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The Pennsylvania State University

The Graduate School

Department of Architectural Engineering

Simplified Methodology for Calculating Building Heating Loads

A Thesis in

Architectural Engineering

by

Steven Danser Heinz

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

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ABSTRACT

A simplified methodology for accurately calculating building heating loads, termed the "Modified Bin Method," is developed and validated. The method is reliable and accurate and combines the simplicity of hand calculations with the accuracy of computer simulations to provide a substantial improvement over the conventional simple degree day and bin methods and the high cost of sophisticated hourly simulations. The Modified Bin Method uses standard steady-state equations for envelope heat loss and heat gain due to lights and occupants. An equation for predicting solar heat gain is developed using multiple regression techniques based upon a statistical analysis of fifty-one computer simulations of test buildings. Example calculations using this method estimate annual bulding heating loads to within 1.5% of the results of an accurate computer simulation at a small fraction of the time and expense.

Key words for this thesis are: building heating load, bin method, degree day method, regression analysis, and Modified Bin Method.

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H	Heat loss, MBtu (1,000 British thermal units)
UA	Product of coefficient of heat transmission (U) and area (A), Btu/hr·°F
HDD	Heating degree day (65°F base), °F·day
C_D	ASHRAE degree day correction factor
Δt	Difference between outside and inside temperature, °F
hr	Hour
F	Slab edge heat loss coefficient, Btu/hr·°F·ft
CFM	Cubic feet per minute of air flow
G	Heat gain, MBtu
UGLASS	Weighted glass U-value, Btu/hr°·F·ft^2
AGLASS	Total glass area, ft^2
UWALL	Weighted wall U-value, Btu/hr·°F·ft^2
AWALL	Total wall area, ft^2
UROOF	Weighted roof U-value, Btu/hr·°F·ft^2
AROOF	Total roof area, ft^2
BWALL	Basement wall area, ft^2
BFLOOR	Basement floor area, ft^2
SLAB	Slab edge length, ft
SLABST	Slab edge insulation, in.
INFIL	Rate of infiltration, CFM
VENT	Rate of ventilation, CFM
LIGHTS	Lighting load, watts/ft^2
PEOPLE	Number of people occupying the space
DAYSET	Occupied thermostat setting, °F
NITESET	Unoccupied thermostat setting, °F

SC	Overall glass shading coefficient
VOLUME	Building volume, ft^3
AREA	Building floor area, ft^2
SGLASS	Area of glass facing 90°-270°, ft^2
BALANCE	Building balance point temperature, °F
Y	Dependent or response variable
β	Regression parameter
ϵ	Amount that Y falls off regression line
Y_p	Predicted value of Y
b	Estimate of parameter β
r	Correlation coefficient
r^2	Coefficient of determination
s	Standard error of estimate
*	Denotes multiplication

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Chapter 1

INTRODUCTION

Buildings consume about one-third of the total energy used in the U.S. today (U.S. Department of Energy, 1979). As national and international political and economic pressures drive energy costs upward, it becomes increasingly important to reduce building energy consumption. Many simple, inexpensive energy conservation measures, such as weather-stripping, caulking, and thermostat setbacks, can be implemented without professional engineering assistance. However, costly energy conservation investments, such as window treatment, wall and roof insulation, and mechanical equipment modifications, must be thoroughly investigated and properly designed by trained architects and engineers. Their first step is normally to conduct a comprehensive building energy audit to determine the thermal characteristics of the building envelope, the energy consumption patterns and schedules of the building occupants, and the operation of the building mechanical systems. This information is used to calculate the annual heating load of the building.

It is here that the engineer faces a dilemma. The heating load calculation methods available today feature either accuracy or simplicity, but not both. Highly accurate, reliable computer simulations may cost thousands of dollars, and every dollar spent on computer time is one less dollar available for energy conservation improvements. Conversely, simple hand calculations are inexpensive but may be too inaccurate to be used with confidence. The purpose of this thesis is to examine the heating load calculation methods in common use today and use statistical analysis techniques to develop an inexpensive, accurate, and reliable simplified methodology, termed the "Modified Bin Method", for

calculating building heating loads. In doing so, it is important first to define the building heating load and to understand why it is so valuable in the energy conservation process.

1.1 Building Heating Load

The building heating load is the demand, or load, placed upon the building's heating system. The annual heating load is the quantity of heat that the system must deliver in order to maintain the space temperatures at the thermostat set points. The heating load is not simply the heat loss of the building; it is the net result of heat loss through components such as the walls and roof, and the heat gain due to the sun, lights, and occupants.

The annual heating load of a building is extremely useful in many facets of energy conservation. Government agencies, such the Pennsylvania Governor's Energy Council and the U.S. Department of Energy, use this information to competitively rank buildings for the award of energy conservation investment grants (U.S. Department of Energy, 1980). Building owners compare the calculated heating load against the actual energy invoices as an indicator of building mechanical system efficiency. Engineers use the heating load to evaluate the performance and the economics of energy conservation options. One of three common methods is usually used to calculate this important value.

1.2 Heating Load Calculation Methods

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recognizes three methods of calculating heating loads: the degree day method, the bin method, and hour-by-hour simulations. The degree day method is a simple technique that uses the overall building

thermal characteristics and the average weather to estimate the annual heating loads. The bin method is somewhat more sophisticated as it uses hourly weather occurrences grouped into 5°F incremental temperature "bins" and permits the use of occupied and unoccupied thermostat settings. Hour-by-hour simulations typically use high-speed computers for hourly time steps through the 8,760 hours in a year to model the actual thermal processes in a building (ASHRAE, 1980). As each method has unique advantages and disadvantages, this is an important area for investigation and innovation.

1.3 Objectives

The general objective of this thesis is to develop a simple, accurate method of estimating the annual heating loads of buildings as an alternative to the questionable accuracy of the degree day and bin methods and the prohibitive expense of accurate computer simulations. The specific objectives are to:

1. Examine the advantages and disadvantages of existing calculation methods.

2. Develop a Modified Bin Method for calculating building envelope heat loss and internal heat gain due to lights and occupants.

3. Apply statistical analysis methods to determine the building characteristics most important to the amount of useful solar energy a building receives.

4. Use multiple regression techniques to define a regression equation which predicts solar gain based upon these important building characteristics.

5. Integrate the regression equation into the Modified Bin Method and establish the validity and the range of application of the method.

1.4 Limitations

The Modified Bin Method developed in this thesis is limited to the calculation of building heating loads; cooling loads and mechanical system simulation are not within the scope of this research. Furthermore, the statistical data base used in the multiple regression analysis is limited to medium construction masonry buildings typical of central Pennsylvania and the weather data represents the actual 1978 State College weather as recorded by The Pennsylvania State University, Department of Meteorology, Weather Station. Buildings other than medium construction masonry and climates other than approximately 5,000-9,000 heating degree days have not been validated for compatibility with the solar gain regression equation. However, the general statistical analysis approach described in this thesis may be applied for other building types in varying climates.

1.5 Contribution

The contribution of this thesis is the development and validation of a simple, accurate Modified Bin Method for calculating building heating loads. Although recognized, widely used methods permit the calculation of heat loss and lighting and occupancy heat gains, there is no simple method available today to calculate building solar gains which must be credited against the heating loss to determine the actual heating load (ASHRAE, 1980). The application of statistical analysis methods to define a regression equation which simply and accurately predicts solar gains represents a positive contribution to the field of energy conservation.

1.6 Overview

Chapter 2 examines the strengths and weaknesses of the three common methods, introduces the Modified Bin Method, and explains its advantages. Chapter 3 describes the procedures used in the Modified Bin Method to calculate annual heat loss, heat gain, and the resulting net heating load. Chapter 3 concludes with a discussion of the requirement for a straightforward procedure to calculate solar gains. Chapter 4 explains the multiple regression techniques used to formulate a solar gain predictor equation based upon a thorough statistical analysis of fifty-one computer simulations of test buildings. Chapter 5 integrates the regression equation into the Modified Bin Method, presents examples to verify its accuracy, and bounds its range of application. Chapter 6 offers conclusions and recommendations for future study.

Chapter 2

HEATING LOAD CALCULATION METHODS

The heating load of a building can be separated into components of heat loss and heat gain, as illustrated in Figure 2.1. The heat loss components are roof, wall, window, floor, infiltration, and ventilation loss; the heat gain components are lighting, occupancy, and solar gain. The first step in developing the Modified Bin Method is to analyze how each of the standard calculation methods treats these heating load components and evaluate the advantages and disadvantages of each method. The oldest and simplest method is the heating degree day method.

2.1 Heating Degree Day Method

The heating degree day method is a simple, one-step procedure for estimating the monthly or annual heating loads of small buildings. This method is based upon studies of residences; however, it is frequently used for other small buildings as well. Studies conducted by the American Gas Association and the National District Heating Association almost fifty years ago showed that for a typical residence, solar and internal heat gains balanced heat losses at approximately 65°F (ASHRAE, 1980). This 65°F balance point, the outdoor temperature at which heat gains equals heat losses for a zero net heating load, led to the definition of the heating degree day.

The heating degree day method can be expressed in various forms but is usually used in energy conservation analyses as:

$$H = UA*HDD*24*C_D \tag{2.1}$$

where (Note: * denotes multiplication):

H = annual heating load, Btu

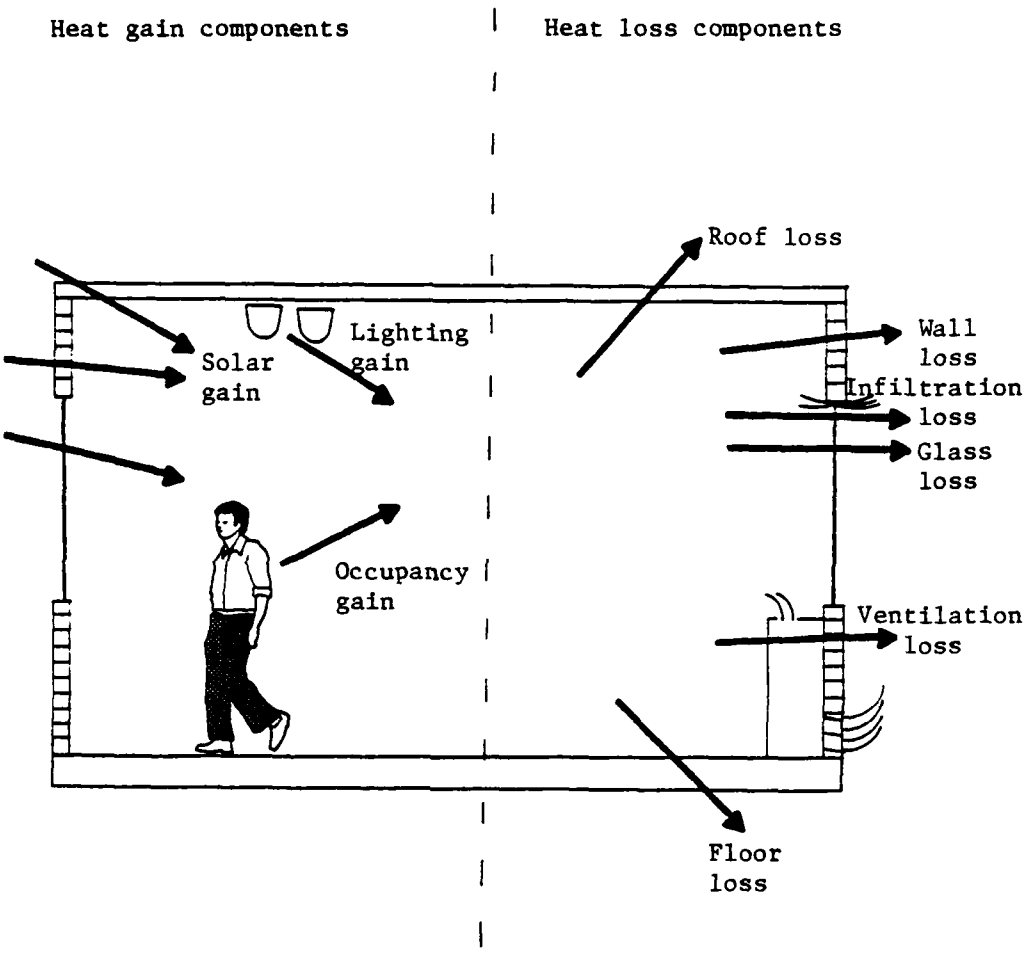

Figure 2.1 Building heating load components

UA = building UA value, the sum of the heat transfer coefficient (U-value) and area (A) products for each building assembly including infiltration and ventilation, Btu/hr·°F

HDD = annual heating degree days, converted to degree hours by the 24 factor for dimensional compatibility with UA, °F·day

C_D = ASHRAE correction factor

The C_D correction factor is a recent ASHRAE modification which accounts for balance point temperatures below 65°F in modern houses. This is due to increased insulation and dramatic increases in internal heat gains attributable to a fourteen-fold average increase in electricity usage over the past fifty years (ASHRAE, 1980).

An elementary school can be used to illustrate the degree day method. Figure 2.2 is the floor plan of Park Forest Elementary School, located on a wooded site in State College, Pennsylvania. The unique design of the small classroom clusters makes the degree day method more compatible with this building than with a conventional building having the same floor area. Using the degree day Equation (2.1) to calculate the annual heating load,

$$H = 12909*7112*24*0.61 = 1{,}340{,}000 \text{ MBtu/yr}$$

for:

UA = 12909 (Appendix A)

HDD = 7112 (actual State College 1978 weather as recorded by The Pennsylvania State University, Department of Meteorology, Weather Station)

C_D = 0.61 (ASHRAE, 1980)

The advantage of this method is that it provides an approximate building heating load with one simple, fast calculation. It has a major disadvantage, though, in that it assumes that the heat gain components of lighting, occupants, and solar set the balance point at 65°F, which

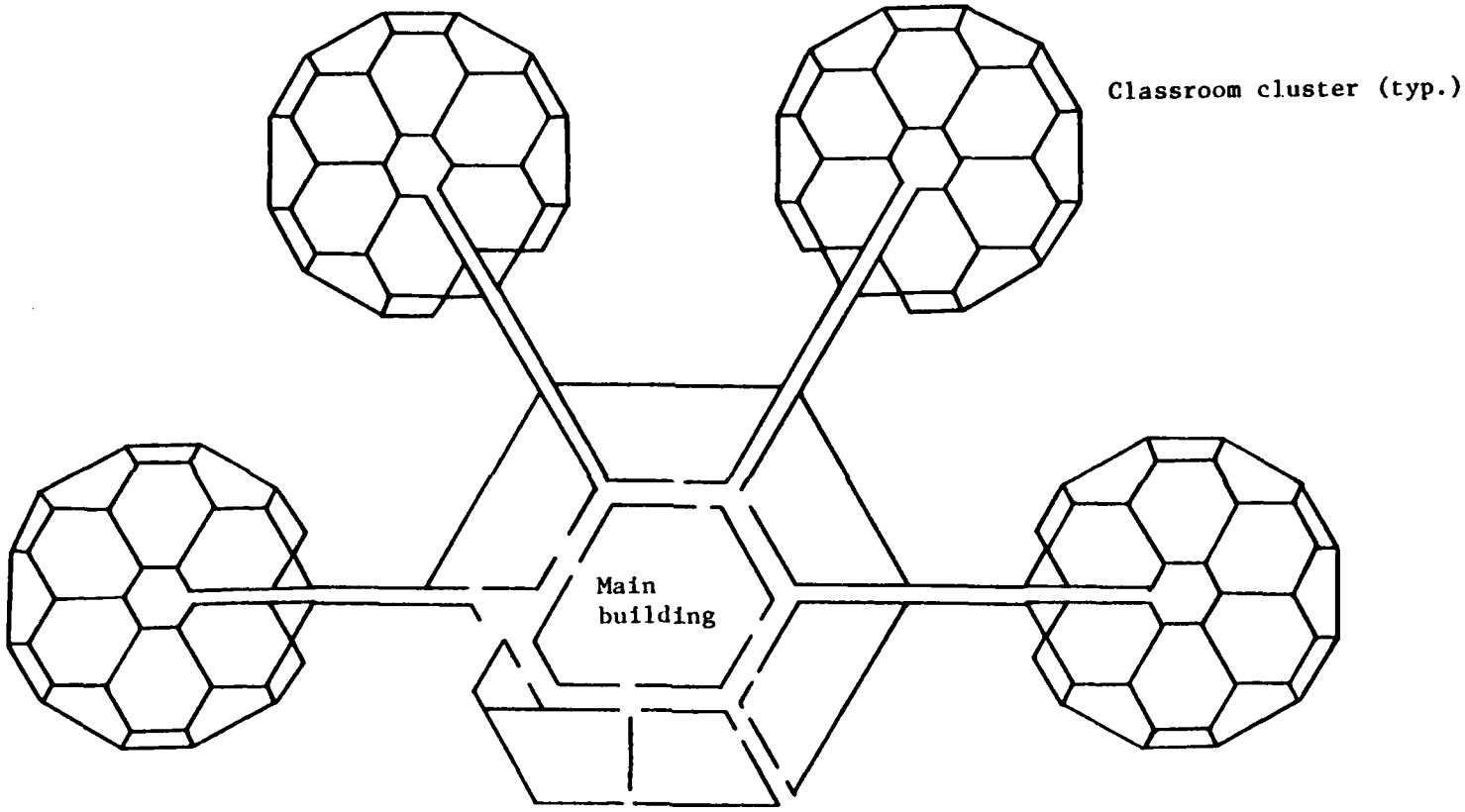

Figure 2.2 Park Forest Elementary School floor plan

may be far from the actual balance point. Also, this single calculation does not account for the different occupied and unoccupied conditions of lighting, occupancy, and thermostat settings.

2.2 Bin Method

The bin method is a major improvement over the heating degree day method. It uses 5°F incremental temperature bins to profile the annual outdoor temperature. Each temperature bin indicates the number of hours in a year that the outdoor temperature falls within that 5°F range. Table 2.1 illustrates the bin data for State College, 1978.

The principal advantage of the bin method is that the three hour groups allow for separate occupied and unoccupied calculations. During the 9 AM - 4 PM occupied hour group, a typical building has a thermostat set point of 68°F and is ventilated in accordance with building code requirements. During the morning and evening unoccupied hour groups, the thermostat is normally set back 10-20°F and the ventilation and lights are turned off. The bin method accounts for these distinct operating conditions.

The basic bin method equation is:

$$H = UA*\Delta t*hr \tag{2.2}$$

where the only changes to the degree day method are the Δt and hr terms. The Δt term is the temperature difference between the average bin temperature and the balance point temperature; hr is the number of hours in the temperature bin. The C_D correction term is not used because it applies only to the degree day method.

The principal difficulty with the bin method is selecting an appropriate balance point temperature. During the unoccupied hour groups, the balance point can be taken as the thermostat set point because there

Table 2.1

State College, Pennsylvania 1978 temperature bin data

Bin Number	Temperature Range °F	Average Temperature °F	Hour Groups 1AM-8AM Hours	9AM-4PM Hours	5PM-12PM Hours	Total Hours
1	95-99	97	0	0	0	0
2	90-94	92	0	3	0	3
3	85-89	87	0	54	12	66
4	80-84	82	0	231	77	308
5	75-79	77	4	185	139	324
6	70-74	72	105	292	282	679
7	65-69	67	265	199	274	738
8	60-64	62	370	251	245	866
9	55-59	57	188	147	193	528
10	50-54	52	232	231	257	720
11	45-49	47	213	168	191	572
12	40-44	42	252	251	266	769
13	35-39	37	259	119	173	551
14	30-34	32	316	209	206	731
15	25-29	27	149	152	136	437
16	20-24	22	162	210	211	583
17	15-19	17	136	112	116	364
18	10-14	12	189	85	116	390
19	5-9	7	60	11	28	99
20	0-4	2	20	7	5	32

are no lighting, occupancy, or solar gains to offset heat loss below the thermostat setting. One method for the occupied hour group is to set the balance point equal to the thermostat setting. Each component of heat gain must then be calculated and credited against the heat loss. This method is extremely difficult because there are no simple equations to calculate solar gains. Accordingly, the normal procedure is to estimate a balance point which accounts for the heat gain components.

For example, the State College 15-19°F temperature bin has an average temperature of 17°F and experiences 112 hours a year during the occupied hour group and 252 hours total during the two unoccupied hour groups. Using an estimated daytime balance point temperature of 45°F (Appendix A) and an unoccupied temperature of 55°F, the respective Δt values are 28°F and 38°F. Park Forest Elementary School has a daytime UA of 14,230 and a lower nighttime UA of 12,249 due to unoccupied infiltration rates replacing the higher daytime ventilation rates (Appendix A). The building heat load at this temperature bin is the sum of the occupied and unoccupied loads:

$$H = (14230*28*112) + (12249*38*252) = 161,923 \text{ MBtu}$$

This same procedure can be repeated for each temperature bin to determine the annual heating load. Table 2.2 tabulates the results for each bin.

The bin method analysis calculates an annual heating load of 1,242,146 MBtus, which is 7% less than the degree day method. The principal advantages of the bin method, its simplicity and its ability to more closely account for actual building operating conditions, must be weighed against its disadvantage of questionable accuracy due to the imprecise methods of estimating heat gain. The only method available to

Table 2.2

Park Forest Elementary School bin method calculation

Bin Temperature °F	Occupied Heating Load Hours	Δt-°F	MBtu	Unoccupied Heating Load Hours	Δt-°F	MBtu	Total Load MBtu
62	251	0	0	615	0	0	0
57	147	0	0	381	0	0	0
52	231	0	0	489	3	17969	17969
47	168	0	0	404	8	39589	39589
42	251	3	10715	518	13	82485	93200
37	119	8	13547	432	18	95248	108795
32	209	13	38663	522	23	147061	185724
27	152	18	38933	285	28	97747	136680
22	210	23	68731	373	33	150773	219504
17	112	28	44626	252	38	117297	161923
12	85	33	39915	305	43	160646	200561
7	11	38	5948	88	48	51740	57688
2	7	43	4283	25	53	16230	20513
TOTALS			265361			976785	1242146

improve upon the accuracy of the bin method is the costly computer simulation.

2.3 Computer Simulation

Modern, high-speed computers permit the engineer to model the complex processes of radiation, conduction, and convection heat transfer; account for the thermal capacitance of the structure; simulate the performance of heating, ventilating, and air-conditioning equipment; and calculate the annual heating load of a building. One such program is the Building Energy Analysis Program (BEAP), developed by the Department of Architectural Engineering at The Pennsylvania State University under the sponsorship of the National Science Foundation. BEAP has been validated through hand calculations using the ASHRAE sol-air method (Donovan, 1979) and is used for research, instruction, and energy conservation studies.

BEAP is an extremely flexible program which gives the user complete control over thermostat settings; occupancy, equipment, and lighting schedules; and ventilation and infiltration rates for each hour of the year. The program uses the ASHRAE sol-air method together with such features as thermal time lag, solar heat gain factors, cooling load factors, and wind velocity corrections to the outdoor film coefficient and the infiltration rate. Although BEAP does not simulate mechanical equipment, it does calculate heating and cooling loads and provides system design information. Because BEAP accounts for the actual building conditions much more accurately than either the degree day method or the bin method, BEAP and similar simulation programs offer the best estimates of annual heating loads.

BEAP was run for the Park Forest Elementary School. The input data consisted of 222 lines of program commands and building information and

required approximately five hours for an experienced user to compile and input the data. BEAP calculated the annual heating load as 1,059,250 MBtu. The clear disadvantage of this method is the time and cost required to prepare the input data and execute the program. The advantage of a computer simulation -- the accurate, reliable results -- must be weighed against the need for increased accuracy and substantial added cost.

2.4 Method Evaluation

It is often extremely difficult to estimate actual building heating loads from records of past consumption due to the varied uses of energy within a building. Park Forest Elementary School was carefully selected for this analysis for several reasons. The school is all-electric, which eliminates the problem of estimating furnace efficiency. There are few major appliances or large pieces of equipment which consume electricity. Most important, the school has a modern, automatic thermostat control system which ensures that the building was actually operated under the same thermostat control schedule that was simulated in BEAP. The actual heating load of the school for fiscal year 1979 was 1,067,075 MBtu (Appendix B). Table 2.3 indicates the accuracy of the three heating load calculation methods.

Table 2.3

Heating load calculation method accuracy

Method	Annual Heating Load, MBtu	Variance MBtu	Variance %
Actual heating load	1,067,075	-	-
Computer simulation (BEAP)	1,059,250	(-) 7,825	0.7%
Bin method	1,242,146	(+)175,071	16.4%
Degree day method	1,340,000	(+)272,925	25.6%

These results highlight the accuracy of the BEAP computer simulation and illustrate the serious disadvantage of using one of the quick, simple methods. Although the bin method is considerably more accurate than the degree day method and both results are "in the ballpark", neither method yields results within the parameters of accuracy and reliability acceptable to professionals. Furthermore, there is no assurance that every bin method calculation will fall within 20% of the actual value. Conversely, the BEAP program produces reliable, accurate results every time, but small firms without access to a large computer find it prohibitively expensive to purchase computer services.

The most practical mix of methods is a combination of the speed and simplicity of the bin method and the accuracy and reliability of the computer simulation. The degree day method lacks the occupied and unoccupied hour group flexibility, which makes it unsuitable to account for modern building operating conditions. BEAP and the bin method can be used to create the Modified Bin Method.

2.5 Modified Bin Method

The basic premise of the Modified Bin Method is that all of the components of heat loss and all of the components of heat gain except solar gain can be calculated within an acceptable degree of accuracy by using conventional ASHRAE equations. Furthermore, solar gains can be readily predicted based upon a thorough statistical analysis of a large number of accurate BEAP computer simulations. This Modified Bin Method combines the ease and simplicity of the bin method with the accuracy of the computer simulation to provide the engineer with a powerful tool for calculating building heating loads. The first step in the development

of this method is to define the standard equations used to predict all components of heating load except solar gains.

Chapter 3

HEATING LOAD COMPONENTS

The first step in developing the Modified Bin Method is to separately analyze each component of heat loss and heat gain which together determine the building heating load. There are typically several different ways to calculate each component. For example, heat loss through a solid wall can be calculated by a simple UA steady-state method (Equation 2.1). A refinement to this method is to adjust the U-value for each hour, day, or month of the year to account for varying average wind velocities. Another method is to simulate the transient nature of heat transmission by using a finite difference technique which "steps" thermal energy through each layer of the wall. A fourth method is to use heat transmission transfer functions, a computerized numerical technique which uses empirically derived coefficients to "transfer" building condition "inputs" to heating load "outputs" (ASHRAE, 1977). In all cases of heat loss and heat gain, the simplest method recognized as acceptable by ASHRAE is used in order to keep the Modified Bin Method simple yet reliable.

3.1 Heat Loss

The heat loss of a building is the sum of the losses through the walls, windows, roof, and floor, and the infiltration and ventilation losses. Although it is possible to combine these terms into an overall building UA value, it is frequently desirable to analyze each component separately in energy conservation studies. The Modified Bin Method calculates each component in this manner.

3.1.1 Wall, window, and roof loss

The hourly heat loss through a wall, window, or roof under steady-state conditions is:

$$H = UA*\Delta t*hr \tag{3.1}$$

which is identical to Equation 2.1 except that it uses the separate component UA values rather than the overall building UA value. The Δt term can be changed for each hour group to reflect actual thermostat control procedures.

3.1.2 Floor loss

The heat loss through the floor depends upon the floor type. The floor loss from an unheated slab can be estimated by:

$$H = F*SLAB*\Delta t*hr \tag{3.2}$$

where F is the heat loss coefficient of the slab edge and SLAB is the linear feet of exposed edge (ASHRAE, 1977). Table 3.1 presents values for F for State College as derived from ASHRAE design data (ASHRAE, 1977).

Table 3.1

Slab edge heat loss coefficients for State College

Slab Edge Insulation inches	Heat Loss Coefficient, F Btu/hr·ft·°F
0	0.80
1.0	0.67
1.5	0.60
2.0	0.53

The heat loss from basement walls and floors is very difficult to calculate directly due to unknown outside conditions of soil thermal conductivity, ground water level, and ground or ground water temperature.

However, basements represent a minor component of heat loss due to the low temperature differential and the relatively small area, which allows an approximation to be used. ASHRAE research indicates that 2.0 Btu/hr per square foot of basement floor and 4.0 Btu/hr per square foot of basement wall are reasonable estimates for heated basements having a Δt of around 20°F. For unheated basements, a simple UA calculation of heat loss through the first story floor is sufficient (ASHRAE, 1977).

3.1.3 Infiltration and ventilation loss

The introduction of cold infiltration and ventilation air creates a source of heat loss expressed as:

$$H = 1.1*CFM*\Delta t*hr \tag{3.3}$$

where CFM is the cubic feet per minute of air flow (ASHRAE, 1977). In a typical building, the ventilation system supplies more air than the exhaust system discharges, creating a positive pressure within the building. This slight pressure greatly reduces infiltration during the occupied hours when the ventilation system is operating. The Modified Bin Method is well-suited for this situation by permitting the ventilation CFM to be used during the occupied hour groups and the infiltration CFM to be used during the unoccupied hour groups. The infiltration and ventilation losses can then be combined with the other heat loss components to calculate the total heat loss of a building.

3.1.4 Example

The total annual heat loss of Park Forest Elementary School, separated into components, can be accurately calculated by using the Modified Bin Method. Table 3.2 illustrates the results for this example. The total unoccupied heat loss matches the unoccupied heating load from

Table 3.2

Modified Bin Method heat loss calculations

Component	Equation H =	Occupied Hour Group Heat Loss, MBtu	Unoccupied Hour Group Heat Loss, MBtu	Total Heat Loss (MBtu)
Wall	$1205 \cdot \Delta t \cdot hr$	67,217	96,092	163,309
Window	$5304 \cdot \Delta t \cdot hr$	295,868	422,962	718,830
Roof	$2665 \cdot \Delta t \cdot hr$	148,659	212,518	361,177
Floor	$1096 \cdot \Delta t \cdot hr$	61,137	87,399	148,536
Infiltration	$1979 \cdot \Delta t \cdot hr$	-	157,813	157,813
Ventilation	$3960 \cdot \Delta t \cdot hr$	220,897	-	220,897
Totals		793,778	976,785	1,770,562

Table 2.2 because there is no heat gain during this time. However, the total occupied heat loss far exceeds the occupied heating load from Table 2.2. Table 2.2 accounted for all gains by the 45°F balance point while Table 3.2 uses a 68°F balance point and does not credit heat gains. The Modified Bin Method uses the actual inside thermostat setting as the balance point and then calculates each component of heat gain separately.

3.2 Heat Gain

The heat gain of a building is the sum of the thermal gains due to occupants, lights, and the sun. There is a distinction between instantaneous heat gain and the heat gain "felt" by the room thermostat. Instantaneous space heat gain is the amount of energy entering the room at any instant, while actual space heat gain is the amount of energy actually transferred to the air and sensed by the thermostat. These two types of heat gain are nearly the same for occupants and lights because there are no major thermal capacitance effects causing instantaneous heat gain to be stored in thermal mass and then slowly released.

This is not true for solar radiation, which contributes to the actual heat gain only after it has been absorbed by a solid surface and then released through convection and thermal radiation. This effect is particularly important in masonry construction typical of the buildings used in this research. The Modified Bin Method accounts for both the immediate heat gain of occupants and lights and the thermal lag of solar gains.

3.2.1 Occupancy gain

People release sensible heat to a room by radiation and convection. A typical profile of men, women, and children engaged in light activity

release approximately 250 Btu/hr·person of sensible heat (ASHRAE, 1977). The actual heat gain of the space is expressed as:

$$G = PEOPLE*250*hr*0.90 \tag{3.4}$$

where the heat gain, G, is the Btu total for each temperature bin and PEOPLE is the number of occupants. The 0.90 factor accounts for an average occupancy rate of 90%.

3.2.2 Lighting gain

All of the electrical energy consumed by lights is released as sensible heat gain to the space. There are minor thermal capacitance effects due to heat storage in the light fixtures, but all of this energy is soon released, so these effects are negligible. Space heat gain is expressed as:

$$G = LIGHTS*3.413*hr*0.90 \tag{3.5}$$

where LIGHTS is the total kilowatt installed load, 3.413 converts KW to Btu/hr, and the 0.90 factor accounts for burned out lamps and unused fixtures. The lighting gain can be combined with the occupancy gain to offset the heat loss during the occupied hour group.

3.2.3 Example

Table 3.3 presents the results of the heat gain calculations for the occupied hour group for Park Forest Elementary School. Only the hours from the temperature bins below 68°F are used because even though heat gain occurs at temperatures above the thermostat set point, these gains do not offset any heat losses and are not useful. Also, gains are not calculated for unoccupied summer and weekend times.

The calculated gains of 529,066 MBtu are 30% of the heating loss from Table 3.2, which highlights the importance of properly determining

Table 3.3

Modified Bin Method heat gain calculations

Component	Equation	Occupied Hour Group Heat Gain, MBtu
Lights	G = 90*3.413*hr	353,553
Occupants	G = 603*250*hr	175,513
TOTAL		529,066

these heat gain components. The only component of the net heating load that has yet to be calculated is solar gain.

3.2.4 Solar gain

Solar gain is without doubt the most difficult component of the building heating load to calculate. Although standard, widely used equations are available to calculate heat loss and lighting and occupancy heat gain, there is no simple method available to calculate solar gain. Many factors, such as glass area, glass orientation, and shading coefficients, influence the amount of useful solar gain that a building receives, yet there is no simple way to evaluate these building characteristics and determine an accurate balance point. Chapter 4 describes the statistical analysis techniques that were used to develop a balance point predictor equation which uses these three factors and ten others to calculate solar gains.

Chapter 4

STATISTICAL ANALYSIS

Solar heat gain is the only component of the building heating load which cannot be estimated by simple methods. Variables such as glass area, glass orientation, shading coefficient, wall and roof areas and U-values, and daytime thermostat settings all clearly have an impact on the amount of useful solar energy that a building receives. Although computer simulations account for these variables and accurately calculate solar heat gain, such methods are much more complex than the Modified Bin Method. However, it is possible to use accurate computer simulations of test buildings to compile a data base consisting of bulding variables and the respective calculated solar gains. Statistical analysis techniques can then be used to develop an equation, or model, which predicts the solar gains for any building based upon the computer simulations of the test buldings. This process involves selecting the proper types of model, planning the analysis, developing the model, and validating the final predictor equation.

4.1 Model Types

There are two types of mathematical models, functional and predictive, which relate to solar gain (Draper and Smith, 1966). A functional model expresses the true functional relationship between various independent variables and the dependent variable of solar gain. Such a functional model is the ASHRAE solar heat gain factor calculation method which uses glass transmission and absorption coefficients, solar geometrical relationships, and atmospheric clearness factors to define instantaneous solar heat gain through windows (ASHRAE, 1977). This model must be

combined with other functional models which describe heat gain through opaque surfaces and which modify instantaneous solar heat gain for thermal lag in order to completely model solar heat gain. Because computer simulations are needed for these functional models, the second type of model is used.

A predictive model is a statistically derived equation based upon past observations which is used to predict future occurrences. For example, to predict the life of an incandescent bulb, it may be possible to formulate a functional model which calculates the tungsten filament vaporization rate as a function of the line voltage and the heat extraction rate. However, it may be extremely difficult to determine the instantaneous heat extraction rate due to the complex processes of convection, conduction, and short and long wavelength radiation. A much simpler procedure is to observe the hours of life of many bulbs under varying line voltages and room ambient temperatures. Having observed the performance of these bulbs, it is possible to formulate a predictive model which predicts the life of a bulb based upon the independent variables of line voltage and room temperature. Even though the predictive model in no way calculates the tungsten vaporization (the actual cause of burn-out), the model is able to predict how long a bulb will last.

A predictive model for solar heat gain can be formulated in much the same way based upon the results of a large number of computer simulations. Although the model itself does not calculate actual thermal processes in any manner, the model successfully "reproduces" the results of the accurate functional models included in the computer program. Before developing this predictive model, it is important to plan the research to assure valid results.

4.2 Analysis Plan

In Applied Regression Analysis (Draper and Smith, 1966), the authors stress that the most important phase of problem solving is a very specific statement of the problem. The specific problem in this case is to develop a predictive model which predicts building solar heat gain based upon various building characteristics. Figure 4.1 presents a flow chart of the process to solve this problem. The first phase, planning, includes selecting the variables, selecting the correlation technique, and establishing the goals.

4.2.1 Variable selection

The independent variables in the predictor equation must be building characteristics that are easily determined in order to maintain the simplicity of the Modified Bin Method. Furthermore, the variables must be independent; a variable such as surface-to-volume ratio is dependent upon the values of surface area and volume and therefore is not independent. As an initial assumption, all of the variables used in the Modified Bin Method, as illustrated in Table 4.1, are included as independent variables. Added to this list are glass shading coefficient, floor area, building volume, and "south" glass area (glass facing 90°-270°) because these characteristics are easily determined and may have a significant bearing on solar heat gain.

There are two possibilities for the dependent variable. The obvious choice is to select annual building solar heat gain. However, because total solar gain varies widely from thousands of MBtus for a small building to millions of MBtus for a large building, it may not be possible to formulate a predictor equation that is accurate over such a wide range of possible values.

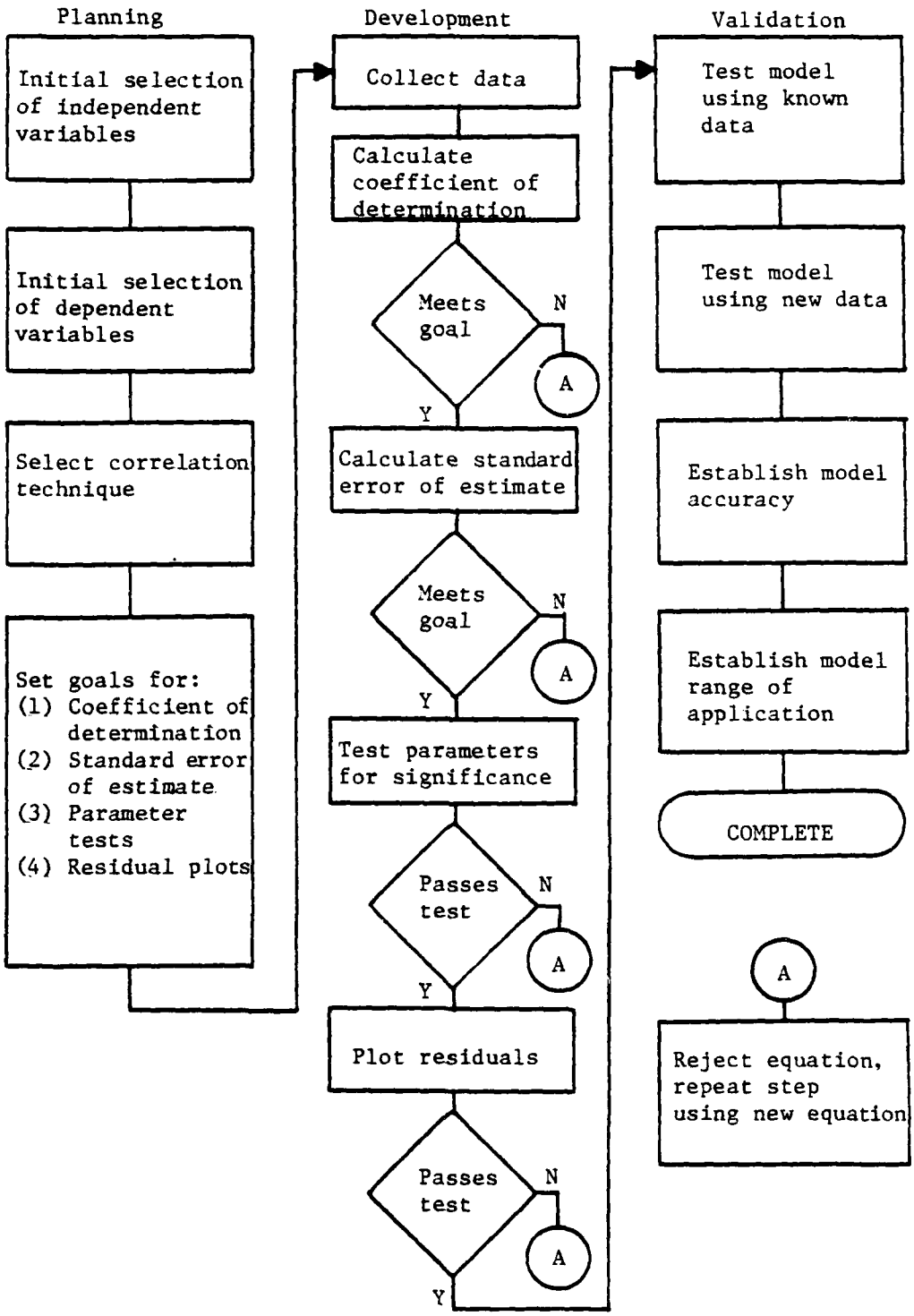

Figure 4.1 Flow chart of the model-building process

Table 4.1

Initial selection of independent variables

Variable	Symbol	Use in Modified Bin Method
Glass U-value	UGLASS	Glass heat loss
Glass area	AGLASS	Glass heat loss
Wall U-value	UWALL	Wall heat loss
Wall area	AWALL	Wall heat loss
Roof U-value	UROOF	Roof heat loss
Roof area	AROOF	Roof heat loss
Basement wall area	BWALL	Basement wall heat loss
Basement floor area	BFLOOR	Basement floor heat loss
Slab edge length	SLAB	Slab heat loss
Slab edge insulation	SLABST	Slab heat loss
Infiltration rate	INFIL	Infiltration heat loss
Ventilation rate	VENT	Ventilation heat loss
Lighting watts/ft^2	LIGHTS	Lighting heat gain
Occupants	PEOPLE	Occupant heat gain
Occupied thermostat setting	DAYSET	Occupied hour group inside temperature
Unoccupied thermostat setting	NITESET	Unoccupied hour group inside temperature
Shading coefficient	SC	Suspected impact on solar heat gain
Volume	VOLUME	Suspected impact on solar heat gain
Floor area	AREA	Suspected impact on solar heat gain
South-facing glass area	SGLASS	Suspected impact on solar heat gain

The other alternative is to predict the building balance point temperature and from that calculate solar gains. By definition, heat loss equals heat gain at the balance point,

$$\text{Heat loss} = \text{Light gain} + \text{Solar gain} + \text{Occupancy gain} \qquad (4.1)$$

Solving this equation for solar gain,

$$\text{Solar gain} = \text{Heat loss} - \text{Light gain} - \text{Occupancy gain} \qquad (4.2)$$

If the balance point temperature is known, Equation 4.2 can be solved for solar gain. Although this method is not as simple as predicting solar gain directly, it may be more accurate. The balance point temperature varies over the small range of perhaps 30-65°F whereas solar gain varies by orders of magnitude. Both of these possible dependent variables must be analyzed by using a statistical correlation technique.

4.2.2 Correlation technique

The most common method used to formulate predictive models from two or more independent variables is multiple regression analysis. The fundamentals of multiple regression analysis are straightforward. A first-order linear regression equation, called a model, has the theoretical form of:

$$Y = \beta_o + \beta_1 x_1 + \ldots + \beta_n x_n + \varepsilon \qquad (4.3)$$

where the x terms are the independent variables, Y is the dependent variable, the β terms are the coefficients, or parameters, and ε is the exact amount that Y falls off the regression line. This equation yields an exact value for Y because the ε term corrects for any deviation from the correct value. This theoretical form of the regression equation cannot be used in practical applications because the ε and β terms can never be exactly determined.

In applied regression analysis, the regression predictor equation is written as:

$$Y_p = b_o + b_1x_1 + \ldots + b_nx_n \tag{4.4}$$

where Y_p is the predicted value of Y and the b terms are the estimated parameters. The residual, analogous to the theoretical ε, is the difference between Y and Y_p. If the residual is very small, Y_p is a good predictor of Y.

The parameters are normally estimated by using least squares. This technique involves selecting values of the b terms so that the sum of the squares of the residuals is minimized. Since the residual represents the amount that any prediction varies from the actual value of Y, the best regression equation occurs when $\Sigma(\text{residual})^2$ is minimized. The mathematical development of this technique is quite lengthy and complex for multiple regression problems, but a simple example using one independent variable suffices to illustrate the method.

Suppose that the problem is to formulate a regression equation that predicts a person's height based upon his weight. Twenty-five volunteers are weighed and measured, and these data are plotted as in Figure 4.2. Many possible regression lines can be fit to the plotted data. To select the best line by least squares, the residuals (the distance from each line to each point) are calculated, squared, and summed. The line having the least sum of squares is the best fit line.

Mutliple regression is fundamentally identical, but the calculations are extremely complex and voluminous which necessitates the use of computer analysis. Two statistical programs supported by The Pennsylvania State University Computation Center have been used in the research. MINITAB is a general purpose statistical program developed by The

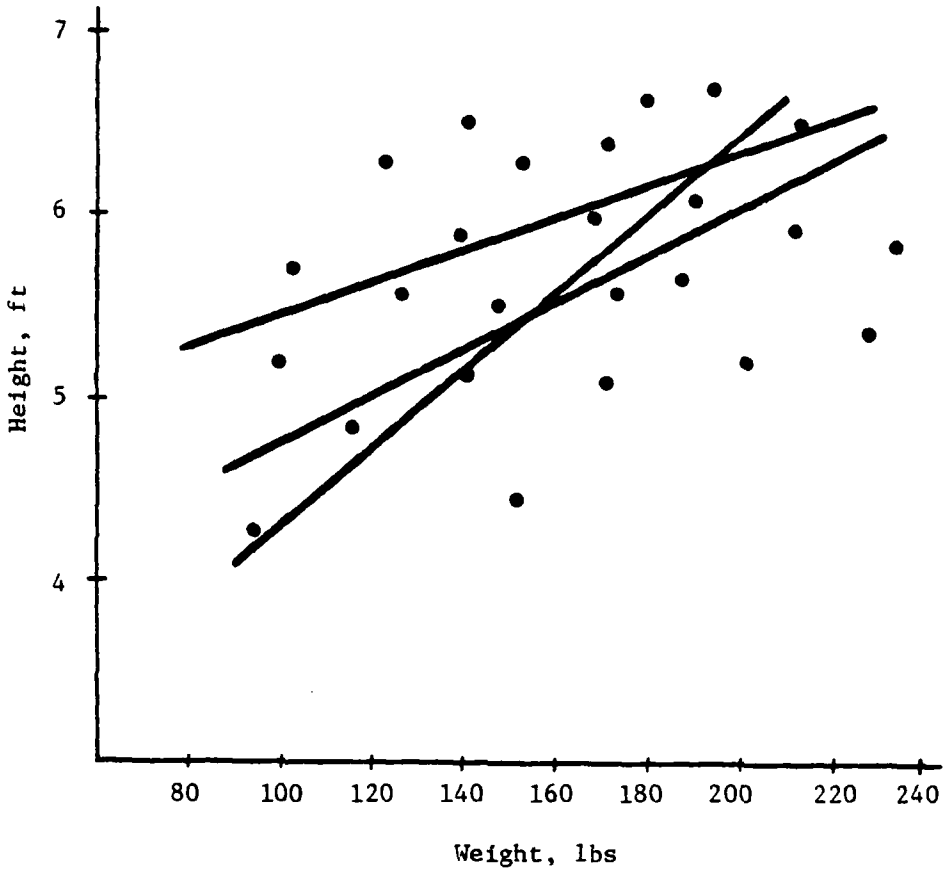

Figure 4.2 Regression analysis example of height vs. weight

Pennsylvania State University Department of Statistics as an adaptation of a National Bureau of Standards program. MINITAB is particularly useful for regression analysis and is widely used in statistical consulting, instruction, business, industry, and government (Ryan, 1976).

SAS is one of the most powerful statistical analysis packages available today. Developed and maintained exclusively by the SAS Institute, SAS is widely used for all types of research, accounting, surveys, instruction, and modeling. SAS offers a wide variety of statistical procedures including a flexible general linear models option that performs multiple regression and produces excellent model diagnostics (SAS Institue, 1979). Before collecting the data required to run these programs, it is important to set the goals of the regression analysis.

4.2.3 Analysis goals

Any multiple regression analysis has $n*2^k$ possible regression equations, where k is the number of independent variables and n is the number of dependent variables (SAS Institute, 1979). Using the twenty independent variables from Table 4.1 and the two proposed dependent variables, there are 2,097,152 possible regression equations for this problem. Certain criteria and goals must be set in order to select the single equation that best meets the needs of the problem. Typical project goals include setting a minimum coefficient of determination and a maximum standard error of estimate, ensuring that all parameters are statistically significant, and eliminating residual patterns (Draper and Smith, 1966).

4.2.3.1 Coefficient of determination

The coefficient of determination, commonly called the r^2 value, is the square of the linear correlation coefficient between the observed Y

values and the predicted Y_p values (Ryan, 1976). The higher the value of r^2, the more useful the regression equation will be as a predictor of Y. The linear correlation coefficient indicates what change in an observed Y brings about a unit change in Y_p. A correlation coefficient of r = 0.95 indicates that when Y changes by 0.95, Y_p changes by 1.0. In general, r^2 is an index of equation usefulness, and the closer r^2 is to 1.0, the more useful the equation is in predicting Y_p. A goal of a minimum r^2 of 0.95 is set to ensure that the final equation will be very useful.

This minimum value of r^2 is very important because SAS has the capability to analyze tens of thousands of possible regression equations in seconds and calculate the r^2 values of each one. Those equations with r^2 values under 0.95 can then be immediately dropped from further consideration. Equations which satisfy the r^2 criterion must then be checked for precision, determined by the standard error of estimate.

4.2.3.2 Standard error of estimate

The residual is the amount that a predicted value varies from the actual observed value. The least squares method selects the parameters such that the sum of the squared residuals is a minimum. The standard error of estimate, s, is the square root of the residual mean square. A high value of s indicates that the residual mean falls far from the regression line and therefore the equation is imprecise. As s approaches zero, the residual mean approaches the regression line and the predictor equation becomes more precise (Draper and Smith, 1966).

The standard error of estimate is normally expressed as a percentage of the mean of the predicted value, called the mean response. A precise equation has an s value that is only a small percentage of the mean

response. The goal for the percentage of 0.1% is set to ensure that a precise equation is selected. Those equations meeting the criteria for usefulness and precision must next be evaluated for parameter statistical significance.

4.2.3.3 Parameter significance

All parameters, the coefficients of the independent variables, must be analyzed for significance. The possibility always exists that a parameter is actually equal to zero, which means that the independent variable cannot be used to predict the dependent variable because there is no correlation.

The first step is to propose the null hypothesis,

$$\beta_n = 0 \tag{4.5}$$

for all n independent variables. If β_n equals zero, that independent variable has zero correlation with Y. The procedure used by statisticians is to establish the probability that the null hypothesis is true. It is not possible to prove that the null hypothesis is true without performing the impossible task of investigating every case, but it is possible to calculate the probability that it is true based upon collected data.

For example, consider the null hypothesis that the age of the building custodian has zero correlation with the amount of useful solar gain that a building receives. This hypothesis can be immediately rejected if one case is found in which there is indeed a correlation. However, the hypothesis cannot be accepted unless every building is investigated and it is proven that no contrary evidence exists. Of course, after investigating a number of buildings, it is possible to establish a high degree of probability that the null hypothesis is true.

SAS performs a standard statistical test, called a t-test, to check the null hypothesis for each parameter against set confidence limits. If a parameter fails the t-test, this indicates that the null hypothesis cannot be rejected within an acceptance degree of confidence and therefore the independent variable should be dropped from the equation. The residuals of those equations which meet the goals for usefulness, precision, and parameter significance must be plotted as a final test.

4.2.3.4 Residual plots

The last step in formulating an accurate regression equation is to evaluate the residuals. Normally, the standardized residuals, which are the residuals divided by the estimate of their standard deviation, are plotted versus the independent variables to ensure that they are completely random (Ryan, 1976). If any trends or patterns occur, there is a high probability that the true regression equation is non-linear or higher order.

Figure 4.3 shows typical residual plots. The gray bands indicate the range of the standardized residuals. Figure 4.3a is a well fit model having residuals randomly distributed in a broad band on either side of zero residual. Figure 4.3b and 4.3c show poorly fit regression equations. Figure 4.3b suggests that the parameter is non-linear and Figure 4.3c shows a trend towards higher standardized residuals as the independent variable increases. Both of these patterns are unacceptable for a proper regression equation (Draper and Smith, 1966). Having set the goals of the research, the regression model can now be developed.

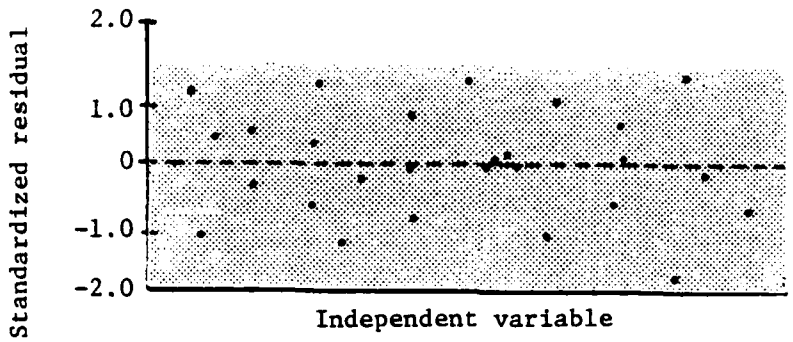

Figure 4.3a Acceptable residual plot

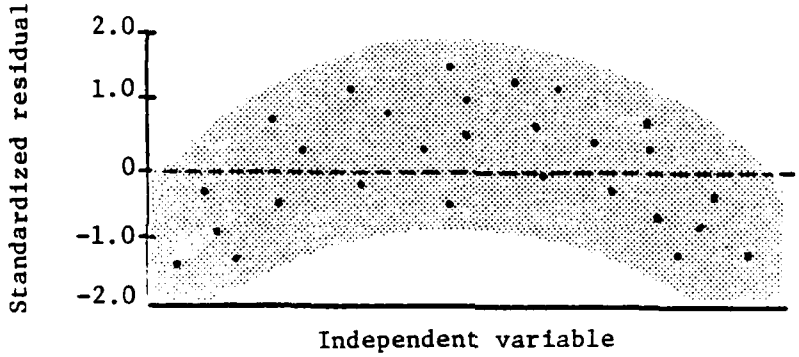

Figure 4.3b Non-linear parameter pattern

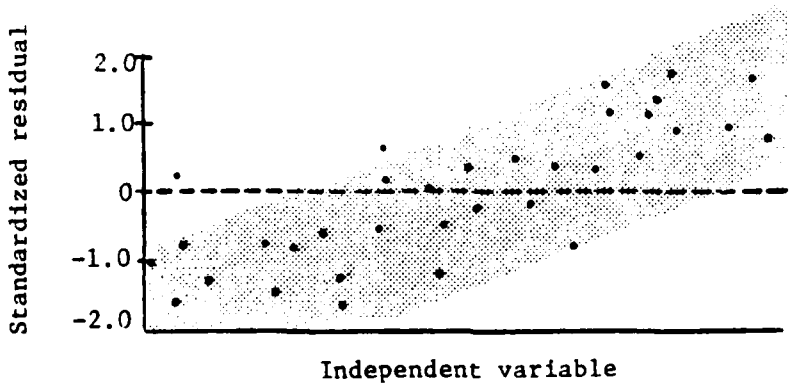

Figure 4.3c Increasing standardized residual trend

4.3 Model Development

The development of the predictive model for solar gain required collecting data on test buldings, performing accurate computer simulations to determine the solar gains, and analyzing over two million possible regression equations to select the best one.

4.3.1 Data collection

Data collection was the first phase of the model development process. Eleven medium construction masonry buildings typical of the State College area were selected for data analysis and computer simulation. Ten of these buildings were State College Area School District school buildings that had recently been thoroughly investigated for energy conservation opportunities under the National Energy Conservation Policy Act Grants Program. The other building was a hypothetical, single story, rectangular (200 ft x 250 ft) office building in which conditions were varied for each computer simulation in order to provide a wide variation in building parameters. Table 4.2 tabulates the general characteristics of each building.

Two sets of data were collected for each building. The first set of data was the Modified Bin Method information (Table 4.1). The second set of data was the detailed input information required by the BEAP computer program to accurately simulate the building, including hourly load and thermostat profiles; area, U-value, density, specific heat, and orientation of each buliding envelope component; and hourly wind velocity, solar radiation, wetbulb and drybulb temperatures, and barometric pressure.

Table 4.2

Test building characteristics

Building	Floor Area ft^2	Volume ft^3	Overall UA Btu/hr·°F	Overall SC -	Occupants -	Lighting $watts/ft^2$	South-Facing Glass ft^2
Hypothetical office building	50000	700000	13251	1.0	200	1.5	1050
College Heights Elementary	9798	116974	15434	0.35	113	1.3	960
Corl Street Elementary	23644	229660	8539	0.36	318	1.5	2982
Easterly Parkway Elementary	36957	248435	37493	0.42	341	2.0	2047
Ferguson Township Elementary	31681	333453	38568	0.41	361	1.5	4038
Lemont Elementary	29000	321177	37601	0.32	256	2.0	1682
Matternville Elementary	16448	164480	15726	0.46	144	1.5	1731
Panorama Elementary	35414	318726	20523	0.45	329	1.6	2269
State College Senior High	169561	1777879	113836	0.36	1491	2.1	15251
Boalsburg Elementary	35945	578011	15399	0.73	138	1.2	5796
Radio Park Elementary	46214	447995	20275	0.75	574	1.4	2892

4.3.2 Computer simulation

The BEAP program was run to provide accurate simulations of each building. In order to increase the data base to include a wider variation of building types, the hypothetical office building was run thirty-one times under various conditions. Table 4.3 shows the variation for each simulation. Each State College school was run twice, once for efficient thermostat operation at 68°F daytime and 55°F setback and once for inefficient operation at a continuous 75°F setting. These various conditions for the eleven buldings yielded a total of fifty-one separate computer simulations. The building characteristics for each simulation, including the twenty characteristics from Table 4.1 and the useful derived values of percent glass area, percent south-facing glass area, infiltration and ventilation per square foot of floor area, and number of occupants per 1,000 square feet of floor area, are listed in Appendix C.

The two dependent variables of solar heat gain and balance point were under consideration. BEAP tabulates solar heat gain directly, so these values were recorded for use in the statistical analysis. However, as BEAP does not calculate balance point temperature, an iterative technique was used to calculate this quantity.

First, the Modified Bin Method was used to calculate heat loss, lighting and occupancy heat gain, and net heating load per square foot, using no solar heat gain. The balance point of each building was then stepped down in 2°F increments from 62°F, the solar gains were calculated by Equation 4.2, and the net heating load per square foot was compared with BEAP. Table 4.4. illustrates this technique for test bulding #12. The balance point was determined as that temperature at which the BEAP

Table 4.3

Variations in hypothetical office building characteristics

Run #	Variation	Quantity	Base Run Condition
1	None	Base run	-
2	Glass percentage	5% Glass	17% Glass
3	"	10%	"
4	"	15%	"
5	"	20%	"
6	"	25%	"
7	"	30%	"
8	"	50%	"
9	Ventilation rate	5 CFM/person	10 CFM/person
10	"	7.5	"
11	"	15	"
12	"	20	"
13	"	50	"
14	Infiltration rate	0 CFM	260 CFM
15	"	1000	"
16	"	4000	"
17	"	10000	"
18	Roof U-value	U-0.05	U-0.115
19	"	0.15	"
20	"	0.30	"
21	Wall U-value	U-0.10	U-0.33
22	"	0.20	"
23	Occupants	0 people	200 people
24	"	500	"
25	Lighting	0 watts/ft^2	1.5 watts/ft^2
26	"	0.5	"
27	"	3.0	"
28	Orientation	Glass faces E & W	Glass faces N & S
29	Shading coefficient	SC-0.8	SC-1.0
30	"	0.6	"
31	"	0.4	"

Table 4.4

Balance point iteration technique

Iteration	Balance Point °F	Heat Loss MBtu	Heat Gain MBtu	Net Heating Load MBtu/ft^2
1	62	1,936,592	364,673	31.4
2	60	1,936,592	365,150	31.4
3	58	1,936,592	366,905	31.4
4	56	1,936,592	402,103	30.7
5	54	1,936,592	461,290	29.5
6	52	1,936,592	520,477	28.3

BEAP net load - 28.3 MBtu/ft^2

and Modified Bin Method net loads were equal. These results were then used in the regression analysis.

4.3.3 Regression analysis

The regression analysis was performed in four parts which paralleled the specific goals established at the beginning of the research. First, the coefficients of determination for all 2,097,152 possible regression equations were calculated; those falling below the 0.95 goals were rejected. Next, the standard error of estimate as a percentage of the mean response was calculated and compared against the goal of 0.1%. These two steps reduced the possible equations down to nine. The third step was to reject those equations having statistically questionable parameters, and finally the residuals of the selected equation were plotted and checked.

4.3.3.1 Coefficients of determination

SAS includes an extremely powerful procedure called RSQUARE in which the r^2 values of a list of independent and dependent variables are calculated. The program matches every possible combination of variables and performs a least squares computation.

RSQUARE was run for the two dependent variables of solar gain and balance point versus the nineteen independent variables listed in Table 4.1. Slab edge insulation was rejected as an independent variable because all of the buildings had the same amount of insulation. The best r^2 values were 0.90 using solar gain as the dependent variable and 0.95 using balance point temperature. Based upon these results, all models involving the dependent variable of solar heat gain were rejected due to r^2 values significantly below the r^2 goal of 0.95.

Table 4.5 shows the best regression equations in terms of the r^2 value for the dependent variable of balance point and from five to nineteen independent variables. The usefulness of the model, expressed as r^2, increases as more variables are added, but increases are slight above eleven variables. Even though the six equations between #11 and #16 fail to meet the 0.95 r^2 goal, they fall no more than 2% low, so the nine equations having eleven to nineteen variables were selected for further analysis.

4.3.3.2 Standard error of estimate

The goal for the standard error of estimate, expressed as a percentage of the mean response, was set at 0.1%. Table 4.6 shows the results for the nine regression equations. Model 1 was rejected for exceeding the 0.1% goal, while the remaining equations passed the test. The next test for the eight regression equations is for parameter significance.

Table 4.5

RSQUARE results for balance point temperature

Number of Independent Variables	r^2	Added Variables
5	0.54	SGLASS, SC, DAYSET, SGLASS, LIGHTS
6	0.70	UROOF
7	0.84	AROOF
8	0.89	INFIL
9	0.91	VENT
10	0.92	BWALL
11	0.93	NITESET
12	0.93	PEOPLE
13	0.94	AWALL
14	0.94	VOLUME
15	0.94	SLAB
16	0.94	AREA
17	0.95	UGLASS
18	0.95	UWALL
19	0.95	BFLOOR

Table 4.6

Standard error of estimate for the final nine equations

Model #	Independent Variables	r^2	Balance Point Mean	s	$\frac{\text{Mean}}{s}(100\%)$
1	11	0.93	48.37	0.915	1.89%
2	12	0.93	48.37	$2.5\text{x}10^{-3}$	0.005%
3	13	0.94	48.37	$1.3\text{x}10^{-4}$	0.0003%
4	14	0.94	48.37	$5.5\text{x}10^{-6}$	0.00001%
5	15	0.94	48.37	$2.1\text{x}10^{-3}$	0.004%
6	16	0.94	48.37	$2.8\text{x}10^{-3}$	0.006%
7	17	0.95	48.37	$2.9\text{x}10^{-3}$	0.006%
8	18	0.95	48.37	$3.1\text{x}10^{-3}$	0.006%
9	19	0.95	48.37	0.015	0.03%

4.3.3.3 Parameter significance

SAS automatically performs t-tests on all parameters to establish the probability that the null hypothesis can be rejected. Table 4.7 shows the results of those tests. Models 5-9 were rejected because the combination of over fifteen independent variables in this regression problem caused the significance of some variables to be questionable.

There is little difference between the remaining models. Model 3 has the same twelve independent variables as model 2 plus wall area, and model 4 adds building volume. Building volume failed the significance tests for models 5-9. Although it just passes the test for model 4, the advantage of using this variable is questionable, so model 4 is rejected. Model 3 has a slightly better coefficient of determination and a significantly better standard error of estimate than model 2 at the cost of only one added variable, so model 3 is chosen as the final regression equation. Model 3 is written as:

$$\begin{aligned} \text{BALANCE} = 353.23 &- 0.00934*\text{SGLASS} - 7.63*\text{SC} - 5.96*\text{DAYSET} \\ &- 0.000589*\text{AGLASS} + 0.000181*\text{AROOF} + 37.65*\text{UROOF} \\ &- 0.000751*\text{INFIL} + 0.000735*\text{VENT} - 5.94*\text{LIGHTS} \\ &+ 0.000707*\text{BWALL} + 1.937*\text{NITESET} - 0.00483*\text{PEOPLE} \\ &+ 0.000144*\text{AWALL} \end{aligned} \tag{4.6}$$

The final test for this equation is to ensure that there are no unacceptable patterns or trends in the residuals.

4.3.3.4 Residual plots

The normal procedure for residual plots is to graph the standardized residuals versus the predicted responses and all of the independent variables (Draper and Smith, 1966). Further analysis is not required unless problems are indicated. Figure 4.4 is the plot generated by MINITAB of

Table 4.7

Tests for parameter significance

Model #	Number of Independent Variables	Parameters Failing Significance Test
1	11	Model #1 rejected previously
2	12	None
3	13	None
4	14	None
5	15	VOLUME, SLAB
6	16	VOLUME, SLAB, UGLASS
7	17	VOLUME, SLAB, UGLASS, UWALL
8	18	VOLUME, SLAB, UGLASS, UWALL, BFLOOR
9	19	VOLUME, SLAB, UGLASS, UWALL, BFLOOR, AREA, BWALL, AWALL

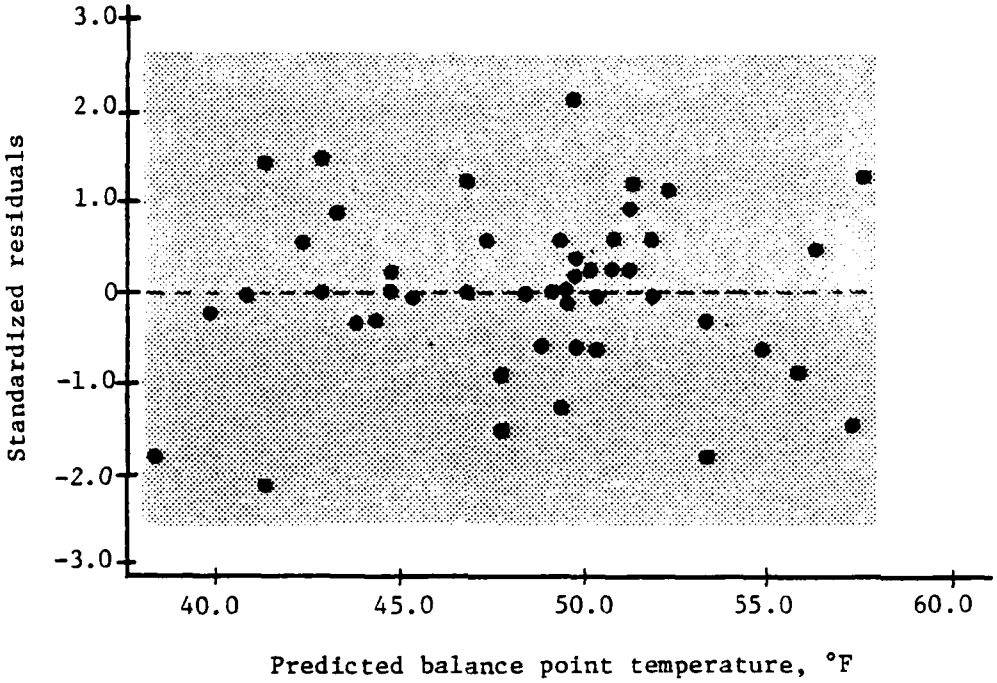

Figure 4.4 Balance point standardized residual vs. predicted response

the balance point standardized residuals versus the predicted responses. The values fall into the proper range without trends or patterns. All of the independent variables were graphed in the same way and no problems were encountered. Accordingly, Equation 4.6 is a statistically useful, precise, and significant predictive model that can be integrated into the Modified Bin Method.

Chapter 5

MODIFIED BIN METHOD

The final step of the model building process illustrated in Figure 4.1 is validation of the model. Validation involves testing the model to ensure that it performs as intended and determining over what range of independent variables the model can be applied (Draper and Smith, 1966). The way to perform these tests is to integrate the model into the final Modified Bin Method, calculate the annual heating loads of several buildings, and compare the results against the BEAP simulations of the buildings.

5.1 Model Integration

The final Modified Bin Method consists of the heat loss, lighting and occupancy heat gain, balance point, and solar gain equations integrated into a single procedure. Figure 5.1 is a flow chart of the complete method. Many variations can be readily made in order to calculate monthly rather than yearly values, simulate some mechanical equipment performance (such as heat pumps) at each temperature bin, or combine the heat loss and heat gain terms in order to reduce the number of equations. The Modified Bin Method can be done by hand, programmable calculator, or computer. The Modified Bin Method was used to evaluate the accuracy of the regression equation.

5.2 Model Validation

The Modified Bin Method was programmed in FORTRAN on The Pennsylvania State University's IBM 370/3033 computer (Heinz, 1980). The program was run for each of the fifty-one test buildings used in the statistical analysis. Each run required approximately five minutes for the user to input the

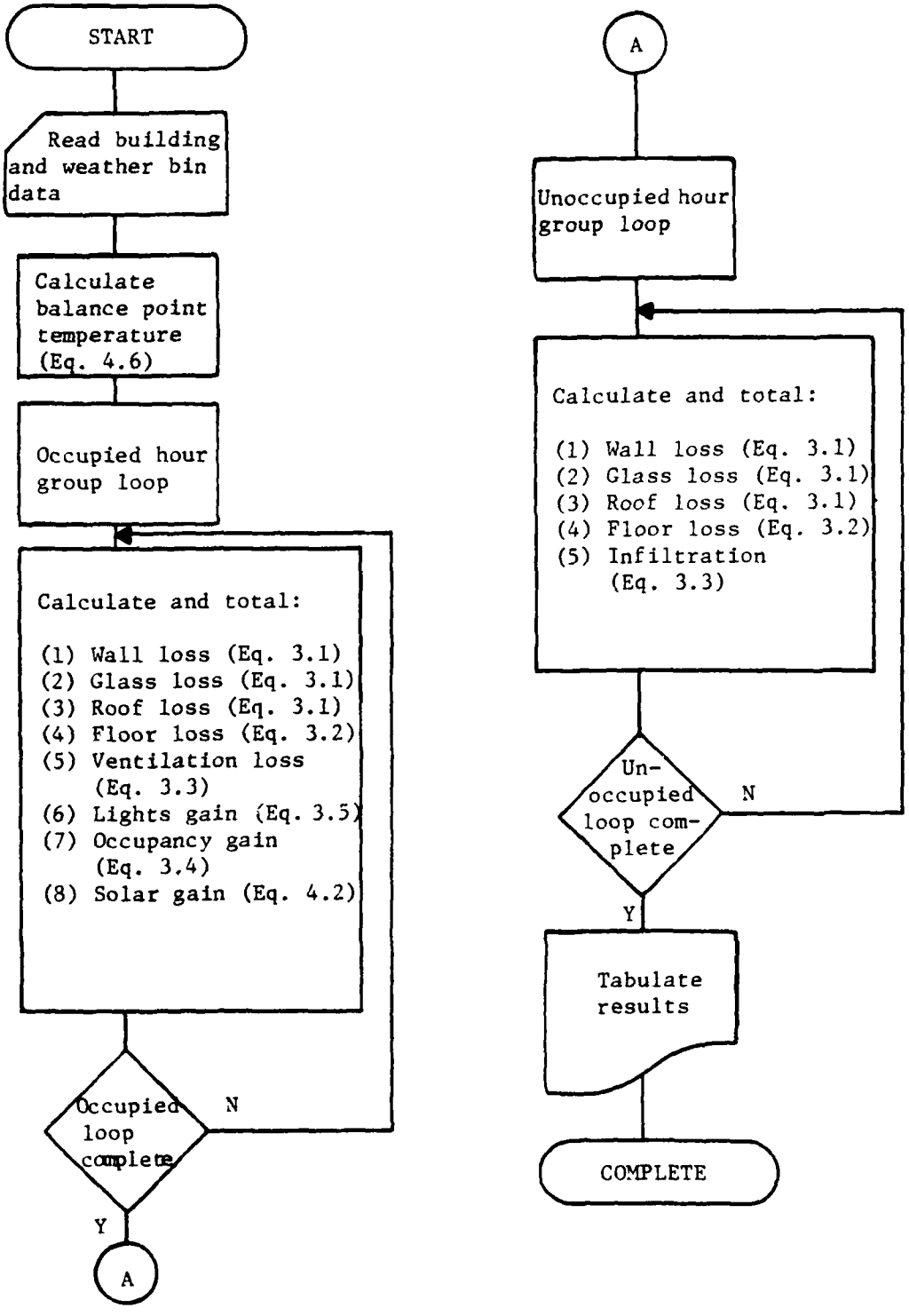

Figure 5.1 Modified Bin Method flow chart

two lines of data (twenty numbers) and computation costs averaged 20¢ per building. Figure 5.2 is a typical output for Boalsburg Elementary School.

As the results in Table 5.1 indicate, the Modified Bin Method calculated the annual heating loads to within an average of 1.6% of BEAP, with over 20% of the Modified Bin Method calculations being exactly equal to BEAP. The worst run, building #2, was 6.3% lower than BEAP, but this was a hypothetical test building with only 5% glass area which is not representative of actual construction.

A similar analysis was performed on two additional buildings, Park Forest Elementary School and Houserville Elementary School, to illustrate the use of the Modified Bin Method for buildings not included in the statistical analysis. Table 5.2 presents the results of this example. Although less than 2% more accurate, the BEAP program required 493 lines of input data (versus four lines for the Modified Bin Method), accessibility to a large computer, and much more expense for computer costs and manpower. Comparing the Modified Bin Method result to the bin method result from Table 2.4 (16.4% error), the Modified Bin Method is a major improvement to the existing bin method due to its greatly increased accuracy at only a slight increase in calculation effort. These examples verify that the regression equation in the Modified Bin Method performs as expected.

The final phase of the validation process is to establish the range over which the method is valid. The standard procedure is to limit the range to the values of the independent variables used in the analysis, unless other ranges are indicated (Draper and Smith, 1966). The only problem was a loss of accuracy at low glass percentages, so the range is limited

BUILDING HEATING LOAD ANALYSIS
MODIFIED BIN METHOD
DATE: 08/27/80

MONTH	HEAT LOSS: WINDOW LOSS (MBTU)	WALL LOSS (MBTU)	ROOF LOSS (MBTU)	FLOOR LOSS (MBTU)	INFIL/VENT LOSS (MBTU)	TOTAL HEAT LOSS (MBTU)	HEAT GAIN: LIGHTS GAIN (MBTU)	PEOPLE GAIN (MBTU)	SOLAR GAIN (MBTU)	TOTAL HEAT GAIN (MBTU)	NET HEAT RQMT: TOTAL RQMT (MBTU)	TOTAL RQMT (MBTU/SF)
JANUARY	169599.	95680.	116285.	23025.	58376.	462964.	18942.	4494.	61359.	84796.	378169.	10.5
FEBRUARY	158953.	89674.	108985.	21208.	54624.	433443.	17109.	4059.	55403.	76571.	356872.	9.9
MARCH	117392.	66227.	80489.	19303.	40452.	323863.	18942.	4494.	59975.	83412.	240452.	6.7
APRIL	57578.	32483.	39478.	11630.	19078.	163046.	17648.	4186.	54433.	76262.	86784.	2.4
MAY	26593.	15002.	18233.	8225.	9254.	77308.	13337.	3117.	40186.	56640.	20668.	0.6
JUNE	2817.	1589.	1931.	1719.	931.	8988.	0.	0.	3289.	3289.	5699.	0.2
JULY	767.	433.	526.	748.	254.	2728.	0.	0.	1973.	1973.	758.	0.0
AUGUST	123.	69.	84.	124.	41.	442.	0.	0.	0.	0.	442.	0.0
SEPTEMBER	6717.	3789.	4605.	3821.	2344.	20877.	9243.	2193.	27849.	39283.	0.	0.0
OCTOBER	45619.	25736.	31279.	12327.	15763.	130724.	18408.	4367.	56375.	79150.	51574.	1.4
NOVEMBER	75222.	42437.	51576.	15455.	25984.	210673.	18026.	4277.	56140.	78443.	132230.	3.7
DECEMBER	126322.	71265.	86633.	19940.	43508.	347648.	18942.	4494.	60190.	83627.	264021.	7.3
TOTALS	787701.	444384.	540088.	139126.	271407.	2182696.	150193.	35601.	477171.	663245.	1519453.	42.1

Figure 5.2 Boalsburg Elementary School Modified Bin Method results

Table 5.1

Modified Bin Method comparison with BEAP

Run	Annual Heating Load BEAP MBtu/ft^2	Modified Bin MBtu/ft^2	Variance %	Run	Annual Heating Load BEAP MBtu/ft^2	Modified Bin MBtu/ft^2	Variance %
1	26.3	26.4	0.4	29	27.0	26.9	0.4
2	23.8	25.4	6.3	30	27.8	27.4	1.5
3	25.4	25.9	1.9	31	28.4	28.0	1.4
4	26.0	26.3	1.1	32	59.5	60.9	2.3
5	26.6	26.7	0.4	33	32.8	33.6	2.4
6	27.1	27.1	0.0	34	34.9	34.2	2.0
7	27.6	27.6	0.0	35	40.4	41.4	2.4
8	29.4	29.4	0.0	36	46.7	45.2	3.3
9	25.9	25.9	0.0	37	35.9	36.2	0.8
10	26.3	26.3	0.0	38	29.5	29.0	1.7
11	27.3	27.5	0.7	39	40.1	41.5	3.4
12	28.0	28.3	1.1	40	102.3	102.3	0.0
13	33.3	33.1	0.6	41	57.5	57.3	0.3
14	26.2	26.3	0.4	42	60.8	60.4	0.7
15	27.7	27.8	0.4	43	72.4	70.5	2.7
16	32.0	32.0	0.0	44	79.3	81.4	2.6
17	40.1	40.2	0.2	45	61.3	59.9	2.3
18	18.8	17.9	5.0	46	49.7	52.3	5.0
19	30.5	31.0	1.6	47	74.1	73.0	1.5
20	50.9	49.4	3.0	48	42.3	42.3	0.0
21	21.3	21.0	1.5	49	37.3	37.9	1.6
22	23.4	23.4	0.0	50	54.4	54.4	0.0
23	26.7	27.4	2.6	51	47.9	47.9	0.0
24	25.5	25.1	1.6			Average	1.6%
25	30.8	31.3	1.6				
26	29.3	29.6	1.0				
27	21.6	22.2	2.7				
28	25.8	25.3	2.0				

Note: See Appendix C for identification of each run.

Table 5.2

Modified Bin Method results for two schools

School	BEAP Lines of Data	BEAP Heating Load, MBtu/ft^2	Modified Bin Method Lines of Data	Modified Bin Method Heating Load, MBtu/ft^2	Variance %
Houserville	271	29.8	2	29.7	0.3%
Park Forest	222	25.5	2	24.7	3.1%
					Ave 1.7%

to a minimum of 10% glass area. Table 5.3 lists the conditions under which the Modified Bin Method has been validated as an accurate heating load calculation procedure.

It is most important that applications of the Modified Bin Method be limited to this validated range of conditions. Although the Modified Bin Method has been proven to be an accurate, simple heating load calculation method when properly used, its accuracy may be adversely affected when applied beyond its proven range.

Table 5.3

Modified Bin Method range of application

Condition	Range
Weather	5,000-9,000 degree days (65°F base)
Construction	Medium construction masonry, 60-110 lb/ft^2 of floor area
South glass area	630-15250 ft^2; 35-100% of total glass area
Shading coefficient	0.32-1.0
Day thermostat setting	68°F; 72°F; 75°F
Night thermostat setting	55°F; 68°F; 75°F
Glass area	1260-28030 ft^2; 10-40% of total wall area
Roof area	9800-146780 ft^2
Wall area	5505-61870 ft^2
Roof U-value	0.04-0.3 $Btu/ft^2 \cdot hr \cdot °F$
Infiltration	0-11390 cfm; 0-0.2 cfm/ft^2
Ventilation	0-11390 cfm; 0-0.2 cfm/ft^2
Lights	0-3.0 $watts/ft^2$
Occupants	0-1490 people; 0-15 people/1000 ft^2
Basement wall area	0-4560 ft^2

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

6.1 Conclusions

1. Existing heating load calculation methods have serious disadvantages which hinder the engineer in energy conservation studies. Both the simple heating degree day and bin methods have questionable accuracy due to the imprecise procedure of accounting for internal and solar heat gains by using a 65°F balance point temperature. Accurate hour-by-hour simulations, usually performed by a high-speed computer, are time consuming and expensive.

2. Simple, widely used ASHRAE equations can be used to calculate all of the components of heat loss and all of the components of heat gain except solar gain.

3. Statistical analysis methods can be used to determine the building characteristics most important to the amount of useful solar gains that a building receives. These characteristics may be used as independent variables in a regression equation.

4. A regression equation is a predictive model which, when properly planned, developed, and validated, can accurately predict building balance point temperature which in turn can be used to calculate solar gains.

5. Integration of the regression equation with the simple ASHRAE equations into a Modified Bin Method provides a useful tool for predicting annual building heating loads. The Modified Bin Method represents a positive contribution to the field of energy conservation by providing the engineer with a simple yet accurate method of calculating building heating loads. The use of actual building data confirms the accuracy of the Modified Bin Method in actual applications generally within 2%.

6. The Modified Bin Method must be used within a defined range of application established by the statistical data base used in the regression analysis. The validity of the solar gain predictor equation has not been tested beyond the limits presented in Table 5.3.

6.2 Recommendations for Future Study

1. The Modified Bin Method should be extended to a wider range of building types and to other climates by using independent variables that account for construction weight, outside temperature, solar radiation, and latitude. This requires using BEAP to simulate typical buildings in a wide range of climates and performing a multiple regression analysis on the data.

2. The range of application of the Modified Bin Method should be extended by repeating the multiple regression analysis used in this thesis with a much larger data base of BEAP results. By doing so, the solar gain predictor equation will be valid over a broader range of values and the method will be applicable to more building types and sizes.

3. A Modified Bin Method for summer cooling should be developed. The same basic statistical methods can be applied to determine the relevant variables and formulate the regression equation.

4. Construction details and energy consumption data should be acquired for actual buildings over a wide climatic range of the U.S. These data are essential to validate energy calculation methods such as BEAP, the Modified Bin Method, and future programs.

One possible local source is The Pennsylvania State University, Office of Physical Plant, which maintains monthly electricity, natural gas, and steam consumption records for all campus buildings.

REFERENCES

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., ASHRAE Handbook - 1972 Fundamentals, New York: ASHRAE, 1972.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., ASHRAE Handbook - 1977 Fundamentals, New York: ASHRAE, 1977.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., ASHRAE Handbook and Product Directory - 1980 Systems, New York: ASHRAE, 1980.

Davies, Owen L. and Goldsmith, Peter, L., ed., Statistical Methods in Research and Production, 4th ed., New York: Hafner Publishing Company, 1972.

Donovan, Douglas A., A Student User's Guide to BEAP, The Pennsylvania State University: Department of Architectural Engineering, 1977.

Donovan, Douglas A., Validation of Heat Gain and Air-Conditioning Load Calculations, The Pennsylvania State University: Department of Architectural Engineering, 1979.

Draper, N. R. and Smith, H., Applied Regression Analysis, New York: John Wiley & Sons, Inc., 1966.

Heinz, Steven D., User's Guide to the Modified Bin Method, The Pennsylvania State University: Department of Architectural Engineering, 1980.

Kurtz, Thomas E., Basic Statistics, Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1963.

Ryan, Thomas A., Joiner, Brian L., and Ryan, Barbara F., MINITAB Student Handbook, North Scituate, Massachusetts: Duxbury Press, 1976.

Ryan, Thomas A., Joiner, Brian L., and Ryan, Barbara F., MINITAB Reference Manual, The Pennsylvania State University: Computer Output, 1980.

Statistical Analysis System Institute, Inc., SAS User's Guide 1979, Raleigh, North Carolina: SAS Institute, 1979.

Thorndike, Robert M., Correlational Procedures for Research, New York: Gardner Press, Inc., 1978.

U.S. Department of Defense, Air Force Manual 88-29, Engineering Weather Data, Washington, D.C.: Government Printing Office, 1978.

U.S. Department of Energy, Building Energy Performance Standards Technical Support Documents, Washington, D.C.: Government Printing Office, 1979.

U.S. Department of Energy, The National Energy Conservation Policy Act Grants Program, Washington, D.C.: Government Printing Office, 1980.

Appendix A

UA CALCULATIONS FOR PARK FOREST ELEMENTARY SCHOOL

Table A.1

Degree day UA calculation

Component	Equation	UA
(1) Glass	1.09*4866	5304
(2) Walls	0.09*13392	1205
(3) Roof	0.06*44412	2665
(4) Infiltration	$1.1*\frac{2}{3}*1799$	1320
(5) Ventilation	$1.1*\frac{1}{3}*3600$	1319
(6) Slab	2132*0.53	1096
	Total UA	12909

(Note: infiltration occurs 2/3rds of the day, ventilation 1/3rd)

Table A.2

Bin Method UA calculation

Component	Equation	Occupied UA	Unoccupied UA
(1) Glass	1.09*4866	5304	5304
(2) Walls	0.09*13392	1205	1205
(3) Roof	0.06*44412	2665	2665
(4) Infiltration	1.1*1799	-	1979
(5) Ventilation	1.1*3600	3960	-
(6) Slab	2132*0.53	1096	1096
	Totals	14230	12249

The selection of the 45°F balance point was made as follows:

Heat loss = Heat gain (at the balance point)

Therefore,

Heat loss = Lighting gain + Occupancy gain + Solar gain

In terms of heat loss and heat gain per hour (MBtu/hr),

Heat loss = UA*(70 - balance point) = 14.2*(70 - balance point)

Lighting gain = 2.26 watts/ft^2*3.413*0.9*$\frac{5}{7}$*44412/1000 = 220 MBtu/hr

Occupancy gain = 670 people*0.25*0.9*$\frac{5}{7}$ = 108 MBtu/hr

Solar gain = 2°F (based upon the few windows in the school, heavy roof and wall insulation, and heavily shaded site)

where the 5/7 factor accounts for five occupied days each week. Solving for balance point,

Balance point = 70 - 2 - (220 + 108)/14.2 = 45°F

Appendix B

ENERGY RECONCILIATION FOR PARK FOREST ELEMENTARY SCHOOL

To compare the actual heating loads of Park Forest Elementary School with BEAP, the actual gross consumption must be adjusted for all uses not simulated by BEAP. BEAP does not calculate loads due to the following: domestic hot water, air-conditioning, all summer electricity consumption (4 June-31 August), and lighting. Other uses of electricity in this building are negligible.

The fiscal year 1979 metered consumption according to school district records was 1,734,804 MBtu. Domestic hot water usage is calculated at 0.6 gallons per student per day for 180 school days as follows (ASHRAE, 1980):

$$DHW = 0.6*670*180*8.33*(140-50) = 54,240 \text{ MBtu/yr}$$

Two small air-conditioning units with a 5.4 KW connected load are used for 200 equivalent full load hours a year.

$$AC = 5.4*200*3.413 = 3,686 \text{ MBtu/yr}$$

All of the summer consumption of 116,725 MBtu/yr must be subtracted because BEAP assumes a total summer shut-down.

Lighting use is estimated at eight hours per day usage for 180 days,

$$LIGHTS = 180*8*100 \text{ KW}*3.413 = 493,070 \text{ MBtu/yr}$$

The net heating load that the building's heating system must supply is the gross minus the corrections, for a total of 1,067,075 MBtu/yr.

Appendix C

BUILDING DATA

Tables C.1 and C.2 present the building data for the hypothetical office building and ten State College Area School District schools used in the statistical analysis and the two elementary schools tested in the example Modified Bin Method calculation. All thirty-one hypothetical office buildings are not listed because each building is identical except for the variations described in Table 4.3. Table C.1 includes the data for the thirteen balance point equation variables while Table C.2 contains the other seven Modified Bin Method variables in addition to the useful derived values of percent glass (percentage of total wall area), percent south-facing glass (percentage of total glass area), ventilation and infiltration CFM per square foot of floor area, occupants per 1,000 square feet of floor area, overall building UA value, and building construction weight in pounds per square foot of floor area.

The run numbers in Table C.1 represent the runs as tabulated in Table 5.1. Table 4.3 identifies the conditions for the hypothetical office building, runs 1-31. Each of the ten State College Area School District schools used in the statistical analysis was run twice, once at efficient thermostat settings (68°F occupied/55°F unoccupied) and once at inefficient thermostat settings (75°F constant). The first run number in Table C.1 is the efficient setting run and the second number is the inefficient setting run.

The Modified Bin Method data for each run consists of all of the data in Table C.1 and the data in columns 2-8 in Table C.2. Input data for each BEAP run is maintained by The Pennsylvania State University, Department of Architectural Engineering, Computer-Aided Design Laboratory.

Table C.1

Building data

Run #	Building	SGLASS	SC	DAYSET	AGLASS	AROOF	UROOF	INFIL	VENT	LIGHTS	BWALL	NITESET	PEOPLE	AWALL
1-31	Hypothetical office building	1050	1.0	68	2100	50000	.115	260	2000	1.5	0	55	200	10500
32,40	College Heights Elementary	960	.35	68	1890	9798	.068	836	836	1.31	1463	55	113	5505
33,41	Corl Street Elementary	2982	.36	68	3225	23614	.05	1293	1293	1.46	0	55	318	7055
34,42	Easterly Parkway Elementary	2047	.42	68	5736	24464	.108	1330	1330	2.0	4559	55	341	8949
35,43	Ferguson Elementary	4038	.41	68	4759	22002	.08	2336	2336	1.5	1400	55	361	11458
36,44	Lemont Elementary	1682	.32	68	2347	20534	.30	1031	1031	2.0	2200	55	256	9764
37,45	Matternville Elementary	1731	.46	68	2008	16448	.039	894	894	1.5	1776	55	144	7229
38,46	Panorama Village Elementary	2269	.45	68	3476	35414	.096	677	677	1.58	1860	55	329	8038
39,47	State College High School	15251	.36	68	28028	146777	.109	11391	11391	2.08	4427	55	1491	61866
48,50	Boalsburg Elementary	5796	.72	68	5994	17382	.231	1760	2033	1.18	2269	55	138	14554
49,51	Radio Park Elementary	2892	.75	68	6012	32591	.198	700	5730	1.44	496	55	574	8976
Table 5.2	Houserville Elementary	2269	.90	68	3476	37352	.10	677	2400	1.57	1860	55	240	8677
Table 5.2	Park Forest Elementary	2741	.73	68	4866	44412	.06	1799	3600	2.26	0	55	670	13392

Note: The run numbers identify the results in Table 5.1

Table C.2

Building data

	UGLASS	UWALL	BFLOOR	SLAB	SLABST	AREA	VOLUME	Building UA	Construction lb/ft^2	Glass %	SGLASS %	INFIL ft^2	VENT ft^2	PEOPLE 1000 ft^2
Hypothetical office building	1.1	.33	0	900	60	50000	700000	13251	96	17	50	.005	.040	4
College Heights Elementary	.97	.32	1957	554	60	9798	116974	15434	99	26	51	.085	.085	12
Corl Street Elementary	.96	.27	0	1083	60	23644	229660	8539	91	31	92	.055	.055	13
Easterly Parkway Elementary	1.02	.24	3154	1028	60	36957	248435	37493	90	39	36	.040	.040	9
Ferguson Elementary	.88	.40	9679	634	60	31681	333453	38568	102	29	35	.074	.074	11
Lemont Elementary	.94	.20	8487	436	60	29000	321177	37601	98	19	72	.036	.036	9
Matternville Elementary	1.0	.21	1368	858	60	16448	164480	15726	93	22	86	.054	.054	9
Panorama Village Elementary	1.06	.15	1460	1298	60	35414	318726	20523	83	30	65	.019	.019	9
State College High School	.96	.31	9845	2056	60	169561	1777874	113836	101	31	54	.067	.067	9
Boalsburg Elementary	.98	.23	585	487	60	35945	578011	25875	96	29	97	.049	.056	4
Radio Park Elementary	.99	.19	6795	1376	60	46214	447995	33476	82	40	48	.015	.012	12
Houserville Elementary	1.06	.17	1460	1298	60	36952	332568	21629	94	29	65	.018	.065	7
Park Forest Elementary	1.09	.09	0	2132	60	44412	381996	11511	92	27	56	.041	.081	15

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