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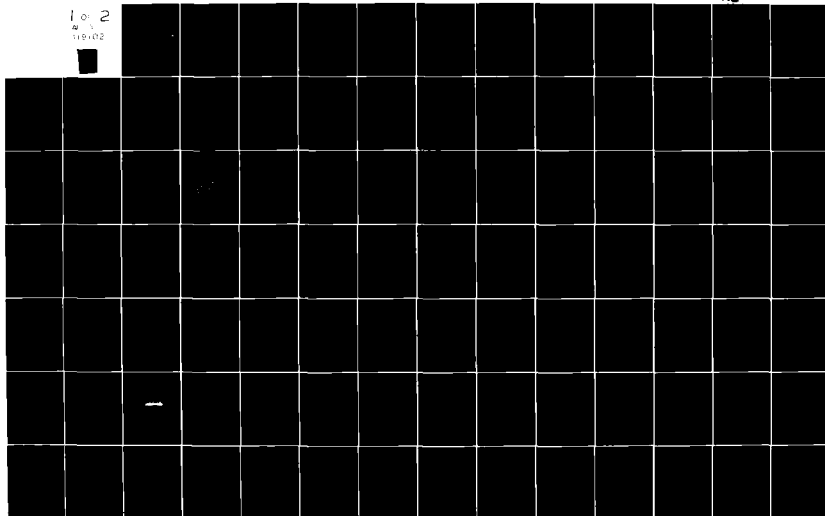
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ABSTRACT

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This thesis develops a straightforward and accurate method to determine mechanical heating system changeover timing. Transitional season weather causes buildings to stay within acceptable thermal comfort ranges without requiring supplemental heating. Significant energy savings can be realized if heating plants can be shut down during periods they are not required. The term "trigger temperature" is used to describe the minimum acceptable comfort conditions which must be maintained before changeover can be made. Computer simulation of ninety-four hypothetical office buildings is used to record data for hourly building temperatures. Statistical regression analysis techniques are employed to analyze the data and develop temperature prediction models for a range of building envelopes and occupancy schedules. Hand calculation and micro-computer applications are offered to provide changeover decision criteria for facility managers using this method.

Key words for this thesis are: transitional seasons, changeover timing, regression analysis, thermal comfort, and Trigger Temperature Method.

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A Methodology for Determining Building Heating System
Changeover Timing

'A Thesis in
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by

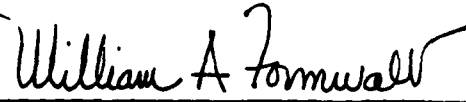
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Submitted in Partial Fulfillment
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ABSTRACT

This thesis develops a straightforward and accurate method to determine mechanical heating system changeover timing. Transitional season weather causes buildings to stay within acceptable thermal comfort ranges without requiring supplemental heating. Significant energy savings can be realized if heating plants can be shut down during periods they are not required. The term "trigger temperature" is used to describe the minimum acceptable comfort conditions which must be maintained before changeover can be made. Computer simulation of ninety-four hypothetical office buildings is used to record data for hourly building temperatures. Statistical regression analysis techniques are employed to analyze the data and develop temperature prediction models for a range of building envelopes and occupancy schedules. Hand calculation and micro-computer applications are offered to provide changeover decision criteria for facility managers using this method.

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TABLE OF CONTENTS

ABSTRACT	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	viii
ACKNOWLEDGEMENTS	x
CHAPTER ONE	
INTRODUCTION	1
Background	2
Objectives	3
Limitations	4
Contribution	5
Overview	6
CHAPTER TWO	
FACILITY MANAGER NEEDS	7
Method Flexibility	7
Application Simplicity	8
Accuracy and Accountablilty	9
CHAPTER THREE	
CHANGEOVER ESTIMATION TECHNIQUES	11
Historical Data	11
Steady State Analysis	13
Balance Point Temperature	13
Solar Gains	16
Thermal Capacitance Effects	16
Transient Thermal Conditions	19
Computer Simulation	19
BLAST Computer Program	20
Method Comparison	21
Trigger Temperature Method	22
CHAPTER FOUR	
STATISTICAL MODEL DEVELOPMENT	24
Statistical Models	24
Model Building Analysis Plan	26
Planning Phase	26
Variable Selection	28
Regression Techniques	32
Analysis Goals	38
Coefficient of Determination	39
Coefficient of Variation	40

Parameter Significance	40
Model Agreement	41
Development Phase	42
Data Collection	42
Regression Analysis	47
Coefficient of Determination	48
Coefficient of Variation	50
Parameter Significance	50
Model Agreement	52
Verification and Validation	55
Residual Plots	55
Model Plausibility	57
Validation	60
CHAPTER FIVE	
TRIGGER TEMPERATURE METHOD	63
Weather Input Data	63
User Requirements	64
Example Problems	67
Problem #1	67
Problem #2	71
Range of Application	74
CHAPTER SIX	
CONCLUSIONS AND RECOMMENDATIONS	76
Summary	76
Conclusions	76
Recommendations for Future Study	77
References	79
Appendix A	
MODEL DEVELOPMENT STATISTICS	81
Appendix B	
USER INPUT INFORMATION	90
Variable Information	90
Prediction Equations	90

LIST OF TABLES

Table		Page
3-1	Steady state heat transfer equations	14
3-2	Balance Point example building	15
4-1	Model dependent variables	29
4-2	Initial variables - building and occupancy	30
4-3	Initial variables - site and weather	32
4-4	Initial interaction variable terms	37
4-5	Variable levels tested in BLAST simulations	44
4-6	R Squared values for TEMP6	49
4-7	Coefficient of Variation for TEMP6	51
4-8	Summary statistics for prediction equations	52
4-9	Summary of model validation	62
5-1	Daily normals of temperature for Harrisburg, Pa	65
5-2	Building data for example problems	68
5-3	Trigger Temperature Method range of application	75
A-1	TEMP6 regression statistics	82
A-2	TEMP7 regression statistics	83
A-3	TEMP8 regression statistics	84
A-4	TEMP9 regression statistics	85
B-1	Continuous variables	91
B-2	Final model indicator variables	92
B-3	Building schedule options	92
B-4	Trigger Temperature prediction equations	93

LIST OF FIGURES

Figure	Page
3-1 Building load profiles	17
3-2 Thermal mass storage effect	18
4-1 Model building flow diagram	27
4-2 Method of least squares	34
4-3a Simple regression example	36
4-3b Multiple regression with interaction term	36
4-3c Transformed interaction example	36
4-4 Daily temperature profiles	46
4-5 Model consistency comparison	53
4-6a Acceptable residual plot	56
4-6b Non-linear residual plot	56
4-6c Non-constant variance residual plot	56
4-7 TEMP6 residual plot	58
4-8 TEMP6 temperature difference distribution	61
5-1 Trigger Temperature Method flow chart	66
5-2 Spring changeover graph	70
5-3 Trigger Temperature Method summary output	72
5-4 Temperature profile computer output	73
A-1 TEMP6 residual plot	86
A-2 TEMP7 residual plot	87
A-3 TEMP8 residual plot	88
A-4 TEMP9 residual plot	89

LIST OF SYMBOLS

APART	Area of partitions, (sf)
ASLAB	Area of building slab, (sf)
AWALL	Opaque wall area, (sf)
BVOL	Building volume, (cf)
DPART	Density of partitions, (lbs/cf)
EGLAS	Projected area of east glass, (sf)
ELEC	Lights, equip gains, (watts/sf)
HVAC	Heat recovery system availability
IDBT	Indoor dry bulb temperature, (F)
INFIL	Infiltration, (air changes/hour)
PEOPLE	Building occupants
RANGE	Daily temperature range, (F)
SCHED1	Daily occupancy schedule option
SCHED2	Early occupancy schedule option
SEASON	Weather season
SGLAS	Projected area of south glass, (sf)
SHADE	Glass shading coefficient, (fraction)
SOLAR	Clearness number, (fraction)
TAVE	Average daily temperature, (F)
TGLAS	Area of total glass, (sf)
TGRND	Ground temperature, (F)
TSDEV	Temperature standard deviation, (F)
ODBMAX	Outdoor dry bulb temp max, (F)

ODBMIN	Outdoor dry bulb temp min, (F)
ODBT	Outdoor dry bulb temperature, (F)
PSLAB	Perimeter of slab, (lf)
UA	U-Value*envelope component area, (Btu/hr*F)
UGLAS	Glass U-value, (Btu/hr*F*sf)
UROOF	Roof U-value, (Btu/hr*F*sf)
UWALL	Wall U-value, (Btu/hr*F*sf)
WATTS	Building electric heat gains, (watts)
b	Regression parameter estimate
B	Regression parameter
e_i	Residual
E	Regression error term
F test	Statistic test for parameter significance
MSE	Mean Square Error
R^2	Coefficient of Determination
s	Standard error of the estimate
SSE	Sum of Squares Error
X	Independent or predictor variable
$\hat{Y}_h$	Y-hat, the predicted value of Y
Y	Dependent or response variable

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CHAPTER ONE

INTRODUCTION

Since the Oil Embargo of 1973, social, economic, and political pressures have underscored the need for energy conservation throughout the world. The recent reduction in crude oil prices has been directly linked with the conservation efforts at work during the past year. The resultant reduction in energy demand has created an oil surplus: a gap between the demand and available supplies. One major contribution in reducing energy consumption has come from the energy conservation accomplishments in building design and operation. From the Federal Energy Administration indoor temperature guidelines established in 1974, there has been a conscientious effort to make buildings more "energy efficient" without sacrificing the comfort of the occupants. Increasing attention is being given to annual energy costs of existing and proposed facilities.

Many different efforts have been directed toward reducing building energy consumption. Improvements have been made in the operating efficiency of heating, ventilation, and air-conditioning (HVAC) equipment, and

facility managers and owners have concentrated on tightening the building thermal envelope. Engineering analysis methods have been developed to maximize energy efficiency. These techniques range from simple energy audits which track fuel consumption to sophisticated computer controlled energy monitoring systems. One area which has not received much attention is that related to facility energy use during transitional seasons.

Background

A critical weather transition period occurs each Spring and Fall for facilities in temperate climates. At this time, the startup or shutdown of the facility heating plant must be considered. The timing of this "changeover" is critical because it directly affects the annual energy consumption of the building. In addition, it is often an irreversible decision which may adversely limit the comfort for the facility occupants. It is important that the timing of the changeover reflects a careful balance between maintaining an acceptable thermal comfort within the building and the economic pressures to save on energy bills when fuel costs are high. The potential for savings lies in a changeover timing which avoids costs associated with running and maintaining a heating plant during a period without any heating requirements. When the facility is

heated by a central plant, the savings potential is the greatest.

Where a central heating plant serves several facilities, the changeover timing has additional impact on energy use and potential savings. Central plants must be prepared for heating load requirements which may not occur. In addition, losses occur in the distribution network serving all facilities. Central heating plants are often constructed where one organization owns and operates all of the facilities in the distribution network. This situation is common on university campuses and military installations as well as in industrial complexes, yet no simple method has been created for changeover estimation. For instance, the United States Air Force has no existing method to use for its numerous (over 100) locations around the world. Nor does ASHRAE, which provides many of the engineering design standards for HVAC equipment, describe a changeover estimation method in any of its publications. The purpose of this thesis is to propose a procedure from which a changeover decision process may be developed.

Objectives

The objective of this thesis is to develop a simple and accurate method to determine changeover dates for office type buildings, by predicting how the buildings will perform

during transitional seasons. It is intended that this method would be used by facility manager and engineer alike when making building energy analyses.

Research will be comprised of the following steps:

1. Evaluate facility manager needs for a changeover methodology from input information to end use.
2. Review existing changeover estimation techniques and their present applications.
3. Use heat balance engineering analysis methods to determine how a range of office type buildings perform during the transitional seasons.
4. Determine the most critical weather, building envelope, and occupant use characteristics affecting the building changeover conditions.
5. Employ statistical regression techniques to predict internal building temperatures.
6. Integrate weather and user input data into the model developed and establish its accuracy and range of application.

Limitations

The methodology developed in this thesis is limited to determining the changeover date for mechanical heating systems only. The changeover decision is based upon building temperatures during the hours of 6am to 10am.

Occupancy schedules used in this research have been developed by studying the weekdays of Tuesday through Friday in a five-day work week. Data generated for the statistical portion of the research are limited to slab on grade single story medium density masonry structures with office type occupancies. Outdoor temperatures used have daily ranges of from 10 F to 30 F, and solar data is typical of from 35 to 45 degrees North or South latitude locations. Applications for weather or building types outside these limits have not been validated by the statistical model developed as part of this thesis.

Contribution

The contribution of this thesis is the development of a method to quickly and accurately determine building heating system changeover dates. This methodology also provides the user with a technique to assess the impact of differing changeover dates on each facility by predicting how each will perform without a heating plant. Although established and accepted methods are available to calculate building performance under these conditions, there is no simple yet accurate approach which accounts for heat gains due to solar radiation and the time lag effects of building thermal mass. These thermal gains and losses are critical if an accurate building temperature is to be calculated for use in making

changeover decisions. The development of a simple and precise model to determine building changeover dates offers the area of energy management a valuable tool to conserve energy without sacrificing building occupant comfort.

Overview

The development of this thesis is presented in the following chapters: Chapter Two reviews facility manager needs when estimating building changeover and describes possible engineering applications. Chapter Three reviews several existing methods which could be used to make changeover date estimations. Chapter Four details the statistical analysis procedures which are used to establish building temperature prediction models. Chapter Five integrates the statistical models into the Trigger Temperature Method for determining changeover timing and provides examples to demonstrate the method's capabilities and applications. Chapter Six offers conclusions and recommendations for future research.

CHAPTER TWO

FACILITY MANAGER NEEDS

The responsibility for an organization's building operation and maintenance program is typically under the central control of the facility manager. The facility manager may direct the needs for a single building or an entire industrial complex. In order to maximize potential energy savings, a changeover method should provide him with a means to ensure buildings are heated adequately, as well as efficiently. Energy savings can be realized if heating plants can be shut down during periods they are not required. An ideal analysis method would offer flexibility in approach, be straightforward and simple in application, yet have a high degree of accuracy when estimating changeover timing.

Method Flexibility

Changeover concepts are addressed by large and small organizations alike. Although the scope of application may differ, any changeover method would need to include buildings of varying size, construction, occupant use, and site conditions. It should apply to older, less efficient

buildings, as well as newer, energy efficient ones. As older buildings are upgraded to be thermally more efficient, their performance during the changeover seasons is altered. A system of changeover analysis should be able to adjust to these energy upgrades.

Application Simplicity

A changeover method should be straightforward and easily applied for a multitude of facilities. Facility management organizations are not always staffed to do detailed energy analyses and must concentrate primarily on the maintenance and running of the "physical plant". This puts a limit on the time and engineering expertise which may be available for changeover estimation. Each hour added to this estimation process by extensive and time consuming engineering calculations is an hour which can be spent in other areas of energy conservation.

Typically, facility management for smaller organizations is not staffed with engineers to perform changeover analysis. This responsibility may rest with central heating plant managers or individual building custodians. They need a method which does not rely upon the expertise of architects or engineers trained in energy analysis techniques. Simplicity and ease of use is their primary concern. Regardless of the end user within a

facility management organization, a changeover method should offer an accuracy level sufficient to ensure thermal comfort for the building occupants.

Accuracy and Accountability

When estimating changeover timing, the accuracy of any method is a function of several parameters. The most accurate method of analysis would be one derived from observations of actual facilities in operation. This is an impracticable approach, however, because it would not be cost effective to gather data from test facilities operated without any heating supply. A more reasonable approach which sacrifices little accuracy is one which employs scientific analysis methods based upon engineering research studies. For exacting engineering analysis techniques, accuracy becomes primarily a function of the input data used. For example, weather data is one uncontrollable factor which can limit the accuracy of an otherwise sound analysis method. Another accuracy constraint is the time interval for which a method predicts changeover.

A method which determines changeover dates on a monthly basis does not offer the sensitivity needed to be of much value to the user. On the other hand, one which can pinpoint this date to a single day of the month may not be considering daily weather fluctuations. The ideal method

would consider at least weekly weather trends, yet retain sufficient precision to determine occupant comfort conditions.

Occupant comfort is the most important accountable item in a changeover analysis. The concept of a changeover date negates all of the reasons buildings are heated in the first place if it cannot in some way estimate whether or not people will be comfortable. Occupant comfort should be recorded in some way so that changeover conditions can be determined as a function of a specified comfort condition. There are several methods which can be used to assess thermal comfort for occupants. The relative merits for these methods are covered in Chapter Three.

CHAPTER THREE

CHANGEOVER ESTIMATION TECHNIQUES

Building changeover dates can be estimated in several ways. The historical data approach uses records of changeovers from previous years as a data base from which future predictions may be made. Engineering calculations may be made for either steady state or transient thermal conditions to determine the optimal changeover date. The end goal in all cases is to assess when weather conditions have established a situation where there is no longer a facility heating requirement.

Historical Data

The simplest approach uses historical data as the basis for estimating changeover timing. This general procedure employs past records of weather and building performance to predict future trends. The number of years observations have been taken is an important facet of this approach. Records for each facility are kept of past years' changeover dates. When the heating plant is turned off (or on), a record is made of how this timing affected the facility occupants. The facility manager assumes that if no

complaints are received, the changeover date chosen was acceptable. Weather data for this period is recorded and compared with weather from previous observations. The goal for the coming seasonal changeover is then selected as a compromise between energy conservation goals and the number of "too cold" complaints from the occupants.

In application, this management by exception approach has several limitations. Building temperatures cannot be determined, and occupant thermal discomfort can be predicted only indirectly. In addition, accuracy in this approach is primarily a function of the quantity of previously recorded observations. Unfortunately, this method rarely accumulates enough sample years to be of much value.

As a facility's use changes or architectural modifications are made, the thermal performance of the facility also changes. Added insulation or new occupancy hours will change how a building will react to the environment. As a result of any changes, the previous years' records become invalid predictors for future performance. With recent efforts to insulate and improve thermal performance of his buildings, a facility manager may find that it is never possible to accumulate enough data years using the historical data method. A more useful and scientific approach involves using engineering heating load calculations to estimate changeover timing.

Steady State Analysis

Steady state analysis is the most widely used and accepted method to determine heating transfer rates (ASHRAE, 1981). Steady state building load calculations are made by assuming that the rate of heat flow through a building component is constant over a period of time and that the rate of flow can be approximated by comparing the potential energy differences at the beginning and end of the period (usually one hour). The thermal transmittance, or U-value, is the coefficient of heat transmission for the material through which the heat is passing (ASHRAE, 1981). Table 3-1 lists ASHRAE steady state equations used for estimating building heat gains and losses.

Balance Point Temperature

The weather condition which causes a building's heat gains to be equal to its heat losses is referred to as the facility's balance point. The outside dry bulb temperature under these conditions is called the balance point temperature (BPT). For residential construction, this has typically been 65 F, but the greater internal loads due to lighting and occupants cause office type facilities to have much lower values (ASHRAE, 1981). By calculating the balance point temperature, conditions can be determined when no net heat will be required.

Table 3-1
Steady state heat transfer equations

Component	Steady state equation	Units
Envelope	$U \cdot A \cdot (IDBT - ODBT)$	Btuh (-)
Infiltration	$1.1 \cdot CFM \cdot (IDBT - ODBT)$	Btuh (-)
Ventilation	$1.1 \cdot CFM \cdot (IDBT - ODBT)$	Btuh (-)
Occupancy	$255 \cdot PEOPLE$	Btuh (+)
Lights and equipment	$3.413 \cdot WATTS$	Btuh (+)

where * denotes multiplication

Btuh = Btu/hour heat gains (+) or losses (-)

UA = U-value*area of the envelope component

IDBT = indoor dry bulb temperature

ODBT = outdoor dry bulb temperature

PEOPLE = number of facility occupants

WATTS = the total internal electric load in watts

Note : 255 Btuh per person is sensible heat only.

An application of the BPT concept can be demonstrated in an example problem:

At the balance point temperature, building heat losses are matched by gains, where:

$$\text{Heat losses} = \text{Transmission} + \text{Infiltration}$$

$$\text{Heat gains} = \text{Lights} + \text{People} + \text{Solar}$$

Table 3-2 lists the building data for a 2000 sf modern construction office building.

Table 3-2
Balance Point example building

Component -----	Value -----	
Transmission	Area, sf	U-Value, Btu/(hr*sf°F)
Walls	1600	0.10
Glass	200	0.55
Roof	2000	0.045
Infiltration	130 cu ft/min	
Occupants	16 people	
Lights	2.2 watts/sf	

Using this data to calculate the building's balance point temperature, the building indoor temperature must first be set. If an indoor setting of 72 F is used,

$$\text{Heat losses in MBtuh} = 503 \cdot (72 - \text{ODBT})$$

$$\text{Heat gains in MBtuh} = 19,097.0$$

By setting the gains and losses equal,

$$\text{ODBT} = \text{balance point temperature} = 34.0 \text{ F} - \text{Solar}$$

The balance point method has some limitations when used for estimating changeover timing. The thermal gains from solar and the time delayed gains from the building mass cannot be determined by steady state analysis techniques.

Solar Gains

Thermal gains due to the sun can be a significant portion of the total heat gain for a facility. Solar gain alone may reduce the annual heating load by 10 - 15 % for an office building having an eight-to-one ratio of building floor area to south-facing glass area (Balcomb, 1980). However, due to the transient nature of solar conditions, these gains cannot be calculated using steady state equations. Figure 3-1 shows how the load profiles for the previous example problem would be affected if solar gains were considered. Steady state analysis methods are also unable to account for the thermal capacitance effects caused by a building's mass.

Thermal Capacitance Effects

The capacitive effect of a building is another significant contribution to the building thermal balance.

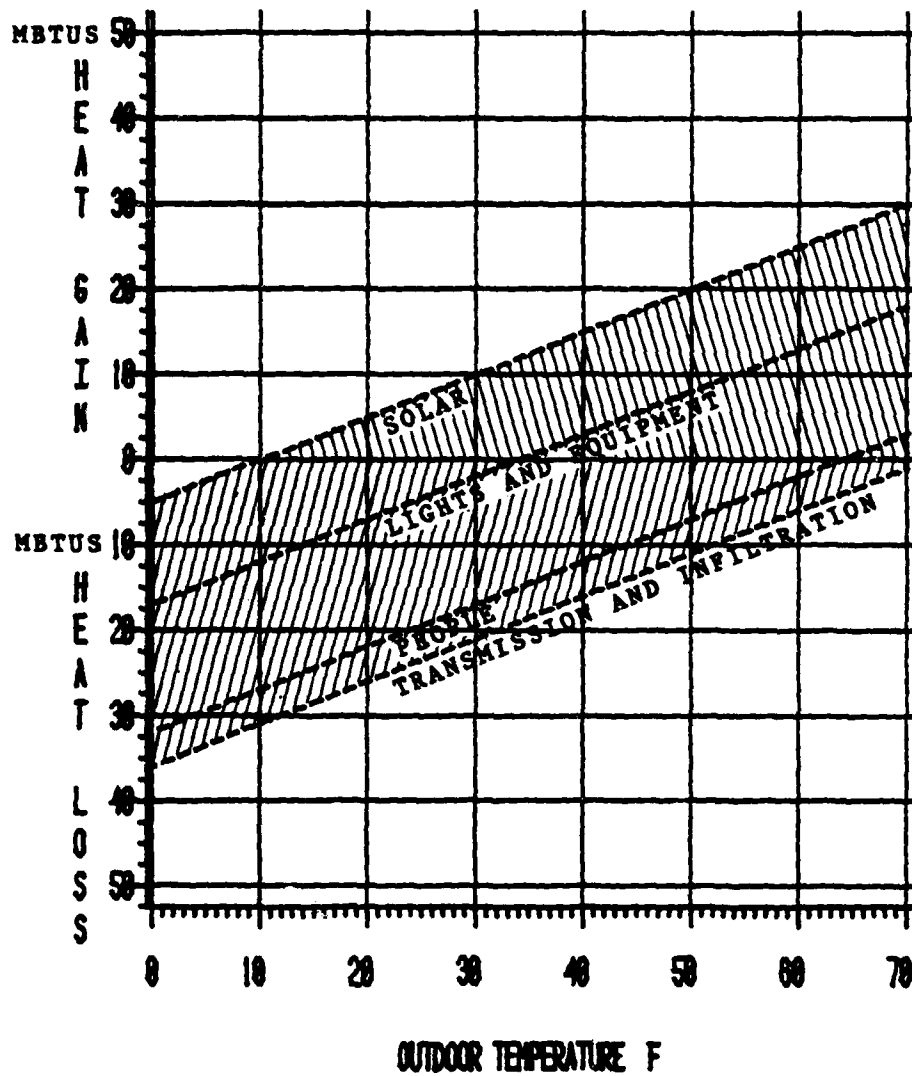


Figure 3-1. Building load profiles

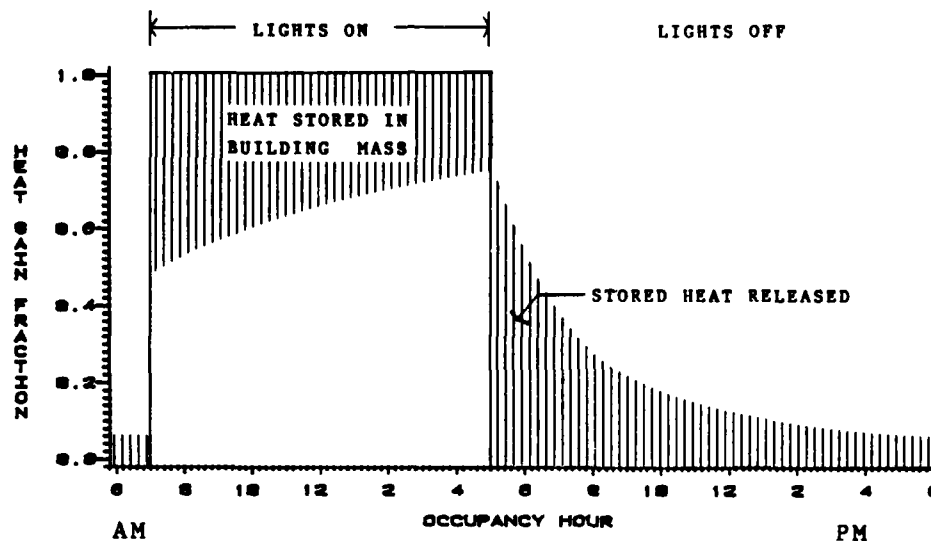


Figure 3-2. Thermal mass storage effect

Each hour of the day, thermal energy is being stored and released by the building roof, slab, walls and partitions. During the occupied hours, this building mass absorbs heat from the lights and sun as well as the ambient air. After the lights are turned off the stored heat is released to the space as the processes reverses during the unoccupied hours. The amount of heat which can be stored in and released by the building thermal mass will depend upon many factors, including the building construction and interior layout.

Though widely used for load calculations, steady state heat transfer analysis is limited because it cannot account

for solar gains and thermal mass capacitance effects inherent in a structure. It lacks accuracy in predicting indoor temperatures when other than steady state conditions are present. In order to achieve precise results under varying thermal conditions, transient heat flow methods must be applied.

Transient Thermal Conditions

Transient thermal analysis offers the greatest precision possible for modeling heat transfer in buildings. The actual radiation, conduction, and convection thermal processes are accounted for with hour by hour load calculations. Because of the complexity and magnitude of the calculation process, computerization of this method is a necessity.

Computer Simulation

Computer analysis is a very flexible method which offers the user numerous options. Energy analysis programs can simulate heat transfer through an entire building structure, and thus can specifically calculate the thermal capacitance effect due to the building mass. Internal zone temperatures can be determined accurately, and hourly heating, ventilating, and air-conditioning loads developed. Solar gains may be recorded from actual or simulated weather

data. One of the most prominent hourly simulation computer programs is called the Building Loads Analysis and System Thermodynamics Program (BLAST).

BLAST Computer Program

Developed by the U. S. Army Construction Engineering Research Laboratory for use by the Department of Defense, BLAST is one of the most widely used programs performing transient thermal calculations. It allows the user to describe the building geometry and construction in detail, control the input weather, and model a number of HVAC systems. It can simulate widely differing facility types, from passive solar architecture to more typical office occupancy facilities. Heat gain through walls, roof, and slab is performed using the ASHRAE transfer function method.

Although extremely capable for performing energy analyses, programs such as BLAST are costly and time consuming. Computer simulation to design the HVAC equipment for a multi-zone office building can be quite costly. This expense is added to the training costs an engineering firm must face before their personnel are familiar with the program input requirements. Although program execution is a time saving process, the time required for training and data input prior to the run can be lengthy. Several hours of time would be necessary to prepare the input deck for a

multi-zone building. The detail required of the input information could also be a problem. Programs of this type require hourly weather data which may not be available to the user. The disadvantages are primarily those of cost and time - the benefits are the high degree of accuracy and reliability.

Method Comparison

The changeover alternatives discussed each have valuable benefits for the facility manager or energy engineer. Although the historical approach cannot determine building thermal performance, it offers a system by which changeover timing can be evaluated. When weather conditions create thermal discomfort for the occupants, the following season's changeover date can be adjusted. Steady state analysis offers simplicity for the user and a method to determine building temperatures. Transient analysis offers precision and flexibility. Solar and thermal mass gains are calculated on an hourly basis, and the user can input the actual building operation schedule as part of the computer simulation.

The ideal changeover method would borrow benefits from each of these approaches. User input information should be kept simple and to a minimum. Accuracy should be a high priority, but it should not depend upon expensive computer

analysis for calculations. The facility manager must be able to assess the thermal comfort for building occupants, yet be able to maximize his savings by conserving energy. One method to ensure thermal comfort is maintained is to set changeover timing as a function of the indoor building temperature.

Trigger Temperature Method

When weather conditions cause a building's temperature to stay within an acceptable comfort range, there is no need for supplemental heating. The acceptable temperature under these comfort conditions can be referred to as the "trigger temperature", a critical condition which is a function of the building responding to the weather. When the weather causes the building trigger temperature to be achieved, heating is no longer required. In the Autumn, this would indicate that the heating season has begun, whereas in the Spring, it would be time to shut the heating system down.

The Trigger Temperature Method uses the building temperature as an index to make changeover decisions. The building temperature can be predicted through statistical analysis of a range of BLAST computer simulations. This can be accomplished for the first few hours of occupancy, when the building is the coldest. The resulting method combines the accuracy of computer simulation with the simplicity of

hand calculation procedures. A high precision level, however, can only be achieved with a carefully developed statistical analysis plan.

CHAPTER FOUR

STATISTICAL MODEL DEVELOPMENT

No simple methods are available to accurately determine interior building temperatures. The thermal capacitance of a structure will cause a time delaying effect so that gains from solar, lighting, and people are not felt in the building immediately. Calculations of instantaneous thermal gains and losses can inaccurately represent the hourly building temperatures. Computer simulation is a necessary tool to accurately describe the hourly temperatures and thermal conditions. Through simulation of hypothetical test facilities, data may be gathered to represent a broad spectrum of building types and weather conditions. It is then possible to employ statistical analysis techniques to develop temperature predictive models which are accurate within the range for which they are developed. These models can be formulated to retain precision without the time and expenses inherent in computer simulations.

Statistical Models

Three mathematical models may be used to determine building temperatures: functional, control, and predictive

(Draper and Smith, 1981). If the basic deterministic relationships among the variables can be defined, the functional model is best suited to the problem. However, in many cases where the underlying mathematical relationships are complex and involved, the functional model becomes difficult to develop.

The control model is used in carefully designed experiments. As the variable relationships become more complex, it is difficult to "control" the variables. This leads to the application of the predictive model.

Predictive models are used when functional relationships are complicated and difficult to control. For example, they are often used to determine the strength and reliability of construction materials. The compressive strength of a concrete mixture can be calculated using a functional model which considers the chemical bonding processes. However, for the purposes required in construction practice, the complexity involved in this procedure can be greatly simplified by using a predictive model. An easier approach involves testing of sample mixtures and recording the forces required to produce measurable failures. From these observations, a model is developed to predict compressive strength based upon the types and quantities of the concrete mixture components. The predictive model need not represent the actual chemical

processes which cause concrete hardening in order to produce an accurate and useful predictive model.

A predictive model can similarly be developed to calculate building temperatures as a function of the envelope, occupancy, and weather conditions. The actual thermal processes, including the solar gains and capacitance effects, can be predicted as part of the indoor temperature. In order to develop the predictive model, it is important to outline the analysis plan and describe the statistical procedures which apply.

Model Building Analysis Plan

An organized analysis plan is a necessary starting point in any problem-solving procedure. Methods to establish goals and evaluate the final solution should be clearly defined. The model building process in statistical studies can be developed in three phases: planning, development, and verification/validation. Figure 4-1 presents the model building flow diagram to be used for this statistical analysis. The planning phase includes defining the problem, selecting variables, outlining regression techniques, and establishing goals.

Planning Phase

The most important part in the planning phase is the

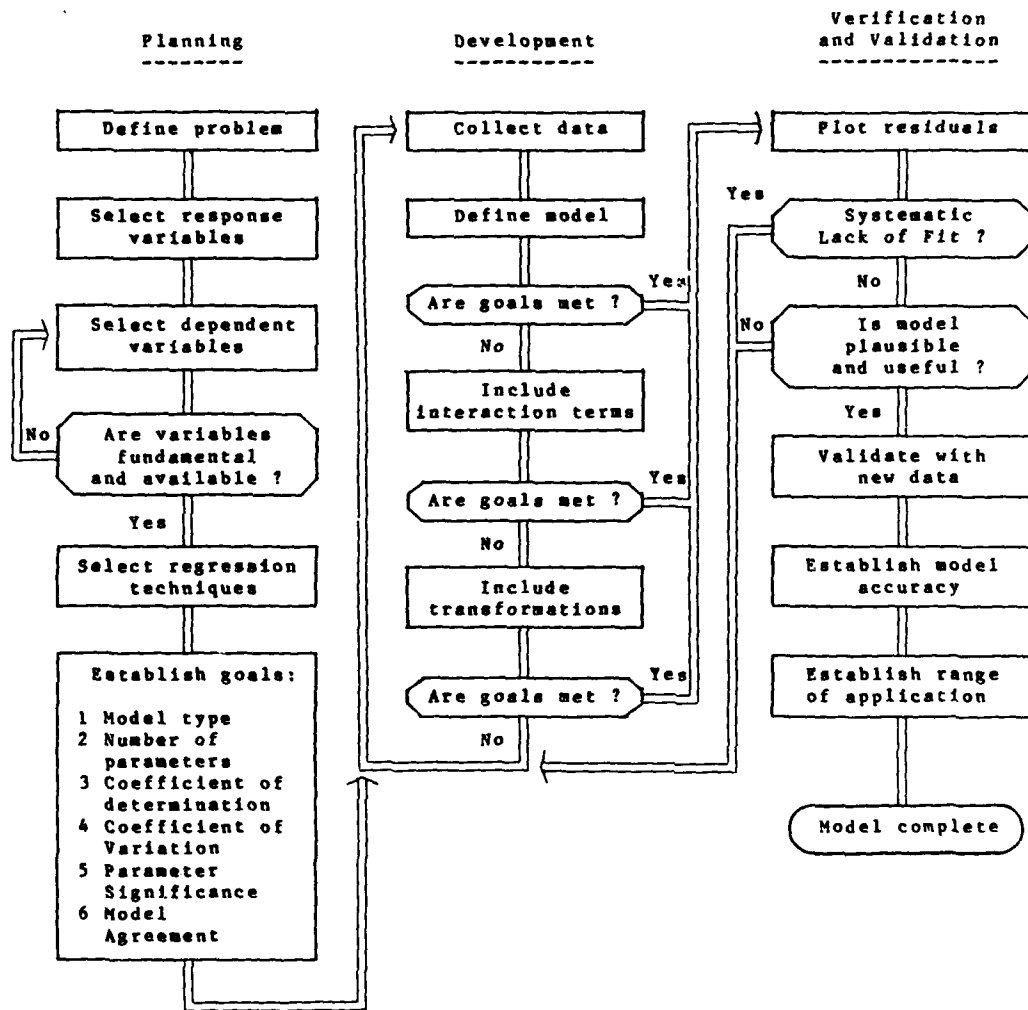


Figure 4-1 Model building flow diagram

development of a specific statement of the problem (Draper and Smith, 1981). For the work presented in this thesis, the predictive model should accurately determine transitional season building temperatures prior to, and during the initial hours of occupancy. Changeover timing will be based upon building and weather conditions which cause the building temperature to fall below a user defined threshold. The term "trigger temperature" will be used in this thesis to describe the acceptable building temperature which must be maintained for occupant comfort. Above this temperature, the building changeover can be made. (The changeover condition has been "triggered".) Prediction models will be developed on an hourly basis during the critical building hours from 6-10am. The first step in the planning phase involves the selection of possible model variables.

Variable Selection

The dependent variables for this study are the hourly building temperatures. For a facility functioning without heat, the coldest and therefore most critical period is prior to, and during the first few occupancy hours. Four dependent variables have been selected to determine the hourly average temperatures from 6-10am (Table 4.1). This enables the user to assess building temperatures during the critical occupancy hours.

Table 4-1
Model dependent variables

<u>Variable</u>	<u>Description</u>	<u>Units</u>
TEMP6	Building DBT from 6am-7am	(F)
TEMP7	Building DBT from 7am-8am	(F)
TEMP8	Building DBT from 8am-9am	(F)
TEMP9	Building DBT from 9am-10am	(F)

Note: DBT indicates Dry Bulb Temperature

Independent variables describe all heat gains and losses from occupancy and weather conditions. These variables must be fundamental to the problem and available to the user (Draper and Smith, 1981). Building envelope variables should be specific and in a usable format. For example, infiltration can be described in either cubic feet per minute (CFM) or as air changes each hour. Both are widely used in load calculations, but the widely varying range for CFM makes it a poor choice for statistical prediction use. A large facility with tight envelope construction could have the same CFM infiltration rate as a smaller, but older facility. The effect 1,000 CFM would have on each of these buildings would vary considerably. The initial variable list, shown in Table 4-2, is developed from ASHRAE standards widely used in heating and cooling load calculations.

Table 4-2

Initial variables - building and occupancy

Variable	Description	Units
-----	-----	-----
APART	Area of partitions	(sf)
ASLAB	Area of building slab	(sf)
AWALL	Opaque wall area	(sf)
BVOL	Building volume	(cf)
DPART	Density of partitions	(lbs/cf)
EGLAS	Projected area of east glass	(sf)
ELEC	Lights, equip gains	(watts/sf)
HVAC	Heat recovery system (70% eff.)	(yes or no)
INFIL	Infiltration	(air changes/hour)
PSLAB	Perimeter of slab	(lf)
SCHED1	Scheduled occupancy begins	(7am or 8am)
SCHED2	Early occupancy	(up to one hour early)
SGLAS	Projected area of south glass	(sf)
SHADE	Glass shading coefficient	(fraction)
TGLAS	Area of total glass	(sf)
UGLAS	Glass U-value	(Btu/hr*F*sF)
UROOF	Roof U-value	(Btu/hr*F*sF)
UWALL	Wall U-value	(Btu/hr*F*sF)

Building schedule options are best described by a special type of independent variable, called an indicator or dummy variable. Indicator variables are used where measurements are not recorded on a continuous and well-defined scale, or when simplicity in model application is desired. The emphasis is on qualitative, rather than quantitative effects. Examples include sex (male or female), and political preference (Republican, Democrat, or Independent). Several variables (Table 4-2) have been described using two level indicator variables (0 = no effect, 1 = some effect).

Weather conditions involve perhaps the most difficult variables to select. A balance is needed between selecting sufficient variables to develop an accurate predictive model and limiting the list to variables generally available to the user. Hourly weather data can provide very accurate building energy calculations, but many potential users do not have access to this information. For this reason, weather variables were selected on the basis of daily records (high and low temperatures). Table 4-3 lists the preliminary selection of weather variables. After identifying the variables, statistical analysis methods can be used to formulate the predictive models.

Table 4-3
Initial variables - site and weather

Variable -----	Description -----	Units -----
ODBMAX	Outdoor dry bulb temp max	(F)
ODBMIN	Outdoor dry bulb temp min	(F)
SEASON	Weather season	Spring or Autumn
SOLAR	Clearness number	(fraction)
TGRND	Ground temperature	(F)
TSDEV	Temperature standard deviation	(F)

Regression Techniques

Regression analysis is the most common statistical method to predict responses from quantifiable independent variables (Draper and Smith, 1981). It is a widely used method where underlying, but unknown, deterministic relationships exist between dependent and independent variables.

The regression equation, or model, may contain one or more independent variables. The highest power of any independent variable is referred to as the order of the model. The general form of a simple, first-order model is:

$$Y_1 = B_0 + B_1X_1 + E_1 \quad (4.1)$$

In this equation, Y_i is the value at the i^{th} trial, B_0 and B_1 are parameters, X_i is the value of the dependent variable at the i^{th} trial, and E_i describes the random error. The error term is the amount by which any observation of Y will differ from the regression line. Linear regression models are linear in parameters only and may contain higher order polynomial terms. Because E changes for each observation and the B terms can only be determined after seeing all of the data, these terms are replaced with estimates in regression analysis. The equation would then be written as:

$$\begin{array}{ccc} \text{Response} & \text{Fit} & \text{Error} \\ \hline Y_h = b_0 + b_1 X_1 + e_1 \end{array} \quad (4.2)$$

In this equation, Y_h is called Y-hat, the predicted value of Y , b_0 and b_1 are parameter estimates, and X is the value of the dependent variable. The difference between Y and Y_h , e_1 , is the error in the equation. This e_1 term is referred to as the residual.

To obtain the best estimate of the model parameters, regression analysis uses the method of least squares. The regression model which fits the data best is one in which the sum of squared error terms (SSE) is the lowest. A sample regression line shown in Figure 4-2 shows how tree diameter may be used to estimate the volume of usable lumber which may be produced.

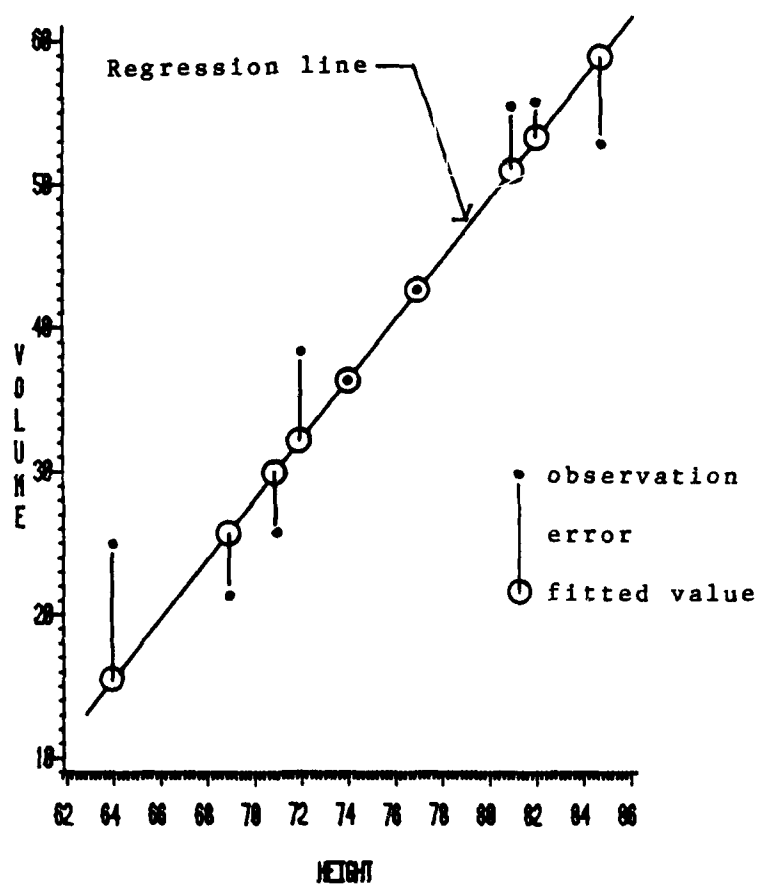


Figure 4-2 Method of least squares

In many research problems, more than one independent variable is required to accurately describe the response. Multiple linear regression techniques are used for these cases. The general form of a first-order model with two independent variables would be written:

$$Y_i = B_0 + B_1X_{i1} + B_2X_{i2} + \underbrace{B_3X_{i1}X_{i2}}_{\text{Interaction Term}} + E_i \quad (4.3)$$

Often the response of one independent variable depends upon its relationship with another related variable. Interaction terms are used to account for this information in multiple regression analysis. In the previous example, the diameter alone was used to predict lumber volume. If the interaction term, diameter*height is used, the observations fall in a pattern closer to the regression line (See Figures 4-3a and 4-3b). However, both of these patterns indicate nonlinear trends. This can be corrected by using a variable transformation. Transformations commonly used in regression analyses include: $1/X^2$, $1/X$, $1/\log(X)$, $\log(X)$, and X^2 . The transformation is clear in this simple example. Figure 4-3c shows the best fit of the data - a result of using the transformation closest to the mathematical equation for a cylindrical volume. The preliminary selection of interaction terms used in this regression analysis is shown in Table 4-4.

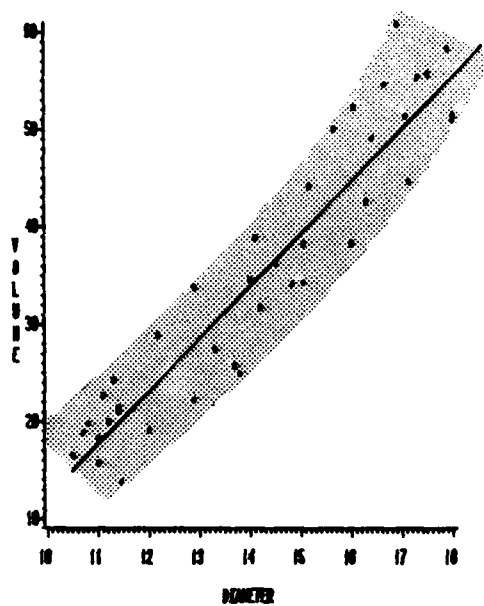


Figure 4-3a

Simple regression example

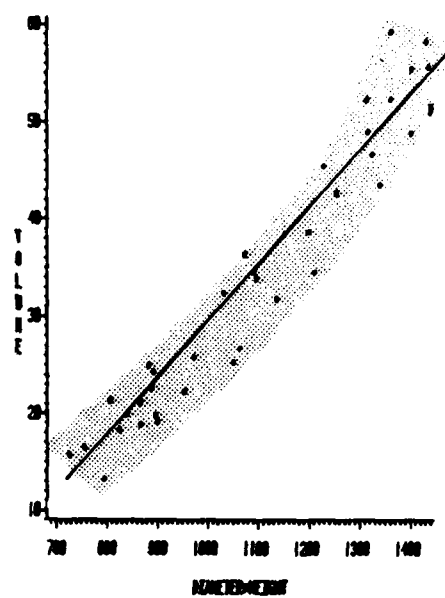


Figure 4-3b

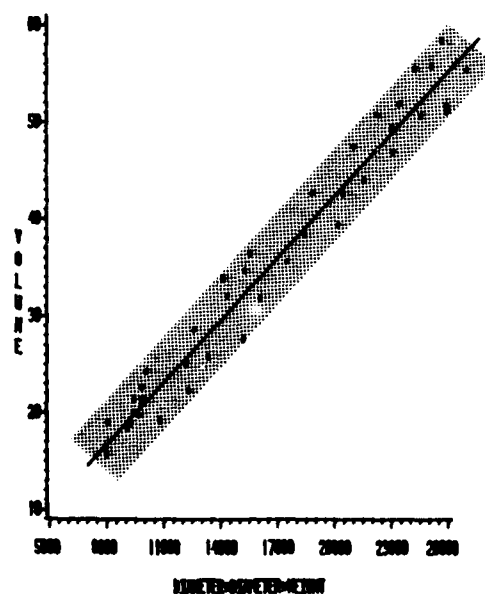
Multiple regression with
interaction term

Figure 4-3c Transformed interaction example

Table 4-4

Initial interaction variable terms

Predictor Significance -----	Interaction terms = f(variables) -----
Heat stored by partitions	ADPART = APART*DPART
Infiltration effect from outside air (see TDIFF)	AIRCH = INFIL*TDIFF
Heat recovered from early occupancy hours	AIRCH1 = INFIL*SCHED1*HVAC*TDIFF
Heat recovered from warm-up lights	AIRCH2 = INFIL*SCHED2*HVAC*TDIFF
Ventilation effect from heat recovery system	AIRCH3 = INFIL*HVAC*TDIFF
East solar gain reduced by glass shading	EGLAS1 = EGLAS*SHADE
East solar effect	EGLAS2 = EGLAS*SOLAR
Combined east solar effect	EGLAS3 = EGLAS*SHADE*SOLAR
7am occupancy light gains	ELEC1 = ELEC*SCHED1
Warm-up light gains	ELEC2 = ELEC*SCHED2
Daily temperature range	RANGE = ODBMAX-ODBMIN
South solar gain reduced by glass shading	SGLAS1 = SGLAS*SHADE
South solar effect	SGLAS2 = SGLAS*SOLAR
Combined south solar effect	SGLAS3 = SGLAS*SHADE*SOLAR
Losses through building envelope	TAVE = (ODBMIN+ODBMAX)/2
Balance point difference	TDIFF = 65-ODBMIN

Multiple linear regression becomes a complex and involved calculation procedure as the number of variables increases. There are $n \cdot 2^k$ possible regression equations in any analysis, where n is the number of independent variables and k is the number of dependent variables (Neter and Wasserman, 1974). In this study, the more than thirty variable terms (variables, interactions and transformations), would result in more than a billion possible regression equations. Computer analysis is necessary to perform regressions of this scope. One of the most powerful statistical packages available is the Statistical Analysis System (SAS). Developed by the SAS Institute in North Carolina, this program includes a variety of statistical procedures ranging from graphics to complex multivariate techniques (SAS Institute, 1979). The extensive descriptive statistics of SAS make it an ideal tool for developing and checking regression equations against specified goals.

Analysis Goals

In order to select the best regression equation from the many possible, it is necessary to define several goals. Preliminary regression goals include establishing the model type and maximum number of variable terms. A predictive regression model will be used in this research. The model

will be limited to having twenty or fewer variable terms (parameters) so that hand calculation methods may be used in follow-on applications. Additional goals will include setting acceptable values for the Coefficient of Determination (R^2), Coefficient of Variation, (C.V.), and parameter significance (F test). Finally, models with different dependent variables will be compared for accuracy and consistency.

Coefficient of Determination

The Coefficient of Determination, or R^2 term, is the square of the correlation coefficient. It indicates what proportion of the total variation in the dependent variable Y is explained by the regression model (Walpole and Meyers, 1978). The R^2 is often given as a fractional value, ranging from zero to one. An R^2 value of zero means that the regression model is of no help in reducing the variation in Y, and a value of one indicates a perfect fit with all observations lying on the regression line.

An R^2 goal of .95 is set to ensure that the final regression equations will be accurate predictors of the building temperature. Any equation failing to meet this minimum value can be rejected as lacking sufficient precision. One limitation of the R^2 statistic is that as the number of parameters increases, the R^2 value cannot decrease.

Coefficient of Variation

The Coefficient of Variation is very useful in statistical analyses because it is a measure of model precision which takes into account the number of parameters in the model. It is a unitless term used to describe the variation unaccounted for by a fitted regression equation. In least squares regression analysis, the goal is to minimize the sum of the squared residuals. One method to measure the variability of the residuals is by calculating the variance of the residuals, called the mean square error (MSE). The Coefficient of Variation, expressed as a percentage of the mean response, is the square root of the MSE divided by the predicted value mean. A value of 1.0% is set as the goal for this research. This will ensure that a very small amount of error will occur in the regression models. The next step is to ensure that all parameters are statistically significant.

Parameter Significance

Before a regression equation can be selected as the best model, The parameters should be tested for significance. The possibility that a parameter is not very valuable in explaining model error is expressed in the form of a test statistic. First, a null hypothesis, H_0 , is proposed that a parameter is equal to zero. Then an

alternative hypothesis, H_A , counters that the parameter is not equal to zero and is indeed significant to the regression equation. Finally, an F test statistic is developed to see if the parameter is equal to zero within specified probability limits. This test is performed at standard significance levels. The significance of a parameter can be evaluated by identifying the amount of error which would be added if that parameter were dropped from the model. In order to ensure that the selected regression models do not contain any questionable parameters, the probability level for the F test is set at 0.01%.

Model Agreement

The final goal to be met is one of model agreement. After regression equations for each of the four hours are developed, they will be used together to estimate the building temperatures from 6-10am. It is necessary that these equations are consistent in accuracy. If one equation differs from the others substantially in its ability to predict temperatures, errors in interpretation could result.

The R^2 term is used to measure accuracy of the final predictive models. The variation in R^2 can be used to ensure that all models are consistent with each other. The difference in the R^2 values for any two predictive models is

set at 1.0% to ensure that all models will be consistent as well as accurate. With all of the goals set, the analysis plan is ready for the next phase - development of the models.

Development Phase

The development phase is central to the statistical model building process. During this phase, data are gathered, and regression equations are developed, tested, and evaluated.

Data Collection

Computer-simulated data were generated for 94 hypothetical single story masonry office buildings, using the Building Loads Analysis and System Thermodynamics (BLAST) program. This program, developed by the U. S. Army Construction Engineering Research Laboratory, uses the ASHRAE transfer functions to perform hourly heat transfer calculations (U.S. Army CERL, 1979). A base condition hypothetical office facility of 5000 sf was developed and then modified through a series of envelope, occupancy, and siting variations. These variations included changes to the building size, area and U-values of envelope components, and infiltration rates, as well as occupancy hours and site orientation. A survey of existing U. S. Air Force

administrative facilities was used as a basis for selecting the ranges for building construction and occupancy criteria.

During 1977 through 1979 the U. S. Air Force conducted an intensive survey and analysis program to reduce energy consumption in existing and proposed buildings. Through this energy audit program, a data base for Air Force facilities was developed. From this data base and informal discussions with Air Force Civil Engineering officials, representative building areas and constructions, envelope component U-Values, infiltration rates, and occupancy schedules have been identified for use in this thesis. Tables 4-5a and 4-5b present a listing of the selected variable levels. A weather data base was then developed for BLAST input.

Design days for three daily temperature ranges (Figure 4-4) representative of Spring and Fall weather were generated by examining the 29-year data base recorded by The Pennsylvania State University Department of Meteorology. The extreme high and low recorded temperatures were set as limits for the design days. Steps of 2 F were used to develop 58 different design days, having lows ranging from 18 F to 54 F and highs ranging from 28 F to 84 F. Simulation of the hypothetical test facilities was then performed.

A minimum of ten observations for each proposed model

Table 4-5a

Variable levels tested in BLAST simulations

Run #s	Description	Levels - See Note #1 (* Denotes base condition)		
1 to 8	Area of building (sf)	1800 2450 3200	* 5000 7200 9800	12800 16200 20000
9 to 16	Area of partitions (sf)	0 625 1250	* 1875 2500 3125	3750 4375 5000
17 to 22	Density of partitions (lbs/sf)	6.16 * 12.36	12.5 25.2	32.8 40.7 59.1
23 to 28	Area per occupant (sf/person)	63 75	100 * 125	150 200 inf
29 to 35	Lighting and elec load (watts/sf)	1.5 2.0	2.25 * 2.50 2.75	3.00 3.25 3.91
36 to 46	Site orientation angle (axis angle - Note #2)	0 30	60 * 90	120 150
47 to 49	Occupancy schedule (% lights and people)	0% 6-7am, 100% 7am-5pm * 20% 6-7am, 100% 7am-5pm 0% 7-8am, 100% 8am-5pm 20% 7-8am, 100% 8am-5pm		
50 to 53	Available sunshine (clearness number)	.00	.25 .50	.75 * .98
54	Seasonal difference	Autumn	* Spring	

Note #1 : The base condition is counted as a single simulation and therefore is not represented as a separate run with each description group.

Note #2 : Orientation levels were run at 20% and 60% glass levels.

Table 4-5b

Variable levels tested in BLAST simulations

Run #s -----	Description -----	Levels (* Denotes base condition) -----		
55 to 61	Infiltration/ventilation (air changes/hour)	.25	* .66	1.00
		.50	.75	2.00
			1.00	3.00
62 to 69	Heat recovery option (Note #1)	yes		* no
70 to 74	Total glass (% glass in ext. walls)	10	30	50
		* 20	40	60
75 to 80	South-facing glass (% of south glass)	0	* 20	40
		10	30	50
				60
81 to 86	Shading coefficient (Note #2)	.24	.25	.88 * 1.00
87	Glass U-value	.55		* 1.10
88 to 90	Wall U-value	.0440	.0786	* .1064 .2754
91 to 93	Roof U-value	.0409	.0691	* .0897 .1401
94	Base condition			

Note #1 : Infiltration levels were run at 30% during occupied hours to simulate heat recovery systems.

Note #2 : Shading coefficients were run for 20% and 60% glass levels, and for single and double glazing levels.

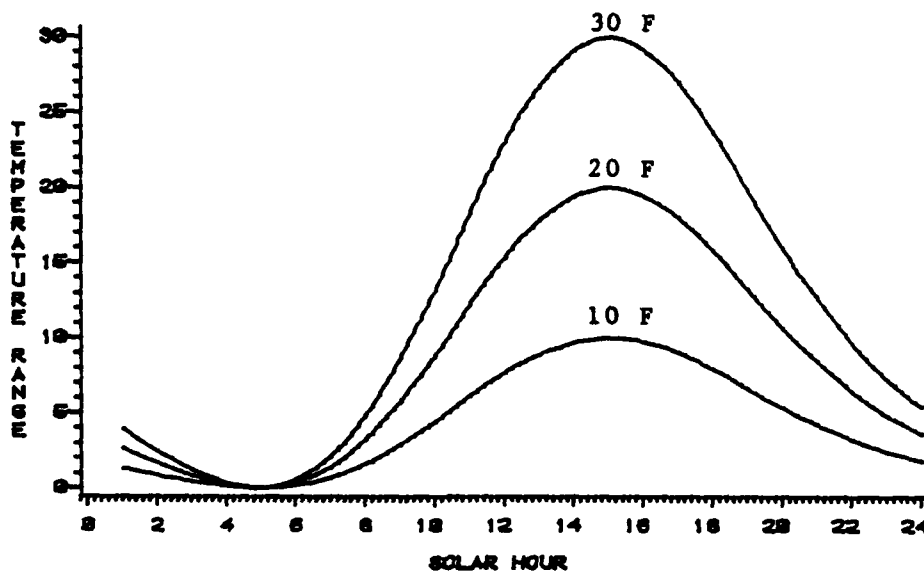


Figure 4-4 Daily temperature profiles

variable is recommended for statistical regression analyses (Draper and Smith, 1981). For the 26 independent and 4 dependent variables, this would require 300 observations. Over 1300 observations were actually recorded so that the variables could be tested at several levels. Validation was also considered prior to data collection.

Model validation requires new observations to prove the stability of a developed regression equation. One of the strongest and statistically useful validation procedures is to use half of the data to generate the equation, and the other half for validation purposes. For this reason, over 2600 observations were collected and divided in half prior to the statistical regression analysis.

Regression Analysis

The regression model building process is a series of development and testing steps. After the variable selection is made, regression equations are formulated and tested against defined goals. The ideal regression equation is not always clear, however. Often a compromise must be made between the accuracy desired and the utility of the final equation. The maximum number of variable terms was limited to 20 or fewer so that the selected regression equations would be relatively simple and easy to use.

Goals were then set for the statistical tests. Any models failing to meet a minimum R^2 value of 0.95 were rejected. Remaining models were tested to meet a Coefficient of Variation of 1.0% or lower. Parameters were then tested for significance with an F test probability level of 0.01%. This regression analysis procedure was followed for each hour from 6-10am. The resultant four regression equations were finally compared for consistency by making certain that the R^2 values did not vary by more than 1.0% for any two models.

Appendix A includes the individual model statistical data for all of the generated predictive models. The detailed results of the analysis approach are described in the following sections for the first hour dependent variable, TEMP6 (6-7am).

Coefficient of Determination

The first step in testing the regression equation was to select only those models with a Coefficient of Determination, or R^2 , of 0.95 as a minimum. One of the most effective statistical methods for this purpose is the STEPWISE procedure available in SAS. Stepwise regression is a selective process which chooses variables for model inclusion based upon their ability to produce a high model R^2 value.

The SAS routine MAXR was selected to perform the stepwise regression analysis. This form of stepwise regression begins with a one variable model having the highest R^2 value and then selectively adds a second variable to give the greatest R^2 increase. As new variables are added, MAXR drops variables in favor of more significant ones so that the "best" R^2 will be achieved for the number of variables present. Table 4-6 shows the results of running MAXR for the dependent variable TEMP6. The R^2 values are listed by the number of variable terms in the model. Although the stated goal of 0.95 was achieved with only 5 variable terms, improvement is seen until 15 terms have been included. All equations meeting the R^2 goal were next tested for error analysis.

Table 4-6 R Squared values for TEMro

Number of Independent Variable Terms	Dropped Variable Terms	Added Variable Terms	R Squared Value
1	---	TAVE	* 0.728
2	---	AIRCH	* 0.883
3	---	SOLAR	* 0.910
4	---	UGLAS	* 0.939
5	---	EGLAS3	0.952
6	---	UWALL	0.961
7	---	TDIFF	0.970
8	---	TGLAS	0.978
9	---	ELEC1	0.983
10	---	UROOF	0.985
11	---	ELEC	0.987
12	---	AIRCH2	0.987
13	---	SGLAS2	0.988
14	SGLAS2	ADPART, ASLAB ^{1/2}	0.990
15	---	SGLAS2	0.991
16	---	INFIL	0.991
17	AIRCH2	ELEC2, AIRCH1	0.991
18	ASLAB1	PEOPLE, ASLAB	0.991
19	---	ASLAB ^{1/2}	0.991
20	---	SHADE	0.991

Note : * Values failed to meet goal of $R^2 \geq 0.95$.

Coefficient of Variation

The maximum value for the Coefficient of Variation was set so that the standard error of the estimate would be no more than 1.0% of the mean response. Two more models were eliminated because they failed to meet this criterion. Table 4-7 lists the results. The remaining equations were tested for parameter significance.

Parameter Significance

The parameter significance F test was set not to exceed a probability of 0.01%. Equations with 18 and 19 variable terms failed this significance test. The remaining equations with from 7 to 17 variable terms met all preliminary goals and were retained for comparison with other dependent variable models. Summary statistics for all models are shown in Table 4-8.

Table 4-7
Coefficient of Variation for TEMP6

Number of Independent Variable Terms	Mean Square Error (MSE)	Standard Error of Estimate (s)	Coeff of Var (C.V.) C.V. = $100*s / \text{Mean}$ (TEMP6 Mean = 60.6 F)
5	0.546	0.739	* 1.219
6	0.447	0.669	* 1.103
7	0.349	0.591	0.975
8	0.256	0.506	0.835
9	0.200	0.447	0.738
10	0.168	0.410	0.676
11	0.155	0.394	0.650
12	0.144	0.379	0.626
13	0.136	0.369	0.609
14	0.117	0.342	0.564
15	0.109	0.330	0.545
16	0.105	0.324	0.535
17	0.102	0.317	0.527
18	0.100	0.316	0.522
19	0.100	0.316	0.522
20	0.099	0.315	0.519

Note : * Values failed to meet goal of C.V. $\leq 1.0\%$

Model Agreement

The last development phase goal was one of model consistency. The goal was set to have all model R^2 values within 1.0% of each other. Figure 4-5 shows a graph of the R^2 values as a function of the number of variable terms in the model. Plateaus in the TEMP6 regression equation can be seen for models with 11 and 15 variable terms. In order to keep the TEMP6 R^2 value within 1.0% of the other equations, the eleven variable term model was selected as the final regression equation.

Table 4-8

Summary statistics for prediction equations

Dependent Variable Term	Number of Independent Variable Terms	R Squared Value	Coeff of Var (C.V.)	Parameters Failing Significance Test
TEMP6	11	0.987	0.650	NONE
TEMP7	15	0.979	0.805	NONE
TEMP8	15	0.982	0.694	NONE
TEMP9	16	0.981	0.732	NONE

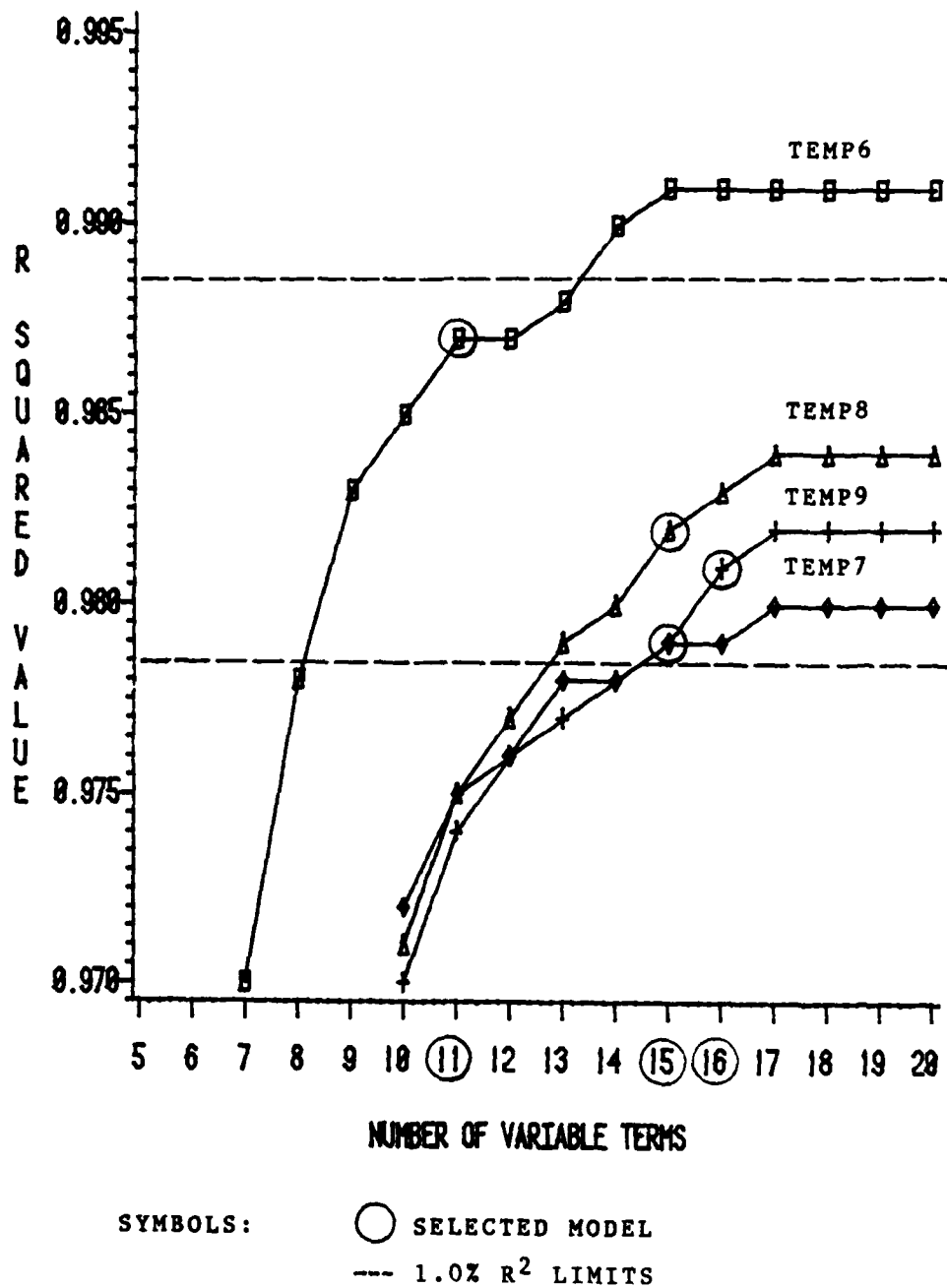


Figure 4-5 Model consistency comparison

The final regression equations for all four hours are then written as:

TEMP6 = (4.4)

$$55.25 - .1841 \text{ * AIRCH} + .2594 \text{ * TAVE} - .08513 \text{ * TDIFF} \\ - .001418 \text{ * TGLAS} + 3.634 \text{ * SOLAR} - 15.029 \text{ * UWALL} - 20.587 \text{ * UROOF} \\ - 4.5821 \text{ * UGLAS} + .7916 \text{ * ELEC} + .4407 \text{ * ELEC1} + .008542 \text{ * EGLAS3},$$

TEMP7 = (4.5)

$$56.64 - .1734 \text{ * AIRCH} + .1388 \text{ * AIRCH1} - 1.214 \text{ * INFIL} + .2720 \text{ * TAVE} \\ - .1007 \text{ * TDIFF} + .01367 \text{ * EGLAS2} + 4.190 \text{ * SOLAR} - 16.424 \text{ * UWALL} \\ - 22.431 \text{ * UROOF} - 5.043 \text{ * UGLAS} + .0454 \text{ * PEOPLE} - .00001926 \text{ * ADPART} \\ + .5775 \text{ * ELEC} + 2.383 \text{ * ELEC1} - .0003305 \text{ * ASLAB},$$

TEMP8 = (4.6)

$$51.07 - .1982 \text{ * AIRCH} + .06307 \text{ * AIRCH1} + .0717 \text{ * AIRCH3} + .3337 \text{ * TAVE} \\ - .02643 \text{ * RANGE} + .002237 \text{ * TGLAS} + .01103 \text{ * EGLAS2} + 4.229 \text{ * SOLAR} \\ - 16.263 \text{ * UWALL} - 25.358 \text{ * UROOF} - 3.9537 \text{ * UGLAS} + .04519 \text{ * PEOPLE} \\ - .00002585 \text{ * ADPART} + 3.102 \text{ * ELEC} - .0003496 \text{ * ASLAB}$$

and

TEMP9 = (4.7)

$$50.51 - .1926 \text{ * AIRCH} + .1353 \text{ * AIRCH3} + .3353 \text{ * TAVE} \\ - .01826 \text{ * RANGE} + .004268 \text{ * TGLAS} + .01348 \text{ * EGLAS2} - .007367 \text{ * EGLAS3} \\ + 5.12 \text{ * SOLAR} - 16.769 \text{ * UWALL} - 25.502 \text{ * UROOF} - 3.8904 \text{ * UGLAS} \\ + .04750 \text{ * PEOPLE} - .00003031 \text{ * ADPART} + 2.821 \text{ * ELEC} + .5003 \text{ * ELEC1} \\ - .0004114 \text{ * ASLAB}.$$

Verification and Validation

Once an equation has met all of the goals set in the planning phase and is considered useful, it should be examined for stability, analyzed for its practicality, and be validated by an accepted method. The stability of a model depends upon the accuracy over its entire range of application. A model appearing to be accurate may still lack precision in a specific range. Verification that this condition does not exist is made by examining plots of the residuals.

Residual Plots

Examination of residuals can offer many insights into a selected model's stability. Residual trends can indicate if important variables have been omitted, if variable transformations are called for, or if the model variance is not constant.

The residuals, or the differences between the observations and the predicted values, are plotted against the dependent variable. Figures 4-6a through 4-6c show residual patterns typically found in regression analyses. If the residuals do not fall within a horizontal band, as in Figure 4-6a, the regression equation may require modification.

The TEMP6 residual plot for the selected regression

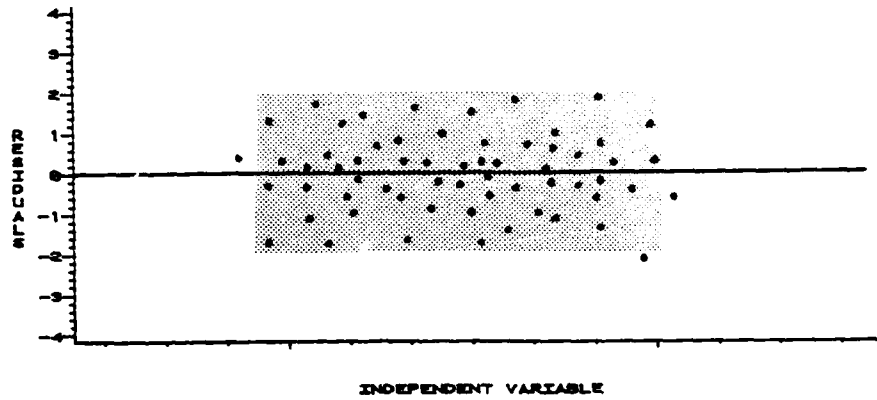


Figure 4-6a Acceptable residual plot

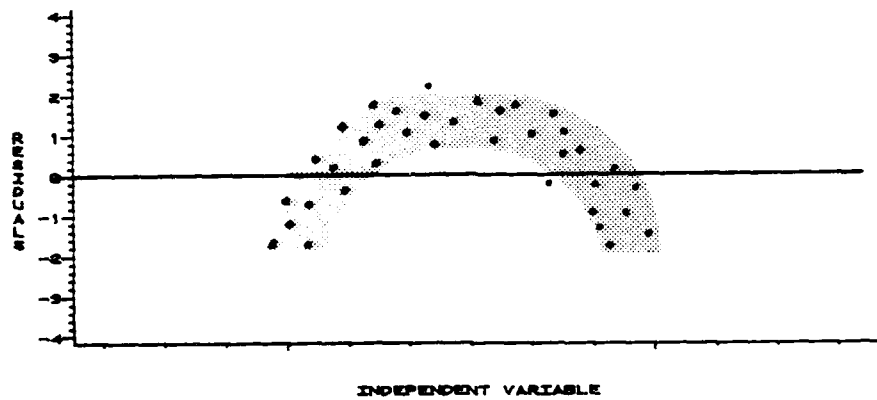


Figure 4-6b Non-linear residual plot

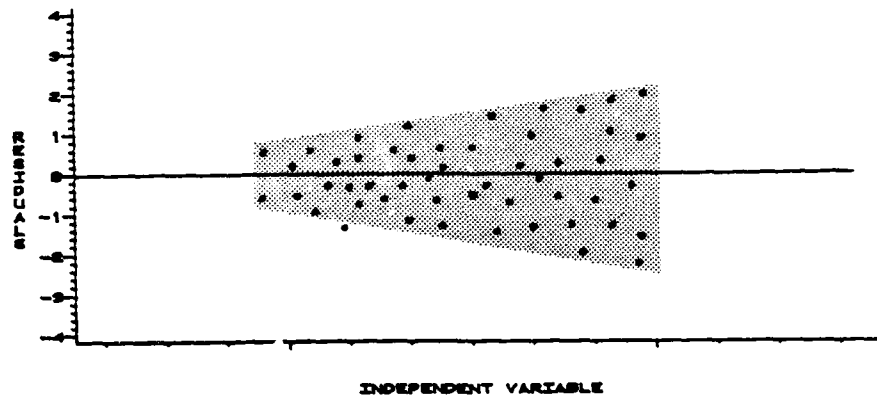


Figure 4-6c Non-constant variance residual plot

equation is shown in Figure 4-7. The pattern shows a central tendency with most points clustered between -1.0 F and +1.0 F. No systematic lack of fit is shown in the residual pattern. Residuals for the remaining dependent variables were plotted, with similar results (See Appendix A). Once the prediction equations have satisfied the statistical requirements, they are analyzed from an engineering perspective to see if underlying functional relationships have been properly reflected.

Model Plausibility

Engineering analysis of a prediction equation should be made by considering the model as a whole. The least squares regression coefficients are determined by adjusting for all model variables. Often in multiple regression models, variables are correlated with each other or with variables not included in the model. It is therefore important to interpret variable coefficients from a perspective of the model as a whole. The parameters which are included in the model should, however, be studied to see if they are plausible and reasonable predictors.

Equation 4.4 (page 54) shows how the building temperature is a function of envelope, occupancy, and site criteria. The 6-7am temperature receives positive temperature gains from solar radiation (SOLAR), average

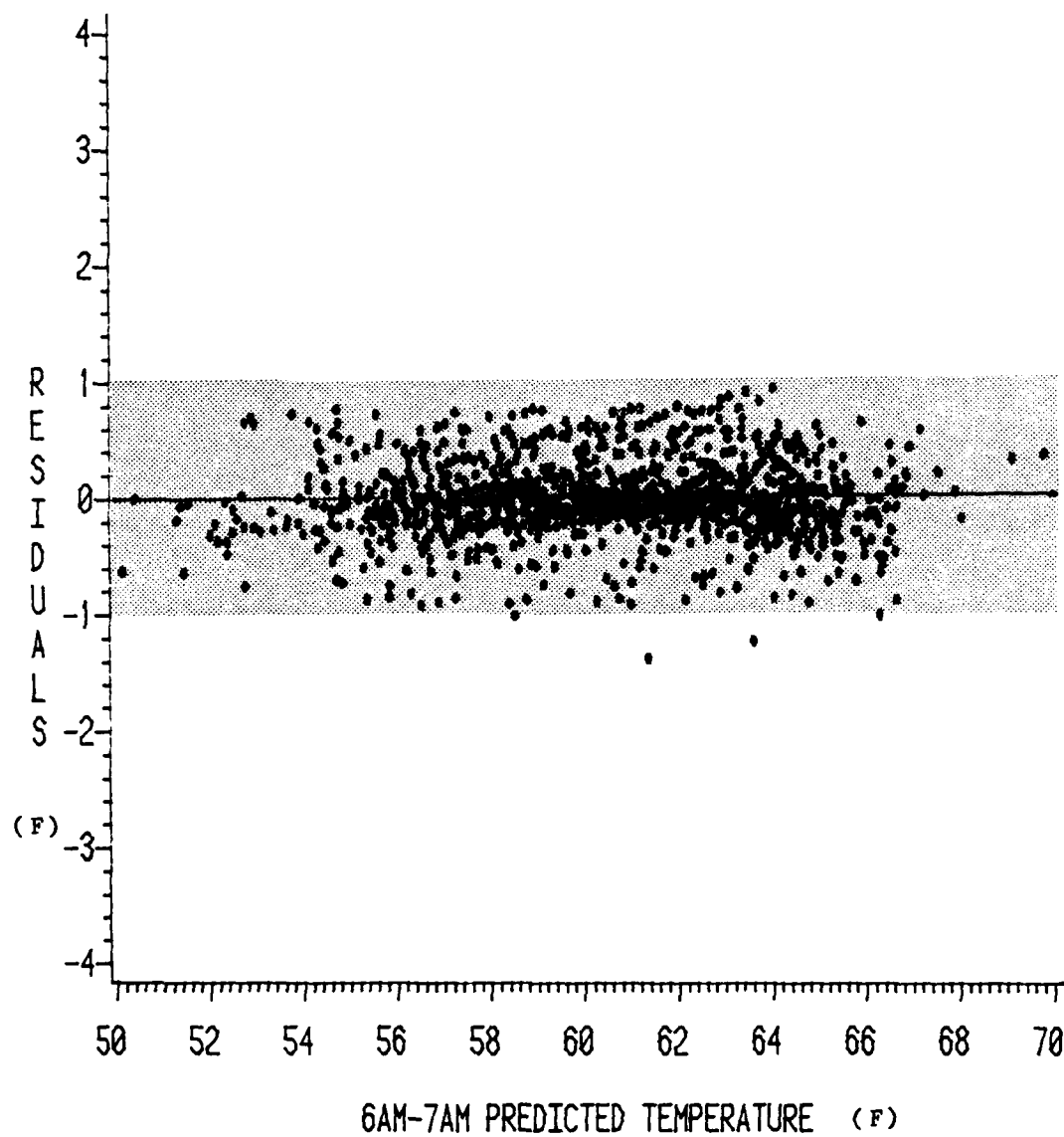


Figure 4-7 TEMP6 residual plot

outdoor temperature (TAVE), east-facing glass (EGLAS3) and internal electric loads (ELEC and ELEC1). Losses are seen in infiltration (AIRCH), the indoor to outdoor temperature difference (TDIFF), the total glass (TGLAS), and the building U-Values (UROOF, UWALL, UGLAS). The variables which are not included in the selected model are also important to consider.

Although R^2 improvement is seen in the TEMP6 equation until 15 variable terms have been included (Table 4-6), the added terms do not improve the model significantly. The infiltration due to a 20% early occupancy option (AIRCH2) and the amount of south-facing glass (SGLAS2) do not substantially affect the calculation of a building temperature. This is possibly due to the fact that the early occupancy does not create a significant infiltration load, and south glass does not receive direct sun until later morning hours. The partitions (ADPART) are not important because by 6-7am most of the stored heat from the previous day has been released to the space. The building area ($ASLAB^{1/2}$) is also unimportant in improving the model predictive ability. Other variable correlations may be causing this. Variable terms which indirectly describe building area are included in the model before the slab area is considered (EGLAS3, TGLAS, SGLAS2, ADPART). They are proportional to the slab area, making $ASLAB^{1/2}$ redundant.

All variables remaining in the selected model are ones developed from steady state heat calculation equations, indicating that the model is both plausible and reasonable from an engineering standpoint. Similar analysis results were concluded after judging the engineering practicality of the remaining models. Before the models can be used confidently, however, they must be validated using new data.

Validation

Validation of a statistical model is a necessary step in the regression process (Draper and Smith, 1981). Even when the selected equation is acceptable in statistical terms, its ability to accurately predict future observations should be tested. At the outset of the model building process, half of the data was reserved for validation purposes. These observations are now used to test the predictive abilities of the model.

Two methods have been used to present the validation summary for the variable TEMP6. Both are intended to describe model accuracy in terms meaningful to the engineer or end user of the equation. The first method defines the model error as a temperature deviation (F) from the BLAST results, and the second method shows the error as a percent of variation. Figure 4-8 shows the frequency distribution for the TEMP6 temperature difference. All observations for

6-7AM TEMPERATURE DIFFERENCE (COMPUTER - PREDICTED)				
(F)	FREQ	CUM. FREQ	Z	CUM. Z
-2.0	0	0	0.00	0.00
-1.9	1	1	0.08	0.08
-1.8	0	1	0.00	0.08
-1.7	0	1	0.00	0.08
-1.6	0	1	0.00	0.08
-1.5	1	2	0.08	0.15
-1.4	1	3	0.08	0.23
-1.3	2	5	0.15	0.38
-1.2	1	6	0.08	0.46
-1.1	2	8	0.15	0.61
-1.0	6	14	0.46	1.07
-0.9	11	25	0.84	1.90
-0.8	28	53	2.13	4.04
-0.7	24	77	1.83	5.86
-0.6	34	111	2.59	8.45
-0.5	40	151	3.05	11.50
-0.4	64	215	4.87	16.37
-0.3	78	293	5.94	22.32
-0.2	130	423	9.90	32.22
-0.1	166	589	12.64	44.86
0.0	175	764	13.33	58.19
0.1	133	897	10.13	68.32
0.2	106	1003	8.07	76.39
0.3	78	1081	5.94	82.33
0.4	69	1150	5.26	87.59
0.5	57	1207	4.34	91.93
0.6	39	1246	2.97	94.90
0.7	24	1270	1.83	96.73
0.8	13	1285	1.14	97.87
0.9	5	1290	0.38	98.25
1.0	8	1298	0.61	98.86
1.1	7	1305	0.53	99.39
1.2	3	1308	0.23	99.62
1.3	2	1310	0.15	99.77
1.4	3	1313	0.23	100.00
1.5	0	1313	0.00	100.00
1.6	0	1313	0.00	100.00
1.7	0	1313	0.00	100.00
1.8	0	1313	0.00	100.00
1.9	0	1313	0.00	100.00
2.0	0	1313	0.00	100.00

Figure 4-8 TEMP6 temperature difference distribution

this hour are within 2 F of the simulated value, indicating a high degree of agreement between the predictive model and the BLAST data. Table 4-9 presents the validation results for all four models, showing the distribution percentages

Table 4-9

Summary of model validations

Description -----	TEMP6 -----	TEMP7 -----	TEMP8 -----	TEMP9 -----
Predictions within 1 F of BLAST	97.8%	91.9%	94.1%	93.3%
Predictions within 2 F of BLAST	100.0%	99.4%	99.5%	98.8%
Maximum difference (BLAST - model)	-1.9 F	+2.6 F	-2.4 F	-2.6 F
Average Error (BLAST - model)/BLAST	0.50%	0.57%	0.48%	0.50%
Maximum Error (BLAST - model)/BLAST	3.1%	3.7%	3.4%	3.6%

Note : Validation data contained 1,313 new observations.

within 1.0 F and 2.0 F. This table also presents the second method, showing the model error as a percentage. The average error is less than 0.60% in all cases, and the maximum error for any observation is only 3.7%.

The prediction equations for all models have proven to be precise and reliable predictors of building temperatures from 6-10am. They now can be integrated into the Trigger Temperature Method and used in changeover analyses.

CHAPTER FIVE

TRIGGER TEMPERATURE METHOD

The Trigger Temperature Method integrates the building temperature prediction equations developed in Chapter Four into a system to determine seasonal changeover timing. This method establishes the weather conditions which cause buildings to fall below a minimum comfort level, or "trigger temperature". Average year weather recorded by The National Oceanic and Atmospheric Administration (NOAA) is used to predict the optimal changeover date. Both hand calculation and computerized methods are available to the user. In this chapter, two example problems are discussed to demonstrate the Trigger Temperature Method capabilities and flexibility.

Weather Input Data

One of the primary concerns in developing a changeover analysis method is the nature of the weather information required. In any energy analysis, weather data should be available and appropriate for the use intended. Daily normal temperature data, developed by NOAA from 30 years of observations, are ideal for changeover purposes. Daily high and low temperatures have been recorded for numerous

locations and compiled into representative "average" weather years. Table 5-1 shows the NOAA daily normal weather data for Harrisburg, Pennsylvania, during February through May. (This table will be used in the example problems discussed later.) NOAA weather information shows the seasonal progression on a daily basis, and thus can be used in changeover estimation methods.

User Requirements

The Trigger Temperature Method provides two procedures for determining changeover timing. If hand calculation methods are required, linear programming techniques can be used to select the changeover date. If micro-computer capability exists, printout options are available to provide changeover decision information. The user flow chart, shown in Figure 5-1, describes the Trigger Temperature Method use. The first step is for the user to set temperature comfort goals. The Trigger Temperature Method determines a changeover date for a facility based upon minimum building temperatures specified by the user. Trigger temperatures are set for each hour to be studied. This is a minimum of two hours - the threshold hour when occupancy begins, and the upper limit when the normal desired building temperature has been reached. The threshold Trigger Temperature would normally be set at the thermostat night setback temperature.

Table 5-1

Daily normals of temperature for Harrisburg, Pa

(NOAA Environmental Data Service, 1973)

Day	February			March			April			May		
	Julian date	Max	Min	Julian date	Max	Min	Julian date	Max	Min	Julian date	Max	Min
1	32	38	23	60	44	27	91	58	37	121	70	47
2	33	38	23	61	45	27	92	58	37	122	70	47
3	34	38	23	62	45	27	93	59	37	123	70	47
4	35	39	23	63	46	28	94	59	38	124	71	48
5	36	39	23	64	46	28	95	60	38	125	71	48
6	37	39	23	65	46	28	96	60	38	126	71	48
7	38	39	23	66	47	28	97	61	39	127	72	49
8	39	39	23	67	47	29	98	61	39	128	72	49
9	40	39	23	68	48	29	99	62	39	129	72	49
10	41	39	23	69	48	29	100	62	40	130	73	50
11	42	39	23	70	48	30	101	62	40	131	73	50
12	43	40	23	71	49	30	102	63	40	132	73	50
13	44	40	23	72	49	30	103	63	41	133	74	51
14	45	40	24	73	50	30	104	64	41	134	74	51
15	46	40	24	74	50	31	105	64	41	135	74	51
16	47	40	24	75	51	31	106	65	42	136	75	51
17	48	41	24	76	51	31	107	65	42	137	75	52
18	49	41	24	77	51	32	108	65	42	138	75	52
19	50	41	24	78	52	32	109	66	43	139	75	52
20	51	42	25	79	52	32	110	66	43	140	76	53
21	52	42	25	80	53	33	111	66	43	141	76	53
22	53	42	25	81	53	33	112	67	44	142	76	54
23	54	42	25	82	54	33	113	67	44	143	77	54
24	55	43	25	83	54	34	114	67	44	144	77	54
25	56	43	26	84	55	34	115	68	45	145	77	55
26	57	43	26	85	55	34	116	68	45	146	78	55
27	58	44	26	86	56	35	117	69	45	147	78	55
28	59	44	26	87	56	35	118	69	46	148	78	56
29				88	57	35	119	69	46	149	79	56
30				89	57	36	120	70	46	150	79	56
31				90	57	36				151	79	57

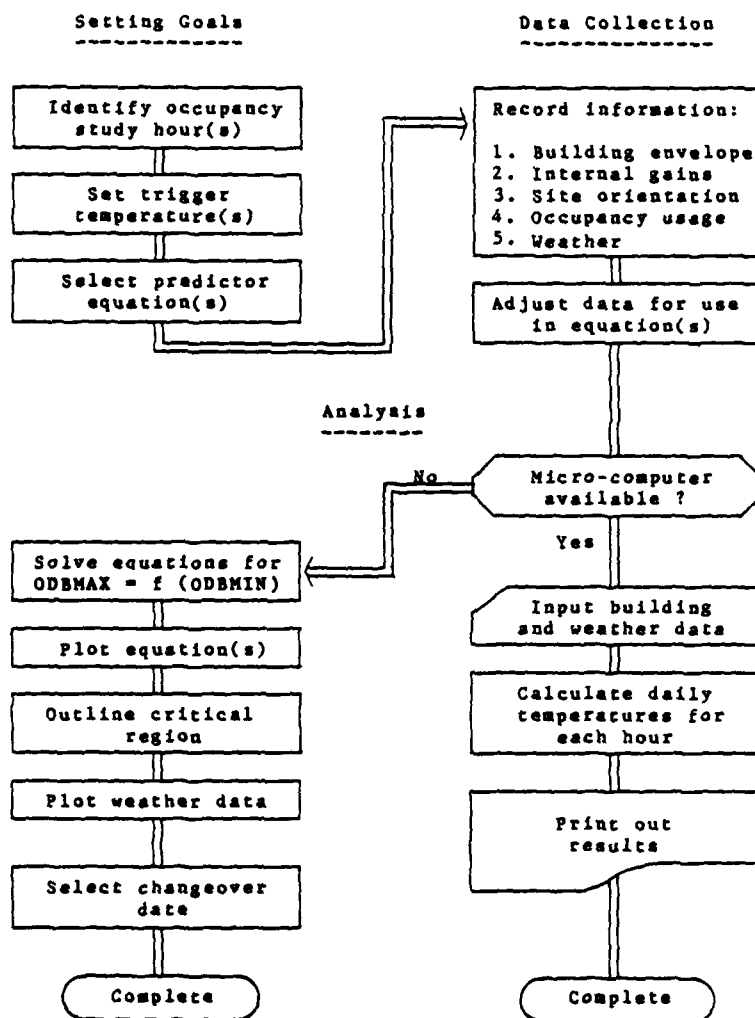


Figure 5-1 Trigger Temperature Method flow chart

The upper limit temperature can be set at any value and for any hour after occupancy begins. The user also has the option of studying any intermediate occupancy hour to see how the building warmup is progressing. After determining the hours to be studied, the user selects the appropriate predictor equations and reviews the building and site characteristics which need to be recorded. The next step is the collection of data required for input into the predictor equations. Weather data for the selected location are gathered (NOAA Environmental Data Service, 1973), and the specific building characteristics are recorded.

Example Problems

Two example problems are developed to demonstrate the different methods available to the user. The building input data for both example problems are presented in Table 5-2.

Problem #1

The first example uses linear programming techniques and hand calculations to determine the Spring changeover date for a hypothetical 5000 sf office building in Harrisburg, Pennsylvania. Although this analysis is made to determine when heating could be turned off in the Spring, a similar procedure would apply for turning the heat on in the Fall. Occupancy hours of 7am-5pm in this example permit

Table 5-2
Building data for example problems

Variable -----	Description/Unit -----	Value -----
APART	Area of partitions (sf)	1875
ASLAB	Area of building slab (sf)	5000
DPART	Density of partitions (lbs/sf)	12.5
EGLAS	Projected area of east glass (sf)	90
ELEC	Lights, equip gains (watts/sf)	2.0
HVAC	Heat recovery system (no)	0
INFIL	Infiltration air changes/hour	.750
PEOPLE	Number of occupants	45
SCHED1	Occupancy hours (7am- 5pm)	1
SGLAS	Projected area of south glass (sf)	180
SHADE	Glass shading coefficient	0.88
SOLAR	Clearness number (fraction)	.50
TGLAS	Area of total glass (sf)	540
UGLAS	Glass U-value (Btu/hr*F*sf)	0.55
UROOF	Roof U-value (Btu/hr*F*sf)	.0897
UWALL	Wall U-value (Btu/hr*F*sf)	.1063

analysis of four hours, 6-10am. For this problem, trigger temperatures have been set as follows:

Trigger Temperature				Variable
55	F	for	6-7am	TEMP6
68	F	for	7-8am	TEMP7
70	F	for	8-9am	TEMP8
72	F	for	9-10am	TEMP9

By substituting into the prediction equations from page 54 and solving in terms of $ODBMAX = f(ODBMIN)$, where $ODBMAX$ and $ODBMIN$ are the outdoor dry bulb high and low daily temperatures, the prediction equations are reduced to ones having with only two variables:

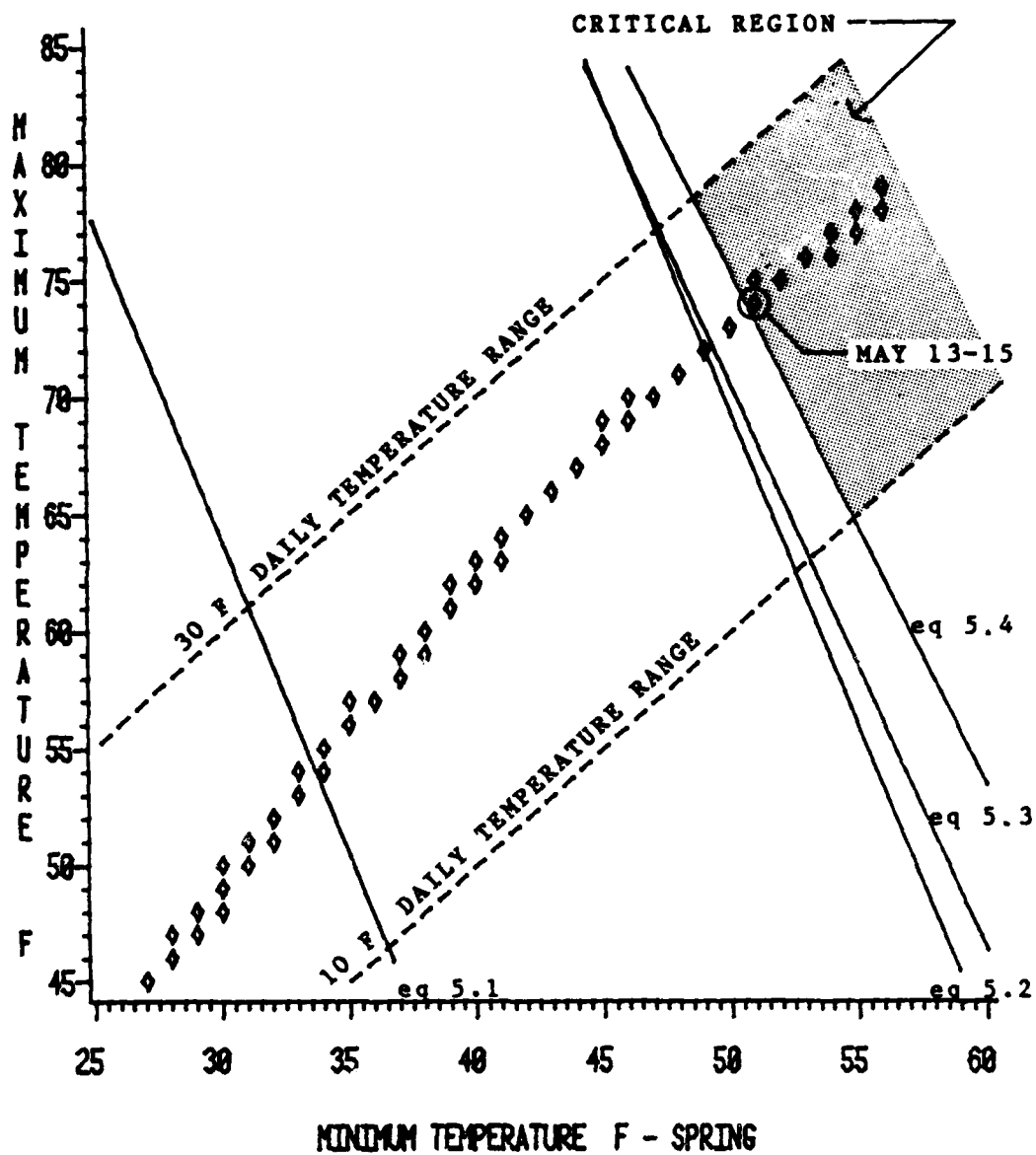
$$ODBMAX = -2.721 * ODBMIN + 145.6 \quad (6-7am) \quad (5.1)$$

$$ODBMAX = -2.696 * ODBMIN + 204.2 \quad (7-8am) \quad (5.2)$$

$$ODBMAX = -2.424 * ODBMIN + 192.4 \quad (8-9am) \quad (5.3)$$

$$ODBMAX = -2.211 * ODBMIN + 186.1 \quad (9-10am) \quad (5.4)$$

These equations can then be graphed, as shown in Figure 5-2. Dashed lines show 10 F and 30 F daily temperature ranges, the limits for which the prediction models were validated. The Trigger Temperature lines are plotted next to determine the critical area during which heat will not be required. (The critical area is shown in Figure 5-2 as a gray band.) The user then selects possible changeover dates from Spring weather days which fall in the critical region.



SYMBOLS : ♦ HARRISONBURG DAILY NORMAL TEMPS (NOAA)

Figure 5-2 Spring changeover graph

Problem #2

Although hand calculation procedures provide a quick and simple method to determine changeover timing, the user may want to consider hourly building temperature profiles when making changeover decisions. This would involve calculating the hourly building temperatures throughout the entire transitional season. Although this can be done with hand calculation or programmable calculator methods, it is a tedious and time consuming process which could be conveniently handled by a micro-computer.

In this example problem, the same hypothetical office building has been used, but the trigger temperatures now have been set at 55 F and 68 F for all hours. For the computer application of the Trigger Temperature Method, the user inputs the weather as well as the building data, indicating the trigger temperatures and applicable hours to be studied. The summary output (Figure 5-3) selects the weather days for which the most stringent trigger temperature condition is met and marks (*) the satisfactory building temperatures. The temperature profile output (Figure 5-4) graphically plots the hourly building temperatures during the transitional season being studied. With micro-computer applications, the user is able to select a changeover date from the hourly temperature profiles.

TRIGGER TEMPS					*****				
55 F					TRIGGER TEMPERATURE CHANGEOVER METHOD				
68 F					EXAMPLE PROBLEM ----- OFFICE BUILDING				
*****					*****				
*****					BUILDING LOCATION - HARRISBURG, PA				
*****					CLEARNESS NUMBER = 0.50				
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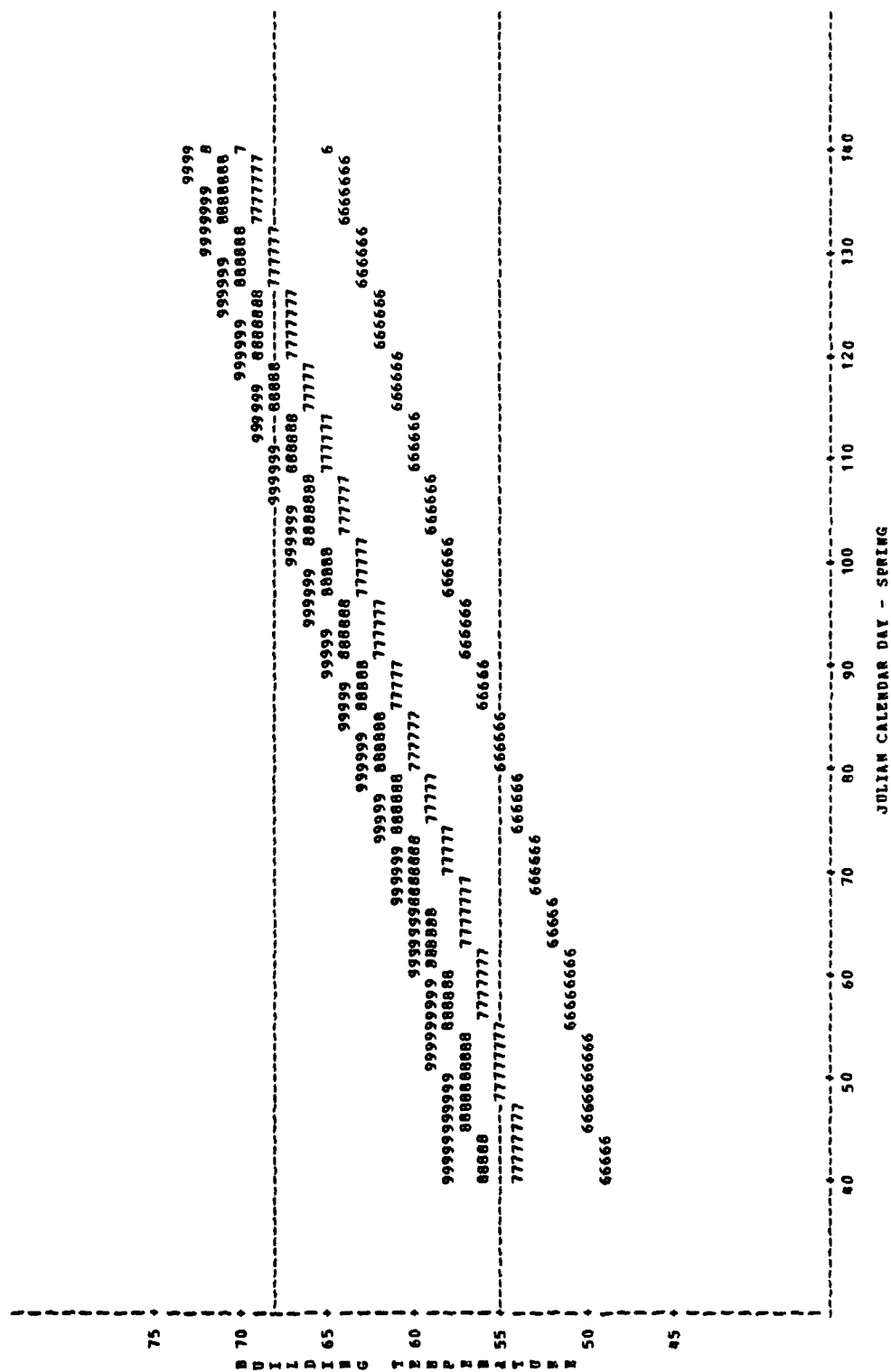


Figure 5-4 Temperature profile computer output

Range of Application

As demonstrated by the two previous example problems, the Trigger Temperature Method provides a valuable tool for facility managers or engineers to evaluate heating needs during Fall and Spring seasons. This methodology is based upon maintaining a user defined comfort level when the building does not benefit from an available heating system. It can provide accurate and useful results when applied within the conditions for which the prediction models have been validated. The user must be careful to limit applications of the Trigger Temperature Method to those within the range of applications listed in Table 5-3.

Table 5-3

Trigger Temperature Method range of application

I N D E P E N D E N T V A R I A B L E S

Description/Units	Minimum	Maximum
B u i l d i n g e n v e l o p e		
Wall U-value (Btu/hr*F*sf)	0.0440	0.2754
Roof U-value (Btu/hr*F*sf)	0.0409	0.1401
Glass U-value (Btu/hr*F*sf)	0.58	1.10
South glass (% of south wall)	10	60
East glass (% of east wall)	10	60
Total glass (% of gross wall area)	10	60
Glass shading coefficient	0.24	1.0
Masonry construction (density lbs/sf)	50	100
I n t e r n a l G a i n s		
Lights, equip gains (watts/sf)	1.5	3.9
Infiltration (air changes/hr)	0.25	3.0
Occupancy schedule	7am-5pm	8am-5pm
Occupants (people/1000 sf)	0	14
Area of partitions (sf)	0	15700
Density of partitions (lbs/sf)	6.16	59.1
Heat recovery system (70 % eff)	no	yes
W e a t h e r F a c t o r s		
Clearness number (fraction)	0.00	0.98
Ground temperature (F)	44	59
Outdoor dry bulb temp max (F)	28	84
Outdoor dry bulb temp min (F)	18	54
Daily temp range (F)	10	30

D E P E N D E N T V A R I A B L E S

Variable	Description/Units	Minimum	Maximum
TEMP6	Indoor temp from 6-7am (F)	47	69
TEMP7	Indoor temp from 7-8am (F)	52	> 78
TEMP8	Indoor temp from 8-9am (F)	54	> 78
TEMP9	Indoor temp from 9-10am (F)	56	> 78

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Summary

Existing methods which could be used for changeover estimation have serious deficiencies in accuracy and application. Steady state heating load calculation procedures lack precision in calculating hourly building temperatures because solar gains and building capacitance effects are not considered. Computer simulations perform accurate heat transfer analyses, but are time consuming and expensive to use.

Changeover decisions are usually the responsibility of a facility manager. A methodology to determine changeover timing should provide the facility manager a procedure to maximize energy savings without sacrificing building occupant comfort. It should be flexible and precise, yet simply applied by engineers and non-engineers alike.

Conclusions

The key concern in a changeover method is the level of occupant thermal comfort. Changeover timing can be

developed in terms of an occupant comfort threshold, or "trigger temperature". When comfort conditions can be maintained without mechanical heating, changeover can be made.

Statistical analysis methods can be used to determine the weather, building envelope, and occupant use characteristics critical to facilities during transitional seasons. Through multiple regression techniques, prediction equations can be generated to calculate building temperatures.

The Trigger Temperature Method provides an accurate, yet straightforward method for changeover determination. User input information is tailored to use widely available weather data and engineering standardized building envelope descriptions. Both hand calculation and micro-computer applications are offered.

Recommendations for Future Study

The Trigger Temperature Method should be extended to include different building types and occupancies. The BLAST simulated data base should be enlarged to encompass varying envelope constructions, floor plan layouts, and occupancy schedules. Multiple regression analysis methods should be used to evaluate new variables and develop broader, more general prediction equations.

Changeover criteria for air-conditioning should be developed. Trigger temperature concepts can be extended to describe cooling equipment changeover timing in terms of occupant comfort.

Comfort conditions for facility occupants should be expanded to consider the mean radiant temperature effects in a building. Trigger temperatures can be described in terms of the operative temperatures to more effectively assess occupant comfort.

Sensitivity analyses should be made to study how thermal storage may be designed to boost morning building temperatures. Thermal flywheel effects could significantly alter changeover conditions, offering an extended application for the Trigger Temperature Method.

Probability studies should be performed on multi-year weather data. Trigger Temperature prediction models should be used to assign probability risk factors associated with each calendar date.

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APPENDIX A

MODEL DEVELOPMENT STATISTICS

The Trigger Temperature Method uses statistical prediction models to determine building temperatures from 6-10am. The prediction models were developed from multiple regression analysis of Building Loads Analysis and System Thermodynamics (BLAST) computer simulations.

Regression Statistics

Regression models were developed and tested against goals defined for three statistics:

1. Coefficient of Determination (R^2)
2. Coefficient of Variation (C.V.)
3. F test for parameter significance

This appendix presents the statistical analysis results used to select the final prediction models. Individual model statistics and residual plots are included. The individual model statistics are presented in Tables A-1 through A-4. Residual plots are shown in Figures A-1 through A-4. User information and variable descriptions are included in Appendix B.

Table A-1 TEMP6 regression statistics

Number of Independent Variable Terms	Dropped Variable Terms	Added Variable Terms	Variable Terms Failing F test	R Squared Value	C. V. Value
1	---	TAVE	---	0.728	2.909
2	---	AIRCH	---	0.883	1.904
3	---	SOLAR	---	0.910	1.676
4	---	UGLAS	---	0.939	1.376
5	---	EGLAS3	---	0.952	1.219
6	---	UWALL	---	0.961	1.103
7	---	TDIFF	---	0.970	0.975
8	---	TGLAS	---	0.978	0.835
9	---	ELEC1	---	0.983	0.738
10	---	UROOF	---	0.985	0.676
11	---	ELEC	---	0.987	0.650
12	---	AIRCH2	---	0.987	0.626
13	---	SGLAS2	---	0.988	0.609
14		ADPART			
14	SGLAS2	ASLAB ^{1/2}	---	0.990	0.564
15	---	SGLAS2	---	0.991	0.545
16	---	INFIL	---	0.991	0.535
17		ELEC2			
17	AIRCH2	AIRCH1	---	0.991	0.527
18		PEOPLE			
18	ASLAB ^{1/2}	ASLAB	---	0.991	0.522
19		ASLAB			
19	---	ASLAB ^{1/2}	ASLAB ^{1/2}	0.991	0.522
20		ASLAB			
20		ASLAB ^{1/2}			
20	---	SHADE	SHADE	0.991	0.519

Table A-2 TEMP7 regression statistics

Number of Independent Variable Terms	Dropped Variable Terms	Added Variable Terms	Variable Terms Failing F test	R Squared Value	C. V. Value
1	---	TAVE	---	0.487	3.953
2	---	EGLAS2	---	0.673	3.157
3	---	ELEC1	---	0.796	2.493
4	---	AIRCH	---	0.889	1.841
5	---	AIRCH1	---	0.921	1.553
6	---	UGLAS	---	0.938	1.382
7	---	SOLAR	---	0.956	1.166
8	---	UWALL	---	0.964	1.054
9	---	ADPART	---	0.969	0.977
10	---	TDIFF	---	0.972	0.919
11	---	UROOF	---	0.975	0.875
12	---	PEOPLE	---	0.976	0.861
13	---	ASLAB	---	0.978	0.826
14	---	INFIL	---	0.978	0.815
15	---	ELEC	---	0.979	0.805
16	---	SGLAS1	---	0.979	0.799
17	---	AIRCH2	---	0.980	0.795
18		SHADE			
18	SGLAS1	SGLAS2	---	0.980	0.792
19	---	TGLAS	TGLAS	0.980	0.791
20			TGLAS		
20			EGLAS3		
20	---	EGLAS3	SHADE	0.980	0.790

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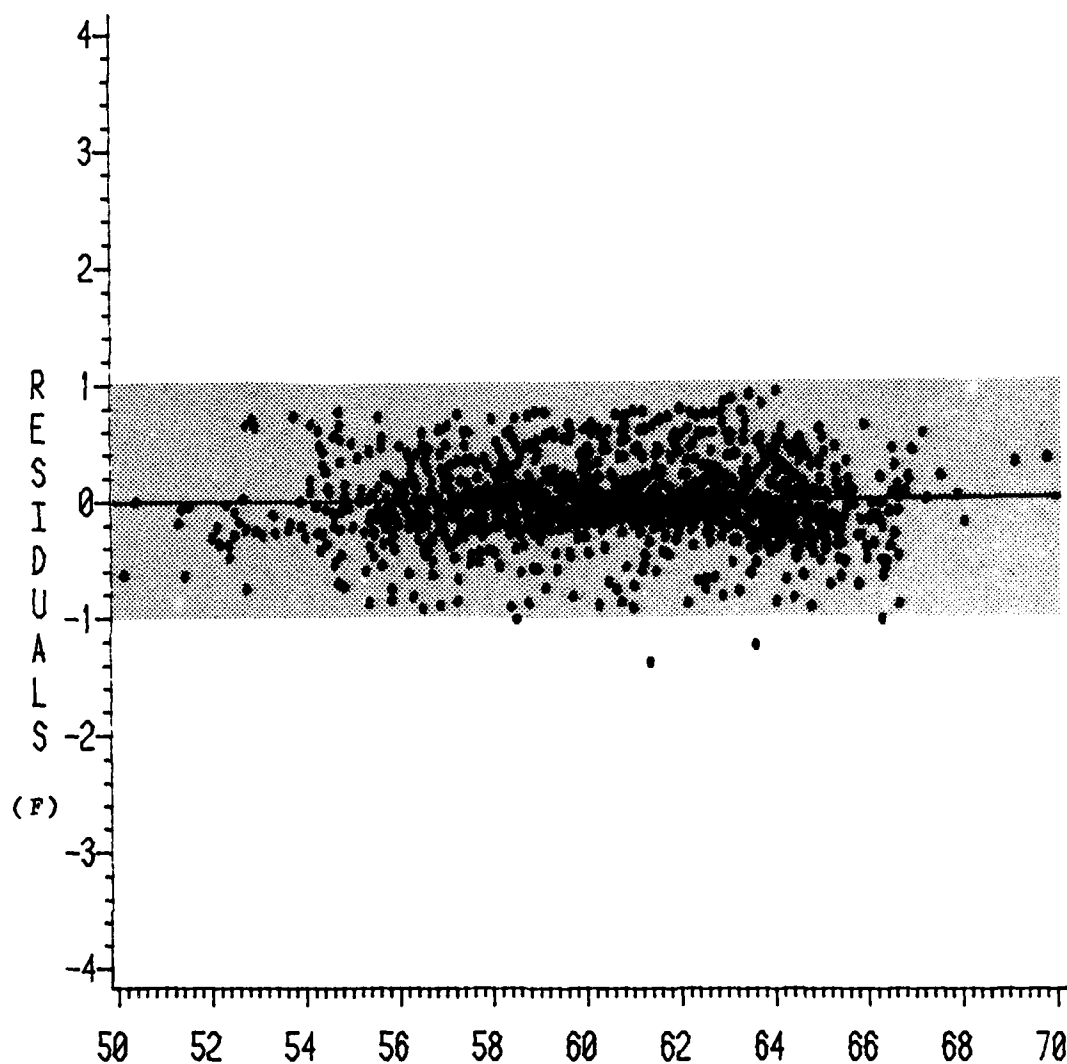
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Table A-3 TEMP8 regression statistics

Number of Independent Variable Terms	Dropped Variable Terms	Added Variable Terms	Variable Terms Failing F test	R Squared Value	C. V. Value
1	---	TAVE	---	0.517	3.571
2	---	EGLAS2	---	0.794	2.332
3	---	AIRCH	---	0.873	1.835
4	---	AIRCH3	---	0.905	1.584
5	---	ELEC	---	0.921	1.447
6	---	SOLAR	---	0.935	1.315
7	---	UWALL	---	0.943	1.225
8		ADPART			
8	AIRCH3	AIRCH1	---	0.952	1.129
9		UGLAS			
9	UWALL	TGLAS	---	0.962	1.002
10	---	UWALL	---	0.971	0.875
11	---	UROOF	---	0.975	0.820
12		AIRCH3			
12	AIRCH1	RANGE	---	0.977	0.785
13	---	AIRCH1	---	0.979	0.744
14	---	SHADE	---	0.980	0.723
15		PEOPLE			
15	SHADE	ASLAB	---	0.982	0.694
16	---	EGLAS3	---	0.983	0.670
17	---	INFIL	---	0.984	0.662
18			SHADE		
18	---	SHADE	EGLAS3	0.984	0.660
19			SHADE		
19			EGLAS3		
19	---	ELEC2	ELEC2	0.984	0.660
20			SHADE		
20			EGLAS3		
20			ELEC2		
20	---	SGLAS1	SGLAS1	0.984	0.660

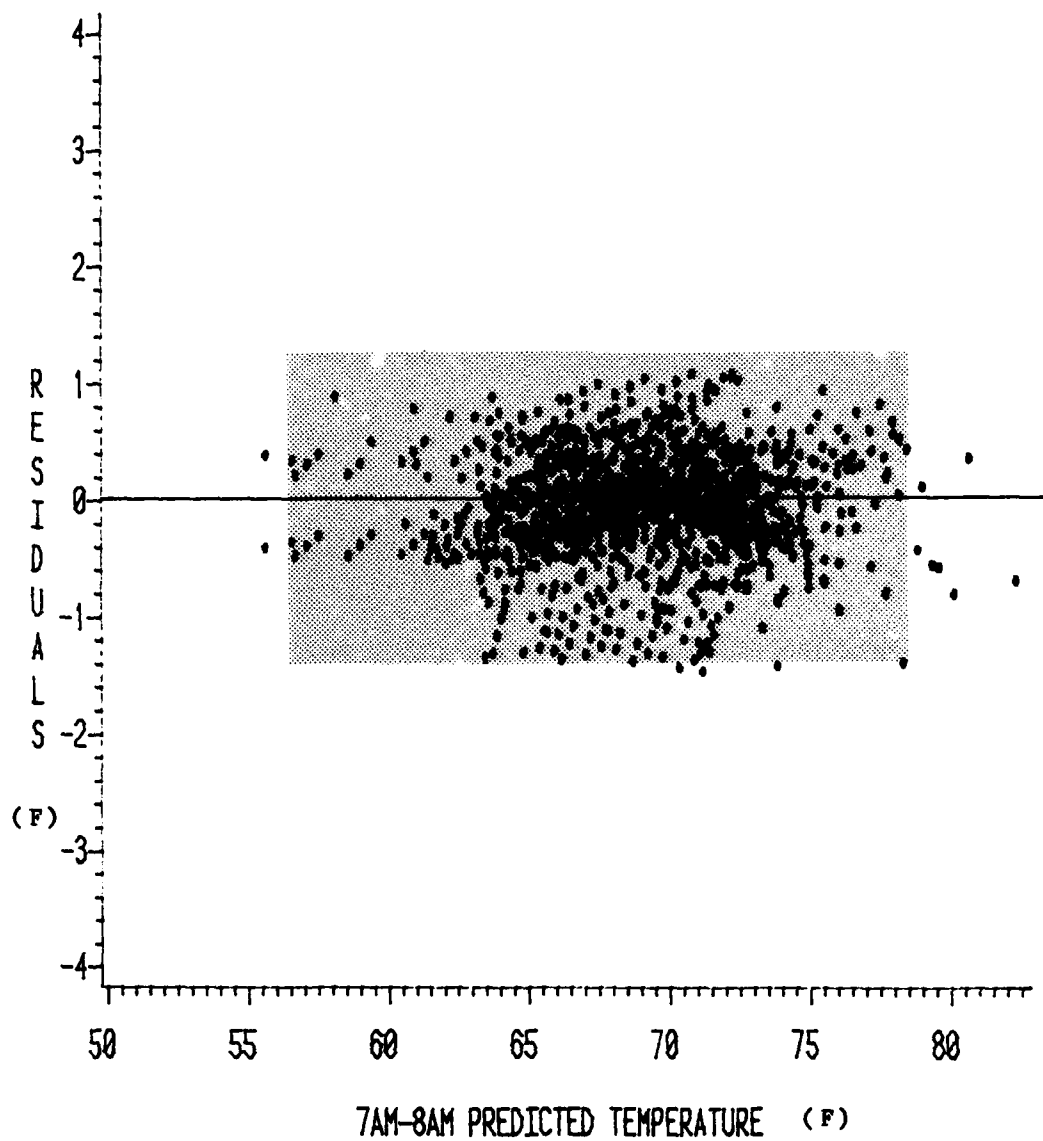
Table A-4 TEMP9 regression statistics

Number of Independent Variable Terms	Dropped Variable Terms	Added Variable Terms	Variable Terms Failing F test	R Squared Value	C. V. Value
1	---	TAVE	---	0.468	3.870
2	---	TGLAS	---	0.782	2.478
3	---	AIRCH	---	0.841	2.116
4	---	SOLAR	---	0.873	1.892
5	---	AIRCH1	---	0.904	1.645
6	---	ADPART	---	0.927	1.439
7	---	ELEC	---	0.944	1.262
8	---	UGLAS	---	0.956	1.119
9	---	UWALL	---	0.965	1.003
10	---	EGLAS2	---	0.970	0.917
11	---	UROOF	---	0.974	0.866
12	---	EGLAS3	---	0.976	0.828
13	---	AIRCH3	---	0.977	0.804
14		RANGE			
14	AIRCH1	ELEC1	---	0.978	0.785
15	---	INFIL	---	0.979	0.779
16		ASLAB ^{1/2}			
16	INFIL	PEOPLE			
16	ASLAB ^{1/2}	ASLAB	---	0.981	0.732
17	---	INFIL	---	0.982	0.725
18	---	ASLAB ^{1/2}	---	0.982	0.719
19	---	SGLAS1	SGLAS1	0.982	0.718
20	---	SHADE	SGLAS1	0.982	0.717
20			SHADE		

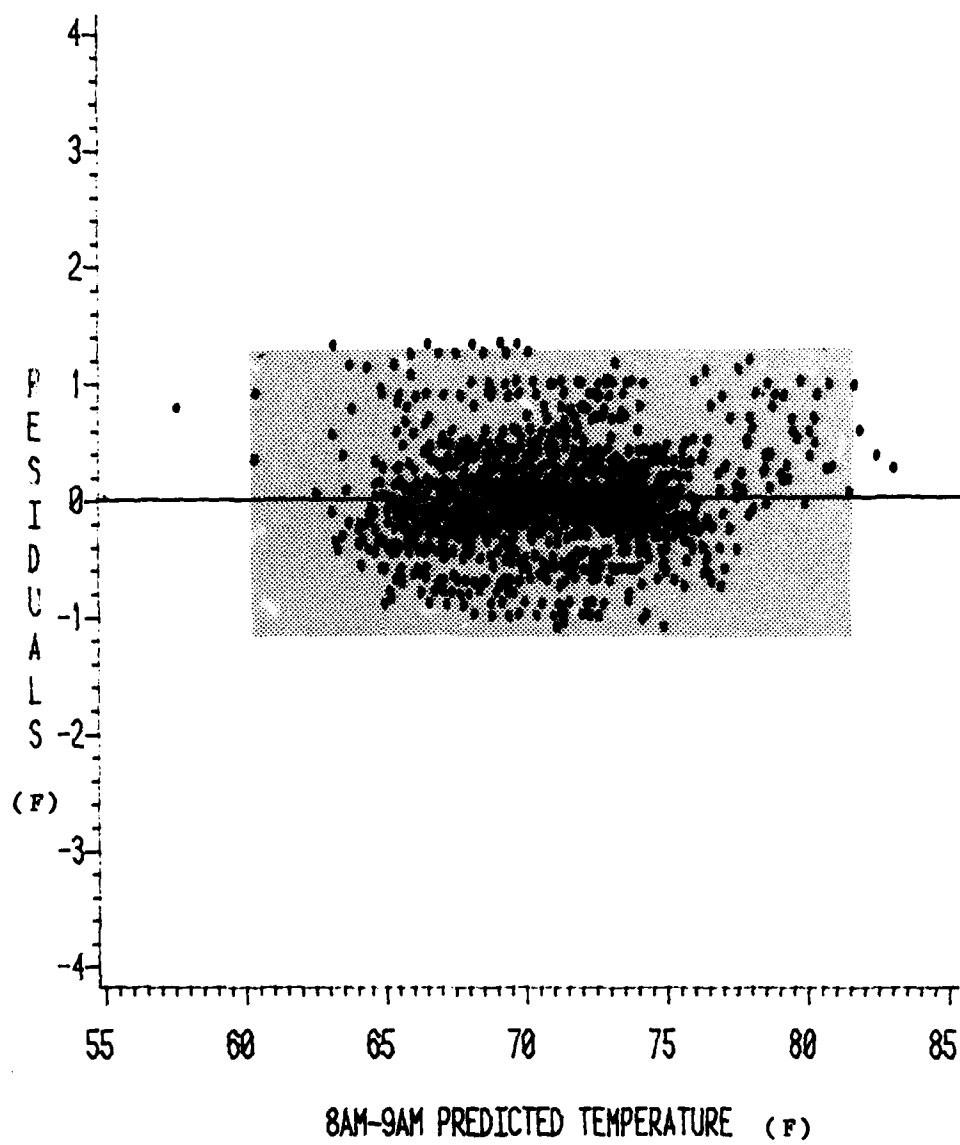


6AM-7AM PREDICTED TEMPERATURE (F)

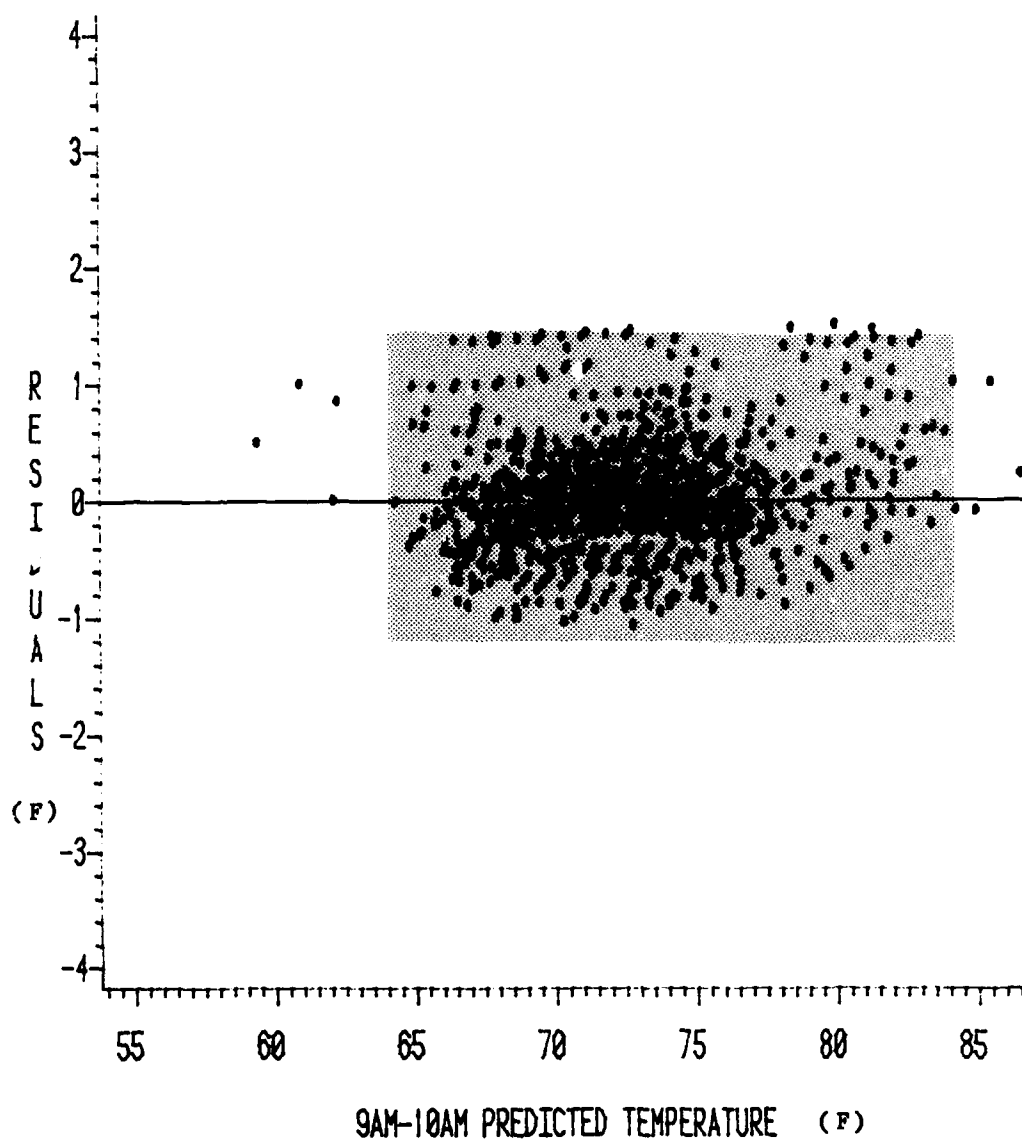
TEMP6 residual plot



TEMP7 residual plot



TEMP8 residual plot



TEMP9 residual plot

APPENDIX B

USER INPUT INFORMATION

This appendix provides user input information for the Trigger Temperature Method. Descriptions of the variables and the prediction equations for the hours of 6-10am are included.

Variable Information

Two types of variables are used in the Trigger Temperature Method prediction equations. Continuous variables are expressed in the engineering units shown in Table B-1. Indicator variables are used to describe several building operation schedule options. Tables B-2 and B-3 present user information for the two indicator variables included in the prediction equations.

Prediction Equations

The statistical regression analysis described in Chapter Four, developed the final prediction equations as a function of variables and transformations (variable terms). In order to simplify the procedures which would be required for hand calculation methods, all prediction equations have

been expressed in terms of single variables only. Final model prediction equations are listed in Table B-4.

Table B-1
Continuous Variables

Variable -----	Description -----	Units -----
APART	Area of partitions	sf
ASLAB	Area of building slab	sf
DPART	Density of partitions	lbs/cf
EGLAS	Projected area of east glass	sf
ELEC	Lights and equip gains	watts/sf
INFIL	Infiltration	air changes/hour
SGLAS	Projected area of south glass	sf
SHADE	Glass shading coefficient	fraction
SOLAR	Clearness number	fraction
TGLAS	Area of total glass	sf
ODBMAX	Outdoor dry bulb temp max	F
ODBMIN	Outdoor dry bulb temp min	F
UGLAS	Glass U-value	Btu/hr*F*sf
UROOF	Roof U-value	Btu/hr*F*sf
UWALL	Wall U-value	Btu/hr*F*sf

Table B-2

Final model indicator variables

Variable Value	Description (use)
HVAC	(Heat recovery system option)
0	No heat recovery system available
1	70% efficient heat recovery system (Recaptures heat by warming ventilation air)
SCHED1	(Hours of full occupancy and lighting)
0	8am to 5pm - 100% occupancy and lighting loads
1	7am to 5pm - 100% occupancy and lighting loads

Table B-3

Building schedule options

Variable Values	Schedule Option	Solar time	06-07	07-08	08-17	17-06
SCHED1 = 0 HVAC = 0	1	People %	0	0	100	0
		Lights %	5	20	100	5
		Recov. %	0	0	0	0
SCHED1 = 0 HVAC = 1	2	People %	0	0	100	0
		Lights %	5	20	100	5
		Recov. %	0	70	70	0
SCHED1 = 1 HVAC = 0	3	People %	0	100	100	0
		Lights %	20	100	100	5
		Recov. %	0	0	0	0
SCHED1 = 1 HVAC = 1	4	People %	0	100	100	0
		Lights %	20	100	100	5
		Recov. %	0	70	70	0

Table B-4

Trigger Temperature prediction equations

TEMP6 =

$$\begin{aligned}
 &49.72 + \text{ODBMIN}*(.2148 + .1841*\text{INFIL}) + .1297*\text{ODBMAX} \\
 &-11.97*\text{INFIL} + \text{SOLAR}*(3.634 + .008542*\text{EGLAS}*\text{SHADE}) \\
 &-.001418*\text{TGLAS} - 20.587*\text{UROOF} - 15.029*\text{UWALL} \\
 &-4.5821*\text{UGLAS} + \text{ELEC}*(.7916 + .4407*\text{SCHED1})
 \end{aligned}$$

TEMP7 =

$$\begin{aligned}
 &50.10 + \text{INFIL}*(-12.48 + 9.019*\text{HVAC}*\text{SCHED1}) \\
 &+\text{ODBMIN}*(.2367 + \text{INFIL}*(.1734 - .1388*\text{HVAC}*\text{SCHED1})) \\
 &+.1360*\text{ODBMAX} + \text{SOLAR}*(4.19 + .01367*\text{EGLAS}) - 22.431*\text{UROOF} \\
 &-16.424*\text{UWALL} - 5.0432*\text{UGLAS} - 1.926*\text{APART}*\text{DPART}*10^{*-5} \\
 &+\text{ELEC}*(.5775 + 2.383*\text{SCHED1}) - 33.05*\text{ASLAB}*10^{*-5} \\
 &+.0454*\text{PEOPLE}
 \end{aligned}$$

TEMP8 =

$$\begin{aligned}
 &51.07 + \text{INFIL}*(-12.88 + \text{HVAC}*(4.661 + 4.010*\text{SCHED1})) \\
 &+\text{ODBMIN}*(.1933 + \text{INFIL}*(.1982 - \text{HVAC}*(.0717 + .06309*\text{SCHED1}))) \\
 &+.1404*\text{ODBMAX} + \text{SOLAR}*(4.229 + .01103*\text{EGLAS}) + .002237*\text{TGLAS} \\
 &-25.358*\text{UROOF} - 16.263*\text{UWALL} - 3.9537*\text{UGLAS} + .04519*\text{PEOPLE} \\
 &-2.585*\text{APART}*\text{DPART}*10^{*-5} + 3.102*\text{ELEC} - 34.96*\text{ASLAB}*10^{*-5}
 \end{aligned}$$

TEMP9 =

$$\begin{aligned}
 &50.51 + \text{ODBMIN}*(.1859 + \text{INFIL}*(.1926 - .1353*\text{HVAC})) \\
 &+.1494*\text{ODBMAX} + \text{INFIL}*(-12.52 + 8.794*\text{HVAC}) + .004268*\text{TGLAS} \\
 &+\text{SOLAR}*(5.122 + \text{EGLAS}*(.01348 - .007367*\text{SHADE})) \\
 &-25.502*\text{UROOF} - 16.769*\text{UWALL} - 3.8904*\text{UGLAS} + .04750*\text{PEOPLE} \\
 &-3.031*\text{APART}*\text{DPART}*10^{*-5} + \text{ELEC}*(2.8210 + .5003*\text{SCHED1}) \\
 &-41.14*\text{ASLAB}*10^{*-5}
 \end{aligned}$$

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-8