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A TRADE SPACE EXPLORATION PROCESS TO OPTIMIZE ADVANCED ENERGY RETROFIT DESIGN FOR BUILDINGS

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by

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ABSTRACT

Trade space exploration and multidimensional data visualization tools have been developed to facilitate design decision-making in an interactive environment. Trade space exploration recognizes the importance of subsystem trade-offs since different domains that are involved in complex engineering system design usually have interdependent, or even conflicting interrelationships. Building system design, as a special case of complex engineering system design, requires decisions to be adaptively developed throughout a long timespan to incorporate changing information, as well as to fully explore the trade space in an efficient manner so that alternative futures are included in the proper planning scenario.

This thesis, and the research behind it, provides a method to incorporate the trade space exploration process into the early design phase for advanced energy retrofit projects for buildings. It uses a developed list of Energy Conservation Measures (ECMs) and their combinatorial impact on the energy and cost performance after identifying the dependency matrix. A potential retrofit building is used as a test bed for this research with the aid of an existing energy simulation application. This case study is used to illustrate the process and value of this approach. Benefits of the trade space exploration process include: (1) identification of the drawbacks of traditional ‘rules-of-thumb’ in building design, (2) sufficient and rigorous evaluation of the trade space for building energy design, and its impact on future needs, contexts, and timelines, (3) identification of ‘optimal’ design options as well as dominated designs and their distinguishing features, and (4) an automatic tool for evaluating building system design performance in a interactive visual environment to facilitate decision-making.

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Chapter 1

Introduction and Overview

1.1 Motivation and Objectives

Advanced energy efficient building retrofits require an efficient and cost-effective design evaluation phase. For engineering product development, de Weck et al. (2010) argue that the design phases have the greatest freedom and yet possess the least knowledge about the target system it wishes to define. Different from traditional mechanical or aerospace design approaches, building energy design for retrofit projects usually involves energy modeling which often relies heavily on assumptions (Pacific Gas and Electric Company, et al., 2007) and 'rules of thumb' (Pratt and Bosworth, 2011). In the building energy design domain, design options are usually not fully explored due to the cost and time required to develop simulations for all possible combinations for a vast number of input parameters. This is because building design involves an overwhelming number of variables from both inside and outside of the building, and these parameters are usually not 'global' in a sense that a different building located in a different place may have drastically different inputs.

This thesis, and the research behind it, explores a methodology to use trade space exploration for building energy retrofit design to facilitate design decision-making in an adaptive and automated way. As opposed to the traditional mechanical design domain, it provides insight into building energy design from a systematic aspect, incorporating sub-system trade-offs and design conflicts. Instead of previous methods of using parametric sensitivity analysis (Sanchez, et al., 2012) or a stepwise factor selection method (Lee, et al., 2010), this method enables comprehensive comparisons and visualization of Energy Conservation Measure (ECM) combinations in order to prescribe optimal design scenarios based on energy efficiency gains and associated life-cycle operating costs. This iterative method enables decision-makers to develop their preferences along the way as new information is obtained, and to explore a specific and narrowed trade space in the next level of exploration.

Figure 1 summarizes the current issues in building energy design. The first design dilemma is associated with large-scale parameter sets (U.S. Department of Energy, 2013) which suggests that researchers capture hourly weather file plus Building Description Language input describing geographic location and building orientation, building materials and envelope components, operating schedules, as well as several other information for whole-building energy analysis with DOE-2 to make sure a gap is bridged between the assumptions and actual conditions and that the simulated model can produce consistent results as to actual scenario. To acquire such comprehensive information is rather difficult considering that buildings vary from type to type as well as from location to location. The second issue is the conflicting objectives. To further analyze engineering system designs, it is critical to recognize the conflicting objectives from a large set of output considerations. For building energy modeling, a few commonly used objectives include life-cycle cost, energy performance, and complexity of maintenance.

Borrowing the concept of goal programming (Schniederjans, 1995), it is rather important to then construct a hierarchy against the identified set of objectives and to understand which ones are prioritized and which can possibly be relaxed in order to improve the scenario from a high-level perspective. The third issue involves a group decision scenario in which different decision-makers tend to have discrete preferred regions. This is often the case in complex engineering system design because a design solution often involves multidisciplinary domain experts who, with their domain-specific experience, tend to develop discrete sets of preference regions. In order to achieve the goal, one critical step is to identify different sets of considerations and priority hierarchies. Also important, if looking back at the first concern, is categorizing common parameters that are presented in discrete design regions and thus can be leveraged as a bridge across the multiple disciplinary. The fourth issue related to existing engineering product design optimization problems is the adaptive information environment. As mentioned at the beginning of this thesis, one dilemma that decision-makers have to face is the uncertainty of information. At an initial stage of engineering design, people are equipped with the most decision flexibility, and yet they have captured the least information then. An ideal design process should enable a rather flexible exploration and evaluation process which, in other words, should enable people to change the preferences, modify the direction of exploration, set different metrics, and to fix variable values as new information becomes available. A fifth issue is the expensiveness as well as the efficiency of exploration. In real-life environment, it is usually critical to make a first decision for engineering product design to establish the computational expense people would prefer the model to run as. The computational expense and the efficiency determines the time of the evaluation, which will determine the possible fidelity of the models. It is often true that high fidelity models will imply more accurate and unbiased modeling results, but they are usually costly in terms of computing time as well as monetary investment. To choose a proper model, not the most costly one, is concerned with all relevant design decision-makers. The last issue of current engineering product design is the generality of design exploration and evaluation model across different industries. This thesis sits in between two fields: (1) mechanical/aerospace engineering design and (2) building system energy design. To use this as an example, it is fairly easy to understand the possible distinctions across different domains, and thus, it leaves a lot of space to understand that a trade space exploration process needs to be a generic one and should reside on the similarities of different industries.

Figure 1: Issues of Building Energy Design Optimization

1.2 Thesis Scope and Objectives

This thesis is targeted at proposing a trade space exploration process for building energy parametric design to avoid the drawbacks of dominance of 'rules-of-thumb' for building energy design, and to propose an efficient and effective design alternative evaluation method for finding optimal design options. The main objectives of this thesis are: (1) to relate the complex mechanical engineering design optimization methods to building energy parametric design; (2) to propose an automated and efficient trade space exploration process to facilitate design decision-making in an interactive environment; (3) to demonstrate the use of multi-dimensional data visualization and advanced 'shopping' controls in trade space exploration; (4) to prescribe an optimal building energy retrofit design option in terms of energy utility consumption and cost; and (5) to define future activities needed to expand the process proposed in this thesis.

1.3 Thesis Overview and Outline

The thesis is structured as follows. Chapter 2 presents a literature review on trade space exploration methods, building energy modeling, and engineering design optimization studies. Chapter 3 assesses the optimizability of building energy retrofit design by presenting the similarities and differences from traditional mechanical design. Chapter 4 proposes a trade space exploration process for building energy retrofit design optimization; including in the analysis are the building decomposition and dependency structures as well as energy simulation model and cost analysis model. Chapter 5 presents a case study on Building 101 in the Philadelphia, PA Navy Yard energy retrofits and utilizes ATSV and product design optimization to identify the optimal Energy Conservation Measures (ECMs) for Building 101 at the Navy Yard. Chapter 6 summaries the thesis and discusses its limitation as well as future work.

Chapter 2

Literature Review

This chapter presents the relevant existing work on trade space exploration, building energy modeling, as well as decision support tools for complex engineering systems analysis such as the Design Structure Matrix. Then, Section 2.3 introduces a typical trade space exploration approach and the Applied Research Lab Trade Space Exploration Visualizer (ATSV) tool. Section 2.4 summarizes the limitations identified in this review.

2.1 Existing Work on Trade Space Exploration

Papalambros and Wilde (1998) suggest that the design process must contain recognition of need (problem definition), act of creation (synthesis), study of configuration's performance (analysis), and selection of alternatives (optimization). He defined design optimization informally but rigorously as a combination of: (1) selection of a set of variables to describe the design alternatives; (2) selection of an objective/criterion we seek to minimize or maximize; (3) determination of a set of constraints which must be satisfied by any acceptable design; and (4) determination of a set of values for the design variables while satisfying all the constraints. To express in formal mathematical models, a generic design optimization problem can be defined as:

$$
\begin{aligned}
&\text{Min } f(x) && (1)\\
&\text{Subject to } \; h_1(\mathbf{x})=0 \quad g_1(\mathbf{x})<=0\\
&\qquad h_2(\mathbf{x})=0 \quad g_2(\mathbf{x})<=0\\
&\qquad\quad \vdots \qquad\qquad \vdots\\
&\qquad h_{m1}(x)=0 \quad g_{m2}(\mathbf{x})<=0\\
&\qquad \text{and } \; \mathbf{x}\in X\subseteq\mathbb{R}^n
\end{aligned}
$$

where $\mathbf{x}=(x_1,x_2,\ldots x_n)^T$ belongs to a subset X of the n-dimensional real space $\mathbb{R}^n$.

de Weck, et al. (2010) define design optimization as a process of finding a system design that will minimize some objective function. The objective function can be a vector comprising measures of system behavior ('performance'), resource utilization ('time', 'money', 'fuel', etc.) or risk ('stability margins', etc.). Extensive study has been focused on Multidisciplinary Design Optimization (MDO), yet it is beyond the scope of this thesis. For further work regarding this topic, Martins and Lambe (2013) provide a rather comprehensive survey on Multidisciplinary Design Optimization (MDO) architectures and optimization frameworks.

Trade space exploration serves as a method to explore the design space and to visualize the designs in plots such as glyph plots and parallel coordinate plots. It is critical to understand the concept of trade space exploration. Ross and Hastings (2005) define trade space as "the space spanned by the completely enumerated design variables, which means given a set of design variables, the tradespace is the space of possible design options." Trade space exploration is the exploration and evaluation of the trade space, which involves trade-offs among its relevant design variables. For the evaluation process, two existing concepts are recognized: (1) point-based design and (2) set-based design. Understanding that the exploration process is a dynamic and complex continuous decision-making process that involves multiple decision stages with different levels of information, one typical method is to set a baseline design which usually comes from previous experience or developed concepts, and then to provide alternatives comparisons. Each alternative is evaluated one at a time until designers arrive at a design that satisfies all the designing constraints. This method is usually referred to as 'Point-Based Design' (Bernstein, 1998). This method has a major drawback. When the last design option generated does not meet all constraints, then designers simply have no remaining solutions. They are then forced to restart from the beginning, which thus results in huge additional costs and time consumption. Set-based design addresses the exploration problem in a different way. Sobek (1997) recognize the properties of set-based design as understanding the design space, integrating by intersection, and establishing feasibility before commitment. Set-based design allows the designers and other decision-makers to develop an initial set of design space based on predefined parameters as well as the limited information at the time the initial decision is made. It narrows down the design space as information becomes more available during the engineering design phase. An important advantage of set-based design is that it enables people to fully realize the changeability of design information. Hence, set-based design generates more unbiased design solutions. In order to realize set-based design, a fully explored trade space must be accessible. The computational tools that enable efficient and effective trade space exploration becomes critical, especially in complex engineering system design where large sets of parameters are to be considered.

Another relevant concept is Concurrent Engineering (CE). Concurrent Engineering is a work methodology that is based on parallelization of tasks and is often referred to as multidisciplinary product development (Rosenblatt and Watson, 1991). Toyota proposed set-based design and concurrent engineering methodology in order to explore a broader space of product design while remaining a relatively short design lead time because it approach the complex engineering design problem from all possible domains, and to develop a set of all design possibilities (Shingo, 1989). Realizing that changes might occur, this approach helps avoid major rework because it forbids rejecting any alternative in an early stage. The concept accurately determines the development status by narrowing down the set of possibilities as more information becomes available (Sobek, et al., 1996).

Simpson, et al. (2008) characterize the trade space exploration process as a shopping process when decision-makers identify what they want while they are looking for it; a negotiating process when decisions involve multiple decision makers with conflicting motives and diverse expertise; and an iterative process when trade space exploration develops more depth and detailas more information is exploited and more knowledge is gained.

Ross, et al. (2004) introduce utility theory into the process to provide a common metric that can be easily communicated throughout the design enterprise. They also discuss the application of multi-attribute trade space exploration as a front end for effective space system design. In the paper, the trade space exploration method is used to improve quality of communication, and to facilitate the transfer of knowledge of important drivers of space system design. He argues that this method ameliorates the high level of ambiguity present in early design phases of aerospace systems, and thus, reduces long and costly design cycles. Ross, et al. (2005) extend the concept by incorporating uncertainty, system flexibility, sustainability, scalability, spiral development, and policy robustness. Roberts, et al. (2009) discuss scenario planning in dynamic multi-attribute trade space exploration. Some other novel methods are developed for quantitative analysis of alternatives. For example, Dynamic MATE uses trade space networks to design for and quantity changeability. Epoch-Era Analysis (EEA) considers the impact of short run and long run context and needs changes on the success of systems (Rader, et al., 2010). Responsive Systems Comparison Method (RSC) uses MATE, EEA and other approaches to gain insights into value robust systems development (Ross, et al., 2009). Valuation Approach for Strategic Changeability (VASC) provides framework and metrics for changeability value in both multi-epoch and era domains (Fitzgerald, et al., 2012). Finally, Epoch Syncopation Framework (ESF) investigates how epoch ordering and change strategies affect timing of design change decisions (Fulcoly, et al., 2012).

One critical issue regarding trade space exploration is how to put human “back in the loop” for adaptive decision making (Simpson and Martins, 2010). Understanding that people make better decisions when visualized materials are presented, several visualization software tools have been developed to provide aid in the automated process of exploration. For example, ATSV is developed by the Applied Research Lab (ARL) at the Pennsylvania State University. Simpson, et al. (2008) propose that ATSV provides a visualized and intuitive data environment that allows design decision-makers to shop for preferred design solutions, and it serves specially for multi-objective design optimization problems. Stump, et al. (2009) discuss the steering commands in ATSV that allow designers to 'steer' the optimization process while searching for the best, or Pareto optimal, designs. This suggests a more reasonable 'optimal' solution because it creates an interactive shopping environment for different domain experts.

2.2 Existing Work on Building Energy Design and Modeling

Building energy retrofit design, however, differs greatly from traditional engineering product design. The dominance of 'rules-of-thumb' in the construction industry leaves little space for design process improvement and optimization. Traditional analysis for building energy efficiency performance usually adopts conditional mean model or parametric sensitivity analysis (Sanchez, et al., 2012). Lam, et al. (2008) gather electricity data for office buildings in subtropical Hong Kong and parameterize it on ten key design variables for sensitivity analysis. Siddharth, et al. (2011) use a building energy simulation to study some of the combinations of critical parameters and their impact on annual energy consumption (AEC) and cost. They used genetic algorithms to generate this database and a statistical fit was formulated between the system variables and the response variables. U.S. Department of Energy (2013) provides a list of whole building energy analysis tools is available. By subject, they can be categorized into: (1) energy simulation, (2) load calculation, (3) renewable energy, (4) retrofit analysis, and (5) sustainable/green buildings. These methods provide sufficient information about factor significance, which help practitioners to put more focus on some of the more influential ones; however, they fail to consider the dependencies/exclusiveness among the design variables. Moreover, a comprehensive set of design combinations has not been studied before drawing the final optimal prescription. This yields a final recommendation that might be biased due to the sampling bias as well as an unrepresentative starting point.

In order to identify the dependencies and trade-offs that exist among sub-systems, one has to learn the principles of system decomposition for buildings. Geyer (2009) exploit a component-oriented decomposition for Multidisciplinary Design Optimization (MDO) in building design. He argues that special setup of optimization model should be adopted considering the uniqueness of buildings. They adopted the component scheme following the Industry Foundation Classes (IFC) as a common Building Information Model (BIM) standard in order to allow a seamless integration into an interactive design process. They propose a systematic perspective on the building system that consists of structural, architectural, lighting and equipment, HVAC, and envelop sub-systems. United Technology Research Center (UTRC) considers four subsystems that are identified to be most contributable to the energy performance of retrofit building: (1) Lighting and Equipment, (2) Envelope, (3) HVAC Terminal Side, and (4) HVAC Supply Side (Desai, et al., 2012). For these recognized subsystems, a total of 45 Energy Conservation Measures (ECMs) are specified and studied. This thesis, and the research behind it, uses the same set of 45 ECMs to demonstrate the proposed methodology and be consistent with the energy auditing task.

After building decomposition, it becomes inevitable to analyze the dependency relationships among sub-systems. Two tools that facilitate this work are Decision Tree (Rahman, et al., 2012) and Design Structure Matrix (Brady, 2002). A decision tree is a decision support tool that uses a tree-like graph to model decisions and their possible consequences, including chance event outcomes, resource costs, and utility. Design Structure Matrix (DSM) has been widely adopted in system engineering and engineering design because it effectively helps capture the essential exclusions or coupling relations of sub-system or components. Eppinger and Browning (2012) argue that a DSM facilitates the decision-making by clearly identifying the processes, information, products, and organization of complex engineering systems. The dependency matrix in Chapter 6 of this thesis borrows the concept from both, but it is not identical to any.

2.3 Typical Trade Space Exploration Approach

Simpson, et al. (2008) state that a typical trade space exploration approach consists of three major steps: (1) building model, (2) running experiments, and (3) exploring the trade space as shown in Figure 2. Building the model includes assembling simulation model and sampling a large number of (1,000+) design points. The modeling process is subject to domain-specific rules and analysis. Running experiments involves a more targeted exploration of the trade space. Often times, the total number of design points of interest will be greatly reduced after imposing domain-specific rules, and this gives an opportunity to focus on a narrower region of the trade space and to augment each design with geometry and related information. The exploration stage often involves identifying trends of interests, applying constraints and optimizing the objective performance, and visualizing preference structures and Pareto frontiers. This is a particularly important and useful phase because it enables "human-in-the-loop" decision-making. Understanding that people make better decisions when they are presented with existing design options each with respective enumerated performance matrix, it is to be expected that people develop a set of more targeted and specific requirements which, in turn, often results in fewer iterations and reduced cost. This type of a posteriori selection process is given a name of 'Design by Shopping' (Balling, 1999). Specifically in ATSV, a 'shopping process' is done by utilizing advance sampler: preference samplers, Pareto samplers, and attractors. Brushed controls are also available whose specific application as well as advanced sampler's functionality is discussed next.

For most of the cases, experiments are run as simulation models. Physical experiments can be a feasible way to obtain design data, but due to the expensiveness both in terms of time and money, it is out of the scope of this thesis's discussion. For simulation experiments, an easier case would be to find or construct mathematical functions for input parameters and their objective functions. For the Basic Sampler in ATSV, uniform, triangular and normal distributions are among the most explored distributions to sample the input space. Obviously, the user needs to specify at the very beginning how 'expensive' she/he wants the exploration process to be by assigning a total number of initial basic samples. It is recommended to start off with more than 1,000 points, but the appropriate number depends on the features of specific domain-specific study, and the cost constraints for running the experiments, as well as availability of computational capability. For other cases where a static physical function is not available, domain-specific simulation models are often deployed in order to obtain the objective results for their corresponding input environment.

Data visualization provides a tool of using demonstrated data forms to enable more perceptual data interpretation. Friendly and Denis (2001) define data visualization as the study of the visual representation of data, meaning "information that has been abstracted in some schematic form, including attributes or variables for the units of information". For such a collaborative decision-making context as trade space exploration, it is important to utilize a visualized engine to allow designers to explore multidimensional trade spaces to understand relationships between variables, visualize the feasible regions, and to help them adaptively form and change their preferences for optimality.

In terms of multiple objectives, conflicting in most cases, the decision-making usually involves multiple parties from different domains who share divergent motives and carry different considerations. What happens in most of the cases is that each individual decision-maker ends up with distant 'optimal set' and no unanimous region can be found. Stump, et al. (2009) introduce the visual steering commands of ATSV to support multidimensional visualization of the exploration process. The advanced "shopping" process is enabled by multiple advanced sampling engines, attractors, as well as brushing control. The visual steering can be categorized into three major functions: (1) to explore around a point of interest, (2) to explore within a region of high preference, and (3) to brush off counter-interest region.

Attractor command enables designers to search near specific existing design points and then to identify more samples around them. The fitness of each new sample point $Zi_{\_sample}$ is based on the normalized Euclidean distance from the specified n-dimensional point (Stump, et al., 2009). Chapter 5 demonstrates the specifics of attractor.

$$\text{Fitness}=\sqrt{\sum_{i=1}^{n}\left(\frac{Z_{i_{sample}}-Z_{i_{attractor}}}{Z_{i_{attractor}}}\right)^2} \quad (2)$$

A Pareto Frontier is a set of non-dominated design points. Lotov and Miettinen (2008) describe techniques for visualizing the Pareto optimal set that can be used if the multi-objective optimization problem in the framework of multiple-criteria decision-making (MCDM) and evolutionary multi-objective optimization (EMO) approaches. They also discussed visualization techniques for convex multi-objective optimization problems based on a polyhedral approximation of the Pareto optimal set as well as for point-wise approximation of the Pareto optimal set. The Pareto sampler uses the Pareto Differential Evolution (DE) algorithm developed by (Storn, et al., 1997) which is proved to be a robust evolution algorithm in trade space exploration. Chapter 5 demonstrates the specifics of Pareto Sampler.

Preference Sampler enables designers to develop and select their preferred objectives before more data points are generated for a specific region. Chapter 5 demonstrates the usage of Preference Sampler in more detail. On the other hand, to brush out counter-interest designs, one can use the brushing control in order to manually remove the ill-performing design options in further sampling processes (Stump, et al., 2007). Brush controls also allow for imposing constraints throughout the exploration process to provide more accurate reflections to incoming information.

All the aforementioned controls ensure that further design explorations are guided into a more specific yet smaller region, and that further designs will incorporate more information as they become available along the way. This greatly reduces the cost as well as ensures the efficiency and effectiveness of the trade space exploration process, which is especially important in simulation-enabled design evaluation. Figure 2 demonstrates a typical trade space exploration process.

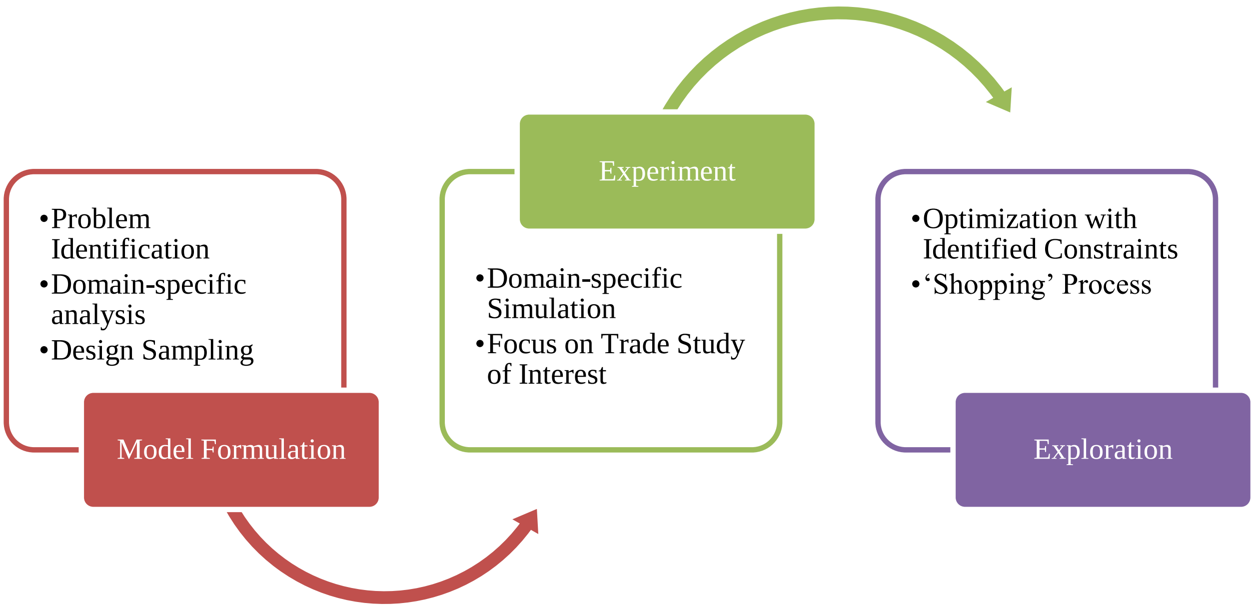


Figure 2: Typical Trade Space Exploration Process

2.4 Limitations and Summary

This chapter reviews the existing work both in trade space exploration as well as building energy modeling and design. The limitations of existing work, or rather the perspective that no existing work has visited is the combinatorial of both domains. Understand from the existing works, one important common feature for all trade space exploration practices is the parametric feature of the design variables. Vast options for N parameters involved in the an engineering product form a N-by-N matrix, which results in $O(N^2)$ total computational complexity, and thus calls for an efficient and effective method in order to explore the whole range of possible solutions that the variability of the initial parameters may allow. This thesis proposes a method to adopt trade space exploration to building energy parametric design to enable an efficient and automated design alternative evaluation process, and to eventually identify optimal design options based upon user preferences in an interactive decision-making environment. In the next chapter, an assessment of optimizability of utilizing trade space exploration on building parametric energy retrofit design is discussed.

Chapter 3

Assessing the Optimizability of Building Parametric Energy Retrofit Design

3.1 Introduction

The interdisciplinary nature of this thesis suggests that both the enabling method as well as the application domain be discussed with importance imposed on the combinatorial area. This chapter starts by discussing the generality of the trade space exploration process across different domains. Then a comparison analysis is conducted between parametric building retrofit design and traditional mechanical design with similarities and differences stated. The last part assesses the feasibility of adopting trade space exploration on integrated building energy design optimization, in other words, the optimizability of building parametric energy retrofit design.

3.2 Generalities of Trade Space Exploration

Understanding the domain-to-domain differences will certainly facilitate the implementation of the trade space exploration method, yet it is important to identify the generalities of the method itself. Wide applications of the trade space exploration method have been presented across different domains for the design of complex systems such as automobiles, aircraft, and spacecraft as discussed in Chapter 2.

One important feature of all previous case studies is that the design problem is parameterized or can be modeled in a quantitative manner. For mechanical component design, spacecraft design as well as structural design that involve clear quantified parameters and variables, trade space exploration serves as a generalized approach. However, for building energy design, it can be difficult to enumerate variables or parameters and to consider them from a purely quantitative perspective. The next section analyzes the special features of building energy retrofit design and then continues by looking at some similarities and the optimizability.

3.3 Comparisons of Traditional Engineering Design Domain and Building Energy Retrofit Design Optimization

Before comparison, it is important to understand the defining scope of building energy retrofit design and traditional engineering design. Pacific Northwest National Laboratory, (2011) categorizes building retrofit into: (1) standard retrofit measures that provide cost-effective and low-risk efficiency upgrade options including equipment, system and assembly retrofits; and (2) deep retrofit measures require a larger upfront investment and may have longer payback periods than Operations & Maintenance (O&M) or standard retrofit measures. They also developed a table of deep retrofit package measures. Deep retrofit measures go beyond the standard retrofit packages because they affect more system types, and the level of retrofit is deeper. The scope of this research is focused on deep retrofit approaches where multiple systems may be redesigned and altered in the retrofit process.

A general method for conducting energy retrofit design is that one or more designers identify potential retrofit measures in a specific building, and then they analyze the potential performance impact through some form of energy simulation. While detailed energy modeling and simulation is not always performed on a retrofit projects, when it is, the mechanical engineer is typically working side-by-side with the architect, lighting engineers, cost estimators as well as project managers throughout the process to make sure the retrofit work proceeds smoothly; however, additional considerations remain. When evaluating whether to embark on a deep retrofit, one has to assess the current situation of the existing equipment, the usage of the building, occupancy schedules, and whether or not the project can be retro commissioned. These extra concerns add to the complexity of building energy retrofit design. Chapter 4 discusses the United Technology Research Center (UTRC) paradigm of energy retrofit design as part of Energy Efficient Building HUB, and further details regarding the identified list of Energy Conservation Measures (ECMs) are provided as well as how they are being evaluated against the whole building energy design.

Different from building energy retrofit design, traditional mechanical engineering system design may have factors that are more easily identified and defined. One of them is that quantifiable effects of input parameters will lead to more concrete results which can yield a higher degree of certainty in the decisions. For example, for a helical compression spring design, (Deb, et al., 2006) consider three variables: the wire diameter d, which is a discrete variable, the mean coil diameter D, which is real-valued parameter with a certain range; and the number of turns N, which is an integer value varied with a certain range in order to designs for minimum volume and for minimum developed stress. Since the contributing variables are obvious and common for all spring design, and that there is a physical function that relates the variables to the objective function with a high degree of certainty, it is relatively easy to construct a mathematical problem to define an optimal solution given specific input parameters.

Understanding the differences between these two domains will shed insight on the trade space exploration and better adjust and tailor the approach to serve for the building energy retrofit design. The following paragraph articulates the distinctions and similarities.

Building design involves a high level of ‘nested’ variables. By ‘nested’, it is to say that the change of one factor will often involve modifications to other factors. For example, to model the orientation of a building and its effect on building energy performance, there is hardly a model to construct such relationship because the change of orientation triggers a difference in natural light utilization, which then triggers different performance on lighting energy usage, and which then yield different heating/cooling loads. To perceive these affecting inputs in an isolated way may not work; however, one applicable way is to treat a specific building as an integrated system that has certain interactions within the building itself as well as with the external environment. An energy simulation engine allows for a relative thorough modeling of a real-world scenario of building energy design and bypasses the dilemma of trying to identify each dependent relationship among an extreme large pool of variables. For this research, an energy simulation engines that focused on the adoption of deep retrofit measures is used for modeling binary energy conservation measure scenarios for building energy design. As discussed in Chapter 6, modeling aesthetic, cognitive and comfort concerns still remains a limitation of the current work; however, under reasonable assumptions, it is operable to relate building energy design to the parametric mechanical or spacecraft design processes, and that building energy design can be approached from an optimization perspective with trade space exploration.

3.4 Summary

This chapter assessed the optimizability of building energy design with analysis on the special features of building energy retrofit as compared to other traditional engineering design fields. After explaining the feasibility of adopting trade space exploration, the next chapter discusses how the proposed method is used on building energy retrofitdesign optimization.

Chapter 4

A Proposed Trade Space Exploration Process for Building Energy Retrofit Design Optimization

4.1 Introduction

This chapter introduces the building energy retrofit design problem along with its objectives, constraints, and decision variables (DV). The data environment needed to support the process is introduced to frame the problem settings and conditions. Finally, the building decomposition, dependency matrix for sub-system trade-offs, as well as the adoption of ATSV to aid in the identification of solutions using the trade space exploration in an interactive and efficient manner is discussed.

4.2 Building Energy Retrofit Design Optimization Problem

This section addresses the proposed methodology of adopting the trade space exploration approach for building energy retrofit design optimization. The problem used to prototype this decision involves two objectives: (1) minimizing energy consumption, which includes Electricity, Natural Gas/Propane, Fuel Oil, and District Heat for building functions consisting of cooling, heating, lighting, equipment, refrigeration, ventilation, water heating, and pump and (2) minimizing initial construction cost. It is well understood that building energy retrofit can involve many additional objectives such as lifecycle cost, architectural quality, water use, indoor air quality, daylighting, and acoustical quality. This thesis uses two objectives in order to simplify the scenario without losing generality. Further discussion is found in the limitation part in Chapter 6 as well. The experiment leverages a building energy retrofit simulation that consists of multiple stages as shown in Figure 3. Stage I is the baseline design in which basic building input data that impacts energy performance are identified and are used to obtain utility consumption in the baseline performance scenario. Stage II is the Energy Conservation Measure (ECM) packages phase. In this stage, each measure is evaluated independently without considering the possible combinations. This stage provides preliminary results in terms of energy conservation ability for each individual ECM. Stage III is the retrofit package stage. In this stage, possible combinatorial measures are taken as input in order to study the effectiveness of utilizing multiple ECMs at the same time. Stage IV, Stage V, and Stage VI are sensitivity analysis stages. Figure 3 shows different stages of the energy audit and retrofit analysis tool.

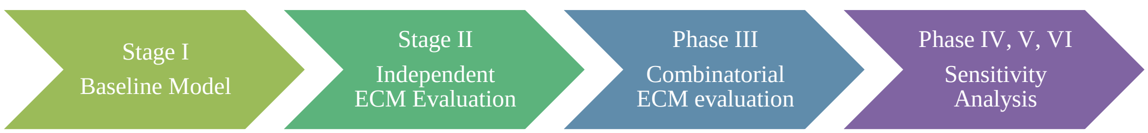


Figure 3: Phases of Energy Audit Retrofit Analysis Tool

This thesis focuses on analyzing the impact of ECM combinations on building energy performance, hence, in terms of energy auditing and analysis package, Stage III engine is used. The relationships of ECMs are studied to eliminate obvious unreasonable combinations. These will be ‘brushed-off’ as infeasible design inputs, and thus will bypass the energy simulation in order to improve computing efficiency. Furthermore, more effort is put to effectively explore the feasible trade space by means of ‘shopping’ steering commands before prescribing the set of optimal design solutions.

The decision variables (DV) for the building energy design optimization problem are defined as follows:

$$X_i=\begin{cases}1 \text{ if the ith Energy Conservation Measure is adopted} \\ 0 \text{ if the ith Energy Conservation Measure is not used}\end{cases} \quad i=1, 2, \cdots 45 \qquad (3)$$

In order to perform the trade space evaluation, other sets of inputs are necessary; however, they are fixed values as soon as a certain project is chosen. In this chapter and Chapter 5, a specific building project is assumed; hence, weather data, baseline building input data as well as others (refer to Appendix A) are treated as control variables.

The constraints for this problem are obtained after identifying the dependency matrix of decision variables. In general, there are three types of constraints: (1) exclusive (one decision variable must not be presented with another decision variable); (2) coupled (one decision variable has to work with another decision variable); and (3) inclusive (one decision variable involves the other decision variable, thus it makes no sense to include both). Appendix B contains a full list of these constraining rules.

Figure 4 demonstrates the general process flow of building energy design optimization in Business Process Modeling Notation (BPMN). The process starts by understanding the input data environment that includes existing building features, ECMs, and the dependency among the inputs. After obtaining all necessary inputs, the building energy auditing and simulation engine is used to obtain corresponding energy and cost performances for each input set. Following that, the exploration process starts by comparing and evaluating among the large pool of design alternatives. As discussed in earlier chapters, using an interactive ‘shopping’ process will greatly improve the trade space exploration results. The last stage is to visualize the multi-dimensional data using various plot, and to eventually shed insight on the optimal design prescription.

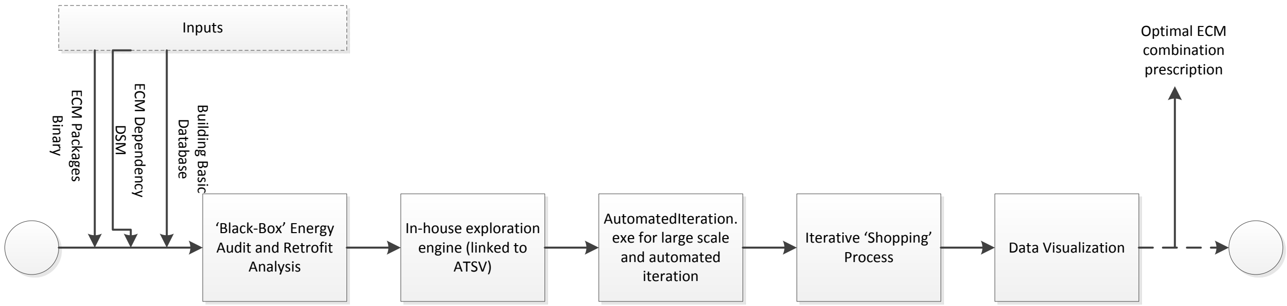


Figure 4: Building Energy Design Optimization BPMN Process Map

4.3 Building Design Decomposition

Design decomposition refers to the process of selecting subsystems based on functional requirements, cohesion, and coupling. For complex engineering systems, it is important to develop a reasonable hierarchy to access different components of the entire system, especially when there are multiple domains involved in the design processes. For a building design, it is especially important to decompose the target building into smaller and manageable components because the design-specific components decomposition can provide a structure for an interactive approach to explore the optimization set considering the uniqueness of building systems. Three perspectives are observed for building design decomposition.

The first is to decompose the building in terms of different domain areas. Building design involves structural engineering domain for structural analysis and load calculations, mechanical and HVAC domain for equipment selection and placement, ventilation and piping design for airflow analysis, and lighting domain which mainly targets on lighting system design as well natural light utilization. For discrepancies that may arise among these areas, it is important to categorize variables or design parameters that are relevant for all and to find inter-relationship among them. A similar concept is Multidisciplinary Design Optimization (MDO) (Martins and Lambe, 2013). Multidisciplinary Design Optimization problems are optimization problems that describe complex coupled engineering systems. The systems are composed of physically interacting subsystems described by disciplinary analyses, each of which possesses a certain degree of autonomy but depends on other subsystems via a number of couplings, also known as interdisciplinary variables (Alexandrov and Kodiyalam, 1998). It is most frequently used in complex engineering system designs such as the space shuttle or submarine designs. Little literature exists on using MDO in building design analysis. Geyer (2009) argues that MDO be used in the building design field, and that it requires a special setup of the optimization model that considers the uniqueness of buildings, and allows the designer to interact with the optimization in order to assess qualities of aesthetics, expression, and building function. He proposes that the Industry Foundation Classes (IFC) can be used in order to allow seamless integration into an interactive computational working environment in the future. This leads to the second perspective of decomposition, namely, to decompose from the Building Information Modeling (BIM) standards hierarchy.

BIM is a process involving the generation and management of computational representations of physical and functional characteristics of a facility (National BIM Standard, 2012). It can be viewed as a large database that contains information to support the interaction between virtual models as well as data of building systems. An open standard data model hierarchy such as the Industry Foundation Classes (IFC) can be used to facilitate interoperability in the architecture, engineering and construction (AEC) domains.

The third perspective is to decompose the building in terms of shearing layers. Brand (1994) breaks down a building system into 6 layers. He clarifies his understanding of buildings as a composition of shearing layers. They are site, structure, skin, services, space plan, and stuff. Schmidt, et al., (2009) then argue that a fundamental issue is how the building components would cluster; he suggests that it could be clustered into these varying layers of time and function or to cluster in order to show strong dependencies between short and long-life components. From a process point of view, it could also be decomposed into Process, Product, Function (Performance), and Organization.

It is to be noted that no single decomposition method serves all purposes. Different sub-systems or methods of decomposition can be used when analyzing different aspects of an integrated building system. Domain designers in each of the aforementioned disciplines will consider a set of objectives and constraints that is most logical to their own area. However, often, certain design outcomes involve compromise in another design domain. Another dilemma that designers must face is that it is rather hard to decide on the actual level of the decomposition. The level of the building system decomposition frequently depends on the fidelity of the model that people wish to construct, and the resource available for the design process.

This thesis approaches building decomposition solely for energy efficiency. Starting from energy-efficiency improvements, the building is divided into four major sub-systems: (1) lighting and plug loads, (2) envelope, (3) terminal HVAC, and (4) supply HVAC. Energy efficiency retrofit measure for each of the systems is considered which have been defined in a listing of 45 Energy Conservation Measures (Appendix C) adopted from the UTRC energy simulation and building diagnostic model. Section 4.5 discusses the UTRC-paradigm as well as details of the energy auditing and analysis tool, which is under development.

4.4 Design Dependency Analysis

From the selected decomposition method, several subsystem dependency analysis methods are available. The dependencies are categorized into three types: (1) dependent, (2) independent (parallel), and (3) interdependent (coupled) (Browning, 1998). For this thesis, dependency analysis is adopted to analyze the interrelationship among each of the identified ECM's. It is noted that not all ECM are independent of each other. For a simple example, it does not make sense to adopt both a Green Roof and a Cool Roof at the same time for the same building since the building will only have one roof surface. Four types of interrelationship were developed in this research: (1) independent, (2) exclusive, (3) inclusive, and (4) coupled. For an ECM that is not to be adopted together with another ECM, the dependency is viewed as exclusive. Using binary notation, only (0, 0), (0, 1), or (1, 0) are possible combinations. For an ECM that includes another ECM, the dependency is viewed as inclusive. Using binary notation, only (0, 0), (1, 0), or (0, 1) are possible combinations. For an ECM that has an impact on another ECM, the dependency is viewed as coupled. Coupling spans between inclusive and exclusive. Table 1 and Table 2 show two DSMs. Table 1 indicates the dependency structure of ECM's on basic building environment, and Table 2 shows the dependency structure of ECM's on each other. Understanding that it is not practical to identify the probabilistic features of an ECM without transferring subjective judgments into a numerical rating system, no chance nodes are presented in the DSM. Hence, no partitioning of DSM, via methods of clustering and sequencing, are modeled or analyzed. Future work describes how Analytical Hierarchy Process (AHP) (Saaty and Forman, 1992) as well as other structured techniques for organizing and analyzing complex decisions could be used in order to aid in the definition of decision maker preferences to the priority of sub-system level analysis.

Analyzing design dependency is beneficial because it greatly reduces the dimensions of the design space as well as the development cycle time. Specifically, for a list of 45 input variables, by identifying an exclusive relationship between 2 variables, the design dimension will reduce $2^{45} - 2^{43}(4 - 1)$ or 8.7961e+12, equals to a reduction of 25% of total possible combinations.

The dependency analysis is enabled by identifying a set of 11 rules collected from discussions with domain experts, faculty, as well as from internal research meetings. It is to be noted that there is no industry standard defining which Energy Conservation Measure (ECM) is related to which other measure and in what specific way. The ECM's are system interventions or changes being evaluated for an existing building; so, the interactions of the individual measures stand as tacit rules a designer would typically consider based on the systems in a given building. Appendix B shows a list rules with which feasibility is checked.

4.5 UTRC-paradigm of Energy Retrofit and Analysis Tool

Desai, et al. (2012) discuss the UTRC developed toolset in more detail. The energy audit and analysis toolset evaluates energy and economic performance of integrated building energy systems under a Department of Defense (DoD) project (SERDP project EW-1709). ECMs and estimated energy usage intensity (EUI) reduction are utilized from the previously developed tools. The toolset utilizes basic building attributes (such as envelope information, lighting, HVAC equipment, etc.) to estimate baseline site-energy and source-energy usage. The energy consumption of the baseline building and of the retrofit scenarios are calculated using a simplified building modeling program designed for this purpose. The model treats a building as a single thermal zone and performs an 8760-hour (one year) mass and energy balance calculation on the components of the building thermal loads. It is calculated for the specific location of the building geographic location using weather data for the area, but it does not include specific building orientation. Heat gain or loss due to conduction through the building envelope is determined using the ASHRAE radiant time series method (Spitler and Fisher, 1999). HVAC system energy consumption is computed from the building hourly loads assuming that the HVAC equipment performance can be represented with constant coefficients and the primary and secondary HVAC loops are assumed to be in a quasi-steady-state.

Surana, et al. (2012) describe the energy analysis model in further details. They demonstrate the tool application with two types of cases from the DoD real property database.

The results illustrate both statistical analysis of the potential for deep retrofits at the DoD portfolio level, which comprises nearly 250,000 facilities in the U.S., and also for a few representative existing DoD buildings. Their energy audit and analysis tool was applied to two types of cases for the DoD building stock: (1) statistical analysis at the portfolio level, and (2) analysis for individual DoD buildings. The research states that they cluster the building stock by Commercial Buildings Energy Consumption Survey (CBECS)-based primary usage categories and ASHRAE climate zones, and that they select a representative building from each cluster based on energy usage, square footage, number of floors and envelope properties. A thorough discussion can be found in their paper.

The UTRC-paradigm of energy auditing and analysis tool was applied to Philadelphia Navy Yard Office Buildings. A case study is imposed on Building 101. The Energy Efficient Buildings Hub team is taking a “living lab” approach, working in a 30,000-square-foot building in the Navy Yard, where they are testing how different technologies interact in the building with sophisticated sensors and modeling equipment (eebhub.org). It currently streams over 1500 data points every 60 seconds, and the information is made available to Hub researchers and staff. Acquired data is continuously stored and is made available to Hub researchers and other building energy efficiency researchers for development, validation and calibration modeling and simulation tools, and for assessment of the impact of building energy technologies and systems on energy use (eebhub.org). The study was able to draw some conclusions on the initial assessments of economically attractive retrofit solutions for Building 101.

4.6 Visualized Trade Space Exploration Model Configuration

This research integrates UTRC’s energy simulation package together with Advanced Trade Space Visualizer (ATSV). The intermediate transporter is a standalone executable file named AutomatedEvaluation.exe which is originally a Matlab® .m file (Refer to Appendix D for the code). The automated trade space exploration and design option evaluation is realized by integrating ATSV and AutomatedEvaluation.exe through command line control.

As discussed in previous sections, the design space is the entire ECM binary combination set; however, due to the identification of dependency analysis, the whole set does not need to be explored. By checking the rules as constraints in the AutomatedEvaluation.exe file, only feasible design inputs are fed to the energy simulation engine. Infeasible options will bypass the simulation, and thus will save evaluation time.

Input data are conveyed into matrix formats. As soon as a simulation output is generated, output results are called from a separate database and stored in matrix form as well. This data is then, fed back to ATSV for data visualization and steering. ATSV is capable of taking the multi-dimensional data and representing them in Glyph Plot. For higher dimensional data, the Parallel Coordinate Plots are also available and a better option for information demonstration.

The model is designed in a way that “human-in-the-loop” interactivity is enabled. After an initial basic sampling of 1,000 designs, for example, decision-makers can plot the data and develop their preferences with existing and incoming information. With the aforementioned advanced visual steering commands, ATSV is able to adaptively ‘zoom in’ at a preferred region to conduct further and more detailed exploration actions. It is also possible to avoid certain regions on purpose. A specific modeling and case study is discussed in Chapter 5.

4.7 Cost Analysis Model

There are three different types of estimates used at different stages of construction: (1) Conceptual, (2) Square Foot, (3) Assembly, and (4) Unit Price (RSMeans and Macaluso, 2009). Conceptual costing is often used in the programming and schematic design phase and has an expected percent error of 10%-20%. Semi-detailed, or assembly, costing is typically adopted in the design development phase and should expect a percentage error of 5%-10%. Detailed costing is used in the final design phase, and roughly 2%-4% error is expected. Cost for building projects is often differentiated into three types: (1) initial investment and (2) maintenance/operating cost (Hendrickson and Au, 1998). Initial investment is the cost which is put into the project at the very beginning, typically focusing on the direct demolition and re-construction costs of the facility. Maintenance and Operating costs indicate the cost for an existing building over longer term. Another concept is Life Cycle Cost (LCC). The LCCA Team, (2005) define Life Cycle Cost Analysis (LCCA) as a process of evaluating the economic performance of a building over its entire life. Sometimes known as "whole cost accounting" or "total cost of ownership," LCCA balances initial monetary investment with the long-term expense of owning and operating the building.

Specifically for this research, the concept of life cycle cost is recommended; however, due to the several constraints of the thesis work, a preliminary unit cost model is being prescribed. In order to take into consideration the initial investment of each ECM as well the operating expenditure of it, a smoothing model that averages the total initial investment and variant unit operating cost is calculated over the total square footage of the target building project. This generalization removes the concern of whether the target building has certain prerequisite equipment installed or not. This is to say, for a specified building, all cost accounts for initial installment of necessary setup, but always smooth it over the operating period as well as the total square footage. Several assumptions for costing exist due to data availability. A more detailed discussion can be found in Chapter 5.

4.8 Summary

This chapter proposes a process for automated trade space exploration for advanced energy retrofit design optimization in a visual and interactive environment. In particular, it proposes an efficient way of evaluating the Energy Conservation Measures as well as to 'shop' for a favored region of energy efficient designs with the aid of data visualization. In the next chapter, a case study on Building 101 at the Navy Yard, Philadelphia, PA will be conducted to show a full process of trade space exploration on energy retrofit design optimization.

Chapter 5

A Case Study: Building 101 Energy Retrofit Design Optimization

5.1 Introduction

This chapter discusses a use case of building energy retrofit parametric evaluation to demonstrate the application of trade space exploration in an interactive environment. The dynamics of the test bed, basic data environment, and parameters are presented. The process of trade space exploration is shown in an automated manner by linking up the ATSV and energy auditing and analysis engine using a separate standalone executable file. Also present is the analysis for 'human-in-the-loop' decision-making.

5.2 Problem Description and Data Environment

This section describes the dynamics of the case study problem. Section 5.2.1 describes the problem. Section 5.2.2 describes the data environment of Building 101.

5.2.1. Problem Description

A case study was performed using Building 101, the temporary headquarters of the U.S. Department of Energy's Energy Efficient Building Hub located in the Philadelphia Navy Yard. The building, owned by the Philadelphia Industrial Development Corporation (PIDC), is used as a test bed for assessing technologies and tools by multiple teams within the EEB Hub (eebhub.org). Building 101 is used as a 'living lab' of actual building environment in order to assess the functionality of the current energy design option.

5.2.2. Data Environment

The collected data have been selected to serve several analytical purposes which include quantifying the major electricity and natural gas uses in the overall building, quantifying the delivered heating and cooling capacity by the HVAC equipment to understand the building loads and equipment efficiencies, and contextualizing local weather conditions to properly consider environmental influences on energy use for the building (refer to Appendix A for the entire table of building inputs).

The input data environment consists of two major parts: (1) the existing building data and (2) Energy Conservation Measures (ECMs) packages. Basic building data consists of all the necessary data that can be utilized to describe a building's physical features, operating schedule, mechanical systems, and other energy use features. The ECM packages file is a list of 45 identified measures that HUB researchers have identified as contributable to improving the energy performance through building retrofitting (refer to Appendix C for the list of ECMs). In parametric design, the list of ECMs is modeled as binary variables with '1' indicating that a particular measure is used, and '0' indicating that the measure is not adopted in the package. The way these two types of data are utilized in energy simulation is that the existing building data being used to compute baseline design energy performance without any retrofitting packages yet considered. For retrofit design options, ECM's are sampled as a 45-rows vector. In this thesis, the baseline design alternative is run first to obtain the energy performance, and then 8,500 ECM packages are randomly sampled to observe the effect.

The original utility output data is stored in the energy auditing and analysis output database as shown in Appendix E. It stores 21 specific energy usage data, including detail system breaks down by energy source. For the purpose of the case study, the focus is placed on Annual Electrical and Annual Natural gas use as the focus for optimization. For the ease of documentation, the baseline column is added to the end of retrofit column to form a 42-row vector named ‘T’.

Another output is the cost data. For this thesis, a preliminary cost analysis model is used with the following assumptions: (1) For Chilled Water loop variable flow and Hot water loop variable flow, there is no available data documenting their costs; hence, this thesis takes missing values as ‘0’. (2) Another important assumption is that the current cost model assumes linearity when grouping ECM’s. A linear model assumes that the cost of adopting two ECMs will be the addition of the cost for each of them. This may not be true because some measures would share costs in the construction process. For example, the scope of demolition for one ECM may provide access to install or support a second ECM, thus reducing the incremental cost for the second ECM. In this case, the actual cost for utilizing multiple ECMs would be lower than the current linear model.

A generalized and validated cost analysis model is being developed by the Penn State EEB Hub research team. The methodology entails an entire thesis which is in progress at the time of analysis. Due to the timeline of this thesis, a preliminary cost model is used for the demonstration.

As discussed in the previous chapter, the input data is subject to certain dependencies. The use of Design Structure Matrix (DSM) helps break down the dependencies among all four sub-systems. Table 1 shows the impact on building basic data when 45 Energy Conservation Measures are imposed. Table 2 shows the impact on other Energy Conservation Measures when each one is adopted. This is derived from analyzing the rules/code compliance by talking to domain experts. A full list of identified rules (11 in total) is listed in Appendix B.

Table 1: Design Structure Matrix: ECM on Building Existing Data

Input Data-ECM Matrix	Light Scheduling	Occupancy Based Lightin	Daylight Based Dimming	Upgraded Lighting/ Delam	Plug Load Control	Efficient Equipment (Plug L	Light Shelves	Added Daylight	Weatherization	Cool Roof	Upgraded Windows	Increased Insulation	Green Roof	Active External Shading
Utility Data (Good to have for baseline model validation)														
Annual elec consumption (thous Btu)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	P	P	P	P
Annual nat gas consumption (thous Btu)									Y	Y	P	P	P	P
Annual fuel oil consumption (thous Btu)									Y	Y	P	P	P	P
Annual dist heat consumption (thous Btu)									Y	Y	P	P	P	P
Electric heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P	
Electric cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P
Electric ventilation use (thous Btu)														
Electric pump use (thous Btu)														
Natural Gas heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P	
Natural Gas cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P
Natural Gas water heating use (thous Btu)														
District Heat heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P	
District Heat cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P
District Heat water heating use (thous Btu)														
Fuel Oil heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P	
Fuel Oil cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P
Fuel Oil water heating use (thous Btu)														

Table 1 shows the potential effect on existing building scenario when adding one or more retrofit conservation measures (refer to Appendix G for a complete table). For the simple example of Upgraded Daylighting, adopting it should impose an effect on the building's original electricity consumption. Meanwhile, it will affect the heating and cooling consumptions because naturally lighting systems dismiss heat, no matter what energy source is being utilized for the target building. In this table, yellow-colored cells represent effect from Lighting ECM's, green-colored cells represent effect from Envelope ECM's, light yellow-colored cells represent effect from Terminal HVAC ECM's, and red-colored cells represent effect from Supply HVAC ECM's. Cells marked with 'P' show positive (increasing) effects. Cells marked with 'N' show negative (decreasing) effects. Cells marked with 'Y' show undirected effects.

Table 2: Design Structure Matrix: ECMs on ECMs

	ECM Matrix		X_{1}	X_{2}	X_{3}	X_{4}	X_{5}	X_{6}	X_{7}	X_{8}	X_{9}	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}	X_{34}	X_{35}	X_{36}	X_{37}	X_{38}	X_{39}	X_{40}
Lighting	Light Scheduling	X_{1}	X																																							
	Occupancy Based Lighting Sensors	X_{2}		X																																						
	Daylight Based Dimming	X_{3}			X																																					
	Upgraded Lighting/ Delamping	X_{4}				X																																				
	Plug Load Control	X_{5}					X																																			
	Efficient Equipment (Plug Loads Only)	X_{6}						X																																		
	Light Shelves	X_{7}							X																																	
	Added Daylight	X_{8}								X																																
Envelop	Weatherization	X_{9}									X																															
	Cool Roof	X_{10}										X			N																												
	Upgraded Windows	X_{11}											X																													
	Increased Insulation	X_{12}												X																												
	Green Roof	X_{13}										N			X																												
	Active External Shading	X_{14}														X																										
Termina	Air Side Economizer	X_{15}															X					N																				
	Fan Assisted Precooling	X_{16}																X																								
	Modified Setpoint & Setback	X_{17}																	X																							
	Supply Air Temperature Reset	X_{18}																		X	N																					
	Supply Static Pressure Reset	X_{19}																		N	X																					
	Water Side Economizer (used in combination with Energy R	X_{20}															N					X															R				N	N
	Demand Control Ventilation	X_{21}																					X																		
	Displacement Ventilation + Radiant Cooling/Heating	X_{22}																						X																		R
	Under Floor Air Ventilation (UFAD) with Personal Supply T	X_{23}																							X																
	Mixed Mode Ventilation	X_{24}																								X															
	NV for night-time pre-cooling	X_{25}																									X														
	HVAC Equipment Upgrade	X_{26}																										X													
Supply H	CAV to VAV	X_{27}																											X	R											
	VAV & Control Retrofit	X_{28}																											R	X											
	Chiller Plant Optimization	X_{29}																													X										
	Heating Plant Optimization	X_{30}																														X									
	On Demand Service Hot Water	X_{31}																															X								
	2 Stage Absorption Chillers	X_{32}																																X						P		
	Condensing Boiler	X_{33}																																	X						
	Hybrid Ground Source Heat Pump	X_{34}																																		X					
	Energy Recovery	X_{35}																				R															X				
	Indirect Evaporative Cooling	X_{36}																																				X			
	Direct Evaporative Cooling	X_{37}																																					X		N	
	Solar Thermal	X_{38}																																P						X	P	
	Desiccant Dehumidification (used only with Solar Thermal)	X_{39}																																					N	P	X	
	DOAS (Used in conjunction with DV +Radiant Systems)	X_{40}																				N		R																		X

Table 2 shows the impacts of ECM on each other. As discussed in earlier chapters, since a proper hierarchy has not been established, analysis of priority-based layers or additional dimensions is not used to show this additional information. According to Browning's (2001) categorization, Table 2 is a Parameter-Based (or low-level schedule) DSM and it is effective for integrating low-level design processes based on physical design parameter relationships. This table helps to breakdown the ECM level so that it can be analyzed from a decomposed point of view.

5.3 Automated Exploration Model Configuration

As discussed in earlier chapters, an automated update of input files enables efficient exploration of design trade space. This is enabled by compiling the energy simulation engine, its multiple input and output files together, and linking it to the exploration engine within ATSV. The model configuration is shown in Figure 5.

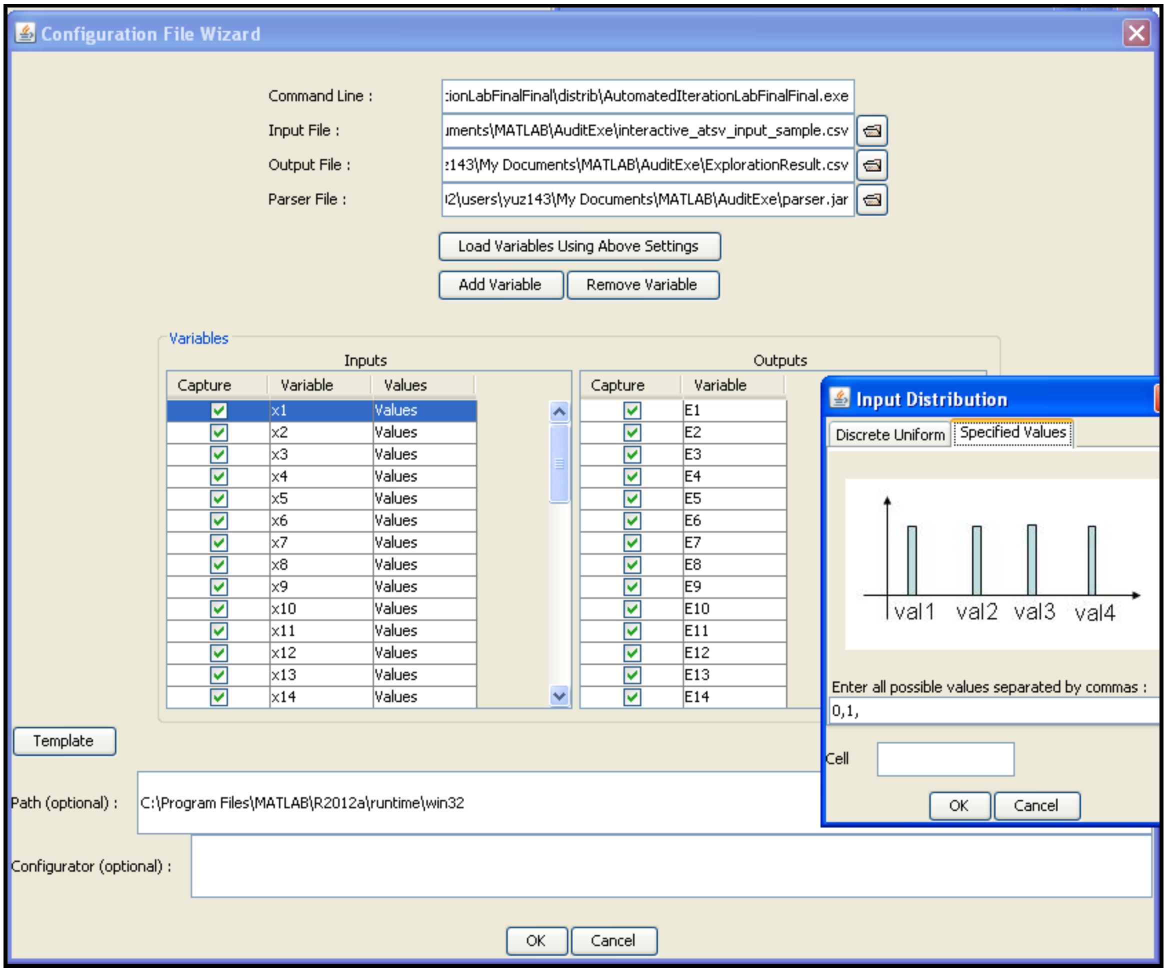


Figure 5: Model Configuration

Figure 5 shows the how the simulation engine as well the exploration engine are connected with a standalone executable file compiled from Matlab® .m code named AutomatedExploration.exe. This model calls the binary inputs for X_1 through X_{45}, and stores the corresponding results into the output list. Binary is set in the input distribution window with values of ‘0’ and ‘1’. The input file from which the binary are sampled is a .csv data file, and the output file from which the simulation result and cost result is called is another .csv formatted database. The automated iteration is based on a one-at-a-time manner. For each run, one set of input files is used in order to run one energy simulation. One set of output is obtained and stored. Then, another set of input is sampled in ATSV to trigger another round of iteration until the predefined total number of samples is finished. The process is shown in Figure 6.

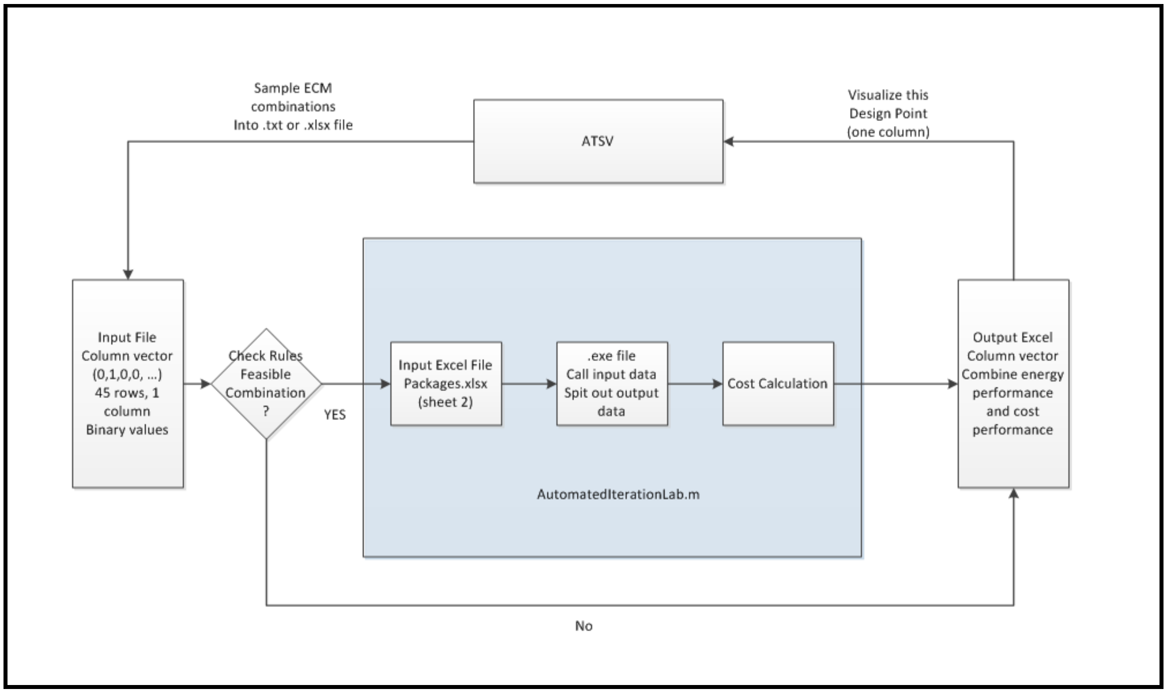


Figure 6: Model Flow Chart

As shown in Figure 6, each design option exploration starts with a sampled binary Energy Conservation Measure list. After that, the specified rules are checked in order to decide if a full cycle of energy simulation is to be started. This is to say, if the sampled ECM binary list passes the rules, then it is seen as a 'feasible' design alternative, and a thorough energy simulation is called within AutomatedExploration.exe. Infeasible designs bypass the simulation engine, and a result matrix is assigned really large values which in this case is 10^{10} for electricity usage and gas/propane usage. This ensures that these infeasible designs are dominated in every possible way. The cost calculation remains as the actual calculation. The AutomatedExploration.exe is a standalone executable file that is compiled with MCR 7.17 compiler from a Matlab® which code can be found in Appendix D. Within this AutomatedExploration.exe, all input data files that are necessary to run the energy simulation is called and stored in matrix format. Also, the ATSV generated sampled measures lists are stored in .txt format and called one row at a time. The utility result is stored in the 'T' matrix. The cost data is computed and stored in a separating cost matrix. The overall result is exported to an exploration result data file which is linked in the exploration engine as the output.

Understanding that the exploration process consists of large number of iterations, all following iterations can be performed in similar manner. To enable automated updating, ATSV calls AutomatedExploration.exe from its Exploration Engine, and the results are plotted, for example, as Glyph Plot. Decision-makers then come into the picture and put their subjective judgment on the existing design options; if they are satisfied with the current solution, then they can stop the exploration engine. If they would like more design alternatives to be sampled and evaluated, then the iteration goes on until reaching either expectation or the maximum affordability of both time and money. The next section talks about the "human-in-the-loop" interactive shopping processes.

In this case study, an initial sampling number is set to 8,500. Figure 7 shows the initial Glyph Plot for these design options.

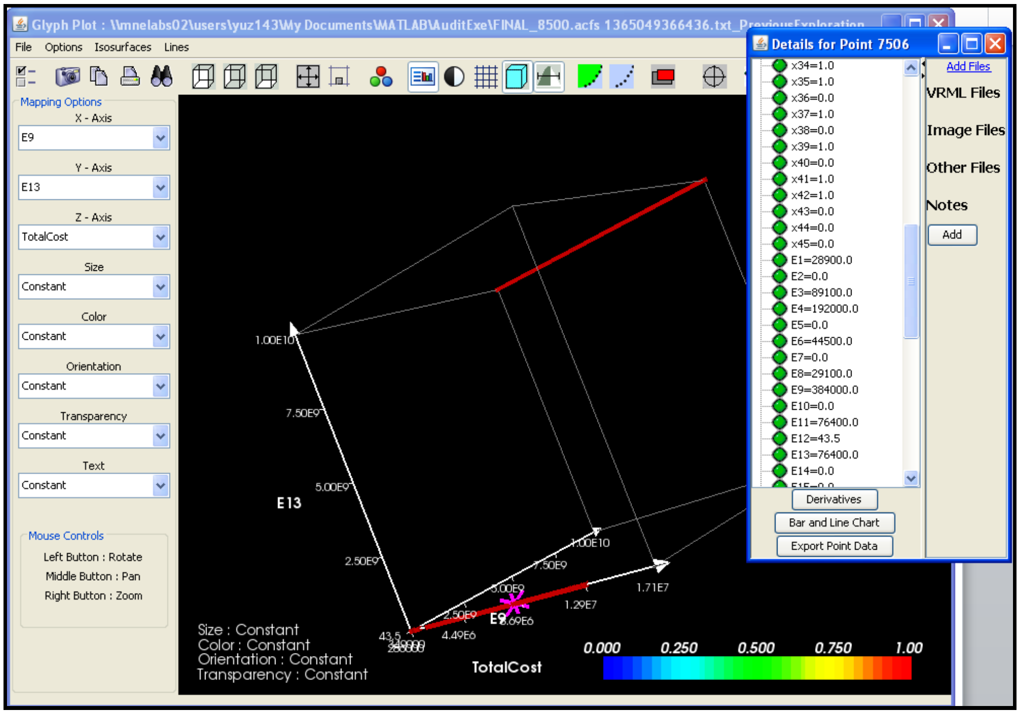


Figure 7: Basic Sampler Glyph Plot (before rescaling)

From Figure 7, it can be observed that the design points seem to converge to two different corners of the cube. This is because the dummy values for infeasible alternatives are set to be 10^{10}, and it makes the feasible design output values incomparable small. Figure 8 is obtained by brushing off the infeasible designs and rescaling the plot.

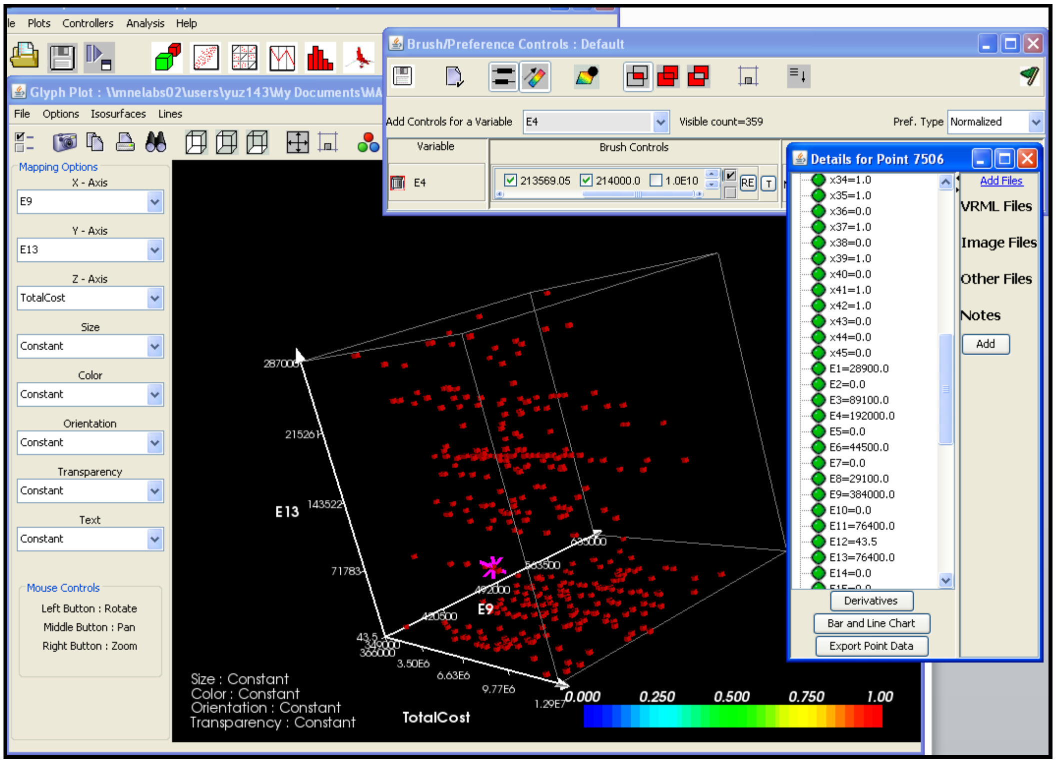


Figure 8: Basic Sampler Glyph Plot (after rescaling)

This figure shows all the feasible data from the initial 8,500 samples. By unchecking 10^{10} value of E4, the infeasible designs are brushed off. The specific design parameters can also be read from the details window. For example, for Design point 7506, inputs are listed, E9 (total electricity consumption) is 384000KWh, and E13 (total gas/propane consumption) is 76400 KWh. TotalCost is 8230000 USD. Going back to the objective of this research, which is to capture the optimal design option and its features from a large set of trade space, a Pareto Frontier can effectively capture the optimality in terms of the current three objectives: (1) minimizing total electricity utilization, (2) minimizing gas/propane utilization, and (3) minimizing total cost. Figure 9, 10, and 11 show the Pareto Frontier. Note that for some of the ECM combination, quite low level of gas/propane is utilized causing some design options with rather small values. This causes the 'gap' on X-axis in Figure 11.

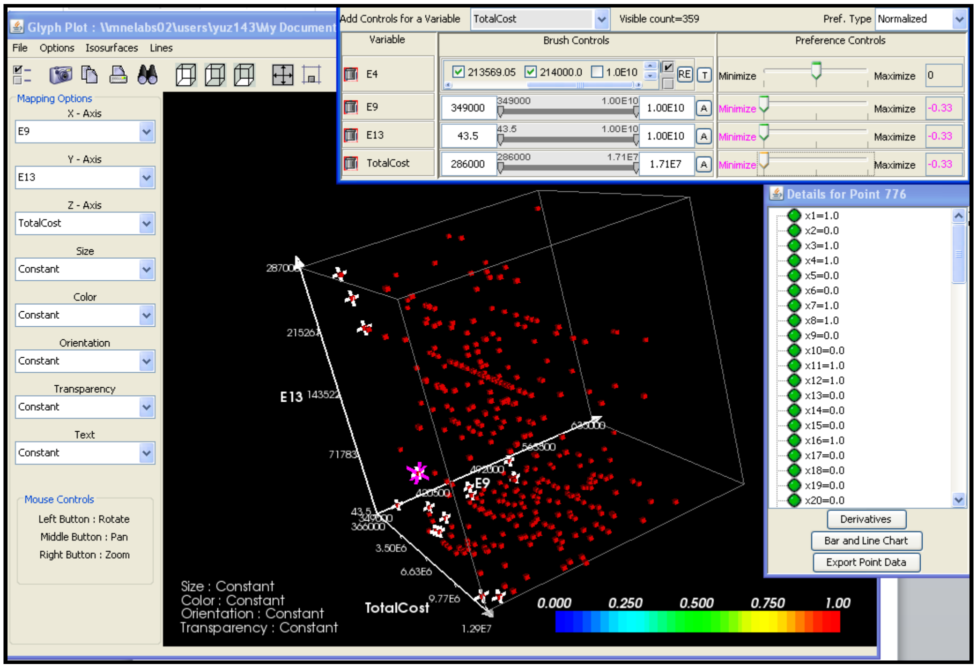


Figure 9: Pareto Frontier in Glyph Plot

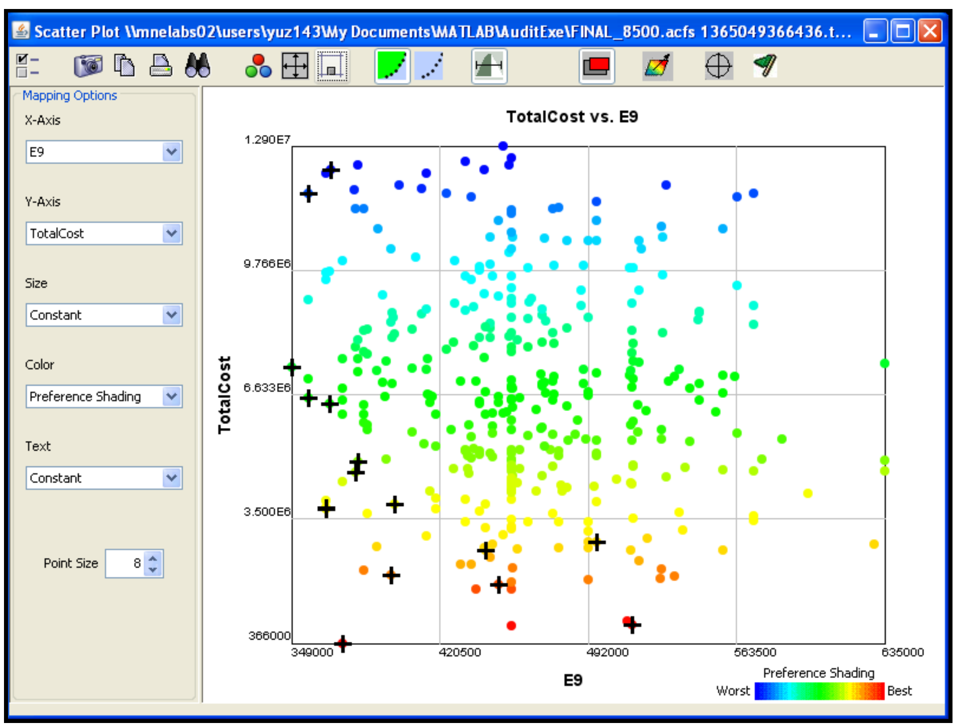


Figure 10: Pareto Frontier in 2D Scatter Plot (Total Electricity vs. Total Cost)

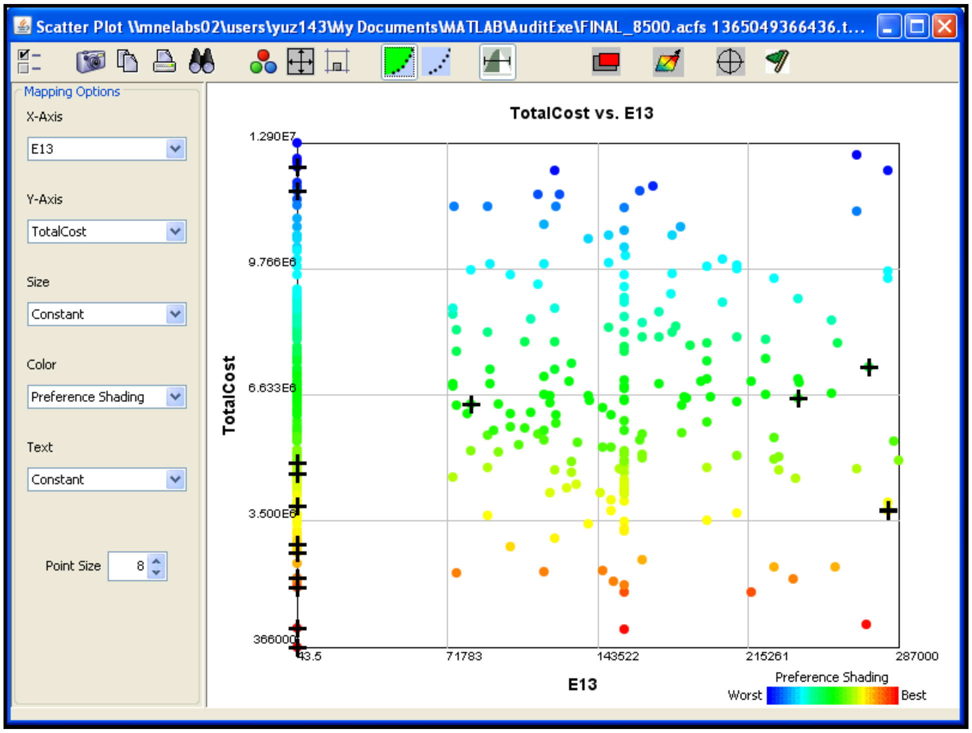


Figure 11: Pareto Frontier in 2D Plot (Gas/Propane vs. Total Cost)

5.4 Interactive Shopping Process in Exploration

The idea of putting human "back-in-the-loop" of the design process is to ensure that decision-makers can place their judgment in the design process as early as possible. The interactive 'shopping' process takes advantage of the advanced sampler controls as well as other built-in features of ATSV to enable a more targeted and focused design exploration process. The advanced sampler in ATSV includes the Pareto Sampler, which samples more design options around the Pareto frontier after an initial basic sampling process. Preference Sampler samples designs according to different preferences for the objectives. Attractor Sampler makes it possible to attract more designs around a recognized 'optimal' point, which is similar to 'zooming in' a specific good region and to explore to more details.

5.4.1 Reducing the input parameter dimensions by observing Pareto design samples

Using the initial 8,500 design data, a list of Pareto Frontier designs are exported to Table 3. A common feature of all the optimal design is observed: All X_{19} values are 0. X_{19} represent ECM=Energy Recovery. An educated guess would be that Energy Recovery (X_{19}) is a costly yet not so effective ECM. Hence, X_{19} is manually set to 0 in order to populate the following designs. This reduces variable dimensions and narrows the design space. Figure 12 shows an additional 100 designs sampled with X_{19} fixed at 0.

Table 3: Table Display of Pareto Frontier Design Data

Table Display of Data : Default

E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E1
49,377.836	137,037.188	213,569.047	0	29,580.611	0	47,033.941	513,186.5	0	0	43.511	43.511	0	0	
18,821.537	83,618.367	192,212.141	0	50,960.727	0	31,465.521	396,997.875	0	0	47.862	47.862	0	0	
0	83,618.367	192,212.141	0	63,107.707	0	20,469.785	367,525.219	0	83,145.164	47.862	83,193.031	0	0	
16,277.044	69,400	192,000	0	52,900	0	22,619.934	357,000	0	0	47.862	47.862	0	0	
0	55,500	192,000	0	51,800	0	29,578.625	349,000	0	272,797.875	43.511	272,841.375	0	0	
21,700	61,100	214,000	0	45,700	0	26,700	380,000	0	0	47.9	47.9	0	0	
0	69,400	192,000	0	45,300	0	29,300	357,000	0	239,000	47.9	239,000	0	0	
24,100	55,500	192,000	0	31,200	0	40,700	374,000	0	0	240	240	0	0	
0	54,300	192,000	0	63,400	0	28,000	366,000	0	282,000	47.9	282,000	0	0	
0	54,300	192,000	0	63,400	0	28,000	366,000	0	282,000	47.9	282,000	0	0	
13,800	180,000	214,000	0	59,000	0	22,400	496,000	0	0	43.5	43.5	0	0	
28,700	115,000	192,000	0	67,900	0	24,200	443,000	0	0	43.5	43.5	0	0	
45,200	73,400	214,000	0	74,500	0	27,600	449,000	0	0	47.9	47.9	0	0	
24,700	71,300	192,000	0	31,000	0	46,400	399,000	0	0	43.5	43.5	0	0	
23,600	93,800	192,000	0	27,900	0	24,500	368,000	0	0	43.5	43.5	0	0	
36,500	55,500	214,000	0	48,900	0	22,200	381,000	0	0	43.5	43.5	0	0	

Table 4: Table Display of Pareto Frontier Design Inputs

Table Display of Data : Default

x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23	x24	x25
0	1	1	1	0	0	0	0	0	0	0	0	0	0	
0	1	1	1	1	0	0	0	0	0	1	0	0	0	
1	1	0	0	0	1	0	0	0	0	0	0	1	1	
1	1	0	1	1	1	0	0	0	0	0	1	1	1	
1	0	0	1	1	1	0	0	0	1	1	0	1	0	
0	0	1	1	1	1	0	0	0	1	0	0	0	1	
0	1	1	1	0	1	0	0	0	1	0	0	1	1	
0	0	0	0	0	0	0	0	0	1	1	1	0	0	
1	0	0	1	0	0	1	1	0	0	0	0	1	0	
1	0	1	0	1	0	0	0	0	0	1	1	0	0	
0	1	0	0	0	0	0	0	0	0	1	0	0	1	
0	0	0	0	1	0	1	0	0	0	1	0	0	0	
0	1	0	0	1	0	0	0	0	1	1	0	0	1	
0	0	0	1	1	0	1	0	0	0	0	1	1	0	
1	0	1	1	1	1	0	0	0	0	1	1	1	1	
1	0	0	1	0	0	0	0	0	0	1	0	0	1	

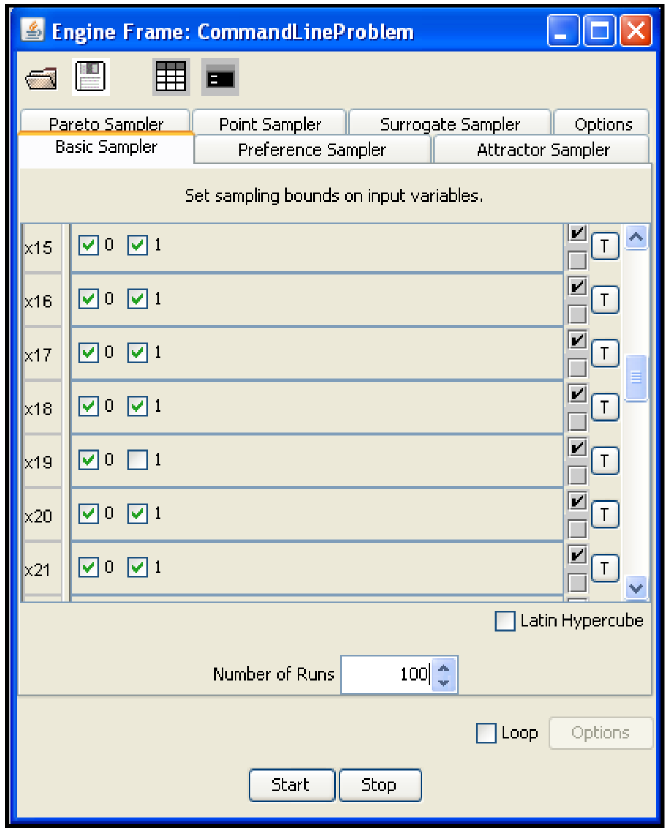


Figure 12: Model Setting for X_{19}=0

These 100 rows of design data are attached to the original 8,500 data, and Figure 13 shows the Glyph Plot and 2D Scatter Plot of the additional basic samples with preferred X_{19} value. It can be clearly observed that this enhances the density around Pareto Frontier.

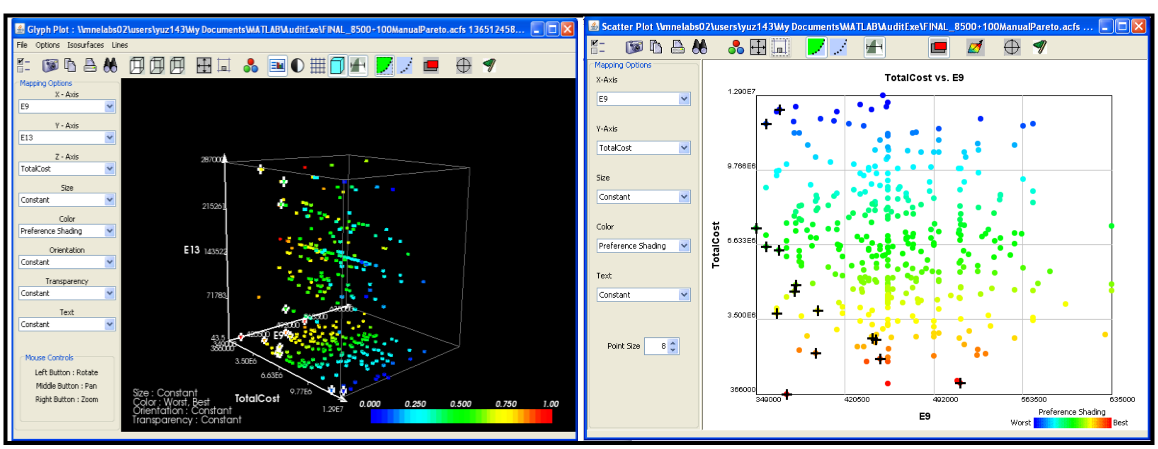


Figure 13: Glyph Plot for Additional 100 Designs with X19=0

Another way to observe is to export the Pareto designs. By using basic sampler with setting any fixed value for inputs, a total of 16 Pareto optimal ones are obtained from 8,500 runs. Yet, by manually setting X_{19}=0, a total of 4 Pareto ones are obtained from 100 runs. It is a sign of improving sampling effectiveness, from a mere ratio of 16/8,500=0.19% to 4/100=4%.

Table 5: Additional Pareto Optimal Designs

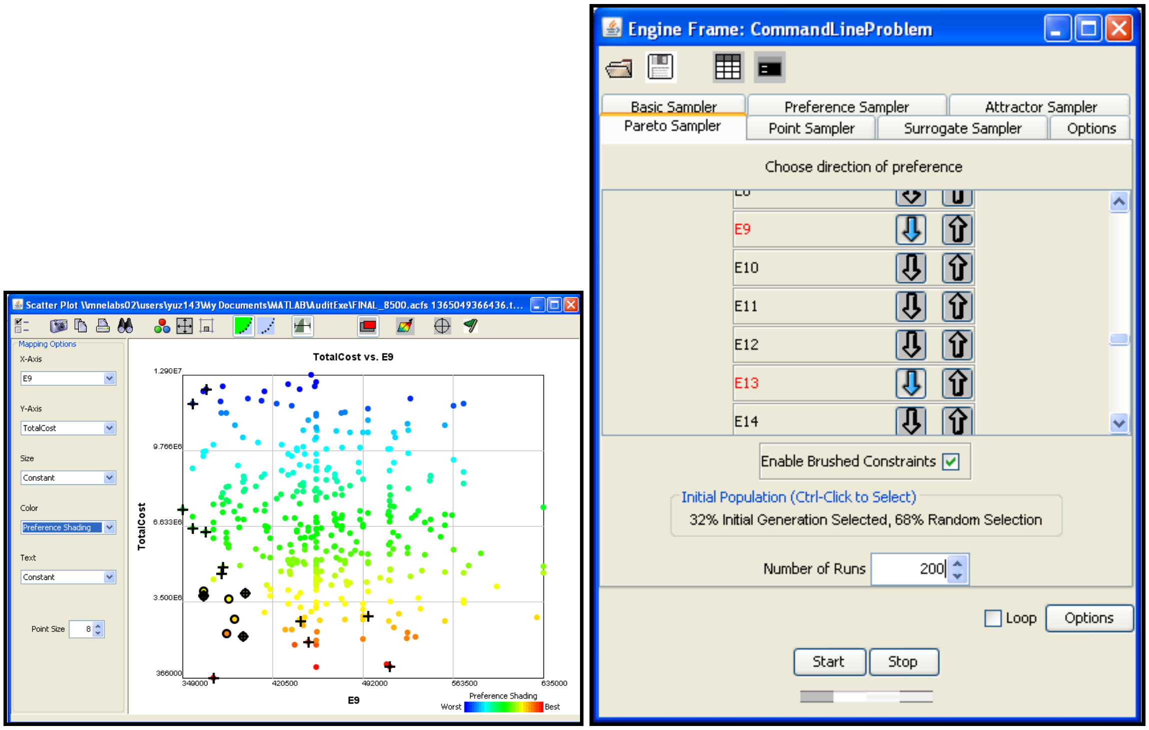
FINAL_ExportParetoDesign+100ManualPareto - Notepad

File Edit Format View Help

x45	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14
1.0	36587.875		49377.836		137037.19		213569.05		0.0	29580.611		0.0	47033.94	
0.0	19919.594		18821.537		83618.37		192212.14		0.0	50960.727		0.0	31465.521	
0.0	8117.234		0.0	83618.37		192212.14		0.0	63107.707		0.0	20469.785		3675
1.0	3947.4275		16277.044		69400.0	192000.0		0.0	52900.0	0.0	22619.934		357000.0	

5.4.2. Pareto Sampler

To further explore a narrow preferred region, another way is to use the Pareto Sampler directly. Figure 14 shows the Glyph Plot of an additional 100 designs on the basis of the initial 8,500 data.



(a) 2D Scatter Plot (b) Exploration Engine Setting

Figure 14: Pareto Sampler Exploration Engine and 2D Scatter Plot

In Figure 14(a), a few preferred designs are selected around the Pareto Frontier from initial 8,500 runs, and the Pareto Sampler model is set up as shown in Figure 14(b) with 32% of Initial Generation Selected and 68% Random Selection. This is to say, in the next 200 runs, a ratio of 32% will be comparable to the previous preferred design while 68% will be randomly selected according to the built-in algorithm (discussed in Chapter 2) for the Pareto Sampler. Three objectives remain unchanged: (1) minimizing E9 (Total Electricity), (2) minimizing E13 (Total Gas/Propane), and (3) minimizing Total Cost as shown in the Figure 14(b).

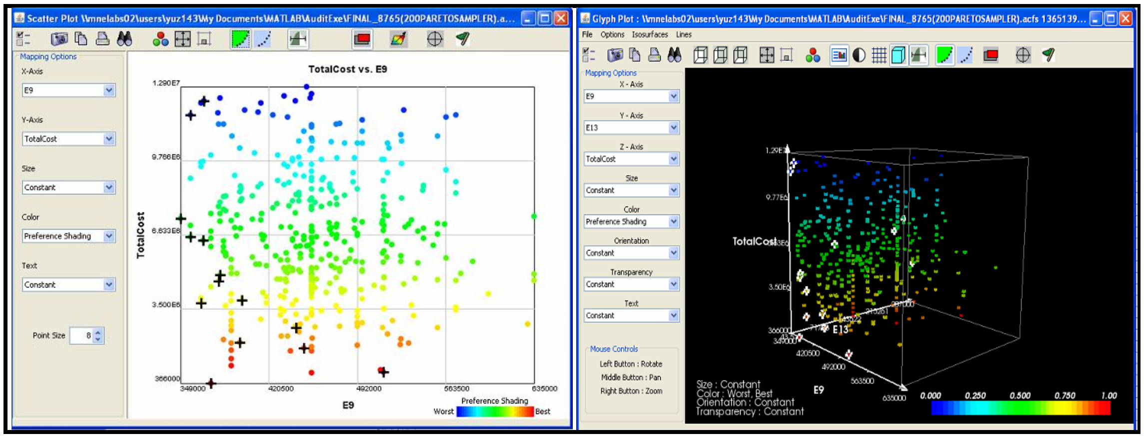


Figure 15: Pareto Sampler Plot (2D Scatter and Glyph)

For less expensive simulation or exploration examples, it is able to monitor the Pareto sampling in a real-time manner, which will present more obviously how designs tend to aggregate around a specific preferred region.

5.4.3. Attractor Sampler for Fixed Total Budget

An actual scenario that might arise in real project scenario is that a budget be fixed before the design work begins. To make sure the design options are cost-reasonable, and to avoid extra work for overly costly design alternatives, an Attractor Sampler can be used in order to generate design options only around a specific total cost. In order to sample around a fixed total cost of 5,000,000 USD, an attractor is used to sample around that specific region to further explore that sub trade space. An additional 200 design points are sampled around the attracted hyperplane by using the Attractor Sampler. Figure 16 shows a Glyph Plot as well as 2D scatter plot of these points.

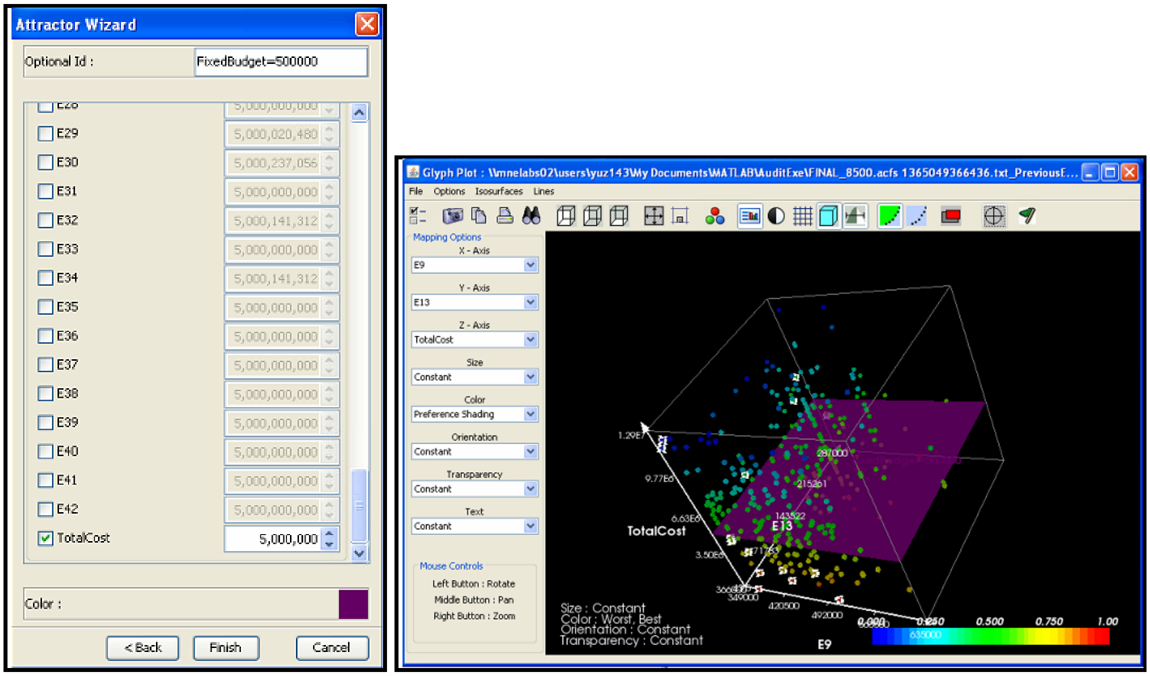


Figure 16: Attractor Wizard and Attractor Hyperplane

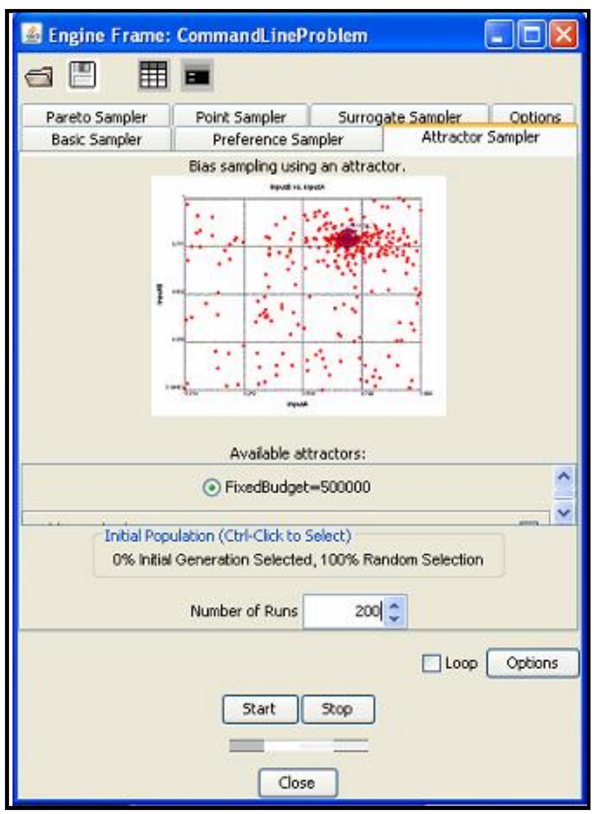


Figure 17: Attractor Sampler Engine Frame

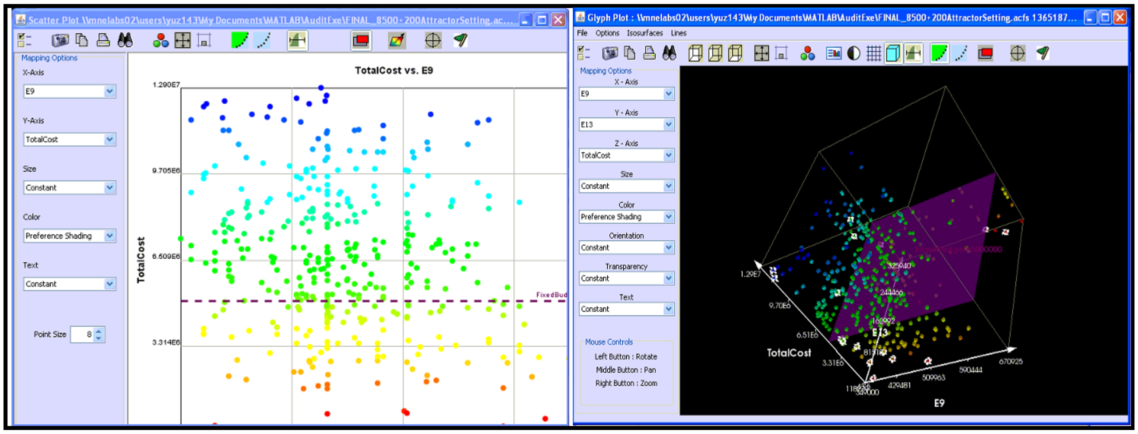


Figure 18: Attractor Sampler Designs

The data list for these 200 attracted designs (with TotalCost all close to 5,000,000USD) is shown in Table 6. Looking at feasible designs, the attracted ones have TotalCost of 2076636.9, 3257143, 2917176, 3312488, 1772024, 349839, 4853754, 4459676, 2893545, 611878.9, 4589061, 4782182, 2180478, and 118278.9. Reading the previous data file for TotalCost values, this set of attracted designs points are relatively close to the predefined 5,000,000 USD. One other observation is that for this additional 200 runs, a total of 14 feasible ones are generated. This yields a 'success' ratio of 14/200=7%, comparing to the original 0.19%, a great improvement can be concluded.

Table 6: Table Display of Attractor Designs

Table Display of Data : Default

43	x44	x45	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
1	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	146,186.953	0	97,719.344	192,212.141	0	102,936.117	0	43,888.605	582,943.188	0	325,676.438	263.646	325,940.094
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	146,186.953	0	97,719.344	192,212.141	0	102,936.117	0	43,888.605	582,943.188	0	325,676.438	263.646	325,940.094
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
1	1	0	146,186.953	0	97,719.344	192,212.141	0	102,936.117	0	43,888.605	582,943.188	0	325,676.438	263.646	325,940.094
0	0	0	146,186.953	0	97,719.344	192,212.141	0	102,936.117	0	43,888.605	582,943.188	0	325,676.438	263.646	325,940.094
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	146,186.953	0	97,719.344	192,212.141	0	102,936.117	0	43,888.605	582,943.188	0	325,676.438	263.646	325,940.094
1	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
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0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
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0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	148,878.688	0	122,149.18	192,212.141	0	106,951.68	0	42,978.633	613,170.312	0	302,483.281	263.646	302,746.906
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	76,255.461	0	122,149.18	192,212.141	0	71,619.453	0	41,405.207	503,641.438	0	283,866.844	263.646	284,130.469
0	1	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...
0	1	0	40,713.465	0	97,719.344	213,569.047	0	109,916.727	0	27,678.033	489,596.625	0	279,444.562	263.646	279,708.219
0	0	0	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...	10,000,000,...

5.4.4. Preference Sampler to Specify Certain Preference Direction

More often than not, a complex design decision involves multiple objectives that are not equally weighted. It is important to specify the different ratios on each of them in order to develop more realistic and more satisfying designs. This can be enabled by using preference arrow. For example, in between Total Cost and Total Electricity Consumption, it is decided to pursue further designs which focus more on minimizing the cost objective. Figure 19 shows a Toggle Preference Arrow setting for preference sampling. An additional 200 runs are sampled using Preference Sampler, 2D scatter plot and 3D Glyph Plot are shown in Figure 20.

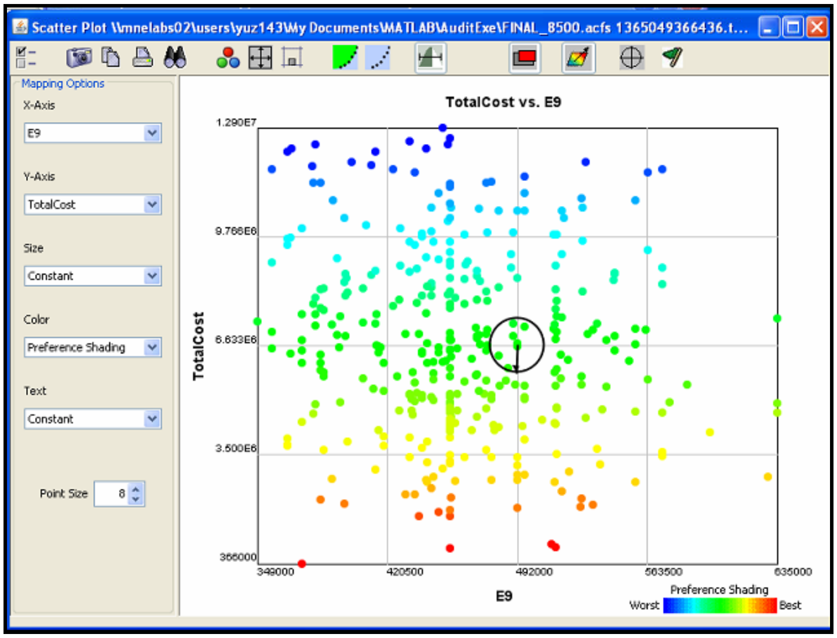

Figure 19: Toggle Preference Arrow (Initial 8,500 Designs)

It is observed that more designs are sampled near the x-axis, creating more options which are in favor of reduced cost than of other objectives.

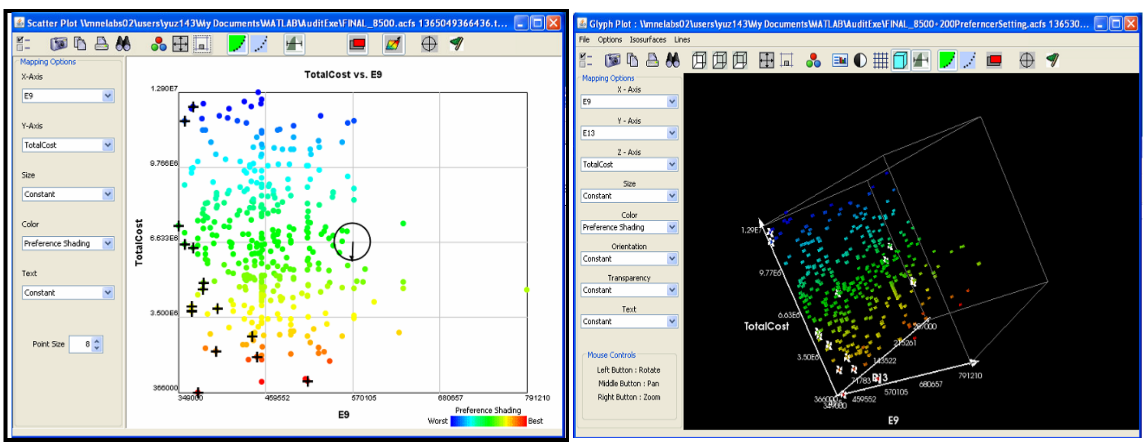

Figure 20: Preference Sampler of Additional 200 Designs (2D Scatter and Glyph)

5.5 Summary

This chapter uses Building 101 as a test bed to demonstrate the proposed trade space exploration process. The data environment and availability is described. The exploration model takes advantage of the energy simulation model that is developed by United Technology Research Center (UTRC) in order to obtain utility performance output for Building 101. A preliminary cost model is also used to estimate cost for this case study. A total of 8,500 initial design inputs are sampled, after checking the rules, 359 are feasible designs, and were passed to simulation engine for energy analysis. The feasible ones are visualized in Glyph plots and rescaled in order to observe the Pareto frontier. Several advanced sampling controls as well as the human judgment are imposed throughout the process in order to either sample more non-dominated designs in less time, or to 'zoom-in' a preferred region to further explore those design alternatives.

Chapter 6

Summary, Limitations, and Future Work

6.1 Summary and Contributions

This thesis presents the application of the trade space exploration for building energy retrofit design optimization. It discusses the typical approach of trade space exploration, its typical applications in the mechanical and aerospace design domains, and its applicability toward building energy retrofit design optimization. The thesis explored the unique features of the building energy retrofit design process, and provides an approach which includes variables that can be explored in the parametric design space. To describe and demonstrate the effectiveness of the proposed approach, Building 101 at the Philadelphia Navy Yard was used as a test bed to demonstrate the process, as well as to propose insights on the effectiveness of the proposed energy conservation measures for the project.

Major contributions of this exploratory work include: (1) providing insight in the adoption of automated evaluation and optimization methods in building energy retrofit design without heavily relying solely on existing "rules-of-thumb"; (2) formulate the building energy retrofit design problem in a parametric modeling manner which use operations research techniques to address the problem in an efficient manner; (3) demonstration of the trade space exploration process and multi-dimensional data visualization techniques to create an interactive decision-making environment which provides insights on how the advanced steering controls can facilitate 'discrete' decisions; and (4) linking the ATSV and building energy audit and simulation model together to enable automated design evaluation and exploration process, to identify energy efficient solutions for retrofit projects.

6.2 Limitations

As mentioned in the previous chapters, one assumption of using trade space exploration is that the design problem can be parameterized. However, for buildings, several values such as architectural quality, water use, indoor air quality, daylighting, acoustical quality, aesthetic cognition and occupants comfort and usability are difficult or time consuming to model depending on the state of design development and ability to interact with future user groups. It is unreasonable to design a building as an isolated system which disregards how occupants interact with the design and what value that level of interaction might demonstrate. For a simple example, the optimal design that is selected might have minimized energy consumption and minimized monetary cost, but it can also be the design that occupants provides a low comfort level to the occupants. Such an environment might cause inefficient work or uncomfortable living conditions. A more realistic question becomes: is it worthwhile to maximize energy savings and minimize cost when the occupants' productivity is sacrificed? One might argue that it is necessary to model such occupant comfort as an additional objective for this research, with a subjective decision rating method such as Analytical Hierarchy Process (AHP) (Saaty and Forman, 1992) used as a method to quantify the psychological impact on different occupants. This would involve a cycle of interviews and statistical sampling and remains a potential direction of future work. Other variables that are not occupant or user related could be added to the approach such as daylighting, water consumption, operational complexity, or other factors which could be quantified through computational modeling, but in some instances, could significantly increase the computational resources required or necessitate the addition of more detailed design input parameters, e.g., performing a detailed daylighting analysis would require a daylighting simulation using more detailed building parameters such as the wall locations, window properties, material reflectance, etc.

Another limitation of this research is that the hierarchy of the dependency matrix could be improved since ECMs do not have parallel importance. It is to be noted that the priority of adopting any one of the ECMs should be ranked in terms of energy saving/cost ratio. With a higher ratio, it indicates that one ECM can save much more energy at an expense of relative lower cost. With a lower ratio, it indicates otherwise. This is especially important when exploring the trade space because some of the combinatorial options are clearly dominated, and thus those options do not necessarily have to be 'explored' by ATSV. This could greatly reduce the trade space and adds to the efficiency of the exploration process.

Lastly, the identified rules listed in Appendix B are only a demonstration of the current feasibility check-list. Rules vary for different building project types. At the same time, for the same project, there might be different rules or different ranking of rules in terms of different sets of objectives. For example, one might consider Lighting Schedule to be in conflict with an occupancy sensor because the former indicates following a certain operating schedule initiated by ASHRAE, while the latter indicates turning on the lights when occupants are present in a certain area of the building, and to turn them off whenever all occupants leave regardless of the ASHRAE recommendations. This rule is not incorporated into this thesis because, in general, designers can control one section of the building by Lighting Schedule while controlling other sections by Occupancy Sensors. There is no standard industry categorization as to which ECM is exclusive of another, and yet these rules are based on, as have been mentioned, experience of domain experts. In this case, limitations of the sampling of interviewees add to the limitation of the result this thesis proposes, and could be modified if standard ECMs are identified along with a clear documentation of the potential to combine ECMs within a particular project. Another limitation of this approach is that we assume the building as a single zone with single system types. This may not be accurate for larger, more complex buildings which can have multiple systems, e.g., a partial green roof and a partial cool roof. The assumption in this research was to limit the system type to one system due to the limitation of the simulation engine's capability to quantify the energy consumption for more complex solutions, along with the limited input data for the design. In order to address these more complex solutions, it is important to note that there would need to be some method to automatically develop some level of design information to be used as input parameters to the energy model so that the modeling could be more accurately performed, and a more detailed energy simulation engine would need to be used, such as Energy Plus or DOE 2.2.

6.3 Future Work

Limitations of this thesis indicate the potential directions for future work. In response to the parameterization limitation and to consider the specific features of buildings, one direction of further work could focus on the development of techniques to parameterize the unquantifiable measures. Previous research on hierarchical group decision-making can be leveraged to formulate a relative numerical hierarchy of building objectives (Saaty and Forman, 1992). The essence of AHP is that human judgments, and not just the underlying information, can be used in performing the evaluations. By rating on a relative importance from 1 to 9, the unique objectives of building energy design such as aesthetic cognition and comfortableness can be modeled as objectives and included in the trade space exploration process. . Another approach would be to leverage the system user to guide the prioritization by presenting the potential design solutions to the user who is guiding the preference.

In response to the occupancy productivity limitation, further research could include more broad involvement of occupants in the design analysis and evaluation. How an energy design alternative reflects on the occupants who work/reside in it remains an important research field. Tools such as discrete event simulation and agent-based simulation can possibly be leveraged to computationally model occupant behavior to more accurately demonstrate the performance of a design options, or quantitative rules may be able to capture some aspects of occupant behavior to guide the design evaluation process. Another potential area for future research would be to evaluate alternative energy simulation engines to model the energy consumption projects used in the trade space exploration. As stated previously, several simulation engines are available to model different aspects of building energy performance; for example, different energy modeling applications could provide more detailed energy consumption projections, and if more detailed input parameters were available, airflow simulation engine could be coupled with the energy modeling engines to provide even better energy consumption projects along with indoor quality metrics (Novoselac ,2005). A scenario for calling multiple simulation engines consecutively during each design evaluation can be envisioned. This reaises many question such as (1) what are the valuable simulations to run?; (2) In what order should they be performed?; (3) How can the multiple packages be synchronization serialized to efficiently provide accurate results to a future user?; and (4) How do you efficiently present the results to a user to be able to solicit their preferences?.

In response to the feasibility rules standardization limitation, future work could focus on developing a more generic and standardized ECM hierarchy in order to frame an unbiased feasible design space, as well as to guarantee the optimal solution is not affected by misleading rules. Further effort could be placed on categorizing different building types influence ECM dependency. By ‘types’, it is not restricted to building structure, but also orientation, geographical location, major building material, and usage etc.

As mentioned in Chapter 4, the cost model used in this thesis is solely a preliminary costing model. More work should be, and is being, conducted to better formulate the economic measuring model for retrofit building design. Different from new construction design, the cost modeling for building retrofit activities can be very detailed and sensitive to specific attributes of a project.

More future work could also focus on improving the computational efficiency of the evaluation. Comparing the work to other engineering system designs, building energy design often involves time-consuming simulation or modeling. As mentioned, often times, more than one simulation models should be used to provide comprehensive performance and results. Given a limited time and other resources, it becomes critical to improve evaluation time, which will enable more interactive and iterative approaches to engage decision-makers directly in the trade space exploration process.

Appendix

Appendix A

Building Input Data

TYPE	INPUTS
Building Input Data	Attributes
	CBECS NREL HVAC Type DOE Glass Library RTS_Roof RTS_Wall TMY3 MetaStations
Energy Conservation Packages	Refer to Appendix II
Relevant Data Files	All Weather Data Assembly Assembly_Light COP_Data COP_Data_TillFeb2011 Definition Health Health_Light Lib Lib_Light LM LM_Light Motel Motel_Light Office Office_Light Pysc_Data Pysc_Data_OLD Restaurant Restaurant_Light Retail_Light RTS_Data Saving_Results_Specific School School_Light Univ Univ_Light Vacant Vacant_Light Warehouse Warehouse_Light
Schedule	Occupancy Lighting

Appendix B

Energy Conservation Rules and Variable Denotation

Rule 1: Only take one from Cool Roof and Green Roof

X10+X13=1

Rule 2: Only take one from Water Side Economizer and Air Side Economizer since they are just two means to cool air. It does not make sense to use cool water and cool air at the same time.

X15+X20=1

Rule 3: Only take one from Static Reset and Supply Air Temp Reset since all but placing an actuator on the VAV damper, and set it to a specific resetting logic. It does not make sense to follow two logics at the same time. (See Note 2)

X18+X19=1

In this research, I consider the method of controlling static set point is by placing an actuator on the VAV damper. Other methods exist but are out of this research consideration. Refer to the ASHRAE Journal technical report for other specific technical methods. (Increasing Efficiency with VAV System Static Pressure Setpoint Reset ASHRAE Journal 2007).

Rule 4: If Absorption Chillers=1, then Solar Thermal=1, and vice versa. They are coupled when in use.

X32=X38

Rule 5: Only take one from Direct Evaporative Cooling and Indirect Evaporative Cooling. Indirect EC adds a heat exchange to Direct EC, but is very similar.

X37+X39=1

Rule 6: If Displacement Ventilation and Radiant Systems (DVRS)=1, then DOAS=1. DOAS is used in conjunction with DVRS.

X22<=X40

Rule 7: If CAV to VAV=0, then VAV and Control Retrofit=0

X27>=X28

Rule 8: If Energy Recovery=1, then Water Side Economizer=1.

X35<=X20

Rule 9: If Water Side Economizer=1, then DOAS=0

X20*X40=0

Rule 10: If Water Side Economizer=1, then Desiccant Dehumidification=0.

X20*X39=0

Rule 11: If Water Side Economizer=1, then Energy Recovery=0

X20*X35=0

All Xi are binary variables.

Appendix C

Energy Retrofit Package List

ECM Packages	Decision ariable
Package.Plug_load_control	X1
Package.Light_scheduling	X2
Package.Weatherization	X3
Package.Occupancy_sensors	X4
Package.Upgraded_lighting	X5
Package.Daylight_baseddimming	X6
Package.Added_daylight	X7
Package.Light_shelves	X8
Package.Proper_space_setpoints	X9
Package.Supplyair_tempreset	X10
Package.Underfloor_ventilation	X11
Package.DCV	X12
Package.Static_reset	X13
Package.Trees	X14
Package.Active_ExternalShading	X15
Package.Upgraded_windows	X16
Package.Cool_roof	X17
Package.Waterside_economizer	X18
Package.ERecov	X19
Package.Chillerplant_optimization	X20
Package.Tankless_waterheating	X21
Package.Condensing_boiler	X22
Package.Solar_heating	X23
Package.Natural_ventilation	X24
Package.NV_precooling	X25
Package.Twostage_absorptionchillers_SteamfromWasteheat_Solar	X26
Package.Night_ventilationforprecooling	X27
Package.Variableflow_VFD	X28
Package.Evaporativecooling_indirect	X29
Package.Evaporativecooling_direct	X30
Package.GSHP	X31
Package.Radiant_cooling_heating_displacmentvent	X32
Package.Dessicant	X33
Package.Efficient_equipment	X34
Package.DOAS	X35

Package.Green_roof	X36
Package.Upgraded_insulation	X37
Package.Heatingplant_optimization	X38
Package.Airside_Economizer	X39
Package.HVAC_Equipment_Upgrade	X40
Package.VAV_ControlRetrofit	X41
Package.CHW_VARFlow	X42
Package.HHW_VARFlow	X43
Package.CHW_PumpVFD	X44
Package.HHW_PumpVFD	X45

Appendix D

Matlab Code (AutomatedExploration.m)

```
%% This code combines ATSV engine and .exe simualation package in an interactive and automated way

% This code is sole property of Ying Zhang, 03/15/2013. All Rights Reserved.
% This code follows the updated flow chart specified in the thesis modeling report.

% package.xlsx sheet2 contains one single column of one instance of ECMs combination
% Output_StageIII_SpecificSolution is passed into a matrix, and the generated
% matrix is sequentially fed back to Output_StageIII_SpecificSolution Sheet4.

% R is input data matrix (45,n), T is output data matrix (42,n) where n is
% the total number of FEASIBLE design options explored.

%% Initialization
% Add the AuitExe folder and all its subfolders to the search path.
addpath(genpath('\\mnelabs02\users\yuz143\My Documents\MATLAB\AuditExe'));
cd'\\mnelabs02\users\yuz143\My Documents\MATLAB\AuditExe'

% Store input in R matrix (45 rows, 1 column)
filename1='interactive_atsv_input_sample.csv';   % This is indeed n .txt file if directly from ATSV
sheet=1;
xlRange='B1:B45';
R=zeros(45, 1);
R=xlsread(filename1,sheet,xlRange);
xlswrite('\\mnelabs02\users\yuz143\My Documents\MATLAB\AuditExe\Project1\Inputs\Packages.xlsx',
R(:,1),'Packages_retrofit', 'B1')          % Call R (single columned) into packages.xlsx sheet 2 while
package.xlsx is closed

%% Check the Rules to determine whether feasible and need to run simulation
% Check if the 11 rules are satisfied for each of the design combination,
% if so, move to Energy Simulation Process, if not, fill up T matrix with
% all zeros for this specific combination.

fori=1
if R(17,i)+R(36,i)<=1
temp1(i)=1;
else
temp1(i)=0;
end;
if R(18,i)+R(39,i)<=1
temp2(i)=1;
else
temp2(i)=0;
end;
if R(13,i)+R(10,i)<=1
temp3(i)=1;
```

```
else
temp3(i)=0;
end;
if R(23,i)==R(26,i)
temp4(i)=1;
else
temp4(i)=0;
end;
if R(29,i)+R(30,i)<=1
temp5(i)=1;
else
temp5(i)=0;
end;
if R(32,i)<=R(35,i)
temp6(i)=1;
else
temp6(i)=0;
end;
if R(19,i)<=R(18,i)
temp7(i)=1;
else
temp7(i)=0;
end;
if R(18,i).*R(35,i)==0
temp8(i)=1;
else
temp8(i)=0;
end;
if R(18,i).*R(33,i)==0
temp9(i)=1;
else
temp9(i)=0;
end;
if R(18,i).*R(19,i)==0
temp10(i)=1;
else
temp10(i)=0;
end;

% Put all temp values into one matrix to check for rule compliance
Rule_Compliance=[temp1; temp2; temp3; temp4; temp5; temp6; temp7; temp8; temp9; temp10];

ifRule_Compliance==ones(size(Rule_Compliance))
Rule_Satisfied=1;                    % This ECM combination passes rule checking, should proceed to Energy
Simulation Phase
else
Rule_Satisfied=0;                    % This ECM combination fails rule checking, should put all 0 values in its T
column and bypass Energy Simulation Phase
end;
end;

%% Energy Simulation Iteration (single)
```

```
T=zeros(42,1);                          % Comprehensive output matrix, n=total number of samples
Retro_Electricity=zeros(9,1);
Retro_Gas=zeros(4,1);
Retro_Oil=zeros(4,1);
Retro_DistrictHeat=zeros(4,1);
Base_Electricity=zeros(9,1);
Base_Gas=zeros(4,1);
Base_Oil=zeros(4,1);
Base_DistrictHeat=zeros(4,1);


if (Rule_Satisfied(i)==1)

% Run .exe to obtain the result for ith iteration/ECM combination
open('\\mnelabs02\users\yuz143\My
Documents\MATLAB\AuditExe\Project1\Start_StageIII_specificSolution.exe')
pause(200)

%!C:
%!cd/
%!cd Users\ANXIN\Documents\MATLAB\AuditExe\Project1
%!cd Start_StageIII_specificSolution.exe

% The above executable file will store the result into a separate file
% named 'Output_StageIII.xlsx'. (specifically its sheet4)
filename2='Output_StageIII.xlsx';
sheet=4;
xlRange1='C3:C11';
xlRange2='C13:C16';
xlRange3='C18:C21';
xlRange4='C23:C26';
xlRange5='B3:B11';
xlRange6='B13:B16';
xlRange7='B18:B21';
xlRange8='B23:B26';

% Take back the results and store them in T matrix
Retro_Electricity(:,1)=xlsread(filename2,sheet,xlRange1);   % input column iretro_electricity results
Retro_Gas(:,1)=xlsread(filename2, sheet, xlRange2);         % input column iretro_gas results
Retro_Oil(:,1)=xlsread(filename2, sheet, xlRange3);         % input column iretro_oil results
Retro_DistrictHeat(:,1)=xlsread(filename2,sheet, xlRange4); % input column iretro_districtheat results
Base_Electricity(:,1)=xlsread(filename2,sheet,xlRange5);    % input column ibase_electricity results
Base_Gas(:,1)=xlsread(filename2, sheet, xlRange6);          % input column ibase_gas results
Base_Oil(:,1)=xlsread(filename2, sheet, xlRange7);          % input column ibase_oil results
Base_DistrictHeat(:,1)=xlsread(filename2,sheet, xlRange8);  % input column ibase_districtheat results

T(:,1)=[Retro_Electricity(:,1); Retro_Gas(:,1); Retro_Oil(:,1); Retro_DistrictHeat(:,1);
Base_Electricity(:,1); Base_Gas(:,1); Base_Oil(:,1); Base_DistrictHeat(:,1)];  %put eight matrix
components into T, to rows.

else
```

```
        T(:,1)=10^10.*ones(size(T(:,i)));        % If the rules are not passed, store extremely large numbers
(10^10) in T vector.

end;
%% Display the output results in matrix T and export into .csv file
T;                                           % Display the full T matrix (n design points)
% Write numeric values of T (all T) into Output_StageIII.csv file
filename3 = 'Output_StageIII.csv';    % This becomes the reference file for MCR Compiler
sheet = 1;
xlRange = 'B1:B42';
xlswrite(filename3,T,sheet,xlRange)



%% Incorporate cost data (cost spreadsheet needs to be updated)
UnitCost=zeros(45,1);
formatshorte
% Call the unit cost (updated version) file
filename4='unit_cost_updated.csv';
sheet=1;
xlRange='C2:C46';   % missing values treated as 0.
UnitCost=xlsread(filename4,sheet,xlRange);

% Compute the total cost value
SqFt=61700;        % Building 101 square footage
TotalCost=UnitCost.*SqFt;   % This is the total cost for a single ECM

% Correspond each cost with its ECM list (14 total cost values)
Package_Cost=(R')*TotalCost;
Q=[R;(Package_Cost')];    % This is the matrix that needs to be fed back to ATSV to visulize
% The last row is the cost, all previous 45 rows are ECM adoptions

%% Output
Overall=[T;Package_Cost];
% Write the eventual energy+cost results into .csv file and export to ...\Matlab\AuditExe folder
filename5 = 'ExplorationResult.csv';
sheet = 1;
xlRange = 'B1:B43';
xlswrite(filename5,Overall,sheet,xlRange)     % This should show two columns, 42 rows of data
% To visualize data in atsv, take 'qmatrix.xlsx' and 'ExplorationResult.csv' for cost
% and energy consumption.
```

Appendix E

Energy Auditing and Analysis Outputs

Output	Variable Name
Retrofit_Electric Cooling Use	E1
Retrofit_Electric Heating Use	E2
Retrofit_Electric Lighting Use	E3
Retrofit_Electric Equipment Use	E4
Retrofit_Electric Refrigeration Use	E5
Retrofit_Electric Ventilation Use	E6
Retrofit_Electric Water Heating Use	E7
Retrofit_Electric Pump Use	E8
Retrofit_Annual Elec. Consumption	**E9**
Retrofit_Natural Gas Cooling Use	E10
Retrofit_Natural Gas Heating Use	E11
Retrofit_Natural Gas Water Heating Use	E12
Retrofit_Annual Nat. Gas Consumption	**E13**
Retrofit_Fuel Oil Cooling Use	E14
Retrofit_Fuel Oil Heating Use	E15
Retrofit_Fuel Oil Water Heating Use	E16
Retrofit_Annual Fuel Oil Consumption	**E17**
Retrofit_District Heat Cooling Use	E18
Retrofit_District Heat Heating Use	E19
Retrofit_District Heat Water Heating Use	E20
Retrofit_Annual District Heat Consumption	**E21**
Baseline_Electric Cooling Use	E22
Baseline _Electric Heating Use	E23
Baseline _Electric Lighting Use	E24
Baseline _Electric Equipment Use	E25
Baseline _Electric Refrigeration Use	E26
Baseline _Electric Ventilation Use	E27
Baseline _Electric Water Heating Use	E28
Baseline _Electric Pump Use	E29
Baseline _Annual Elec. Consumption	E30
Baseline_Natural Gas Cooling Use	E31
Baseline _Natural Gas Heating Use	E32
Baseline _Natural Gas Water Heating Use	E33
Baseline _Annual Nat. Gas Consumption	E34
Baseline _Fuel Oil Cooling Use	E35
Baseline _Fuel Oil Heating Use	E36
Baseline_Fuel Oil Water Heating Use	E37
Baseline _Annual Fuel Oil Consumption	E38
Baseline _District Heat Cooling Use	E39
Baseline _District Heat Heating Use	E40
Baseline _District Heat Water Heating Use	E41
Baseline _Annual District Heat Consumption	E42

Appendix F

Design Structure Matrix (ECM impacts on existing building scenario)

Input Data-ECM Matrix	Light Scheduling	Occupancy Based Lightir	Daylight Based Dimming	Upgraded Lighting/ Delam	Plug Load Control	Efficient Equipment (Plug	Light Shelves	Added Daylight	Weatherization	Cool Roof	Upgraded Windows	Increased Insulation	Green Roof	Active External Shading	Air Side Economizer	Fan Assisted Precooling	Modified Setpoint & Setba	Supply Air Temperature R	Supply Static Pressure Re	Water Side Economizer (u	Demand Control Ventilatic	Displacement Ventilation	Under Floor Air Ventilation	Mixed Mode Ventilation	NV for night-time pre-coo	HVAC Equipment Upgrade	CAV to VAV	VAV & Control Retrofit	Chiller Plant Optimization	Heating Plant Optimizatio	On Demand Service Hot W	2 Stage Absorption Chiller	Condensing Boiler	Hybrid Ground Source He	Energy Recovery	Indirect Evaporative Coolir	Direct Evaporative Cooling	Solar Thermal	Desiccant Dehumidificatio	DOAS
	Lighting and Equipment								Envelope						Terminal HVAC												Supply HVAC													
Usage																																								
Total weekly operating hours	Y		Y				Y																																	
Open 24 hours a day	Y		Y				Y																																	
Open during week	Y		Y				Y																																	
Open on weekend	Y		Y				Y																																	
Operating Schedule (Opening and closing times)																																								
Mon, Open	Y		Y				Y																																	
Mon, Close	Y		Y				Y																																	
Tue, Open	Y		Y				Y																																	
Tue, Close	Y		Y				Y																																	
Wed, Open	Y		Y				Y																																	
Wed, Close	Y		Y				Y																																	
Thurs, Open	Y		Y				Y																																	
Thurs, Close	Y		Y				Y																																	
Fri, Open	Y		Y				Y																																	
Fri, Close	Y		Y				Y																																	
Sat, Open	Y		Y				Y																																	
Sat, Close	Y		Y				Y																																	
Sun, Open	Y		Y				Y																																	
Sun, Close	Y		Y				Y																																	
Utility Data (Good to have for baseline model validation)																																								
Annual elec consumption (thous Btu)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	P	P	P	P	P	Y		Y	Y	P	P	Y	Y	Y	Y	P	Y	Y	P	P	P	P		P	P	P	P	P		Y
Annual nat gas consumption (thous Btu)									Y	Y	P	P	P	P	P	Y		Y	Y	P	P	Y	Y	Y	Y	P	Y	Y	P	P	P	P		P	P	P	P	P		Y
Annual fuel oil consumption (thous Btu)									Y	Y	P	P	P	P	P	Y		Y	Y	P	P	Y	Y	Y	Y	P	Y	Y	P	P	P	P		P	P	P	P	P		Y
Annual dist heat consumption (thous Btu)									Y	Y	P	P	P	P	P	Y		Y	Y	P	P	Y	Y	Y	Y	P	Y	Y	P	P	P			P	P			P		Y
Electric heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P									Y				P								P	P			P		
Electric cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P	P	Y		Y	Y	P		Y	P	P	Y	P	Y					P				P	P			
Electric ventilation use (thous Btu)																							Y	Y		P	Y	Y												Y
Electric pump use (thous Btu)																										P		Y	P	P										Y
Natural Gas heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P													P								P	P			P		
Natural Gas cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P	P	Y		Y	Y	P		Y	P	P	Y	P	Y					P				P	P			
Natural Gas water heating use (thous Btu)																										P					P							P		
District Heat heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P									Y				P								P	P			P		
District Heat cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P	P	Y		Y	Y	P		Y	P	P	Y	P	Y					P				P	P			
District Heat water heating use (thous Btu)																										P					P							P		
Fuel Oil heating use (thous Btu)	Y	Y	Y	Y			Y	P	Y	N	P	P	P									Y				P								P	P			P		
Fuel Oil cooling use (thous Btu)	Y	Y	Y	Y			Y	N	Y	P	P	P	P	P	P	Y		Y	Y	P		Y	P	P	Y	P	Y					P				P	P			
Fuel Oil water heating use (thous Btu)																										P					P							P		
HVAC Equipment																																								
Primary HVAC System Type																										P		Y												
Airside Economizer: Present or not															**P**					P																				
Airside Energy Recovery: Present or not																																								
Airside Energy Recovery Effectiveness																																								
Demand Control Ventilation: Used or not																					P																			
Supply Fan Total Rated Power (kW)																			Y								Y		P	P										
Return Fan Total Rated Power (kW)																			Y								Y		P	P										
Total Zone Fan Rated Power (kW)																			Y								Y		P	P										
VFD Pumps?																											Y		P	P										
Chilled Water Pump Power (kW)																													P			P							Y	
Hot Water Pump Power (kW)																														P	P									
Condenser Pump Power (kW)																													P	P										
Aircooled Condenser/ Cooling Tower Rated Capacity (KBtu)																													P	P										
Aircooled Condenser/Cooling Tower Power Consumption (kW)																													P	P										
Efficiency of Hot Water System																															P		P							
COP of Refrigeration System																								Y																

COP of Primary Cooling																Y			Y				Y	Y	Y															
Efficiency/COP of Primary Heating																																		P	P					
HVAC Nominal Temperature Conditions																																								
Design Heating Supply Temperature (Degree F)																										P														
Design Cooling Supply Temperature (Degree F)																										P														
Design Preheat Temperature (Degree F)																										P														
Cooling Coil Design Leaving Temperature (Degree F)																										P														
Temperature Set Points																																								
Cooling set up implementation																Y	Y	Y	Y						Y															
Heating set back implementation																	Y	Y																						
Cooling Set Point (Degree F)																Y	Y	Y	Y						Y															
Cooling Set Back (Degree F)																Y	Y	Y	Y						Y															
Heating Set Point (Degree F)																	Y	Y																						
Heating Set Back (Degree F)																	Y	Y																						
Occupant Load																																								
Number of computers					Y	Y																																		
Flat screen monitors					Y	Y																																		
Number of servers					Y	Y																																		
Number of cash registers					Y	Y																																		
Number of printers					Y	Y																																		
Type of printers					Y	Y																																		
Number of photocopiers					Y	Y																																		
Number of residential refrigerators					Y	Y																																		
Number of vending machines					Y	Y																																		
Religious worship seating capacity					Y	Y																																		
Assembly seating capacity					Y	Y																																		
Number of classroom seats					Y	Y																																		
Food service seating capacity					Y	Y																																		
Licensed bed capacity					Y	Y																																		
Lighting Load (Provide either of them)																																								
Electric lighting use (thous Btu)	Y	Y	Y	Y			Y	Y																																
Interior Lighting Power Density(Watts/ft^2)	Y	Y	Y	Y			Y	Y																																
Equipment Load																																								
Electric (included plug and process equipment) use (thous E					Y	Y																																		
Refrigeration Load (Provide either of them)																																								
Electric refrigeration use (thous Btu)					Y	Y																			Y															
Refrigeration Power Density (Watts/ft^2)					Y	Y																			Y															
Hot Water Load																																								
Electric water heating use (thous Btu)																															P							P		
Infilteration Load																																								
Leakage Rate																																								
Fenestration and Conduction Load																																								
Percent exterior glass (With respect to wall area)																																								
Window glass type																																								
Tinted window glass																																								
Reflective window glass																																								
Wall and Roof Conduction																																								
Uwall (Btu/h-ft^2-F)									Y	Y		P	P																											
Uroof (Btu/h-ft^2-F)									Y	Y		P	P																											

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