last section.

4.3.4 Stage 3 – Refine Model

From a normative perspective, the value of a model (or any information source) is that it helps to make better decisions (Nickerson and Boyd, 1980). As such, a refinement to a value model is only valuable if the expected benefit of the information exceeds the expected costs. The third stage of the SMDVM focuses on identifying potential refinements and abstractions and determining whether they are worth pursuing. Once new elements are identified, the decision maker is directed to return to the first or second stage in order to repeat the process of identifying additional related elements and relationships until the model is complete. The model is defined as complete when the cost of performing additional refinements exceeds the benefits of those steps.

4.3.4.1 Identify Omitted Explicit and Tacit Knowledge

The purpose of this task is to critically investigate the value model in an attempt to convert the value modeler's tacit knowledge about the context into explicit knowledge, and to identify useful knowledge that has been omitted.

3.1	**Attempt to identify knowledge that may be difficult to specify by asking:** **For the given decision element, what other possible states could occur that have not been included?** **Or, Describe a story in which something unexpected has or could happen involving the decision element.**

Tacit Knowledge is by definition difficult (or impossible) to encode or write down (Ambrosini and Bowman, 2001), and so therefore it is naive to believe that any one process will be successful for eliciting any and all pieces of knowledge. The first approach listed is focused primarily on identifying tacit knowledge through directed focus similar to the Self-Q technique originally developed by Bougon (Bougon, 1983), and has been found to be useful because 1) the target of the elicitation is the expert on their own knowledge, and 2) because targets tend to feel less restricted and are more free-flowing with elicitation when they ask the questions themselves. The second approach is based on the concept of a semi-structured interview. It has been shown that 'stories are one of the many forms of implicit communication used in organisational contexts' and that they can serve to transmit tacit knowledge (Martin, 1982). The author acknowledges that many other methods for examining tacit knowledge are discussed in the literature, for example through the usage of Metaphors (Martin, 1982; Ortony, 1975). However, they are not included as part of this method in order to restrict the extent of the method to within reasonable bounds.

4.3.4.2 Examine Explicit Knowledge

The purpose for this task is to identify abstractions made during the modeling process to determine whether it is worthwhile to include them in the value model.

3.2 Examine the current state of the value model and determine whether it is worthwhile to include any refinements by analyzing the expected net value of the potential information.

If the expected value of gaining the information is non-negative, then refine the value model. If the expected value for every such refinement is negative, then the value model is sufficiently complete that the modeler should not continue to refine the model.

Value of Information (VoI) is defined as the difference in value between a decision made with or without the piece of information (Lawrence, 1999). Consider a scenario in which a decision maker must select artifact $a \subseteq A$, for which he predicts that he would receive a value of $\Pi_A(a)$. In the scenario, the decision maker has the opportunity to improve the accuracy of his prediction, such that his new prediction of value for a given decision a is $\Pi'_A(a)$. The cost of developing and then optimizing against the new value model is C_M.

First neglecting uncertainty for illustrative purposes, the value[5] of refining the value model can be determined as in Equation (**4.1**).

$$VoI = \Pi'_A(a_1^*) - \Pi'_A(a_0^*) - C_M \qquad \textbf{(4.1)}$$

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[5] Note that the form of Equations (**4.1**) and (**4.2**) assume risk neutrality on the part of the decision maker. If risk neutrality is not valid, then similar equations hold, but account for the cost of the refinement inside the value function.

where $\Pi_A(a_0^*) = \max_{a \subseteq A} \Pi_A(a)$ and $\Pi'_A(a_1^*) = \max_{a \subseteq A} \Pi'_A(a)$. This directly compares the result of the refinement and optimization (a newly chosen optimal design) against the new prediction of value for the previously optimal design. If the VoI is positive, then the information provided enough information to offset its cost. On the other hand, if the VoI is negative, then the cost associated with performing the refinement was greater than its benefit to the decision maker. Unfortunately, Equation (4.1) can only be used after the refinement has been performed to calculate the value of the model improvement. This is because it is only possible to know a_1^* and $\Pi'_A(a_1^*)$ after the refinement and following optimization have been performed. As a result, VoI is not useful in practice in this form, as it only provides advice on actions already performed.

Rather than VoI, Equation (**4.2)** can be used to calculate the Expected Value of Information (EVoI). Because the EVoI relies on predictions of the value gained through refinement as opposed to knowledge of the actual outcome, it can be used to evaluate potential refinements prior to their actual implementation.

$$EVoI = E[\Pi'_A(a_1^*)] - E[\Pi'_A(a_0^*)] - C_M \qquad (\mathbf{4.2})$$

The determination of EVoI can be performed quantitatively via explicit elicitation of the beliefs of the decision maker about the likelihood of various value model predictions. In such a case, the optimal action for each scenario could then be identified via optimization, essentially resulting in an optimization loop within a probabilistic sampling loop. For each such scenario, the deterministic could then be determined using Equation (**4.1)**.

Alternatively, the EVoI can be determined quantitatively via direct elicitation of the two main terms in Equation (**4.2)**. Such an elicitation focuses less on predicting the potential value models that could result, and more so on the potential for other decision alternatives to become optimal. While the two quantitative approaches may yield different predictions of EVoI, the second approach offers a significantly reduced cost of application. By focusing on belief elicitation of the expected values directly, little to no computational analysis is required. Provided that the modeler is comfortable with the process of belief elicitation[6], the benefit of the significant reduction in cost for analysis cannot be disputed.

4.3.5 Applicability of the Method

The SMDVM can be applied at the conceptual or detailed design stages, in order to evaluate a given alternative. The same process could be followed for any given information state, or for different scopes of decisions to be made. Early in the design phase, the system will not have been thoroughly specified, and so the concerns, actions, and properties identified in the first stage will be more abstract in nature. However, this does not preclude the usefulness of the approach at the conceptual stage. Rather, because the decision elements identified in the first stage will be more abstract, the models developed in the second stage will be correspondingly more abstract. Therefore, while there will be greater uncertainty at this stage, the cost of modeling and simulating the mappings between the elements will be significantly lower. Since a large amount of the

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[6] If the modeler is not comfortable with the process of eliciting beliefs subjectively, then a prescriptively derived method for developing value models not likely to be of use to the modeler, as subjective elicitation of beliefs is required for the normative theory. As such, the author does not believe that this assumption is of significant concern.

resources are allocated based upon decisions made early in the design process, a systematic approach to modeling value may actually provide significant benefits at this stage.

4.4 Cognitive Evaluation of the SMDVM

The remainder of this chapter will focus on evaluating the SMDVM, relative to an approach based upon Hazelrigg's Framework for Value-Driven Design (Hazelrigg, 2012). The evaluation was performed via a pilot study in which 35 graduate students in a course on the role of Modeling and Simulation in Engineering Design.

4.4.1 Pilot Study Participants

Thirty five graduate students in ME6105: Modeling and Simulation in Engineering Design participated in the study. The participants were all either first or second year graduate students in the departments of mechanical engineering, aerospace engineering, electrical engineering, or architecture and had no industrial experience. The participating students were selected for inclusion due to their familiarity with value models and their use throughout the engineering design process. The core focus of ME6105 is the application of a value-driven approach to design, as outlined by Hazelrigg in (Hazelrigg, 2012), which is also the course textbook. By the date of the study, the graduate students had received at least four and a half hours of instruction on normative decision making in design, with one lecture (one and a half hours) devoted specifically to the development of value models in accordance with Hazelrigg's approach. As such, the participants should have been reasonably familiar with the standard approaches to modeling value. However, none of the participants had been exposed to the SMDVM prior to the pilot study. As such the pilot study would examine how users familiar with

Hazelrigg's approach would perform using a more generically applicable method, like the SMDVM, relative to Hazelrigg's approach.

4.4.2 Pilot Study Test Procedure

The study was conducted under review by the Georgia Tech Institutional Review Board (Protocol H13345: Evaluation of a Proposed Method for Specifying Engineering Value Models, PI: Christiaan J.J. Paredis) in September 2013.

The pilot study was proctored under the inspection of a neutral third party, under the context of an in-class assignment. It was expected that by performing the pilot study under such a context, the participants would be properly motivated to perform well, and that additional motivation via compensation would not be required.

Participants were randomly assigned to one of two groups (SMDVM or HAZELRIGG) via a coin toss, and then given a problem statement and value modeling procedure. The problem statement (See §4.4.2.1) was identical for both groups. The HAZELRIGG Group received a value modeling procedure (See §4.4.2.2) derived directly from Hazelrigg's Framework for Engineering Design (Hazelrigg, 2012), while the SMDVM Group received a value modeling procedure (See §4.4.2.3) based upon the proposed SMDVM. Due to time limitations, the study participants were given 10 minutes to read the initial problem statement (approximate length of one page) as well as to familiarize themselves with their procedure. The participants were then given 40 minutes to develop an initial value model.

4.4.2.1 Problem Statement

The same problem statement was given to participants in both groups to analyze within the limits of the pilot study. Solution of the problem statement would require consideration of several aspects of traditional systems engineering, including consideration of technical as well as social factors. The problem statement is included below.

Problem 1. MIMO Hybrid Energy System - (Multiple Input Multiple Output)

It has been noted that a key shortcoming of renewable energy generation technologies such as wind turbines and photovoltaic solar panels is that the sources (wind, solar radiation) tend to fluctuate unpredictably, resulting in rapidly fluctuating generation capabilities. Such fluctuations tend to be difficult to absorb into the power grid, restricting the amount of renewable energy sources that an electrical utility is willing to support.

Traditional Hybrid Energy Systems (HES) seek to resolve this issue by combining the fluctuating renewable energy sources with more stable generating systems, such as nuclear reactors or natural gas turbines, as well as energy storage systems to help level out more rapid fluctuations. It has been proposed that some of the (non-radioactive) steam generated by the nuclear reactor could be diverted to secondary usage when not required to meet grid demand (i.e. when renewable production is high). In one proposed system, this secondary usage involves the incorporation of a chemical plant complex, which would produce chemical products such as methanol. This Advanced Hybrid Energy System (AHES) could offer a new potential revenue source for the power generation company, but also introduces significant costs associated with the development and operation of the facility**.**

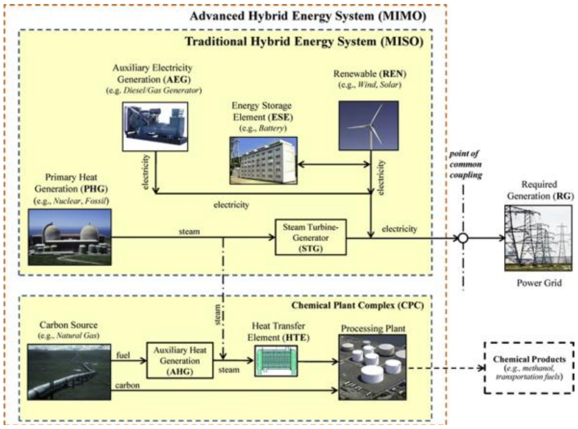

Figure 4.3. Architectural Topology of the Considered Advanced HES.
(credit Humberto Garcia, Idaho National Labs)

Your task is to develop a value model that can be used to evaluate the proposed AHES for an electrical utility company that is considering constructing a new facility in Arizona. In the next few pages, a process for developing a value model is described. Please review the process completely to ensure you understand the complete process before beginning. Once you begin, you will have 40 minutes to develop the initial value model as described in the process.

4.4.2.2 HAZELRIGG Group Procedure

The HAZELRIGG group (18 participants) received a value modeling procedure derived from Hazelrigg's Framework for Engineering Design (Hazelrigg, 2012), included below.

Step 1: Design Context
Identify the Decision Maker (DM) for the decision being considered. Identify the fundamental objective for the DM as Profit and write it in appropriate box in the attached form.

Step 2: Revenue
Identify Revenue from products as an influence of Profit. Label this on the attached form, and then to show relation between the elements, draw an arrow from Revenue to Profit.

Step 3: Demand and Price
Identify Demand for products and the Price at which they are sold as the influences of Revenue. Label these on the attached form, and then to show the relation between the elements, draw an arrow from Demand to Revenue, from Price to Revenue, and from Price to Demand.

Step 4: Performance Attributes
Identify which Performance Attributes influence the Demand for the product. Label each of these on the attached form, and then to show the relation between the elements, draw an arrow from each Performance Attribute to Demand.

Step 5: Cost

Identify Total Cost as an influence of Profit. Label this on the attached form, and then to show relation between the elements, draw an arrow from Total Cost to Profit.
Identify which Types of Costs influence the Total Cost associated with the product. Label each of these on the attached form, and then to show the relation between the elements, draw an arrow from each Type of Cost to Total Cost.

Step 6: Detailed Design

Identify the Detailed Design Alternatives that describe the system and influence either the Performance Attributes or Types of Cost. Label each of these on the attached form, and then to show the relation between the elements, draw an arrow from each Detailed Design Alternative to the associated Types of Cost and Performance Attributes.

Step7: Uncertainty
Identify the Exogenous Variables that result in uncertainty about the values of the Performance Attributes, Demand, and Types of Costs. Label each of these on the attached form, and then to show the relation between the elements, draw an arrow from each

Detailed Design Alternative to the associated Performance Attributes, Demand, and Types of Cost.

4.4.2.3 SMDVM Group Procedure

The SMDVM Group (17 participants) received a value modeling procedure derived from the proposed SMDVM, which is included below.

Phase 1. Identify the Decision Context

1. Identify the Decision Maker (DM) for the decision being considered. If multiple Stakeholders must act, select one Stakeholder to analyze first. Identify the fundamental objective for the DM by examining Table 4.3 below and then write it in appropriate box in the attached form.

Table 4.3. Example Fundamental Objectives

Type of Entity	Business	Government / Non-Profit	Scientific Organization
Fundamental Objective	Profit	Benefit to Society	Scientific Value

2. Identify the potential system being evaluated. Decompose the system into the currently specified subsystems and components and label them in the appropriate boxes in the attached form.

3. Identify the other Stakeholders by asking "*Might another entity have the ability to directly impact the system or another Stakeholder's Concern*?" and by using Table 4.4below and then label them in the appropriate boxes in the attached form.

Table 4.4. Common Types of Stakeholders

		Design	**Production**	**Sales and Distribution**	**Operation**	**End-of-Life**
Stakeholders	**May Impact System**	Regulators Developers	Regulators Suppliers	Regulators Distributors	Regulators Maintainers Operators	Regulators Disposers
	May Impact Stakeholders	Environment Competitors	Environment	Environment Users Financers Acquirers Competitors Complementers	Environment Users	Environment

In the attached form, write the potential Stakeholder's Actions (SA) in the columns corresponding to the Life Cycle Phases in which the Stakeholder may take the Action.

Determine the relevant Stakeholder Concerns (SC) by asking "At the time the action may be taken, what affordances / liabilities will the Stakeholder perceive to be granted / imposed by the system or other Stakeholders?" In the attached form, write these Concerns in the columns corresponding to the Life Cycle Phases in which the action may be taken by the Stakeholder.

4. Determine the Decision Maker's Concerns (DMC) by asking "*What affordances / liabilities might the system or Stakeholders grant to / impose on the Decision Maker*?" In the attached form, write these Concerns in the columns corresponding to the Life Cycle Phases in which the affordances / liabilities are granted to / imposed on the DM.

Decompose the identified DMCs by asking "*What do you mean by that*?" In the attached form, write these Concerns in the columns corresponding to the Life Cycle Phases in which the affordances / liabilities are granted to / imposed on the DM For the system alternatives under evaluation, identify the defining subsystem and/or component properties that can be directly specified by the DM by asking "*Does the DM have the ability to directly impact the system, a Decision Maker's Concern, or a Stakeholder Concern*?" In the attached form, write the Decision Maker's Actions (DMA) in the columns corresponding to the Life Cycle Phases in which the Actions occur.

5. Identify important System Properties by asking "Which properties of the system directly affect the identified SCs and DMCs?" and then "Which properties of the system are directly impacted by the identified SAs and DMAs?" In the attached form, write the System Properties (SP) in the appropriate box.

Identify important Environmental Properties by asking "*What phenomena / properties that are exogenous to the system may directly affect the identified SCs, DMCs, and SPs?*" In the attached form, write the Environmental Properties (EP) in the appropriate box corresponding to the related element.

Phase 2. Identify Relationships

1. Identify the relationships that define the Decision Maker's Concerns (DMC) by asking the following questions for each DMC.
   A. "Which other Concerns of the DM define the Concern of the DM?" (DMC→DMC)
   B. "Which Stakeholder Actions directly impact the Concern of the DM?" (SA→DMC)
   C. "Which System Properties directly impact the Concern of the DM?" (SP→DMC)
   D. "Which Environmental Properties directly impact the Concern of the DM?" (EP→DMC)
   E. "Which DM Actions directly impact the Concern of the DM?" (DMA→DMC)
   For such elements, draw an arrow from the element towards the DMC.

2. Identify the relationships that define the System / Environmental Properties (SP / EP) by asking the following questions for each SP / EP.

A. "Which design alternatives of the DM impact the value of the System Property?" (DMA→SP)

B. "Which Actions by the other Stakeholders impact the value of the System Property?" (SA→SP)

C. "Which Environmental Properties impact the value of the System Property?" (EP→SP)

D. "Which System Properties directly impact the value of the System Property?" (SP→SP)

E. " Which System Properties directly impact the value of the Environmental Property?" (SP→EP)

For such elements, draw an arrow from the element towards the SP / EP.

3. Identify the relationships that define the Stakeholder Concerns (SC) by asking the following questions for each SC.

A. "Which other Concerns of the Stakeholder define the Concern of the Stakeholder?" (SC→SC)

B. "Which System Properties directly impact the Concern of the Stakeholder?" (SP→SC)

C. "Which Environmental Properties directly impact the Concern of the Stakeholder?" (EP→SC)

D. "Which Actions by the DM impact the Concern of the Stakeholder?" (DMA→SC)

E. "Which Actions by Stakeholders directly impact the Concern of the Stakeholder?" (SA→SC)

For such elements, draw an arrow from the first element towards the SC.

4. Identify the relationships that define the decision making rationale (Actions) of the other Stakeholders by asking the following questions and draw an arrow from the element towards the SA.

"Which of the Stakeholder's Concerns will drive the Stakeholder's decision making?" (SC→SA)

5. If the value of an element cannot be defined precisely given exact knowledge of its impacting elements, then include this uncertainty by asking "*What additional information would the DM need to possess in order to know the value of the element with certainty?"* Write the cause of this uncertainty under the element, and then draw an arrow from the cause to the element.

Phase 3. Refine Model

1. Assume that you are the Decision Maker, and that you must make the decision identified. Assume that you are limited in the amount of time you are able to allocate to developing and then analyzing the value model. Examine the initial value model you have developed. It is possible that some of the identified elements do not strongly impact the Fundamental Objective.

Using your judgment, determine which elements and relationships you believe are important enough to include. Be sure to consider how difficult it will be to develop and then analyze the elements. Use a highlighter to identify the Elements and Relationships that you think are important to include.

4.4.3 Pilot Study Results

In this section, I briefly review some sample value models from each group, describe quantitative scoring of each group's models, and perform a statistical analysis of the data.

4.4.3.1 Example Responses

Figure 4.4(a-c) presents three HAZELRIGG Group participants' submissions of value models as example responses to the problem statement[7]. In general, the responses shown varied in complexity and quality, from those that were quite simple and poorly analyzed (such as (a)), to those that were quite complex and well analyzed (such as (c)). Of the 18 participants, 17 submitted influence diagrams depicted as influence diagrams that could be categorized as complete.

Figure 4.5(a-c) presents three HAZELRIGG Group participants' submissions of value models as example responses to the problem statement. Similar to the HAZELRIGG Group, the SMDVM Group exhibited variation in model complexity and quality. However, whereas most HAZELRIGG Group participants were able to complete the task within the desired time frame, none of the participants in the SMDVM Group developed models that could be categorized as complete. Further, one submission was sufficiently illegible that it was deemed unscorable, and was removed from consideration.

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[7] Due to space considerations, reduced size images are presented in this chapter. Full scale images are attached in APPENDIX A, alongside full scale images of example SMDVM Group value models.

As such, only 16 of the 17 submissions were included in the analysis performed in the following sections.

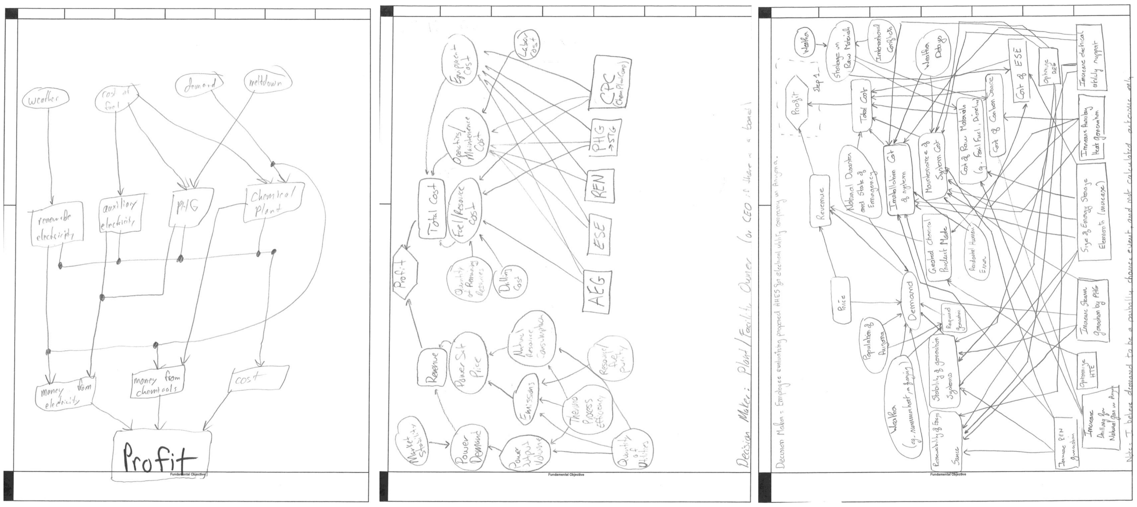
4.4.3.2 Scoring Procedure

The following metrics were used to evaluate the submissions by both groups:

- Number of Decision Maker Actions Included (NDMAI)
- Number of Stakeholders Included (NSI)
- Number of Stakeholder Actions Included (NSAI)
- Number of Concerns and Properties Included (NCPI)
- Total Number of Decision Elements (NTDE)

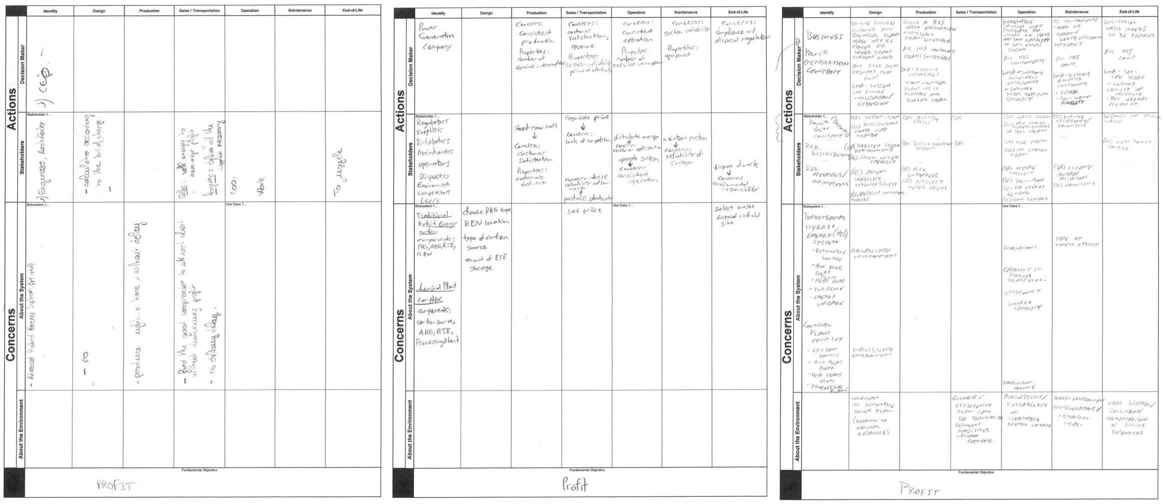
These metrics were posed as interesting because of their explanatory power in comparing the two methods as well as their fairness in terms of measurability for each method. For Example, the #CPI could have been decomposed into several metrics, each focusing individually on the number of Stakeholder Concerns, Decision Maker Concerns, or System Properties identified. However, the two methods do not similarly distinguish between these properties, and as such they are lumped together into a single metric.

Each submission was coded by two reviewers in order to reduce the opportunity for bias and to increase confidence in scoring. The two scorers generally had good agreement in scoring. For the five metrics, the correlations between the scores were 0.8618, 0.9566, 0.8998, 0.7858, and 0.9065, respectively. The average of the two scores was then used for analysis in the next section.



(a) *(b)* *(c)*

Figure 4.4(a-c). Example HAZELRIGG Group Value Models



(a) *(b)* *(c)*

Figure 4.5(a-c). Example SMDVM Group Value Models

With regards to explanatory power, let us first recall the major aspects of the decision model: Decision Maker, Stakeholders, the actions taken by each, the concerns of each, and the system properties that serve to relate them. The previous paragraph discusses why the concerns and system properties are measured using only a single

Table 4.5. Pilot Study Scoring Results - HAZELRIGG Group

Complete	NDMAI	NSHI	NSHAI	NCPI	NTDE
yes	10	3	2	14	27
yes	9	1	0	8	18
yes	5	3	1	16	22
yes	5	1	0	12	17
yes	3	1	0	12	16
yes	10	1	0	19	29
yes	4	2	1	10	15
no	4	1	1	16	21
yes	6	1	0	17	23
yes	5	1	0	16	22
yes	4	1	0	10	14
yes	4	1	1	11	16
yes	10	1	0	17	27
yes	2	1	1	8	11
yes	6	1	0	13	20
yes	7	1	0	13	21
yes	5	1	1	14	21
yes	8	2	1	18	28

metric. The number of decision makers is taken as unitary by default, and therefore a metric is not required. #DMAI indicates how deeply the participant has investigated the potential design alternatives available to the decision maker. #SI reflects how broadly the participant has investigated the interactions between the system and other actors. #SAI reflects how deeply the participant has investigated the manner in which the Stakeholders can impact the system.

4.4.3.3 Analysis Results

The results of the scoring are reported Table 4.5 and Table 4.6, with the mean and standard deviation for each method for each metric calculated in Figure 4.6 and in Table

Table 4.6. Pilot Study Scoring Results - SMDVM Group

Complete	NDMAI	NSHI	NSHAI	NCPI	NTDE
no	6	6	5	10	20
no	0	8	0	8	8
no	0	9	2	13	15
no	13	3	10	24	46
no	6	10	7	23	36
no	0	13	0	26	26
no	0	10	14	16	30
no	1	8	9	16	26
no	0	7	1	12	13
no	3	7	2	8	13
no	4	3	1	2	7
-		-	-	-	-
no	0	5	3	5	8
no	0	12	6	16	22
no	0	14	9	7	16
no	1	1	3	20	24
no	2	11	0	9	11

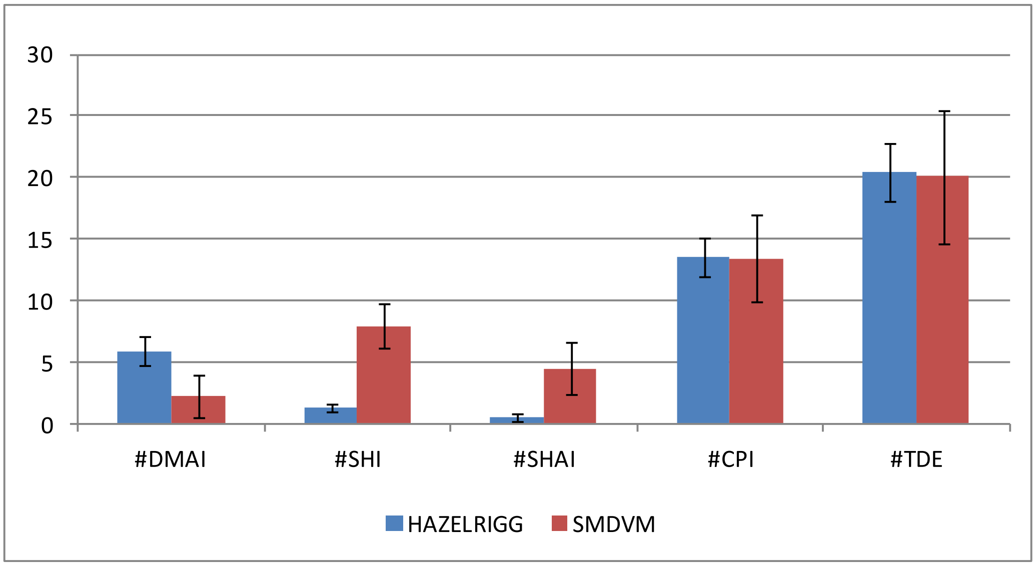


Figure 4.6. Comparison of Methods by Pilot Study Metrics

4.7. Figure 4.6 also shows the calculated 95% confidence intervals for the mean value of the metrics.

Table 4.7. Sample Mean and Standard Deviation of Pilot Study Metrics by Method

		#DMAI	#SI	#SAI	#CPI	#TDE
CONTROL	**MEAN**	5.94	1.33	0.50	13.56	21.78
(n=18)	**STDEV**	2.51	0.69	0.62	3.35	5.02
STUDY	**MEAN**	2.25	7.94	4.50	13.44	23.88
(n=16)	**STDEV**	3.57	3.73	4.26	7.12	11.34

Two sample t-tests were also conducted for each of the five metrics, to determine whether the methods could be differentiated with statistical significance. For the first metric (#DMAI) the investigated null hypothesis is that the SMDVM Group mean value is larger than that of the HAZELRIGG Group. For the second (#SI) and third (#SAI) metrics, the null hypotheses are that the SMDVM Group mean values are less than those of the HAZELRIGG Group. For the fourth (#CPI) and fifth (#TDE) metrics, the null hypotheses are that the mean values of the two methods are equivalent. As is shown in Table 4.8, the null hypotheses for the first three tests can be rejected for p=0.05, while the null hypotheses regarding the fourth and fifth metrics cannot be rejected, even for p=0.1

In addition to the two sample t-test, the sample populations were also compared using the Mann-Whitney U-Test, which is equivalent to the Wilcoxon Rank sum Test and compares whether the medians of the two distributions are different. The Mann-Whitney U-test does not require the restriction that data samples come from a normal distribution, and therefore may provide a more exact estimation of the p-value under circumstances in which the distributions are non-Gaussian. However, the Mann-Whitney U-Test does

Table 4.8. Two-Sample t-Test Results by Metric

	#DMAI	#SHI	#SHAI	#CPI	#TDE
NULL HYPOTHESIS	C<S	C>S	C>S	C=S	C=S
RESULT	REJECT	REJECT	REJECT	FAIL TO REJECT	FAIL TO REJECT
p-Value	00007	0.0000	0.0004	0.7186	0.7329

Table 4.9. Mann-Whitney U-Test Results by Metric

	#DMAI	#SHI	#SHAI	#CPI	#TDE
NULL HYPOTHESIS	C<S	C>S	C>S	C=S	C=S
RESULT	REJECT	REJECT	REJECT	FAIL TO REJECT	FAIL TO REJECT
p-Value	0.00034	0.000003	0.0015	0.4673	0.4681

assume the condition that the variance of the two sample sets are equivalent. This assumption is particularly strong, and likely invalid. Therefore, interpretation of the test results (see Table 4.9) must be made carefully. On their own, they provide little support for the conclusions drawn regarding the Null Hypotheses. However, when considered alongside the two sample t-test, they provide an increased level of confidence in the rejection of the null hypotheses that the first three attributes of the HAZELRIGG group and SMDVM Group are statistically significantly different, while the fourth and fifth are not.

This indicates that it can be stated (with quite strong confidence) that the SMDVM Group participants, and therefore the proposed SMDVM, do not include as many potential actions by the Decision Maker, but include many more potential Stakeholders, and account for many more actions by those Stakeholders. However, it cannot be stated with confidence that the proposed SMDVM yields value models with any increased or decreased focus on Concerns and System Properties. Similarly, the total number of included decision elements are similar, indicating that the proposed method does not lead to significantly more detailed models, at least within the context of this study.

4.4.4 Pilot Study Discussion

The main finding of the pilot study relate to the indication that the SMDVM appears to direct focus away from the actions by the decision maker, and towards those by other stakeholders, relative to the standard approach. However, this effect can be explained as merely an indirect result from another root cause; the SMDVM Group would have identified all types of decision elements to a greater level of detail, but lacked sufficient time to complete the specification of the value model at the desired level of abstraction.

This hypothesis is supported by the similarity in the number of considered elements between the two methods in terms of #TDE. Neither group was significantly more productive in terms of identifying relevant decision elements. Since the SMDVM focuses on identification of stakeholders, their actions, their concerns, and system properties before addressing the decision maker's actions, participants correctly following the approach would have focused first on these elements. If the participants did not have sufficient time to fully complete these steps then they would not reach the stage at which decision maker actions are identified, and no (or few) such actions would be identified. This is consistent with the data shown in Table 4.6, in which eight of the sixteen participants (50%) produced zero decision maker actions. It is also noted that upon completion of the test, the proctor noted numerous comments by the participants in both groups that there was insufficient time to complete the assignment.

Of course, the proposed root cause of insufficient time biasing the findings of the study would lead to a different conclusion; the SMDVM requires a greater amount of time to produce a functional value model in practice, relative to the standard approach. However, this argument assumes that all value models presented are of equal quality, and are therefore could all be used to make decisions in a justifiable manner. However, many of the decision model elements included by the HAZELRIGG Group are non-meaningful, or not correctly descriptive of the context. For example, many submissions referred to a nebulous "Price" and "Revenue" of the system, failing to acknowledge the actual salable outputs of the system, electricity and refined petroleum. Indeed, only three of the eighteen HAZELRIGG Group submissions accounted for the price of these output products specifically.

The cause of this omission is likely confounded between a lack of true understanding by the participants about Hybrid Energy Systems and the lack of applicability of standard practice methods to evaluate them. Hybrid Energy Systems are not simple consumer goods that operate in open markets, but typically would be privately owned and operated systems that then produce goods of interest to consumers. This disconnect in terms of the target of the design process makes it difficult to apply the standard method to such contexts.

Therefore, the final conclusion is that strong conclusions cannot be derived regarding the relative performance of the two methods given the complications with this study. In order to more fully understand and evaluate the potential merits of the SMDVM, it is recommended that another study be conducted, using knowledge gained during this pilot study. Specifically, participants should be given additional time to perform the test, likely in excess of one and a half hours.

Further, this study has focused only on comparing the SMDVM to an approach based upon Hazelrigg's Framework for Value-Driven Design (Hazelrigg, 2012). Future work could instead compare the results of analyses made using the SMDVM to other standardized approaches to Requirements Elicitation in order to better understand the differences in decision making that results from focusing on maximizing value instead of identifying and meeting constraints on performance, cost, etc. Such a study could be conducted in a similar context, where one group of participants elicit requirements and then evaluate whether the proposed system configuration meets these requirements, while another group attempts to develop a value model of the system context to make their evaluations.

4.5 Summary

In this Chapter, I first presented a Systematic Method for Developing Value Models. The value modeling method directs engineers, designers, and decision makers in a systematic manner, such that key decision elements are included, and provides a process by which they can derive confidence that their modeling effort has resulted in an actionable model. The SMDVM was compared to a method based on the state of the art using a pilot study involving 35 graduate students. Statistically significant differences between the two methods were determined with respect to the focus on the actions of the decision maker, stakeholders, and the actions of the stakeholders. However, the pilot study was inconclusive about the merits of the SMDVM relative to the standard method, due to limitations in the testing procedure. It was recommended that future studies increase the duration of the examination, such that a complete, unbiased examination of the pragmatism of the two methods could be made.

CHAPTER 5

APPLICATIONS TO ENERGY CONSCIOUS BUILDINGS

5.1 Introduction

In this Chapter, the design and retrofit of buildings for low energy consumption is introduced as a domain of interest for application of value-driven approaches. First, the history of buildings and energy consumption is briefly reviewed. Then, §5.2.2 reviews standard practice for modeling the energy consumption of buildings for use in design and retrofit decisions. §5.2.3 provides a background on other approaches to uncertainty analysis of building energy and identify opportunities for improvement. Then, in §5.3 the Georgia Tech Uncertainty and Risk Analysis Workbench is introduced as a tool to reduce the cost of value-driven design of buildings. The variability in the meteorological conditions is identified as a dominant driver of uncertainty in the simulation of building performance, and the Stochastic Meteorological Year (SMY) is introduced as a tool to capture its uncertainty in §5.4.

5.2 Building Energy Consumption and Modeling

5.2.1 Building Energy Consumption

Buildings, both residential and commercial, comprise a major end-use of energy in the United States, and throughout the world. In the United States alone, non-industrial related buildings account for over 40 Quadrillion BTUs each year, or roughly 41% of all end use consumption (see Figure 5.1) (U.S. Energy Information Administration, 2012). In financial terms, the consumption accounts for over 500 billion dollars or roughly 3.4% of

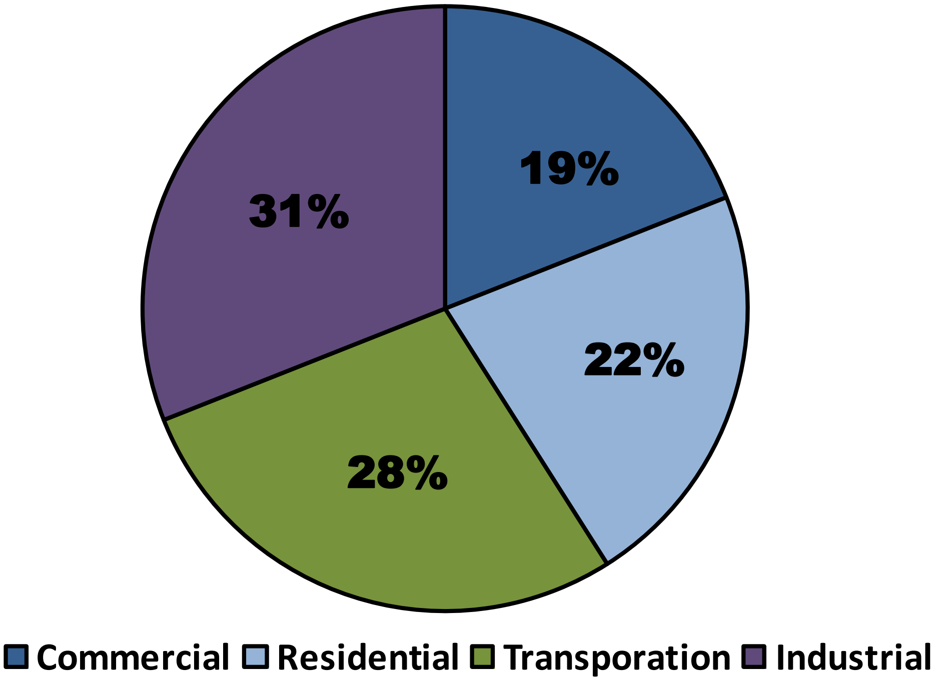


Figure 5.1. End-Use Sector Shares of Total Consumption, 2011

the Gross Domestic Product of the United States (U.S. Energy Information Administration, 2012).

Examining the long term trend in energy consumption (see Figure 5.2), one can see that on the whole, end use consumption has increased steadily since at least 1950. The residential and commercial sectors exhibit this long term trend specifically, and it is only in recent years that this trend has begun to slow down. A portion of this trend can be explained as due to construction of new homes and business structures. As the energy consumption per household (see Figure 5.3) and per commercial building (see Figure 5.4) have decreased or remained relatively stable for the most recent period.

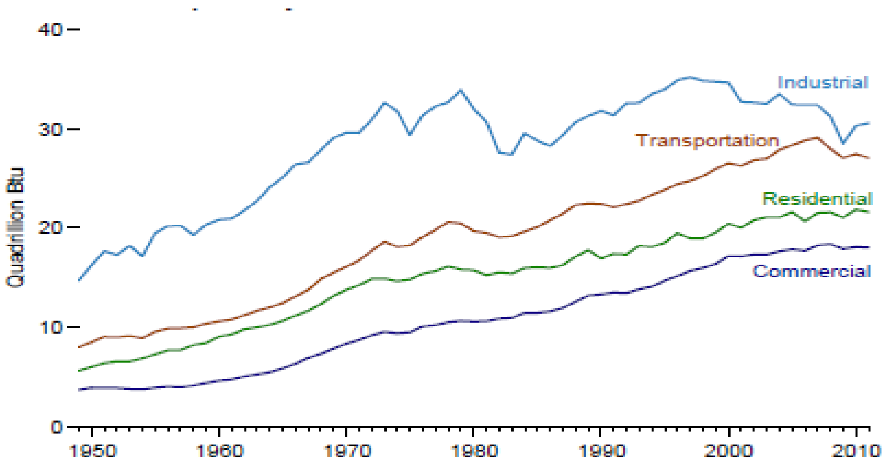


Figure 5.2. Total Consumption by End-Use Sector, 1949-2011

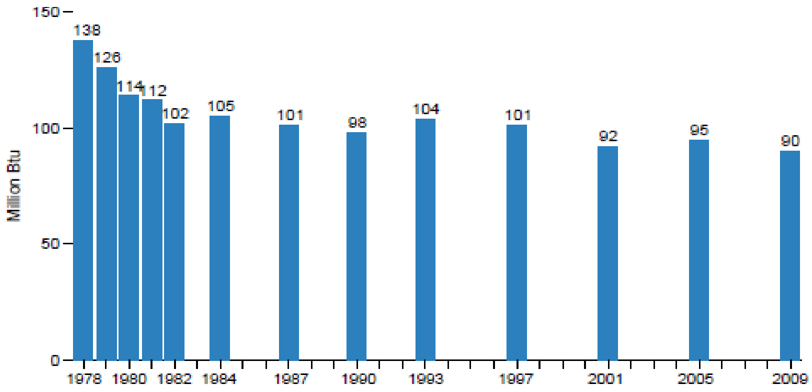


Figure 5.3. Energy Use per Household, Selected Years, 1978-2009

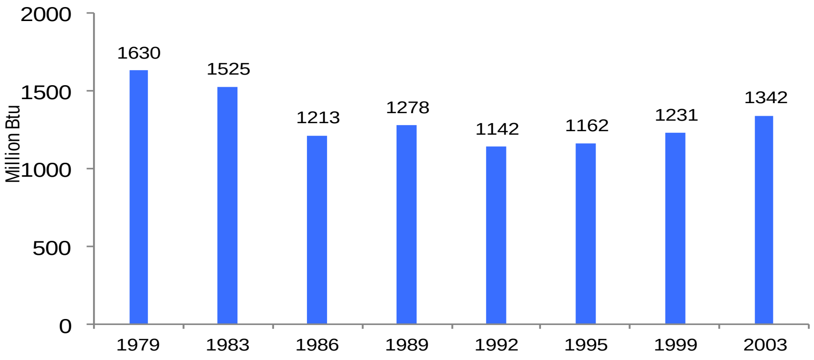


Figure 5.4. Energy Use per Commercial Building, Selected Years, 1979-2003

Examining Figure 5.3 and Figure 5.4 more closely, it can be seen that significant advances in energy consumption were made from the late 1970's through the early 1990's. In the residential domain, much of this energy savings can be attributed to advances in appliance efficiency (Voglewede, 2011), which have made significant improvements in technology. However, the recent trend in commercial building energy consumption has been increasing, potentially due to the increasing prevalence of computer equipment and other electrical loads.

5.2.1.1 Executive Orders and Acts of Congress

As declared in Federal Energy Management Improvement Act of 1988 (US Congress, 1988), the energy consumption of building stock in the United States has significant impacts on the costs suffered by the government as well as requires dependence on foreign nations for energy resources. It amended the National Energy Conservation Policy (US Congress, 1988) to require 10% percent reductions of energy consumption for each federal agency over 7 years, and marked one of the first recognitions by the United States government of the importance of energy efficiency.

Congress then passed the Energy Policy Act in 2005 (US Congress, 2005), strengthening the call for increased energy efficiency in federal buildings by an additional 20% within ten years, and required that all new structures be built to a design standard 30% below the ASHRAE Standard (ASHRAE, 2007). In 2007, President Bush issued Executive Order 13423: Strengthening Federal Environmental, Energy, and Transportation Management (Bush, 2007). The EO calls for a stricter improvement to energy efficiency by 30% in 2015. Congress then made these goals into law in the Energy Independence and Security Act of 2007 (US Congress, 2007). President Obama has since called for all new federal buildings to be designed to achieve net zero energy, and issued Executive Order 13514 (Obama, 2009) requiring this for any building designed after 2020.

These Acts and Executive Orders provide direct objectives to the federal agencies that must meet their requirements. However, they also introduce strange complications. The required improvements to the existing building stock, as well as those for future buildings, are generally quite expensive to perform, and require significant upfront investment. However, many of the federal agencies subject to the requirements do not possess the funding capability to perform such extensive retrofits. Further, many buildings contain specifically energy intensive activities that make retrofits impractical. As such, the government has needed to continually revise the requirements to allow for such considerations (US Congress, 2012; US Congress, 1988).

5.2.1.2 LEED

The U.S. Green Buildings Council developed LEED (Leadership in Energy and Environmental Design) in 1994 as a set of ratings to quantify the sustainability of buildings (U.S. Green Building Council., 2009). The LEED rating system consists of four rating levels, from Certified, to Silver, to Gold, to Platinum which are obtained based upon the number of points earned by a particular project (U.S. Green Building Council., 2009). The rating scores are based upon a number of factors related to sustainability, including: Location and Transportation, Materials and Resources, Water Efficiency, and Energy an Atmosphere, among others (U.S. Green Building Council.).

LEED is, itself, an entirely voluntary program[8] that seeks to improve the energy efficiency and sustainability of buildings by providing a clear metric by which competing buildings can be compared. However, in order to predict the energy consumption of the building, the certification system requires dynamic simulation of the building using the normative guidelines of ASHRAE 90.1 Appendix G (ASHRAE, 2007), rather than predicted or measured values for building occupancy and usage. Therefore, the predictive power of the Building Energy Models used can be relatively low. Further, the cost of obtaining LEED certification can be quite high (from 4-11% of construction cost), as the building must be certified by an independent third party that reviews all documentation and performs commissioning on the building (Northbridge Environmental Management Consultants, 2003).

Since LEED is a private certification process, there are no direct benefits from achieving / obtaining certification. However, the certified buildings generally receive tangible economic benefits through reduced operation / maintenance costs, as the building is designed to operate more efficiently. LEED certification may also lead to improvements in attributes of concern to other stakeholders, such as those related to

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[8] However, several local governments have mandated that buildings shall obtain LEED certification (Northbridge Environmental Management Consultants, 2003).

sustainability improvements in the environment (Northbridge Environmental Management Consultants, 2003).

5.2.2 Building Energy Modeling

In order to improve the energy efficiency of buildings, it must be possible to predict how a particular design choice will affect the energy consumption of the building. One tool for making these predictions are computational simulations. These simulations typically consider some abstraction of the physics of heat transfer in buildings, as well how the systems inside the building would respond. For decades, researchers and practitioners have developed ever more sophisticated simulations of the behavior of buildings (Malkawi and Augenbroe, 2003). They have allocated significant effort in establishing a variety of highly detailed and specialized models for a range of different materials, systems, heat transfer phenomena, electrical equipment, and occupant behavior. As a result, simulation programs are now able to make estimations about the performance of a building under a wide range of scenarios.

5.2.2.1 EnergyPlus and Other Dynamic Simulation Tools

Energy Plus (Crawley et al., 2000) is one of the most common energy simulation tools for predicting building energy performance. It is written in FORTRAN 90 and combines aspects from two previous simulation engines BLAST and DOE-2. The simulation engine is currently maintained by the U.S. Department of Energy, and has been configured to rely on modular code blocks that can be configured to describe the complete behavior of a building.

The overall structure of the program is described in Figure 5.5. Because the program is solely concerned with the simulation engine, third party graphical user

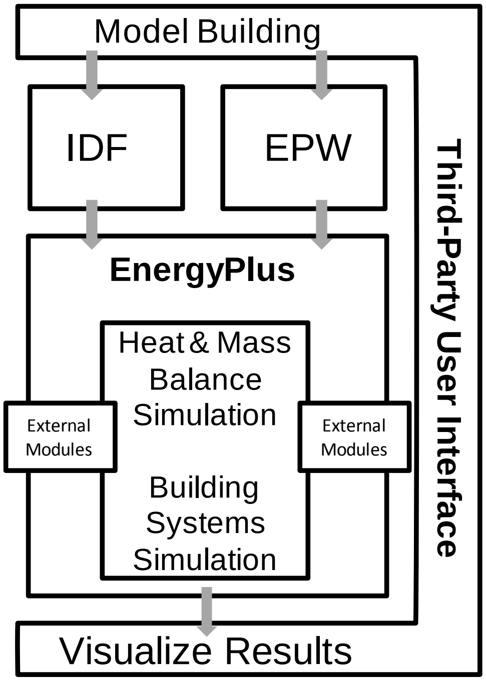

Figure 5.5. Overall EnergyPlus Structure

****Adapted from (Crawley et al., 2000)***

interfaces are typically used to develop an initial model of the building, and to ultimately display the simulation results. The third party UI creates two text documents: the Input Data File (IDF) describes the construction and operation of the building, while the Energy Plus Weather file (EPW) describes the meteorological surroundings of the building. EnergyPlus can be configured to interact with outside calculation modules to perform advanced computational analysis, or using the Developer's license, the raw FORTRAN 90 code can be edited to include additional desired functionality.

Of course, there are a multitude of other dynamic simulation tools that are commonly used, such as eQuest (Hirsch, 2005) or IES-VE (IES, 2008). Additionally, several generic modeling languages have been extended to provide special functionality for the simulation of buildings and their systems, such as TRNSYS (Klein, 1979), Modelica (Elmqvist et al., 1997) and MATLAB (The Mathworks Inc., 2005). Models built using these languages are typically highly customized (Lee et al., 2013) and may require significant user experience in order to develop. Regardless of which of simulation engine is utilized, a similar process for simulation is followed; the construction and operation schedule of a structure is defined and then the response of the building's systems are predicted in an iteratively for a given length of time.

5.2.2.2 Building Energy Simulation for Design

Simulation models are typically used in the design phase to predict energy consumption and comfort levels of a building, at the delivery phase to guarantee performance, during the use phase to monitor performance or in a model-driven control loop, or during retrofit decisions to decide about the potential benefits of different interventions (Malkawi and Augenbroe, 2003). However, it has been shown that model predictions can differ significantly from measured energy consumption by as much as 100%, and often by 30% (de Wilde et al., 2002). A study by the New Buildings Institute found that the difference could be even larger in some projects (Turner et al., 2008). The models' inaccuracy can make it difficult to obtain consistent useful information about the energy consumption of one design alternative relative to another. As a result, the simulation tools tend to be used primarily as a verification process to confirm that a given design alternative is feasible, rather than for steering design decision making (Malkawi and Augenbroe, 2003).

In order to increase the simulation tools' suitability for design decision making, this thesis continues the recent trend of calling for a consideration of the uncertainty[9] in the models and the modeling assumptions. Some of the early work in exploring UA capabilities in the field of building simulation was done by (de Wit and Augenbroe, 2002; Gero and Dudnik, 1978; Jiang and Hong, 1993; Macdonald and Strachan, 2001). Among these UA studies, de Wit and Augenbroe (de Wit and Augenbroe, 2002) developed a framework for decision-making based around propagation of input parameter uncertainty using Latin Hypercube Sampling (LHS) of a custom thermal building model.

It has since been shown that uncertainty can have a significant impact with respect to building design and retrofit decisions. De Wit and Augenbroe show how uncertainty in various aspects of the building and weather can lead to a probability distribution in thermal comfort in (de Wit and Augenbroe, 2002). Moon and Augenbroe quantify risk in terms of the probability of mold growth based on a consideration of uncertainty in (Moon and Augenbroe, 2007). Hu shows how uncertainty in weather and building properties can drastically impact the risk of power reliability for an off-grid solar decathlon home (Hu, 2009). Uncertainty can also have a significant impact in the evaluation of performance based contracts for energy retrofits, and may render some otherwise reasonable alternatives as unacceptable due to their riskiness (Heo et al., 2012).

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[9] The discussion here is limited to the consideration of the principles of uncertainty quantification and analysis as related to energy consumption prediction using simulation tools. Discussion and analysis of software tools and workbenches that have been developed for building energy models is reserved for §5.2.3.

As such, clearly uncertainty in the energy consumption of a building should clearly be considered during the decision making processes of design and retrofit.

5.2.2.3 Normative and Normative-derived Models

One class of simulation does not focus on making accurate predictions of energy consumption, but instead calculates a normative[10] scoring for building based upon prescribed occupancy and operation. An example of this class is the Energy Performance Standard Calculation Toolkit (Lee et al., 2011). Such tools are utilized in order to calculate a score for the energy performance of buildings, relative to design codes and standards, such as ISO 13790:2008 (ISO, 2008) or EN 15603: 2008 (CEN, 2008). The concept motivating the use of normative models instead of predictive models is to remove any opportunity for modelers to bias (intentionally or unintentionally) the rating.

The simulations are often highly simplified, involving many assumptions about the structure of a building as well as its components. As a result, the simulations may have relatively low predictive power. However, due to their simplicity of development and speed of execution, normative models may be transformed into Normative-derived models, which are intended to predict the actual energy consumption of buildings for use in design decisions. When using these normative-derived models however, one must be sure to remember that their predictions are extremely uncertain.

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[10] Normative here indicates a process developed to determine adherence to local law or code, and should not be confused with the interpretation of normative decision making.

5.2.3 Uncertainty Analysis of Building Energy

Case studies that propagate the combined effect of uncertainty through building simulation models have provided evidence that explicit consideration of uncertainty is relevant in many cases, ranging from the design of off-grid buildings (Hu, 2009; Lee et al., 2012) to energy retrofits (de Wilde et al., 2002; Heo, 2011 ; Hu, 2009; Sun et al., 2011) to the risk of mold growth (Moon, 2005). In addition, it has been suggested that explicit consideration of uncertainty is of importance to quantify risk measures for a variety of scenarios, including:

- Energy Savings Performance Contracts
- Issuing Guarantees for LEED Certification
- Certifying Ultra-Energy Efficient Buildings
- Reduced Availability Power Contracts
- Evaluating Reduced Availability Power Contracts
- Peak Power Tariff Avoidance Strategies
- Delayed Investment Strategies for Retrofits

Each of these scenarios have two common aspects. First, they consider the design, retrofit, or evaluation of a given building or group of buildings. Second, in each scenario at least one party is subject to significant (financial) risk resulting from uncertainty in the performance of the building or building stock or proposed strategy.

When faced with risk in such situations, it is generally regarded that more information is always better, or at least not worse (Hazelrigg, 2003; Pareto, 1971). This notion is reinforced through the understanding that a rational decision-maker will act based upon all of the information at his or her disposal. As such, a rational decision-maker should seek to gain as complete a state of information as possible. Additional information cannot guarantee that a decision will result in a good outcome; but it can increase the likelihood of the decision being a good one, in turn increasing the likelihood of a good outcome. Hence, I argue that decision makers (i.e. the stakeholders in the mentioned scenarios) should rely upon probabilistic rather than deterministic models.

In spite of this recognition, it is conceded that the adoption of Uncertainty Analysis (UA) into the mainstream building design profession and energy contracting business will depend on the availability of robust and automated environments for building energy models. In the time since its early investigation, researchers have developed sampling tools for various simulation engines to support sample-based UA. For example, Modelica (Burhenne et al., 2010), normative simulation models (Heo, 2011), EnergyPlus (Eisenhower et al., 2011; Kim et al., 2011), or other tools (Hopfe et al., 2007). Except the work by (Eisenhower et al., 2011) none of the above efforts have led to a generic platform to perform UA. Some general purpose UA tools have been developed outside of the building simulation community, such as (Andrianov et al., 2007; Malone and Papay, 1999; Wojtkiewicz et al., 2001).

The vast majority of these tools are similar in the process by which they quantify uncertainty in some quantity of interest in the output. First, a set of model inputs are designated as uncertain, and then a parametric distribution (usually Gaussian or Uniform) is applied as a quantification of that parameter's uncertainty. Next, a specialized program-wrapping script is defined so that the parameter uncertainties can be propagated automatically through some simulation model via Monte Carlo sampling.

In most current platforms, the user is forced to quantify uncertainty in parameters for which he or she may not have much experience. The user must then manually tailor the wrapping script to the specific instance, leading to possible transcription errors, and minimizing the possibility of future reuse. In addition, it is likely the user will only include a portion of the complete set of uncertain variables, even in initial screenings of parameters; the effort required to include each additional parameter in the wrapping script and then define a distribution could be cumbersome to the point of fatigue. This is indeed the case of performing UA for dynamic building energy models, e.g., EnergyPlus, which contain hundreds of uncertain input parameters accessible in the input file, called IDF. Therefore, it is beneficial to develop a dedicated building simulation tool for UA by creating an integrated UA platform that includes parameter uncertainty quantification (UQ), sampling, propagation, and post-processing capabilities. Such an integrated environment may not only enhance the quality of UA by embedding a reference parameter UQ database, but it also helps to bridge the gap between researchers and practitioners through an integrated user-interface design. Offering this integrated UA environment differentiates our tool (GURA-W) from others that instead focus on parametric analysis, i.e., jEplus (Zhang, 2009), DesignBuilder (DesignBuilder, 2006), OpenStudio (Guglielmetti et al., 2011), etc.

Lastly, following the terminology of Draper (Draper, 1995), Hodges (Hodges, 1987), and Morgan (CCSP, 2009), uncertainty about a prediction made using a model can be allocated into two parts: Structural (model) Uncertainty, and Input (parameter) Uncertainty. Whereas almost all UA tools allow some expression of Input Uncertainty, few of the tools surveyed offer some form of quantification of the Structural Uncertainty introduced by the energy model itself. It is this set of deficiencies that motivated the development of the Georgia Tech Uncertainty and Risk Analysis Workbench, which is introduced in the next section.

5.3 The Georgia Tech Uncertainty and Risk Analysis Workbench

There are two key aspects that motivated the development of the Georgia Tech Uncertainty and Risk Analysis Workbench (GURA-W):

- ♦ *Automation* - The GURA-W should maximize ease of use by automating the quantification of input uncertainties.
- ♦ *Flexibility* - The GURA-W should acknowledge that that predictions should be specific to a context, and therefore always allow the user to override any automated process or quantification.

Early in the process, the desire for flexibility led to the modularization of the UA process; an all-in-one tool would be very easy to automate, but then users would be limited in where and how they could override defaults introduced by the workbench. As such, the entire UA process was broken down into a set of individual steps that either occur in series or parallel. Each step was then designated as an individual module, giving users complete control of information at interfaces (inputs and outputs). Figure 5.6 shows the set of planned module separations, as well as how they interact. The modules were developed within ModelCenter, a model integration framework, using an open API java interface (Malone and Papay, 1999). Additional functionality is provided by an UQ Repository, with an interface created through Microsoft Excel. The next section will describe each module, detailing the state of information at each interface, as well as the internal processes occurring.

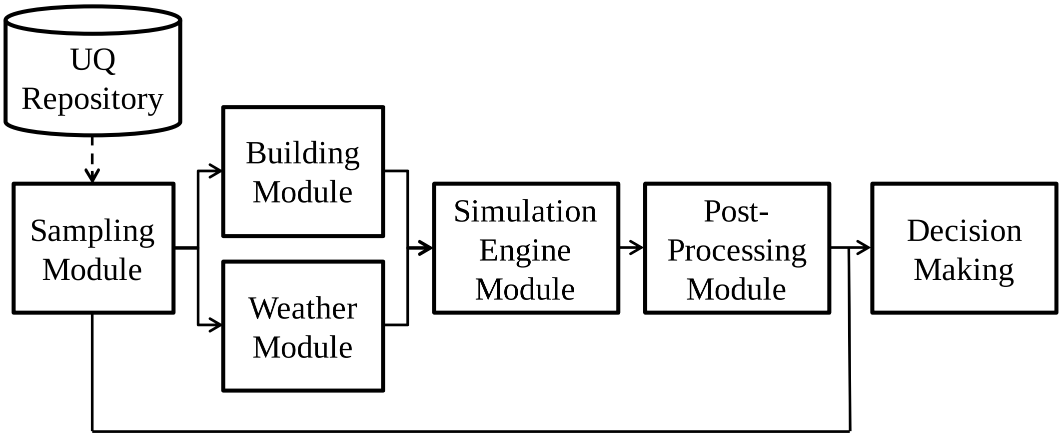

Figure 5.6. Separation of Tasks into Modules for the GURA-W

5.3.1 Module Descriptions

5.3.1.1 Simulation Engine Module

Of primary importance in any simulation workbench is the capability to execute the simulation program given a set of inputs. While the approach used to develop the UQ capabilities is generic, the authors have focused on implementation for EnergyPlus V7.0.0 in the current release. The simulation requires two text input files, one specifying the weather context for the simulation, and another specifying the geometry, construction, and operation of the building and its systems. The module specifically calls the *RunEPlus.bat* batch executable file, which is included in the standard release of an EnergyPlus distribution. In order to account for the structural uncertainty from certain models the *EnergyPlus.exe* and *Energy+.idd* files were modified using the EnergyPlus developer's toolkit (See Table 5.1 for a complete list of models for which structural uncertainty has been assessed. See (Sun et al., 2011) for more detailed description of methodology for modifications).

Table 5.1. Models for which Structural Uncertainty is Investigated

Description	**Required Alteration of IDD and Executable**
Convection Coefficient Calculation (Interior)	Yes
Convection Coefficient Calculation (Exterior)	Yes
Site Wind Speed Calculation	Yes
Infiltration Calculation (Low Rise Building)	Yes
Internal Mass Effect	Yes
Temperature Gradient Calculation	Yes
Thermal Bridge Effect	No
Urban Heat Island Effect	No
Ventilation Calculation (Single Side)	Yes
Wind Pressure Calculation (Low Rise Building)	Yes

5.3.1.2 Building Module

The Building Module is responsible for handling any parameter that is uncertain in the construction, operation, or physics of the simulation. In the current release, which has been implemented specifically for EnergyPlus, the Building Module is specifically responsible for parsing any parameter defined in the IDF. In order to accomplish this, a parser is developed for each type of module in an IDF. As seen in Figure 5.7, the parser searches for occurrences of a given identifier tag, which then initiates automated parsing of the variables contained within the module. The values, which are either numeric or text, are then stored for manipulation in the GURA-W. Once one of these parsers is

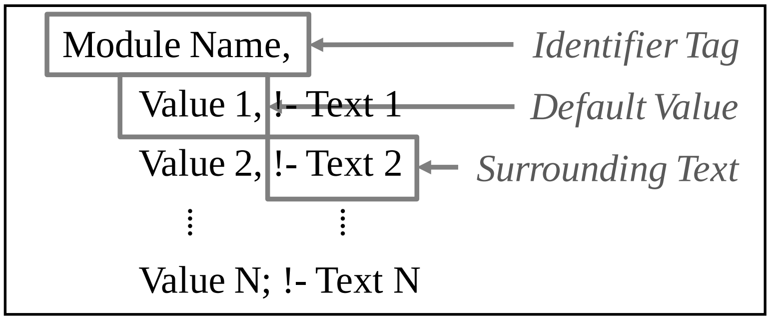

Figure 5.7. Information Required to Create Building Module IDF parsers

defined for a given module type, any occurrence of the module type in any target IDF will be automatically parsed by the Building Module. Once any given set of parameters have been automatically parsed and introduced into the ModelCenter environment, the designer is capable of easily changing the value manually, either by using any of ModelCenter's in-built tools, or through the use of the Sampling Module, which is introduced below. The module then recreates a text version of the IDF for execution by the Simulation Module.

5.3.1.2.1 Within Batch Variability

An additional task of the Building Module addresses the definition of construction material instances. For many modelers, it is convenient to specify a single definition of a construction material, and then to apply that definition throughout the entire building for every instance of that material. In deterministic simulation, where every material property is assumed as perfectly known, this assumption of uniformity is generally acceptable. However, when uncertainty is considered, the uniformity assumption requires that all construction materials are identical, ignoring "within batch" uncertainty. The implications of this required assumption are investigated further in the case studies later in this section, but here I will quickly explain the process which the Building Module uses to create a unique material type for each instance, if desired.

The Building Module first creates a network of objects that includes all originally defined *Construction Materials*, *Construction Types*, and *Surfaces* as shown in Figure 5.8. Then, a new set of *Construction Types* is created for each *Surface*[11]. Once this step is done, the last step is to define a new, instance-level set of *Construction Materials*, each corresponding to a different location throughout the building. The *Surfaces* are not modified during this process, except to update the name of the updated corresponding *Construction Type.* The result is a new IDF that contains the modified network of *Construction Materials* and *Construction Types* instances.

To illustrate the importance of accounting for the "within batch" variability, consider the following case study. The building being investigated in all scenarios is the Cherry L. Emerson building, which is located centrally on the Georgia Tech campus. The building was originally constructed in 1959, contains 61 offices and rooms, and is rectangular shaped and oriented with the longer sides facing north-south.

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[11] In actuality, the logic is slightly more complex than this. If one surface is the reverse of another (opposite sides of the same wall) then this must also be taken into account to ensure that identical material instances are used, only in reverse ordering.

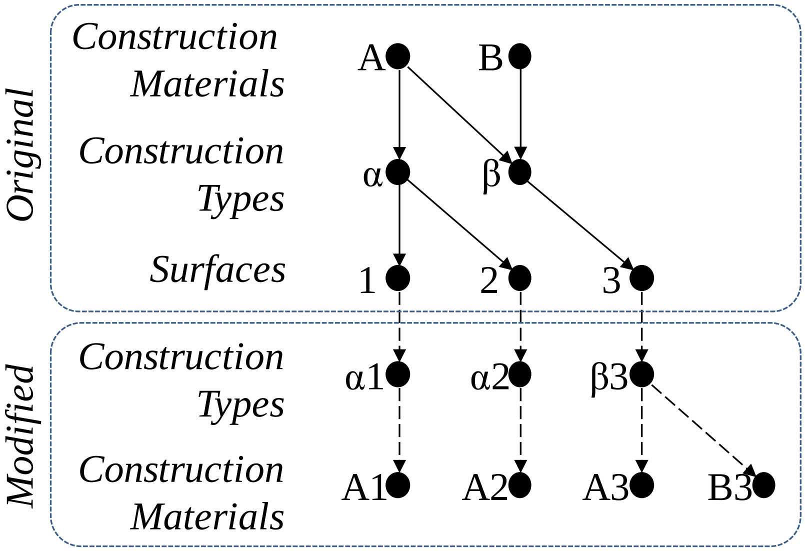

Figure 5.8. Building Module Process used to Address Material Instances

The IDF for the Cherry L. Emerson building was created using the DesignBuilder front end tool. The model was created using 13 different material types, as well as one additional window type. For the materials, the thickness was assumed to be exact, while the conductivity, density, specific heat, thermal absorptance, solar absorptance, and visible absortances were each sampled from Normal distributions as previously discussed. For the window material, the thickness was again assumed exact, but all other properties were each sampled from Normal distributions as previously discussed. All other parameters were fixed. See Table 5.2 for a complete list of the material properties considered uncertain in scenarios 1 and 2, as well as description of the number of occurrences of each type.

One hundred LHS samples were drawn and then propagated through the workbench, completing in slightly less than 1.5 hours. The annual cooling (left column) and heating (right column) loads for two zones were then tabulated into a set of

Table 5.2.Examined Uncertain Material Parameters

Description	**Number of Occurrences**
Material,	*(11 Material Types, 142 Instances)*
Conductivity	
Density	
Specific Heat	
Thermal Absorptance	
Solar Absorptance	
Visible Absorptance	
Material:NoMass,	*(2 Material Types, 30 Instances)*
Thermal Resistance	
Thermal Absorptance	
Solar Absorptance	
Visible Absorptance	
WindowMaterial:Glazing,	*(1 Material Type, 44 Instances)*
Solar Transmittance	
Front Side Solar Reflectance	
Back Side Solar Reflectance	
Visible Transmittance	
Front Side Visible Reflectance	
Back Side Visible Reflectance	
Infrared Transmittance	
Front Side Infrared Hemispherical Emissivity	
Back Side Infrared Hemispherical Emissivity	
Conductivity	
Dirt Correction Factor	

histograms, as shown in Figure 5.9 (rows 1 and 3). Also plotted (vertical line) are the nominal cooling and heating loads corresponding to the simulation containing nominal values for material properties. As could be expected, the variability of the cooling and heating loads as a result of material property uncertainty is modest, but still significant.

In scenario 2, the IDF for the Cherry L. Emerson building was modified using the instance process explained in the Building Module section previously. This functionality allows users to automate the process of assigning a unique material definition to each instance occurring throughout the building model. This allows users to investigate the impact of "within batch" uncertainty, as introduced previously.

In scenario 1, 81 variables were included as uncertain. The ease and speed with which the distributions of the samples were developed and then propagated offered a glimpse at the value of GURA-W. By comparison, for scenario 2, 1,456 variables were included as uncertain. Including such a large number of variables as uncertain would not have been possible if performed manually. Or at best, doing so would have resulted in numerous transcription errors. Yet the GURA-W was able to automatically develop uncertainty distributions for these parameters and then propagate 100 LHS samples in slightly less than 1.5 hours. Histograms for the cooling and heating loads for the same two zones as scenario 1 are shown in Figure 5.9 (second and fourth rows). Also plotted (vertical line) are the same nominal cooling and heating loads corresponding to the default values for material properties. For convenience of interpretation, the extent of the horizontal axes (cooling/heating load) are the same for corresponding plots from scenarios 1 and 2.

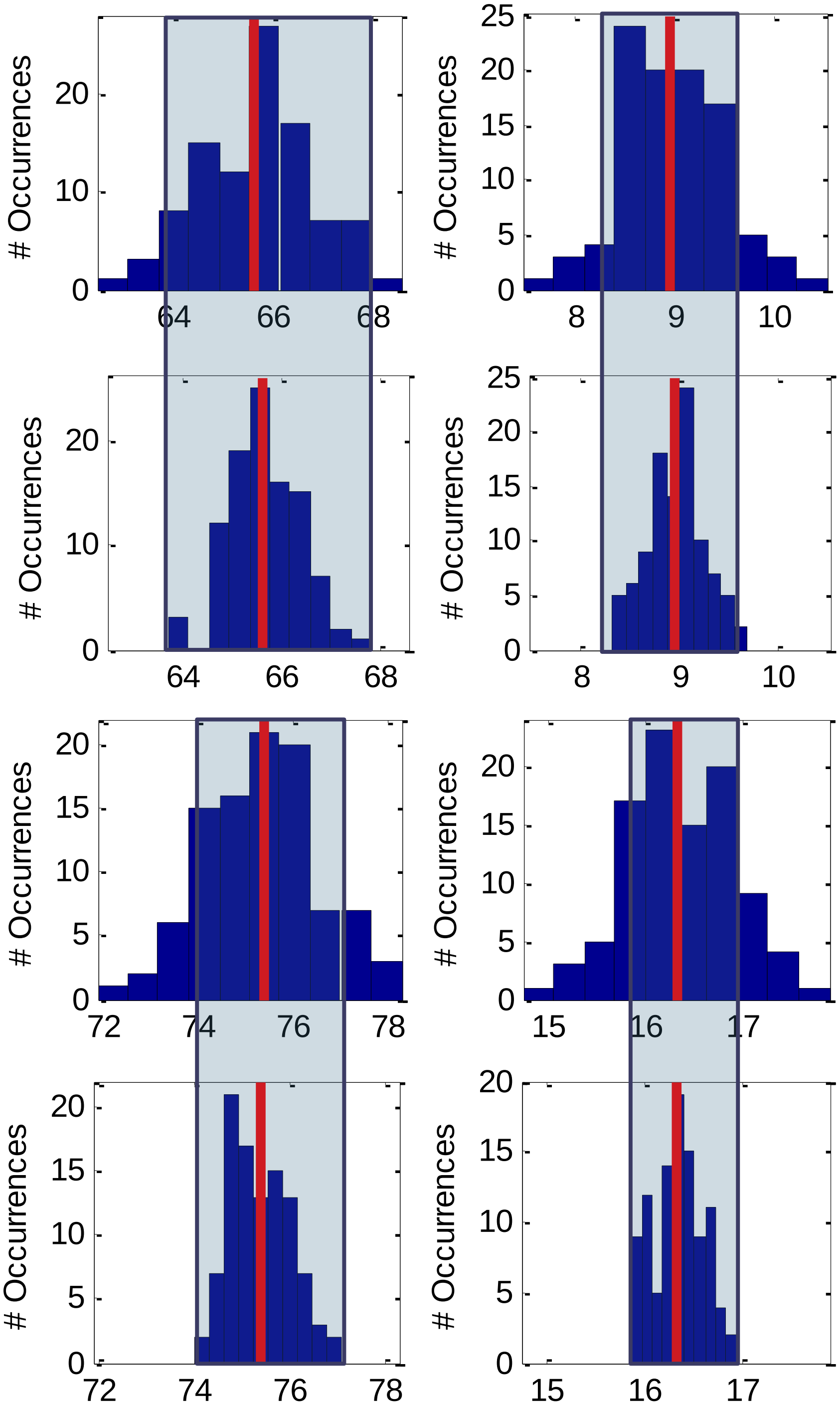

Figure 5.9. Effect of Within Batch Variability on Modeled Heating/Cooling Demand

Reviewing Figure 5.9, note a strange phenomenon, that upon further reflection makes conceptual sense. Relative to scenario 1, it could be said that scenario 2 includes a greater level of uncertainty; it is not assumed that every instance of a construction material is identical. Comparing rows 1 and 2, and 3 and 4, the variability in the heating and cooling loads are greatly reduced in scenario 2. The standard deviations calculated in scenario 1 are on average 1.81 times greater for the cooling loads, and 2.02 times greater for the heating loads (including all six zones). This reduction of uncertainty seems counterintuitive, but can be explained via covariance. If a model of the heating / cooling demand is specified as Equation (**5.1)**:

$$demand = f(R_1, R_2) \tag{5.1}$$

where R_1, R_2, are material properties for a similar type of material at different locations in a building, then the model can be approximated by using a Taylor series expansion, at least for small deviations:

$$demand = \frac{\partial f}{\partial R_1} R_1 + \frac{\partial f}{\partial R_2} R_2 + f_0 \tag{5.2}$$

If only R_1, R_2 are considered as uncertain, with f_0 assumed to be scalar, then the variance of the demand can be given as (Leon-Garcia, 1994),

$$\sigma_{load}^2 = \left(\frac{\partial f}{\partial R_1}\right)^2 \sigma_{R_1}^2 + \left(\frac{\partial f}{\partial R_2}\right)^2 \sigma_{R_2}^2 + 2\rho \frac{\partial f}{\partial R_1} \frac{\partial f}{\partial R_2} \sigma_{R_1} \sigma_{R_2} \tag{5.3}$$

where σ_*^2 refers to the variance of the random variable, respectively, and ρ is the correlation of the random variables. In scenario 1, it was assumed that construction materials were identical throughout the building, and thus the material properties at each particular surface were perfectly correlated with one another, such that:

$$\rho = 1; \tag{5.4}$$

$$\sigma_{load}^2 = \left(\frac{\partial f}{\partial R_1}\right)^2 \sigma_{R_1}^2 + \left(\frac{\partial f}{\partial R_2}\right)^2 \sigma_{R_2}^2 + 2\frac{\partial f}{\partial R_1}\frac{\partial f}{\partial R_2}\sigma_{R_1}\sigma_{R_2} \tag{5.5}$$

while in scenario 2, the construction materials were assumed to be completely independent, and so:

$$\rho = 0; \tag{5.6}$$

$$\sigma_{load}^2 = \left(\frac{\partial f}{\partial R_1}\right)^2 \sigma_{R_1}^2 + \left(\frac{\partial f}{\partial R_2}\right)^2 \sigma_{R_2}^2 \tag{5.7}$$

Comparing Equations (5.5) and (5.7), it is clear that scenario 2 should have a smaller variance than scenario 1, which is as observed.

5.3.1.3 Weather Module

The Weather Module is responsible for handling any uncertainty or variability in local weather that the designers wish to consider. In the current release for EnergyPlus, the Weather Module is specifically responsible for parsing and altering values defined in the Energy Plus Weather file (EPW). The variability in weather can arise from the incorporation of microclimate effects such as the Urban Heat Island effect (Sun et al., 2011) or the utilization of Stochastic Meteorological Years[12] (Lee et al., 2012) to quantify the uncertainty in weather variation. The module then creates a text replication of the EPW for execution by the Simulation Module.

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[12] The definition of and a process for generating Stochastic Meteorological Years is provided in §5.4.

5.3.1.4 Post-Processing Module

The Post-Processing Module is responsible for parsing the various output files that are exported by the Simulation Module. These post-processors are themselves defined in a modular nature, such that energy modelers can select exactly in which outputs they are interested in capturing uncertainty. Standard outputs include cooling or heating loads, electricity or natural gas consumption, and temperature and comfort profiles.

5.3.1.5 Decision Making

Decision Making is arguably one of the most important functions in using GURA-W. Because decisions are necessarily subjective, the GURA-W cannot directly advise the user what to choose in a context without taking that user's preferences into account. However, it can do the support work for a given number of scenarios to organize the problem for the user, making sure that the important model outputs are accounted for in the correct manner. The decision maker can then be further supported through standardized sensitivity analyses.

5.3.1.6 Sampling Module

The previous modules have been mainly concerned with meeting the flexibility requirement. Using only these modules, the user is capable of setting the value for any parameter in any way wished, either manually or through the use of ModelCenter's in-built tools. That is not to say that they do not address the automation requirement though; they each automate some portion of an otherwise tedious task of finding and modifying variable values, running simulations, and parsing outputs as well. However, the Sampling Module is primarily concerned with meeting the automation requirement. Rather than

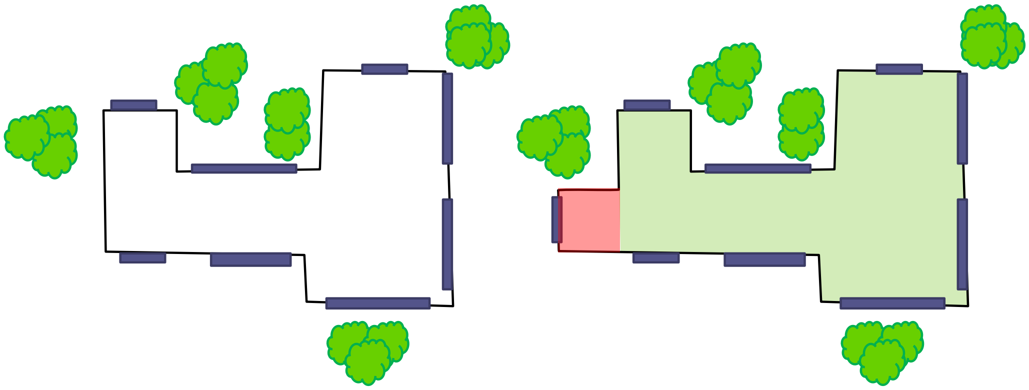

Figure 5.10.Pre (left) and Post (right) Retrofit Example Building

forcing users to manually describe several hundred uncertainty distributions, the Sampling Module, in coordination with the UQ Repository, is responsible for importing default distributions for each parameter, based on the parameter type. These default distributions can of course be overridden by the user. The Sampling Module then propagates uncertainty by drawing samples from these distributions, using Latin Hypercube Sampling (LHS) (McKay et al., 1979).

Worthy of special mention is a feature of the Sampling Plug-in focused on sampling for retrofit analyses. Consider the following example shown in Figure 5.10 in which a building is proposed to be retrofit by adding an extension to the western facade.

Considering the uncertainties present in the prediction of the energy consumption in both scenarios, it is noted that some properties, such as those of the western wall are only relevant before the retrofit occurs. Similarly, some properties, such as all of those related to the new extension, are only relevant after the retrofit. However, in this scenario, a large bulk of the building remains unaltered, and therefore the uncertainty in the parameters related to the remainder of the building should persist throughout the retrofit.

This distinction between Pre-Retrofit, Post-Retrofit, and Persistent uncertainties is important, as the uncertainty in the prediction of energy savings can strongly depend on the correlation between the pre- and post-retrofit parameters. Since retrofit energy savings can be declared as the difference between the pre- and post-retrofit energy consumptions, each of which is predicted using the properties relevant for the given prediction, the savings can be predicted as in Equation (**5.8)**.

$$E_{savings} = E_{pre}\left(\theta_{pre}, \theta_{persist}\right) - E_{post}\left(\theta_{post}, \theta_{persist}\right) \tag{5.8}$$

Then, when quantifying the uncertainty in $E_{savings}\left(\theta_{pre}, \theta_{post}, \theta_{persist}\right)$, it is necessary to account for the common relationship to $\theta_{persist}$ in the pre- and post-retrofit savings, lest the correlation between the distributions be neglected. Due to this correlation, the mean and variance of the difference between the two energy consumptions cannot be computed accurately via independent sampling of the distributions.

The retrofit sampling capability of the workbench was developed to address this specific deficiency in current practice in retrofit savings uncertainty quantification. A java executable was developed to automatically parse and identify common parameters in the pre- and post-retrofit building IDFs. Once identified, common random samples are used for each instance of the common parameter.

The functionality was explored using a case study investigating a deep retrofit to the Cherry Building (recall from §0). As part of the analysis, uncertainty was quantified for the relative savings for Total Facility Electricity, Peak Electricity, Total Cooling Electricity, and Total Natural Gas. The analysis was performed using the standard, naive practice assuming zero correlation, as well as with the retrofit sampling capability of the

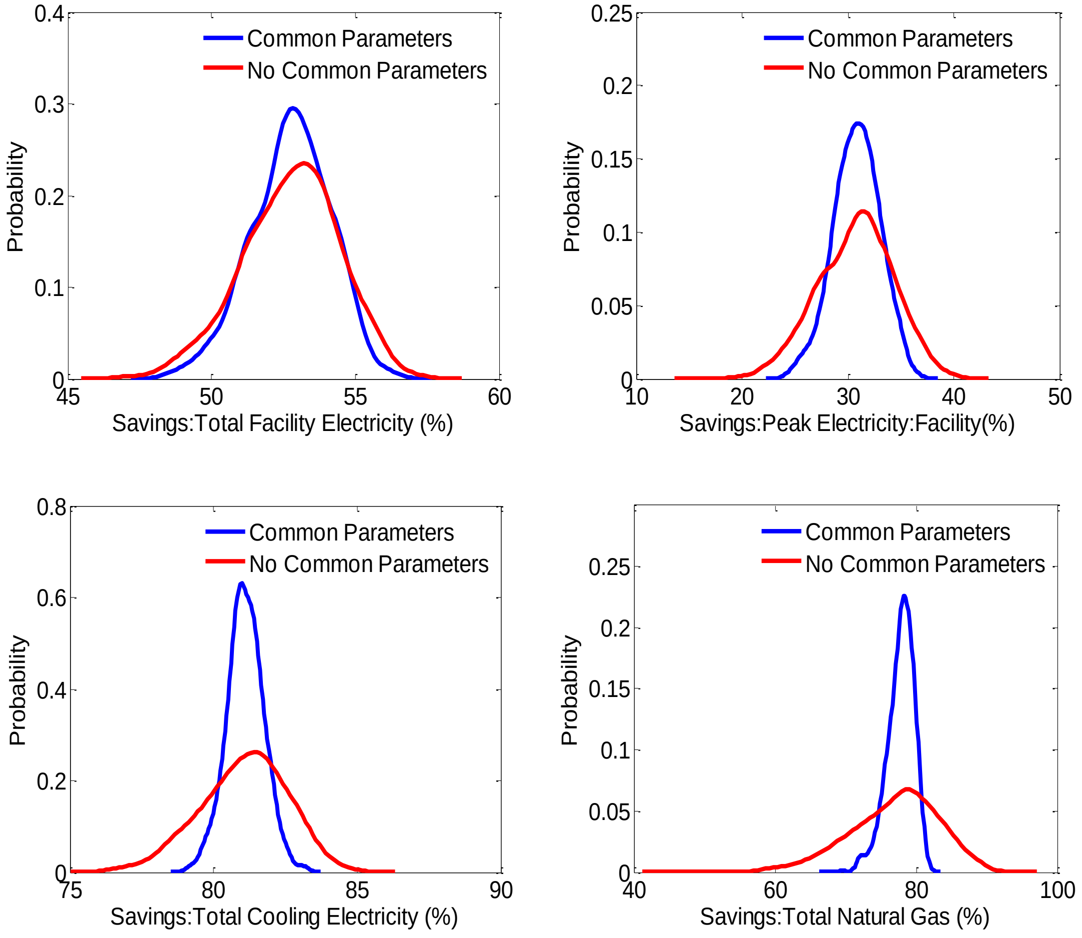

Figure 5.11. Uncertainty in Retrofit Energy Savings Cherry Building Case Study

workbench. The resulting PDFs are presented in Figure 5.11. As shown in the figure, the naive approach calculates PDFs with significantly increased variance. Even though a trend cannot be generalized from a single data point, it is comforting to see that, at least in this instance, the modes and means appear to be similar between the approaches.

5.3.1.7 UQ Repository

The UQ Repository is a set of data files stored in XML format that define default parameter uncertainty distributions as alluded to in the previous paragraph. The repository can be accessed using an interface developed in Microsoft Excel, a portion of which is shown in Figure 5.11. A unique XML file exists for each modeling scenario. For example, the building investigated in the case study is a low rise building in an urban location on the Georgia Tech campus, so the Urban-Low Rise data file is utilized. In each XML file, a set of information elements is defined for each parameter. First, the information describes whether the parameter is numeric or text, and then clarifies whether the user wishes to consider a numeric value as uncertain. Then, the probabilistic distribution and necessary parameters are stored.

5.4 Stochastic Meteorological Years

Among various uncertain sources, meteorological variability has been shown as having among the strongest impact on building performance (Bhandari et al., 2012; Hassan, 2009). For example, Hu’s research found that the risk in the weather pattern dominated the risk level of off-grid houses (Hu, 2009).

In general, building simulations are conducted using reference years, such as the Typical Meteorological Year (TMY) in the United States, and Test Reference Year (TRY) in the United Kingdom. These reference years, developed from multi-year historical data may be adequate to calculate the average energy consumption, its variation, however, cannot be revealed. Hence, they are not adequate for risk assessment.

A recent study compared building energy consumption between using multi-years (1971-2000) and TMY’s in different climates in China (Yang et al., 2008). They found that monthly heating load and cooling loads calculated from 30-year simulations differ from those using TMY’s by about 10% to 100% and 10% to 20%, respectively. A study in the UK demonstrated that reference years did not always represent the average energy use for certain architectural types and gave no indication of the expected range of energy use (Kershaw et al., 2010). In some cases they also found that TRY-based predictions of heating energy consumption, a dominant percentage of building energy usage in the UK, were off by as much as 40%.

In response to the limitation of reference years in the application of uncertainty quantification and risk assessment, some stochastic weather models have been developed to capture the random behavior of meteorological conditions.

A primary investigator in the field, Van Paassen (Van Paassen and De Jong, 1979) developed the Synthetical Reference Year to reduce the amount of simulation days required for analysis of building performance. The Synthetic Reference Year relies on derived correlation structures and Monte Carlo sampling to predict daily means of meteorological phenomena. These stochastically generated means are then applied to shape functions to determine hourly values.

Multiple authors have developed similar Auto-Regressive processes, attempting to predict one particular phenomena, such as solar radiation for use in analyzing photovoltaic panel sizing (Aguiar and Collares-Pereira, 1992; B.J, 1977; Goh and Tan, 1977; Gordon and Reddy, 1988a; Gordon and Reddy, 1988b) or wind speed for analyzing turbine sizing (Blanchard and Desrochers, 1984; Chou and Corotis, 1981; McWilliams and Sprevak, 1982).

Knight et. al. developed a more complex series of Auto-Regressive processes in which Temperature and Radiation are progressed simultaneously. However, cross correlations between the two phenomena are not considered (Knight et al., 1991).

Hong and Jiang (Hong and Jiang, 1995) took a more complex approach, in which several meteorological phenomena are considered in a Vector Auto-Regressive process.

In addition to daily means, measures of the daily variance of each phenomenon are predicted as well, such that the shape function used to develop hourly values is also stochastically generated. To make the model tractable, they made a particularly strong assumption of stationarity and separated the year into summer and winter seasons, treating all days, and therefore hours, identically.

Of the models developed, few allow for consideration of more than one meteorological phenomena concurrently. Even less include cross-correlations between phenomena, none having done so at an hourly level. Rather, they rely upon shape functions.

The next section briefly introduces the field of time series analysis and Vector Auto-Regression as a method for modeling the behavior and variability of meteorological phenomena in a given location. Then, I present a framework for generating a set of Stochastic Meteorological Years (SMY), which serve to characterize variation of meteorological conditions at the location specified. The framework is validated on the simulation case study of an off-grid, zero-energy home. The differences between evaluations of the zero-energy home using a third generation TMY, historical meteorological data, and SMY are investigated, and concluding remarks are offered.

5.4.1 Background

As defined by (Chatfield, 2004), a time series is "a collection of observations made sequentially through time." The analysis of time series, is then an attempt to better understand the relationships between observations for some purpose. In addition to the ability to estimate the meteorological state at a given time, the ability to characterize the uncertainty in that estimate is of principal interest in this work. By modeling the meteorological state using time series analysis, different possible years can be generated to evaluate the effects of variability in the weather on the performance of a particular building.

5.4.1.1 Auto-Regressive Processes

A simple example of a model developed using principles from time series analysis is a Auto-Regressive (AR) model. AR models take the form of Equation (**5.9)**.

$$Y_i = \sum_{j \in J} \left(\phi_{i,j} \cdot Y_{i-j} \right) + \varepsilon_i \tag{5.9}$$

As implied by the name, an AR model is developed by performing a regression in which the indicator variables are the same variable's previous values. The fit produced by an AR model is linear in nature, as the $\phi_{i,j}$ are not functions of Y_{i-j}. When solving for the values of $\phi_{i,j}$, it is convenient to restructure Equation 1 into the form of Equation (**5.10)**, where Φ_i is the row vector of $\phi_{i,j}$ with L entries.

$$Y_i = \Phi_i \cdot \begin{bmatrix} Y_{i-j(1)} \\ \vdots \\ Y_{i-j(L)} \end{bmatrix} + \varepsilon_i \tag{5.10}$$

For the special case that $\Phi_i = \Phi_i$ for all i and j, the correlation between the state at two different times is defined only by the amount of time between them. This property, which is known as stationarity, enables modelers to greatly reduce the complexity of the model. However, many time series cannot be adequately modeled as stationary. Such is the case for meteorological data, which tend to have significantly different statistical properties throughout the day and year.

When stationarity cannot be exploited, then it may be possible for the weaker assumption of seasonality to be utilized instead. Seasonal data exhibit repetitive patterns of behavior, such as those arising from daily or annual cycles. For M seasonal observations of Y_i, each complete with observations of $Y_{i-j}, \forall\, j \in J$, Equation (**5.10)** takes the matrix form of Equation (**5.11)**.

$$\begin{aligned}\left[Y_{i,1}, \cdots, Y_{i,M}\right] &= \Phi_i \cdot \begin{bmatrix} Y_{i-j(1),1}, \cdots, Y_{i-j(1),M} \\ \vdots \quad \ddots \quad \vdots \\ Y_{i-j(L),1}, \cdots, Y_{i-j(L),M} \end{bmatrix} \\ &\quad + \left[\varepsilon_{i,1}, \cdots, \varepsilon_{i,M}\right] \\ &= \Phi_i \cdot \mathbf{Y_i} + \left[\varepsilon_{i,1}, \cdots, \varepsilon_{i,M}\right]\end{aligned} \tag{5.11}$$

Using the linear least squares approach (Equation (**5.12)**), it is possible to solve for the values of Φ_i such that the sum of the square residuals, ε_i, is minimized.

$$\Phi_i = \left[Y_{i,1}, \cdots, Y_{i,M}\right] \cdot \mathbf{Y_i}^{\mathbf{T}} \cdot \left(\mathbf{Y_i} \cdot \mathbf{Y_i}^{\mathbf{T}}\right)^{-1} \tag{5.12}$$

Once the values of Φ_i have been determined, it is possible to then determine the vector of residuals as:

$$\left[\varepsilon_{i,1}, \cdots, \varepsilon_{i,M}\right] = \left[Y_{i,1}, \cdots, Y_{i,M}\right] - \Phi_i \cdot \mathbf{Y_i} \tag{5.13}$$

Once the vector of residuals have been determined, a statistical characterization can be made. If it is assumed that the residuals are normally distributed, then the mean and variance of ε_i can be estimated. Thus, with the regression parameters and the corresponding uncertainty defined, the model of the AR process is complete and ready for prediction.

5.4.1.2 Vector Auto-Regression

A simple extrapolation of AR process arises when the state at a given time is specified by more than one value. For example, the weather at a given time is not fully specified by the Dry Bulb Temperature, but must include information regarding the Wind Speed, Humidity, Barometric Pressure, etc. In these cases, AR models fail to capture the interdependencies between phenomena, and a Vector Auto-Regressive (VAR) model is required. For VAR processes, a similar progression is followed to determine the relationships between the current and previous states, and results in a similar structure for the regression coefficients and statistical properties of the residuals. The major changes include the notion that the regression coefficients now form a matrix $\mathbf{\Phi}_i$ that reflect the relationships between current values of a state and previous values of all phenomena, not each phenomenon independently. Further, the covariance between the residuals in a given hour is also considered, rather than simply the variance of each individual phenomenon. These principles are further expanded in the next section, in which a framework for generating Stochastic Meteorological Years is presented.

5.4.2 Generating a Stochastic Meteorological Year

The framework for generating SMY (as shown in Figure 5.12) consists of three stages: Collect Data for Location, Calibrate Model for Location, and Generate SMY for Location. The next sections will further describe the specifics of each stage.

5.4.2.1 Obtain Data for Location

The first stage in developing a SMY is to gather the required meteorological data. Strictly speaking, the minimum number of years of data required for a statistical fit is quite small. However, the model fit produced by a smaller sample size is not likely to be accurate. As such, it is recommended that longer datasets be used, similar to the 30 year dataset used to develop the Typical Meteorological Year datasets. For reference, the dataset used in the case study introduced later contains 39 years of data for most phenomena, and at least 33 for all phenomena. This data can be obtained for several cities

Collect Data for Location

- Retrieve hourly meteorological data of interest from database
- Ensure that all missing or corrupted data are flagged, and not used for model calibration.
- For each phenomenon,
    - For each hour, *i*
        - Collect the set of all instantiations, $[D_i]$
        - Normalize the data using a Rosenblatt transformation.
        - Store the transformed data set, [*Y*], as well as the information required to invert the dataset.

Calibrate Model for Location

- For each hour, *i*:
    - Collect the set of current and previous transformed observations, [*Y*].
    - For each possible set of Lags, [*j(1), ..., j(L)*]:
        - Using linear least squares approach, solve for the model coefficients, $\mathbf{\Phi}_{\mathbf{i}}$.
        - Solve for the covariance matrix and means of the residuals.
    - Select the set of Lags that minimizes MSE of the residuals.
    - Store the set of Lags, model coefficients, covariance matrix, and means.

Generate SMY for Location

- Generate a ‘warm-up’ period of random white noise.
- For each hour, *i*:
    - Generate $\vec{Y_i}$ by multiplying the previous values of $\vec{Y}$ by the model coefficients, and sampling $\vec{\varepsilon_i}$ using the means and covariance matrix.
- Using the stored information, invert the correlated noise [*Y*] via an inverse Rosenblatt Transformation into the proper domain for each phenomenon [*Y*]
- Calibrate each complete Stochastic CDF by the CDF of the original data set.
- Store the modeled meteorological phenomena in the appropriate format for the simulation tool of use.

Figure 5.12. A Framework for the Generation of SMY

from several sources, including the National Climactic Data Center (NCDC, 2012) and National Renewable Energy Laboratory (NREL, 2012).

The next step is to take advantage of the seasonality in the data, and gather a sufficient number of samples. This is done in two steps. First, the annual seasonality is exploited, such that if N_{year} years of data are available, N_{year} samples of each hourly phenomena are gathered. Next, the daily seasonality is exploited, such that for each hour in the year, the data from preceding and following N_{day} days is also included, resulting in $M = (N_{\mathrm{year}} - 2) \cdot (2 \cdot N_{\mathrm{day}} + 1)$ available data points.

As stated in the discussion of VAR processes, in order for the residuals of a linear process to be Gaussian, the measured values themselves should be Gaussian as well. In some rare situations, the M data points gathered in the last step may closely approximate samples from a Gaussian (normal) distribution. However, this is not generally the case, and the distributions tend to be skewed. For this reason, a Rosenblatt Transform is used to 'normalize' the data. In a Rosenblatt Transformation, sampled data are inverted through an approximate Cumulative Distribution Function (CDF), and then through the inverse standard normal CDF to obtain a set of samples that more closely approximate samples from a normal distribution (Rosenblatt, 1952). Once the data have been normalized for each hour and for each phenomenon, the data and information required to invert the data are stored in preparation for model calibration.

5.4.2.2 Calibrate Model for Location

A Vector Auto-Regressive model can be specified in the form of Equation (**5.14)**.

$$\begin{bmatrix} Y_1 \\ \vdots \\ Y_W \end{bmatrix}_i = \mathbf{\Phi}_i \cdot \begin{bmatrix} Y_{1,i-j(1)} \\ \vdots \\ Y_{W,i-j(1)} \\ \vdots \\ \vdots \\ \vdots \\ Y_{1,i-j(L)} \\ \vdots \\ Y_{W,i-j(L)} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_W \end{bmatrix}_i \qquad \mathbf{(5.14)}$$

Where $\begin{bmatrix} Y_1 \\ \vdots \\ Y_W \end{bmatrix}_i$ correspond to the W different phenomena of interest at a given hour[13], $\mathbf{\Phi}_i$ is the $WxLW$ matrix of coefficients defining the VAR model, multiplied by the vector of lagged values of the phenomena. For the model calibration to be complete, the modeler must define the matrix $\mathbf{\Phi}_i$, as well as the values of the means and covariance used to sample the residuals.

The first step in calibrating the model is to determine the set of lags of interest. In this context, a set of lags is defined as the values $[j(1), \cdots, j(L)]$ that define which previous hours the current state is regressed upon. While this step may appear trivial, it is quite important to the proper calibration of the model. Because only a limited amount of data will be available at each hour, only a limited number of lags can be included. Using too many previous coefficients as predictors can lead to over-fitting, resulting in poor predictive capability. Before defining how a set of lags is chosen, I will first briefly digress to introduce how the model is calibrated given a set of defined lags. The reasoning will become clear later in this section.

Once a particular set of lags has been chosen, the modeler creates a set of equations of the form shown in Equation (**5.15)**.

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[13] The author chooses to include Dry Bulb Temperature, Humidity, Wind Speed Magnitude along the East-West direction, Wind Speed along the North-South direction, Cloud Cover (in fourths), Barometric Pressure, Direct Solar Radiation, and Diffuse Solar Radiation. However, the inclusion of fewer or additional phenomena is allowed.

$$\begin{aligned}\left[\vec{Y}_{i,1},\cdots,\vec{Y}_{i,M}\right] &= \mathbf{\Phi_i}\cdot\begin{bmatrix}\vec{Y}_{i-j(1),1} & \cdots & \vec{Y}_{i-j(L),1}\\ \vdots & \ddots & \vdots\\ \vec{Y}_{i-j(L),1} & \cdots & \vec{Y}_{i-j(L),M}\end{bmatrix}\\ &+\left[\vec{\varepsilon}_{i,1},\cdots,\vec{\varepsilon}_{i,M}\right]\\ &= \mathbf{\Phi_i}\cdot\overrightarrow{\mathbf{Y}_\mathrm{i}}+\left[\vec{\varepsilon}_{i,1},\cdots,\vec{\varepsilon}_{i,M}\right]\end{aligned} \tag{5.15}$$

where the $\vec{\cdot}$ operator denotes the vector defining the complete set of phenomena or residuals for each phenomenon, and there are M observations of the process where $M=\left(N_{\text{year}}-2\right)\cdot\left(2\cdot N_{\text{day}}+1\right)$ as previously discussed. Once the set of equations have been thusly defined, $\mathbf{\Phi_i}$ can be defined via linear least squares using Equation (5.16).

$$\mathbf{\Phi_i}=\left[\vec{Y}_{i,1},\cdots,\vec{Y}_{i,M}\right]\cdot\overrightarrow{\mathbf{Y}_\mathrm{i}}^{\mathbf{T}}\cdot\left(\overrightarrow{\mathbf{Y}_\mathrm{i}}\cdot\overrightarrow{\mathbf{Y}_\mathrm{i}}^{\mathbf{T}}\right)^{-1} \tag{5.16}$$

The next step is to define the residuals in the fashion of Equation (**5.17)** and then to capture the vector of means and covariance matrix for each hour using standard statistical methods.

$$\left[\vec{\varepsilon}_{i,1},\cdots,\vec{\varepsilon}_{i,M}\right]=\left[\vec{Y}_{i,1},\cdots,\vec{Y}_{i,M}\right]-\mathbf{\Phi_i}\cdot\overrightarrow{\mathbf{Y}_\mathrm{i}} \tag{5.17}$$

Based on the amount of data available to the authors, a set of seven lags was chosen. The specific lags were selected based upon an algorithm considering iterative improvement. For each hour, each of the 48 preceding hours are considered as the sole predictor, and compared against each other based upon the Mean Square Error of the prediction residuals. After the single best predictor is chosen as the first lag, the process is repeated to find the second lag, third lag, and so on. It should be noted that the algorithm followed may not produce the truly optimal set of lags, since it follows an iterative, rather than all-at-once, optimization process. However, it was deemed that the difference in regression quality was not significant enough to merit the additional computational effort required for exhaustive search (~300 vs. ~$1.2\text{x}10^{10}$ function evaluations). Once performed for each hour of the year, the model is fully specified, and is ready to be implemented.

5.4.2.3 Generate SMY for Location

The final step in the process of creating an SMY is the generation of a time series of correlated noise using the model developed in the previous stage. First, a "warm-up" period of uncorrelated white noise is generated. The uncorrelated white noise serves as the values of the previous states, and as such should be as long as the largest lag considered. Then, for each hour, $\vec{Y}_i$ is determined by multiplying the linear model coefficients by the previous values and adding $\vec{\varepsilon}_i$, which is generated by sampling a multivariate normal distribution with means and covariance matrix specified by the model. The model should be allowed to "warm-up" by repeating this process for at least 10 days, and then continued until the desired number of SMY years have been created. With the time series thusly generated, an inverse Rosenblatt Transform is used to convert the "normalized" time series into the original domain of the measured data.

The final step is to calibrate the generated time series by the original historical CDF. In this step, a kernel-smoothed approximate CDF is determined for each stochastically generated time series, and then transformed, via a Rosenblatt Transform, into the form of the CDF of the historical data. This ensures that particularly difficult to model phenomena, like direct radiation, have a distribution similar to that found in nature. When completed, the generated time series need only be stored into the correct formatting for the analysis tool of choice. In the next section, a case study is presented in which a set of 100 SMY's are generated, and then compared to TMY3 data and a historical dataset for the city of Atlanta, GA, USA.

5.4.3 Analysis of an off-grid home in Atlanta, GA, USA

This section introduces a case study to demonstrate the impact of weather dataset selection on predicted building performance, especially in cases where occurrence of rare events, such as insufficient power to service the home, is of more concern than average performance.

The case study building is an off-grid solar house designed and built by the Georgia Tech Solar Decathlon (GTSD) team as their entry to the Solar Decathlon competition 2007 (Way, 2007). The GTSD house features a single family house, and is powered entirely by 39 photovoltaic (PV) modules with storage provided by 8 battery modules. Further details of the GTSD design and resulting performance have been reported previously (Choudhary et al., 2008).

As the GTSD house is designed to be a zero energy home and completely powered by the installed PV system, power adequacy is one of the most critical performance aspects in design evaluations. There are three basic power adequacy performance indicators: failure rate, outage duration, and annual power unavailability (Billinton and Li, 1994). Failure rate refers to the frequency of power interruptions, which occur when insufficient power is available to perform a house function (such as cooking, shower, etc). This case study does not differentiate between different house functions and counts any time that the total house energy demand is not met as a power interruption. Outage Duration refers to the length of time a power interruption lasts. Specifically, this study will use the mean Outage Duration as the performance indicator for comparison. Annual power unavailability is an aggregated measure of total power outages within a year, namely the percentage time of a year during which power is

Table 5.3. Summary of Performance Indicators

Performance Index	Description	Units
λ	Failure Rate	# /yr
$\bar{r}$	Mean Outage Duration	hr
U	Annual Power Unavailability	%
EN	Energy Needed	kWh/yr
EW	Energy Wasted	kWh/yr
EP	Electricity Production	kWh/yr

insufficient to meet the demand. In addition to the basic power adequacy indices, two other indices are also included to measure the energy performance of the GTSD house: Wasted Energy (due to finite energy storage capacity) and Energy Needed. The remaining performance indicator chosen for this study is the annual power production, considering the high correlation between PV production and available solar radiation in a location. Table 5.3 lists all performance indicators used in this case study.

Three weather datasets are compared in this study: TMY3, historical weather, and the SMY generated based on the approach described in previous sections. The historical meteorological data as obtained from the database includes several gaps when data are not available. These gaps must be filled in order for it to be possible to execute the simulation of the GTSD home. The process followed to fill the gaps in data is similar to that specified in the National Solar Radiation Database 1991-2005 Update (NREL, 2012). If three or less sequential data points are missing, they are filled using linear interpolation of the immediately preceding and following hours. For gaps of four or more, the data is

Table 5.4. Average Performance using Different Meteorological Year Types

	E(λ)	E($\bar{r}$)	E(U)	E(EW)	E(EN)	E(EP)
Hist	41.5	8.91	4.20%	1911	236	9370
SMY	50.4	8.01	4.70%	1894	270	9301
TMY3	57	6.71	4.40%	1364	250	9531

linearly interpolated between the same times at the preceding and following days. In the few cases that remained, interpolation between already-interpolated values was allowed. While the techniques utilized allow for the possibility of discontinuities, they do not significantly affect the statistical properties of the meteorological data over the course of a year, and were deemed sufficient for this analysis.

One hundred SMY were generated for the city of Atlanta using the 39 years of un-edited meteorological data from the Hartsfield-Jackson International airport (ISH ID# 722190). Seven lags were selected at each hour using the simple algorithm described previously. Results of the analyses using TMY3, historical, and SMY are presented in the next section.

5.4.3.1 Results and discussion

Table 5.4 compares the expected values of the performance indicators of the GTSD house for the three weather datasets. From Table 5.4, SMY seems to predict slightly more failures per year, but of lesser duration, such that the average percentage of time in which power is unavailable to meet supply is quite similar to the historical average. The TMY3, historical, and SMY-based predictions of average energy needed, produced, and wasted are also similar.

While the averages are somewhat useful for making initial comparisons between the historical data set and SMY, they are less useful for comparisons against TMY3 or the occurrence of extreme events. Especially in the context of a risk-conscious decision making process, the mean of a performance indicator is not sufficient to describe acceptability. Rather, the variation away from the mean should also be captured, such that a proper risk analysis can be performed. To better analyze the effect of different types of meteorological years, the distributions of the various performance metrics are investigated as well.

As shown in Figure 5.13 and Figure 5.14, empirical CDFs can be generated to visualize the spread of data around the average value. In Figure 5.13, note how even though all three meteorological year types result in similar averages, TMY3 fails to account for any variation away from mean. In Figure 5.14, note how the TMY-based simulation fails to capture the Mean Outage Duration as predicted by historical or SMY. In order to make statistical comparisons, Kolmogorov-Smirnov hypothesis testing (Kolmogorov, 1933; Smirnov, 1948) can be applied to the CDFs to determine whether the two sets of samples could have been sampled from the same distribution. For a given confidence level $\alpha=0.05$, the maximum vertical difference between the two CDFs is the only factor which determines whether the hypothesis is accepted (the samples come from the same distribution) or rejected (they do not).

For the metrics considered in the case study, the results of the Kolmogorov-Smirnov hypothesis tests are shown in Table 5.5. When the p value is less than 0.05, the null hypothesis is rejected, else it is accepted. As seen in the hypothesis testing of the given samples, the null hypothesis is rejected for the Failure Rate and Mean Outage

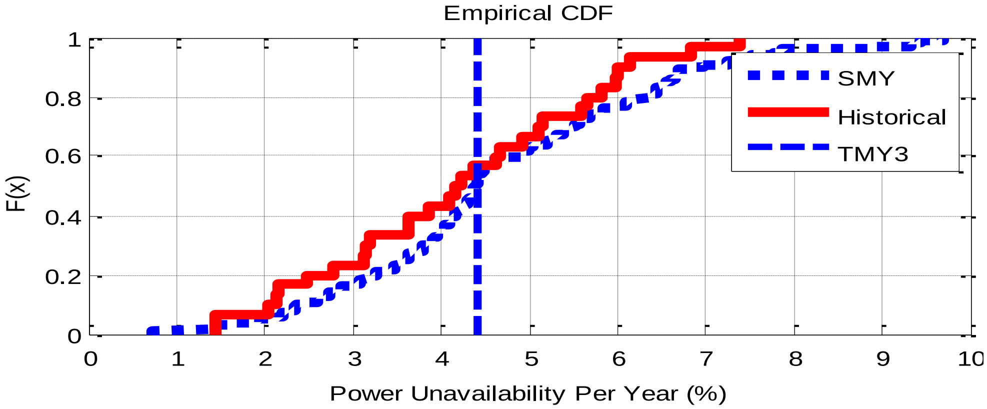

Figure 5.13. Power Unavailability Predictions using TMY, AMY, and SMY

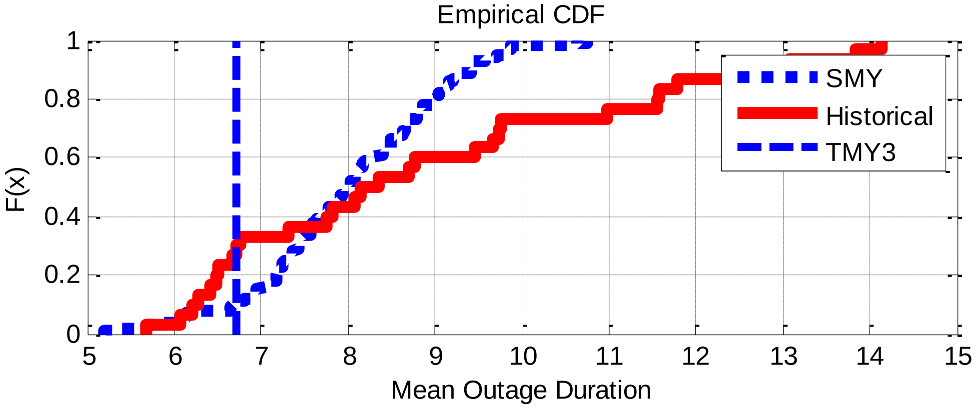

Figure 5.14. Mean Duration of Failure Predictions using TMY, AMY, and SMY

Duration in a given year. However, for the remaining factors, namely the Annual Power Unavailability, as well as the Energies Needed, Wasted, and Produced, the null hypothesis is accepted. A possible explanation as to why these particular attributes appear to match historical data closely, while the duration of failure (and therefore mean and frequency of occurrence) do not, concerns the nature of a stochastic prediction.

Table 5.5. Hypothesis Testing of Similarity Between SMY and historic data sets

	λ	E(r)	U	EW	EN	EP
p Value	0.015	0.010	0.696	0.174	0.383	0.320
Test Value	Reject	Reject	Accept	Accept	Accept	Accept

When calibrating the model, the modeler assumes that any behavior not captured by the indicator variables is stochastic, and captures it using the residuals, $\vec{\varepsilon}$. In reality, there are some phenomena that could better explain these residuals, but are not considered in the model. When using a VAR model, any phenomenon not captured is assumed to be completely stochastic, such that correlations between residuals at subsequent hours are not considered. As such, a stochastic replication of a natural process may appear 'noisy' in comparison. In the context of the meteorological data captured in the model, this is relevant to Temperature, which appears to not maintain sustained levels in the same manner as in reality. Future work to reduce and possibly eliminate this error could include: the incorporation of additional meteorological phenomena to serve as indicator variables (for example: Precipitation); the inclusion of additional lags, tailored to each phenomenon, or the inclusion of a Moving Average (Chatfield, 2004) process to consider correlations between sequential residuals.

In light of the hypothesis test results, it is not advisable that the model, in its current state, be used for decision-making when the duration of outages is of key concern. However, when annual percentage of power unavailability is of primary concern, especially when uncertainties beyond those regarding the meteorological surroundings are of interest as well, the use of SMY as the meteorological basis would allow the modeler to perform Monte-Carlo sampling without relying upon a finite set of historical years. Rare weather events, as generated in the production of SMY, could then be included. Future work should also further investigate the effect of uncertainty in meteorological phenomena relative to other uncertainties prevalent in the design of building systems. Such a comparison could identify scenarios in which the benefit gained by consideration of meteorological uncertainty does not fully offset the cost of doing so.

5.5 Summary

In this chapter, I have reviewed the predictive capabilities of the tools and methods in the building energy modeling domain. Based upon the need to enable decision makers in the field to make informed decisions in a more pragmatic manner, I introduced the Georgia Tech Uncertainty and Risk Analysis Workbench. The GURA-W allows architects, designers, and other practitioners that may lack expertise in the field of uncertainty quantification to perform such analyses with significantly reduced manual effort and training. The GURA-W is not meant to replace informed and deep consideration of a particular decision context, but rather fits within a pragmatic framework for decision making. By connecting the practitioner with the UQ Repository of rigorously quantified uncertain properties and model forms, the workbench grants the capability to perform initial analyses that can be refined based upon sensitivity analyses.

Additionally, the Stochastic Meteorological Year was introduced as a tool for quantifying the variability in the meteorological surroundings of a building, and a framework for its development is presented. Evaluations of an off-grid net zero energy solar decathlon house using three different meteorological year formats were performed as a case study. Relative to historically and TMY-based predictions, SMY-based predictions accurately represented the performance of the house with respect to power unavailability, among other design attributes.

CHAPTER 6

VALUE-DRIVEN ANALYSIS OF ENERGY SAVINGS PERFORMANCE CONTRACTS

6.1 Introduction

The primary focus of this chapter is the evaluation of the tools and methods developed in this research. The evaluation focuses on their application to Energy Savings Performance Contracts (ESPC), which are reviewed in §6.2. Then, §6.3 begins the investigation through the development and evaluation of a generic value model of energy savings performance contracts for commercial contexts. §6.4 presents an analysis of the generic model and offers conclusions about the practice. Lastly, §6.5 presents a case study examining the specific ESPC context of retrofit of a public middle school in Pennsylvania.

6.2 Energy Savings Performance Contracting Fundamentals

Due to strong economic and environmental stimuli, it is common for building owners and operators to desire to retrofit their building stock in order to meet guidelines on sustainability and energy consumption. However, many possess limited funding authority, and therefore cannot necessarily afford the sizable upfront costs associated with large scale building retrofits. A potential solution to the problem is to collaborate with Energy Services Companies (ESCo), who are willing to perform the retrofits with no initial payments, and be repaid through savings in the building's operations and management costs (utility payments)[14]. However, uncertainty in the effectiveness of the retrofit, the operation of the building, and the future weather among other sources results in risk to both parties about whether the predicted energy savings will actually be realized.

6.2.1 Types of Clients in an ESPC

6.2.1.1 Government

As early as 1988 (US Congress, 1988), the United States' Congress had realized that:

> *"(1) The Federal Government is the largest single energy consumer in the Nation;*
>
> *(2) the cost of meeting the Federal Government's energy requirement is substantial;*
>
> *(3) there are significant opportunities in the Federal Government to conserve and make more efficient use of energy through improved operations and maintenance, the use of new energy efficient technologies, and the application and achievement off energy efficient design and construction;*

---

[14] Other financing models similar to energy savings performance contracting are reviewed in §6.2.3

> *(4) Federal energy conservation measures can be financed at little or no cost to the Federal Government by using private investment capital...; and*
>
> *(5) an increase in energy efficiency by the Federal Government would benefit the Nation by reducing the cost of government, reducing the national dependence on foreign energy resources, and demonstrating the benefits of greater energy efficiency to the Nation."*

The Federal, state, and local governments are then unique among types of ESPC clients, in that they can be mandated to achieve given levels of energy efficiency improvements. For example, as a direct result of several executive orders (Bush, 2007; Obama, 2009) and congressional acts (US Congress, 2007; US Congress, 2005), many government agencies are required to retrofit their current building stock, or design more efficient buildings. In recognition of the limited funding authority of the many agencies the various governments include, the agencies have been explicitly allowed to utilize contracts such as ESPCs. This minimizes the risk for the Federal government, offers savings to ESCOs that implement the retrofits, and leads to efficiency improvements that benefit the public in general in terms of reduced cost of operation. Due to the clear value proposition made for government buildings, this sector (also including universities and hospitals that receive federal funding) accounts for roughly 80% of the entire energy savings contracting market (Hopper et al., 2007).

6.2.1.2 Commercial

Commercial industries may select to finance energy retrofits independent of a performance contract, such that they reap all benefits and suffer all of the risk. However, for retrofits that are sufficiently deep, risky, or offer a low return on capital, commercial building owners may select to enter into a performance contract. ESPC's offer the opportunity to realize long term energy savings beyond the term of the contract, as well as several benefits which may be less likely to be identified, such as increased occupant health, or building desirability to tenants. Commercial and industrial investments account for roughly 15% of the entire energy savings contracting market (Hopper et al., 2007).

6.2.1.3 Residential and Public Housing

As noted by Hopper et. al (Hopper et al., 2007), the residential and public housing sectors are not a common target of energy contracts, as they comprise only 5% of the energy performance contracting market. This is likely due to a confluence of factors, but among them a dominant factor regards the cost of investment, which for the residential scale is often so low that the owners are capable of accepting the entire cost of installation, as well as the corresponding risk. Further, due to the limited extent of common residential units, the available savings often do not provide sufficient margins to account for extensive predictive analyses or validation and verification to be performed.

6.2.2 Energy Savings Performance Contract Procedure

Figure 6.1 presents the key stages of a performance contract. The contract begins with initial investigations, which may performed by multiple ESCOs bidding for the project. During this initial investigation, the ESCO will propose a set of Energy Conservation Measures (ECMs) to be performed as part of the retrofit procedure, as well as an initial projection of savings and pricing. These investigations may be repeated, and eventually a specific ESCO and set of ECMs are selected, and a contract is developed. Depending on whether or not third party financiers are brought in, the ESCO is either

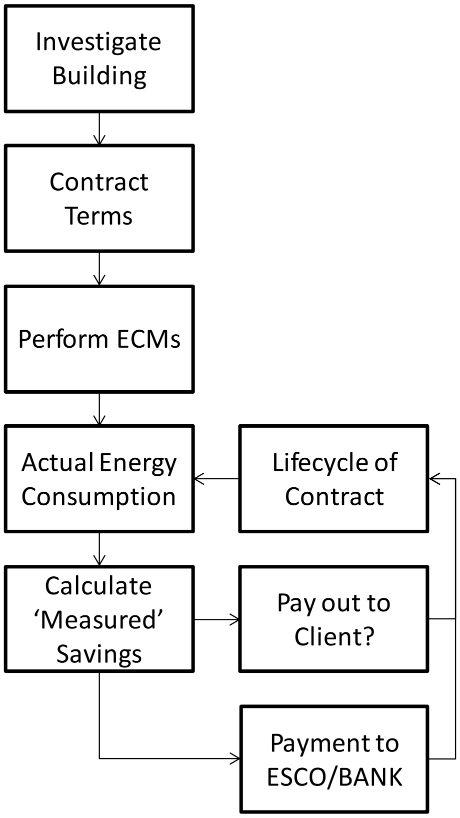

Figure 6.1. Key Stages of Energy Savings Performance Contracts

paid in full initially, or over time. The ECMs are conducted, and then the energy savings are 'measured' according to the contractual verification scheme. If the 'measured' savings are less than the amount of savings guaranteed by the ESCO as part of the contract, then the ESCO must repay the Client the difference.

The results of hypothetical performance contract are also depicted in Figure 6.2. Generally, some amount of historical energy consumption or demand information is available, such as from previous utility bills or direct measurement. Then, the ECMs are performed, and only the actual post-retrofit energy consumption can be known with near certainty. Calculations of 'Measured' Savings are therefore predictions that rely upon predictions of how much energy the pre-retrofit building would have consumed during

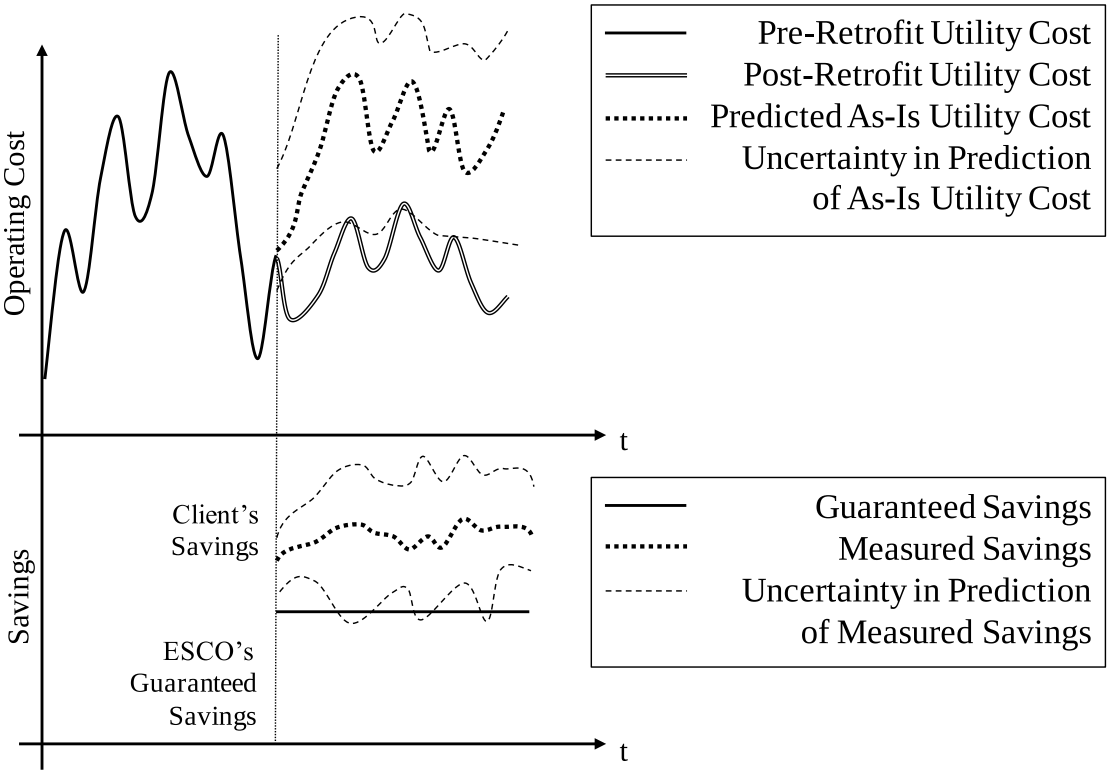

Figure 6.2. Terminology in Energy Savings Performance Contracts

the same period. These predictions are by definition uncertain, and therefore the magnitude of the 'Measured' Savings is also uncertain. The Guaranteed Savings are fixed based upon the contract, and therefore any risk arising from uncertainty in the measurement and verification procedure is held solely by the Client.

6.2.3 Other Types of Financing Models

It is noted that other financing models beyond ESPC exist as options for clients to perform energy efficiency retrofits. Here, I briefly describe the major aspects of some of the more popular of these models.

Property Assessed Clean Energy (PACE) is a financing model in which local governments issue bonds to energy efficiency investors. These investors then make loans available for energy efficiency improvements, which are repaid through property assessments annually, in addition to property taxes. These bonds are only facilitated by the local government, which does not typically guarantee the bond. However, risk due to foreclosure or bankruptcy is limited as the PACE load ranks higher in repayment priority than other debts (Dyer, 2011).

On Bill Financing is another financing model in which no guarantee of savings is made, and where the ESCO is also the providing utility company. On Bill Financing can be structured such the tenant is responsible for payments even if they leave the structure, or can be associated with the meter, such that if the tenant leaves the structure, the payments transfer to the new tenant. On Bill Financing can be supported using public funds, third party loans, or utility funds, and offers benefits that target small residential projects more efficiently than larger buildings, as the charges are organized as part of the utility bill, do not require extensive external verification and measurement.

Power Purchase Agreements typically focus only on implementation of renewable systems, as opposed to more general ECMs that focus on reducing demand for energy. In a Power Purchase Agreement, the owner allows a developer to install the renewable system on the owner's property, who agrees to purchase the energy from the system at a given fixed or escalating price. In this financing model, the renewable system is owned by the developer, who is responsible for maintenance and operation. The initial funding for the renewable system may come from the developer, or an external third party financier.

Energy Savings Agreements (ESA) are another financing model that offer the potential for a building owner to have the ECMs performed at no upfront cost. In an ESA, the building owner enters into a contract with a third party financier to have the ECMs performed. An ESCO performs the ECMs as a contractor to the financier, and no guarantees of savings are made to the building owner. Instead, the financier charges the building owner a fixed monthly fee. Under such a contract, neither the building owner nor the ESCO accepts any significant risk, and so the financier accepts all risk, but also receives most, if not all, of the monetary gains.

6.2.4 Designing Energy Savings Performance Contracts

The retrofit of a building under an ESPC poses an interesting design problem. The ESCO must decide which ECMs to propose, and also the amount of savings to guarantee. In general, the choice of which ECMs to propose is non-trivial, as the interaction between multiple ECMs can be highly non-linear. For example, ECMs that replace old lighting or other electrical equipment with newer, more energy efficient models may drive the system to require more heating energy as the lights subsidized the heating demand. The amount of savings to guarantee is also similar to the specification of price and warrantees on consumer products, and requires careful consideration of the present uncertainty and the resulting risk. The next sections utilize the SMDVM to model the value in various design contexts, and includes evaluations of the proposed alternatives.

6.3 Modeling Value in Energy Savings Performance Contracts

The primary focus of this chapter is the application of the tools and methods developed in this research to investigate the practice of energy savings performance contracting. This section begins this investigation through the development and evaluation of a generic value model of energy savings performance contexts, including the various decision makers, stakeholders, the system and environment, and the relationships between them. The Systematic Method for Developing Value Models described in Chapter 4 is utilized to guide the specification process.

6.3.1 Decision Makers, Stakeholders, the System, and Decision Context

6.3.1.1 Decision Makers

In any given ESPC, there are generally a limited number of key decision makers with the necessary authority to affect the terms of an Energy Savings Performance Contract. Specifically, the ESCO that implements the ECMs and the Client that owns the building (or an agent that acts on his or her behalf, such as a property manager). For the remainder of this Chapter, rather than referring to the Decision Maker, I will refer to either the ESCO or the Client specifically, in order to minimize the opportunity for misinterpretation.

Because the ESCO is a corporate entity, it is assumed that its fundamental objective is to maximize Net Present Value of Profit. Depending on the specification of the Client, the same could be true, or it could be a government agency or entity, in which case it would instead focus on benefit to society. Because the case study introduced at the end of this Chapter will focus on contracts involving a public school, a government funded and run entity, this analysis will instead focus on a commercial context, such that both dominant cases can be investigated.

6.3.1.2 System and the Environment

For both the ESCO and the Client, the system of interest is the building being evaluated for a potential retrofit. Buildings have a variety of purposes, but primary among them in a commercial context is to enable the inhabitants of the structure to perform tasks as comfortably and efficiently as possible. To accomplish this task, Building Systems themselves consist of several integrated subsystems. The lighting system is exists to allow inhabitants to see effectively. The heating, ventilation, and air conditioning systems exist to create a temperate environment suitable for the inhabitants to work. The envelope and construction of the building exist to divide the building into units conducive to perform work, and provide structural support to increase the usable floor space of the building, and to provide aesthetic appeal, among other concerns. In addition, buildings include an electrical system, which can include direct electrical equipment. Buildings also generally include water systems that provide domestic hot water, among other uses.

The system of interest interacts with the environment in a complex manner. From an energy-transfer focused perspective, a building requires either electricity or fuel to produce the energy required to operate its various systems. Alternatively, the building may obtain heating and cooling energy from a centralized plant that in turn requires fuel or electricity. A building also interacts with its environment via heat and mass transfer, including conduction, convection, radiation, and air flow.

6.3.1.3 Stakeholders

Considering the building and its integrated systems, several stakeholders will be affected by and may also be able to impact the outcome of an ESPC. Of primary note are the Financiers, who may be required to provide the initial funding for the retrofit, and who will base their decision upon their expectation of risk. This funding decision will ultimately affect the ultimate cost of the project, as investments deemed higher risk are usually subject to higher interest payments.

Next, the Tenants / occupants of the building often are directly impacted by retrofits. During the design phase, the Tenants may have influence in the selection of a retrofit package. During the installation phase, the Tenants are often displaced. During the operation phase, the Tenants are often a key driver of building energy consumption. As such, their specific concerns in terms of comfort level, and potentially desire for a sustainable environment should be considered.

In addition, Regulatory agencies often have a legal responsibility to provide oversight to ensure health and safety of the public. Their approval is necessary for a project to be successfully executed.

Local, State, or Federal governments may offer incentive plans for energy efficiency retrofits. These may be structured as tax credits or subsidies, and may be based upon estimated or actual energy consumption, or other sustainability related upgrades.

6.3.1.4 Concerns and Actions

Operating the building requires the assumption of cost by the building Owner in terms of equipment maintenance, and may also include the cost of utilities, depending on the arrangement with the Tenants.

The ESCO is not only concerned about the cost and revenue gained from the single retrofit, but should also be concerned about the future profitability of the firm. The future profitability is related to the reputation of the firm, as firms that are forced to "pay out" often gain a reputation of not being able to deliver promised savings. The cost incurred during the specific contract may be decomposed into the cost of any payout, installation cost, measurement and verification cost, and operating and maintenance cost, depending on the terms of the contract. The major actions include the amount of savings that will be guaranteed, and the particular set of retrofits that are proposed.

The Owner is concerned with primarily with the cost of having the retrofit performed, the reductions in cost associated with operations and maintenance, and potential increases in revenue due to rent premiums or Tenant productivity. The major action is the acceptance or rejection of the ESCO's bid for the ESPC.

6.3.2 Relationships and Uncertainty

This purpose of this section is to identify the structure of the value model, uniting the various stakeholders, their decisions and concerns, and system properties. Then knowledge about the relationships can be encoded using a set of models, and uncertainty in these models in analyzed. However, due to the abstract nature of the treatment of ESPCs in this section, explicit analytical models cannot be described to exact detail, as such analysis would require specific contextual knowledge, which is beyond the scope of this section.

6.3.2.1 Identifying Relationships

In this section, the forms of the value models of both decision makers are presented, including the identified relationships between the stakeholders' actions and concerns, and the relevant system properties. Figure 6.3 presents the combined value model formulation for both the ESCO and Client for a generic commercially-focused ESPC. Each individual decision maker is only interested in optimizing according to not only their own preferences, but also their beliefs. As such, Figure 6.3 could be interpreted differently by each decision maker, as each might, in general, have different beliefs about the likelihood of occurrence of different events. More to the same point, each decision maker will have significant information about their own preferences, but may be only able to predict the preferences of the other party within some accuracy. For example, while the Client may understand that maintaining a good Reputation is important for ESCO, such that it can continue to attract future contracts, the ESCO and the Client may not have identical beliefs about nature of the analytical relationship. As such, a complete development of the value model for each decision maker would require an independent elicitation of beliefs and preferences for each decision maker. This task will be more completely addressed in the case study, later in this chapter.

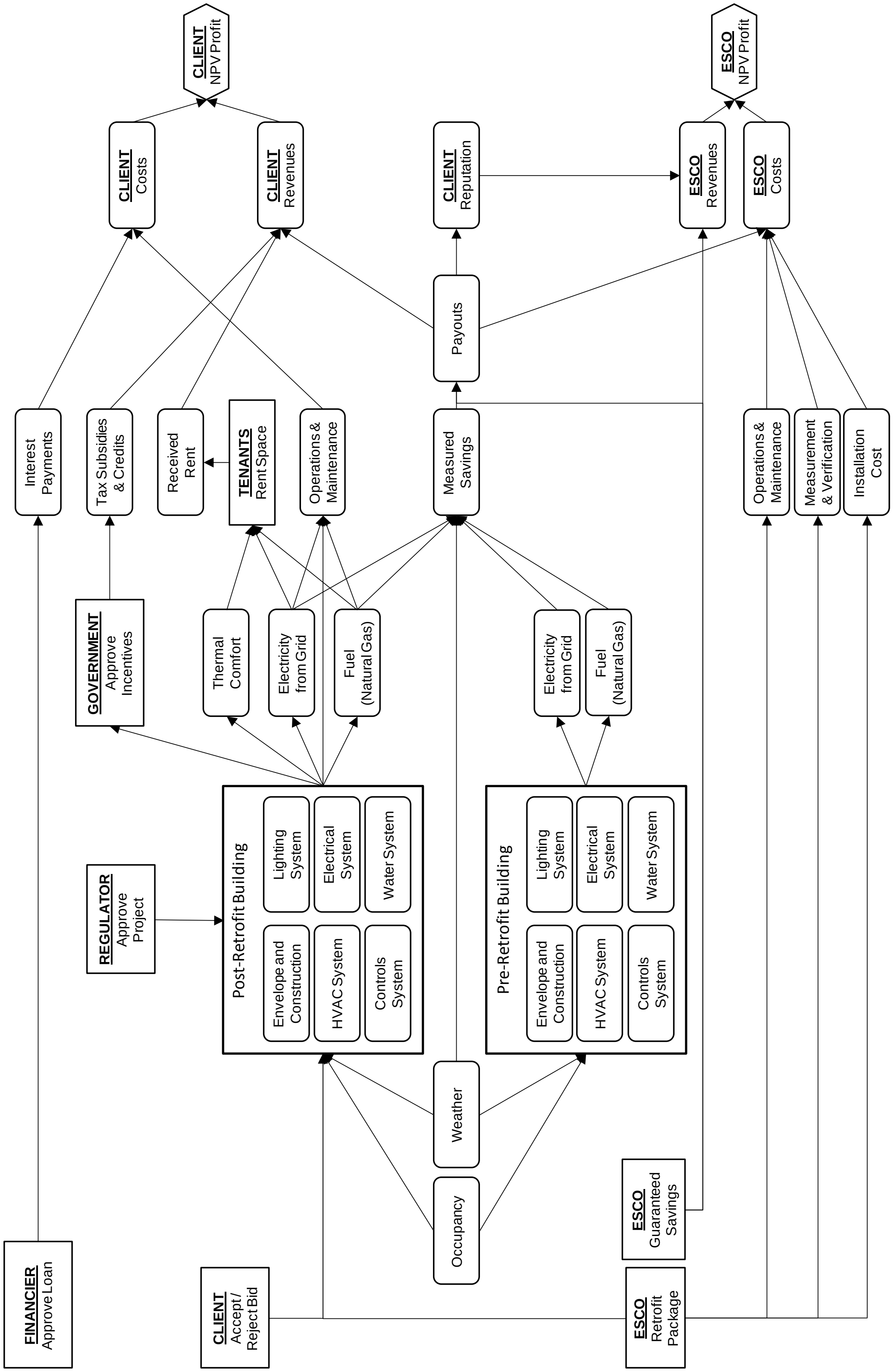

Figure 6.3. Combined Value Model for ESCO and Client in Commercial ESPC

Beginning from the Client's Fundamental Objective (NPV of Profit), this can be decomposed into Revenues and Costs. Costs can be decomposed into Operations and Maintenance Costs, and Interest Payments to the Financiers. The revenues are due mainly to either Rent Received from Tenants, but should also include any subsidies received as part of an energy efficiency upgrade incentive program, as well as any potential payouts from the ESCO in response to insufficient measured savings being realized. The Operations and Maintenance Costs are impacted by the cost to operate the building's systems, and also by the set of equipment in the building. If equipment is replaced as part of an ECM, for example a new boiler replaces an aging, inefficient unit, then the costs associated with maintaining the equipment may also reduce, or may be addressed entirely by the ESCO as part of the contractual terms. The Tenants desire to rent space may depend on their own utility costs, as well as the thermal comfort of the building. The actual behavior of the building will ultimately depend upon the operation and performance of the various systems within the post-retrofit building, which will depend on whether or not the retrofit is implemented, as well as the weather and occupancy of the building.

Beginning from the ESCO's Fundamental Objective (NPV of Profit), this can be decomposed into their Revenues and Costs. Revenues can be decomposed into those from this particular project, which correspond to the guaranteed savings, and those from future projects, which are assumed to be related to the Reputation of the firm with respect to how frequently Payouts occur. The Costs can be decomposed into those related to Payouts, Operations and Maintenance, Measurement and Verification, and Purchase and Installation. Each of these are then strongly related to the ESCO's decisions of Retrofit

Package and Guaranteed Savings. The Payouts specifically only occur when Measured Savings are less than Guaranteed Savings. Measured Savings refers to the difference between the metered energy consumption and the hypothetical amount of energy the pre-retrofit building would have required for the same period of weather an occupancy.

6.3.2.2 Typical Sources of Uncertainty

The exact sources and quantifications of uncertainty are always context-specific. However, many sources of uncertainty are common throughout various scenarios. This section provides an overview of typical sources of uncertainty for energy savings performance contracts, as relevant to the relationships identified and modeled in §6.3.2.1.

Within the building envelope and construction, several properties that impact the behavior of the building are generally uncertain. The thermal properties of the Envelope and Construction are generally uncertain. The exact efficiencies and performance curves for the HVAC equipment, lighting system, water system, control systems, and amount of direct electrical load are also generally significantly uncertain. The uncertainty in these values may be somewhat reduced via testing or verification, but these tests can be expensive to perform, and therefore some amount of residual uncertainty is typical.

These parameters are often stipulated in the contract for the determination of Measured Savings. The Client usually bears the risk associated with the uncertainty in the pre-retrofit building, since they accept the contractual specification for how savings will be measured. For the post-retrofit building, the ESCO will bear the risk, Depending on which Measurement and Verification procedures are implemented. If the ECMs fail to deliver the promised level of performance, then the ESCO will have to Payout to the

Client. Or, if direct energy bills are not utilized, but rather stipulated values are utilized to predict Measured Savings, then the Client will absorb this risk.

Another dominant source of uncertainty is the variability in the weather. Years of milder weather can have significant effects on the demand for heating and cooling, and drastically reduce the efficacy of ECMs. The effects of the weather are often stipulated in the calculation of Measured Savings, but the models of these effects are often overly simplistic, such as linear adjustments according to the number of heating or cooling degree days.

Occupancy is another of the major sources of uncertainty in the operation of the building that impacts the demand for heating and cooling. High occupancy can lead to increased direct electrical loads, but also drives lighting and ventilation as well. Contracts also typically allow for non-standard adjustments based upon changes in occupancy, such that the Client bears all risk associated with significant changes. If the Owner is not also the Tenant, then these adjustments may be quite likely.

Operations and Maintenance Cost is also uncertain, because equipment may suffer non-conformances and need to be replaced before the expected life has been reached. The cost of electricity and natural gas (or other fuels) is also likely uncertain, and a strong influence on the cost of operating the building.

Further, the models used to predict the values of several elements are uncertain, as any model is merely an abstraction of reality, and therefore the source of an imperfect prediction. Figure 6.4 shows an updated version of the value model, including the identified sources of uncertainty. Uncertain aspects are shown as ovals.

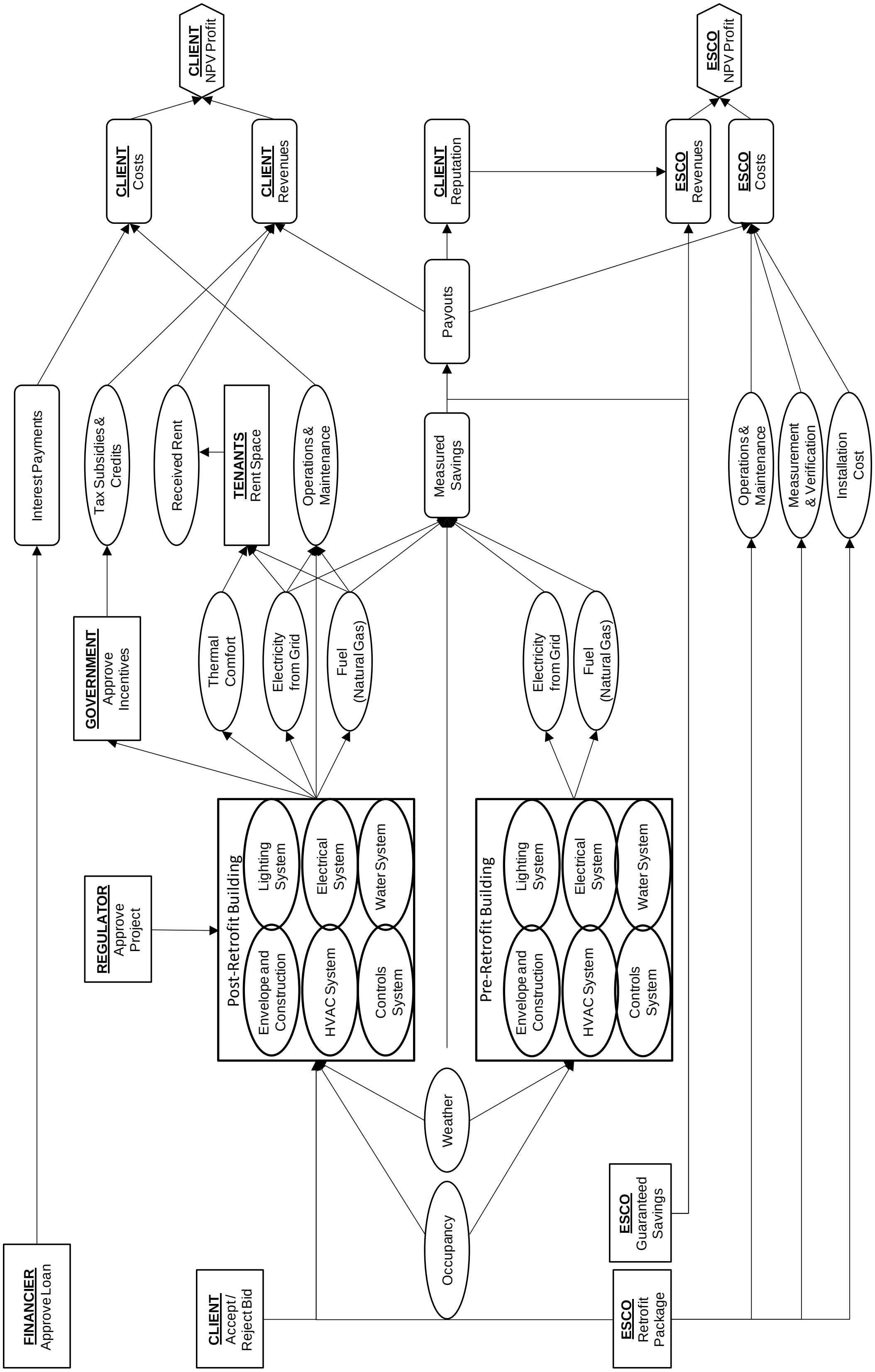

Figure 6.4. Final Combined Value Model for ESCO and Client in Commercial ESPC

6.4 A Game Theoretic Investigation of ESPC

In this section, I present a game theoretic analysis of the decision context developed in the previous section. §6.4.1.1 describes a set of assumptions made about the general form of beliefs and preferences of the decision makers meant to reduce the game into solvable forms while maintaining sufficient contextual accuracy such that meaningful results can still be abstracted. §6.4.2 then presents analyses of the game. The results are then analyzed and a case for transparency in the specification of Energy Savings Performance Contracts is presented in §6.4.3.

6.4.1 Setting up the Game

The value model developed in the previous section is meant to be generic, such that it could apply for a generic ESPC decision in a commercial context. In this section, assumptions are made regarding the form of the beliefs and preferences of the decision makers. Then, two games are proposed that include different types of decision authority on the part of the Client

6.4.1.1 Assumptions about Beliefs and Preferences

As described in the previous sections, once all decisions in either of the games have been made, the only certainty is that the building will or will not be retrofitted, and that retrofit will include the selected ECMs. Following the value model of Figure 6.4, there still exists uncertainty in the Occupancy, Weather, Pre- and Post-Retrofit Building Construction, HVAC, Control, Equipment, Lighting, Water Systems, Resource Consumptions, Thermal Comfort, and various other Costs and Revenues. The contractual guarantee on savings is meant to shift the risk of poor building performance from the Client, onto the ESCO, and indeed it does exactly this. However, because the Client knows that the ESCO would prefer not to pay out, the Client may not fully trust that the Measured Savings will be fairly calculated. Specifically, the Client may fear that the ESCO would utilize non-routine adjustments to predicted energy consumption or biased calculations to maximize their own gain. As such, while the contractual guarantee of savings will shift most of the uncertainty in the energy savings of the building, it may not shift all uncertainty. Further, the Client still has uncertainty regarding potential non-energy related Operational Costs such as equipment failure for both the pre- and post-retrofit scenarios. The client may also be uncertain about the perception of the retrofits by potential Tenants, and their ultimate decision to rent space in the building. Also, certain tax subsidies or credits may require actual measurements of energy improvements (instead of predicted values), and therefore the Client may be uncertain about whether those credits will be received. Therefore, even though the Guaranteed Savings offer some protection from risk, it does not remove all uncertainty from the Client.

First, it is assumed that both the ESCO and the Client prefer greater profits, and that they are risk averse over the range of possible outcomes. The degree of their risk aversion, and the exact form of their preferences is not of key importance. Then, it holds that:

$$\frac{\partial U_E}{\partial NPV_E} \geq 0, \frac{\partial^2 U_E}{\partial {NPV_E}^2} < 0 \tag{6.1}$$

$$\frac{\partial U_C}{\partial NPV_C} \geq 0, \frac{\partial^2 U_C}{\partial {NPV_C}^2} < 0 \tag{6.2}$$

where $U_E$and U_C are the ESCO's and Client's utility, respectively, and NPV_E and NPV_C are the their Net Present Values.

Then, given that the net present values are uncertain for both the ESCO and the Client, their expected utilities can be determined as:

$$\mathrm{EU_E} = \mathrm{EV_E} - \mathrm{RP_E} \tag{6.3}$$

$$\mathrm{EU_C} = \mathrm{EV_C} - \mathrm{RP_C} \tag{6.4}$$

where $\mathrm{EV_E}$ and $\mathrm{EV_C}$ are the expected net present values, and $\mathrm{RP_E}$and $\mathrm{RP_C}$ are their corresponding risk premiums.

Next, recall that the ESCO possesses significantly more experience in performing and analyzing retrofits than the Client. Therefore, the Client will have a greater degree of uncertainty in the projected energy savings, and will also have uncertainty in its projection of other revenues and operational savings. Because the Client's beliefs are private, the ESCO will not have exact information about them, but rather can only estimate them as:

$$\mathrm{EU_C} = \mathrm{EV_C} - \alpha \cdot \mathrm{RP_C} \tag{6.5}$$

where α is a random variable describing the ESCO's beliefs about the magnitude of the risk premium resulting from the increase in uncertainty[15].

6.4.1.2 Ultimatum Game

Figure 6.5 presents the format of an ultimatum game corresponding to the decision context of the commercial ESPC. In the game, the ESCO first makes a selection of which ECMs to propose, and then proposes a contract to the Client including the

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[15] Many proofs exist that show that the risk premium increases with an increase in magnitude of uncertainty, see for example (Lee et al., 2010).

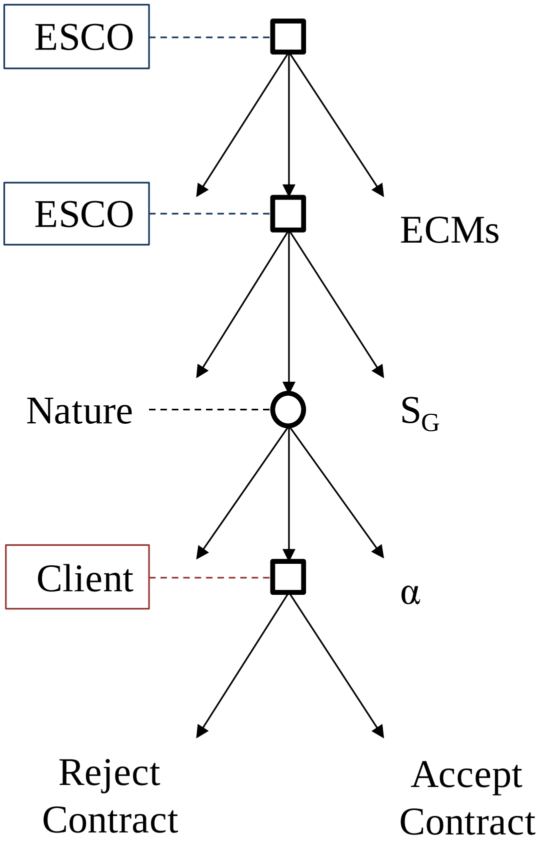

Figure 6.5. Ultimatum Game of ESPC

Guaranteed Savings. In this Ultimatum Game, the Client may only decide to either Accept or Reject the contract terms. Based upon the actions taken by each decision maker, the building will either be retrofit or not, as indicated in Figure 6.4. Examining the remainder of Figure 6.4, the ultimate value received by each decision maker is then still uncertain, at the time that the last decision is made. The beliefs of each of the decision makers, as well as their preferences to that uncertainty must then be explored such that the outcomes can be resolved into an expected utility.

6.4.1.3 Counter-Offer Game

Figure 6.6 presents a slight modification of the Ultimatum Game. In the Counter-Offer Game, the ESCO still proposes a set of ECMs, and then a contract that includes the

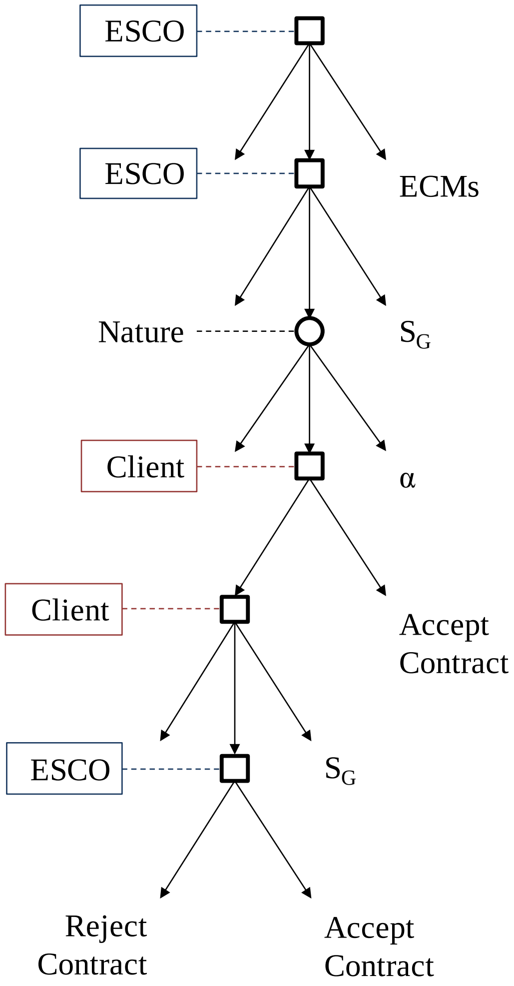

Figure 6.6. Counter-Offer Game of ESPC

Guaranteed Savings. However, now the Client has the capability to present a counter offer in addition to Accepting or Rejecting the ESCO's original offer. Once the Client has presented a counter-offer to the ESCO, the ESCO must now Accept or Reject the proposal. Then, similar to the Ultimatum Game, the beliefs and preferences of the decision makers will define an expected utility for the selected strategy combination. The difference in the Counter-Offer Game is that the negotiation process requires resources (specifically time, but possibly also financial resources) and so the actual implementation of the project, and therefore all cash flows would be delayed.

Additional games involving additional negotiation stages could be created. However, as is shown in §6.4.2, negotiation games focus primarily on how a value surplus will be divided.

6.4.2 Solving the Games

6.4.2.1 Ultimatum Game

Returning to the Ultimatum Game shown in Figure 6.5, solution of the game is performed using backwards induction. The Client performs the final decision, which is to either accept or reject the contract. If the contract is rejected, then the Client expects to receive an expected utility of:

$$\mathrm{EU_C^0} = \mathrm{EV_C^0} - \mathrm{RP_C^0} \qquad \textbf{(6.6)}$$

And if the contract is accepted, the Client expects to receive an expected utility of:

$$\mathrm{EU_C^R} = \mathrm{EV_C^R} - \alpha \cdot \mathrm{RP_C^R} - \mathrm{S_G} \qquad \textbf{(6.7)}$$

Therefore, the Client would choose to reject if $\mathrm{EU_C^R} < \mathrm{EU_C^0}$, and the ESCO would expect to receive an expected utility of:

$$\mathrm{EU_E^0} = \mathrm{EV_E^0} - \mathrm{RP_E^0} \qquad \textbf{(6.8)}$$

The Client would accept if $\mathrm{EU_{CR}} > \mathrm{EU_{C0}}$. If $\mathrm{EU_{CR}} = \mathrm{EU_{C0}}$ then the Client is indifferent between the decisions. Assume that the Client will accept if indifferent, and then the ESCO would expect to receive an expected utility of:

$$\mathrm{EU_E^R} = \mathrm{EV_E^R} - \mathrm{RP_E^R} + \mathrm{S_G} \qquad \textbf{(6.9)}$$

The next decision to consider is the value of savings that the ESCO should guarantee. Figure 6.7 shows the decision for the ESCO at this point. For $\mathrm{S_{G-1}} < (\mathrm{EV_E^0} - \mathrm{RP_E^0}) - \left(\mathrm{EV_E^R} - \mathrm{RP_E^R}\right)$, the revenue is so low that the ESCO would prefer

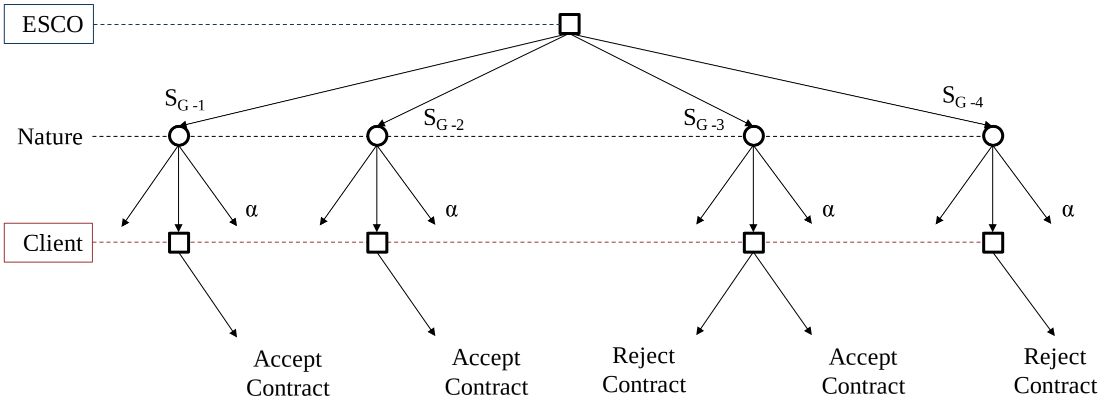

Figure 6.7. Backwards Induction of the Ultimatum Game - 2

that the retrofit not occur, but the Client will (almost assuredly) be willing accept the contract and the ESCO's expected payout is:

$$\mathrm{EU_E(S_{G-1}) = EU_E^R = EV_E^R - RP_E^R + S_{G-1}} \tag{6.10}$$

For $(\mathrm{EV_E^0 - RP_E^0}) - (\mathrm{EV_E^R - RP_E^R}) \leq \mathrm{S_{G-2}} \leq (\mathrm{EV_C^R} - \alpha_{\max} \cdot \mathrm{RP_C^R}) - (\mathrm{EV_C^0 - RP_C^0})$, even the most untrusting Client will still accept the contract and the ESCO's expected payout is the same as in Equation (6.10), except that the value of the guaranteed savings have increased.

$$\mathrm{EU_E(S_{G-2}) = EU_E^R = EV_E^R - RP_E^R + S_{G-2}} \tag{6.11}$$

For any higher of a guaranteed savings, the ESCO cannot be sure that the Client will either accept or reject the contract, since he is unsure of how distrusting the Client is. Therefore, for $(\mathrm{EV_C^R} - \alpha_{\max} \cdot \mathrm{RP_C^R}) - (\mathrm{EV_C^0 - RP_C^0}) \leq \mathrm{S_{G-3}} \leq (\mathrm{EV_C^R} - \alpha_{\min} \cdot \mathrm{RP_C^R}) - (\mathrm{EV_C^0 - RP_C^0})$ the ESCO's expected payout is:

$$\mathrm{EU_E(S_{G-3})} = p_{Reject}(\mathrm{EV_E^0 - RP_E^0}) + p_{Accept}(\mathrm{EV_E^R - RP_E^R + S_{G-3}}) \tag{6.12}$$

where p_{Accept} and p_{Reject} will depend on the distribution of α.

For any higher Guaranteed Savings, the Client will undoubtedly reject the contract, and so the ESCO's expected payout is:

$$\mathrm{EU_E(S_{G-4}) = EV_E^0 - RP_E^0} \tag{6.13}$$

For the remainder of this section, it will be assumed that some value surplus can be generated from performing the retrofit. If not, then the ESCO and Client would likely both agree to not perform the contract. Then, comparing Equations (**6.10)** and (**6.11)**, the payout from selecting $\mathrm{S_{G-2}}$ should dominate that from $\mathrm{S_{G-1}}$. Further, comparing Equations (**6.11)** and (**6.13)**, $\mathrm{S_{G-2}}$ should also dominate $\mathrm{S_{G-4}}$. Effectively, the ESCO should select the guaranteed savings to be some amount higher than their cost (including opportunity costs) but be sufficiently low that at least Client would accept the contract. The exact value for an optimal Guaranteed Savings will depend on the specifics of given decision context. Therefore, I present the following characteristics as potentially reasonable for most circumstances, and identify the impact on the resulting optimal value.

First, consider the guaranteed savings consistent with Equation (**6.11)**. Potential for payouts is quite low in this section, due to the conservatism of pricing. Therefore, the potential losses in reputation are also quite low, and it is expected that while these would grow as the guaranteed savings increased, they will still grow more slowly than the revenue received, as in Equation (**6.14)**.

$$\frac{\delta}{\delta \mathrm{S_G}}\left(\mathrm{EV_E^R - RP_E^R}\right)\Big|_{\mathrm{S_{G-2}}} \geq -1 \tag{6.14}$$

As such, the optimal value for Guaranteed Savings within this range would be the upper limit, or $\mathrm{S_G} = \left(\mathrm{EV_C^R} - \alpha_{\max} \cdot \mathrm{RP_C^R}\right) - \left(\mathrm{EV_C^0 - RP_C^0}\right)$. However, once within the range of Equation (**6.12)**, Equation (**6.14)** may no longer hold. In this range, payouts become more commonplace, which may lead to increasingly damaging effects to reputation. Further, as S_G continues to increase, the likelihood that the Client will accept the contract continually reduces. Therefore, the optimal value for Guaranteed Savings within this range will either be the lower limit, which is the same as the optimal value for the second range, or at some point within this range. Figure 6.8 offers a visualization of how the expected utility might vary with Guaranteed Savings for a hypothetical scenario. Depending on the particular scenario, the optima could either occur at the lower margin or within S_{G-3}.

The final stage in analyzing the Ultimatum game is then to determine which ECMs should be selected. In general, there may be a wide range of potential retrofits that can be offered. These retrofits may vary in risk, as well as expected savings. Typically, it would be expected there will be certain ECMs that are almost guaranteed to produce savings, such as replacing an old boiler in a heating-dominated climate, or an air-conditioning unit in a cooling dominated climate. However, other retrofits that correlate with high uncertainty may require that the ESCO reduce the guarantee on savings to the point that they reduce the expected profitability. As a result, it is not necessarily true that the retrofit package with the highest expected net savings (after accounting for costs) will be the most profitable.

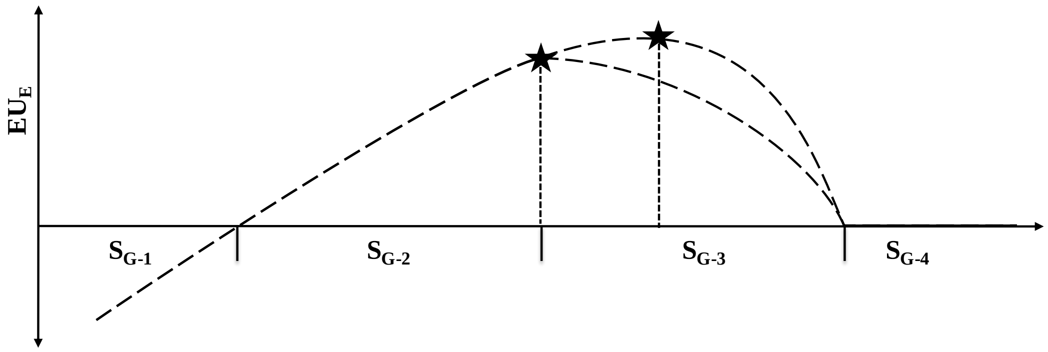

Figure 6.8. Determining Optimal Guaranteed Savings by the ESCO

6.4.2.2 Counter-Offer Game

In a game with a counter-offer being made by the Client, the ESCO no longer makes the final decision on the guaranteed savings. As shown in Figure 6.6, if the Client rejects the ESCO's initial offer, then the ESCO will be forced decide between accepting or rejecting the Client's offer. However, in this situation, some amount of time has passed, and so the payouts of retrofit scenarios are reduced by the discount rate.

$$\mathrm{EU_E^{R2}} = {\left(\mathrm{EV_E^R} - \mathrm{RP_E^R} + \mathrm{S_G}\right)}\Big/{(1+\delta_\mathrm{E})} \tag{6.15}$$

$$\mathrm{EU_C^{R2}} = {\left(\mathrm{EV_C^R} - \alpha \cdot \mathrm{RP_{EC}^R} - \mathrm{S_G}\right)}\Big/{(1+\delta_\mathrm{C}\ \cdot)} \tag{6.16}$$

If the Client rejects the first offer, the last decision in this game is then made by the ESCO, which would accept if $\mathrm{EU_E^{R2}} \geq \mathrm{EV_E^0} - \mathrm{RP_E^0}$, or if $\mathrm{S_{G2}} \leq \left(\mathrm{EV_E^R} - \mathrm{RP_E^R}\right) - (1+\delta_\mathrm{E}) \cdot (\mathrm{EV_E^0} - \mathrm{RP_E^0})$. In counter-offer games like this, the ultimatum is effectively reversed, and so now the Client possesses most of the power in the negotiation. Provided that the ESCO's costs, and therefore payoffs, are relatively well known, the Client could propose a guaranteed savings in one of two ranges, as in Figure 6.9. For $\mathrm{S_{G-5}} <$

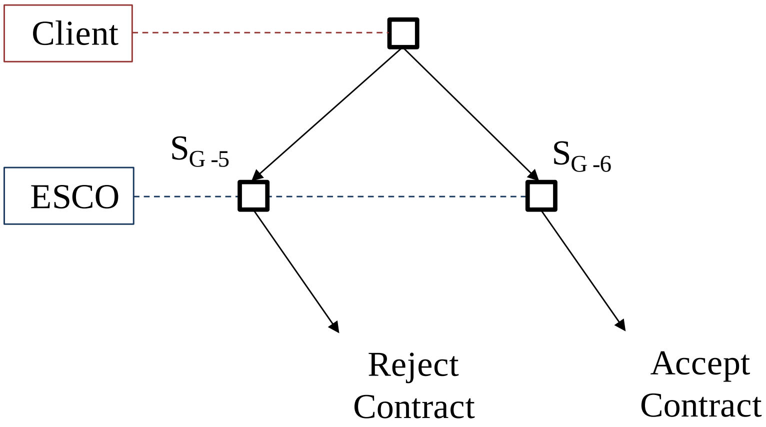

Figure 6.9. Backwards Induction of the Counter-offer Game

$\left((EV_E^0 - RP_E^0) - (EV_E^R - RP_E^R)\right)$, the ESCO will not be able to cover its costs, and therefore would reject the proposal. However, for $S_{G-6} \geq (EV_E^0 - RP_E^0) - (EV_E^R - RP_E^R)$, the ESCO would accept the offer, leading to:

$$EU_E(S_{G-6}) = EU_E^{R2} = {EV_E^R - RP_E^R + S_{G-6}}\big/{(1+\delta_E)} \qquad \textbf{(6.17)}$$

$$EU_C(S_{G-6}) = EU_C^{R2} = {EV_C^R - \alpha \cdot RP_C^R - S_{G-6}}\big/{(1+\delta_C)} \qquad \textbf{(6.18)}$$

Then, because $EU_C(S_{G-6})$ increases as Guaranteed Savings are reduced, the Client would propose the minimum acceptable value to the ESCO, which is roughly equivalent to their cost of performing the retrofits. As a result, during the first stage the ESCO would propose the value for guaranteed savings which would result in the Client being indifferent:

$$S_{G-7} = (EV_E^0 - RP_E^0) - (EV_E^R - RP_E^R) + \frac{\delta_C}{1+\delta_C}(EV_C^R - \alpha \cdot RP_C^R) \qquad \textbf{(6.19)}$$

Thus, as $\delta_{\mathrm{C}} \rightarrow 0$, the time costs become less significant, and ESCO must give away all surplus savings. However, as the δ_{C} increases, the ESCO is able to retain more of the savings, as the Client would prefer not to have to renegotiate.

However, recall that the ESCO does not know the exact value for α, and so therefore must act based upon its limited knowledge. If the Client were to reject the bid, then the Client would pose the minimum acceptable counter-offer, and the ESCO would receive

$$\mathrm{EU}_{\mathrm{E}}^{\mathrm{R2}} = \left(\mathrm{EV}_{\mathrm{E}}^{\mathrm{R}} - \mathrm{RP}_{\mathrm{E}}^{\mathrm{R}}\right) + \left(\mathrm{EV}_{\mathrm{E}}^{0} - \mathrm{RP}_{\mathrm{E}}^{0}\right) - \left(\mathrm{EV}_{\mathrm{E}}^{\mathrm{R}} - \mathrm{RP}_{\mathrm{E}}^{\mathrm{R}}\right) = \mathrm{EV}_{\mathrm{E}}^{0} - \mathrm{RP}_{\mathrm{E}}^{0} \qquad (\mathbf{6.20})$$

Therefore, the optimal bid would maximize Equation (**6.21**), which is equivalent to Maximizing (**6.22**):

$$\max_{\alpha_{\mathrm{s}} \in [\alpha_{\mathrm{min}}, \alpha_{\mathrm{max}}]} \frac{\delta_{\mathrm{C}}}{1 + \delta_{\mathrm{C}}} \left(\mathrm{EV}_{\mathrm{C}}^{\mathrm{R}} - \alpha_{\mathrm{s}} \cdot \mathrm{RP}_{\mathrm{C}}^{\mathrm{R}}\right) * p_{Accept}(\alpha_{\mathrm{s}} A) \qquad (\mathbf{6.21})$$

$$\max_{A \in [\alpha_{\mathrm{min}}, \alpha_{\mathrm{max}}]} \alpha_{\mathrm{s}} * p_{Accept}(\alpha_{\mathrm{s}}) \qquad (\mathbf{6.22})$$

Which is identical to the scenario shown in Figure 6.8, in that the optimum will occur either at α_{max} or at some interior point. The difference is that the payout is significantly reduced to the ESCO.

6.4.3 The Case for Transparency

In Figure 6.8 it is shown that the optimal level of savings for the ESCO to guarantee may be sufficiently high such that an untrusting Client would reject the contract. This outcome is not desirable for either stakeholder. The ESCO does not receive a contract, and therefore earns no profits. Meanwhile, the Client's building does not get

Table 6.1. Analogy to Akerlof's Market for Lemons

Used Cars	Retrofits
Asymmetry of Information	ESCO Has More Experience
Sellers Incentivized for Low Quality	ESCO Wants Profit
Buyers are Worried about Quality	Client Wants Savings
Sellers cannot Prove Quality	ESCO cannot "Guarantee Everything"
Sellers Lack Effective Assurances	ESCO Reputation Limited

retrofitted. Assuming that the retrofit is expected to produce savings, then both parties would better off if an agreeable price could be arranged.

However, this can only be guaranteed if the Client and the ESCO have similar beliefs about the potential savings available. The ESCO will generally possess a great wealth of information about the realistic savings to be generated by a retrofit. The Client is typically less well-informed, which causes asymmetry of information between the two key players. Indeed, there are several key similarities to Akerlof's Market for Lemons (Akerlof, 1970). Akerlof showed how the market for used cars would decay as any honest seller would be forced from the market, given several key assumptions about the market (See Table 6.1). Akerlof described how third party verification of an automobile's quality could be used to provide effective assurances, and lead to a successful market for used cars.

Similarly, a third party verification of the potential savings to be gained through a retrofit would provide neutral evidence that could help the Client to make more informed decisions. If the Client could trust this third party verification of the risk of a retrofit, then the issue of pricing savings too high could be avoided, and any retrofit that actually produces savings could be achieved.

Note, that by setting both parties on the same information level, the payoffs of a contract negotiation depends only upon the decision power of the two decision makers. In the circumstance where the ESCO possesses most of the decision power, perhaps because they have specialized experience, then the ESCO would reap the majority of the savings. However, in circumstances where the Client possesses more decision authority, perhaps because many ESCOs are competing for the bid, then the Client will reap the majority of the savings.

6.4.4 Government Incentivization of Energy Savings

The model can also be used to derive additional insights regarding the power of third parties to influence the decision making of the ESCO or a Client. This section more deeply investigates these extensions, examining potential options for how the government or other entities could encourage energy savings. These are by no means an exhaustive set of options for governments to incentivize energy savings, but only provide an example of how a value model could be analyzed in order to abstract actions by which a third party could increase its own value.

6.4.4.1 Tax Credits for Efficiency Improvements

The most straightforward incentive that a government could provide would be to provide tax credits or subsidies. These could be applied to suppliers, to reduce the effective prices associated with the production of the equipment or other resources needed to conduct the retrofit. Or they could be applied based upon the measured energy savings, which would might directly incentive building owners and tenants to curb their energy consumption.

6.4.4.2 Mandate Third Party Audits of Large Retrofits

A government seeking to increase the number of retrofits performed could mandate the use of third party audits for any project greater than some minimum value. Because the audit would provide a neutral evaluation of the potential retrofits, only those retrofits that actually provide value would be performed. Because "bad" projects are removed from consideration, every project can expect to yield a savings surplus, meaning that a negotiation range will exist for every project. At this point, the matter becomes merely an issue of deciding how to divide the profits to be gained. Assuming the government is concerned only with reducing energy consumption, and not on how the profits of a given project are divided, this solution seems quite reasonable.

6.4.4.3 Mandate Building Efficiency Ratings

The government cannot (currently) compel individual building owners to perform energy related retrofits to their buildings. However, it does have the ability to regulate an industry and mandate the rating of buildings for energy consumption. This could then address the split incentives problem commonly posed for commercial buildings. By mandating the energy efficiency rating of buildings, tenants could more easily compare different buildings based on their projected energy consumption. Owners of buildings would then be more directly incentivized to improve energy efficiency, so that they are able to command higher rent premiums or to obtain higher occupancy.

6.5 Case Study: ESPC for Public School Retrofit

This section presents a case study for a specific energy savings performance contracting scenario. The main purpose of this case study is to provide an opportunity to apply the methods, tools, and principles introduced throughout this dissertation to a deeply examine their pragmatism in a real-world decision. The SMDVM provides a clear, systematic process for guiding the specification of a value model for decision makers within the decision context. The UQ Repository and Stochastic Meteorological Years reduce the amount of effort required for decision makers to identify and quantify uncertainty in relevant parameters of the value model. The GURA-W enables the decision makers to more easily evaluate decision alternatives by automating key tasks related to the simulation and analysis of building energy consumption.

In this section, the target of the case study and the manner in which the potential retrofit is investigated using standard practice are introduced. Then, a value model is developed and analyzed for the decision context. Finally, the results are interpreted to evaluate the performance of the proposed tools and methods.

6.5.1 Background

The building being investigated is Westmont Hilltop Middle School in Johnstown, Pennsylvania (shown in Figure 6.10). The building is 105,200 ft^2 in area, and it serves approximately 500 students. Being in Pennsylvania, the climate of the school is heating dominated. The building requires roughly 55,000 Therms/year, and about 790,000 kWh/year.

Figure 6.10. Westmont Hilltop Middle School

****images from (Maps, 2014)***

ESCOMP[16], an energy services company, proposed to perform a retrofit of the building's systems to improve the energy efficiency of the building. Due to the high cost of the retrofits, a performance contract was deemed as a useful method to create buy-in from the Westmont Hilltop School District Board of Education (BoE). The proposal contract included the following ECMs:

- ECM1: Lighting retrofit
- ECM2: Lighting control with occupancy sensor
- ECM3: HVAC setback control

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[16] Due to a non-disclosure agreement, the name of the actual ESCO involved in the ESPC with the Westmont Hilltop School District Board of Education and the exact details of the proposed contract are not included. Instead, the ESCO is referred to as ESCOMP, and all data have been slightly altered to maintain the privacy of the ESCO.

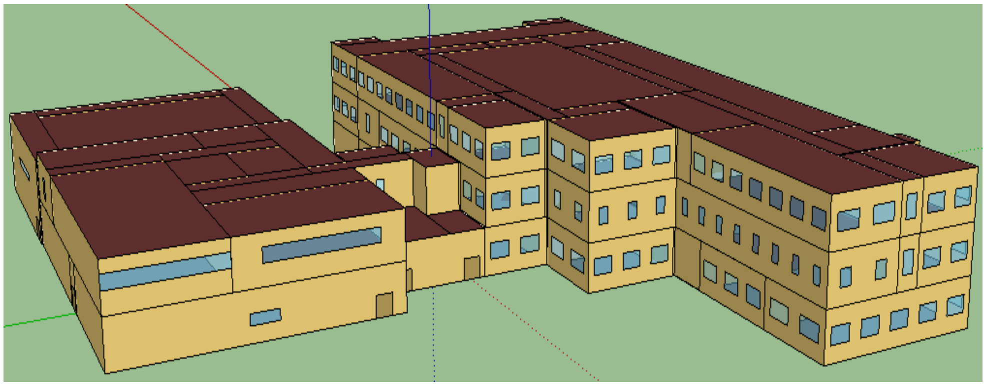
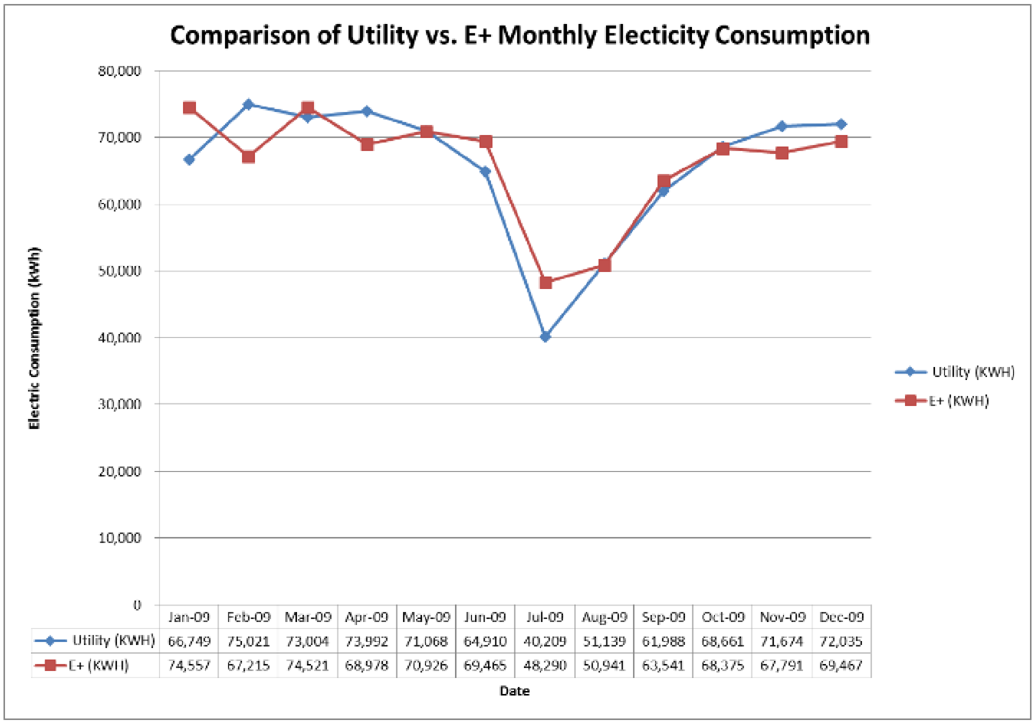


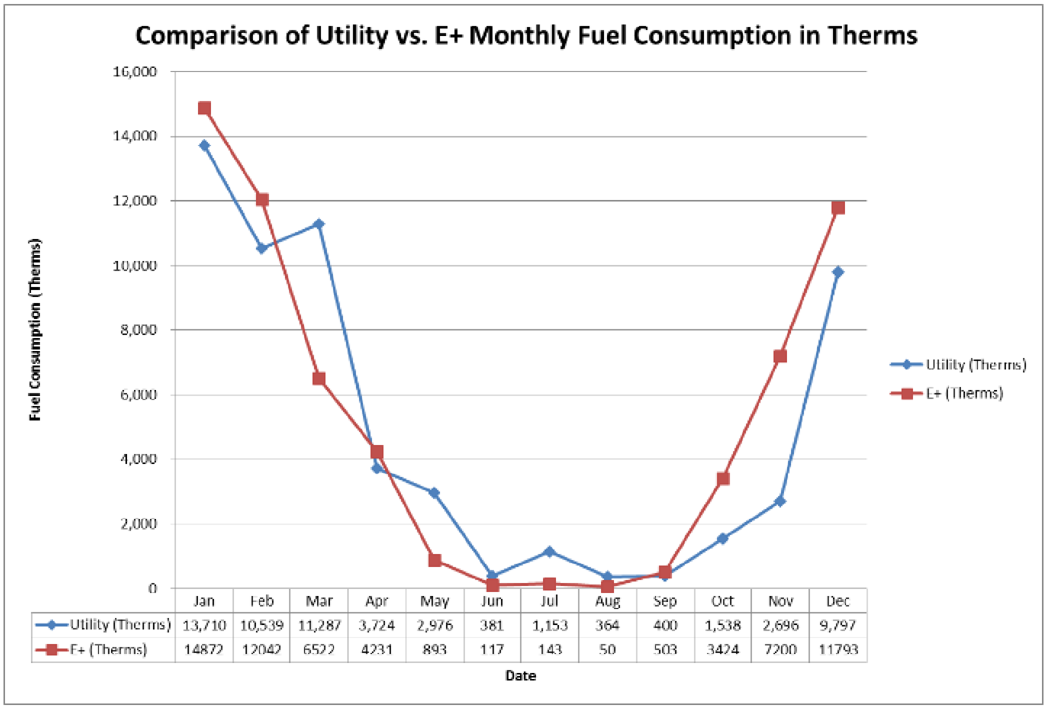
Figure 6.11. Model of Construction of Westmont Hilltop Middle School

- ECM4: Demand control ventilation
- ECM5: High efficiency boiler

To estimate the potential savings to be gained via the retrofit, an energy model of the building was developed for Energy Plus (see Figure 6.12). The model results were compared to actual utility measurement data and found to be acceptably accurate (see Figure 6.12). The current flat utility rate structure was utilized: $0.082/kWh total usage, $3.63/kW peak usage, and $0.785/therm. The savings to be gained by performing the retrofits was estimated at $74,829/year and after applying a 'factor of safety' to the estimated savings, the Guaranteed Savings were declared as $60,000/year. In comparison to the pre-retrofit average energy utility bills, the retrofit promised to reduce the cost of operation by roughly 50%. However, the BoE decided to not accept the contract, and so the retrofit was not conducted. The next section examines this case study more deeply from a value-driven perspective to determine whether the decisions made by both parties were well justified.



	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09
Utility (KWH)	66,749	75,021	73,004	73,992	71,068	64,910	40,209	51,139	61,988	68,661	71,674	72,035
E+ (KWH)	74,557	67,215	74,521	68,978	70,926	69,465	48,290	50,941	63,541	68,375	67,791	69,467



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Utility (Therms)	13,710	10,539	11,287	3,724	2,976	381	1,153	364	400	1,538	2,696	9,797
E+ (Therms)	14872	12042	6522	4231	893	117	143	50	503	3424	7200	11793

Figure 6.12. Verification of Energy Plus Model for WHMS

6.5.2 Value-Driven Optimization

This section presents a value-driven analysis of the decision context for the ESPC of the Westmont Hilltop Middle School. In the next sub-sections, value models are developed for the ESCO and the Board of Education. Then, the decision context is analyzed to determine an optimal portfolio of Energy Conservation Measures to propose, as well as the savings that the ESCO should guarantee to maximize its own value.

6.5.2.1 Developing a Value Model for ESCOMP and BoE

For any ESCO, as for companies in general, the dominant driver for decision-making should be the net present value of profit.

The Board of Education for the district possesses the ultimate decision authority over whether or not to accept a particular contract. Their fundamental concern is the sustained operation of the school building, which is related to the school's safety, comfort, and cost of operation. Operating the building requires the assumption of cost by the BoE in terms of equipment maintenance, and the cost of utilities.

The system of interest includes the entire school building and its constituent systems. The decomposition of the systems for this specific context is similar to that for the generic building identified in the previous section, and includes the Lighting System, the HVAC system, the Building Envelope and Construction, Electrical System, and Water System. The system also requires electricity and natural gas to produce the energy and heat required to operate its various systems. The building also interacts with its environment via heat and mass transfer, including conduction, convection, radiation, and air flow.

Considering the building and its integrated systems, several stakeholders will be affected by and may also be able to impact the outcome of an ESPC.

Also of interest are the Financiers, who will be required to provide the initial funding for the retrofit, and who will base their decision upon their expectation of risk. This funding decision will ultimately affect the ultimate cost of the project, as investments deemed higher risk are usually subject to higher interest payments.

Next, the Occupants (students, teachers, staff) of the building often are directly impacted by retrofits. During the design phase, the Occupants may have influence in the selection of a retrofit package. The occupants are not displaced during installation, since the retrofits can be performed during school breaks. During the operation phase, the Occupants are often a key driver of building energy consumption, as they control the operation of windows, lights, and the set point temperature. As such, their specific concerns in terms of comfort level, and potentially desire for a sustainable environment should be considered.

In addition, Regulatory agencies often have a legal responsibility to provide oversight to ensure health and safety of the student occupants. Their approval is necessary for a project to be successfully executed.

Local, State, or Federal governments may offer incentive plans for energy efficiency retrofits. These may be structured as tax credits or subsidies, and may be based upon estimated or actual energy consumption, or other sustainability related upgrades.

ESCOMP is not only concerned about the cost and revenue gained from the single retrofit, but is also concerned about the future profitability of the firm. The future profitability is related to the reputation of the firm, as firms that are forced to "pay out" often gain a reputation of not being able to deliver promised savings. The cost incurred during the specific contract may be decomposed into the cost of any payout, installation cost, measurement and verification cost, and operating and maintenance cost. The major actions include the amount of savings that will be guaranteed, and the particular set of retrofits that are proposed.

The sustained operation of the school building can be decomposed into BoE's ability to remain financially positive, as well as safe and comfortable. The latter two concerns can be seen as costs to the BoE, because if their levels were to degrade below certain levels, the BoE would be required to suffer costs to address them. Therefore, the BoE's concerns about safety and comfort can be 'priced-out' to be in the same units as their financial concerns.

Figure 6.13 presents the combined value model formulation for both the ESCOMP and BoE for the considered ESPC. Each individual decision maker is only interested in optimizing according to not only their own preferences, but also their beliefs. As such, Figure 6.13 could be interpreted differently by each decision maker, as each might, in general, have different beliefs about the likelihood of occurrence of different events. More to the same point, each decision maker will have significant information about their own preferences, but may be only able to predict the preferences of the other party within some accuracy. For example, while the Client may understand that maintaining a good Reputation is important for ESCO, such that it can continue to attract future contracts, the ESCO and the Client may not have identical beliefs about nature of the analytical relationship.

Beginning from the BoE's Fundamental Objective (NPV of Profit), this can be decomposed into Revenues and Costs. Costs can be decomposed into Operations and Maintenance Costs, Interest Payments to the Financiers, the cost of poor safety, and the cost of comfort. The revenues are due mainly to the operating budget granted by the local municipality, but should also include any subsidies received as part of an energy efficiency upgrade incentive program, as well as any potential payouts from the ESCO in response to insufficient measured savings being realized. The Operations and Maintenance Costs are impacted by the cost to operate the building's systems, and also by the set of equipment in the building. If equipment is replaced as part of an ECM, for example a new boiler replaces an aging, inefficient unit, then the costs associated with maintaining the equipment may also reduce, or may be addressed entirely by the ESCO as part of the contractual terms. The amount of the budget allocated to the district may depend on energy costs of the school, as well as the thermal comfort of the building. The actual behavior of the building will ultimately depend upon the operation and performance of the various systems within the post-retrofit building, which will depend on whether or not the retrofit is implemented, as well as the weather and occupancy of the building.

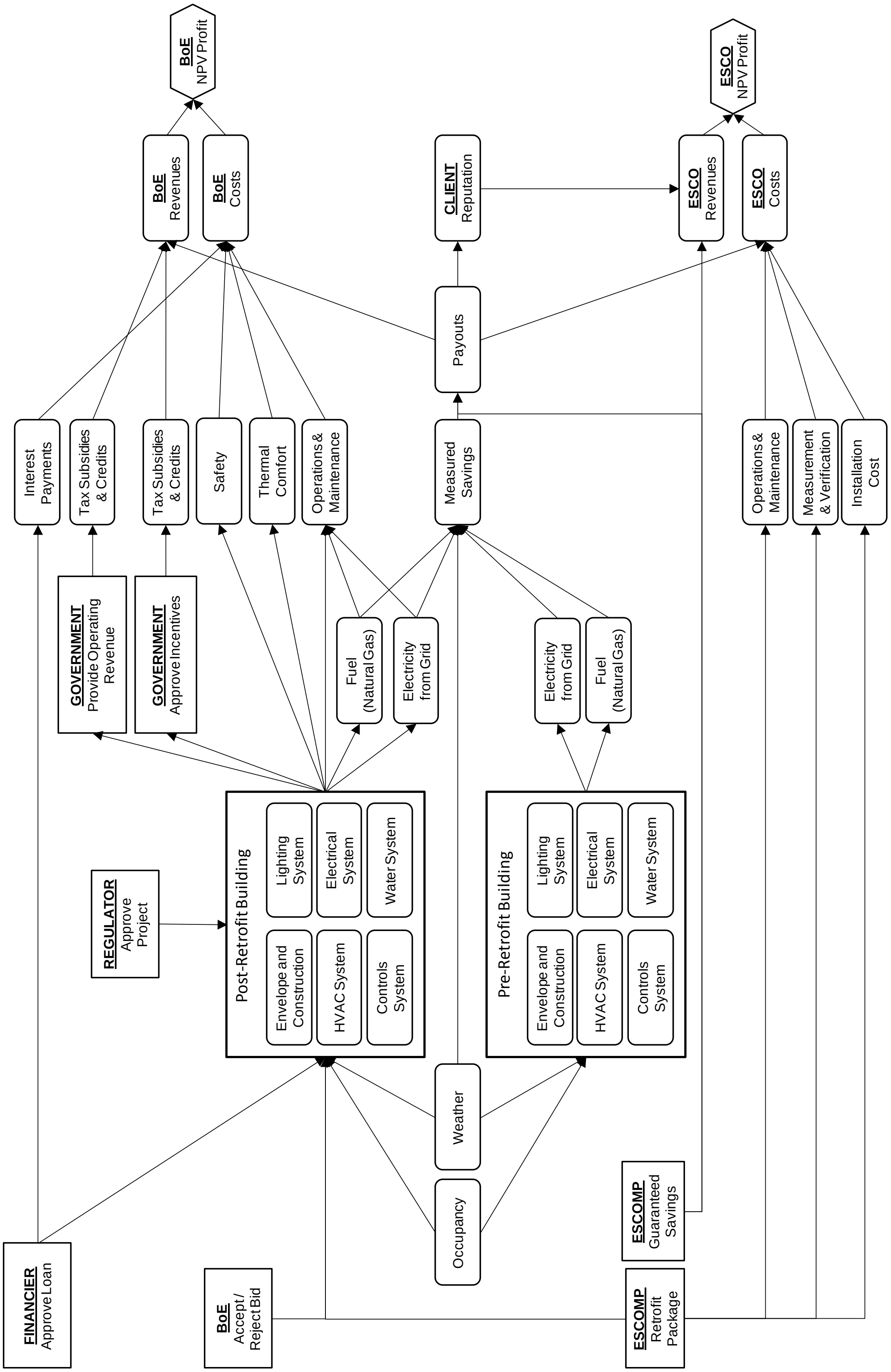


Figure 6.13. Combined Value Model for ESCOMP and BoE

Beginning from the ESCOMP's Fundamental Objective (NPV of Profit), this can be decomposed into their Revenues and Costs. Revenues can be decomposed into those from this particular project, which correspond to the guaranteed savings, and those from future projects, which are assumed to be related to the Reputation of the firm with respect to how frequently Payouts occur. The Costs can be decomposed into those related to Payouts, Operations and Maintenance, Measurement and Verification, and Purchase and Installation. Each of these are then strongly related to the ESCO's decisions of Retrofit Package and Guaranteed Savings. The Payouts specifically only occur when Measured Savings are less than Guaranteed Savings. Measured Savings refers to the difference between the metered energy consumption and the hypothetical amount of energy the pre-retrofit building would have required for the same period of weather an occupancy.

Beginning from the decisions, EnergyPlus v7.0.0, is utilized to relate the ECMs, weather, occupancy, and internal operation of the post-retrofit building to predict the energy consumption of the building. Meanwhile, the prediction of the pre-retrofit building's energy consumption in Therms due to heating needs is made using a regression formula as specified in the contractual terms,

$$\mathrm{E_{heat}} = \mathrm{HDD} \cdot 19.07 - 28{,}250 \tag{6.23}$$

where HDD are the number of Heating Degree Days in a year. The prediction of energy consumption of the building is made using the prior year's energy consumption, as ECMs 1-4 only directly impact the electrical energy consumption of the building. Since the climate does not strongly impact the amount of lighting required, nor the demand ventilation, it was deemed unnecessary to address the impact of the climate on electrical energy consumption.

Table 6.2. Cost Breakdown by Energy Conservation Measure

Energy Conservation Measure	BoE Maintenance Cost	ESCOMP Maintenance Cost	Installation Cost	Measurement Verification Cost
Lights and Lighting Sensors	-$30,900	0[+]	$135,200[+]	$5,000[*]
HVAC Set-Points and Demand Ventilation	-$10,500	$6,400	$205,700	$5,000[*]
High Efficiency Boiler	-$1,450	$450	$45,600	$5,000[*]

[+] Installation cost includes a 10 year maintenance plan that covers all normal maintenance.
[*] If any ECMs are performed, then the total Measurement and Verification cost is assumed.

Measured Savings can then be calculated by sum of prior year's electricity consumption (not adjusted for changes in electricity) and the result of Equation (**6.23**), less the utility bills experienced in a given year.

If any of the retrofits are conducted, then the Board of Education stands to gain from potential changes to the Operations and Maintenance, as shown in Table 6.2. Table 6.2 also shows the corresponding Maintenance Cost accepted by the ESCOMP, as well as the costs associated with measuring and verifying the effective operation of the ECMs and the installation cost, which includes the cost of any equipment and labor.

It is assumed that the local government will continue to provide the same level of funding for the duration of the contract. Therefore, if any savings are realized by the school district, then they would retain those to use for other purposes. The cost of utilities and operations & maintenance over the past years were $179,000. This value is used to estimate the continued operating income received for the school. In this scenario, tax credits and incentives are not available, due to the nature of the retrofits considered.

None of the proposed ECMs pose safety issues in terms of health of the students, teachers, staff, or other occupants. Similarly, the ECMs do not impact the capability of the system to respond to demand for heating or cooling, and therefore do not affect the comfort of the system. As such, they are excluded from further consideration here.

Due to the conservative nature of the Board of Education, they are relatively risk averse. Their preferences are modeled using a Constant Absolute Risk Tolerance of R_{BOE}=\$100,000, and with a discount rate of 7%. By contrast, the ESCOMP is a large company that can support a large degree of risk on a given project. As such, they are modeled using constant absolute risk tolerance of R_{ESCOMP}=\$1,000,000. Similarly, the ESCOMP does not have as easy access to capital, and so their discount rate is given as 10%.

Within the building envelope and construction, several properties that impact the behavior of the building are generally uncertain. The thermal properties of the Envelope and Construction are generally uncertain. The exact efficiencies and performance curves for the HVAC equipment, lighting system, water system, control systems, and amount of direct electrical load are also generally significantly uncertain. Exact information about many of these properties is inaccessible without extensive testing. As such, uncertainty for each of these parameters is quantified according to the default recommendations for the properties in the UQ Repository of the GURA-W. Specifically, the types of parameters considered uncertain, the number of occurrences in the building are shown in Table 6.3.

Table 6.3. Uncertainty in Parameters of the Building System

Parameter Description	**Number of Occurrences**
Material Thermal Conductivity	16
Material Density	14
Material Specific Heat	14
Material Absorptance	16
Lighting Level per Zone	23
Zone Infiltration Flow Rate	23
Miscellaneous Electrical Equipment Gain	5
Water Peak Flow Rate	1
Occupancy per Zone	23
Fan Efficiencies	23
Motor Efficiencies	24
Fan Pressure	9
Cooling Coil COP	18
Supply Pump Rated Head	1

These parameters are often stipulated in the contract for the determination of Measured Savings. The BoE would bear the risk associated with the uncertainty in the pre-retrofit building, since they accept the contractual specification for how savings will be measured. For the post-retrofit building, the ESCO will bear the risk, because Option C of the Measurement and Verification procedures from (Efficiency Valuation Organisation, 2012) are implemented. If the ECMs fail to deliver the promised level of performance, then the ESCO will have to Payout to the Client.

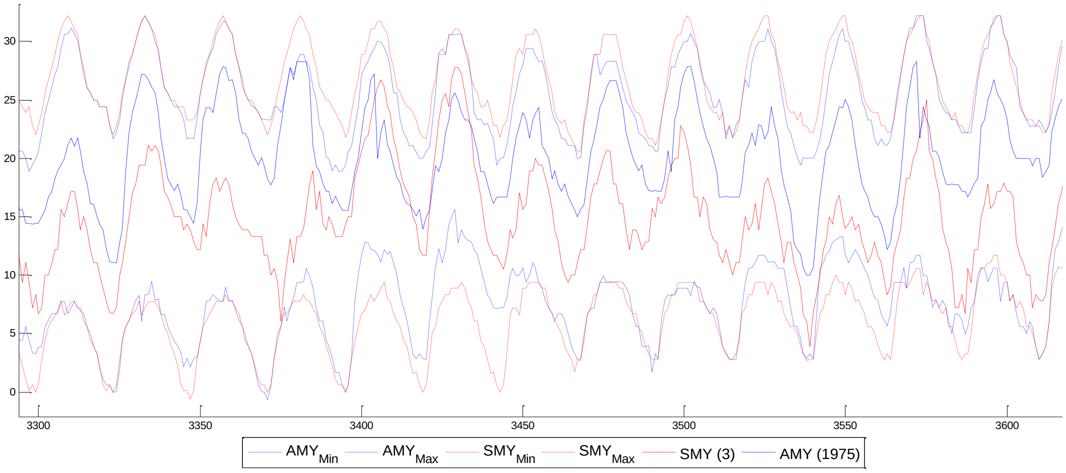


Figure 6.14. Visualization of SMY for Pittsburgh PA

Another dominant source of uncertainty is the variability in the weather. Years of milder weather can have significant effects on the demand for heating and cooling, and drastically reduce the efficacy of ECMs. The effects of the weather are often stipulated in the calculation of Measured Savings, but the models of these effects are often overly simplistic, such as linear adjustments according to the number of heating or cooling degree days. To account for the variability in the weather, Stochastic Meteorological Years have been developed using 33 years of historical meteorological data for Pittsburgh, Pennsylvania. A visualization of the SMYs developed is shown in Figure 6.14. The minimum and maximum temperatures for the 33 year meteorological record (blue dotted lines) and the 100 generated SMYs (red dotted lines) are plotted alongside the measured temperature for 1975 (blue dashed line) and a randomly selected SMY (red dashed line. As expected, the extreme temperatures over the 100 SMY years are generally slightly more extreme than for the 33 measured years, and the SMY follows a pattern similar to the AMY.

Operations and Maintenance Cost is also uncertain, because equipment may suffer non-conformances and need to be replaced before the expected life has been reached. The cost of electricity and natural gas (or other fuels) is also likely uncertain, and a strong influence on the cost of operating the building. Uncertainty for each of these factors are taken as normally distributed, with standard deviation equal to 5% of the expected value.

Further, the models used to predict the values of several elements are uncertain, as any model is merely an abstraction of reality, and therefore the source of an imperfect prediction. Figure 6.15 shows an updated version of the value model, including the identified sources of uncertainty. Uncertain aspects are shown as ovals.

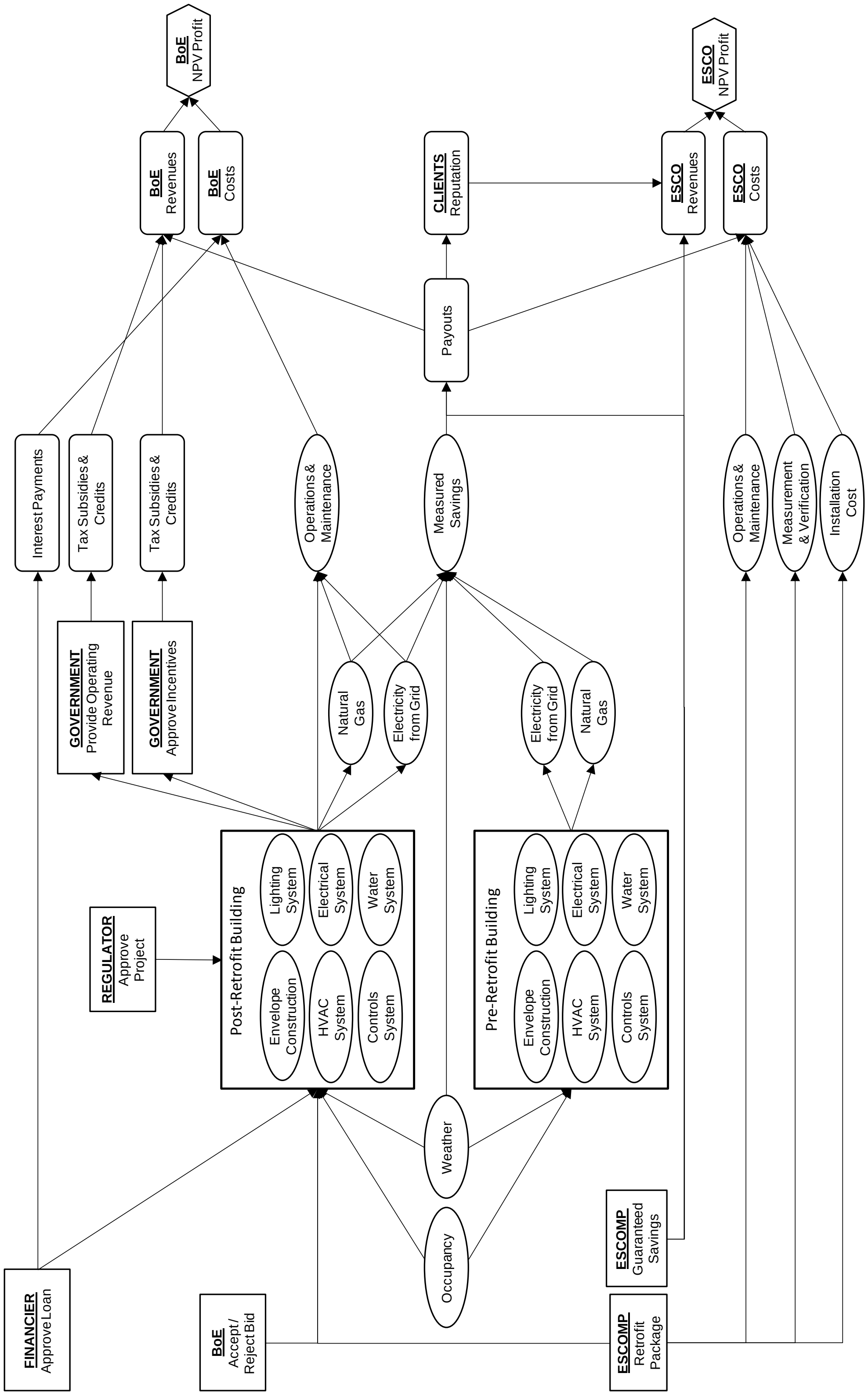


Figure 6.15. Final Combined Value Model for ESCOMP and BoE

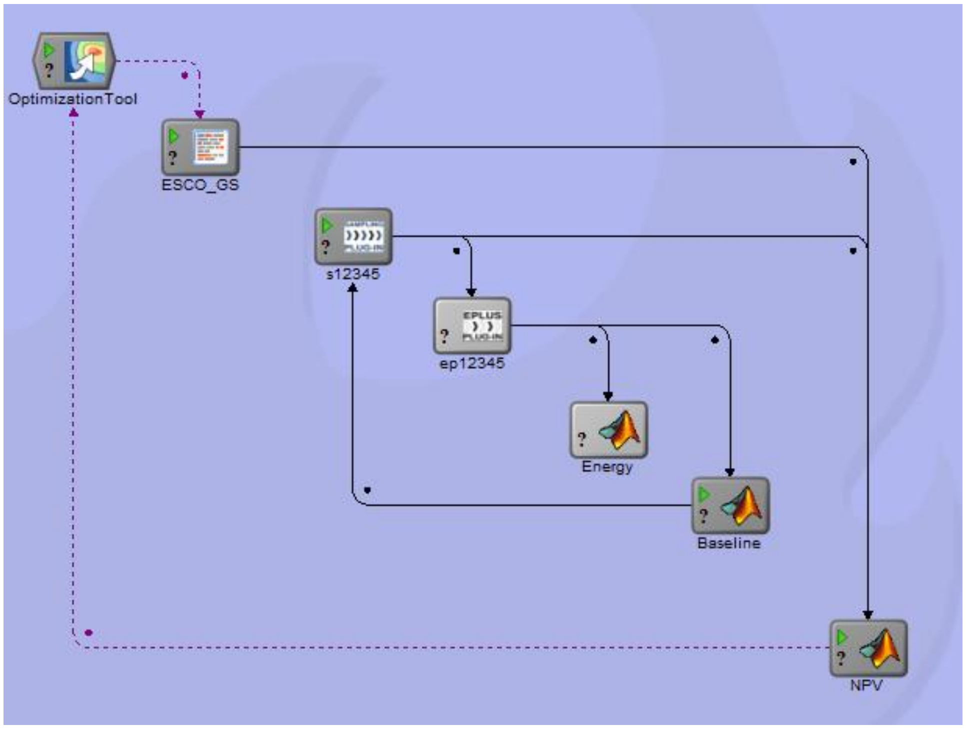


Figure 6.16. Implementation of Value Model in ModelCenter using GURA-W

6.5.2.2 Solving the Decision Context

Recalling the sequence of decisions, the ESCOMP first declares a set of ECMs and then a Guaranteed Savings. Then, the BoE determines whether or not to accept the contract. Depending on the decisions made, different potential outcomes may occur, but an expectation of utility can be determined for each decision maker.

In order to calculate the expected utility for a given decision, the GURA-W was utilized to automate the simulation of building energy consumption under the identified uncertainties. Figure 6.16 presents a screen capture of the models as captured in ModelCenter.

To evaluate the expected utility for each combination of decisions, the GURA-W performs a Latin-Hypercube Sampling of the uncertain variables using a given sampling size. In recognition of the 'pruning' nature of design decision making, and the need for more accurate analyses only as the concept is refined, a series of progressively larger sample sizes are proposed. A first analysis of 20 LHS samples is used mainly as a screening analysis to remove clearly inferior options. For Latin Hypercube Sampling, the variance in the estimate of the mean scales inversely with the number of samples, such that if the number of samples quadruples, the error in the estimate of the mean reduces by a factor of two. With this in mind, the second analysis adds 80 additional samples to the original 20 samples, for a total of 100[17] for the remaining alternatives. A final stage introduces 400 additional samples, for a total of 500 samples.

From the first stage, it is visible that the ESCOMP clearly would not prefer to propose the scenario in which no ECMs are made. In this scenario, the ESCOMP stands to gain nothing. This is a powerful finding for this case study, for it declares that so long as the ESCOMP is willing to guarantee a sufficiently low value for Guaranteed Savings, then a valuable deal is available to both parties; a surplus appears to exist.

While each individual ECM leads to profitable gains for the ESCOMP (and also for the BoE) the expected utilities for these alternatives are lower than for any of the remaining alternatives. Additionally, for all decision contexts, a payout rate of 0% is the

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[17] The two sets of LHS samples are both randomly sampled, and the error in the estimate of the mean for any Monte-Carlo method scales on the order of one divided by the square root of the number of total samples. Therefore, the error will still scale similarly. However, because the aggregation of the two sets were stratified separately, it cannot expected to provide results that are as accurate than a single stratified sample of the same magnitude of samples.

Table 6.4. Results of Stage 1 Evaluation using 20 Samples

ECMs	Expected Measured Savings (k$/yr)	Optimal Guaranteed Savings (k$/yr)	Payout Rate (%)	ESCOMP Expected NPV Profit (k$)	BoE Expected NPV Profit (k$)	ESCOMP Expected Utility	BoE Expected Utility
Baseline				0.0	50.6	0.0	40.0
Lights	21.2	20.4	0.0	7.8	224.4	7.7	89.3
HVAC	38.7	34.5	0.0	37.2	112.1	36.6	66.5
Boiler	17.1	14.3	0.0	33.3	49.6	32.7	38.1
Lights & HVAC	57.7	53.6	0.0	95.1	281.9	90.8	94.0
Lights & Boiler	35.6	33.2	0.0	87.4	244.7	83.7	91.3
HVAC & Boiler	48.2	44.8	0.0	90.5	87.6	86.5	57.7
Lights & HVAC & Boiler	66.9	63.4	0.0	141.7	270.3	132.1	93.3

optimal target by the ESCOMP. This aspect will be investigated in more depth during the second and third stages.

The relationship between Guaranteed Savings and expected utility and profit for both the ESCOMP and the BoE are illustrated in Figure 6.17 for the full retrofit package. The ESCOMP's expected profitability slowly increases with Guaranteed savings until it is capable of 'breaking even' at a Guaranteed Savings of approximately $40,000. Then, as Guaranteed Savings continue to increase, eventually Payouts begin to occur, and the expected profit increases only slightly, then begin to crash suddenly as the loss in reputation begins to impact future revenues. On the other hand, the BoE fares best when the Guaranteed Savings are low. Their payout decreases linearly while the guaranteed savings are met, then enter a non-linear transitional region, and finally stagnate. In the highest range for Guaranteed Savings, any energy savings are reaped by the ESCOMP, but the BoE still enjoys significantly reduced Operations and Maintenance costs for the life of the contract, and is therefore willing to accept the contract.

If a decision about a retrofit package must be made at this point, then the ESCO should decide to propose the full retrofit package, as it has the highest expected utility. The ESCO should propose a Guaranteed Savings of $63,400, and would expect to receive an average profit (adjusted to net present value) of $141,700. However, it is possible that the numerical estimate of the true expected utility is inaccurate due to the limited number of samples involved. It is therefore possible that any of the last four ECM scenarios could be optimal. Because the GURA-W workbench was utilized to automate the uncertainty propagation in the case study, the amount of effort required to perform a second stage analysis is only two computational hours times four scenarios, or eight hours of computational effort and approximately one man-hour to set up and the simulations. The expected benefit of such an analysis is on the order of tens of thousands of dollars. Therefore, a second stage evaluation involving 80 samples was performed.

Table 6.5 presents the results of the second stage evaluation. The second evaluation stage again shows that the ESCOMP would most prefer the full retrofit package, and would offer $62,600 as Guaranteed Savings. Of the four considered retrofit/savings combinations, the BoE would most prefer the Lights and HVAC be selected. However, again recall that the BoE does not have decision authority here. If it did, the alternative still would not be optimal, as the BoE would obviously prefer that the Guaranteed Savings be reduced to zero, such that they receive the retrofits for free.

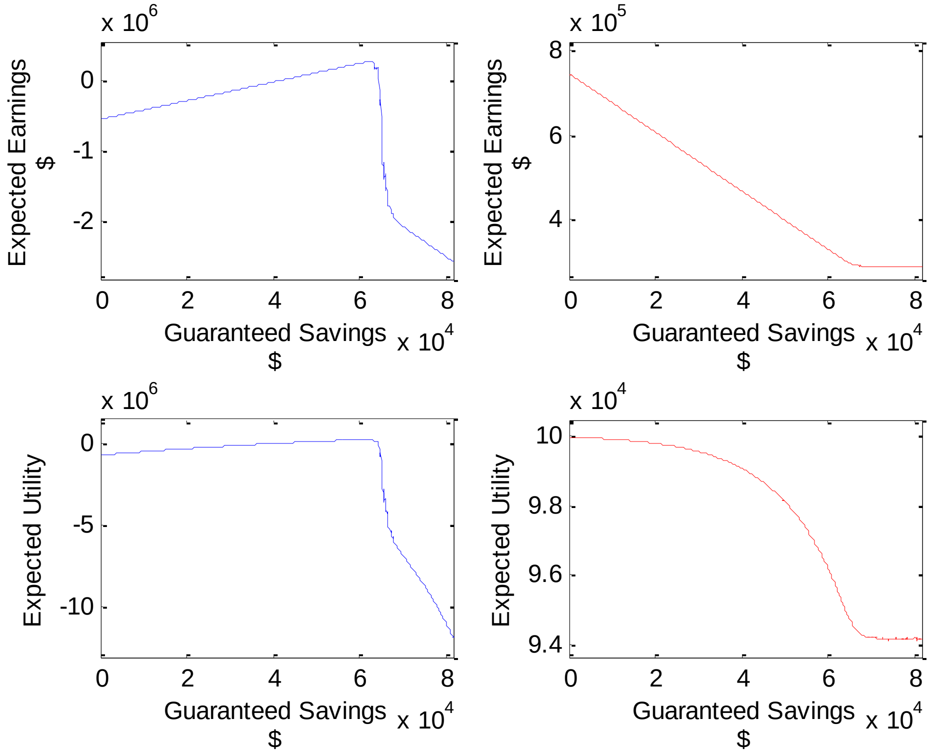


Figure 6.17. Expected Earnings and Utility for ESCOMP (left) and BoE (right)

It is also noted that the rate at which Payouts occur have increased in all scenarios. This can be explained as an artifact of the previously sparse sampling of energy consumptions. With only 20 sampled potential buildings, the empirical distribution of Measured Savings is not smooth, and the tails of the distribution are not well characterized (see Figure 6.18). As such, with a small change in Guaranteed Savings, large changes in the expected amount paid out are possible. Comparing this with the CDF estimated using 80 samples, the tails transition much more smoothly, such that small changes in savings correspond to small changes in Payouts. As a result, the ESCOMP may be able to trade off a smaller amount Payouts for an increase in Guaranteed savings.

Table 6.5. Results of Stage 2 Evaluation using 80 Samples

ECMs	Expected Measured Savings (k$/yr)	Optimal Guaranteed Savings (k$/yr)	Payout Rate (%)	ESCOMP Expected NPV Profit (k$)	BoE Expected NPV Profit (k$)	ESCOMP Expected Utility	BoE Expected Utility
Lights & HVAC	57.7	53.8	2.125	92.9	278.1	88.2	93.8
Lights & Boiler	35.8	32.8	1.88	83.0	252.2	79.6	91.9
HVAC & Boiler	48.2	44.3	2.1	85.3	90.3	81.3	58.4
Lights & HVAC & Boiler	66.6	62.6	1.75	125.2	275.0	115.6	93.6

Before a final recommendation is made, a third evaluation is performed using 400 samples. It is unlikely that either the Lights & Boiler or HVAC & Boiler will become the optimal alternative, and so they are not included in the last evaluation. Evaluating each alternative with 400 samples requires approximately 60 hours of computational effort, but still only one man-hour. The results of the analysis are shown in Table 6.6.

The results of the third stage analysis again yield that the Lights, HVAC, and Boiler should be recommended for retrofit. It is noted that the same retrofit package has been identified in each stage of the analysis. While this may seem to convey that the decision could have been made earlier, the continued analysis yielded a change in guaranteed savings corresponding to a more accurate depiction of the risk associated with failure to deliver the savings.

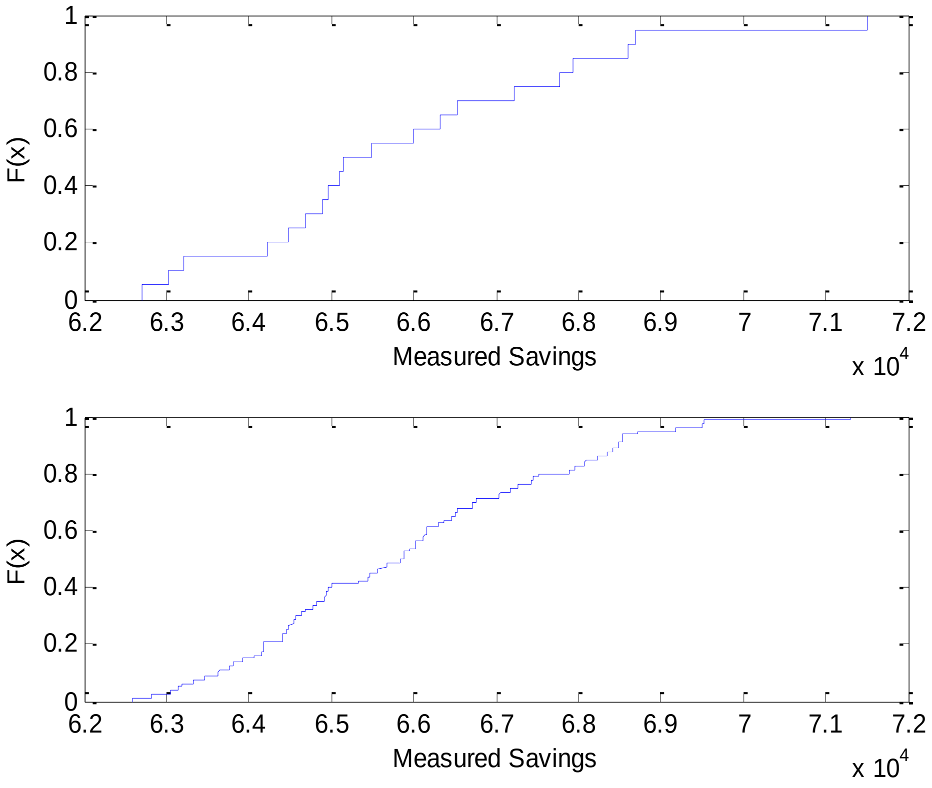


Figure 6.18. Empirical CDF of Measured Savings for Stage 1 (Above) and 2 (Below)

Table 6.6. Results of Stage 3 Evaluation using 400 Samples

ECMs	Expected Measured Savings (k$/yr)	Optimal Guaranteed Savings (k$/yr)	Payout Rate (%)	ESCOMP Expected NPV Profit (k$)	BoE Expected NPV Profit (k$)	ESCOMP Expected Utility	BoE Expected Utility
Lights & HVAC	57.6	55.2	1.25	110.5	266.3	104.6	93.0
Lights & HVAC & Boiler	66.7	63.1	1.25	130.7	270.9	121.8	93.3

6.5.2.3 Discussion

In consideration of the case study, it is not particularly interesting that one retrofit package was selected over another. The important aspect regards the process with which this determination is made. The Systematic Method for Developing Value Models provided a guided path to develop an evaluation model for the decision context while the GURA-W enabled the automated simulation and analysis of the value model. The decision context solution was found using a process of iterative refinement, where poor solutions were pruned from future analysis until the single best alternative remained.

The amount of man-hours required to perform the analyses are quite limited. Once familiar with the process, the model development could be performed at similar effort to current practice, which involves a deterministic estimation of the utility savings. The quantification of uncertainties in the decision context could become the new standard practice, and would yield substantially improved estimates of the variation in expected energy savings. As such, decision makers can make substantially more informed decisions regarding the amount savings to guarantee in an ESPC, or whether or not an investment decision is a good venture to pursue.

6.6 Summary

In this chapter, I have applied a value-driven approach to analyze the practice of Energy Savings Performance Contracting. §6.2 offered a review of the fundamental aspects of ESPCs. §6.3 analyzed ESPCs for a commercial context, and led to a framework for modeling value in such contracts. §6.4 presented a game theoretic investigation of the context, leading a case for transparency in the negotiation of ESPCs. §6.5 then performed an in-depth analysis of an illustrative case study.

CHAPTER 7

CONTRIBUTIONS, DISCUSSION, AND FUTURE WORK

This thesis concludes with a summary of the contributions and a critique of the research presented. The purpose of this dissertation is to provide a foundation for the pragmatic value-driven design of energy-conscious buildings. A review of the methods and tools developed presented up to this point is provided in §7.1. The research questions and hypotheses are revisited in §7.2, and the contributions of the thesis are then summarized in §7.3. Finally, the thesis is concluded with suggestions for future work in §7.4 and some closing remarks in §7.5.

7.1 A Summary of This Dissertation

For an enterprise to be successful, operational practices must be well aligned with strategic objectives. Indeed, one would expect every process within an enterprise to be structured to contribute to the overall value of the organization. However, current practice in engineering design treats the design of products and services as fixed practice, seeking only to satisfy requirements on performance and cost. This misalignment between objectives and practice has been shown to be at least part of the cause of the trend of significant cost and schedule overruns. Within the design community, a growing number of researchers have shown interest in extending the value context to include design, such that designers focus on maximizing the 'value' of the product or service, rather than simply satisfying a set of requirements. Thus, by applying a value-driven approach to design, the design community hopes to show that the magnitude of cost and schedule overruns may be reduced, or even eliminated.

However, a criticism of value-driven approaches is that they are difficult to implement, and not sufficiently pragmatic to be used for large scale engineering problems. To begin to reconcile these disparate viewpoints, this dissertation presents research focused on enabling the implementation of value-driven approaches to design in practice at a reasonable cost.

The literature is first reviewed to provide a clear definition of the normative foundation for decision making in Chapter 2. The foundation leads to a set of characteristics of effective value models. These characteristics relate not only to axiomatic requirements on value-models to ensure rationality, but also to the specific context of the design of artifacts and the interaction of the artifact with stakeholders.

In Chapter 3, a conceptual framework is developed as value in design is examined from three perspectives. First, the current state of the art in value-driven approaches to design are related to an artifact-focused perspective of design. Then, a process-focused perspective is utilized to examine the importance of considering the costs of the design process and leads to the finding that it is rational to resort to heuristics during the design process in order to halt an infinite recursion of planning processes. Lastly, an organization-focused perspective provides a basis for examining the value of the structure of incentives and information sharing in organizations. The three perspectives are then applied to derive a set of desired characteristics for a method for specifying value models in design. These characteristics include that the method should be widely applicable to a range of design contexts, repeatable, and utilize gradual refinement to address the cost-benefit tradeoff of added accuracy

In Chapter 4, current practice with respect to requirements elicitation in the domains of Systems Engineering, Software Engineering, Engineering Design, and Business Development Processes are reviewed. These practices illustrate an emphasis on creating 'acceptable' designs that fit within a given resource allocation or budgetary constraints, rather than on identifying the value of a concept, which could potentially be optimized by deviating outside these requirements. Motivated by the desire to be able to pragmatically evaluate the value of design concepts in a systematic manner, the Systematic Method for Developing Value Models (SMDVM) is presented. The SMDVM involves a systematic consideration of the decision context, identifying the key elements that drive the decision-making and the relationships between them, and then refining the model of the context as appropriate. It is argued that a systematic procedure that emphasizes iterative refinement of the value model will decrease the cost with which an effective value model can be developed, and thereby make their usage more pragmatic.

The primary aspect of the SMDVM that distinguishes it from other value modeling approaches is that it prescribes a process for identifying a value model in generic contexts instead of describing a framework that can only be used to analyze a particular scenario. This is first evidenced in the example case study of the Hybrid Energy System as part of the pilot study test described in §4.4, and then reinforced in the analysis of Energy Savings Performance Contracts in Chapter 6. Neither scenario could have been otherwise addressed, except via ad hoc processes.

While Chapter 4 is focused on the specification of a Systematic Method for Developing Value Models, Chapter 5 focuses on the development of specialized tools to reduce the costs associated with implementing the method to the specific domain of energy-conscious buildings. The Georgia Tech Uncertainty and Risk Analysis Workbench is introduced as a tool to aid in the automated identification of uncertain parameters, as well as relevant decision elements. Stochastic Meteorological Years are also introduced as an extension to Typical Meteorological Years for modeling the uncertainty resulting from the variability of the weather conditions near a building in rare conditions.

Finally, in Chapter 6, the developed methods and tools are used to analyze an interesting decision context in the retrofit of buildings under energy savings performance contracts. It is shown how a value-driven approach can be applied pragmatically in order to determine which energy conservation measures a decision maker should propose and the amount of savings which should be guaranteed for those measures. It is also shown how a third party to the contract, such as a local, state, or federal government could utilize such a value-driven approach to determine an incentive structure to encourage stakeholders to pursue higher levels of energy savings.

7.2 Revisiting the Research Questions and Hypotheses

From Chapter 1, the Motivating Question for this dissertation is:

MQ: How can Value-Driven Approaches be made pragmatic for application in large scale engineering problems?

The hypothesis is that the cause for the lack of practicality in value-driven approaches is attributable to the lack of well established and verified methods and tools. This hypothesis is validated conceptually first in Chapter 3, where a conceptual model of design is presented from three perspectives. The conceptual model is investigated to show how the costs associated with the process of developing a product can lead to significant impacts on the net value. Therefore, by introducing new tools and methods that attempt to reduce the cost of their implementation, the net value of the design process can be increased. This hypothesis is then support again with a specific focus on the retrofit of buildings for low energy consumption in Chapters 4- 6. The tools and methods developed in Chapters 4 and 5 are shown to be applicable to large scale engineering problems, and lead to valuable solutions at a lower cost of design.

The first two research questions refer to the first stage of value-driven approaches, developing a value model. The first question focuses on the effectiveness of value model specification methods:

RQ 1: What are the characteristics of an effective approach for developing a value model?

The hypothesis is that a set of core characteristics can be derived from the normative theory of decision-making under uncertainty and by considering the value of information derived from models of multiple abstractions. This hypothesis is validated in Chapters 2 and 3, where a concise set of characteristics are presented for not only effective value models, but also for effective methods for developing value models.

The second question focuses on the efficiency of value model specification methods:

RQ 2: How can the process of developing a value model for a building performance scenario be made more efficient?

The hypothesis is that a systematic approach should provide the benefit of efficiency. By steering designers' efforts, a systematic approach reduces the costs of value model specification by minimizing time and resources wasted when attempting to determine the next step in an ad-hoc process. This hypothesis is validated using the conceptual framework in Chapter 3. It is described how the ultimate value derived from a design process is impacted not only by the cost of identifying the optimal design alternative. Rather, the process-focused value is also self-referentially related to the cost of selecting the process steps by which the design alternative is selected. In an ad hoc approach, this second level process is associated with constant re-evaluation of the current process status, in order to determine the next step. However, a systematic method can provide clear guidance to bypass the need for these decisions with respect to the specification of a value model for evaluating design alternatives. A pilot study was introduced in Chapter 4 to support a process developed to meet these characteristics, but was inconclusive.

The third research question focuses on the efficiency with which a posed value model can be solved:

RQ 3: How can the process of solving a value model for a building performance scenario be made more efficient?

The hypothesis is that tools that emphasize automation, knowledge reuse, and iterative refinement can reduce the cost of solving a value model. The hypothesis is validated primarily using the case study of the energy savings performance contract in Chapter 6. The workbench and SMY's introduced in Chapter 5 are used to automate the analysis stage of the design process. The UQ Repository of the workbench, or more specifically the knowledge captured within it, reduces the amount of time and resources required to create and execute the computational quantifications of the uncertainty in the outcomes. Iterative pruning of the design space enabled the efficient allocation of computational resources required to determine the optimal combination of design alternatives. By reducing the cost of performing such analyses, the cost of evaluating the design space in general is reduced, and the solution of the value model can be made at less cost.

7.3 Contributions

The contributions in this dissertation can be categorized as relating to: fundamental study of value-driven Approaches, application of a value-driven approach to the design and retrofit of buildings, and observations from the illustrative case study.

7.3.1 Fundamental Study of Value-Driven Approaches

The two primary research contributions of this thesis are the characterization of effectiveness for value-driven approaches, and development of a Systematic Method for Developing Value Models for application in engineering design.

- *Conceptual Framework for Value in Design* - Chapter 3 presents a conceptual framework which describes the role of value in design from three perspectives: Artifact-, Process-, and Organization-Focused. The conceptual framework can be utilized to evaluate design practices to determine the circumstances under which it would provide value, or to justify that the practices should not be performed.
- *Characteristics of Effective Value Models* - Chapter 2 introduces a set of characteristics by which the effectiveness of a given value model can be judged. These criteria can help modelers to determine whether a value model should be used to provide justifiable predictions of value for use in design decision making. The characteristics are repeated in Table 7.1.

Table 7.1. Characteristics of Effective Value Models

Axiom	**Explanation**
Single DM	Model describes the preferences of a single decision maker
Ranking	Model describes preference using a scalar value metric, allowing a cardinal ranking
Uncertainty	Model describes the beliefs and uncertainty of the decision maker
Risk Preference	Model describes the preferences for outcomes under uncertainty by considering the vN-M utility of the value driver
Rationality	Model prescribes action based on the maximization of the expectation of the vN-M utility.
Driver of Value	The driver of vN-M utility is the net present value of profit for a company, or societal benefit for a non-profit entity
Impact of Actions	Model predicts impacts of design decisions on the system of interest and environment
System Behavior	Model predicts how the system of interest and environment interact to impact outcomes of decision maker's concern
Stakeholder Actions	Model predicts how the potential actions of stakeholders impact the system, environment, and decision maker
Stakeholder Concerns	Model predicts what aspects of the system and environment drive the decision making of stakeholders

- *Desired Characteristics of a Method for Developing Value Models* - Chapter 3 then introduces a set of criteria for effective methods for developing value models. These criteria form a basis for analyzing methods or frameworks for modeling value in the context of engineering design decisions. The characteristics are repeated in Table 7.2.

Table 7.2. Desired Characteristics of Effective Method for Developing Value Models

Characteristic	**Explanation**
Result	Method results in an effective value model
Repeatable	Method yields same value model if repeated
Refinement	Method allows a value model to be improved as new information is obtained
Guidance	Method aids users to identify omitted aspects and relationships
Stopping Criterion	Method provides a basis for determining when the refinement is complete.

- *A Systematic Method for Developing Value Models* - Chapter 4 presents a Systematic Method for Developing Value Models. A key aspect of the SMDVM is the manner in which it addresses not only the direct concerns of the decision maker, but also the indirect concerns. Because the SMVMS provides a guided approach to the creation of value models, it can be applied to a wider range of contexts than other currently developed frameworks for Value-Driven Design in engineering contexts. The SMVMS can also be utilized to develop a framework for value models for a specific design context, as in Chapter 6 for Energy Savings Performance Contracts for commercial building owners.
- *Pilot Study Evaluation of SMDVM* - Chapter 4 presents a pilot study undertaken to evaluate the SMDVM. While the results of the pilot study were inconclusive regarding the overall value of the method, the results show that study participants that used the SMDVM focused their effort to identify a wider range of stakeholder actions and concerns.

7.3.2 Application of a Value-Driven Approach to the Design and Retrofit of Buildings

An independent contribution is the application of a value-driven approach to a new domain: the energy-conscious design and retrofit of buildings.

- *Impact of "Within-Batch" Variability* - In Chapter 5, the "within-batch" variability of material properties is shown to impact the magnitude of uncertainty in aggregated measures such as annual facility heating and cooling demand. Failure to account for the "within-batch" variability can lead to overly conservative predictions in these aggregated measures.
- *Pre-Retrofit, Post-Retrofit, and Persisting Uncertainties* - In Chapter 5, three categories for uncertainty in retrofit scenarios are proposed: Pre-Retrofit, Post-Retrofit, and Persisting. Failure to properly account for Persisting Uncertainties can lead to overly conservative predictions of energy savings in retrofit scenarios.
- *Stochastic Meteorological Years* - In Chapter 5, the Stochastic Meteorological Year is introduced as a tool to account for uncertainty arising from variability in the weather. Predictions made using Stochastic Meteorological Years are shown to yield statistically similar results to Actual Meteorological Years, and allow the consideration of statistically rare meteorological phenomena.
- *Georgia Tech Uncertainty and Risk Analysis Workbench* - Chapter 5 presents the Georgia Tech Uncertainty and Risk Analysis Workbench. The Workbench enables architects, engineers, and other practitioners to easily incorporate uncertainty into analyses of building energy consumption, as part of a value-driven approach to design and retrofit.

7.3.3 Observations from Illustrative Case Study

- *Framework for Value in Commercial Energy Savings Performance Contracts* - Chapter 6 presents a framework for value for energy savings performance contracts for commercial buildings. The framework can be used to facilitate the value-driven retrofit of buildings.
- *Value of Transparency in ESPCs* - In Chapter 6, transparent quantification of risk is shown to increase expected utility for all decision makers negotiating energy savings performance contracts. By making information open and accessible to all parties, decision makers can have greater confidence in the accuracy of predictions of energy savings, leading to reductions in risk premiums and a corresponding increase in expected utility.
- *Illustrative Usage of Value-Driven Approach to Design and Retrofit* - Chapter 6 presents a value-driven optimization of the Energy Conservation Measures and Guaranteed Savings for the specific decision context of a middle school in Pennsylvania. The case study illustrates the usage of the tools and methods presented in this dissertation and helps to make the previously claimed contributions more concrete

7.4 Limitations and Future Work

In the previous section, the many research contributions discussed in this thesis were enumerated. However, there are certain limitations that warrant further discussion.

7.4.1 Self-Defeating Nature of Pursuing Happiness

This dissertation presents research focused on improving our capability to predict value, such that that value can then be maximized through value-focused decision making. However, it has been argued that the very pursuit of happiness can be self-defeating (Schooler et al., 2003). Opponents of a value-driven approach to design may suggest that by focusing on maximizing value, designers will fall subject to the same limitation, and therefore the status quo should be maintained. Therefore, an intriguing open question for the design community is whether value-driven approaches actually lead to more desirable outcomes in practice. This essentially begs the question of whether rationality is a desirable driver for decision making in design. One approach to answer this question would be to utilize an extensive cross-sectional analysis in which multiple entities agreed to pursue value-maximization approaches to design, while others pursued conventional approaches for design decision making. While an empirical analysis of this type may provide significant evidence in support of or against the maximization of value, it would also require significant financial investment. Therefore, this is likely to remain an open research question for the time being.

7.4.2 The Value of Heuristics

In Chapter 3, it is argued that heuristics for design are necessary in order to break the infinite recursion present in the Process-focused perspective of the Conceptual Framework for Value in Design. Future work could examine the circumstances under which certain commonly-used heuristics appear to result in reasonably valuable outcomes. This investigation may yield principles that could then be utilized to reduce the cost of comparing heuristics for future decisions.

7.4.3 Complexity of Incentives in an Organization

The Organization-focused perspective of the Conceptual Framework for Value in Design acknowledges that when design is performed with an organization context, the decision maker will offer incentives in an attempt to align the actions of the employees with the preferences of the decision maker. However, this dissertation has primarily focused on the process perspective of value, and assumed that the organizational structure is beyond the decision scope. Future work should investigate whether the conclusions drawn regarding effectiveness of a method for developing value models hold under varying organizational contexts.

7.4.4 Modeler's Knowledge

A limitation of any analysis or evaluation model is that it can only account for the phenomena that are included. The refinement stage of the SMDVM can only advise the modeler to revisit the aspects of the model to identify omitted knowledge, but it cannot guarantee that a value model contains all relevant information if a modeler himself simply does not possess knowledge about the element. As such, the accuracy of a value model is ultimately limited by the modeler's knowledge about the context.

7.4.5 Pilot Study

In Chapter 4, a pilot study is conducted in order to evaluate the SMDVM. Participants in the study were unable to complete the requested tasks within the imposed time limits. As a result, while those participants using the SMDVM appeared to investigate certain aspects of the decision context more deeply, the pilot study results are inconclusive overall. As such, to evaluate the SMDVM more fully it would be beneficial to conduct a follow-up analysis in which the time is at least 2 hours, or possibly unrestricted. Additionally, it would likely be valuable for the participants to be given a lecture/presentation displaying the proper usage of the SMDVM, such that the SMDVM and HAZELRIGG Groups have similar experience with the method they are to use.

7.4.6 Georgia Tech Uncertainty and Risk Analysis Workbench

The current implementation of the Georgia Tech Uncertainty and Risk Analysis Workbench was developed as a research level tool, and is not intended for commercial deployment. As such, there are certain limitations to its functionality. Primary among these is the restriction on the version of EnergyPlus. The current release of GURA-W utilizes a modified executable of EnergyPlus v7.0.0, and so buildings modeled using other versions must be converted for simulation. In practice, this means that certain modules of newer releases must be removed, as EnergyPlus files are typically not forwards compatible.

Additionally, the current implementation of GURA-W utilizes a combination of Phoenix Integration's ModelCenter model integration framework and customized plug-ins written in Java. Future effort could lead to the development of a standalone program in order to reduce the requirement for ModelCenter.

7.4.7 Stochastic Meteorological Years

Stochastic time series models of a natural process may appear 'noisy' in comparison. This is noise is a result of the incapability of the model to predict the next time series value with perfect precision. Future work to reduce this model error could include: the incorporation of additional meteorological phenomena to serve as indicator variables (for example: precipitation); the inclusion of additional lags, tailored to each phenomenon, or the inclusion of a moving average process to consider correlations between sequential residuals.

Further, the possibility of global climate change is not considered in the development of the Stochastic Meteorological Years. In order to perform the Rosenblatt transformation, it is assumed that the weather from year to year is stationary in nature. Additional formulations could adjust for the potential non-stationarity due to changes in the mean value or variance of meteorological phenomena over time.

7.4.8 Value of Transparency

In Chapter 6, it was shown that transparent quantification of risk can increase the expected utility of all decision makers by reducing the magnitude of risk premiums arising from uncertainty. This argument assumes that a framework and tools for openly sharing information exists and can be easily accessed by all parties. Future work could focus on identifying and developing technology to increase the ease with which the decision makers could effectively collaborate.

7.4.9 Interpreting Case Study Results

Chapter 6 presents a value-driven analysis of the retrofit of a middle school in Jonestown, Pennsylvania. To protect the ESCO and the client, numerical figures were altered, and estimations were made of particular parameters that were not directly measured. As such, the results of the optimization should not be utilized as the basis for actual decision making, and may not be indicative for any other building.

7.5 Closing Remarks

Previous frameworks for value-driven engineering design are well defined only for relatively simplistic design contexts, and provide little guidance for tailoring to a particular decision. The methods and tools introduced in this dissertation extend the knowledge base for how engineers that seek to maximize their own value should design artifacts. The Systematic Method for Developing Value Models guides engineers through the process of eliciting the key elements of concern and the relationships between them, and can be applied to a wider range of decision contexts. By focusing modeler effort in a systematic manner, the cost of developing an effective value-model can be reduced. When combined with tools that have been developed for the specific domain of building energy consumption, it has been shown that the value-driven design or retrofit of buildings can be performed pragmatically, and lead to significant benefits.

The conceptual framework for value introduced in this dissertation will affect the state of the art for value-driven approaches to design. By shifting the focus from the artifact to the process and organization under which the artifact is designed and developed, the conceptual model provides a basis by which various design methods and processes can be compared. Researchers can utilize the framework to determine the circumstances under which a particular design method is likely to be useful. By providing a clear, consistent "measuring stick" for the value of such methods, rational decisions can be made regarding the need for novel design methods in various domains.

Lastly, the domain of building energy modeling is poised to become a powerful tool in the ongoing endeavor to minimize our society's environmental impact. This dissertation introduces tools and methods that will enable architects and engineers to make more informed decisions regarding the energy consumption of a building. It also reduces the costs associated with gathering this information, such that practitioners will be able to make better design or retrofit decisions in pragmatic fashion. The gains to be reaped by designing and retrofitting for efficiency should not be limited by how difficult it can be to identify valuable designs; they should be limited only by the technical capability to innovate.

APPENDIX A

PILOT STUDY EXAMPLE SUBMISSIONS

This appendix presents six example submissions from the cognitive examination of the Systematic Method for Developing Value Models. The test procedure, scoring procedure, results, and interpretation of the results are described more completely in §4.4. Figure A.1, Figure A.2, and Figure A.3 correspond to three submissions from the HAZELRIGG group, and offer a representative level of variety of submissions. As is evidenced in the figures, participants employed the formulation of influence diagrams, even though not explicitly told to do so in the instructions. Figure A.3 offers the greatest level of detail amongst the three control submissions, and offers a relatively complete decomposition of key decision elements.

Figure A.4, Figure A.5, and Figure A.6 correspond to three submissions from the SMDVM Group, and offer a representative level of variety of submissions. As is evidenced in the figures, participants struggled to complete the assignment within the imposed time limits. Figure A.6 offers the greatest level of detail amongst the three control submissions, and offers a relatively complete decomposition of key decision elements. However, even this submission is incomplete with respect to the identification of relationships and uncertainties.

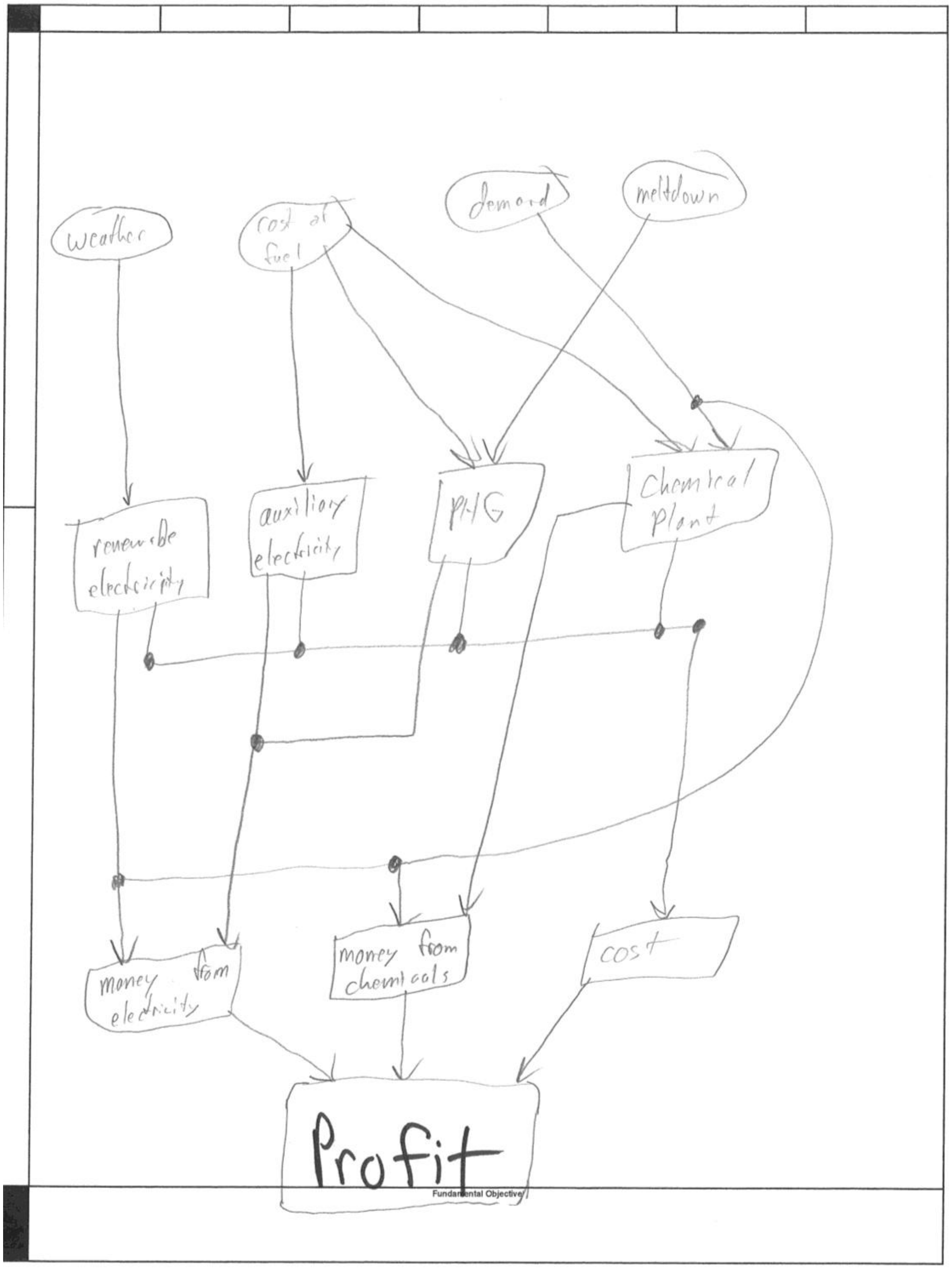


Figure A.1 Example Value Model C1

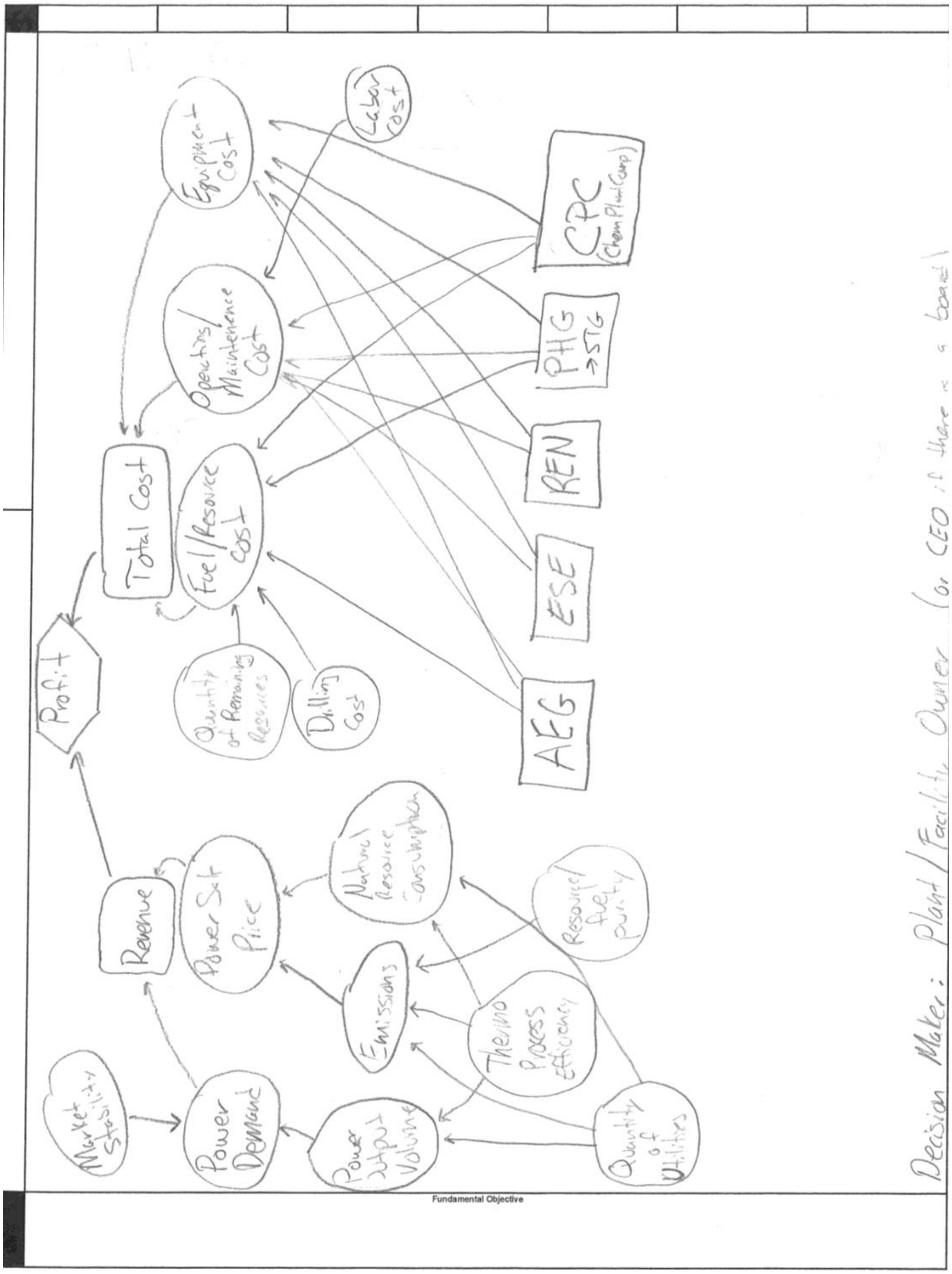


Figure A.2 Example Value Model C2

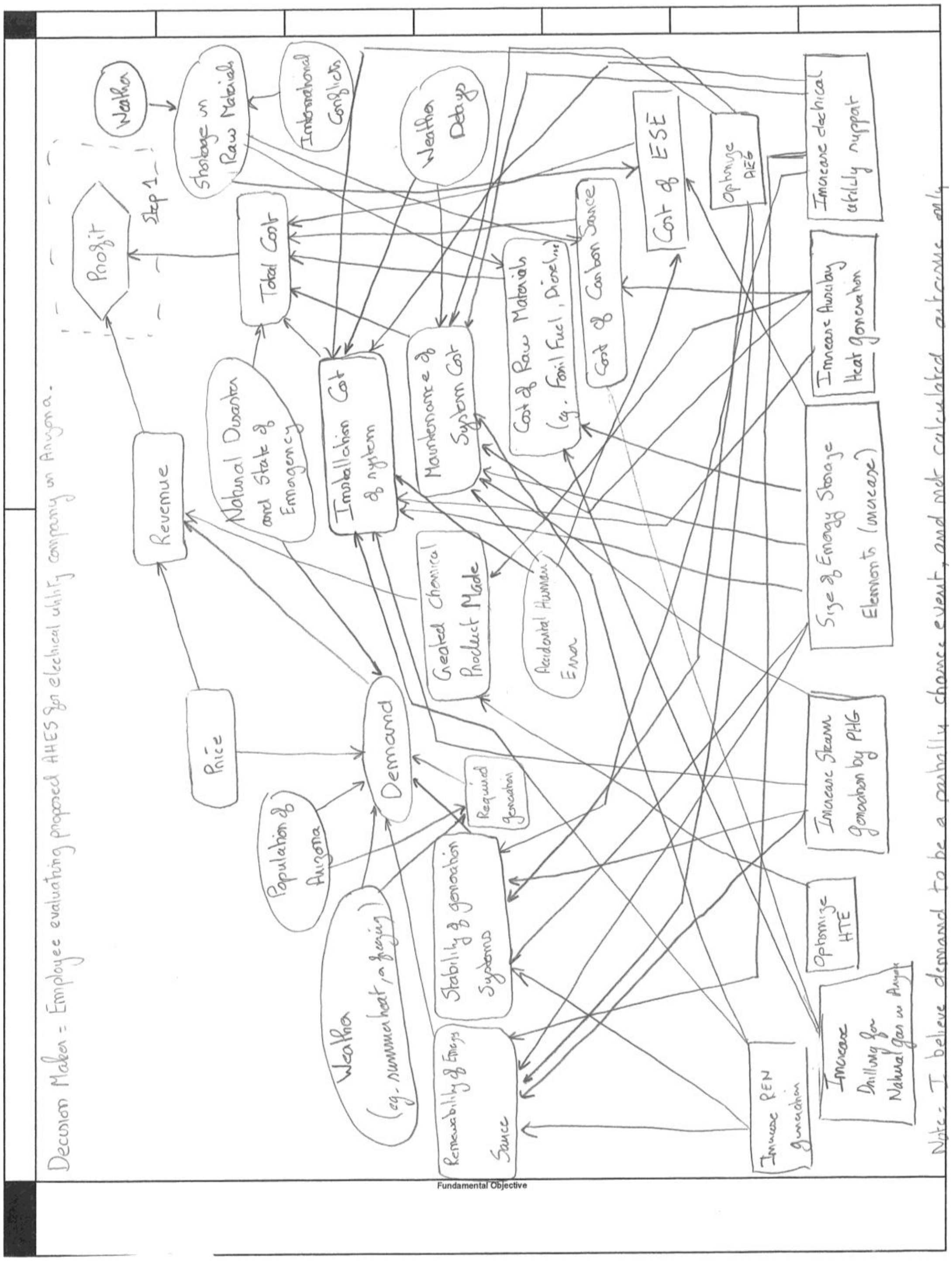
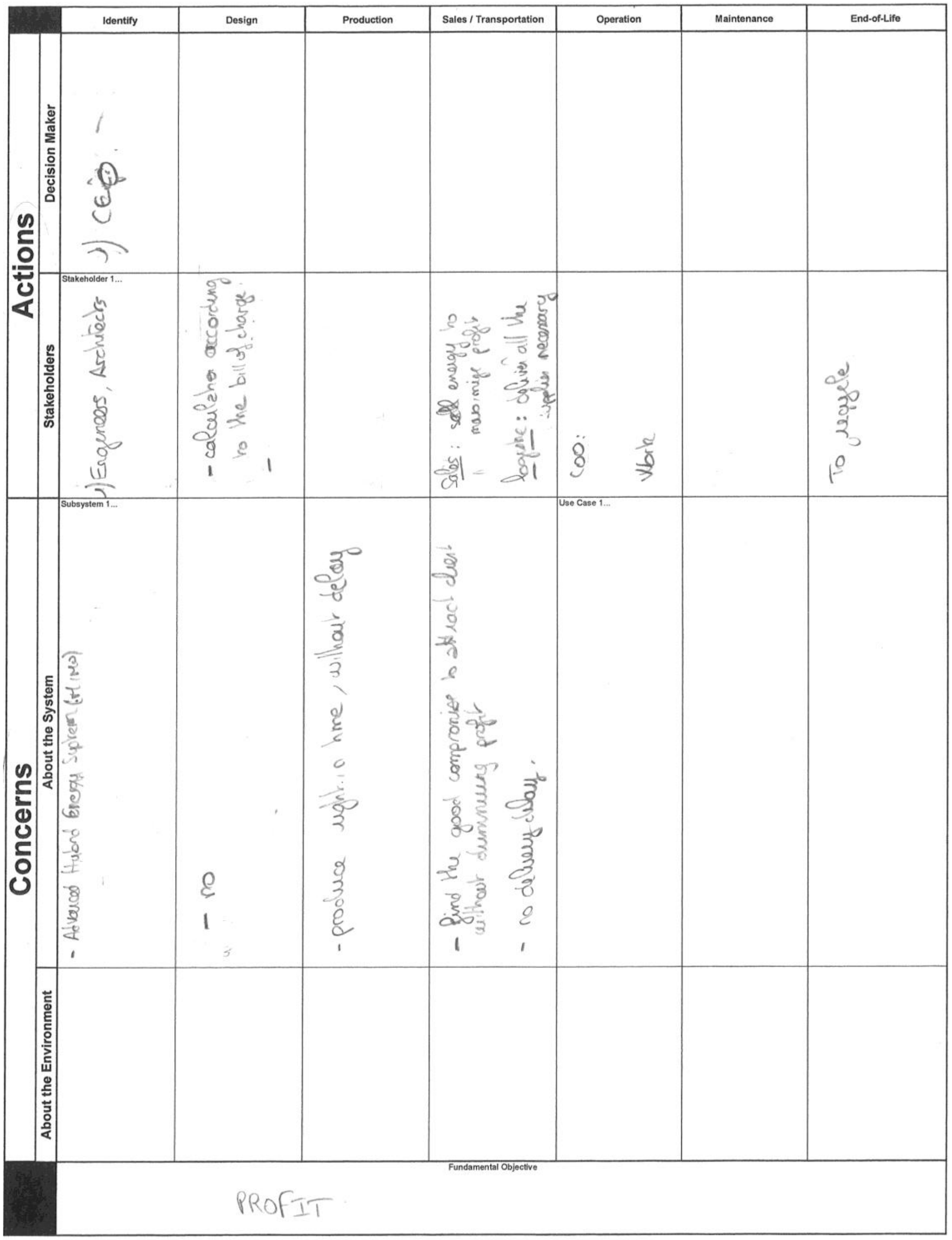


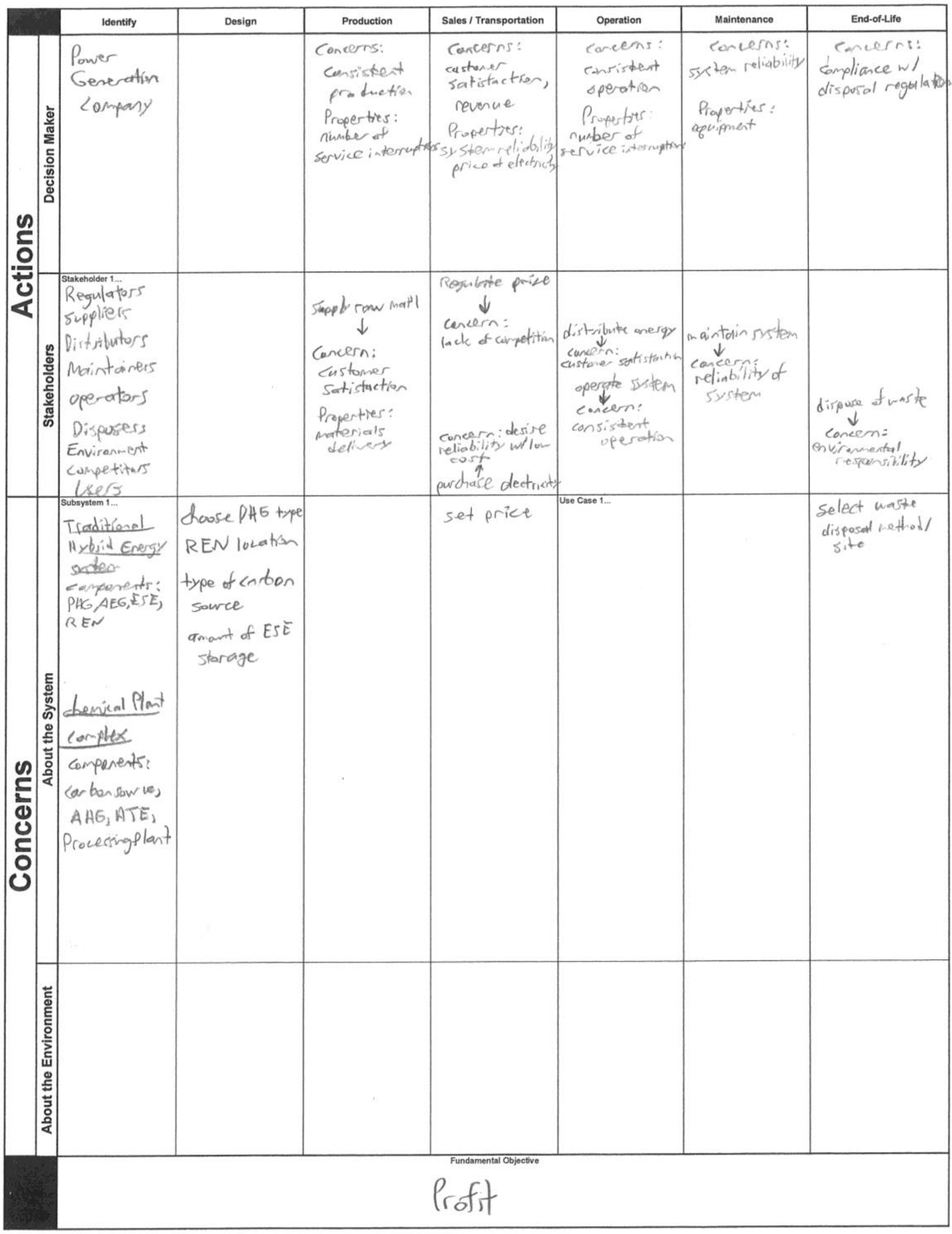
Figure A.3 Example Value Model C3



	Concerns		Actions	
	About the Environment	About the System	Stakeholders	Decision Maker
Identify		- Advanced Hybrid Energy System (of 1MW)	1) Engineers, Architects	1) CEO
Design		- no	- calculate according to the bill of charge -	
Production		- produce right on time, without delay		
Sales / Transportation		- find the good compromise to attract client without diminishing profit - no delivery delay.	Sales: sell energy to maximize profit logistic: deliver all the supplies necessary	
Operation			COO: Work	
Maintenance				
End-of-Life			To recycle	

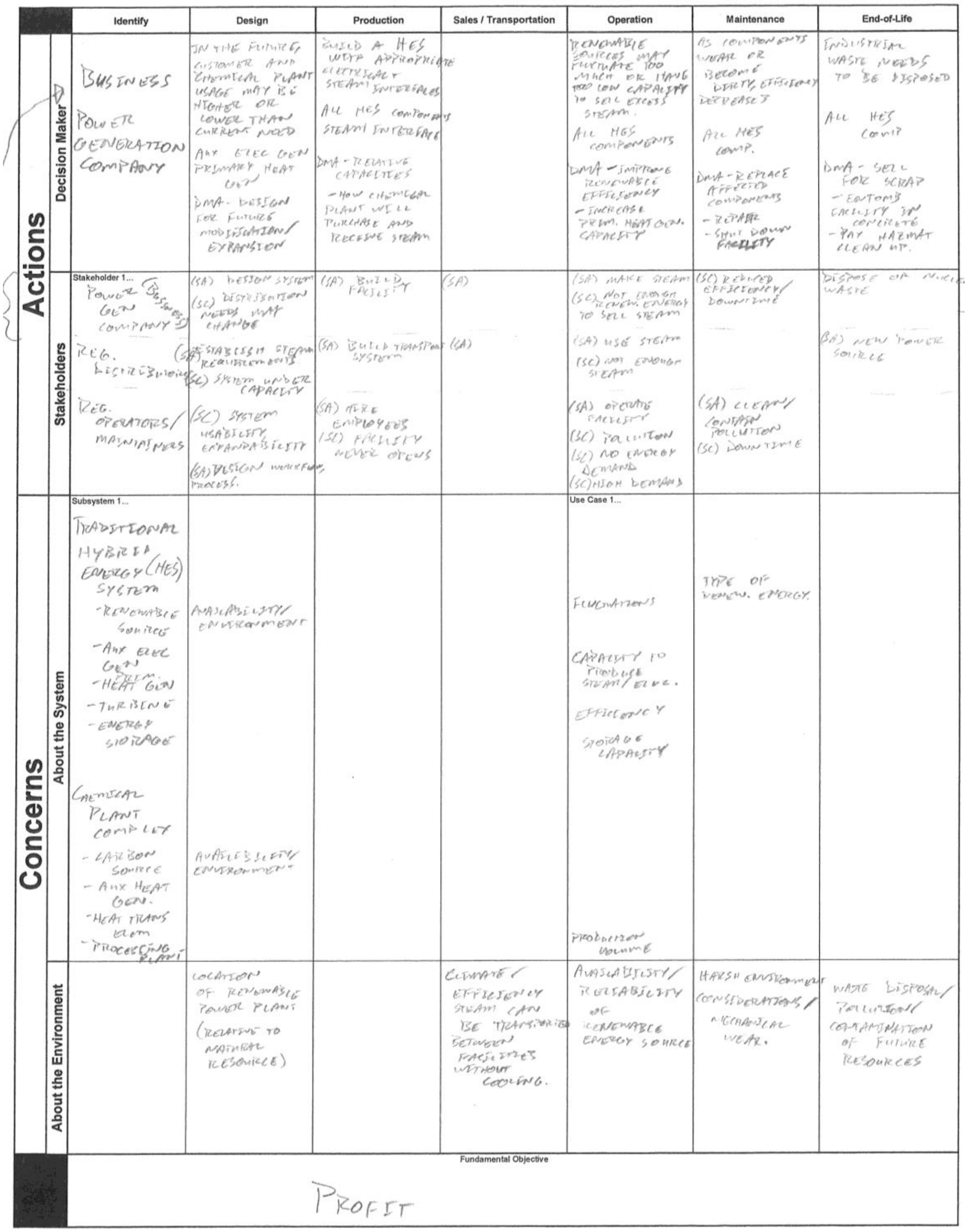
Fundamental Objective: PROFIT

Figure A.4 Example Value Model S1



		Identify	Design	Production	Sales / Transportation	Operation	Maintenance	End-of-Life
Actions	Decision Maker	Power Generation Company		Concerns: consistent production Properties: number of service interruptions	Concerns: customer satisfaction, revenue Properties: system reliability price of electricity	concerns: consistent operation Properties: number of service interruptions	concerns: system reliability Properties: equipment	concerns: compliance w/ disposal regulations
	Stakeholders	Stakeholder 1... Regulators suppliers Distributors Maintainers operators Disposers Environment competitors Users		Supply raw mat'l ↓ Concern: customer satisfaction Properties: materials delivery	Regulate price ↓ concern: lack of competition concern: desire reliability w/ low cost ↑ purchase electricity	distribute energy ↓ concern: customer satisfaction operate system ↓ concern: consistent operation	maintain system ↓ concern: reliability of system	dispose of waste ↓ concern: environmental responsibility
Concerns	About the System	Subsystem 1... Traditional Hybrid Energy system components: PHG, AEG, ESE, REN Chemical Plant complex components: carbon source, AHG, ATE, Processing Plant	choose PHG type REN location type of carbon source amount of ESE storage		set price	Use Case 1...		select waste disposal method/site
	About the Environment							
		Fundamental Objective Profit						

Figure A.5 Example Value Model S2



		Identify	Design	Production	Sales / Transportation	Operation	Maintenance	End-of-Life
Actions	Decision Maker	BUSINESS POWER GENERATION COMPANY	IN THE FUTURE, CUSTOMER AND CHEMICAL PLANT USAGE MAY BE HIGHER OR LOWER THAN CURRENT NEED ANY ELEC GEN PRIMARY HEAT GEN DMA - DESIGN FOR FUTURE MODIFICATION/ EXPANSION	BUILD A HES WITH APPROPRIATE ELECTRICAL + STEAM INTERFACES ALL HES COMPONENTS STEAM INTERFACE DMA - RELATIVE CAPACITIES - HOW CHEMICAL PLANT WILL PURCHASE AND RECEIVE STEAM		RENEWABLE SOURCES MAY FLUCTUATE TOO MUCH OR HAVE TOO LOW CAPACITY TO SELL EXCESS STEAM. ALL HES COMPONENTS DMA - IMPROVE RENEWABLE EFFICIENCY - INCREASE PRIM. HEAT GEN. CAPACITY	AS COMPONENTS WEAR OR BECOME DIRTY, EFFICIENCY DECREASES ALL HES COMP. DMA - REPLACE AFFECTED COMPONENTS - REPAIR - SHUT DOWN FACILITY	INDUSTRIAL WASTE NEEDS TO BE DISPOSED ALL HES COMP DMA - SELL FOR SCRAP - ENTOMB FACILITY IN CONCRETE - PAY HAZMAT CLEAN UP.
	Stakeholders	Stakeholder 1... POWER GEN COMPANY (BUSINESS)	(SA) DESIGN SYSTEM (SC) DISTRIBUTION NEEDS MAY CHANGE	(SA) BUILD FACILITY	(SA)	(SA) MAKE STEAM (SC) NOT ENOUGH RENEW. ENERGY TO SELL STEAM	(SC) REDUCED EFFICIENCY/ DOWNTIME	DISPOSE OF NUCLE WASTE
		REG. DISTRIBUTORS	(SA) ESTABLISH STEAM REQUIREMENTS (SC) SYSTEM UNDER CAPACITY	(SA) BUILD TRANSPORT SYSTEM	(SA)	(SA) USE STEAM (SC) NOT ENOUGH STEAM		(SA) NEW POWER SOURCE
		REG. OPERATORS/ MAINTAINERS	(SC) SYSTEM USABILITY, EXPANDABILITY (SA) DESIGN WORKFLOW, PROCESS.	(SA) HIRE EMPLOYEES (SC) FACILITY NEVER OPENS		(SA) OPERATE FACILITY (SC) POLLUTION (SC) NO ENERGY DEMAND (SC) HIGH DEMAND	(SA) CLEAN/ CONTAIN POLLUTION (SC) DOWNTIME	
Concerns	About the System	Subsystem 1... TRADITIONAL HYBRID ENERGY (HES) SYSTEM - RENEWABLE SOURCE - AUX ELEC GEN - PRIM. HEAT GEN - TURBINE - ENERGY STORAGE CHEMICAL PLANT COMPLEX - CARBON SOURCE - AUX HEAT GEN. - HEAT TRANS ELEM - PROCESSING PLANT	AVAILABILITY/ ENVIRONMENT AVAILABILITY/ ENVIRONMENT			Use Case 1... FLUCTUATIONS CAPACITY TO PRODUCE STEAM/ ELEC. EFFICIENCY STORAGE CAPACITY PRODUCTION VOLUME	TYPE OF RENEW. ENERGY.	
	About the Environment		LOCATION OF RENEWABLE POWER PLANT (RELATIVE TO NATURAL RESOURCE)		CLIMATE/ EFFICIENCY STEAM CAN BE TRANSPORTED BETWEEN FACILITIES WITHOUT COOLING.	AVAILABILITY/ RELIABILITY OF RENEWABLE ENERGY SOURCE	HARSH ENVIRONMENT CONSIDERATIONS/ MECHANICAL WEAR.	WASTE DISPOSAL/ POLLUTION/ CONTAMINATION OF FUTURE RESOURCES
		Fundamental Objective PROFIT						

Figure A.6 Example Value Model S3

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