

**UTILIZATION OF PERFORMANCE AND COST CRITERIA IN
EVALUATING ENERGY SAVING ALTERNATIVES**

by

Douglas Eric Leivonen

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APPROVED:



Wolter J. Fabrycky, Chairman



Benjamin S. Blanchard Jr.



Roderick J. Reasor

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**Committee Chairman: Wolter J. Fabrycky
Industrial and Systems Engineering**

(ABSTRACT)

A methodology is developed to evaluate residential energy cost reduction options in response to increasing concern over rising fuel costs and diminishing energy reserves. Energy use factors such as climate and local geographic features are identified and energy monitoring techniques are proposed.

A flexible, computer-based decision and risk analysis tool is developed as a tool for the economic comparison of energy saving options. Single- and multi-variable sensitivity analysis is performed. A multi-criteria optimization method is presented which includes performance and cost factors. An efficient HVAC control program is developed using multiple sensors and fully automatic control.

Finally, a case study of two energy saving alternatives is conducted for two cities in different climatic regions. The results show that the desirability of various energy saving options is a function of local climate conditions, rate of energy cost increase and predicted savings attributable to the options.

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Chapter 1: Introduction

BACKGROUND

Energy conservation is an issue of worldwide importance. Increased energy efficiency translates directly into the conservation of precious natural energy reserves, lower pollution levels and reduced operating costs.

The energy crisis of the 1970's that occurred during the OPEC oil embargo revealed the potential danger of a dependency on foreign energy supplies. Oil prices experienced an unprecedented increase and gasoline rationing was implemented due to restricted distribution and availability of oil products.

Despite the profits from increased energy consumption, power producers are aggressively working to reduce consumption and peak system loads. Control of peak loading allows current systems to operate at maximum capacity. The expenses of construction, purchase, installation and operation of new power generating equipment are postponed through effective energy use management practices. The availability of existing energy resources is extended.

Pollution as a by-product of energy generation poses a serious threat to the global environment. Coal and crude oil burning produce harmful atmospheric toxins. Residential wood burning stoves and fireplaces add to the airborne contaminants. Fuels for nuclear power generation plants decay into highly

radioactive waste. Hydroelectric power is the only commonly used energy generating source that does not add to pollution levels, although other environmental factors are involved such as the flooding of wildlife habitats. Pollution is a cause of many short- and long-term health problems. Expenses associated with reducing pollution and cleaning the environment are increasing as pollution levels become less tolerable. Reduced energy consumption and increased efficiency both tend to reduce the amount of pollution that is produced as a result of energy production.

The costs of energy production include the purchase of fuel, new construction, maintenance, operation of production facilities, pollution control measures, environmental cleanup efforts and distribution costs. These costs are passed on to consumers according to the type of fuel used, amount of energy consumed and current power grid loading conditions. The price of nonrenewable energy resources is expected to increase dramatically, with some industry experts predicting a fourfold increase in consumer energy rates within ten years [1]. Increased energy efficiency and conservation measures reduce both production and consumption costs.

Currently implemented conservation measures have improved the cost, availability and pollution factors associated with energy consumption. However, many more energy saving measures remain to be exploited. Accurate predictions of cost and savings benefits for current conservation measures, such as

the value of adding increased wall insulation, are often unavailable to the end user. Many operational measures rely on manual control, such as thermostat adjustment, and are therefore subject to individual use patterns and unnecessary waste [2]. Other methods of energy use control such as strict energy budgeting and electrical brownouts result in discomfort and inefficiency. Results of improper energy management include property damage such as burst water pipes due to unintentional interior freezing in winter. Still other effects are the adverse psychological and physiological effects of temperature extremes on human performance [3].

OBJECTIVES

The objectives of this project are to develop a methodology to effectively evaluate and select an energy cost reduction option. The evaluation and selection are based on existing needs, objectives, possible options and project constraints. Energy monitoring techniques are proposed.

A flexible, computer based economic decision and risk analysis tool is presented. Decision-making aids are presented to evaluate energy savings and economic feasibility based on utilization of both performance criteria and the evaluation of life-cycle costs.

APPROACH

A six step life-cycle model is used to evaluate energy

saving alternatives. The life-cycle model is shown in Figure 1. The evaluation of performance and cost criteria for evaluating residential energy saving alternatives focuses on the first three stages of the life-cycle through system selection.

This approach begins with a basic Feasibility Study to identify current needs, objectives, alternatives and constraints. The Feasibility Study is followed by a structured analysis to develop requirements, project lifetimes and economic assessments of the alternatives. The next step is the Selection of the Primary Alternative, which compares both performance and equivalent costs to determine the most suitable energy saving alternative. The final stages in the life-cycle following System Selection are Implementation, Utilization and Retirement.

Two case studies are used to demonstrate the evaluation of energy conservation alternatives using energy use data, computer based economic evaluation and utilization of multiple criteria techniques. Each of the two case studies compares two energy saving options for a particular city.

Performance deals with energy efficiency and the ability of the system to maintain comfortable conditions through seasonal climate changes and temperature variations between night and day. Performance also deals with the ease of operation and maintenance of the system. Energy efficiency of a heating and

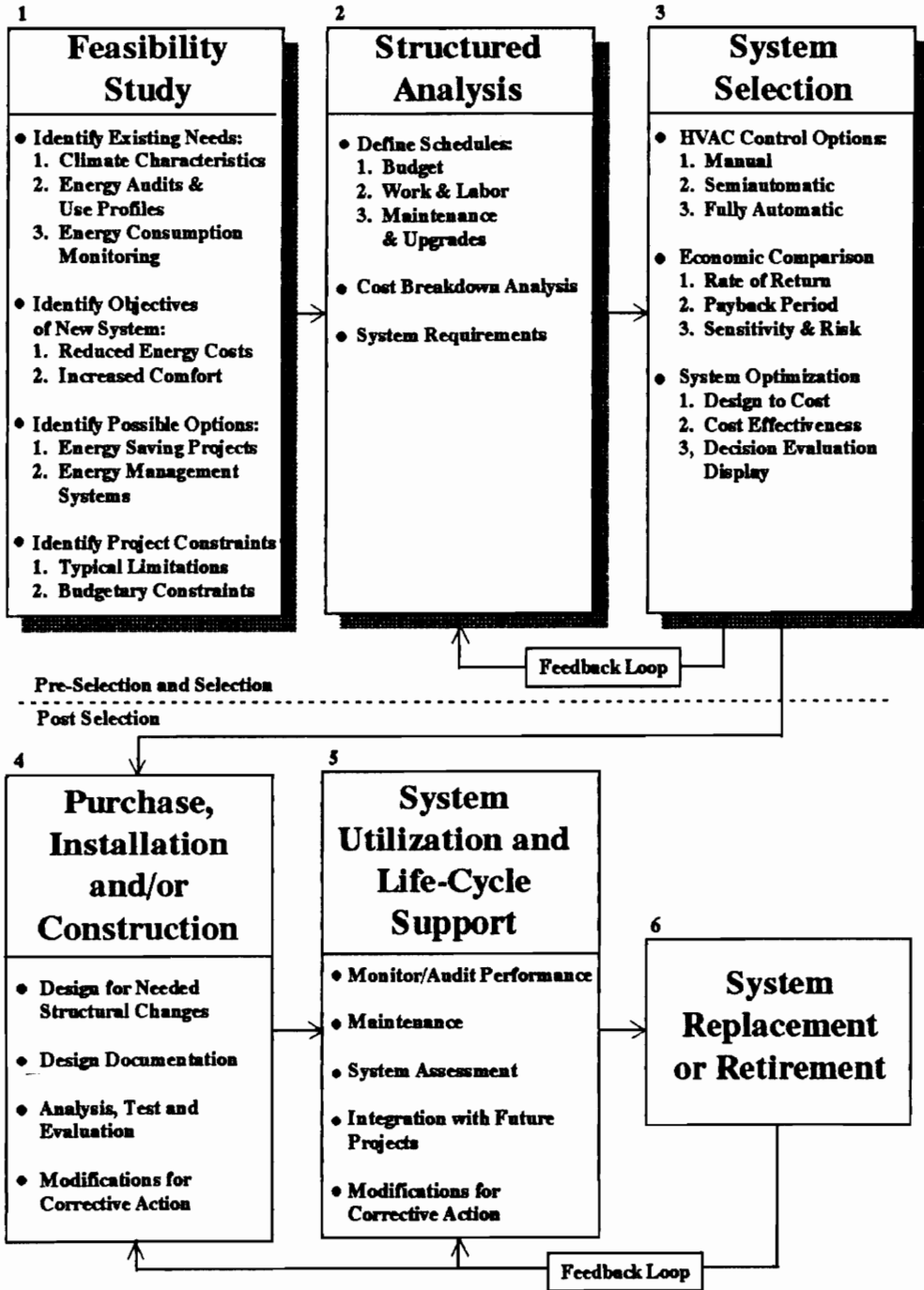


Figure 1. Energy Saving Project Life-Cycle

cooling system is a function of the design efficiency of the unit, operating cycle times, and the degree to which waste is minimized. An issue that can be addressed by every consumer energy project evaluation is utilization of such factors as ease of use, convenience and system management to maximize comfort while minimizing costs.

SCOPE

The energy use evaluation utilizing performance and life-cycle cost criteria provides the basic tool needed to effectively evaluate energy consumption and conservation options. Systems engineering analysis of cost and performance criteria is performed to assess the feasibility and utility of such an approach. The approach is specifically tailored to evaluate residential energy use and conservation measures. The basic principles of the evaluation approach are applicable to a wide range of alternative selection situations.

The life-cycle stages subsequent to System Selection are discussed in the Summary and Conclusions Section. This report concentrates on the steps leading to the selection of an energy saving alternative.

ASSUMPTIONS

Existing dwellings and places of business that need a HVAC, and whose owners can afford one, are assumed to be already equipped with a system that can adequately meet

heating and cooling demands. The design efficiency is therefore a given, unless the original equipment is replaced by an upgraded unit. An upgrade of the original HVAC system is one option to conserve energy and reduce life-cycle cost.

The final assessment of economic feasibility is critically dependent on assumptions about cost and availability of conventional sources of fuel, projected savings, interest and inflation rates, statistical parameters and the interdependencies of propose alternatives. Assumptions are made to simplify the analysis or provide a valid framework for comparisons.

The costs and alternatives are assumed to apply to an end user of energy or energy saving products. As a result, costs associated with engineering design and development, production, distribution, marketing and markup are combined in the acquisition cost to the consumer. Typical costs for an end user include custom design fees, purchase, installation and any additional material and labor changes [4].

All parameters are assumed to be annual amounts consistent throughout each year for economic evaluation purposes. Considering yearly costs along with any discount and inflation factors to occur once each year simplifies the required numerical analysis involved in the economic assessment. Gains in accuracy from a more complex analysis in which annual variations are considered are insufficient to offset the increased complexity that is introduced. The accuracy of predicted variation is uncertain, increasing the validity of annual

approximations.

Similarly, inflation and interest rates are assumed to be uniform throughout the evaluation period. Early in the life-cycle, the influence of inflation and interest are relatively slight. Towards the end of a life-cycle the discount effect can be dramatic. The actual rates during the life-cycle period will undoubtedly vary differently than predicted rates. Consistent interest and inflation rates between options provide a basis for comparison between the options relative to the discount factors predicted. Although inflation factors should be estimated on a year-to-year basis to achieve the greatest accuracy, the uncertainty of inflationary adjustments more than five years in the future prevents any reliable prediction of future rate changes [5]. The net effect of normalized discount factors can be an effective indicator of the actual economic effects resulting from an alternative.

The assumption is made that all probability regions are based on normally distributed and independent variables to allow the use of standard statistical evaluation methods for sensitivity analysis of estimation errors. Such conditions are typical in real world situations depending upon the sample population and procedures used in the prediction analysis. Similar distributions between proposals being compared allows a straightforward comparison using the sensitivity results from each and the resulting probability regions.

Alternatives are assumed to be mutually exclusive and

independent. As a result, separate cost models may legitimately be developed for each option and a direct comparison made between them. Dependent proposals require some form of integrated or joint cost modelling with feedback loops and mapped interdependencies between the options. In many decision situations a group of proposals are related to one another in that the acceptance of one influences the acceptance of the others [5]. Very little is known about the synergy between various energy conservation products when applied in different combinations. The application of all the conservation measures, with their respective projected savings, would seem to save over one-hundred percent of the energy costs [1]. The dependent relationships between the proposals establishes a pattern of diminishing returns. The undertaking of one project may diminish the benefits of another.

The evaluation of alternatives is assumed to be on a before tax basis. Tax impacts are likely to vary widely between alternatives. Many solar heating systems and energy conservation measure qualify for a tax credit from federal, state and local governments. Most conservation measures qualify for current home improvement or capital investment tax deductions. Differences in taxation also greatly increase the complexity of the analysis and are not considered in the evaluation.

Chapter 2: Feasibility Study

OVERVIEW

The Feasibility Study is a method to identify existing needs, objectives, possible options and constraints for the evaluation of energy saving projects. As the first step in the evaluation of energy saving alternatives the Feasibility Study may indicate that further evaluation is unwarranted based on the current needs, available options and project constraints.

The cost of conducting the Feasibility Study must be included in the cost breakdown for the project alternatives. In some cases the Study costs may be traded against the amount of manual effort involved. The entire evaluation approach may be performed manually. The costs of conducting a manual evaluation are primarily limited to labor costs. The level of effort required for a manual evaluation is much greater than if automated tools are used or evaluation steps are contracted out to professional construction or energy auditing companies.

EXISTING NEEDS

The existing needs for improving HVAC cost or performance are determined by the amount of heating and cooling required for a particular residence and the degree of efficiency already achieved. The amount of heating and cooling required is a function of the local climate conditions and the size and physical characteristics of the residence.

Climate Regions

Local climate has the greatest impact on energy consumption and costs. The five factors that have the greatest impact on climate conditions are latitude, elevation, the presence of large bodies of water, prevailing winds, and mountain ranges.

The closer to the poles an area is located, the more exaggerated are the seasonal shifts. Elevation above sea level has the same general effect as a higher latitude. Large bodies of water such as oceans have a moderating effect on temperatures. Conversely, areas located in the middle of large land masses away from water experience large temperature swings.

Prevailing winds in the United States blow from west to east. Cities on the west coast feel the beneficial effects of the ocean breeze even hundreds of miles inland. The prevailing winds on the east coast blow outward from the shore. Consequently, cities on the east coast do not experience the temperature stabilizing effects of the Atlantic Ocean nearly as much as cities on the west coast benefit from the effects of the Pacific Ocean.

Mountain ranges act as barriers that deflect and channel winds and weather. The weather and climate on one side of a mountain range is often radically different from the opposite side. Mountain ranges are natural dividing points between climate zones.

Climatic regions within the continental United States are depicted in Figure 2. Prevailing climatic conditions during winter and summer for the general regions in Figure 2 are summarized in Table 1. Many locations near regional boundaries experience a combination of climatic influences, depending on winds and local geographic factors [6].

Heating-Cooling Degree Days

The number of heating-cooling degree days is useful to compare the probable heating and cooling requirements between locations. The standard base temperature for arriving at heating- and cooling-degree days is sixty-five degrees Fahrenheit as the standard established by the American gas industry. For an average temperature over a given day of sixty-six degrees, one degree of cooling is needed, which counts as one cooling-degree day. Similarly, if the average temperature on a particular winter day is fifty-five degrees, ten degrees of heating are needed, yielding ten heating-degree days. The sum of the heating- and cooling- degree days over the course of a year is the total heating-cooling degree day value for that location [6].

The number of heating-cooling degree days is not a complete indicator of heating and cooling requirements. The effect of humidity on the apparent temperature and level of comfort is significant. Indicators which include humidity, such as the heat index, are more accurate. However, in the absence

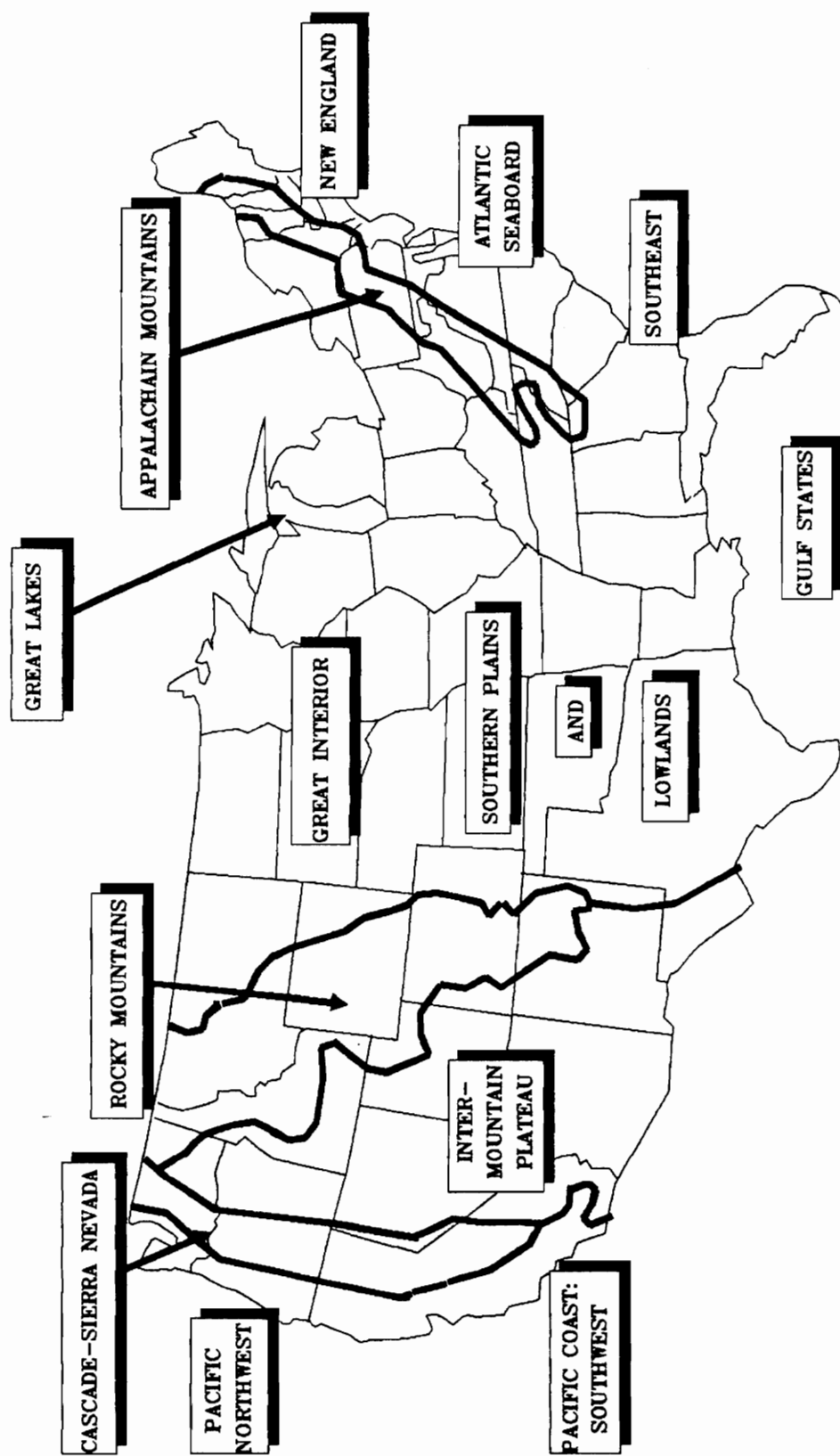


Figure 2: Climatic Regions in the Continental United States

Table 1: Summary of Regional Climatic Tendencies

U.S. Climatic Region	Prevailing Climatic Conditions	
	Winter	Summer
Atlantic Seaboard	Mild	Hot
Great Lakes	Long, Cold	Mild
Gulf States	Very mild	Hot, humid
New England	Cold	Moderate
Pacific Northwest	Relatively mild	Pleasant
Plains	Long, Cold	Hot
Rockies	Rigorous, snowy	Cool
Southeast	Very Mild	Hot
Southwest	Mildest in U.S.	Pleasant

of national data on annual heat index values for various locales within the United States, the heating-cooling degree day value provides important information for the evaluation of energy saving alternatives.

Energy Audits and Use Profiles

Energy usage profiles are compiled by many government and commercial organizations. State energy offices or utility companies are able to assist residential or business enterprises in conducting an energy audit. The energy audit, in conjunction with energy monitoring techniques, is useful in determining which candidate energy conservation measures should be considered to save energy and reduce costs. The audits are based on general guidelines and accepted industry norms for energy use and conservation measures. Local climate patterns, architectural features, types of fuel used, rated appliance efficiencies and utility rates are considered. Actual energy costs for individual structures are difficult to predict accurately.

Energy Consumption Monitoring

Accurate energy use monitoring is necessary to obtain reliable energy usage and cost data to identify current system usage. Several methods are available to evaluate energy use and identify excessive energy consumption. The methods range in accuracy and usefulness from national statistical averages to precise energy monitoring.

One method requiring little effort on the part of the consumer is to obtain statistical data for energy usage, costs and climatological conditions. The data is available from national agencies, reference materials, local weather services and building contractors. Such information is useful as a rough indication of expected individual energy costs. The variance within a locality can be great, depending on the size and orientation of the structure, amount of insulation, energy fuels and equipment efficiency. Individual habits and patterns of energy use also have a great impact on energy costs. One study was conducted of two families of similar composition and income living next door to each other in matched dwellings with comparable insulation, structural orientation and furnace efficiencies. The study revealed that the difference in gas heating use and costs due to consumption alone can vary by as much as fifty percent over a one year period [7].

Another method of evaluating energy use is a review of previous utility bills. Correlation of energy usage and costs with other information such as outside weather conditions, occupancy patterns and equipment operating times may provide additional insight into operating costs, which would allow greater accuracy of the input data for evaluating energy saving options. The accuracy and ease of evaluation are improved if a variety of energy sources are used. The energy use data for structures which use natural gas or fuel oil for heating and electricity for other appliances provides cost data that is pre-

separated on the utility bill according to the type of fuel used. Heating costs are then distinguishable from other sources of energy use to a high degree of certainty.

All-electric dwellings and offices do not provide the same level of convenience. The typical electric bill provides little more than dates, meter readings, surcharges and tax adjustment values. Further information can be gleaned for all-electric dwellings by tracking usage patterns. Heating and cooling equipment is seldom operated during the mild weather of Spring and Fall. The utility bills for that period may be compared to winter and summer bills to determine the increased costs of operating heating, ventilation and cooling (HVAC) equipment. Likewise, if a structure is unoccupied over a billing period the costs of operating the hot water heater combined with refrigerator and freezers may be estimated.

Even more detailed information may be obtained by carefully monitoring the use of each type of electrical appliance and energy driven device. Records of HVAC operating times, times of use for stoves and ovens along with heat settings, laundry machines, electronic equipment and lights may be combined with the rated power requirements for each device to determine the amount of energy used. The information collection process is typically a manual effort and is subject to time estimation errors, errors of omission and deviations in power and efficiency ratings due to aging of equipment, inadequate maintenance and other operational factors.

Automated Energy Monitoring

The most promising energy data collection method is the use of energy monitoring devices attached directly to major appliances, gas meters and electrical circuits. The exact amount of usage for each device is automatically recorded over the course of a day. The amount of usage at different utility rates from peak to nonpeak usage or be recorded. The amount of electronic storage required to record such information over a five year period is the product of the number of energy monitors, number of different rates and the number of days in five years. For fifteen energy monitors and three utility rates the storage required for five years of data is calculated by

$$\# \text{Bytes} = (15 \text{ monitors}) (3 \text{ rates}) (1,825 \text{ days}/5 \text{ years}), \quad (1)$$

for a total of 82 KBytes. Electronic memory requirements are easily satisfied by common computer memory chips, tape recorders, disk drives and other electronic media such as bubble memory chips. Additional information may be stored with the energy use data. Daily temperature data may be measured using exterior mounted temperature sensors. Occupancy data may be recorded as integrated room occupancy sensors and security systems achieve greater functionality and acceptance. Such recorded data provides exact, detailed energy use information to allow effective energy management.

IDENTIFICATION OF OBJECTIVES

Identification of objectives allows the life-cycle evaluation to target specific energy consumption areas that need improvement. Typical objectives include reduced HVAC life-cycle costs and increased comfort and convenience.

Reduced Energy Costs

Consumer energy costs are a function of the amount of energy consumed and the cost of the energy. The amount of energy consumed is influenced by local climate and weather conditions, the size of the structure, number of appliances, number of occupants and individual energy use habits. The cost of the energy is a function of the type of fuel used, times of peak electrical loads, and which utility district is serving the area. Residences and businesses located in the Pacific Northwest, a service area that gets power from hydroelectric generating facilities, experience the lowest electric rates in the nation. Energy consumers located in Texas and the oil belt experience lower utility rates due to reduced distribution expenses. The difference in utility rates can vary more than three hundred percent, based on location [2].

Typical energy cost percentages for various appliances according to region are summarized in Table 2. The values are based on residential usage for a family of four living in a three bedroom, two bath home with about 1,500 square feet of heated living space. The annual average total kilowatt hours (KWH)

Table 2: Percentage of Regional Annual Costs for Residential Usage

Appliance	New England	Atlantic Seaboard	Great Lakes	Plains	South-east	Gulf States	Rockies Northwest	Pacific Northwest	South-west	National Average
Central Heating	65.9	57.4	57.3	54.6	48.5	36.7	50.8	50.4	34.9	50.7
Air Conditioning	3.4	8.45.7	5.7	9.7	15.5	35.6	5.1	0	13.4	10.7
Water Heater	17.8	19.4	23.0	21.8	19.4	14.0	25.4	30.8	29.4	22.3
Cooking	3.7	4.5	4.0	3.9	4.7	3.5	3.8	4.8	4.3	4.1
Refrigerator Freezer	4.7	6.1	5.4	5.8	5.9	6.4	9.1	5.5	7.7	6.3
Dishwasher	1.1	1.0	0.7	1.0	1.2	1.5	0.5	2.1	2.2	1.3
Clothes Washer	0.3	0.4	0.4	0.2	0.3	0.3	0.5	1.2	1.1	0.5
Clothes Dryer	3.1	2.8	3.4	3.1	4.7	1.9	4.8	5.3	7.1	4.0
Annual Avg. Kilowatt Hours	32,021	30,908	26,374	30,975	30,945	28,612	19,700	20,534	15,631	26,190

are normalized for electricity, heating oil and natural using the conversion factors of

$$1 \text{ KWH} = 0.033 \text{ Therms Gas} = 0.024 \text{ Gallons Oil.} \quad (2)$$

The cost percentages vary dramatically between different regions. Table 2 shows that energy costs for locales with mild climates such as the Pacific Southwest are substantially less than for locales that experience a true winter and hot summer. The percentages for the various regions are averaged across the nation to allow a comparison of individual regions to the national average values [8]. Office and business energy percentages are comparable, with the exception that roughly one-fourth of office costs are accounted for in lighting costs. However, in all cases the costs associated with heating and cooling account for more than fifty percent of the total [9].

Increased Comfort

The concept of comfort is a subjective measure that is affected by temperature, air movement, humidity, pressure, level of exertion, type of clothing worn and acclimatization of individuals within the environment. The definition of a comfortable environment is not only different between individuals, but is subject to redefinition by the same individual from one day or one moment to the next due to subjective evaluation. Many attempts have been made to categorize

reasonable comfort zones in a single psychometric chart or table.

An acceptably defined comfort region can be described for any given set of conditions. However, the range is derived by combining information from several composite indices. The number of parameters involved and the interaction between them precludes an easy description in a unified fashion. A good example is given by Sanders and McCormick, which takes into account air temperature, wet bulb temperature, relative humidity, level of activity and clothing worn [3]. The chart is reproduced in Figure 3. The wet bulb temperature is an indication of humidity effects on cooling through evaporation.

The amount of clothing worn is measured in the number of clo units. Clo units are an indication of the thermal insulation properties of clothing while resting in a ventilated room at seventy degrees Fahrenheit. One clo unit has roughly the amount of insulation needed to compensate for a drop in temperature of sixteen degrees. Light clothing is about 0.5 clo, while an average businessman wears medium clothing of about 1 clo. The values in Figure 3 are for a low level of air velocity only. In such conditions, the temperature may vary as much as 0.75 degree Fahrenheit for every foot of elevation within a closed structure [10]. Also unaccounted for are factors such as air pressure, acclimatization, individual differences in perceived comfort, criticality of the performed activity, age, health, emotional state, and previous temperature exposures.

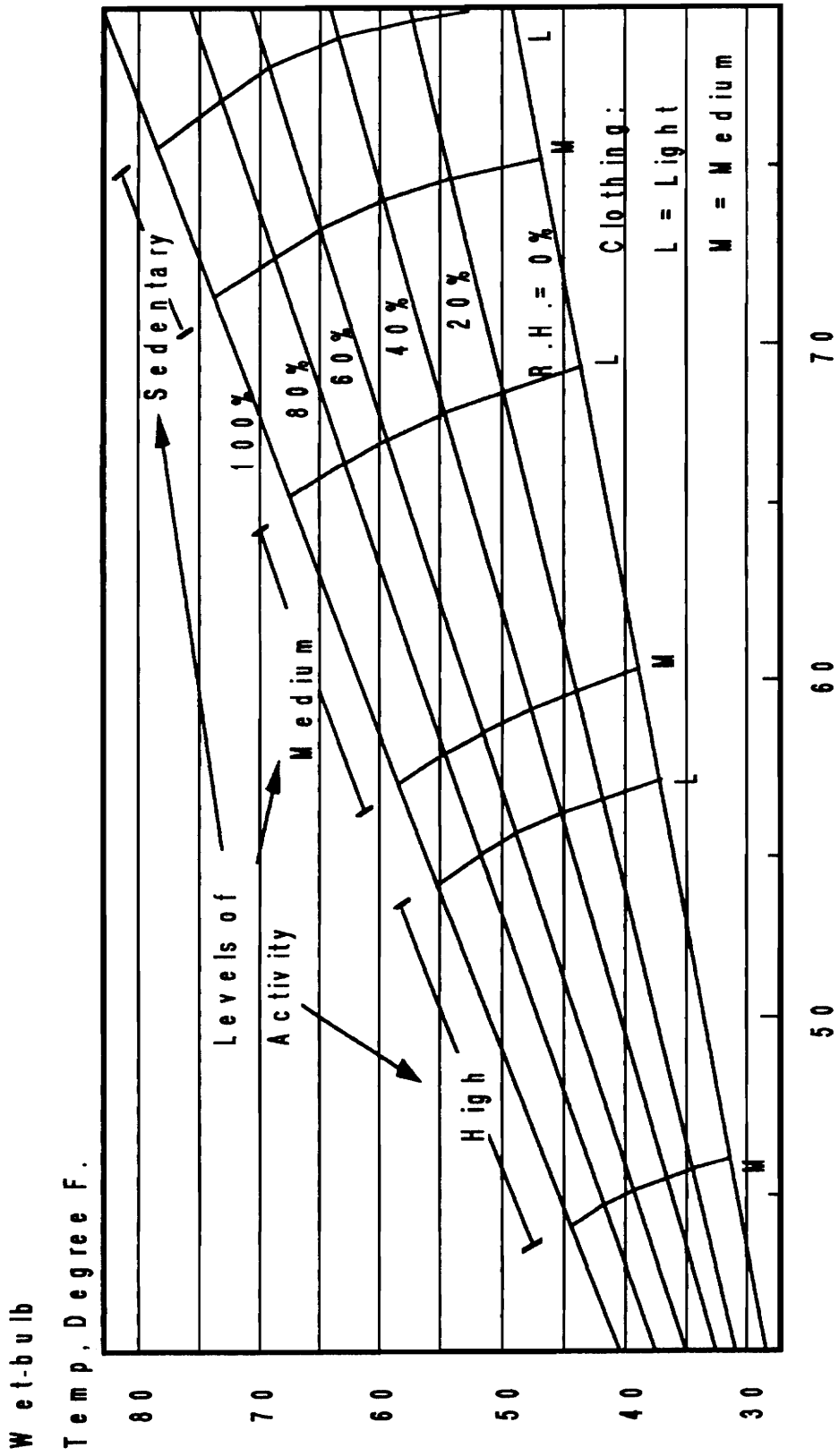


Figure 3: Comfort Lines for Three Levels of Work

Acclimatization to changing seasonal temperature extremes is less practicable as technology becomes more advanced. It is not at all uncommon for people to leave the comfort of their residences, drive to work in climate controlled vehicles, enter carefully controlled work or classroom environments, and return home, all with less than a few minutes of total exposure to the outside environment.

POSSIBLE OPTIONS

The potential alternatives available as energy saving projects range from simply modifying use habits of current HVAC systems to major structural renovations and addition of new HVAC system components. Increased energy savings are also possible through more effective energy management techniques.

Energy Saving Projects

Some typical alternatives are shown in Tables 3 through 5, separated according to heating, cooling or both heating and cooling alternatives. The actual percentage savings compared to the predicted savings depends upon the energy saving characteristics of the current HVAC system, including thermal properties of the structure. A reasonable price is included for several of the projects based on recent advertisements for similar systems. The predicted energy savings are for an average dwelling with only one option being implemented.

Energy Management Systems

One energy management system known as the TranstexT Advanced Energy Management System (EMS), developed by Integrated Communication Systems, is already offered by several utility companies across the country. The system offers benefits both for the consumer and the utility company. The Smartlink Thermostat which is integrated with the TranstexT EMS receives information from the utility company over standard telephone circuits. The system allows the customer to select several preprogrammed options. The thermostat may be programmed to follow different settings based on instantaneous utility rate information. Slightly less comfortable conditions may be selected during critical, peak load energy rates. Appliances such as the water heater or dishwasher may be programmed to operate only during low rate periods. The customer is rewarded with significantly lower energy costs.

Additionally, the customer may allow the utility company to dynamically control thermostat programming and major appliances directly. Such a feature allows the utility company to manage peak loads effectively. Management of peak loads allows current power generating capacities to be used to their fullest potential. The need to build additional generating facilities is effectively delayed. The system is self monitoring, and reports malfunctions to the utility company and customer. Meter reading is not needed because meter information is electronically collected through the TranstexT system. The

Table 3: Energy Conserving Alternatives for Reduced Heating and Cooling Costs

OPTION	% SAVINGS	COMMENTS
Caulking [8]	4-7%	Much higher savings in well insulated houses.
Ceiling [8] Insulation [8]	R-19 R-19 R-30 40% 20% 40%	For heating in mild climates. If heavy insulation required, figure drops slightly. For cooling. In severe winter climates, more in milder climates, though cost may outweigh advantages gained.
Replace Air Filters monthly [1],[8]	2-15%	Another benefit is a possible reduction in furnace repair costs.
Setback Thermostat with zoned temperature control [1],[8]	5-30% 20%	Price = \$700 and up [11]. For heating, ideal setting is < 76°F; For cooling, > 80°F. For cooling. Ideal setting is 65°F days, 60°F nights.
Shade A/C or Heat Pump from sun [8]	5%	This will cut machine running time.
Superinsulation [12]	70-90%	The cost is 3-6% of home construction costs. Resale value of the house may be enormously increased.
Weatherstripping [8]	4-7%	For poorly insulated houses, more in well insulated ones.
Window Coverings - Thermal Shutters, Draperies [1],[8]	Vinyl Shades [8] 1% 7% 12% 4-5%	For heating. For heating with R-5 value. For heating with R-11 value. For cooling.

Table 4: Energy Conserving Alternatives for Reduced Cooling Costs

OPTION	% SAVINGS	COMMENTS
Attic ventilation to 1.5 cubic feet/min. [8]- using static vents using power vents	0-marginal 16% marginal	If ceiling is insulated to R-30. If uninsulated or poorly insulated. Could replace A/C in some climates.
Daytime shading [1]- to reduce solar heat gain by 60% to reduce solar heat gain by 80%	45% 63% 53%	In regions of high daytime temperatures and cool overnight temperatures, exterior shading of sun wall windows (especially east and west-facing). In regions where overnight temperatures remain high, savings are much less because of heat gain at other points. With exterior shading. With interior shading.
Raise daytime thermostat setting from 70°F during cooling season [8]	5% per °F	Up to 80°F.

Table 5: Energy Conserving Alternatives for Reduced Heating Costs

OPTION	% SAVINGS	COMMENTS
Combustion Air Modifier [1]	10-30%	Can also be used for fossil fuel home furnaces.
Draft Hood Diverter [1]	20%	Operates on gas and oil furnaces.
Furnace Flue Damper [1]	10-30%	Price = \$80 [11]. Operates on gas and oil furnaces.
Furnace outside air Intake [1]	5-20%	Price = \$125 [11]. For gas furnace.
	5-30%	For oil furnace. Other advantages might include a decrease of drafts around doors and windows and an increase in humidity in the heating season.
Gas furnace with electronic igniter [8]	5-10%	Keeping the pilot properly adjusted saves energy.
Heat Stratification Recycler [1]	19%	Only use for a difference of 20°F or more floor to ceiling.
Insulating- basement [1]	8-14%	Even if not heated with ducts from central heating system.
ducting [8]	10%	With R-4 save up to 40% if airtight and filters are clean.
floor with R-11 [8]	10%	In severe winter regions, figure is lower. In mild winter regions, underfloor insulation is ineffective.
floor with R-19 [8]	10-13%	In severe winters. Savings can be slightly more where winters are less severe though cost is likely to outweigh gain.
wall with R-11 [8]	10%	Only if entire living space is thoroughly insulated.
Daytime thermostat above 72°F in heating season [8]	5% per °F	Up to 80°F.
Oil flame retention burner [8]	5-7%	Of annual oil use.
Tape leaky joints in ducts [8]	10-13%	Estimates vary widely; most frequent figure is 10%.

system provides the utility company a much more accurate and up-to-date database to determine energy use patterns.

A similar device is the Teletimer, an energy management system currently available directly to consumers in Washington D.C., Austin, Texas and parts of Florida. The teletimer automatically adjusts according to weather and solar conditions and a preselected customer energy program. A transponder in the home or facility receives commands from a remotely located computer via television cable, FM broadcast or telephone paging systems. Commands from the transponder are transmitted through electrical power wiring to responders located near furnaces, air conditioners or pool pumping and heating equipment.

Other devices allow energy use to be budgeted on a pay-as-you-go basis. Customers buy encoded magnetic stripe cards which act as debit cards. The thermostat allows the customer to use an amount of energy equivalent to the worth of the card. A readout is given of the amount of energy used per hour in dollars and cents, amount of energy remaining and the amount used over the last twenty-four hours and thirty days. Rather than disconnect service for nonpayment, a cold weather protection mode restricts service to preset limits for safety reasons [9].

Effective energy management measures may be implemented once accurate energy monitoring has been performed. Heating and cooling factors are selected for further

evaluation and analysis due to the high percentage of energy costs attributable to HVAC systems. The analysis should apply equally well to other types of energy consuming systems.

PROJECT CONSTRAINTS

Project constraints may be imposed by factors such as available investment capital, fixed moving time due to work related reassignment, and restrictions of local homeowners associations or city zoning ordinances. Other constraints may be imposed by individual preferences. Examples of individual preference constraints include a minimum desired rate-of-return and maximum acceptable payback period.

Extensive renovations are generally not approved or economically attractive for individuals leasing or renting residences. Exceptions may exist for long term lease agreements that provide for the approval of such projects and afford sufficient time for payback of the original investment, as well as improving the comfort and convenience of the residence.

The projected completion timeline, in conjunction with the time an alternative may be initiated and the useful life of an alternative, creates constraints on the lifetime of the project. An option that may be implemented immediately and is designed to function for ten or more years affords a higher potential for payback than one that cannot be implemented until several years in the future and has a short operational life.

The ability to finance or budget the project is typically one

of the most important project constraints. Many of energy saving alternatives require significant investment costs. Projects that require a high initial investment are unsuitable for many homeowners.

Chapter 3: Structured Analysis

OVERVIEW

The structured analysis phase of the approach defines key project elements such as schedules, budgets and requirements. The results of the Feasibility Study are used as inputs to focus the analysis on the most important evaluation issues according to the objectives, potential options and project constraints.

SCHEDULES

The development of schedules during the Structured Analysis phase serves to coordinate the events associated with project evaluation, selection and implementation. The schedules pertinent to the evaluation and implementation of residential energy saving options include finance payment, purchase, delivery, installation, operating, maintenance, upgrade and phaseout schedules.

Budgeting Schedules

Finance payment schedules must be included in the overall life-cycle costs associated with researching and pursuing energy saving alternatives. Long-term financial plans should be formulated to identify financial goals and predictable changes in earning and spending ability. The impacts of future retirement, occupational changes, relocations, college tuition for children, new cars, medical bills and other financial changes

must be considered. Financial and budgetary schedules may be evaluated with the life-cycle costs and predicted savings due to a particular energy saving option to determine the economic suitability of that alternative. For example, savings due to an energy saving option may match with the planned retirement schedule to allow for the initial investment in an alternative while the earning power is still strong, and reduced payments after retirement.

The appropriate time to invest in an energy saving project is based in part on the budgetary schedule. Investment options should be prioritized if several investments are in contention for limited budget resources.

Because energy consumption depends largely on weather and climate, the time of investment may be delayed or expedited to immediately precede the season of maximum benefit from energy savings. The purchase of systems or materials at reduced prices during an inventory clearance or promotional sale should also be considered.

Work Schedules

A work schedule to install the system is appropriate for many energy saving projects. Projects such as superinsulating may require several months to complete due to remodeling and extensive structural modification requirements.

Homeowners who desire to reduce investment costs for contractor and technical labor may elect to perform much of the

labor themselves. The work schedule must then be based on the amount of time available after work and on days off from work.

Projects that require outside work, such as the mounting of solar panels for a solar hot water system, must consider local weather and climate patterns. Outside work should be scheduled to avoid seasons known for high rainfall or sub-zero weather.

Maintenance/Upgrade Schedules

The manufacturers of most energy saving systems specify a suggested routine maintenance schedule which should be followed to ensure efficient and safe operation of the system. The maintenance may include replacement of filters, fluid changes, inspections and technical service at regular service intervals.

A plan of when and how much to upgrade is important for systems that are purchased with the objective of increasing capacity or capability. Phased upgrades may be scheduled based on budgetary considerations or increasing demand due to growth of the family unit. The capabilities of high technology systems, particularly computer and microprocessor based systems, are improving dramatically each year. An interim energy saving system may be purchased and installed to provide immediate savings while allowing for upgrades as features that are not available in current systems become available.

COST BREAKDOWN ANALYSIS

A life-cycle cost analysis evaluates expenses that occur at different times and combines them into one decision number that can be use for comparisons between alternatives. The expenses are made equivalent by considering the time value of money.

Economic Equivalence

One method of economic evaluation is the present equivalent approach, which transforms all costs occurring throughout the lifetime of the system to present day costs. One dollar received or spent in the present is worth more than one dollar a year later since the first dollar can be invested to collect interest. Dollars in the future are given less value than present dollars.

The present equivalent value accounts for the time value of money by multiplying costs and income occurring in future years by a fractional discounting factor which is smaller each year. The reduced annual costs of future dollars are then equivalent to present dollars, and may be summed to arrive at a total present equivalent value. This amount represents the amount that could be invested at interest in the present to pay all of the future annual costs as they occur. Thus, the present equivalent value is less than the sum of all future undiscounted dollars. The factor used to reduce the future amounts is determined by the interest rate. The annual costs are reduced

each year by an amount calculated using

$$PE = F_t \frac{1}{(1+i)^t}, \quad (3)$$

where PE is the present equivalent amount, F_t is the difference between receipts and disbursements for year t , and i is the interest rate. Equation (3) may be expressed as

$$PE = F_t \left(\frac{P/F, i, t}{1} \right), \quad (4)$$

in which P/F is the designation for present value given future amount. The value within the parentheses in Equation (4) is available from standard interest factor tables as well as by using Equation (3).

The total sum of present equivalent values over the lifetime of an evaluation is expressed by

$$PE = \sum_{t=0}^n F_t \left(\frac{P/F, i, t}{1} \right), \quad (5)$$

in which n is the number of years being evaluated.

When an evaluation includes the effects of inflation, the interest rate may be adjusted for inflation factors using

$$i' = \frac{1 + i}{1 + f}, \quad (6)$$

where i' is the adjusted discount factor and f is the inflation rate [5]. The value for i' is then substituted for the value i in Equations (4) and (5) to determine the discounted dollar amounts.

Life-cycle Costs

The life-cycle cost of a system considers all the costs associated with the system from initial investment to system salvage or disposal. This allows for an accurate comparison to be made between two or more alternatives. The purchase and installation costs of any original HVAC components which have been absorbed into the home mortgage are assumed to be sunk costs, and are not considered in the economic evaluation.

Most of the life-cycle costs for an HVAC system are accrued during the operation and maintenance phase which includes both energy and repair costs. Operating costs are impacted by energy conservation features built-in during construction, additional energy saving devices and special measures taken to minimize waste and usage costs.

Energy Saving Project Costs

The first step in determining the life-cycle cost of a system is to perform a detailed, accurate cost breakdown. Separate cost breakdown structures are required for each alternative,

including the "do nothing" option. Some cost categories include research and design, engineering, purchase, installation, material, production, operation, maintenance, distribution, marketing, logistic support and markup [5]. Cost breakdowns are totaled by year. The resulting annual totals may then be combined with resulting profits or savings in a money flow diagram to clearly show the net economic effect of an alternative on both a year-by-year and overall basis.

Money Flow Diagrams

The yearly costs from the cost breakdown analysis are represented as yearly money flows in the money flow diagram. An example of a money flow diagram is shown in Figure 4. The top money flow shows undiscounted sample energy costs for a fifteen year period. The costs are represented as downward arrows whose lengths are determined by the magnitude of the expenses.

The middle money flow in Figure 4 shows the money flow for an energy saving alternative. The initial acquisition cost is portrayed as a downward arrow. The effects of yearly savings projected as a result of the alternative are shown as up arrows, indicating a positive cash flow due to the energy savings. The savings are combined with the initial energy cost flow in the bottom money flow to show the net energy costs with the energy saving system in use. The arrows are reversed to point upward so that the values may be expressed in terms of cost.

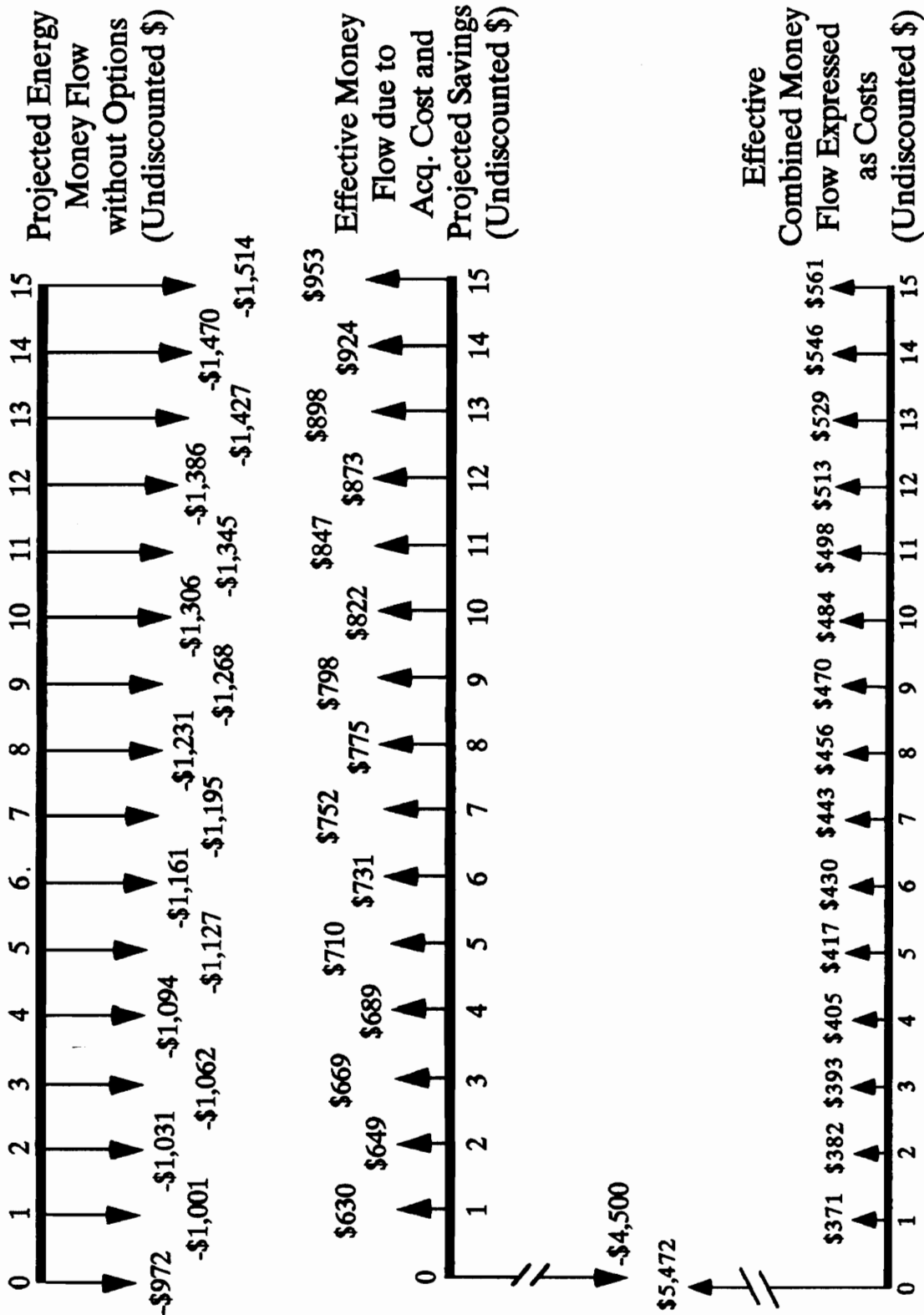


Figure 4: Development of Money Flow Diagrams

SYSTEM REQUIREMENTS

The system requirements are developed from the stated objectives and project constraints identified in the Feasibility Study. The requirements are tailored to the needs of a particular residence.

The budget, schedules, size of the residence, climate, needed HVAC capacity and characteristics of the existing HVAC system design must all be considered when defining requirements. Requirements such as needed airflow, number and type of control devices and components, and conformance to zoning ordinances and building codes should be explicitly and unambiguously stated.

The requirements are used to ensure that all energy saving options under consideration are able to fulfill the assigned purpose according to the specified standards. Therefore, system requirements should delineate the minimum and maximum bounds of acceptable system operation and performance. The performance and effectiveness criteria to be used in evaluating energy saving alternatives are defined based directly on the stated requirements.

Chapter 4: Computer Based Economic Evaluation

OVERVIEW

The widespread availability of personal computers provides a valuable tool for economic evaluations. The number processing abilities of digital computers are well suited to perform the large amount of calculations required to solve the economic equations and arrive at resulting life-cycle costing information. One powerful software package for IBM PC-AT and compatible computers is MathCAD2.5 from Mathsoft, Incorporated [13]. The software serves as a numerical processing engine to allow simple entry of complex numerical relations. Computational tools and automated routines are incorporated to allow the solution of a variety of mathematical processes.

PROGRAM USE

Equations are entered in the same format as they appear in reference or written material, expanded fully on the screen to provide a direct correlation between the entered formula and the original expression. The screen is treated as a paper worksheet. Functions and variables defined at the top left of the screen are evaluated first. Parameters may be used or redefined to the right of or below the location at which the variable is originally designed. Online help, a command line

interface and pulldown menus are provided to supplement the reference manual and prompt messages.

Built-in functions iteratively solve for minimums, maximums, roots, differentials, integrals and other key results. Matrix and array operations are supported. A full set of statistical functions are included, as well as documentary features such as text fields and document formatting. Entered information may be edited and revised quickly.

SAMPLE PROGRAM

A sample MathCAD2.5 program is listed in Appendix A. The computer printout is a faithful reproduction of what is displayed on the screen. New values and functions are entered by positioning the cursor and using the keyboard to type in values. Values are deleted or updated by positioning the cursor over the value and deleting or typing over the data.

Navigation through the worksheet is by cursor keys, page up or down keys, and a search function. The program stores all variables and arrays, overwriting values that are redefined later in the worksheet. Iterations and range calculations are performed on the same line as the entered function.

The program in Appendix A provides output for an economic assessment of energy conservation alternatives. The MathCAD program is organized into five basic sections. The data entry section defines evaluation parameters. The life-cycle money flow section converts the input data into undiscounted

money flows. The rate-of-return and payback section iteratively solves for the internal rate of return and the payback period. The sensitivity analysis section computes appropriate variable ranges and computes the present equivalent total life-cycle cost over the determined ranges. Finally, the results section summarizes and organizes the output of the analysis.

PROGRAM INPUTS

All input variables are defined and entered on the opening screen. The number of years being evaluation is the first entry, and is variable up to the memory constraints of the PC. Interest and growth factors are entered as decimal amounts. A separate energy growth rate is included to account for energy rate increases above the normal inflation rate.

Annual amounts for both overall energy consumption and a separate amount for consumption affected by the energy saving alternative, in this case HVAC use, are input. Initial acquisition costs and any annual costs added by alternative are input, as well as the number of years from the present at which the purchase of the alternative is being considered, to allow the program to compute yearly cost values. Alternatively, individual values may be entered directly into a matrix for more precise estimation. The expected useful life is input so that acquisitions with different lifetimes may be compared using equivalent present amounts.

A range of predicted savings may be entered along with an

expected value of predicted actual savings. Finally, a percent uncertainty is entered to bound the sensitivity analysis.

The outputs of the numerical calculations are listed towards the bottom of the worksheet in Appendix A. Functions needed to economically assess options taken from Equations (3) through (8) are incorporated directly into the program. The yearly cumulative equivalent life-cycle costs are shown to give insight into the overall effect of an alternative as the number of years increases. Internal rates-of-return and payback periods are automatically calculated. Single variable sensitivity analysis is performed over the uncertainty range for all key input parameters. Multivariable sensitivity analysis is performed for the combined influence of the interest rate with the predicted savings over a wide range of potential values. Plots and number tables of the results are automatically generated and formatted. A sample analysis using environmental, energy rate and energy consumption data for Bismark, North Dakota and a thermal zone control system with a semiautomatic thermostat option is used for the listing shown in Appendix A.

Chapter 5: System Selection

OVERVIEW

The System Selection phase uses the data from the Structured Analysis to compare energy saving alternatives. Hardware and control options are explored. Life-cycle costs and other economic indicators for suitable options are compared. The sensitivity of the evaluation to key parameters is determined using single and joint sensitivity analysis.

A technique to use both cost and performance data in the selection of the most desirable alternative is presented in the following Chapter. The method is based in part on design-to-cost principles. A decision evaluation display is presented to aid in the visualization of the cost and performance measures for each alternative.

HVAC CONTROL OPTIONS

Controls for HVAC systems may be either manual, semiautomatic or fully automatic. The ease of use and costs efficiency of each are distinctly different. The type of control depends in part on factors such as on frequency of use and extremes of climatic variation.

The optimization of HVAC systems involves both performance and cost. The essential tradeoffs are between minimizing costs and maximizing comfort. Other factors such as ease of use, maintainability and dependability are involved.

Both the costs and performance of an HVAC system may be improved by enhancing the operational cycle characteristics of the overall system. The operating cycle is dependent upon the control mechanism, control programming, and availability of appropriate feedback data.

Manual Control

Manual control requires constant attention and manual regulation at frequent intervals using a hand operated switch. Examples of manually controlled HVAC devices include manually operated fans to regulate air movement and room heaters that are not regulated by thermostat. The stimuli to activate or deactivate the control is typically when the environment becomes either too cold or too hot, at which point energy has already been wasted and the comfort level exceeded.

The level of effort needed to manage energy use and temperature make this type of control suitable only in climates with practically no heating or cooling requirements throughout the year. The initial acquisition cost is the lowest of the HVAC control types, but the level of effort and life-cycle costs due to waste are the greatest.

Semiautomatic Control

A semiautomatic HVAC control is typical of the thermostatically controlled systems currently installed in most structures. Such control devices may also include timers and

some features that increase automation. The savings of using a semiautomatic over a manual control system are substantial.

Typical semiautomatic devices require very little attention or effort. Inefficiency and waste may occur when operators are unfamiliar with the operating characteristics of a particular HVAC system such as reducing the operating time of a heat pump device by frequent, short use of auxiliary heat in an attempt to reduce costs.

Extra costs result when the system maintains full or overly comfortable conditions during times of peak use rates. A typical scenario involves unknowingly running full air conditioning in the middle of a hot summer afternoon rather than decreasing the comfort level slightly to compensate for the greatly increased utility rates. The thermostat may remain at full comfort settings while a dwelling remains uninhabited for extended periods of time. Or, the system may be secured when unattended during situations when some temperature control is needed, such as preventing burst pipes during a heavy freeze.

Semiautomatic controls may typically be retrofitted into centrally managed manual control systems with relative ease and little cost [10].

Fully Automatic Control

A fully automated system is the most suitable control mode for climates that require even a moderate amount of heating and cooling capacity. Such a system is able to respond

to changing loads, schedules and utility rates virtually instantaneously without operator intervention.

A large number of sensors and instruments are required such as clocks, interior and exterior temperature sensors, occupancy sensors, humidity sensors, and powered air dampers in zone controlled systems. No effort is required for maintaining the proper temperatures in response to various conditions. Operating costs are constantly monitored and kept at a minimum. The user is not required to manual select heating or cooling operation. The system does not need to be secured when the structure is unoccupied or activated upon entry into the structure.

The optimum operational control mechanism utilizes climate data, comfort and occupancy data and dynamic cost changes as they occur. Automatic HVAC control provides the highest ratio of cost savings versus reliable, consistent comfort and operational performance improvements of any control type. An economic assessment may be performed to evaluate the differences in the purchase cost of an automatic system compared to the life-cycle savings due to automated energy management optimization.

Figures 5 and 6 show a proposed optimum HVAC control program and operational system response, respectively. The optimum HVAC control program in Figure 5 responds to actual and scheduled occupancy patterns by adjusting the level of comfort slightly in anticipation of program schedules.

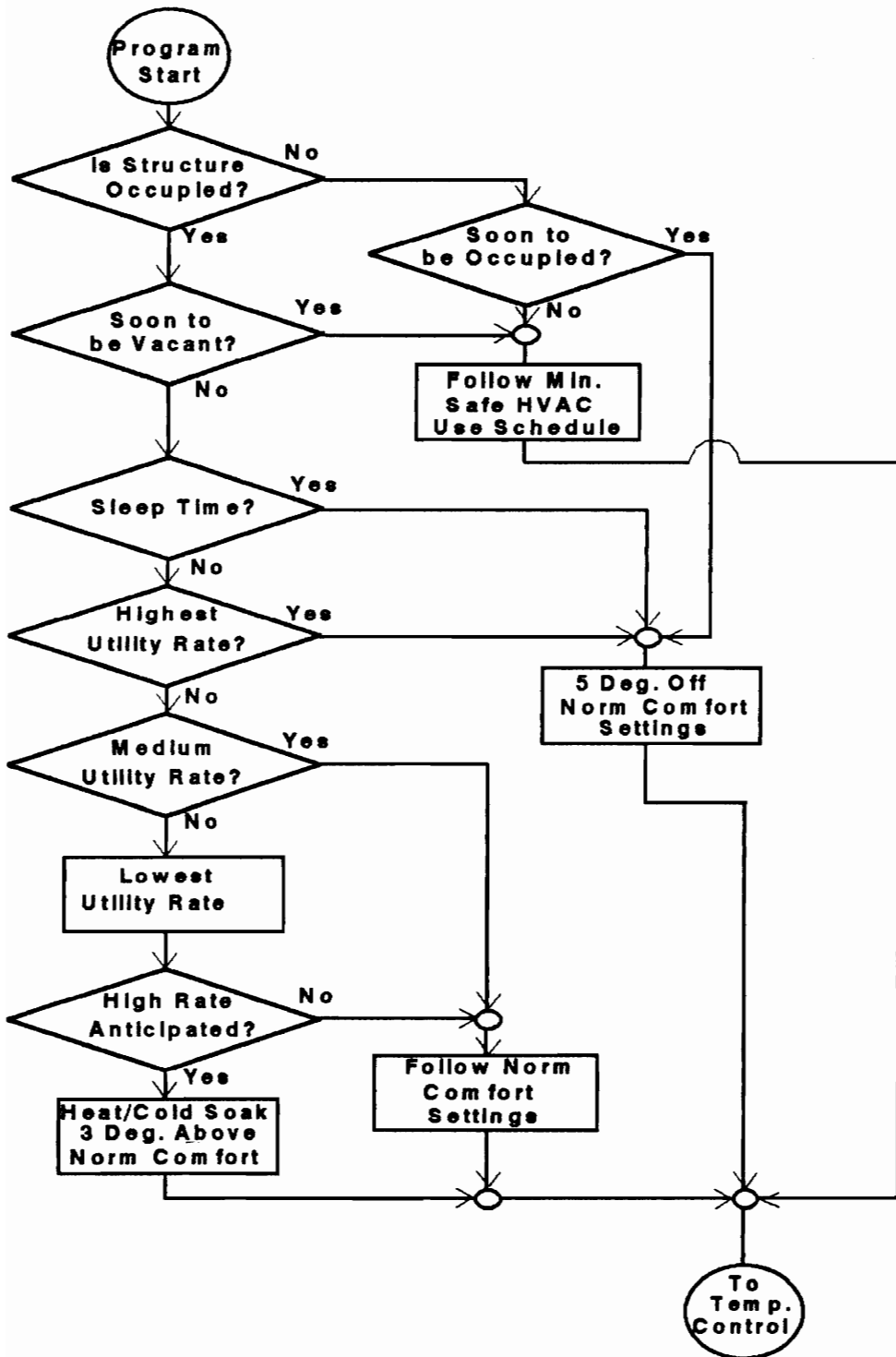


Figure 5: Flow Diagram for Optimum HVAC Programming

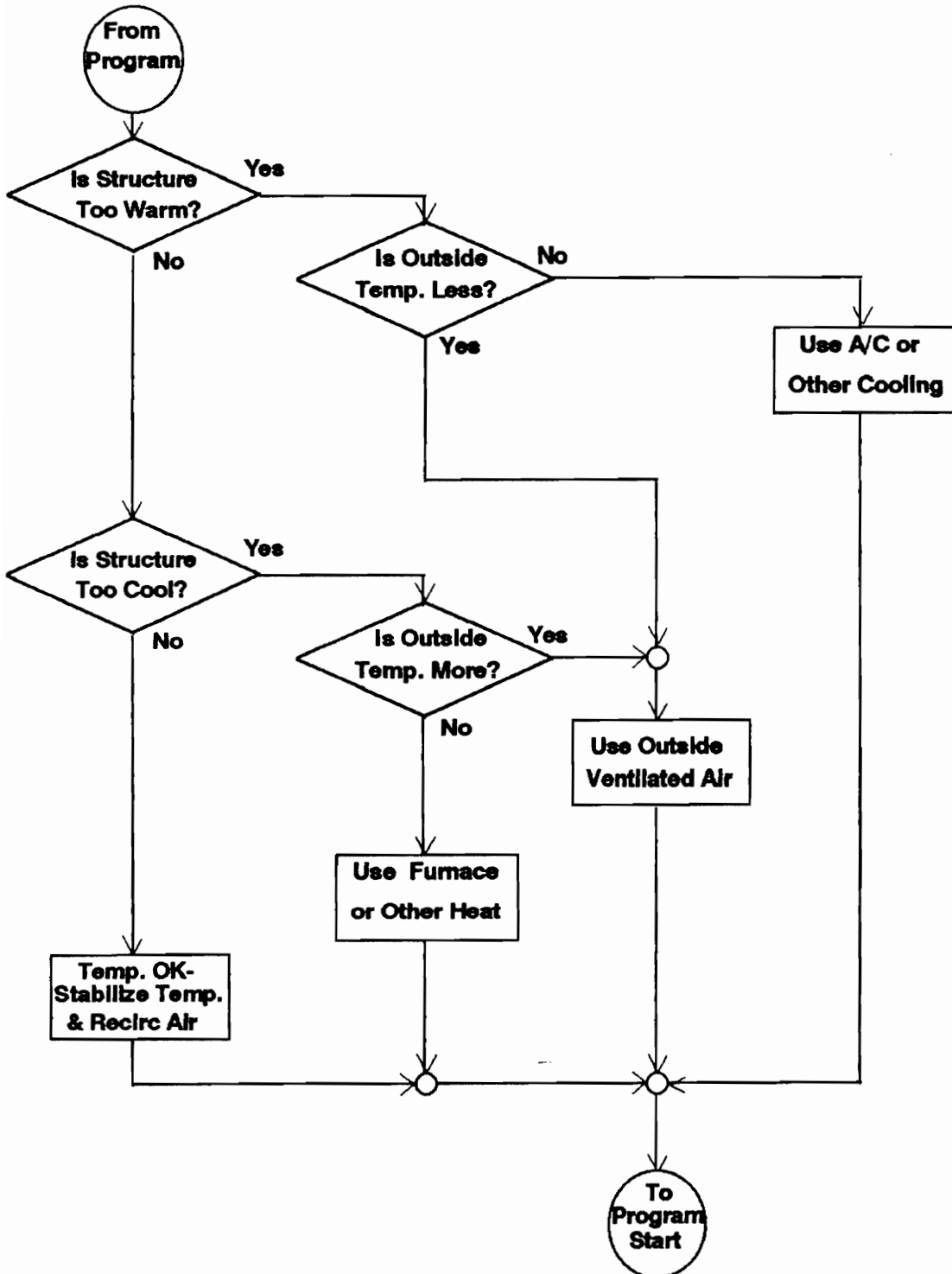


Figure 6: Flow Diagram of Optimum HVAC Operation

Night and day settings are accommodated when the dwelling is occupied. Utility rates are either constantly monitored or entered according to utility company announced rate change schedules. A constant balance is maintained between comfort and operating cost. Climatic conditions that require heating and cooling are noted. If higher rates are anticipated following a current low rate operating period the system is able to increase the level of comfort prior to the rate increase, effectively heat- or cold-soaking the structure to allow reduced operation during prime rate periods.

The optimum operating cycle depicted in Figure 6 responds to program input and the values received from additional sensors. Outside temperature conditions are checked to see if ventilation alone is able to modify the interior temperature if heating or cooling is required. Such a condition exists when an interior is cold due to overnight low temperatures but the outside is warm from a hot morning sun. Or, inside activity such as cooking, crowded party or operation of electronic and power equipment can increase the latent heat of the structure sufficiently to require cooling even though the outside temperature is mild. An acceptable temperature range results in stabilization of temperature changing influences and continued recirculation of interior air to prevent thermal stratification.

Equipment with special operating characteristics such as heat pumps or solar heating and cooling units are able to be

integrated with the control system. The type of fuel used in cogenerators may be dynamically controlled to minimize operating cost. The entire HVAC control system may ultimately be integrated with a multifunction control system as shown in Figure 7. The separate functional areas such as security, economy, comfort and safety may share information to improve functional capability by combining and comparing inputs from different sensors.

The system must be equipped with overrides for all HVAC programming controls. Illness, pregnancy, acclimatization changes and guests may all dictate a requirement to temporarily override the most efficient settings. The system should be factory programmed to optimum default values for individuals who do not desire to understand system programming. The default settings should be resettable to the defaults at any time in case a new program does not achieve the desired results. A twenty-four hour central help telephone service may provide the capability for a technician at the central office to reprogram the settings over the telephone.

ECONOMIC COMPARISON

The economic comparison of energy saving alternatives is based on the cost breakdown analysis and life-cycle costs of the various options. Additional economic indicators such as rate-of-return and payback period may be used to more clearly point out the differences between various alternatives.

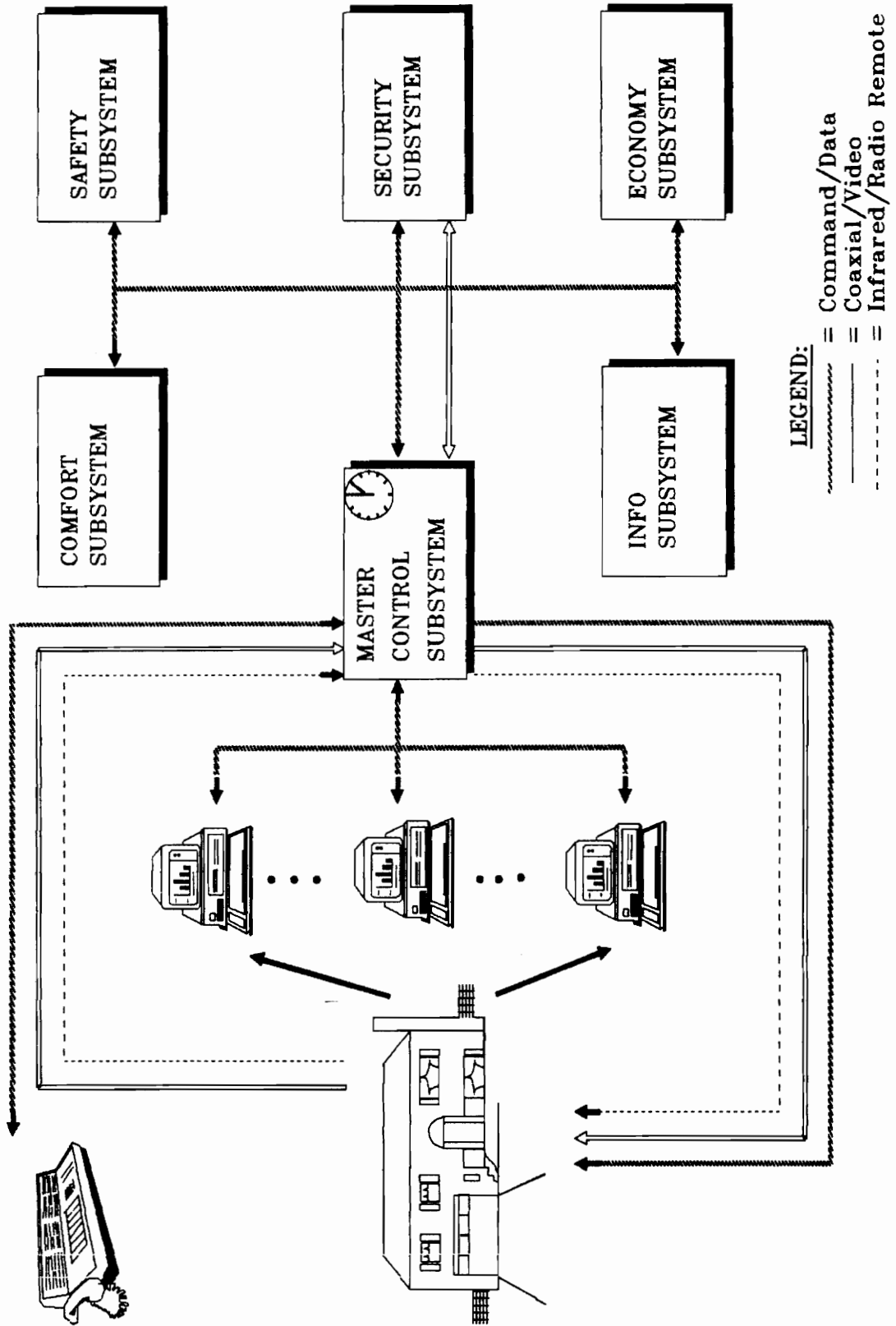


Figure 7: Integration of HVAC with Multi-Function Control System

Internal Rate-of-Return

The rate-of-return is a universally accepted measure of economic success and an index of profitability. As such, it is particularly useful in comparing a specific alternative with other opportunities that have not been specified. The comparison of the alternative is against accepted norms in lieu of other options.

The definition of rate-of-return is that interest rate which causes the equivalent receipts of a money flow to be equal to the equivalent disbursements for a cumulative PE amount of zero [5]. In the evaluation of energy conservation and energy cost reduction alternatives, the amount of money saved as a result of the option is considered "earned" income received from the project. The rate-of-return is determined according to

$$0 = PE = \sum_{t=0}^n F_t \left(\frac{P/F, i^*, t}{}, \right), \quad (7)$$

where i^* is the calculated rate-of-return that satisfies the equation. The rate-of-return is an indication of the percent profitability over the life of the evaluation. A rate-of-return that is higher than the prevailing interest rate is an indication that an alternative is economically attractive. The higher the rate-of-return, the more desirable the option is. Typically, a

target rate-of-return that is ten to fifteen percent better than the prevailing interest rate is set to ensure profitability. A high rate-of-return provides a margin for errors in estimation. A low or negative rate-of-return indicates an economically undesirable option.

Payback Period

Energy consumers are particularly interested in estimating how long it will take before an investment is rewarded by revenues or savings that offset the cost of the investment. A quick payoff is desirable because capital funds needed to finance the investment may then be quickly recovered and applied elsewhere. Also, the estimation of the national economy and economic estimators become much less certain as predictions are made for periods farther in the future.

The time value of money has significant impact on the payback period. The initial investment costs are typically at or close to "today's" full dollar value. Future rewards become less significant as time progresses due to the effects of the discount rate. However, the effect of the discount rate may be offset by the amount of accumulated savings over several years.

The payback period using the present equivalent amount is determined by

$$0 \leq \sum_{t=0}^{n^*} F_t(P/F, i, t), \quad (8)$$

where n^* is the number of years required for the cumulative present equivalent savings to exceed the cumulative costs at a given interest rate. A value may not be found that satisfies Equation (8) if a positive equivalent net money flow is never achieved over the lifetime of an option. Alternatives with excessive or indeterminate payback periods are economically undesirable.

Sensitivity Analysis

The results of economic analysis may be misleading if the impact of errors in predicted values are not known with relative certainty. Errors in estimation introduce an unknown amount of bias into evaluation results. A difference of just a few percentile between predicted and actual interest or inflation rates may completely change the desirability of pursuing an alternative. Accumulated errors in expenses or receipts over the lifetime of a proposal may significantly alter or reverse profits and losses. Sensitivity analysis should be performed to investigate the sensitivity of the analysis to errors of key parameters. One method of sensitivity analysis is to establish the baseline evaluation values and then vary each parameter one at a time over a suitable range of uncertainty to determine

the impact on the evaluation. Single variable sensitivity analysis identifies critical analysis factors and shows which parameters require further refinement or greater accuracy to ensure the validity of the economic analysis.

Joint Sensitivity Analysis

The effect of cumulative errors from a number of variables is not always discernible using single variable sensitivity analysis. The combined effect of several errors may significantly alter the results of the evaluation, while the individual effect of the errors in two or more variables may not.

Joint sensitivity analysis varies two or more parameters through a range of values concurrently. The effects of lowering both, values raising one and lowering another, or of raising both may be observed. Greater insight into proposal estimates is gained through joint sensitivity analysis. The identification of critical evaluation parameters enables further safeguards to be taken to mitigate the risk of errors in estimation.

The use of joint sensitivity analysis in the comparison of alternative proposals is beneficial to both the consumer and the producer of energy and energy saving products. The producer is protected from unexpected costs overruns or unprofitable enterprises. The joint sensitivity analysis allows the developer to target areas of highest risk and uncertainty to ensure a rewarding endeavor. The consumer is protected against higher life-cycle costs that may result from unforeseen estimation

errors. The impact of such errors may occur late in the life-cycle of a project, after the funding and purchase phases are complete. Techniques such as joint sensitivity analysis show the impacts of errors in estimation for the purpose of identifying such problems early in the life-cycle before a large amount of resources have been invested.

Any analysis requires the use of the best data available as well as sound engineering judgement to balance out the resulting numbers and statistics. Accurate energy use monitoring and energy audits provide a foundation using solid data. However, individuals conducting an economic assessment do not always consider every factor, or even key parameters, in conducting the evaluations. Sensitivity analysis which evaluates a range of cost and savings data should be made to safeguard against overly optimistic estimates and protect against unexpected economic losses.

Chapter 6: Utilization of Multiple Criteria

OVERVIEW

The purchase of energy management devices is typically driven either by a desire to save money in operating costs in a particular area or to obtain greater utility and ease of use over a current system. Energy conservation measures are often selected on the basis of acquisition cost alone. An effective economic comparison may reveal that the advantage of a lower acquisition cost is lost after several years of less efficient operation, or may show that the less expensive option is in fact more economic over the life-cycle. Acquisition cost should not be addressed without considering the overall life-cycle costs along with performance and effectiveness factors.

ECONOMIC EVALUATION

The evaluation of economic factors in HVAC systems is closely related to the operational factors. Aside from operating the system in the most cost effective manner, the primary cost factors are the economic feasibilities of various energy conserving options. The energy data monitoring and economic assessment methods such as the MathCAD2.5 program in Appendix A are provided as tools to analyze the life-cycle economics of energy use and energy conservation alternatives.

Design-to-Cost

A design-to-cost approach may be used to incorporate life-cycle cost as one of several design parameters, along with performance, effectiveness, capacity, accuracy, maintainability, supportability, ease of operation and others. Each factor must be actively considered when evaluating design alternatives. In some cases, cost alone may drive the selection of one option over another as a result of budget limitations. However, the long term effect of life-cycle costs may ultimately result in greater savings if a cost-effectiveness approach is maintained.

Design-to-cost figures-of-merit are usually applied in terms of life-cycle cost at a system level to establish which system is to be designed, produced and supported. A similar approach may be used to compare energy saving alternatives against original or current cost and performance estimations to determine if implementation of an alternative is warranted.

Cost Effectiveness

Some cost-effectiveness measures applicable to HVAC and energy use are shown in Figure 8, which is adapted from the format found in Fabrycky and Blanchard's text Life-Cycle Cost and Economic Analysis [5]. System effectiveness is a measure of how the system fulfills stated objectives or goals. The figures of merit used to describe effectiveness may change based on the alternatives being compared. Three requirements for applying cost-effectiveness analysis to systems are that the systems being

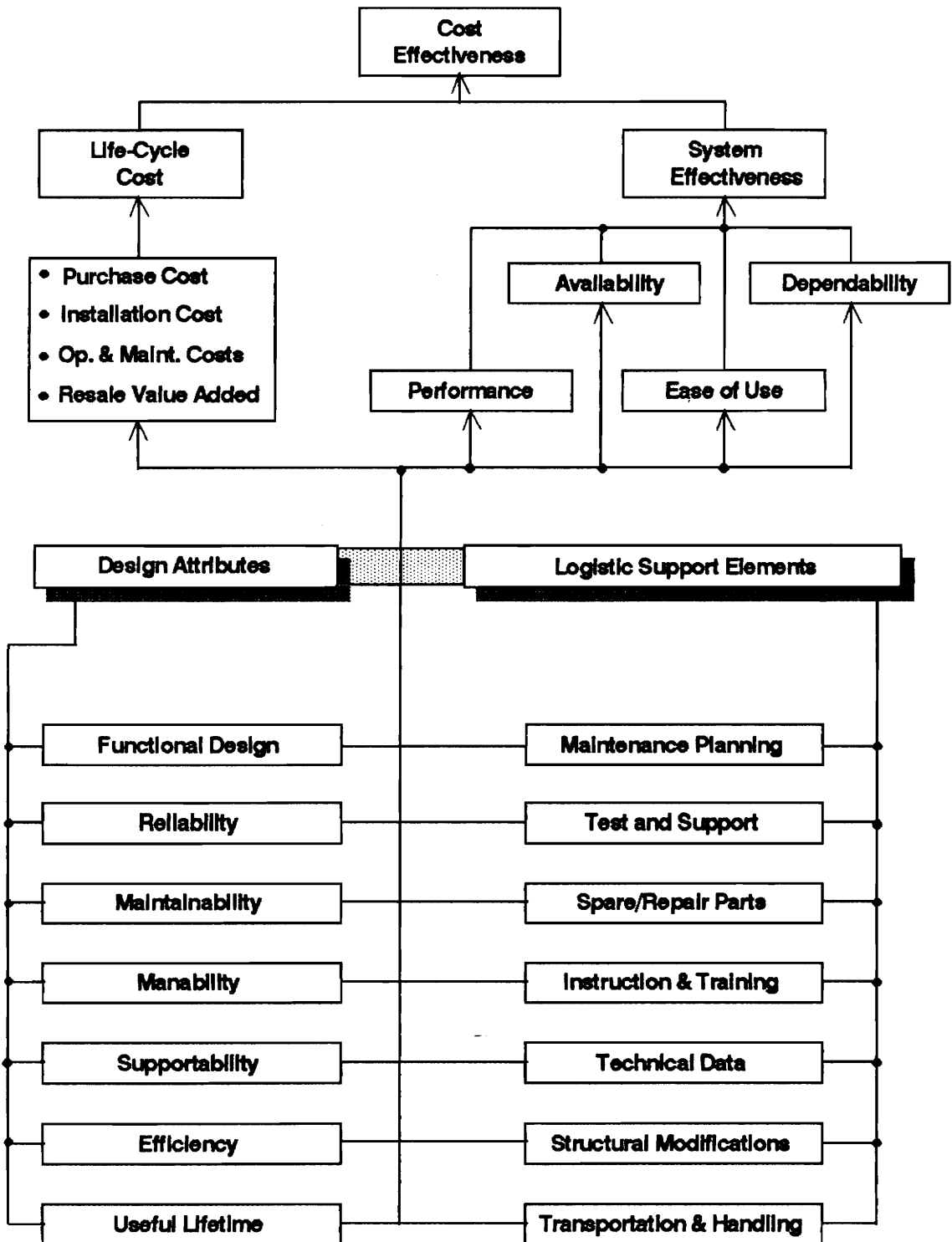


Figure 8: Elements of Cost Effectiveness for Energy Saving Options

evaluated must have common goals, several alternatives must in fact exist for satisfying the goals, and critical details about each system must be known or able to be estimated with relative accuracy.

A standardized approach to cost-effectiveness evaluations is described in Fabrycky and Blanchard's text on economic evaluation [5]. First, the desired goal or goals of the system must be defined. A suitable goal for HVAC systems is to conserve energy, reduce operating costs, increase operability, decrease maintenance requirements or a combination of these objects. Second, alternatives to accomplish the goals must be identified or developed. A cost-effectiveness evaluation is meaningless for a single alternative. Selection of alternatives must be made based on an optimum configuration for each system in terms of economic evaluation and performance suited to the prospective task. System evaluation criteria must then be established for both the life-cycle costs and the effectiveness aspects of the systems.

Although precise quantitative measures are not always available for effectiveness measures, these criteria remain useful as a basis for describing system effectiveness. The design attributes in Figure 8 are sometimes available as technical specifications for a given system. Logistic support elements are equally important in selecting a final system, as many car owners have discovered from their automotive dealerships. Cost considerations should attempt to quantify any "hidden"

costs such as the cost and frequency of changing filters or need for expensive service calls.

Fixed-Cost versus Fixed-Effectiveness

A decision must then be made to use either a fixed-cost or fixed-effectiveness approach. The fixed-cost method is used for multiple alternatives that have the same cost but different levels of effectiveness. The fixed-effectiveness approach is used for systems with different costs that provide the same level of effectiveness. In either case, the alternatives should be ranked according to merit with the most important criteria listed first.

The choice is obvious if the cost and effectiveness of one alternative are both superior to other candidates. Otherwise, the selection must be made on the relative merits of each proposal and the value assigned to both cost and performance. A proper selection must be based on sound judgement and a critical evaluation of the relative merits of each option.

The final step is to document the objectives, goals, assumptions, methodology, evaluation criteria and conclusions. Accurate documentation serves as a basis for a reference database on which to make subsequent evaluations, perhaps between a previous alternative and a newly presented option.

DECISION EVALUATION DISPLAY

A visual device known as a decision evaluation display is useful in exhibiting one or more effectiveness measures

simultaneously as an aid in decision making. Effectiveness thresholds are shown with equivalent life-cycle cost data.

The effectiveness measures, while subjective, are an important criteria in the decision making process. The display provides the information needed to select the alternative with the lowest life-cycle costs that satisfies most of the effectiveness measures. An example of a Decision Evaluation Display is shown in Figure 9, which is adopted from Fabrycky and Blanchard's text on Economic Evaluation [5].

The effectiveness and performance measures are positioned on the left vertical axis. The total equivalent life-cycle costs are positioned horizontally across the bottom. The alternatives are depicted as vertical lines opposite the effectiveness and performance measures positioned over the respective total equivalent life-cycle cost. The threshold values for the effectiveness and performance criteria are positioned as horizontal lines beginning at the respective criteria and intersecting the alternative lines. The values assigned to each alternative for performance measures are depicted as circles positioned according to the effectiveness and performance evaluation scores. The display shows at a glance which alternative is least expensive and the relative ability of each alternative to satisfy the effectiveness and performance measures.

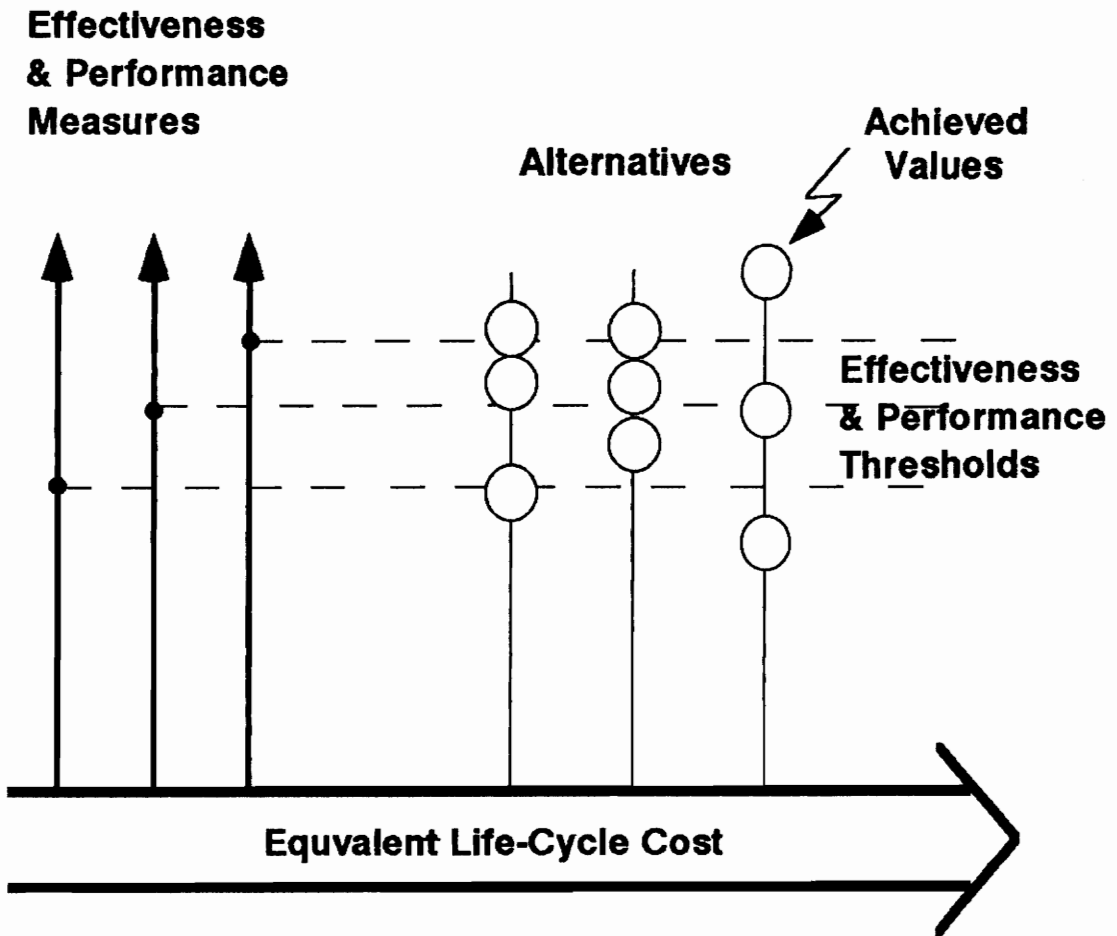


Figure 9: Decision Evaluation Display

Chapter 7: Bismark, N.D. Case Study

The city of Bismark, North Dakota is selected for the first case study due to the severe climatological conditions which exist there. A medium sized house is used as the basis for a demonstration of the evaluation methodology.

The evaluation is conducted to determine the availability and suitability of energy saving projects to achieve greater comfort and reduced costs. The alternatives are selected to demonstrate the effects of a range of acquisition costs and potential savings.

STEP 1- FEASIBILITY STUDY

Existing Needs

The city of Bismark, North Dakota is located in the Great Interior climate zone shown in Figure 2. This zone is the least desirable in terms of mildness and human comfort with one of the most extreme climates found anywhere in the United States. Winters are long and severely cold. Summers are hot and humid. The pleasant Spring and Autumn seasons are disappointingly short. The normal average temperature range from summer to winter is 135 degrees Fahrenheit. Temperature readings in excess of 100 degrees in summer and -30 degrees in winter occur regularly. Winter conditions exist from mid October to mid April. Summer conditions exist from early June

to early September. The number of heating-cooling degree days is 9,531.

Energy use data used based on average values of an energy audit and profile published by the Places Rated Almanac are used for energy use and cost data [6]. The energy costs for the economic evaluation are determined by applying local average energy use and cost ratios. The number of heating-cooling degree days are used as an approximation of proportional energy use between different areas. Data from the Places Rated Almanac for Bismark, ND indicates that annual energy bills average \$972, with approximately \$720 used for heating and cooling purposes [6].

System Objectives

Due to the increasing price of energy, a more energy efficient HVAC system is desired to reduce both consumption and cost. Also, a means to efficiently maintain interior temperature at comfortable levels is needed to eliminate drafts, chills and hot spots experienced with the current system.

The performance and effectiveness measures selected to compare the two energy saving options with the current system are comfort, energy conservation and ease of use. Comfort and ease of use are evaluated using a scale from zero to four, with two being no different than the current system. Energy conservation is compared using the predicted percent energy savings values of the energy projects considered.

The potential for each option to increase the level of comfort in the interior environment is the primary consideration due to health, personal comfort and purchase justification factors. The ease of use is determined by the individual products and the current system. An existing structure with maximum insulation and a fully automated climate control system may see little benefit from energy saving projects. The amount of energy conservation achieved by a project option may be a significant cost factor. Increased conservation of energy may be a desirable objective regardless of the economic feasibility of an alternative.

Possible Options

Two options are selected for comparison that meet the objectives of the new HVAC system. Both options potentially reduce energy operating costs and increase the comfort level within a house.

The first option, a zoned control system, is selected as a low-cost option that primarily improves the control and distribution of heating and cooling. The second option, superinsulation, is a relatively high cost option that improves the thermal retention capabilities of a structure with potentially large energy savings.

Option 1- Zone Control

Zone control allows control of individual room or zone

temperatures. A zoned control system, or ZCS, with automatic setback thermostat is an option that may be retrofitted onto existing forced air HVAC systems with relative ease. Separate temperature control of each zone is achieved using inflatable or motorized dampers to redirect HVAC airflow. An acquisition cost of \$700 is used for the case study. The ZCS is able to save between five and thirty percent of HVAC costs, as shown in Table 3. The actual amount of savings is a function of temperature selections and the types of physical barriers separating the zones. A properly designed and installed ZCS solves a variety of common heating-cooling problems.

Many structures experience discomfort zones in which conventional HVAC systems are ineffective at maintaining comfortable temperature ranges. Multifloor structures commonly experience thermal stratification between floors. The heating air on cold winter days tends to rise to the upper floors. Consequently, the downstairs are uncomfortably cold while the upstairs becomes increasingly hot. A reverse condition exists during hot summer temperatures. A flue effect is created in high-rise office and apartment buildings in which warm air is constantly circulated upward. The flue effect makes temperature control difficult throughout the year. Modern glass office buildings often experience a unique phenomenon in which the sunward facing rooms require cooling while the rooms on the shaded side simultaneously require heating [10]. Additionally, temperature control in unoccupied rooms

accounts for a significant percentage of heating and cooling costs each year.

A ZCS product is able to send heated or cooled air exactly where it is needed most in each of the HVAC problems described. The system is even able to redirect air between sunward and shaded sides of a glass walled structure. The result is greatly increased comfort and reduced energy demands.

Several cautions apply to ZCS operation. Many central HVAC units are susceptible to severe damage and fire hazard due to back pressure if the airflow of the ventilation system is restricted. Care must be taken to ensure adequate airflow for safe HVAC operation.

The status of damper operation and current position must be readily available to prevent situations in which the thermostat setting is repeatedly increased in an attempt to maintain comfort while the dampers remain closed. Failed dampers must be easily detectable to provide continued energy saving and comfort benefits.

Option 2- Superinsulating

The principles of superinsulating (SI) structures are covered in detail by Shurcliff in Superinsulated Houses and Air-to-Air Heat Exchangers [12]. Superinsulation is able to save between seventy and ninety percent of HVAC costs, as shown in Table 3. An acquisition cost of \$4,500 is used based on five percent of a \$150,000 new home price. Although SI is typically

implemented during initial construction, retrofits are possible at comparable costs. Superinsulation achieves nearly airtight structural integrity by using sealants and plastic film air barriers in walls, floor and ceiling. All sides of the structure are insulated to a prescribed maximum amount including floors, ceilings, windows and exterior walls and doors. Air-to-air heat exchangers are needed to allow adequate fresh air ventilation while minimizing thermal loss.

The primary benefit of SI is reduced heating costs. The natural heat generated by appliances, lights and the human body is adequate to maintain a comfortable environment in all but the most severe cold. Maintaining comfortably cool temperatures in warmer seasons typically requires auxiliary cooling to overcome the heat from both exterior and interior sources. However, the SI design prevents thermal transfer of interior cool to the outside much better than in ordinary structures. The energy savings in the cooling season are substantial.

Superinsulating requires careful attention to structural design and safety features. Windows are naturally counter to the principles of SI. Interior ambiance and natural light are somewhat reduced in a strict SI implementation. Discomfort zones are not improved as a result of continued thermal stratification, the flue effect and incident solar radiation. Auxiliary heating and cooling equipment to supplement the capabilities of the air-to-air heat exchangers are still required.

The retrofitting of SI into existing structures causes severe disruption of normal living activities as walls are removed, ceilings are bared and floors are lifted to install the proper insulation and air barriers. The potential lack of fresh air during a ventilation failure poses a potentially serious health and safety risk. The likelihood of a buildup of radon and other indoor pollutants is increased by the sealed nature of SI structures.

Project Constraints

Extensive renovation of the current system and structure is considered acceptable because the case study dwelling is assumed to be privately owned. The project should be completed within one year to achieve the savings and benefits of the new system as soon as possible. The useful life of the new system may vary, depending upon the cost and payback period.

The payback period should be less than fifteen years. Financing for the project is not needed for projects costing less than six thousand dollars.

STEP 2- STRUCTURED ANALYSIS

Schedules

The budget schedule is not required for projects less than five thousand dollars. The work and labor schedules must provide for project completion within the twelve month project

timeframe.

The installation of the Zone Control System may be completed in one or two afternoons. A professional electrician may be needed to verify the correct installation of the thermostat and other electrical devices. No remodelling should be required.

Superinsulation requires extensive remodelling and approximately one hundred hours of labor. Special skills may be needed for the detail finish work. A private contractor and crew may be employed to perform the labor so that the conversion to Superinsulation is completed within a few weeks time. Even with a hired work crew, some of the labor may still be performed by the homeowner to reduce installation costs.

A long term maintenance agreement will be purchased for each of the projects, assuming such an agreement is available. The maintenance schedule is a function of the maintenance agreement. The cost of maintenance may then be included in the acquisition costs. Maintenance costs are paid completely at the start of the project, while the earning power of the homeowner is at a maximum. No upgrades are planned for the new system.

Cost Breakdown Analysis

The life-cycle cost items for the energy conservation alternatives and estimated cost values are itemized in Table 6. The costs are itemized by year. The yearly energy expenses are

Table 6: Cost Breakdowns for Bismark, N.D. Case Study

Year	Energy Saving Alternatives and Cost Items					
	Current System	Cost (\$)	Zone Control	Cost (\$)	Superinsulation	Cost (\$)
0	Energy Use	972	R&D (by Owner) Acquisition: - Control Module - \$6/Temp Sensors @ 7 Zones - \$40/Dampers @ 7 Zones - Wiring - Additional Ducting - Pressure Control Installation (by Owner) Maintenance Contract (15 yrs) Energy Use (Before Completion)	0 78 42 280 25 50 75 0 150 972	R&D (by Owner) Eng. Data (Plans) Acquisition: - Plastic Vapor Barrier - Additional Ext'r Wall Insulation - Floor Insulation - Additional Ceiling Insulation - High Thermal Efficiency Windows - Remodeling Mat'l and Paint - Sealant, Caulking, Tape, etc. - Air-Air Heat Exchanger Installation \$22/hr @ 100 hrs Maintenance Contract (15 yrs) Energy Use (Before Completion)	0 175 75 100 200 200 800 300 100 200 2,200 150 972
1	Energy Use [972 + (972 * 3%)]	1,001	Energy Use [1001 - (1001*10%)]	927	Energy Use [1001 - (1001*85%)]	371
2	Energy Use	1,031	Energy Use	955	Energy Use	382
3	Energy Use	1,062	Energy Use	983	Energy Use	393
4	Energy Use	1,094	Energy Use	1,013	Energy Use	405
5	Energy Use	1,127	Energy Use	1,043	Energy Use	417
6	Energy Use	1,161	Energy Use	1,075	Energy Use	430
7	Energy Use	1,195	Energy Use	1,107	Energy Use	443
8	Energy Use	1,231	Energy Use	1,140	Energy Use	456
9	Energy Use	1,268	Energy Use	1,174	Energy Use	470
10	Energy Use	1,306	Energy Use	1,210	Energy Use	484
11	Energy Use	1,345	Energy Use	1,246	Energy Use	498
12	Energy Use	1,386	Energy Use	1,283	Energy Use	513
13	Energy Use	1,427	Energy Use	1,322	Energy Use	529
14	Energy Use	1,470	Energy Use	1,361	Energy Use	546
15	Energy Use	1,514	Energy Use	1,402	Energy Use	561

adjusted each year by a three percent cost growth increase above normal inflation rates. The energy costs for the two energy saving projects include the appropriate percentage savings over the current system energy costs.

The undiscounted money flow diagrams from the cost breakdown analysis are shown in Figure 10. The relatively high initial cost and percent savings for the superinsulating option are readily apparent.

System Requirements

The system requirements are derived from the stated objectives and project constraints. The alternatives will be evaluated against the requirements in the system selection phase.

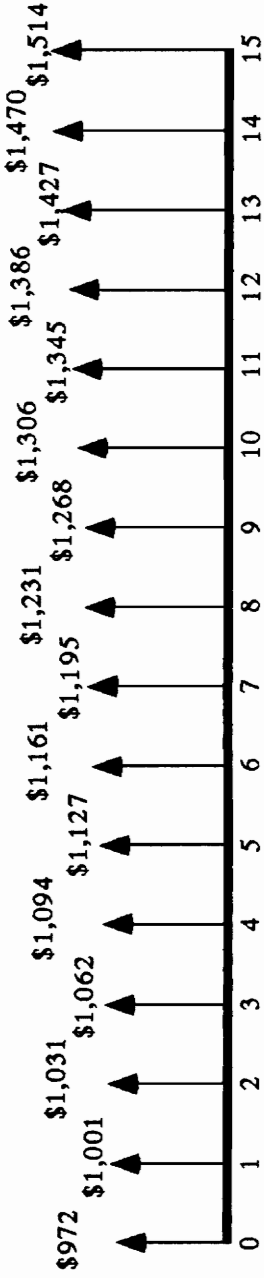
The project must be completed within one year. The minimum useful life of the new system is set at fifteen years. The payback period must be less than fifteen years. The rate of return must be greater than or equal to eleven percent. Finally, the comfort level and convenience must match or exceed the performance of the current system.

STEP 3- SYSTEM SELECTION

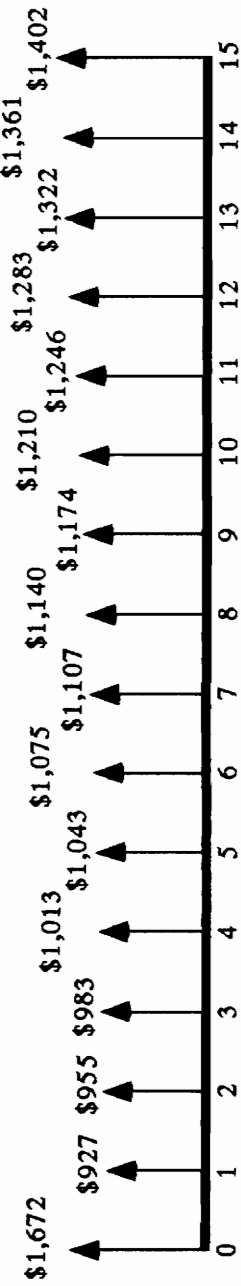
HVAC Control Options

The Zone Control System uses an improved semiautomatic control. Feedback from the zone temperature sensors is used

Projected Energy Costs without Options- (Undiscounted \$)



Projected Energy Costs with Option 1- Zone Control (Undiscounted \$)



Projected Energy Costs with Option 2- Superinsulation (Undiscounted \$)

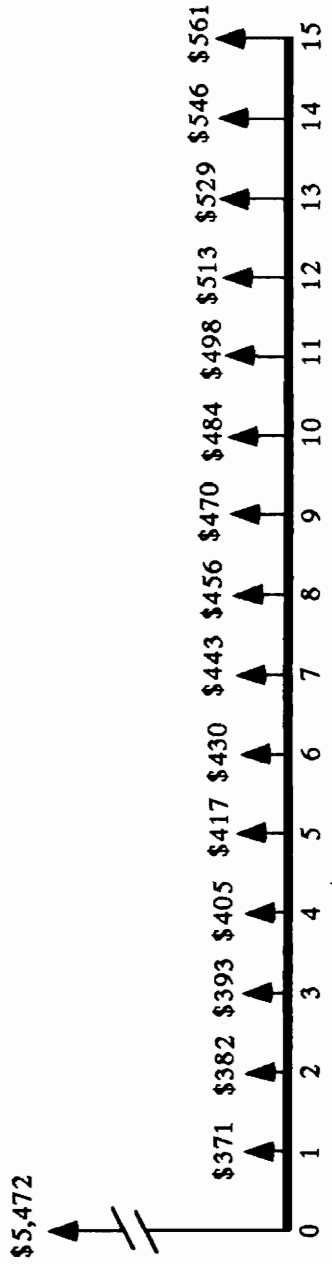


Figure 10: Money Flow Diagrams for Bismark, North Dakota Case Study

with the programmed setting to meter airflow and regulate the thermostat. The control unit is programmed according to individual zone and time of day and week. The control program ensures the ease of use is only slightly less than the existing system despite the increased functionality and complexity.

The Superinsulation option uses the existing thermostat to control HVAC operation. No special controls are required. The air-to-air heat exchanger is interfaced with the existing thermostat. A command for a temperature change will first be routed to the heat exchanger. If the heat exchanger alone is unable to produce the desired change, the HVAC unit is employed. The operation is transparent to the homeowner.

Economic Comparison

The inputs used in the Bismark, ND Case Study are summarized in Table 7. A system lifetime from now through fifteen years is considered. Inflation and interest rates of 5% and 11% respectively are used. Energy costs reflect a growth rate of 3% above the national inflation rate. An estimated value of 10% savings of heating and cooling costs for the zone control option and 85% savings for the superinsulating option is used. A 20% uncertainty is used for the sensitivity analysis.

The inputs are used for a computer based economic evaluation of the two options using the program listed in Appendix A. Cumulative equivalent life-cycle costs for both options are summarized in Table 8. Both options achieve

Table 7: Inputs for Bismark, North Dakota Case Study Evaluation

Bismark, ND Case Study		
INPUT PARAMETER	OPTION 1- ZONE CONTROL	OPTION 2- SUPERINSULATING
# Years Evaluated	15 years	15 years
Annual Inflation Rate	5 %	5 %
Annual Interest Rate	11 %	11 %
Annual Total Energy Cost	\$972.00	\$972.00
Annual Energy Growth Rate	3 %	3 %
Annual HVAC Costs	\$720.00	\$720.00
Acquisition Cost of Option	\$700.00	\$4,500.00
Range of Savings from Option	5 to 25 % of Heating/Cooling	70 to 90 % of Heating/Cooling
Cost Increase due to Option	0	0
Expected Value of Savings	10 %	85 %
Year # of Acquisition	year 0	year 0
Useful Lifetime of Option	15 years	15 years
Percent Uncertainty for Sensitivity Analysis	20 %	20 %

Table 8: Life-Cycle Costs for Bismark, North Dakota Case Study

Bismark, ND Case Study- Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$)							
Year	With No Option	Option 1- Zone Control			Option 2- Superinsulating		
		Low Savings	Expect'd Value	High Savings	Low Savings	Expect'd Value	High Savings
0	972	1,672	1,672	1,672	5,472	5,472	5,472
1	1,919	2,584	2,549	2,444	5,928	5,823	5,788
2	2,842	3,473	3,403	3,196	6,372	6,165	6,095
3	3,741	4,338	4,236	3,928	6,805	6,497	6,395
4	4,617	5,182	5,047	4,642	7,227	6,822	6,687
5	5,470	6,004	5,837	5,337	7,638	7,138	6,971
6	6,302	6,804	6,607	6,015	8,038	7,446	7,249
7	7,112	7,585	7,357	6,675	8,428	7,746	7,519
8	7,901	8,345	8,088	7,318	8,808	8,038	7,782
9	8,670	9,085	8,800	7,945	9,179	8,323	8,038
10	9,420	9,807	9,494	8,555	9,539	8,601	8,288
11	10,150	10,510	10,170	9,150	9,891	8,871	8,531
12	10,861	11,195	10,829	9,730	10,234	9,135	8,768
13	11,555	11,863	11,471	10,295	10,567	9,391	9,000
14	12,230	12,513	12,096	10,845	10,892	9,642	9,225
15	12,888	13,147	12,705	11,381	11,209	9,885	9,444

payback based on the total life-cycle cost after fifteen years. The values in Table 8 are plotted as line graphs in Figures 11 and 12. Figure 11 depicts the estimated values over fifteen years and shows graphically the payback periods at the crossovers of the option costs with the costs of the do-nothing option. The lines in Figure 12 show the equivalent costs over the lowest and highest potential saving ranges.

The internal rate-of-return and payback periods for both options are summarized in Table 9. Although the zone control system is economically feasible by paying for itself within the fifteen year lifetime of the evaluation, the 9% rate-of-return indicates that the zone control system is not a good investment from strictly an economic perspective. The superinsulating option is a good investment with a 14% internal rate-of-return over fifteen years.

The single variable sensitivity analysis results for the zone control option and the superinsulating option are plotted in Figures 13 and 14 respectively. The primary influence apart from the discount rate is the percent savings, followed by the lifetime and the acquisition cost. However, the maximum difference in present equivalent costs is only 3% due to changing a single variable over 20%. The economic evaluation is not sensitive to errors of that magnitude occurring in single variables.

The results of jointly varying both the interest rate and percent savings are summarized in Tables 10 and 11. The values

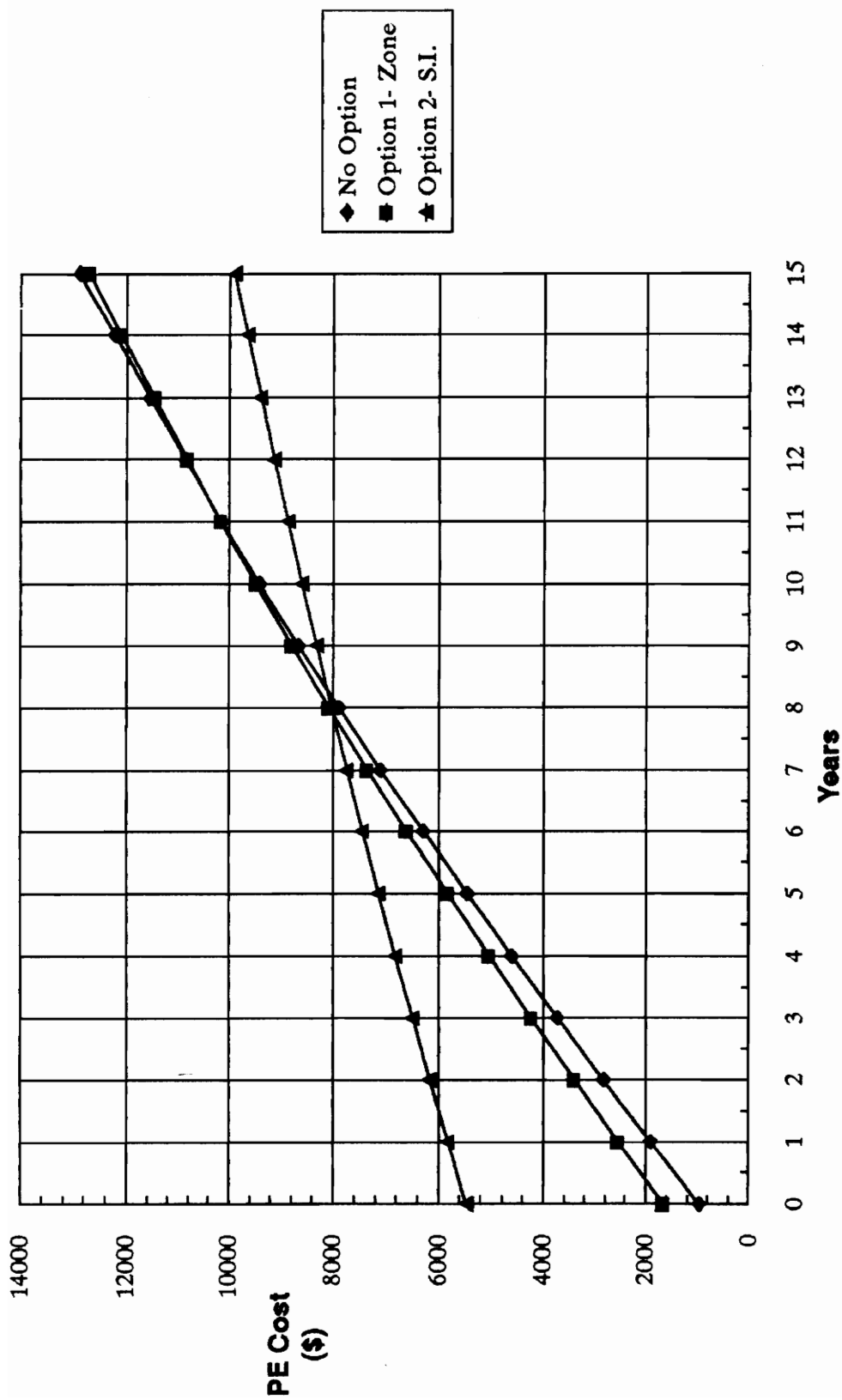


Figure 11: Plot of Cumulative P.E. Life-Cycle Costs for Bismark, North Dakota Case Study

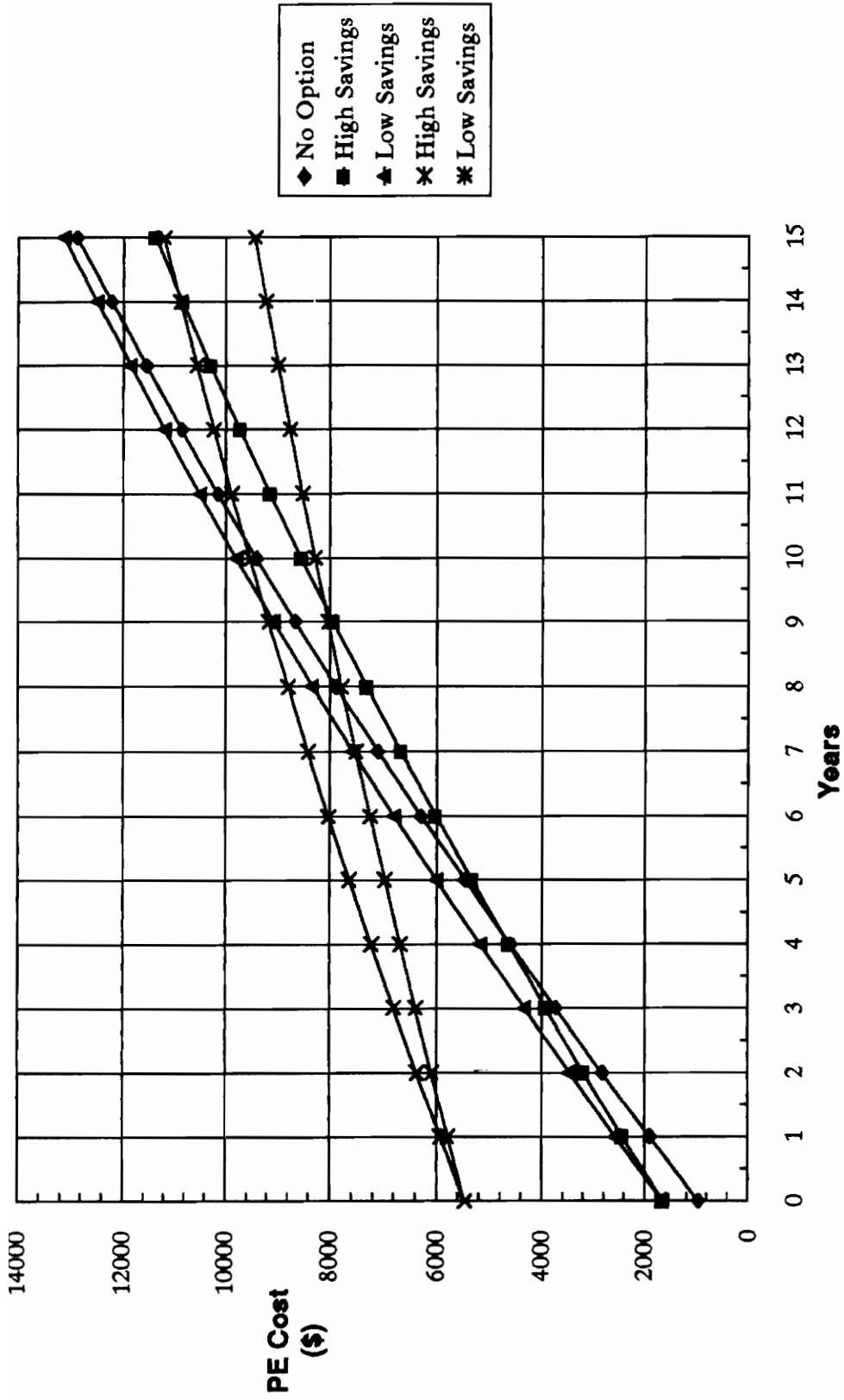


Figure 12: Plot of Cumulative P.E. Life-Cycle Cost Ranges for Bismark, North Dakota Case Study

Table 9: Rates of Return and Payback for Bismark, ND Case Study

Bismark, ND Case Study- Economic Evaluation Indicators						
Economic Indicator	Option 1- Zone Control			Option 2- Superinsulating		
	Low Savings	Expect'd Value	High Savings	Low Savings	Expect'd Value	High Savings
Rate of Return	0 %	9 %	29 %	11 %	14 %	15 %
Payback	>15 yrs.	11 yrs.	4 yrs.	10 yrs.	8 yrs.	8 yrs.

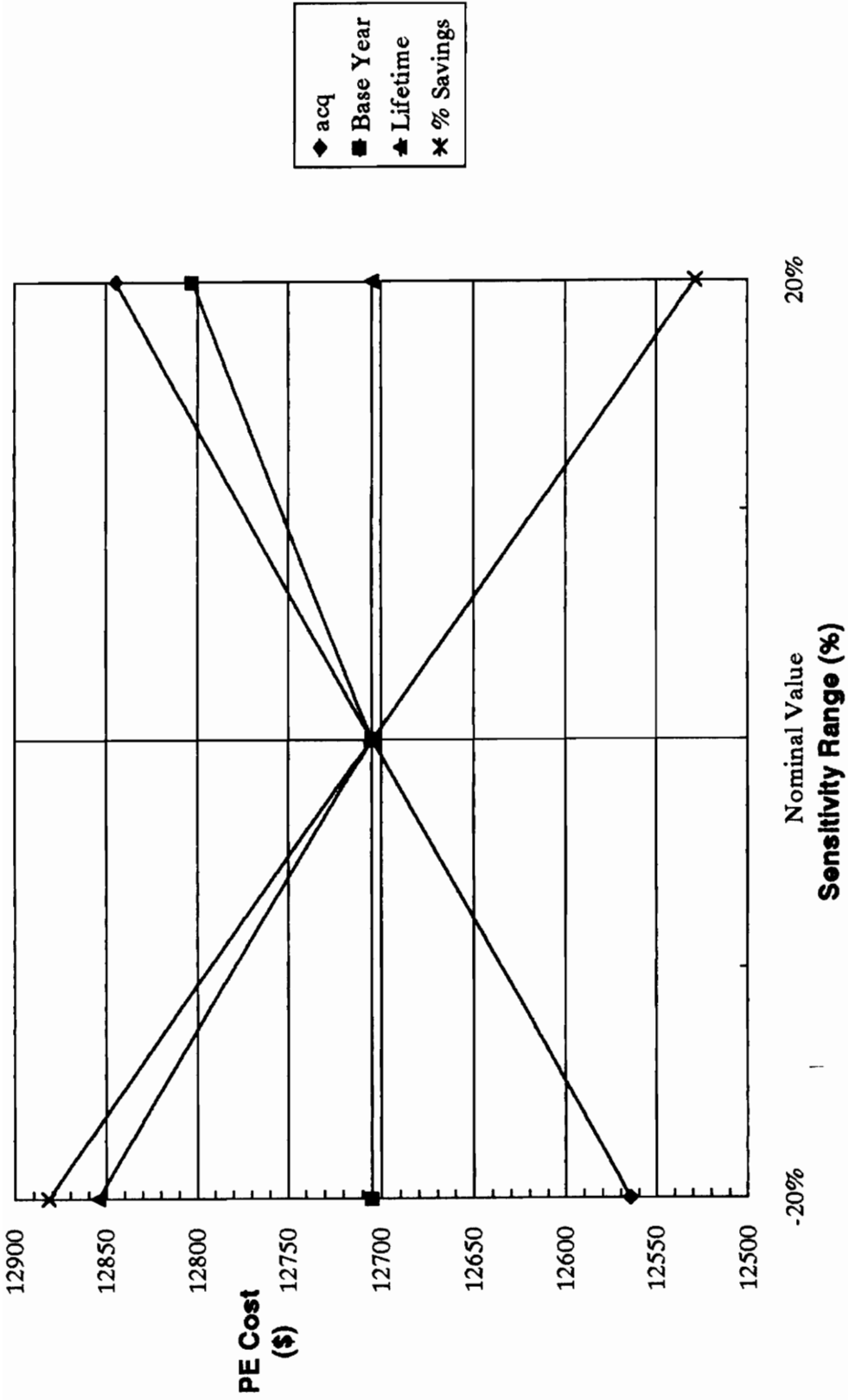


Figure 13: Equivalent LCC for 20% Variations for Bismark, ND Case Study Zone Control Option

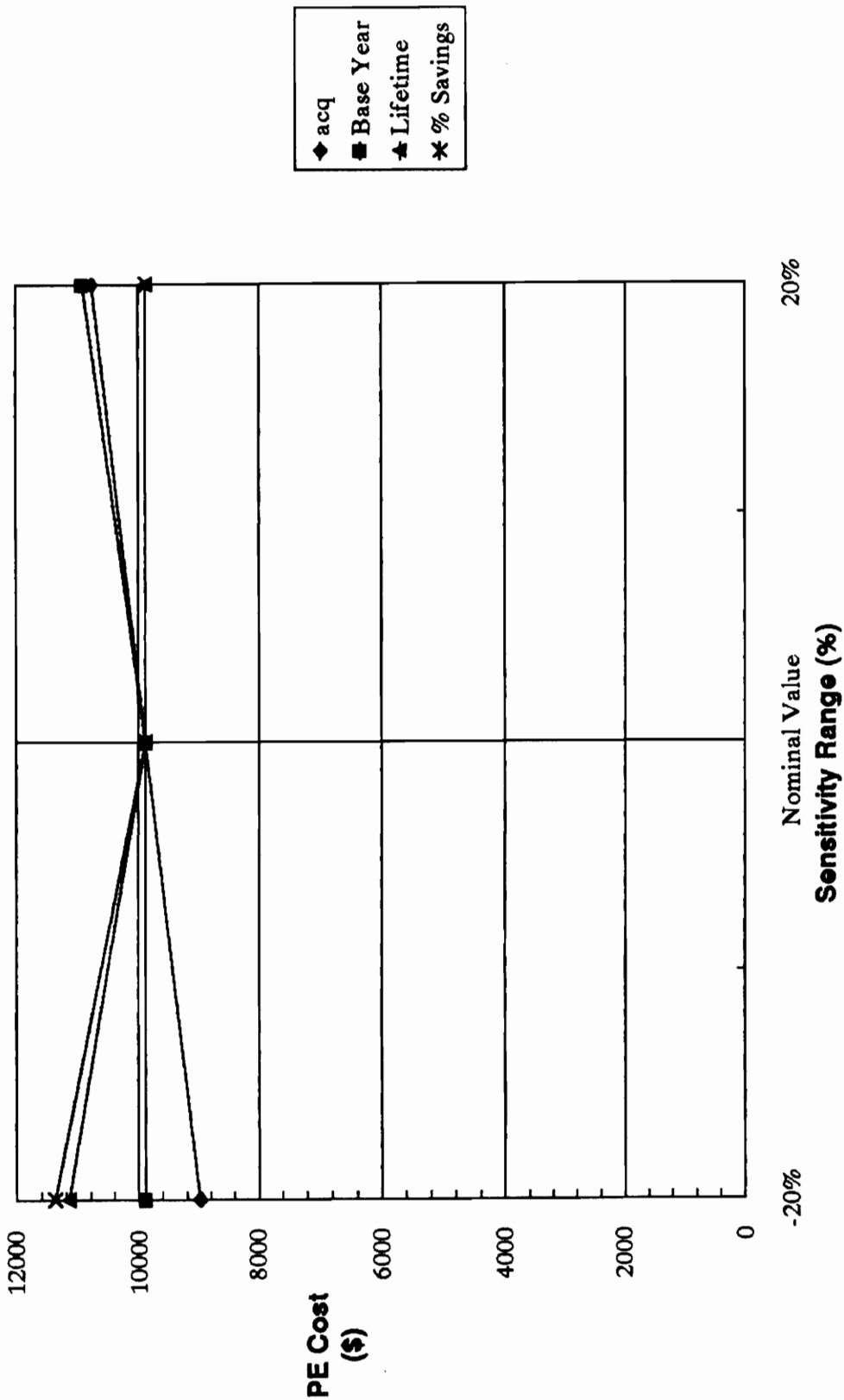


Figure 14: Equivalent LCC for 20% Variations for Bismark, ND Case Study Superinsulation Option

Table 10: PE LCC vs. Interest and Savings for Bismark, ND Case Study Zone Control Option

Bismark, ND Case Study, Option 1- Zone Control Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$) as a Function of Percent Savings and Percent Interest											
Savings (%)	Interest (%)										
	10	20	30	40	50	60	70	80	90	100	
10	16,281	14,179	12,484	11,106	9,976	9,040	8,260	7,604	7,048	6,574	
20	15,112	13,178	11,619	10,352	9,311	8,451	7,733	7,129	6,618	6,181	
30	13,943	12,178	10,754	9,597	8,647	7,861	7,206	6,655	6,188	5,789	
40	12,775	11,177	9,889	8,842	7,983	7,272	6,679	6,180	5,758	5,397	
50	11,606	10,177	9,024	8,087	7,319	6,662	6,152	5,706	5,328	5,005	
60	10,437	9,176	8,159	7,333	6,654	6,093	5,625	5,231	4,898	4,613	
70	9,269	8,175	7,294	6,578	5,990	5,503	5,098	4,757	4,467	4,221	
80	8,100	7,175	6,429	5,823	5,326	4,914	4,571	4,282	4,037	3,829	
90	6,931	6,174	5,564	5,068	4,661	4,325	4,044	3,807	3,607	3,437	
100	5,762	5,174	4,699	4,314	3,997	3,735	3,517	3,333	3,177	3,044	

Table 11: PE LCC vs. Interest and Savings for Bismark, ND Case Study Superinsulation Option

Bismark, ND Case Study, Option 2- Superinsulating Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$) as a Function of Percent Savings and Percent Interest											
Savings (%)	Interest (%)										
	10	20	30	40	50	60	70	80	90	100	
10	23,081	20,979	19,284	17,906	16,776	15,840	15,060	14,404	13,848	13,374	
20	21,912	19,976	18,419	17,152	16,111	15,251	14,533	13,929	13,418	12,981	
30	20,743	18,978	17,554	16,397	15,447	14,661	14,006	13,455	12,988	12,589	
40	19,575	17,977	16,689	15,642	14,783	14,072	13,479	12,980	12,558	12,197	
50	18,406	16,977	15,824	14,867	14,119	13,482	12,952	12,506	12,128	11,805	
60	17,237	15,976	14,959	14,133	13,454	12,893	12,425	12,031	11,698	11,413	
70	16,069	14,975	14,094	13,378	12,790	12,303	11,989	11,557	11,267	11,021	
80	14,900	13,975	13,229	12,623	12,126	11,714	11,371	11,082	10,837	10,629	
90	13,731	12,974	12,364	11,868	11,461	11,125	10,844	10,607	10,407	10,237	
100	12,562	11,974	11,499	11,114	10,797	10,535	10,317	10,133	9,977	9,844	

in Tables 10 and 11 are represented as surface plots in Figures 15 and 16 respectively. The values in Tables 10 and 11 show that both interest and savings have a much greater effect on overall equivalent life-cycle costs than the other input parameters. The combined effect of interest and savings changing together illustrate the magnitude of the impact which is possible as a result of estimation errors. A ten percent increase in either savings or interest rates causes a seven to nine percent change in overall life-cycle cost for the zone control option. A combined increase of ten percent for both savings and interest reduces the overall equivalent life-cycle costs by more than nineteen percent. A similar combined error for the superinsulating option results in a thirteen percent decrease, which is a difference of over \$3,000.

Decision Evaluation Display

The decision evaluation display shown in Figure 9 is adapted to the Bismark, ND Case Study using the relevant performance and evaluation criteria. Values for the existing system are established as baseline performance and effectiveness measure thresholds. The zone control system improves comfort dramatically by eliminating discomfort zones. The ease of use of the zone control option is dependent upon the type of thermostat chosen and any additional room sensors such as individual room thermostats, occupancy detection devices and method of zone selection. The zone control system

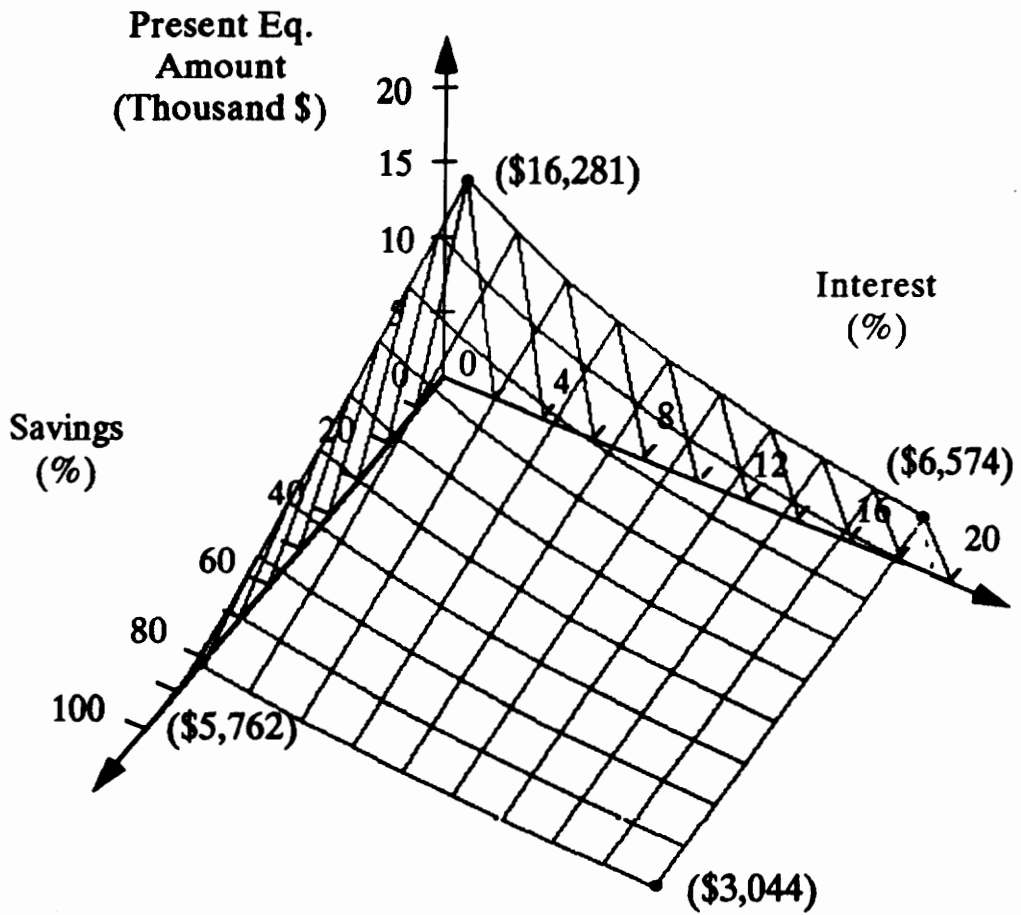


Figure 15: Surface Plot of PE LCC vs. Interest and Savings for Bismark, ND Case Study Zone Control Option

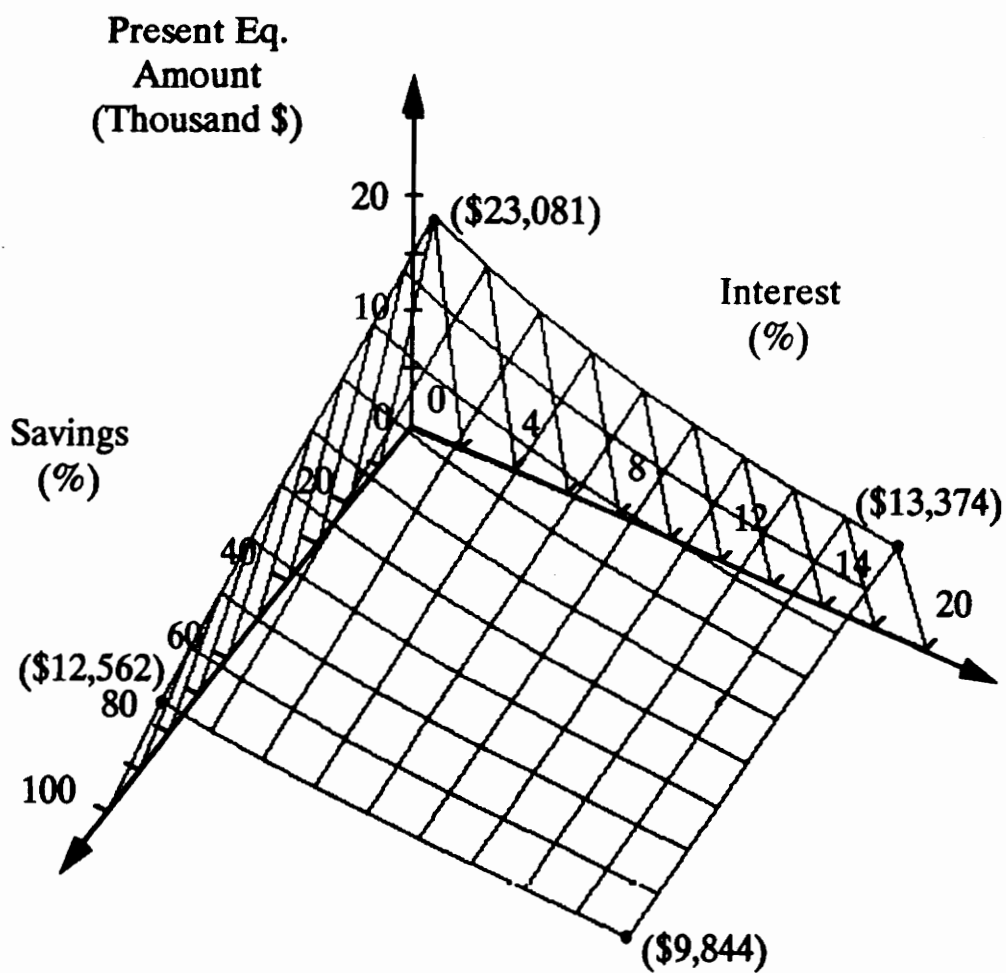


Figure 16: Surface Plot of PE LCC vs. Interest and Savings for Bismark, ND Case Study Superinsulation Option

may require frequent manual adjustments and control inputs. The ease of use for the ZCS is slightly less compared to the existing HVAC control system depending upon the automated features offered with the system. A value equivalent to the expected value of predicted energy savings is used for the energy conservation measurement. The completed decision evaluation matrix is shown comparing both options with the baseline system in Figure 17.

Although both alternatives save energy over the existing HVAC system, the Superinsulation option is the clear winner. The Zone Control System does not achieve the required rate of return, and the energy savings are marginal. The strong point of the ZCS is the increased comfort that is possible.

Despite a very high initial cost, the expected savings of eighty-five percent results in substantially lower energy costs and high rate of return, with no loss in comfort or convenience. Based on an evaluation using life-cycle costs and utilization of multiple criteria, the Superinsulating option results in the best performance and greatest economic benefit for the Bismark, North Dakota Case Study.

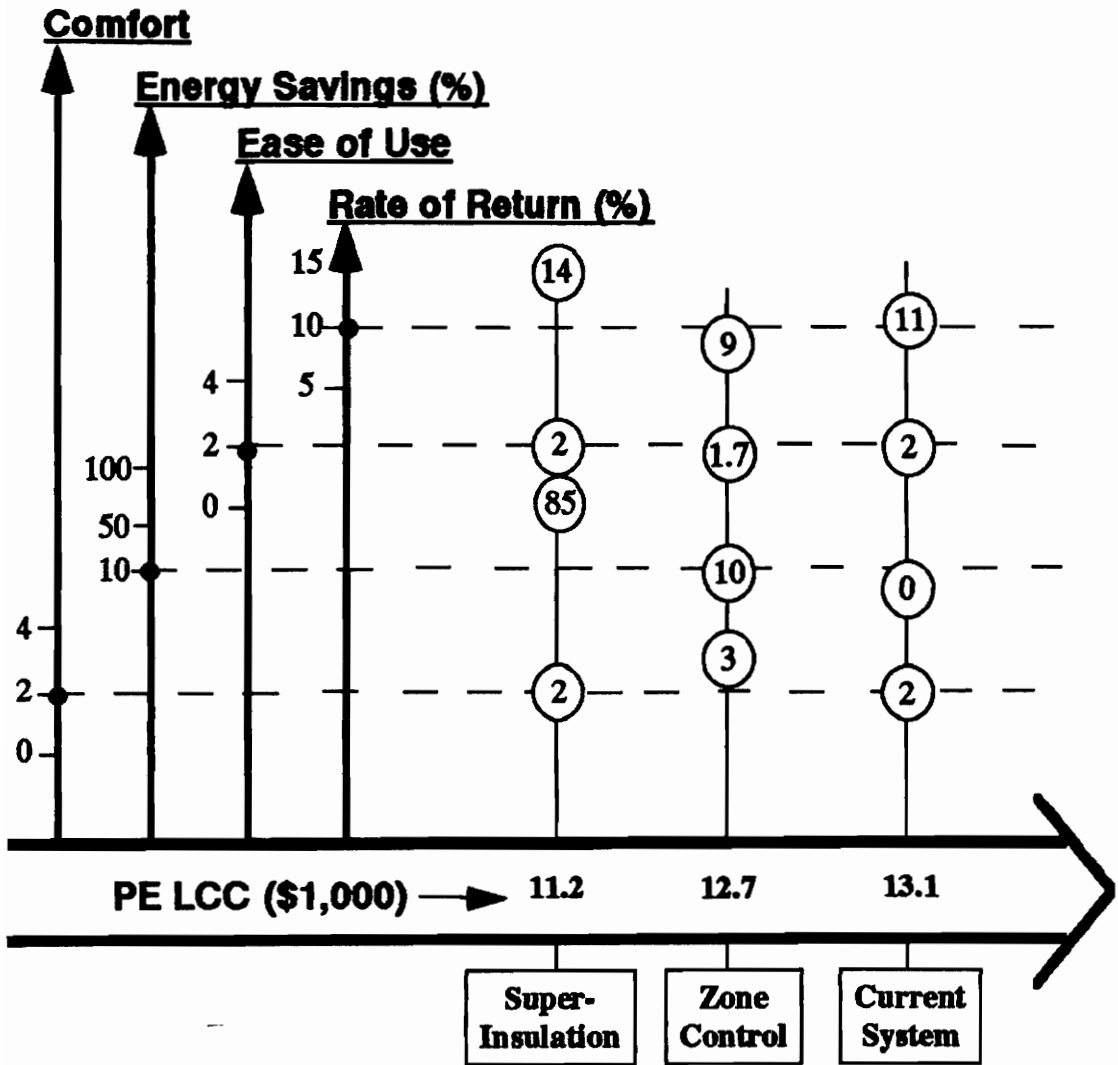


Figure 17: Decision Evaluation Display for Bismark, ND Case Study

Chapter 8: Blacksburg, VA Case Study

The city of Blacksburg, Virginia is selected for the second case study due to the relatively mild climate existing throughout most of the year. A medium sized house is again used as the basis for an evaluation to determine the impact of a different climate on selecting an energy saving option.

STEP 1- FEASIBILITY STUDY

Existing Needs

Blacksburg, VA is located in part of the Great Valley between the Appalachian Mountains and the Eastern Seaboard. The climate is relatively mild and comfortable. The mountain barrier moderates cold air from the north. The elevation of the city usually produces cool summer nights. Summer temperatures rarely exceed ninety degrees Fahrenheit. Winter temperatures are below freezing on average for ninety-two days of the year. Summer conditions exist from early May through September. The number of heating-cooling degree days for Blacksburg averages 5,337.

The energy cost inputs for the economic evaluation are determined in the same manner as for the Bismark, ND Case Study. Data from the Places Rated Almanac for Bismark, ND indicates that annual energy bills average \$756, with approximately \$420 used for heating and cooling purposes. The

values are based on a family of four living in a medium sized house.

System Objectives, Options and Constraints

The system objectives and energy saving options evaluated are the same as those evaluated in the Bismark, North Dakota Case Study. Performance and effectiveness measures, project lifetimes, and constraints remain unchanged. The primary difference between the case studies is the amount of heating and cooling required at each location and the subsequent cost of operating an HVAC system.

STEP 2- STRUCTURED ANALYSIS

The schedules and system requirements from the Bismark, ND Case Study apply to the Blacksburg, VA Case Study. The cost breakdown analysis shown in Table 12 reflect the difference in energy used.

Identical energy saving alternatives, with the same components, acquisition costs and potential savings are evaluated. The energy costs of the existing system experience a three percent cost growth above inflation.

The money flow diagrams for the undiscounted yearly costs in Table 12 are shown in Figure 18.

STEP 3- SYSTEM SELECTION

The inputs used in the Blacksburg, VA Case Study

Table 12: Cost Breakdowns for Blacksburg, VA Case Study

Year	Energy Saving Alternatives and Cost Items					
	Current System	Cost (\$)	Zone Control	Cost (\$)	Superinsulation	Cost (\$)
0	Energy Use	567	R&D (by Owner) Acquisition: - Control Module - \$6/Temp Sensors @ 7 Zones - \$40/Dampers @ 7 Zones - Wiring - Additional Ducting - Pressure Control Installation (by Owner) Maintenance Contract (15 yrs) Energy Use (Before Completion)	0 78 42 280 25 50 75 0 150 567	R&D (by Owner) Eng. Data (Plans) Acquisition: - Plastic Vapor Barrier - Additional Ext'r Wall Insulation - Floor Insulation - Additional Ceiling Insulation - High Thermal Efficiency Windows - Remodeling Mat'l and Paint - Sealant, Caulking, Tape, etc. - Air-Air Heat Exchanger Installation \$22/hr @ 100 hrs Maintenance Contract (15 yrs) Energy Use (Before Completion)	0 175 75 100 200 200 800 300 100 200 2,200 150 567
1	Energy Use [567 + (567 * 3%)]	584	Energy Use [584 - (584*10%)]	541	Energy Use [584 - (584*85%)]	216
2	Energy Use	602	Energy Use	557	Energy Use	223
3	Energy Use	620	Energy Use	574	Energy Use	229
4	Energy Use	638	Energy Use	591	Energy Use	236
5	Energy Use	657	Energy Use	609	Energy Use	243
6	Energy Use	677	Energy Use	627	Energy Use	251
7	Energy Use	697	Energy Use	646	Energy Use	258
8	Energy Use	718	Energy Use	665	Energy Use	266
9	Energy Use	740	Energy Use	685	Energy Use	274
10	Energy Use	762	Energy Use	706	Energy Use	282
11	Energy Use	785	Energy Use	727	Energy Use	291
12	Energy Use	808	Energy Use	749	Energy Use	299
13	Energy Use	833	Energy Use	771	Energy Use	308
14	Energy Use	858	Energy Use	794	Energy Use	318
15	Energy Use	883	Energy Use	818	Energy Use	327

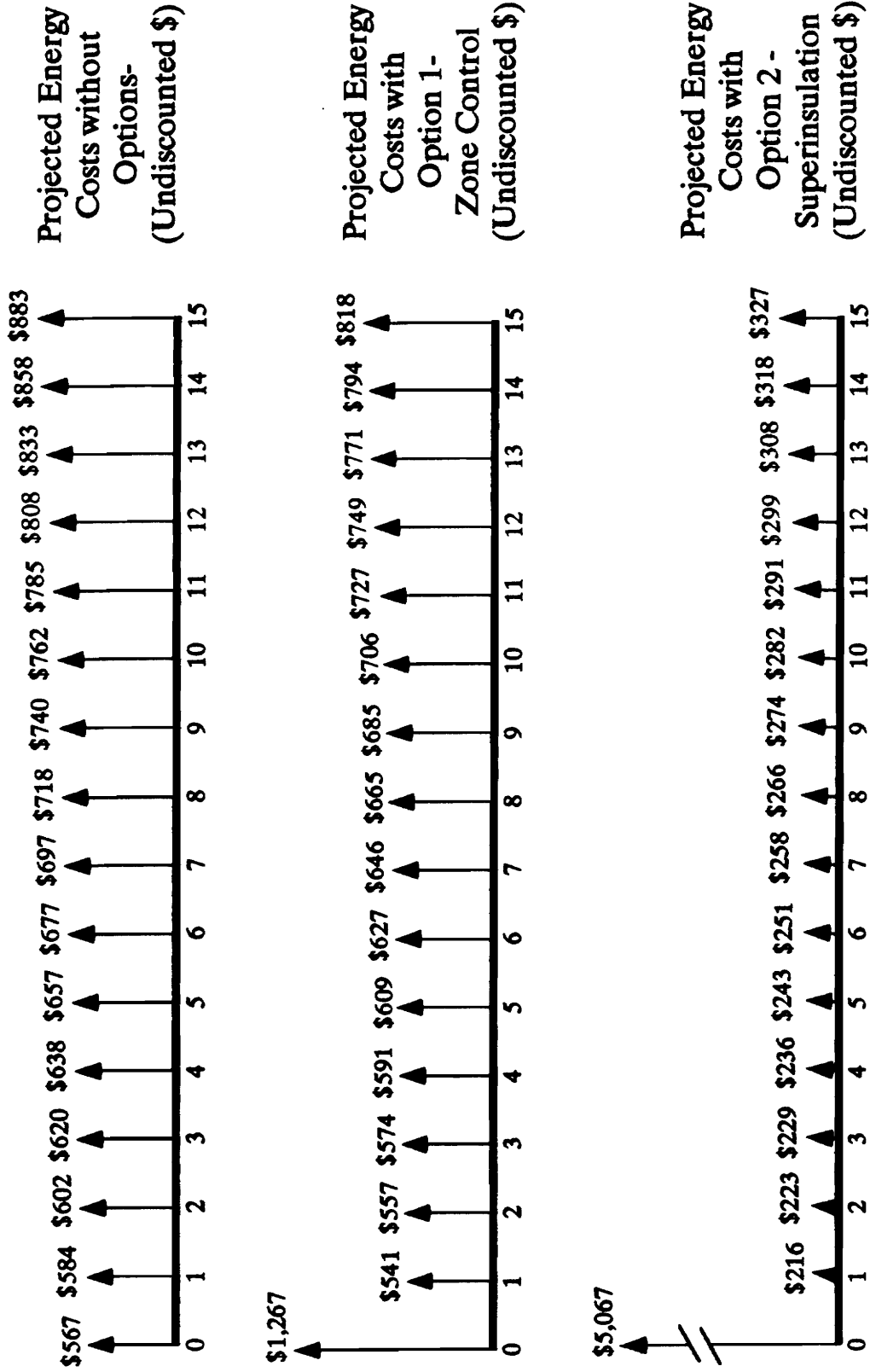


Figure 18: Money Flow Diagrams for Blacksburg, Virginia Case Study

computer economic evaluation are summarized in Table 13. The inputs are consistent with the Bismark, ND Case Study.

The lower energy costs for the Blacksburg, VA area result in less differentiation between the zone control option and the baseline current HVAC system. The impact of the difference in acquisition costs between the Zone Control System and the Superinsulating options becomes more exaggerated.

Cumulative equivalent life-cycle costs for both options are summarized in Table 14. Both options are not economically desirable based on the total life-cycle cost after fifteen years. The values in Table 14 are plotted as line graphs in Figures 19 and 20. Figure 19 depicts the expected values over fifteen years and shows graphically the payback periods at the crossovers of the option costs with the costs of the do-nothing option. The lines in Figure 20 show the equivalent costs over the lowest and highest potential saving ranges.

The internal rates-of-return and payback periods for both options exceeds the fifteen year evaluation lifetime as shown in Table 15. The low rates-of-return indicate that both options are a poor economic investment compared to the estimated interest rate.

The single variable sensitivity analysis results are plotted in Figures 21 and 22 for the zone control option and the superinsulating option, respectively. The primary influence apart from the discount rate is again the percent savings, followed by the lifetime and the acquisition cost. The economic

Table 13: Inputs for Blacksburg, Virginia Case Study Evaluation

Blacksburg, VA Case Study		
INPUT PARAMETER	OPTION 1- ZONE CONTROL	OPTION 2- SUPERINSULATING
# Years Evaluated	15 years	15 years
Annual Inflation Rate	5 %	5 %
Annual Interest Rate	11 %	11 %
Annual Total Energy Cost	\$567.00	\$567.00
Annual Energy Growth Rate	3 %	3 %
Annual HVAC Costs	\$420.00	\$420.00
Acquisition Cost of Option	\$700.00	\$4,500.00
Range of Savings from Option	5 to 25 % of Heating/Cooling	70 to 90 % of Heating/Cooling
Cost Increase due to Option	0	0
Expected Value of Savings	10 %	85 %
Year # of Acquisition	year 0	year 0
Useful Lifetime of Option	15 years	15 years
Percent Uncertainty for Sensitivity Analysis	20 %	20 %

Table 14: Life-Cycle Costs for Blacksburg, Virginia Case Study

Blacksburg, VA Case Study- Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$)							
Year	With No Option	Option 1- Zone Control			Option 2- Superinsulating		
		Low Savings	Expect'd Value	High Savings	Low Savings	Expect'd Value	High Savings
0	567	1,267	1,267	1,267	5,067	5,067	5,067
1	1,119	1,799	1,779	1,717	5,333	5,272	5,251
2	1,658	2,317	2,277	2,156	5,592	5,471	5,431
3	2,182	2,822	2,762	2,583	5,845	5,665	5,605
4	2,693	3,314	3,236	2,999	6,091	5,854	5,776
5	3,191	3,794	3,697	3,405	6,330	6,039	5,942
6	3,676	4,261	4,146	3,800	6,564	6,218	6,103
7	4,149	4,716	4,583	4,185	6,791	6,394	6,261
8	4,609	5,159	5,010	4,561	7,013	6,564	6,414
9	5,058	5,591	5,425	4,926	7,229	6,730	6,564
10	5,495	6,012	5,830	5,282	7,440	6,892	6,710
11	5,921	6,423	6,224	5,629	7,645	7,050	6,852
12	6,336	6,822	6,608	5,968	7,845	7,204	6,990
13	6,740	7,212	6,983	6,297	8,039	7,353	7,125
14	7,134	7,591	7,348	6,618	8,229	7,499	7,256
15	7,518	7,960	7,703	6,931	8,414	7,641	7,384

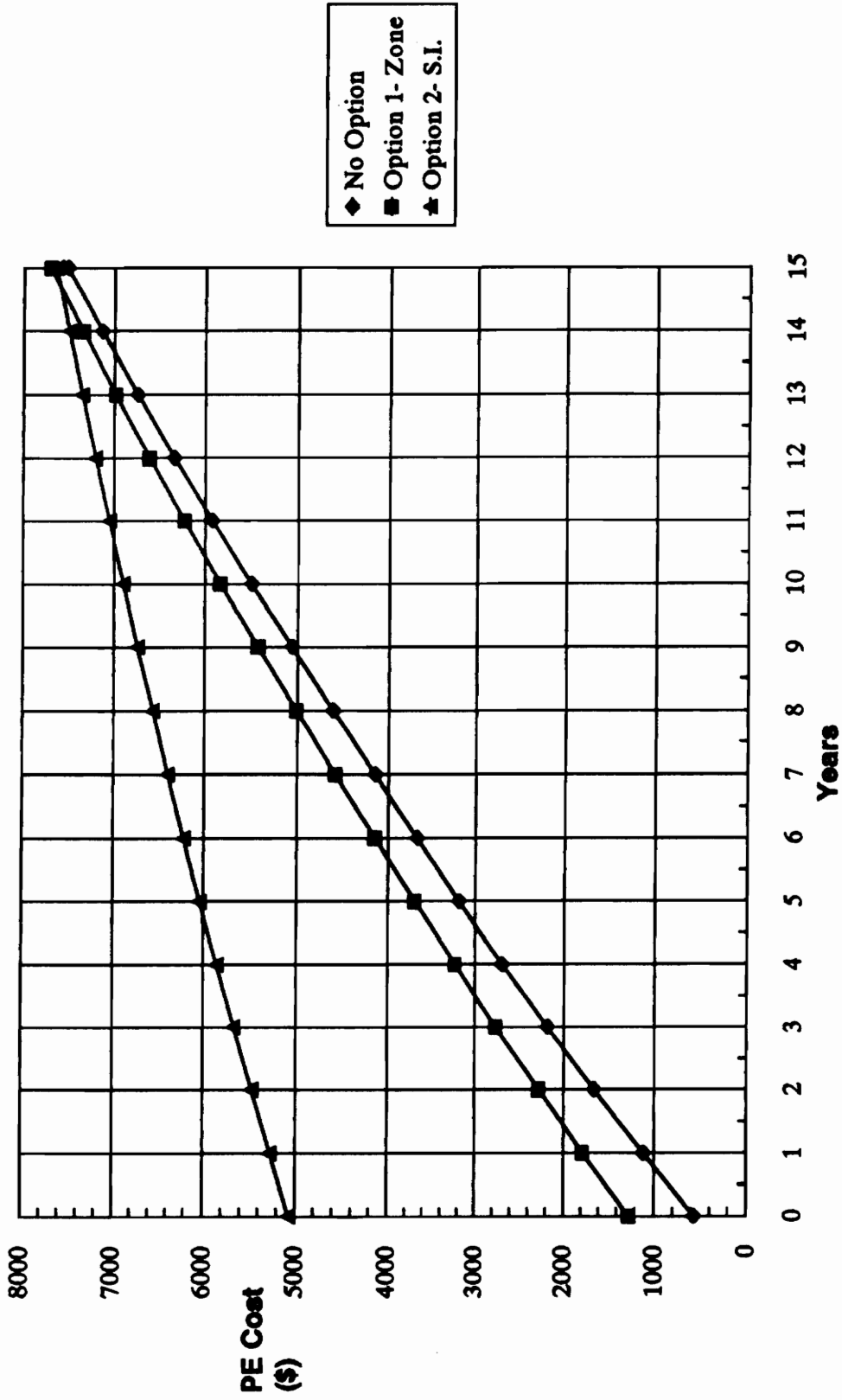


Figure 19: Plot of P. E. Life-Cycle Costs for Blacksburg, VA Case Study

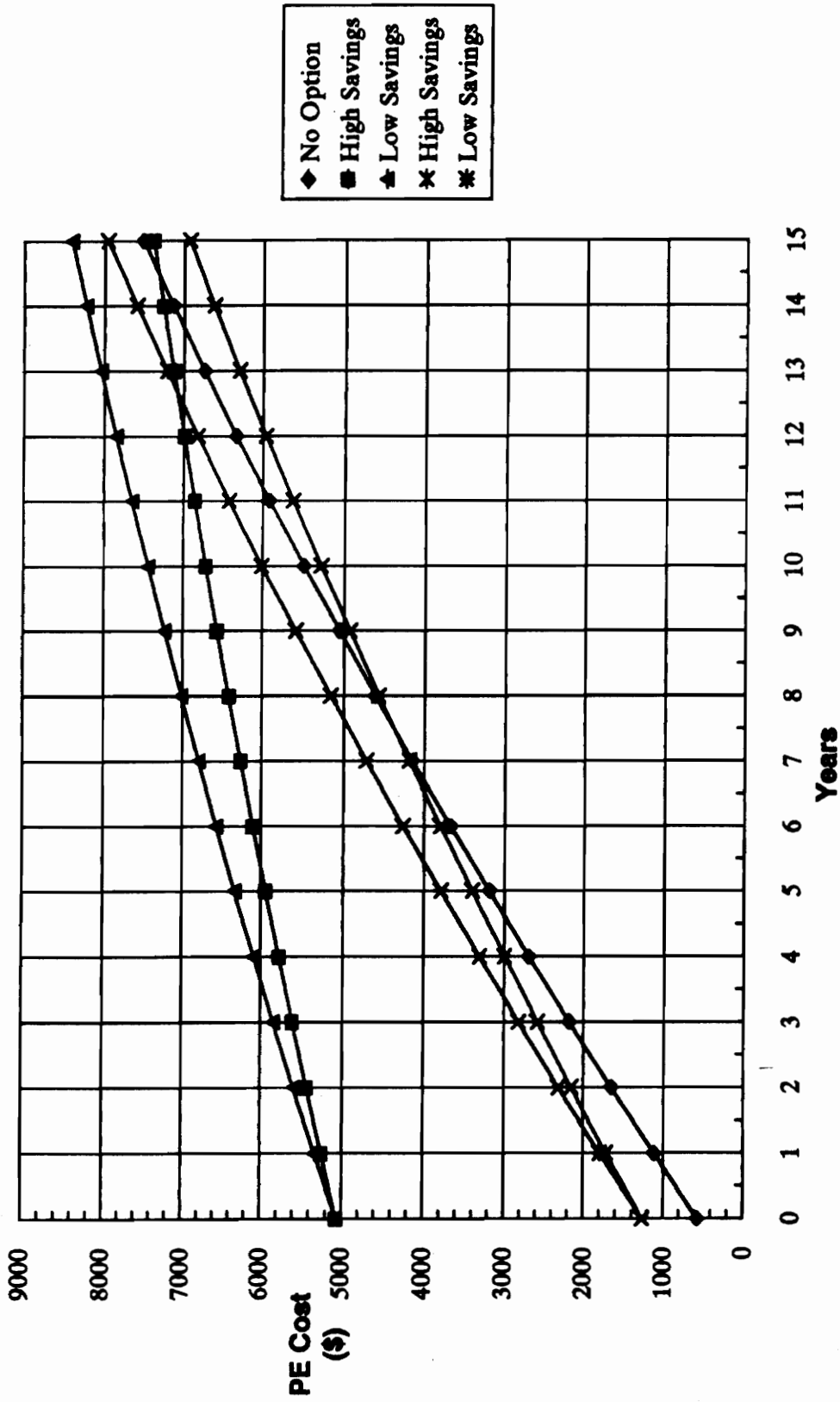


Figure 20: Plot of P.E. Life-Cycle Cost Ranges for Blacksburg, VA Case Study

Table 15: Rates-of-Return and Payback for Blacksburg, VA Case Study

Blacksburg, VA Case Study- Economic Evaluation Indicators						
Economic Indicator	Option 1- Zone Control			Option 2- Superinsulating		
	Low Savings	Expect'd Value	High Savings	Low Savings	Expect'd Value	High Savings
Rate of Return	-6 %	2 %	16 %	3 %	5 %	6 %
Payback	>15 yrs.	>15 yrs.	7 yrs.	>15 yrs.	>15 yrs.	14 yrs.

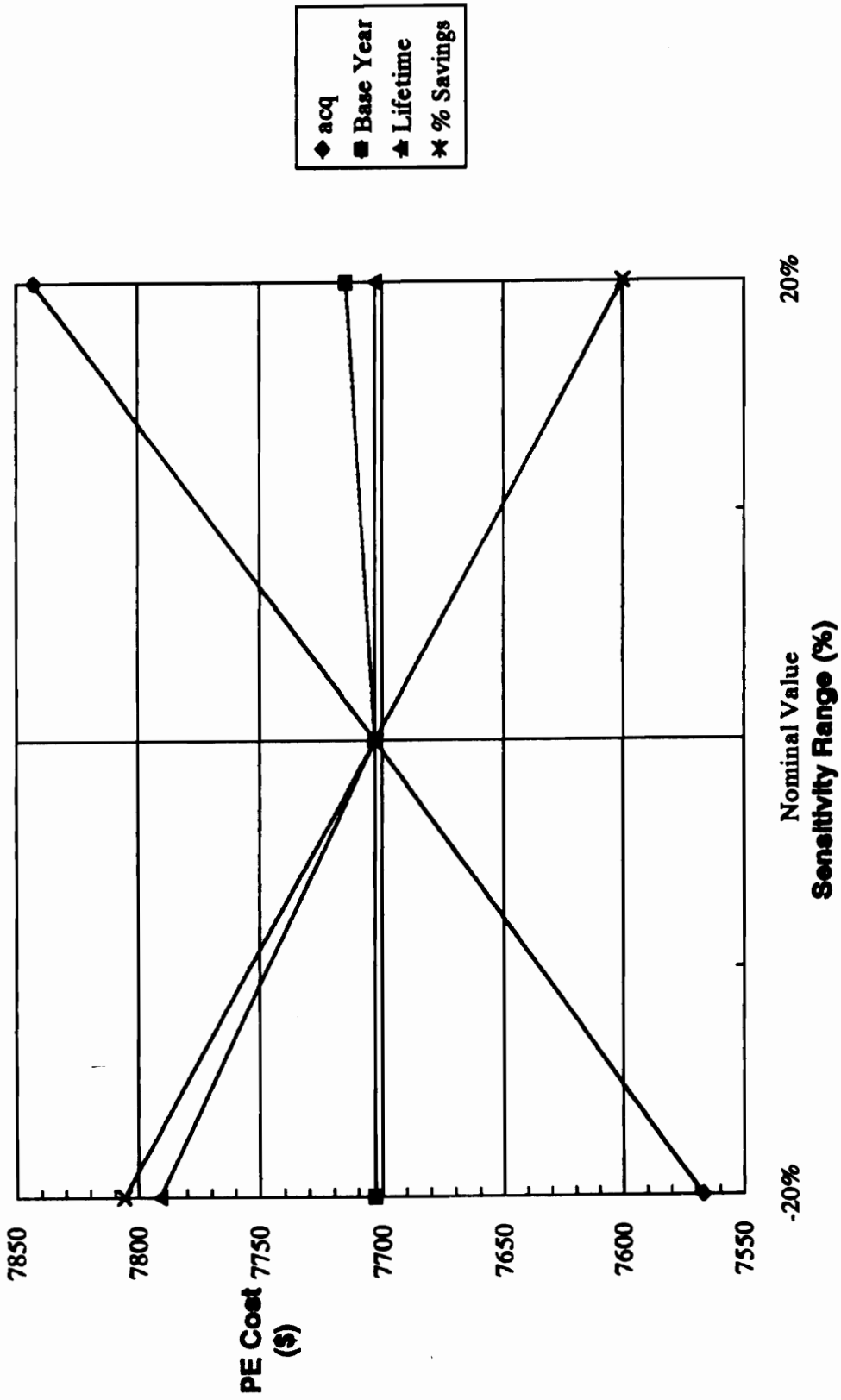


Figure 21: Equivalent LCC for 20% Variations for Blacksburg, VA Case Study Zone Control Option

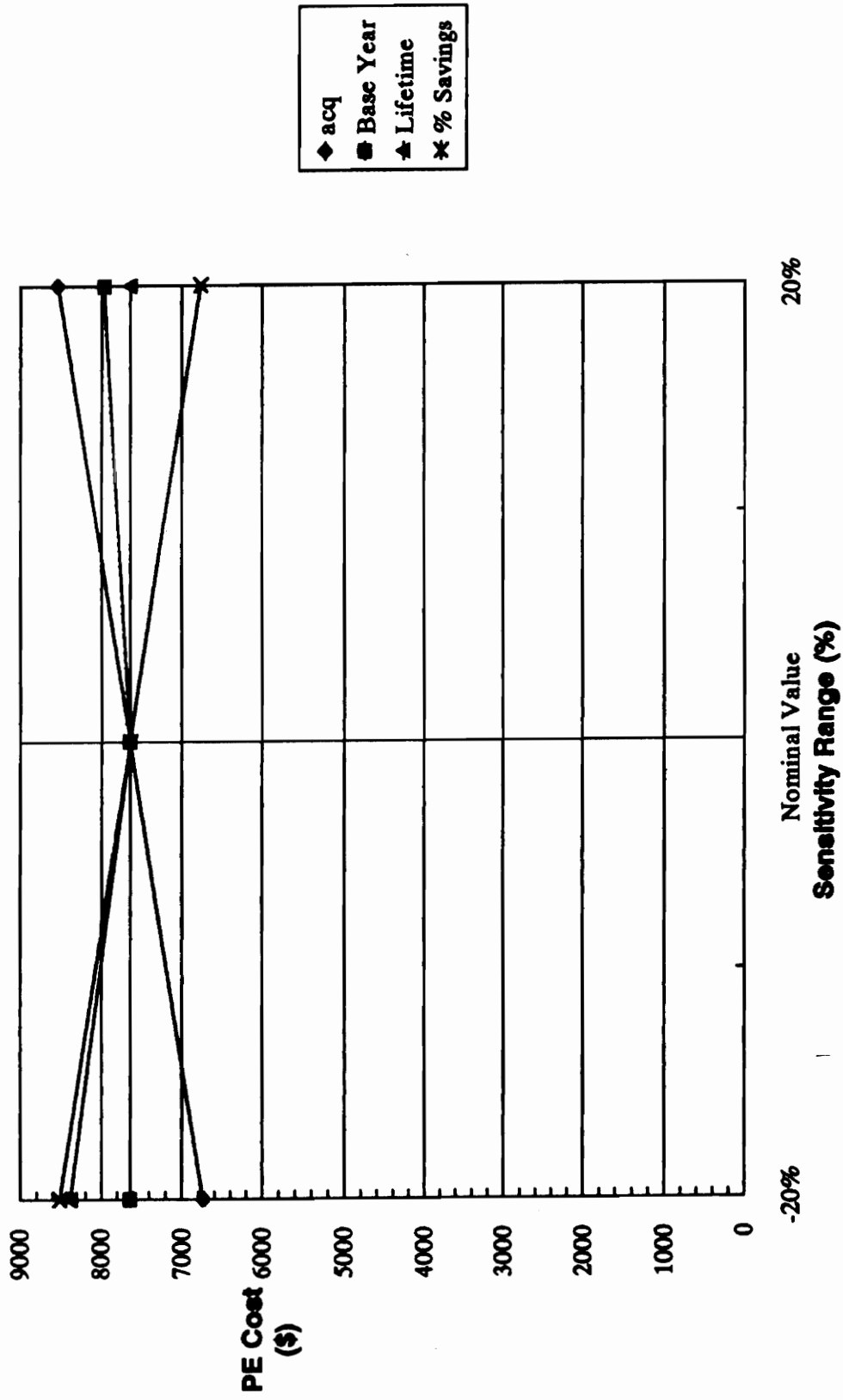


Figure 22: P.E. LCC for 20% Variations for Blacksburg, VA Case Study Superinsulation Option

evaluation is not sensitive to errors of that magnitude occurring in single variables.

The results of jointly varying both the interest rate and percent savings are summarized in Tables 16 and 17. The values in Tables 16 and 17 are represented as surface plots in Figures 23 and 24 respectively. The values in Tables 16 and 17 show that both interest and savings again have a much greater effect on overall equivalent life-cycle costs than the other input parameters.

Decision Evaluation Display

The decision evaluation display shown in Figure 7 is adapted to the Blacksburg, VA Case Study using the relevant performance and evaluation criteria. Values for the existing system are again used as baseline performance and effectiveness measure thresholds. Zone control and superinsulating performance and effectiveness evaluation criteria are the same as those used for the Bismark, ND Case Study. The completed decision evaluation matrix is shown comparing both options with the baseline system in Figure 25. _

The energy saving alternatives, while saving a substantial amount of energy, are less desirable than the current system in terms of overall performance and life-cycle cost. The expenses of operating the HVAC in the Blacksburg, VA area are not sufficient to warrant either of the two options at this time. The rates of return, life_cycle costs and ease of use of the options

Table 16: PE LCC vs. Interest and Savings for Blacksburg, VA Case Study Zone Control Option

Blacksburg, VA Case Study, Option 1- Zone Control Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$) as a Function of Percent Savings and Percent Interest										
Savings (%)	Interest (%)									
	10	20	30	40	50	60	70	80	90	100
10	9,789	8,563	7,574	6,770	6,111	5,565	5,110	4,727	4,403	4,126
20	9,107	7,979	7,070	6,330	5,723	5,221	4,802	4,450	4,152	3,867
30	8,425	7,395	6,565	5,890	5,336	4,877	4,495	4,174	3,901	3,669
40	7,744	6,812	6,060	5,450	4,948	4,534	4,188	3,897	3,650	3,440
50	7,062	6,228	5,556	5,009	4,561	4,190	3,880	3,620	3,399	3,211
60	6,380	5,644	5,051	4,569	4,173	3,846	3,573	3,343	3,149	2,983
70	5,698	5,061	4,547	4,129	3,786	3,502	3,265	3,066	2,898	2,754
80	5,017	4,477	4,042	3,688	3,398	3,158	2,958	2,789	2,647	2,525
90	4,335	3,893	3,538	3,248	3,011	2,804	2,650	2,513	2,396	2,296
100	3,653	3,310	3,033	2,808	2,623	2,470	2,343	2,236	2,145	2,068

Table 17: PE LCC vs. Interest and Savings for Blacksburg, VA Case Study Superinsulating Option

Blacksburg, VA Case Study, Option 2- Superinsulating Yearly Accumulated Eq. Life-Cycle Cost (P.E. \$) as a Function of Percent Savings and Percent Interest											
Savings (%)	Interest (%)										100
	10	20	30	40	50	60	70	80	90	100	
10	13,589	12,363	11,374	10,570	9,911	9,365	8,910	8,527	8,203	7,926	
20	12,907	11,779	10,870	10,130	9,523	9,021	8,602	8,250	7,952	7,697	
30	12,225	11,195	10,365	9,690	9,136	8,677	8,295	7,974	7,701	7,469	
40	11,544	10,612	9,860	9,250	8,748	8,334	7,988	7,697	7,450	7,240	
50	10,862	10,028	9,356	8,809	8,361	7,990	7,680	7,420	7,199	7,011	
60	10,180	9,444	8,851	8,369	7,973	7,646	7,373	7,143	6,949	6,783	
70	9,498	8,861	8,347	7,929	7,586	7,302	7,065	6,866	6,698	6,554	
80	8,817	8,277	7,842	7,488	7,198	6,958	6,758	6,589	6,447	6,325	
90	8,135	7,693	7,338	7,048	6,811	6,614	6,450	6,303	6,196	6,096	
100	7,453	7,110	6,833	6,608	6,423	6,270	6,143	6,036	5,945	5,868	

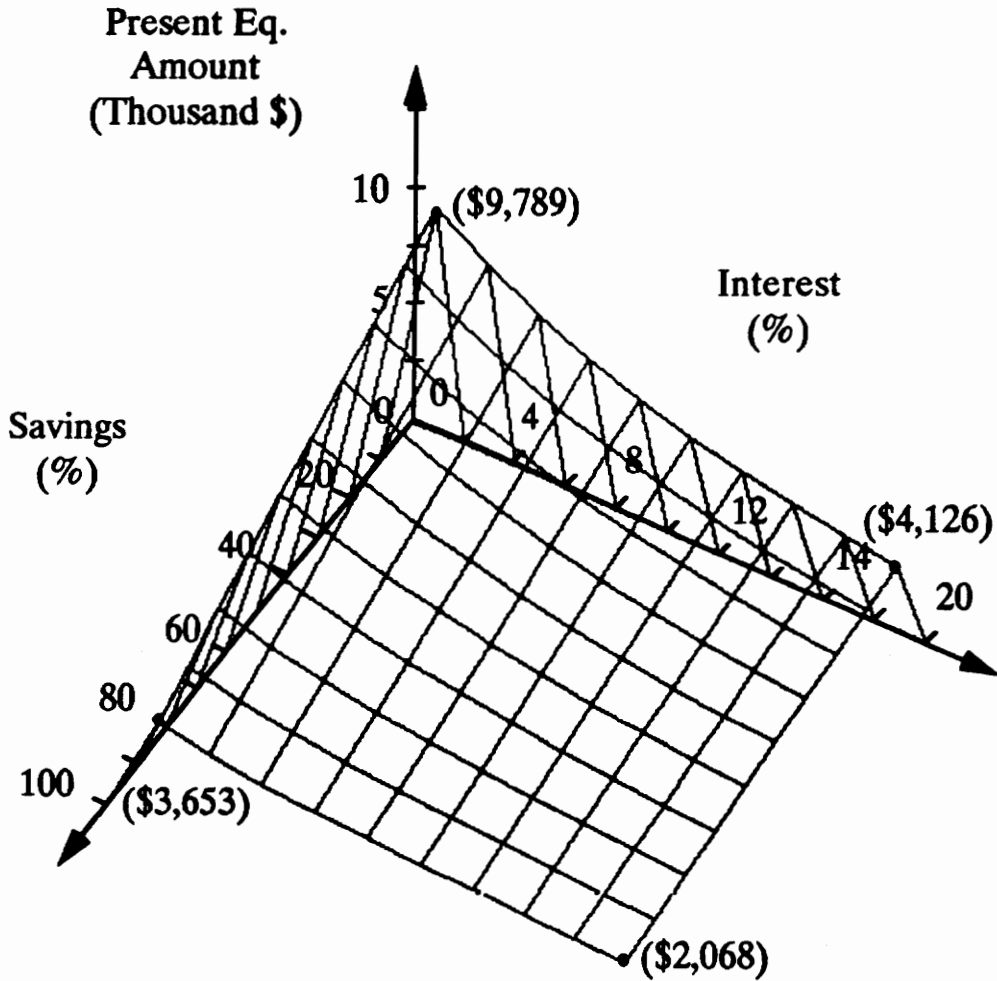


Figure 23: Surface Plot of PE LCC vs. Interest and Savings for Blacksburg, VA Case Study Zone Control Option

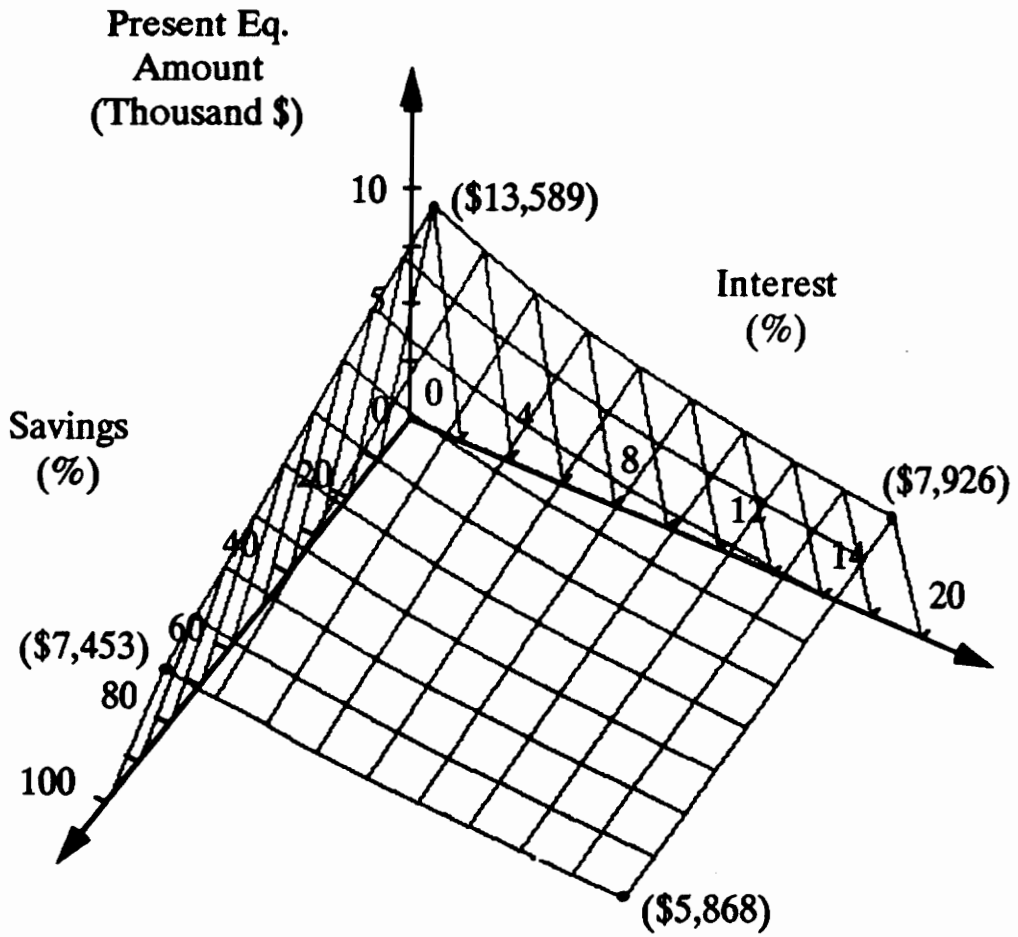


Figure 24: Surface Plot of PE LCC vs. Interest and Savings for Blacksburg, VA Case Study Superinsulating Option

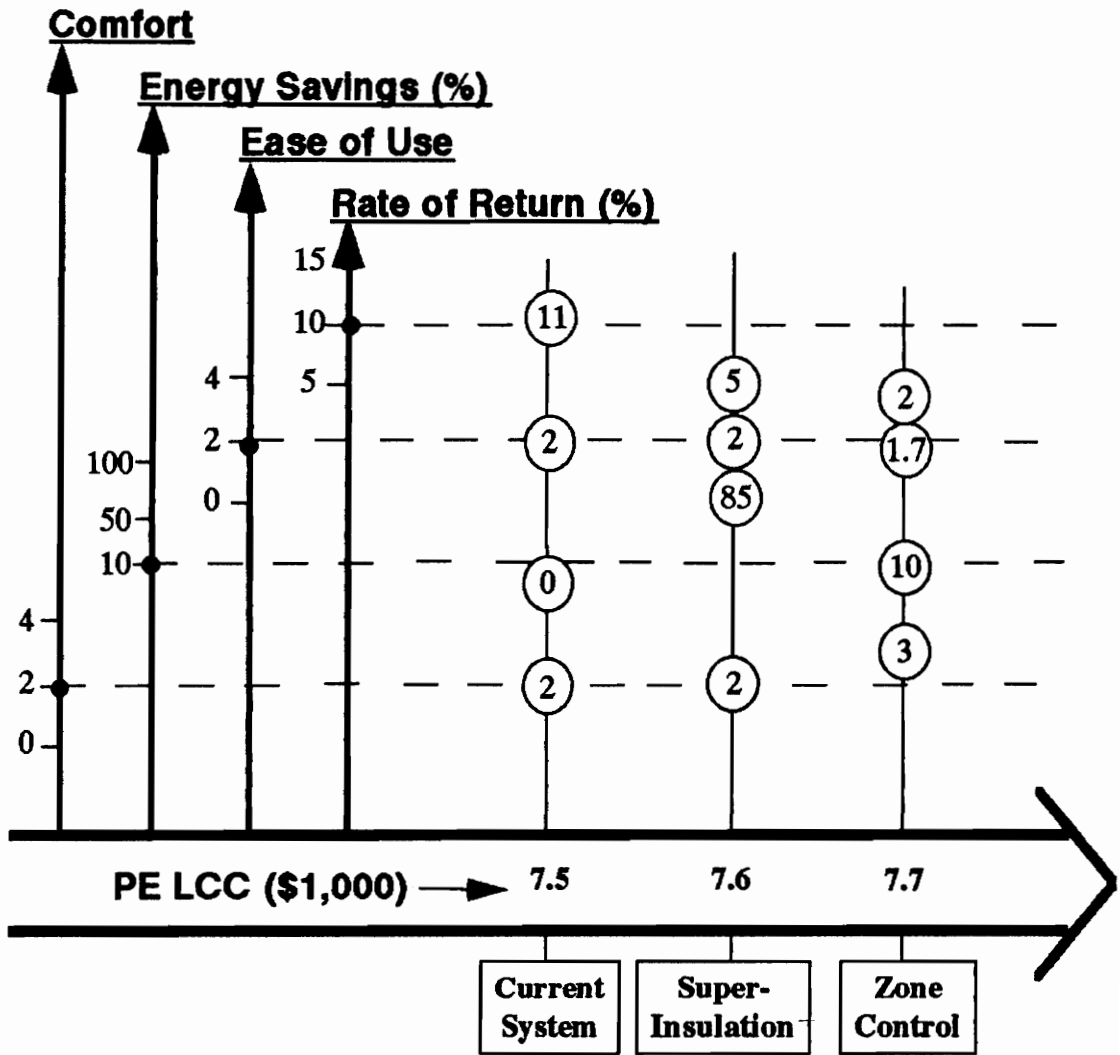


Figure 25: Decision Evaluation Display for Blacksburg, VA Case Study

are less than or equal to those of the current system. Although the options achieve benefits in terms of comfort and energy savings, the current system remains the most desirable option when considering both performance and cost issues.

Chapter 9: Summary and Conclusions

SUMMARY

An energy evaluation methodology provides a logical approach to effectively evaluate energy saving alternatives based on both economic and performance criteria. The Feasibility Study develops the need and limitations for an energy saving alternative. The Structured Analysis phase determines project schedules, requirements and costs. The System Selection phase uses economic evaluation techniques and cost effectiveness principles to determine the best alternative using an integrated decision evaluation display with multiple criteria.

Methodology

The methodology begins with an accurate assessment of existing needs according to energy use through monitoring energy consumption patterns and an energy audit of the energy conservation characteristics of the structure. The results of the collected energy use data serve to identify high cost and excessive energy consumption areas that are candidates for energy conservation improvement measures. The tools for an economic evaluation of the equivalent life-cycle costs are presented to determine the overall costs and benefits of energy conservation options. Sensitivity analysis of the impact of estimation errors for key variables is performed to identify

critical evaluation parameters.

Computer Aided Evaluation

A comprehensive computer program based on the MathCAD2.5 mathematical calculating software package for IBM PC-AT's and compatibles is offered as an aid in the economic evaluation of options. Finally, a technique for jointly evaluating multiple criteria is presented that includes both performance and cost factors. Other tools include design-to-cost analysis techniques and an efficient HVAC operating program and duty cycle.

CASE STUDY RESULTS

The two Case Studies show the value of an accurate economic assessment and consideration of multiple criteria when comparing alternatives. The higher energy costs for the Bismark, ND area result in more favorable economic assessments of both options than the Blacksburg, VA Case Study. The Zone Control System, despite the relatively low acquisition costs and fair amount of energy savings, proves to be less desirable than using the unmodified current HVAC system. Neither option proved desirable for Blacksburg, VA, primarily due to the lower energy use predicted there.

The use of an orderly evaluation methodology allows the determination of decision reversal points, at which an undesirable option becomes the preferred option. Decision

reversal is demonstrated by using both Case Studies and showing at which point the combination of acquisition cost, project lifetime, projected energy savings and/or amount of energy consumed by an existing system causes a less desirable option in one case to become the preferred option.

FUTURE APPLICATIONS

The analysis and evaluation techniques presented supports a wide range of economic and performance analysis in addition to HVAC and related energy systems. The methodology provides the fundamental components that will allow the development and large scale distribution of an operational evaluation and optimization system suitable for residential, industrial and government use. The proposed methodology is suitable for applications in water conservation, pollution control measures, and other enterprises which involve both cost and performance factors.

Alternate Methodology Uses

The energy conservation methodology may be expanded to incorporate alternative energy sources such as solar power [4], electricity generating wind turbines, photovoltaic panels, energy storage methods [14], new fuels and new power generation methods. The energy use conservation principles may be integrated into an overall conservation, economy, safety, comfort and security control system.

The economic evaluation principles may be readily applied to the evaluation of original equipment installations in new structures for a detailed life-cycle cost evaluation, giving buyers the ability to choose either the lowest acquisition cost approach or a cost-effective life-cycle alternative. The economic analysis methods may be expanded to include the effects of taxation, interdependent alternatives, and nonexclusive options. The inclusion of warranty impacts and reliability analysis from specifications supplied by the manufacturer is possible to increase the accuracy of predicted costs and the resulting economic feasibility of energy saving alternatives.

Post-Selection Life-Cycle Stages

The later stages of the system life-cycle which include installation, utilization and retirement phases are as important to an evaluation of energy systems as the selection process. Careful monitoring of actual system performance is necessary to assess both the validity of the evaluation methodology and provide feedback data for future project evaluations. The installation stage may require further planning and modifications to an existing structure in response to unforeseen circumstances. The data and decisions in the evaluation process should be carefully documented to provide important information for feedback into future energy saving evaluations.

Integration with future energy saving projects and modifications and corrective actions after several seasons of

operation must be performed and recorded. Finally, the means of system phaseout or retirement must be considered, in terms of both expenses and project timelines.

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Appendix A

MATHCAD2.5 PROGRAM LISTING

ECONOMIC ASSESSMENT OF HVAC MONEY-SAVING OPTIONS

City := Bismark, ND

Option := Zone Control

INPUTS

INPUT DESCRIPTION

yrs := 15	<-- Number of Years Evaluated
f := .05	<-- Annual Inflation Rate
i := .11	<-- Annual Interest Rate
E := 3658.00	<-- Annual Total Energy Cost
Eg := .03	<-- Annual Energy Growth (Above Inflation)
HVAC := 1045.00	<-- Annual Heating and Cooling Cost
acq := 700	<-- Acquisition Cost of Option
savl := .05	<-- Annual Predicted % Savings- Low
savb := .09	<-- Annual Predicted % Savings- Best Guess
savh := .25	<-- Annual Predicted % Savings- Optimistic
M := 25	<-- Annual Maint. Cost Increase of Option
YRb := 0	<-- Year of Acq. (0=now to yrs.
L := 15	<-- Useful Lifetime of Option
U := .20	<-- % Uncertainty for Sensitivity Analysis

OUTPUTS - Yearly Cumulative Equivalent Life-Cycle Costs

***** - Internal Rate of Return on Investment

- Payback Period

- Single/Joint Sensitivity Analysis

 LCC, RATE OF RETURN AND PAYBACK

$PF(i,n) := (1 + i)^{-n}$: Define Equivalence

$ip(i,g) := \frac{1 + i}{1 + f} - 1$: Define Discount

$i := ip(i,f)$
 $OC := E - HVAC$: Other Energy Costs

$n := 0 \dots yrs$
 $y := 0 \dots yrs$: # of Years Eval
 $x := 1 \dots yrs$

$HVACN := HVAC$: Initialize Arrays
 $OCN := OC$

$HVACN_x := HVACN_{x-1} + [HVACN_{x-1} \cdot Eg]$: Future HVAC Costs

$HC_n := HVACN_n$: Preserve Costs
 : Savings + Maint.
 : Apply Savings

$HVACL_n := HVACN_n + [(n > YRb) \cdot (n \leq L) \cdot M - [HVACN_n \cdot savl]]$
 $HVACB_n := HVACN_n + [(n > YRb) \cdot (n \leq L) \cdot M - [HVACN_n \cdot savb]]$
 $HVACH_n := HVACN_n + [(n > YRb) \cdot (n \leq L) \cdot M - [HVACN_n \cdot savh]]$

$OCN_x := OCN_{x-1} + [OCN_{x-1} \cdot Eg]$: Future Other Costs

$HVACL_{YRb} := HVACL_{YRb} + acq$: Acquisition Cost

$HVACB_{YRb} := HVACB_{YRb} + acq$

$$\text{HVACH}_{\text{YRb}} := \text{HVACH}_{\text{YRb}} + \text{acq}$$

$$\text{HVACN}_n := \text{HVACN}_n + \text{OCN}_n \quad : \text{ Combined Future Energy Costs}$$

$$\text{HVACL}_n := \text{HVACL}_n + \text{OCN}_n$$

$$\text{HVACB}_n := \text{HVACB}_n + \text{OCN}_n$$

$$\text{HVACH}_n := \text{HVACH}_n + \text{OCN}_n \quad \text{MONEY FLOW DIAGRAM VALUES}$$

$$\text{HN}_n := \text{HVACN}_n \quad \text{HB}_n := \text{HVACB}_n \quad : \text{ Preserve MFD Values}$$

$$\text{HL}_n := \text{HVACL}_n \quad \text{HH}_n := \text{HVACH}_n$$

$$\text{HVACN}_n := \text{HVACN}_n \cdot \text{PF}(i,n) \quad : \text{ Apply Equivalence}$$

$$\text{HVACL}_n := \text{HVACL}_n \cdot \text{PF}(i,n)$$

$$\text{HVACB}_n := \text{HVACB}_n \cdot \text{PF}(i,n)$$

$$\text{HVACH}_n := \text{HVACH}_n \cdot \text{PF}(i,n)$$

$$\text{HVACN}_x := \text{HVACN}_x + \text{HVACN}_{x-1} \quad : \text{ Cumulative LC Costs}$$

$$\text{HVACL}_x := \text{HVACL}_x + \text{HVACL}_{x-1}$$

$$\text{HVACB}_x := \text{HVACB}_x + \text{HVACB}_{x-1}$$

$$\text{HVACH}_x := \text{HVACH}_x + \text{HVACH}_{x-1}$$

YEARLY EQ. LC COSTS

ih := 0 ib := 0 il := 0 : Rates of Return
Given

$$\sum_n \left[\begin{array}{c} \text{HN} \\ n \end{array} - \begin{array}{c} \text{HH} \\ n \end{array} \right] \cdot \text{PF}(\text{ih}, n) = 0$$

RORH := find(ih) RORH := RORH (RORH < 10000)

Given

$$\sum_n \left[\begin{array}{c} \text{HN} \\ n \end{array} - \begin{array}{c} \text{HB} \\ n \end{array} \right] \cdot \text{PF}(\text{ib}, n) = 0$$

RORB := find(ib) RORB := RORB (RORB < 10000)

Given

$$\sum_n \left[\begin{array}{c} \text{HN} \\ n \end{array} - \begin{array}{c} \text{HL} \\ n \end{array} \right] \cdot \text{PF}(\text{il}, n) = 0$$

RORL := find(il) RORL := RORL (RORL < 10000)

nl := yrs - 1

nx := 0 ..nl

: Payback Period

PH := HH - HN PB := HB - HN
0 0 0 0 0 0

PL := HL - HN
0 0 0

PH_{nx+1} := until $\left[\begin{array}{c} \text{PH} \\ \text{nx} \end{array} \right], \text{PH}_{\text{nx}} + \left[\begin{array}{c} \text{HH} \\ \text{nx+1} \end{array} - \begin{array}{c} \text{HN} \\ \text{nx+1} \end{array} \right] \cdot \text{PF}(i, \text{nx})$

PB_{nx+1} := until $\left[\begin{array}{c} \text{PB} \\ \text{nx} \end{array} \right], \text{PB}_{\text{nx}} + \left[\begin{array}{c} \text{HB} \\ \text{nx+1} \end{array} - \begin{array}{c} \text{HN} \\ \text{nx+1} \end{array} \right] \cdot \text{PF}(i, \text{nx})$

PL_{nx+1} := until $\left[\begin{array}{c} \text{PL} \\ \text{nx} \end{array} \right], \text{PL}_{\text{nx}} + \left[\begin{array}{c} \text{HL} \\ \text{nx+1} \end{array} - \begin{array}{c} \text{HN} \\ \text{nx+1} \end{array} \right] \cdot \text{PF}(i, \text{nx})$

PBH := last(PH) - 1

PBB := last(PB) - 1

: Test for Valid Solution

PBL := last(PL) - 1

$$PBH := PBH \begin{bmatrix} PH < 0 \\ PBH \end{bmatrix}$$

$$PBB := PBB \begin{bmatrix} PB < 0 \\ PBB \end{bmatrix}$$

$$PBL := PBL \begin{bmatrix} PL < 0 \\ PBL \end{bmatrix}$$

Sensitivity Analysis

$$\text{var} := \begin{bmatrix} 1 - U \\ 1 \\ 1 + U \end{bmatrix} \quad : \text{Uncertainty Ranges}$$

$$r := 0 \dots 2$$

$$\text{acqv} := \text{acq} \cdot \text{var} \quad : \text{Variable Ranges}$$

$$Mv := M \cdot \text{var}$$

$$r \quad r$$

$$iv := i \cdot \text{var}$$

$$YRl := (YRb - \text{ceil}(\text{yrs} \cdot U)) \quad : \text{Valid Base Years}$$

$$YRl := YRl \cdot (YRl > 0)$$

$$YRh := (YRb + \text{ceil}(\text{yrs} \cdot U))$$

$$YRh := YRh - ((YRh - \text{yrs}) \cdot (YRh > \text{yrs}))$$

$$Yv := \begin{bmatrix} YRl \\ YRb \\ YRh \end{bmatrix}$$

$$Ll := (L - \text{ceil}(\text{yrs} \cdot U)) \quad : \text{Valid Lifetimes}$$

$$Ll := Ll \cdot (Ll > 0)$$

$$Lh := (L + \text{ceil}(\text{yrs} \cdot U))$$

$$Lh := Lh - ((Lh - \text{yrs}) \cdot (Lh > \text{yrs}))$$

$$Lv := \begin{bmatrix} Ll \\ L \\ Lh \end{bmatrix}$$

savv := savb var

: Acq Cost Range

acqr := HVACB + ((acqv - acq) · PF(i, YRb))
 yrs

: Maint Cost Calcs

Mr := HVACB + $\left[\sum_n \left[\frac{Mv}{r} - M \right] \cdot (n > YRb) \cdot (n \leq L) \cdot PF(i, n) \right]$
 r yrs

ir := $\sum_n \left[\frac{HB}{n} \cdot PF \left[\frac{iv}{r}, n \right] \right]$: Interest(+Inflation)

s := savb y := YRb

Y := acq · PF $\left[\frac{i, Yv}{r} \right]$: Base Year Calcs

Y := Y
 r r ...

+ $\sum_n \left[\frac{HN}{n} + \left[\frac{n > Yv}{r} \right] \cdot (n \leq L) \cdot \left[M - \left[\frac{HC \cdot s}{n} \right] \right] \right] \cdot PF(i, n)$

l := L

L := acq · PF(i, y) : Lifetime Calcs
 r

L := L

 r r ...

+ $\sum_n \left[\frac{HN}{n} + (n > y) \cdot \left[\frac{n \leq Lv}{r} \right] \cdot \left[M - \left[\frac{HC \cdot s}{n} \right] \right] \right] \cdot PF(i, n)$

S := acq · PF(i, y) : Savings Calcs
 r

s := savv

$s_r := s_r$
 $r \dots$

$$+ \sum_n \left[HN_n + (n > y) \cdot (n \leq 1) \cdot \left[M - \begin{bmatrix} HC & s \\ n & r \end{bmatrix} \right] \right] \cdot PF(i, n)$$

$z := 0 \dots 10$ $w := 0 \dots 10$: Joint Sensitivity
 $I := z \cdot 0.02$ $s := w \cdot 1$
 z w

$m_{z,w} := \text{acq PF} \begin{bmatrix} I, y \\ z \end{bmatrix}$
 $m_{z,w} := m_{z,w} \dots$

$$+ \sum_n \left[HN_n + (n > y) \cdot (n \leq 1) \cdot \left[M - \begin{bmatrix} HC & s \\ n & w \end{bmatrix} \right] \right] \cdot PF \begin{bmatrix} I, n \\ z \end{bmatrix}$$

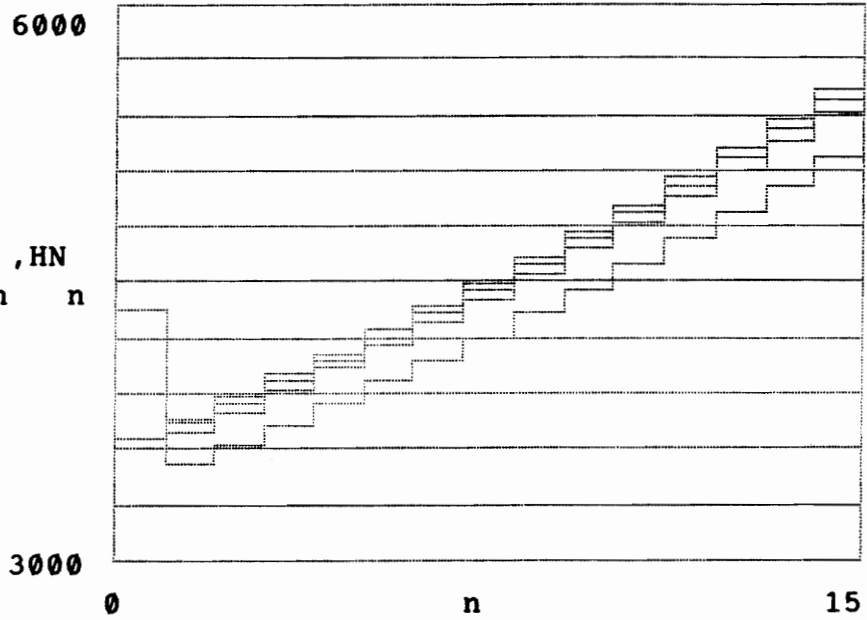
$m_{0,w} := 0$ $m_{z,0} := 0$
 $m := m^{\uparrow}$

RESULTS

Money Flows:

G R B Y
6000

HH ,HL ,HB ,HN
n n n n



Equivalent LCC:

HVACN =

3658
7222
10695
14078
17375
20586
23716
26765
29736
32630
35450
38198
40876
43484
46026
48502

HVACB =

4358
7854
11260
14577
17809
20957
24024
27012
29922
32758
35520
38210
40832
43385
45873
48296

HVACL =

4358
7895
11340
14696
17966
21151
24253
27276
30220
33089
35883
38605
41257
43840
46357
48809

HVACH =

4358
7691
10938
14101
17182
20184
23107
25956
28730
31433
34066
36632
39130
41565
43936
46247

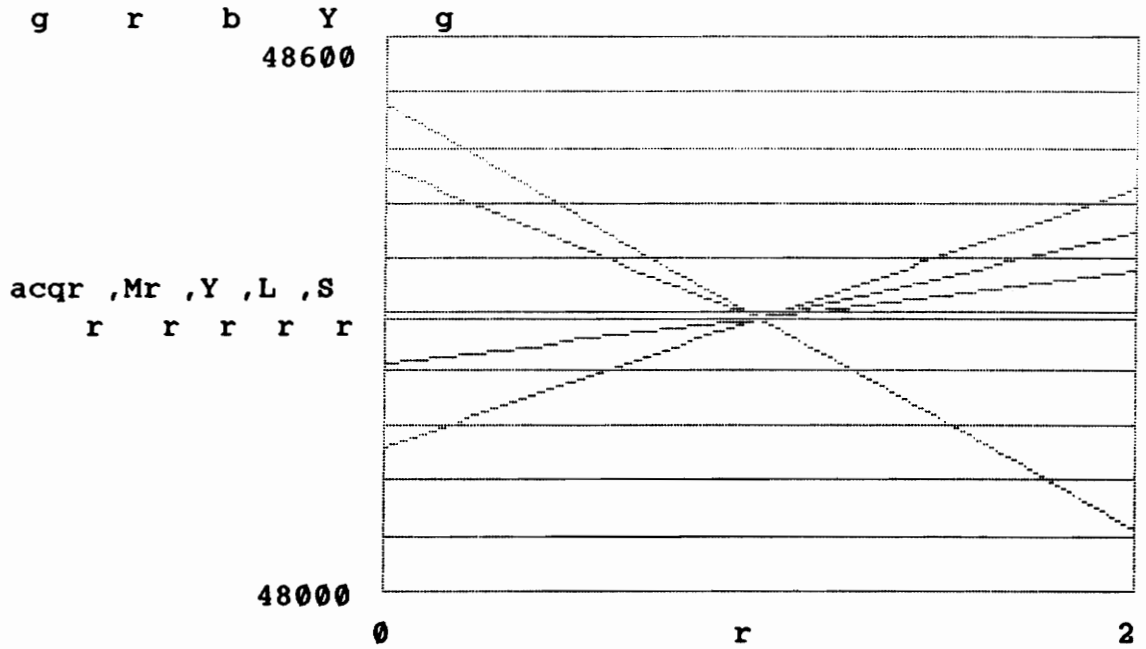
Internal Rates of Return (%):

RORL = -0.01
 RORB = 0.09
 RORH = 0.38

Payback Period (Yrs):

PBL = 0
 PBB = 11
 PBH = 3

Single-Variable Sensitivity Analysis:

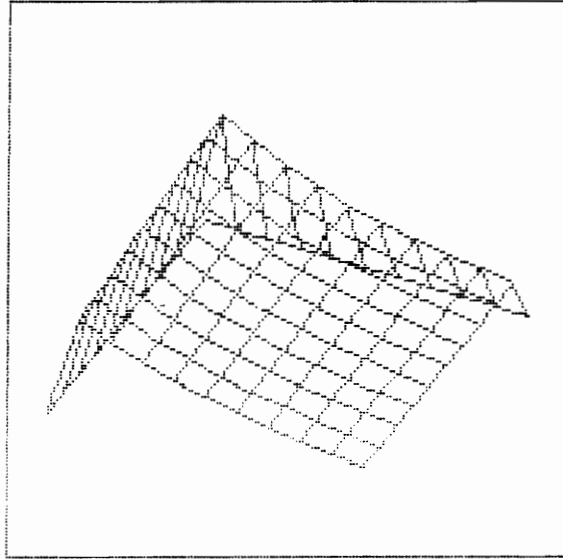


**Joint
Sensitivity
Analysis**

**Savings
(0-100%)**

m = 62360
1,1

m = 47094
10,1



m

**Interest
(0 - 20%)**

m = 23828
1,10

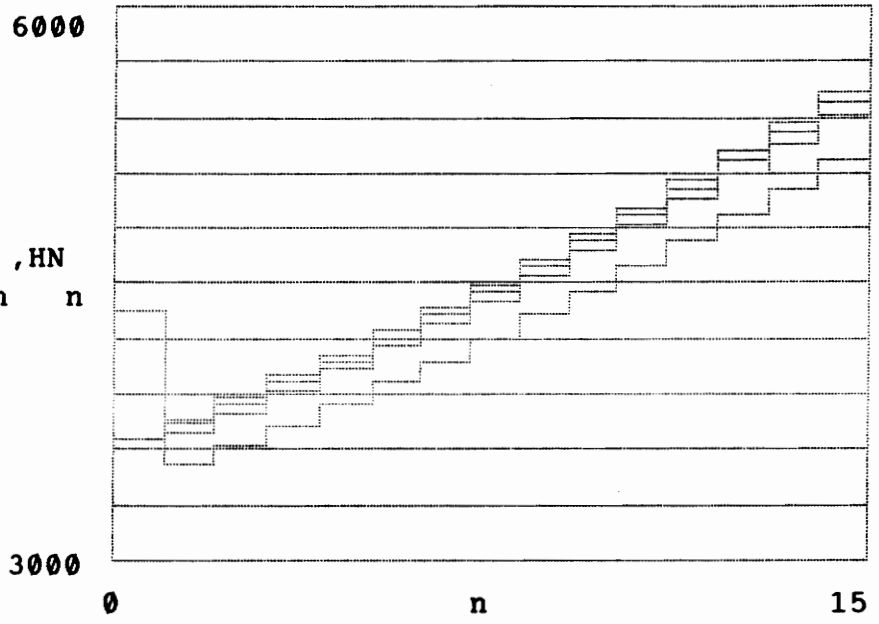
m = 18706
10,10

RESULTS

Money Flows:

G R B Y
6000

HH ,HL ,HB ,HN
n n n n



Vita

Douglas E. Leivonen was born on August 7, 1957 in Carlsbad, California, to Richard A. and Donna L. Leivonen. In 1976 he graduated from Carlsbad High School and attended the Naval Academy Preparatory School at Newport, Rhode Island for one year. In 1977 he attended the United States Naval Academy at Annapolis, Maryland. He graduated in 1980 and was commissioned an Ensign in the United States Navy. After completing Naval jet flight training, he deployed aboard an aircraft carrier as a Naval Aviator flying an antisubmarine aircraft. Later he served as a Naval Jet Flight Instructor. He left the service in 1988 and went to work with the General Electric Company in Springfield, Virginia as a test and evaluation engineer. His current assignment is as a project advisor in Valley Forge, Pennsylvania, where he is working to finish his Master's Degree from Virginia Tech.

Doug married Brenda L. Mapes in March of 1982. They have two daughters, Michelle and Anne.