Advanced Building Science

- Energy Estimating
  - General considerations
  - Component modeling and loads
  - System modeling
    - Degree-day methods (primarily heating)
    - Bin method (heating & cooling)

- Readings
  - HF Chapter 19.1 to 19.8
  - HF Chapter 19.15 to 19.33

Energy Estimating

Key Components of Mathematical Modeling

- Input variables
  - controlled
  - uncontrolled
- System structure and parameters/properties
  - physical description of the system
- Outputs
  - Response or dependent variable
  - Reaction of the system

Energy Estimating

- Forward (or classical) Approach
  - starts with physical parameters
  - use sound engineering principles
  - predict the response
  - ideal for preliminary design

- Inverse (or data-driven) Approach
  - starts with empirical behavior and known inputs and outputs
  - uses statistical analysis to describe the system or determine key parameters/properties
  - ideal for existing systems

Analysis Methods

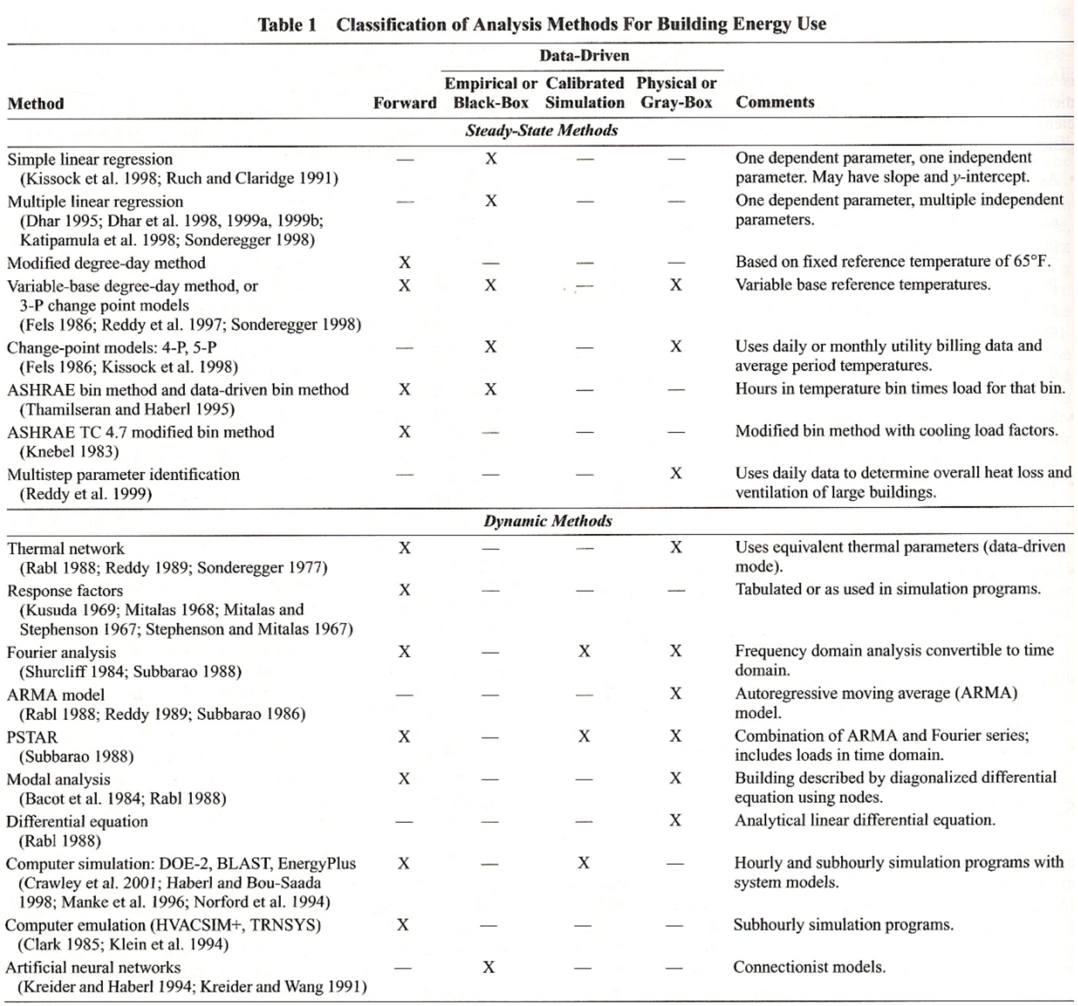


Table 1 Classification of Analysis Methods For Building Energy Use

		Data-Driven			
Method	**Forward**	**Empirical or Black-Box**	**Calibrated Simulation**	**Physical or Gray-Box**	**Comments**
		Steady-State Methods			
Simple linear regression (Kissock et al. 1998; Ruch and Claridge 1991)	—	X	—	—	One dependent parameter, one independent parameter. May have slope and *y*-intercept.
Multiple linear regression (Dhar 1995; Dhar et al. 1998, 1999a, 1999b; Katipamula et al. 1998; Sonderegger 1998)	—	X	—	—	One dependent parameter, multiple independent parameters.
Modified degree-day method	X	—	—	—	Based on fixed reference temperature of 65°F.
Variable-base degree-day method, or 3-P change point models (Fels 1986; Reddy et al. 1997; Sonderegger 1998)	X	X	—	X	Variable base reference temperatures.
Change-point models: 4-P, 5-P (Fels 1986; Kissock et al. 1998)	—	X	—	X	Uses daily or monthly utility billing data and average period temperatures.
ASHRAE bin method and data-driven bin method (Thamilseran and Haberl 1995)	X	X	—	—	Hours in temperature bin times load for that bin.
ASHRAE TC 4.7 modified bin method (Knebel 1983)	X	—	—	—	Modified bin method with cooling load factors.
Multistep parameter identification (Reddy et al. 1999)	—	—	—	X	Uses daily data to determine overall heat loss and ventilation of large buildings.
		Dynamic Methods			
Thermal network (Rabl 1988; Reddy 1989; Sonderegger 1977)	X	—	—	X	Uses equivalent thermal parameters (data-driven mode).
Response factors (Kusuda 1969; Mitalas 1968; Mitalas and Stephenson 1967; Stephenson and Mitalas 1967)	X	—	—	—	Tabulated or as used in simulation programs.
Fourier analysis (Shurcliff 1984; Subbarao 1988)	X	—	X	X	Frequency domain analysis convertible to time domain.
ARMA model (Rabl 1988; Reddy 1989; Subbarao 1986)	—	—	—	X	Autoregressive moving average (ARMA) model.
PSTAR (Subbarao 1988)	X	—	X	X	Combination of ARMA and Fourier series; includes loads in time domain.
Modal analysis (Bacot et al. 1984; Rabl 1988)	X	—	—	X	Building described by diagonalized differential equation using nodes.
Differential equation (Rabl 1988)	—	—	—	X	Analytical linear differential equation.
Computer simulation: DOE-2, BLAST, EnergyPlus (Crawley et al. 2001; Haberl and Bou-Saada 1998; Manke et al. 1996; Norford et al. 1994)	X	—	X	—	Hourly and subhourly simulation programs with system models.
Computer emulation (HVACSIM+, TRNSYS) (Clark 1985; Klein et al. 1994)	X	—	—	—	Subhourly simulation programs.
Artificial neural networks (Kreider and Haberl 1994; Kreider and Wang 1991)	—	X	—	—	Connectionist models.

Source: ASHRAE Handbook Fundamentals 2013 Chapter 19.4

General Considerations

Levels of Calculation Sophistication

- single-method measures
- simplified multiple-measures
- detailed simulation methods

Note: Because systems that consume energy in buildings are nonlinear, dynamic, and very complex, few methods other than computer modeling are available for accurately calculating energy consumption.

General Considerations

Selecting a Program

- Complexity of input procedures
- Quality of user’s manual
- Availability of support system
- Quality of output
- Availability of weather data
- Auxiliary capabilities

General Considerations

- Always use manual calculations to develop an understanding of the system and to verify inputs and outputs
  - Review computer documentation to determine procedures used
  - Compare results with manual calculations and/or measured data
  - Conduct sample tests to confirm results

- Understanding the outputs
  - Absolute consumption
  - Change in consumption

General Considerations

Choosing an Analysis Method

- Relative accuracy
- Sensitivity to desired options
- Versatility or range
- Speed and cost
- Reproducibility
- Ease of use

Energy Estimating

Component Modeling & Loads (mostly commercial)

- Space loads
  - heat balance method or weighing factor method
  - both are based on conduction transfer functions; principle difference is methods used for internal heat transfers
- Secondary system components
  - energy to operate fans & pumps
  - duct & pipe gains or losses
- Primary system components
  - usually in big buildings (i.e. chillers, boilers, cooling towers, etc.)
  - need to consider part-load conditions

Inputs & Outputs for Simulation

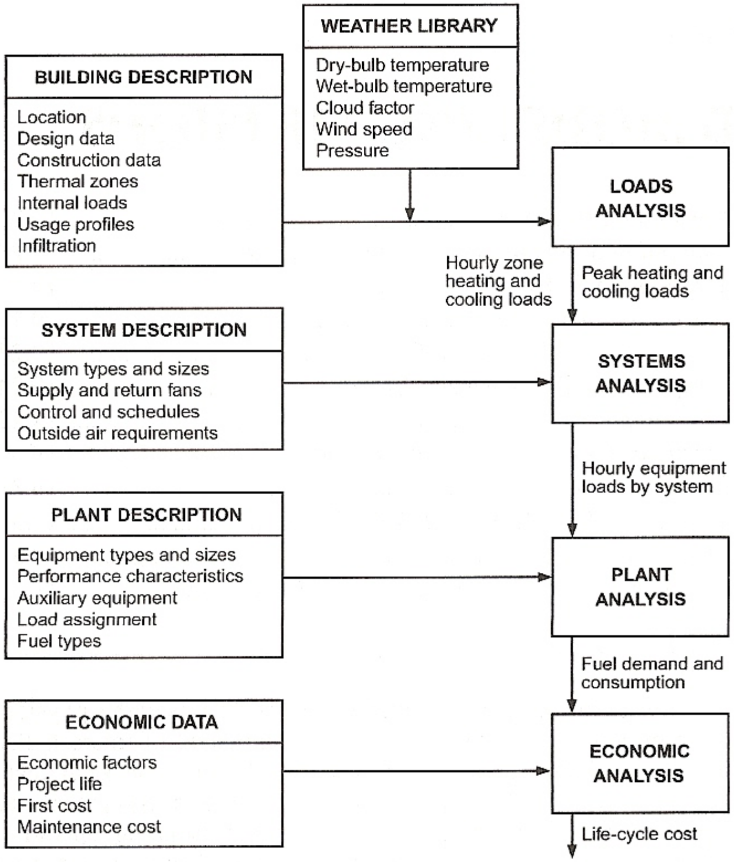


Fig. 1 Flow Chart for Building Energy Simulation Program
(Ayres and Stamper 1995)

Source: ASHRAE Handbook Fundamentals 2013 Chapter 19.1

Overall System Modeling

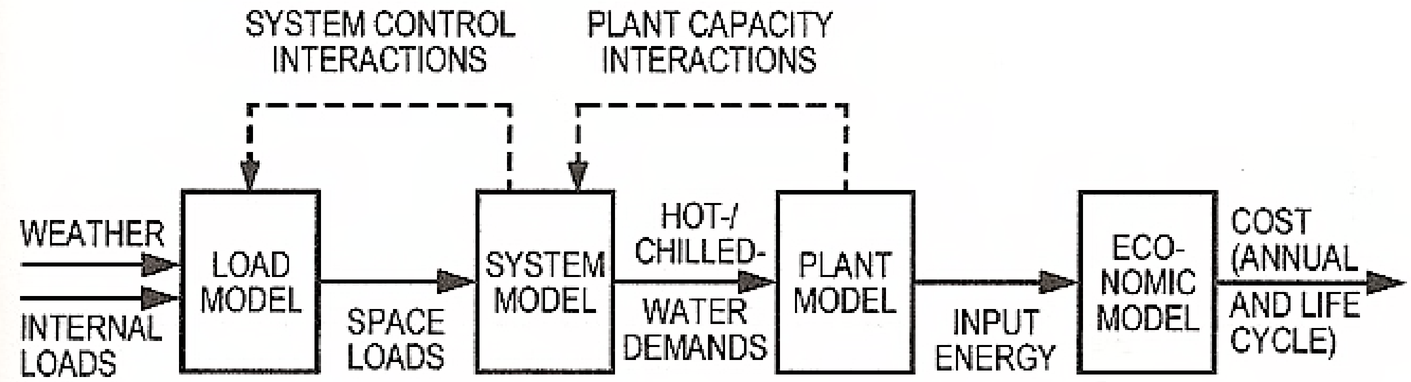


Fig. 10 **Overall Modeling Strategy**

Steady-State vs. Dynamic
Steady-state can work if indoor temperature is steady, internal gains are constant, and heating/cooling use and efficiency is fairly consistent.

Source: ASHRAE Handbook Fundamentals 2013 Chapter 19.16

Degree-Day Methods

- Simplest method for energy analysis
- Appropriate when loads are dominated by indoor-outdoor temperature difference and the building use and equipment efficiency are reasonably constant
  - heating degree-days have been successful for residential
  - cooling degree-days hasn’t work as well, because cooling is generally dominated by solar and internal gains
- Reliability increases with longer periods of operation
  - generally will give good results over a full heating season
  - as the time period shortens there are more chances that a factor not directly accounted for will deviate from its long-term average

Degree-Day Data from Monthly Averages

Can convert monthly average temperature data to degree-days using Equation 38 in Chapter 14.

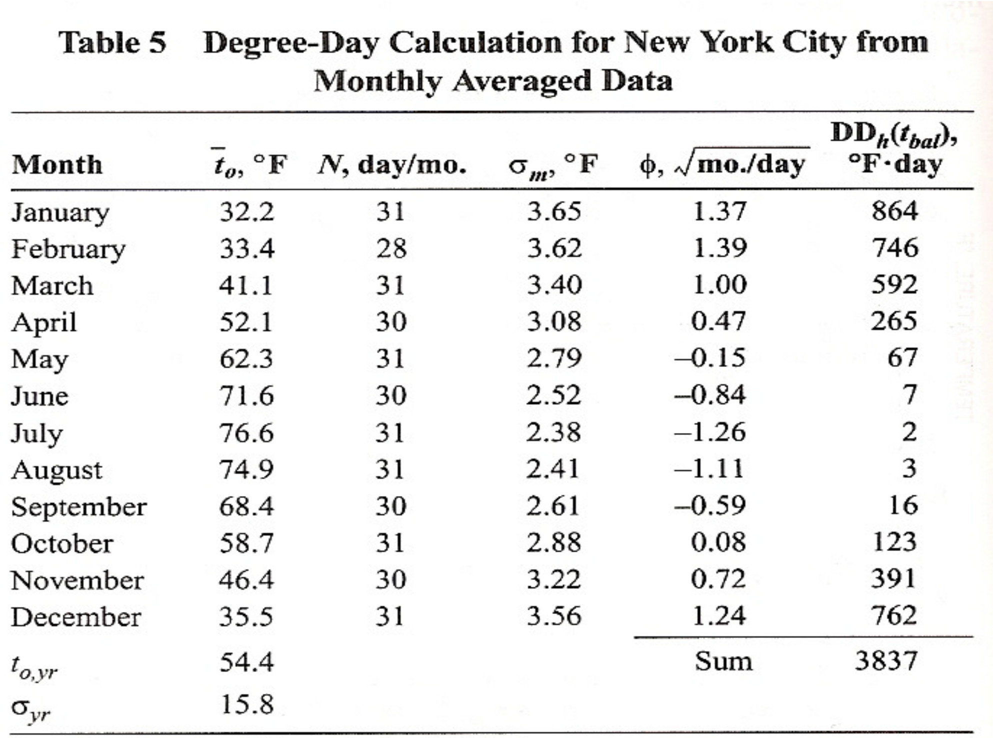


Table 5 Degree-Day Calculation for New York City from Monthly Averaged Data

Month	$\bar{t}_o$, °F	N, day/mo.	σ_m, °F	ϕ, $\sqrt{\text{mo./day}}$	$DD_h(t_{bal})$, °F·day
January	32.2	31	3.65	1.37	864
February	33.4	28	3.62	1.39	746
March	41.1	31	3.40	1.00	592
April	52.1	30	3.08	0.47	265
May	62.3	31	2.79	–0.15	67
June	71.6	30	2.52	–0.84	7
July	76.6	31	2.38	–1.26	2
August	74.9	31	2.41	–1.11	3
September	68.4	30	2.61	–0.59	16
October	58.7	31	2.88	0.08	123
November	46.4	30	3.22	0.72	391
December	35.5	31	3.56	1.24	762
$t_{o,yr}$	54.4			Sum	3837
σ_{yr}	15.8				

Note: Use Equation (65) to calculate $DD_h(t_{bal})$.

Source: ASHRAE Handbook Fundamentals 2009 Chapter 19.20

Balance Point Temperature

Definition: The outdoor temperature at which (for a specified indoor temperature), the total heat loss (to outdoors) is equal to all space heat gains from solar, lights, people, equipment, etc.

$$q_{gain} = K_{tot} \times (t_i - t_{bal}) \qquad \textit{(equation 34)}$$

or

$$t_{bal} = t_i - (q_{gain} / K_{tot}) \qquad \textit{(equation 35)}$$

Source: ASHRAE Handbook
Fundamentals 2013
Chapter 19.16

Auxiliary Energy = Loads – Internal Gains

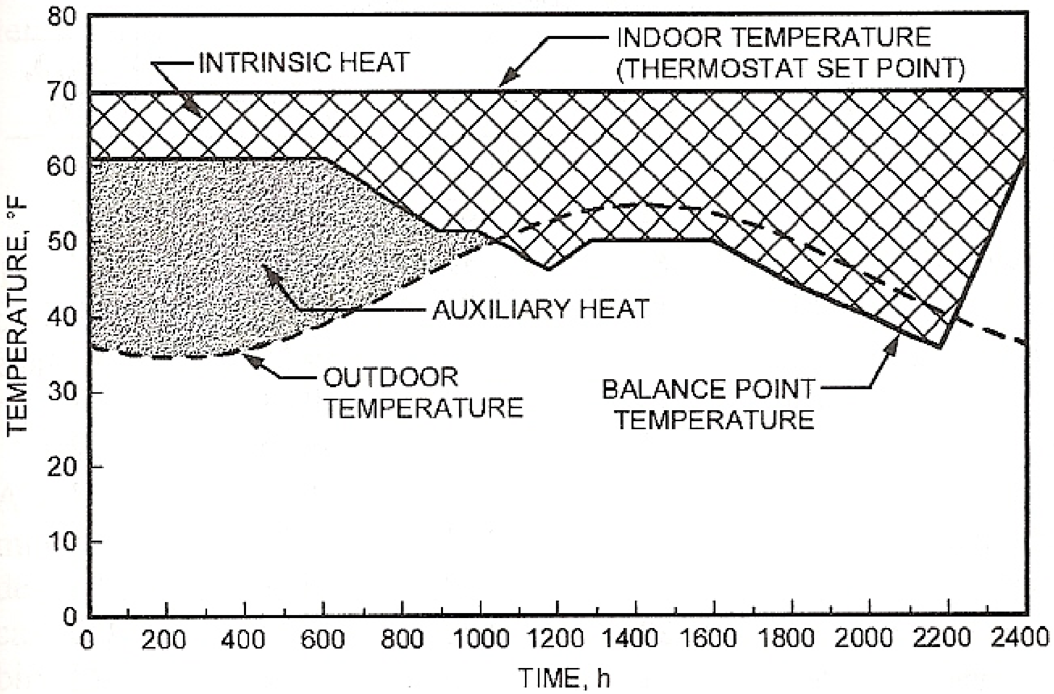


Fig. 12 Variation of Balance Point Temperature and Internal Gains for a Typical House (Nisson and Dutt 1985)

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.17

Role of Balance Point in Cooling

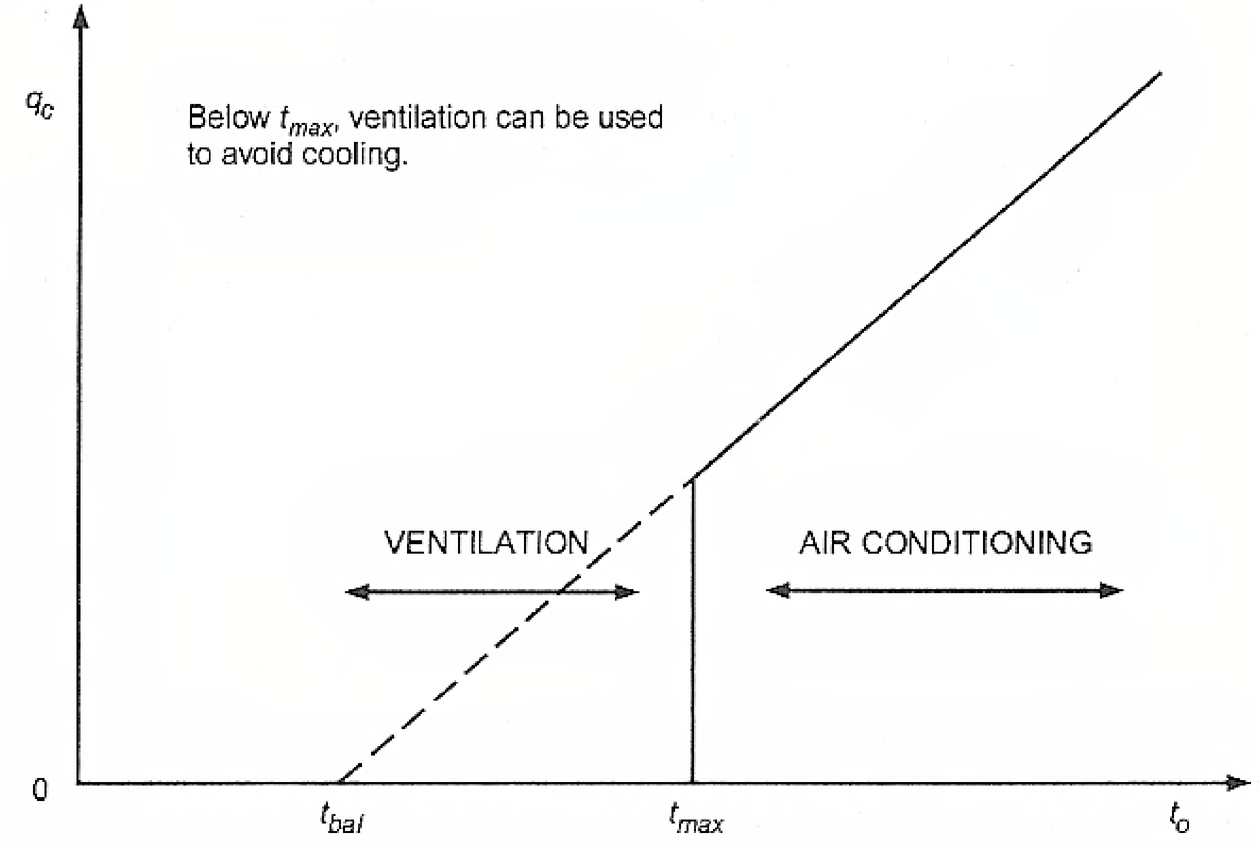


Fig. 11 Cooling Load as Function of Outdoor Temperature t_o

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.17

Balance Point Temperature and Degree-Days

- Can use degree-days to calculate heat loss

$$Q_{hr,yr} = K_{tot} \text{ x } (24 \text{ x } DD_{h,t(bal)})$$

- Add heating efficiency to estimate energy consumption

$$Q_{hr,yr} = (K_{tot} / eff) \text{ x } (24 \text{ x } DD_{h,t(bal)})$$

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.17, Equation 39

Seasonal Efficiency

- To calculate part-load efficiency of equipment you need to adjust the steady state efficiency based on:
  - building loss coefficient
  - equipment output
  - outdoor temperature

- Use *equation 45* on 19.18 (HF 2013)

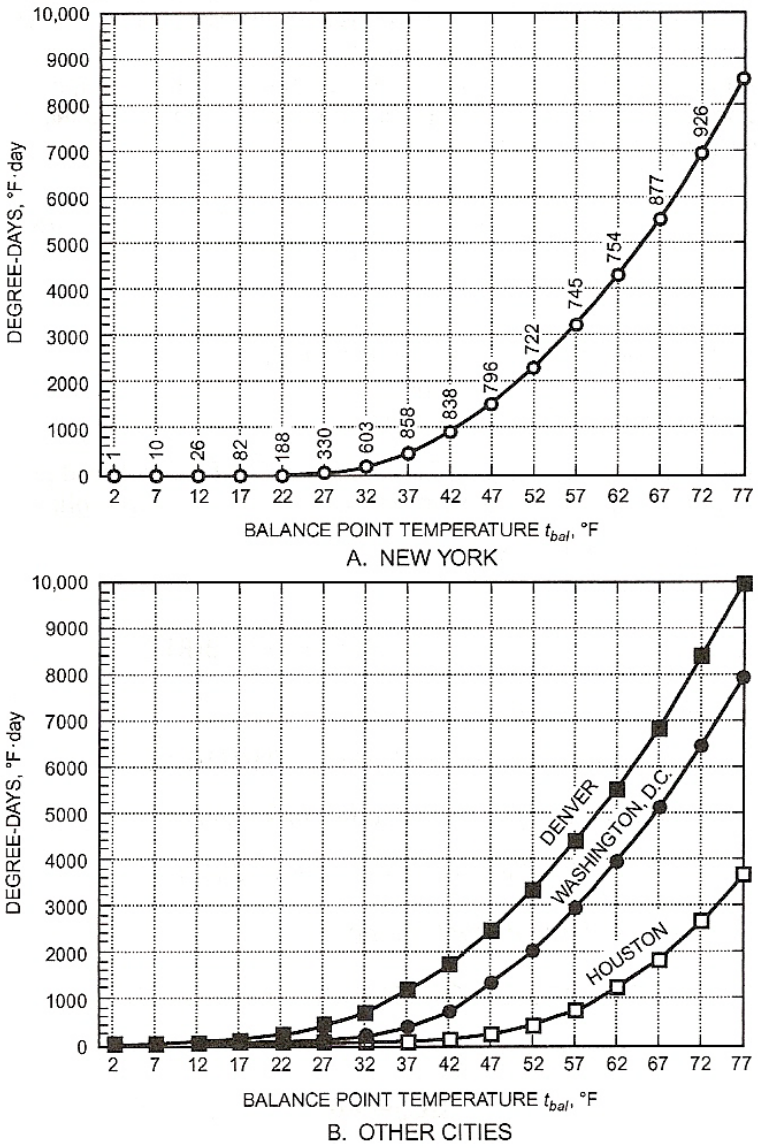
- However, for residential equipment you can use
  - AFUE
  - HSPF

Heating Degree-Day Method

Need:

- design heat loss & design temperature difference
- efficiency of heating system & heating value of fuel
- heating degree days
- correction factor
  - CF = 0.6 to 0.8 if HHD_{65}
  - CF = 1.0 if variable base heating degree days at balance point temperature [see Table 6 in slide 21]

$$E_{units} = \frac{q_{dhl} \times HDD \times 24 \times CF}{\Delta T_{dc} \times eff \times HV}$$



A. NEW YORK

B. OTHER CITIES

Fig. 13 Annual Heating Days $DD_h(t_{bal})$ as Function of Balance Temperature t_{bal}

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.18

Variable Base Heating Degree Days

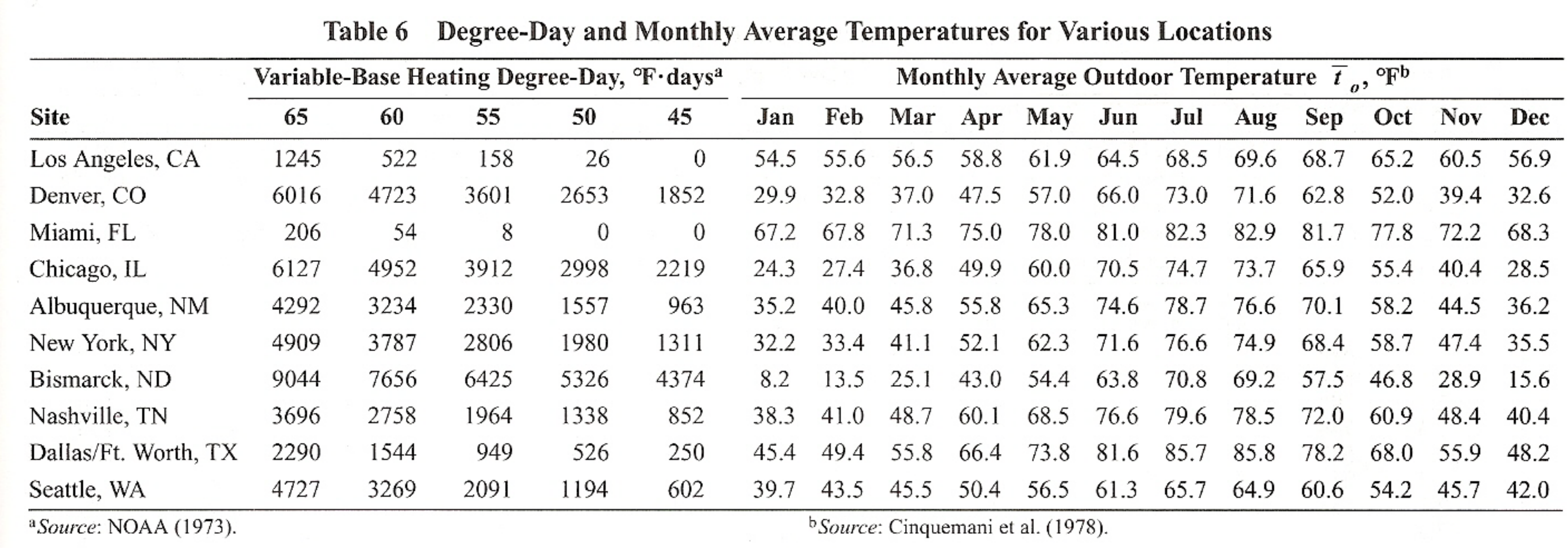


Table 6 Degree-Day and Monthly Average Temperatures for Various Locations

	Variable-Base Heating Degree-Day, °F·days[a]					Monthly Average Outdoor Temperature $\overline{t}_o$, °F[b]											
Site	**65**	**60**	**55**	**50**	**45**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Los Angeles, CA	1245	522	158	26	0	54.5	55.6	56.5	58.8	61.9	64.5	68.5	69.6	68.7	65.2	60.5	56.9
Denver, CO	6016	4723	3601	2653	1852	29.9	32.8	37.0	47.5	57.0	66.0	73.0	71.6	62.8	52.0	39.4	32.6
Miami, FL	206	54	8	0	0	67.2	67.8	71.3	75.0	78.0	81.0	82.3	82.9	81.7	77.8	72.2	68.3
Chicago, IL	6127	4952	3912	2998	2219	24.3	27.4	36.8	49.9	60.0	70.5	74.7	73.7	65.9	55.4	40.4	28.5
Albuquerque, NM	4292	3234	2330	1557	963	35.2	40.0	45.8	55.8	65.3	74.6	78.7	76.6	70.1	58.2	44.5	36.2
New York, NY	4909	3787	2806	1980	1311	32.2	33.4	41.1	52.1	62.3	71.6	76.6	74.9	68.4	58.7	47.4	35.5
Bismarck, ND	9044	7656	6425	5326	4374	8.2	13.5	25.1	43.0	54.4	63.8	70.8	69.2	57.5	46.8	28.9	15.6
Nashville, TN	3696	2758	1964	1338	852	38.3	41.0	48.7	60.1	68.5	76.6	79.6	78.5	72.0	60.9	48.4	40.4
Dallas/Ft. Worth, TX	2290	1544	949	526	250	45.4	49.4	55.8	66.4	73.8	81.6	85.7	85.8	78.2	68.0	55.9	48.2
Seattle, WA	4727	3269	2091	1194	602	39.7	43.5	45.5	50.4	56.5	61.3	65.7	64.9	60.6	54.2	45.7	42.0

[a] *Source*: NOAA (1973).

[b] *Source*: Cinquemani et al. (1978).

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.21

Cooling Degree-Day Method

- Could use *Equation 41* on 19.17 (HF 2013), or

$$E_{kWh} = \frac{q_{dcl} \times CDD \times 24 \times CF}{\Delta T_{dc} \times COP \times 3{,}412}$$

- But be careful
  - assumes no ventilation for cooling
  - assumes the balance-point temperature is constant, not so!
  - generally is a better practice to use cooling degree-hours, but that still assumes that consumption it is driven by exterior temperatures.

Bin Method (Heating and Cooling)

- For many applications, the degree-day method simply doesn’t work, especially if the heat loss coefficient, the equipment efficiency, or balance-point temperature are not constant
- But these can be approximated by evaluating different time periods and temperature intervals separately
  - temperature bins are usually in 5 degree increments
  - can get mean coincident wet-bulb temperatures to match each bin for latent calculations
  - when hour of occurrence is not critical, use Table 6, 14.11 HF 2013

Bin Method (Heating and Cooling)

- 5 degree bin data for selected cities
- Typical hours in each bin

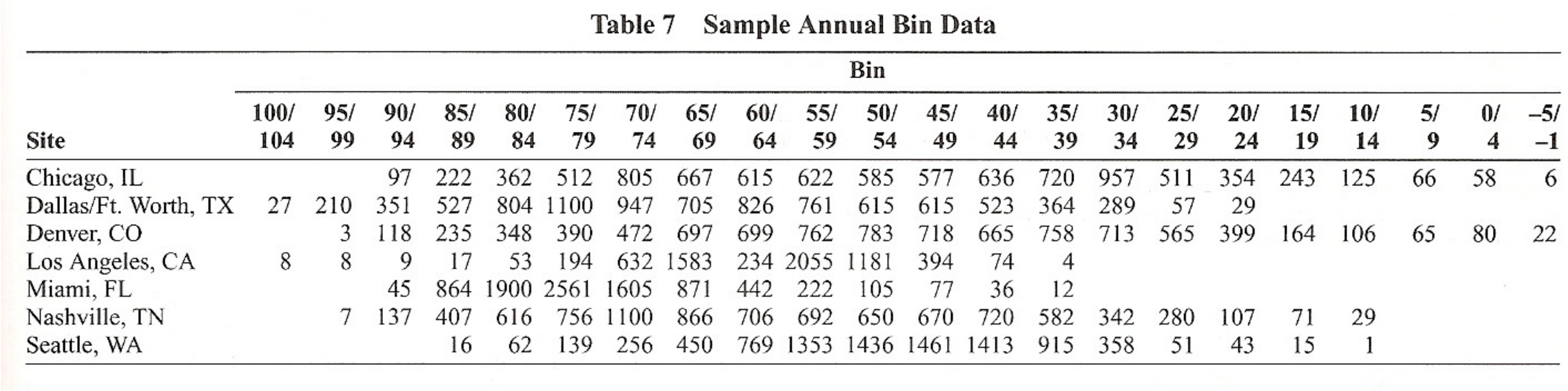


Table 7 Sample Annual Bin Data

	Bin																					
Site	**100/ 104**	**95/ 99**	**90/ 94**	**85/ 89**	**80/ 84**	**75/ 79**	**70/ 74**	**65/ 69**	**60/ 64**	**55/ 59**	**50/ 54**	**45/ 49**	**40/ 44**	**35/ 39**	**30/ 34**	**25/ 29**	**20/ 24**	**15/ 19**	**10/ 14**	**5/ 9**	**0/ 4**	**–5/ –1**
Chicago, IL			97	222	362	512	805	667	615	622	585	577	636	720	957	511	354	243	125	66	58	6
Dallas/Ft. Worth, TX	27	210	351	527	804	1100	947	705	826	761	615	615	523	364	289	57	29					
Denver, CO		3	118	235	348	390	472	697	699	762	783	718	665	758	713	565	399	164	106	65	80	22
Los Angeles, CA	8	8	9	17	53	194	632	1583	234	2055	1181	394	74	4								
Miami, FL			45	864	1900	2561	1605	871	442	222	105	77	36	12								
Nashville, TN		7	137	407	616	756	1100	866	706	692	650	670	720	582	342	280	107	71	29			
Seattle, WA				16	62	139	256	450	769	1353	1436	1461	1413	915	358	51	43	15	1			

Source: ASHRAE Handbook Fundamentals 2009, Chapter 19.21

Bin Method (Heating and Cooling)

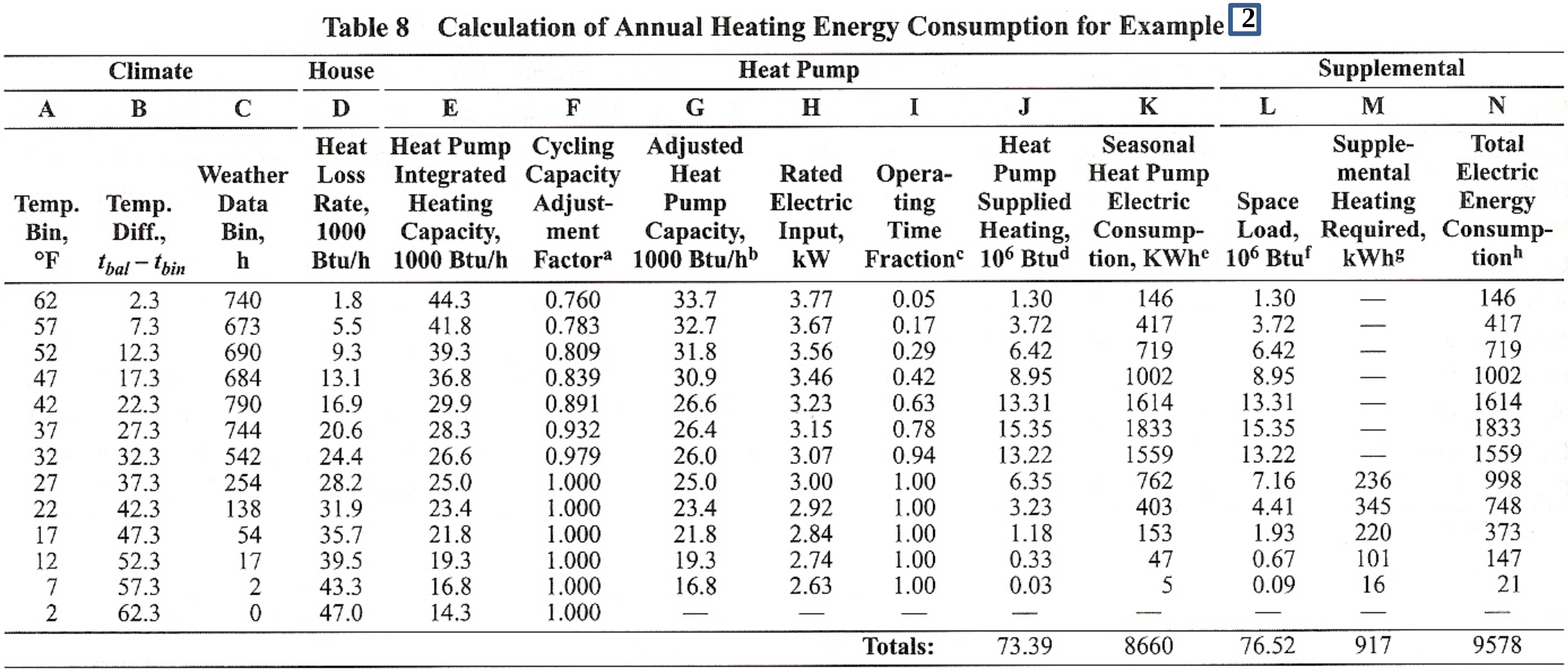


Table 8 Calculation of Annual Heating Energy Consumption for Example 2

Climate			House	Heat Pump							Supplemental		
A	B	C	D	E	F	G	H	I	J	K	L	M	N
Temp. Bin, °F	Temp. Diff., $t_{bal} - t_{bin}$	Weather Data Bin, h	Heat Loss Rate, 1000 Btu/h	Heat Pump Integrated Heating Capacity, 1000 Btu/h	Cycling Capacity Adjustment Factor[a]	Adjusted Heat Pump Capacity, 1000 Btu/h[b]	Rated Electric Input, kW	Operating Time Fraction[c]	Heat Pump Supplied Heating, 10^6 Btu[d]	Seasonal Heat Pump Electric Consumption, KWh[e]	Space Load, 10^6 Btu[f]	Supplemental Heating Required, kWh[g]	Total Electric Energy Consumption[h]
62	2.3	740	1.8	44.3	0.760	33.7	3.77	0.05	1.30	146	1.30	—	146
57	7.3	673	5.5	41.8	0.783	32.7	3.67	0.17	3.72	417	3.72	—	417
52	12.3	690	9.3	39.3	0.809	31.8	3.56	0.29	6.42	719	6.42	—	719
47	17.3	684	13.1	36.8	0.839	30.9	3.46	0.42	8.95	1002	8.95	—	1002
42	22.3	790	16.9	29.9	0.891	26.6	3.23	0.63	13.31	1614	13.31	—	1614
37	27.3	744	20.6	28.3	0.932	26.4	3.15	0.78	15.35	1833	15.35	—	1833
32	32.3	542	24.4	26.6	0.979	26.0	3.07	0.94	13.22	1559	13.22	—	1559
27	37.3	254	28.2	25.0	1.000	25.0	3.00	1.00	6.35	762	7.16	236	998
22	42.3	138	31.9	23.4	1.000	23.4	2.92	1.00	3.23	403	4.41	345	748
17	47.3	54	35.7	21.8	1.000	21.8	2.84	1.00	1.18	153	1.93	220	373
12	52.3	17	39.5	19.3	1.000	19.3	2.74	1.00	0.33	47	0.67	101	147
7	57.3	2	43.3	16.8	1.000	16.8	2.63	1.00	0.03	5	0.09	16	21
2	62.3	0	47.0	14.3	1.000	—	—	—	—	—	—	—	—
								Totals:	73.39	8660	76.52	917	9578

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.20

Heat Pump Balance Point

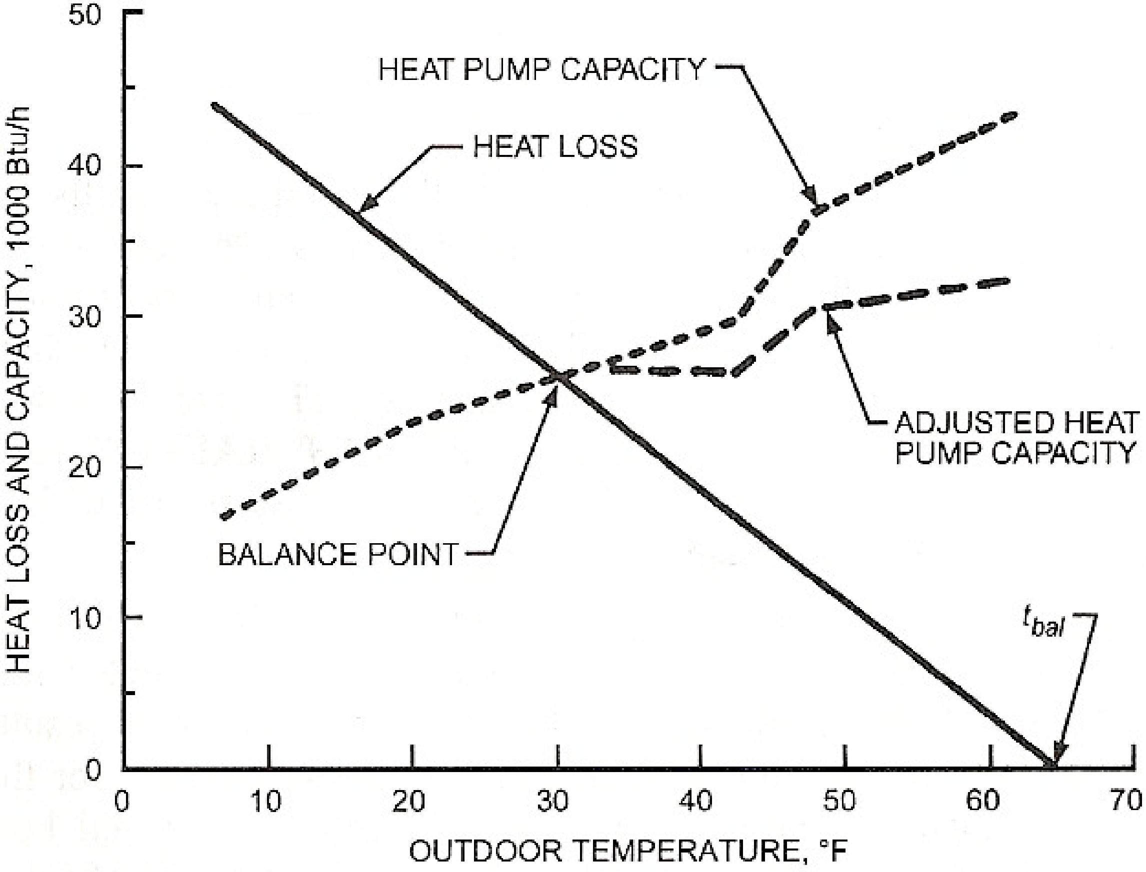


Fig. 14 Heat Pump Capacity and Building Load

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.19

Modified Bin Method

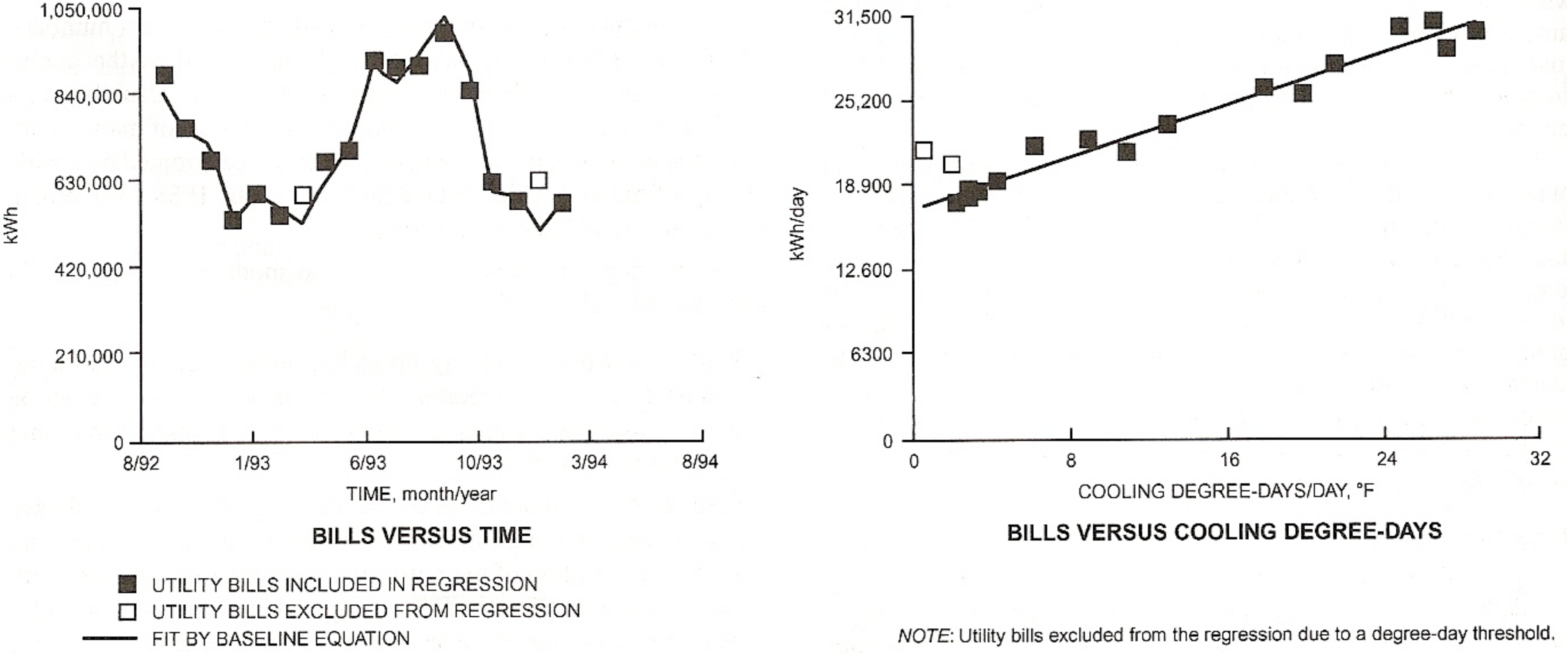
- Vary solar, internal gains, and CLTD values by bin
- Use two to six bins per day
  - three is common

Energy Estimating Using Utility Bills

- Data Driven (Inverse) Modeling
  - Categories of Data Driven Methods
    - Review 19.24 to 19.29
  - Applications
    - Modeling Utility Bill Data
      - statistical regression
    - Neural Network Models

- Model Selection
  - Capabilities
    - See Table 6, 19.29 (HF 2013)
  - Validation and testing

Simple Bill Analysis

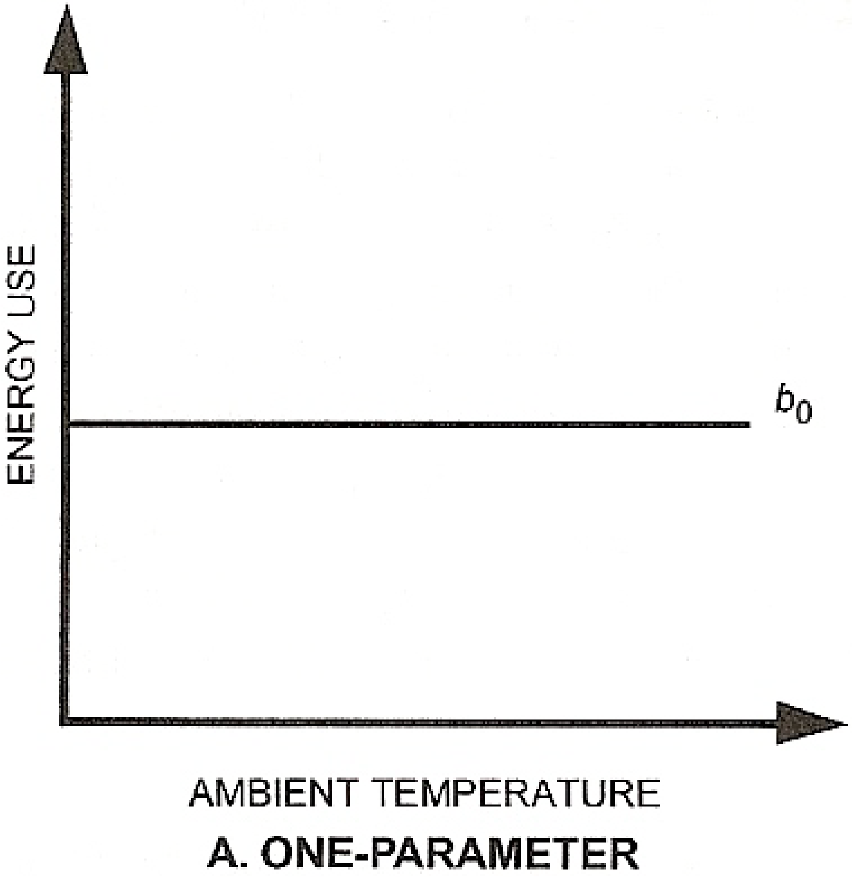


NOTE: Utility bills excluded from the regression due to a degree-day threshold.

Fig. 18 Variable-Base Degree-Day Model Identification Using Electricity Utility Bills at Hospital

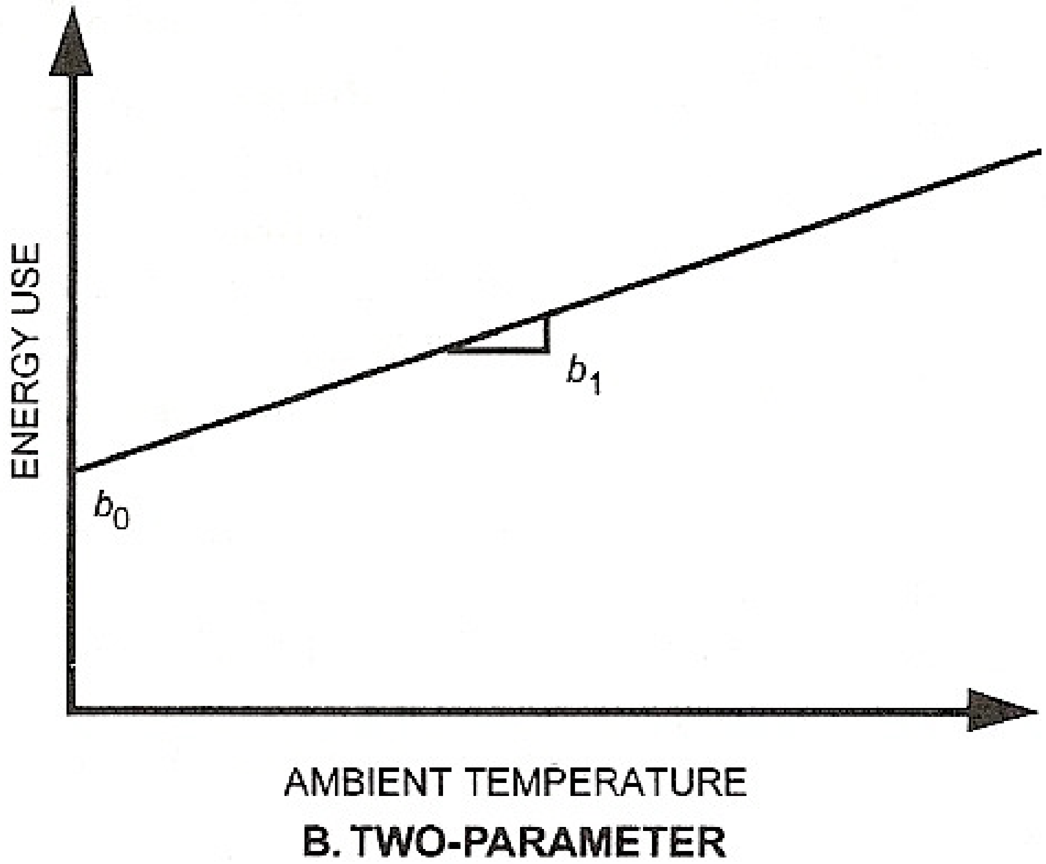
Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.28

Baseline Only



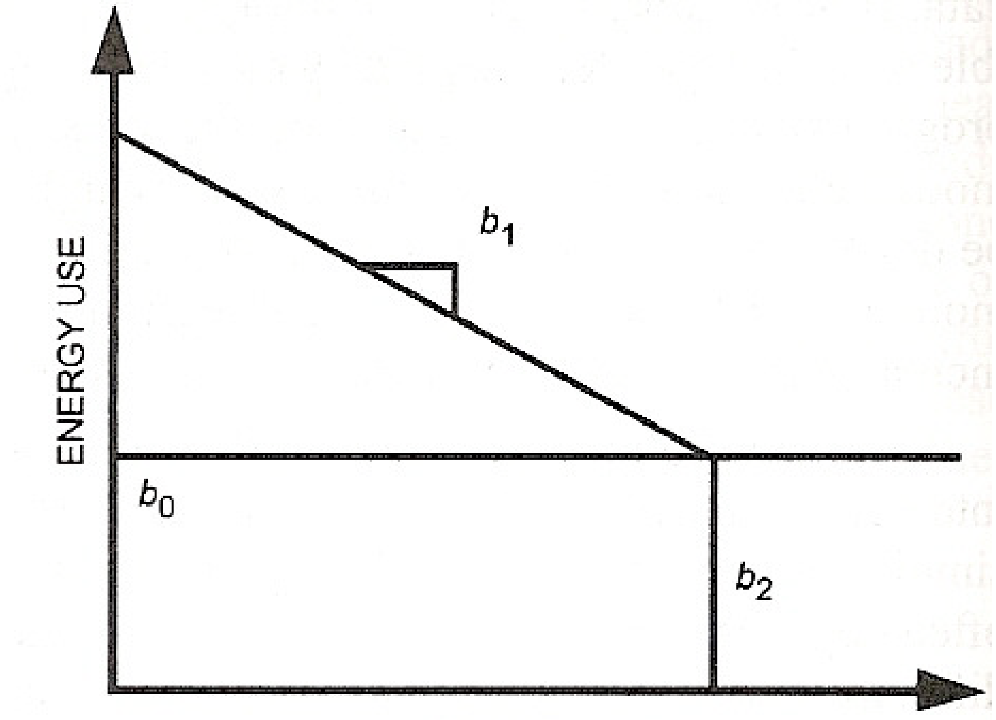
Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Baseline + Cooling



Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

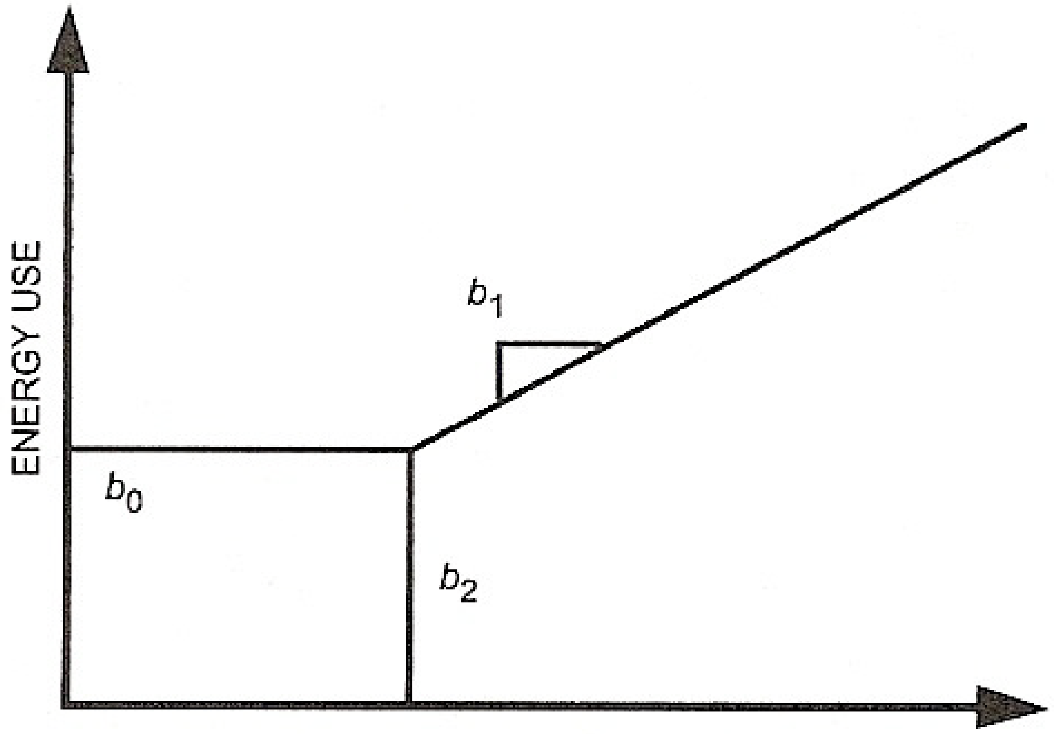
Baseline + Heating w/ Change Point



C. THREE-PARAMETER CHANGE-POINT, HEATING

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

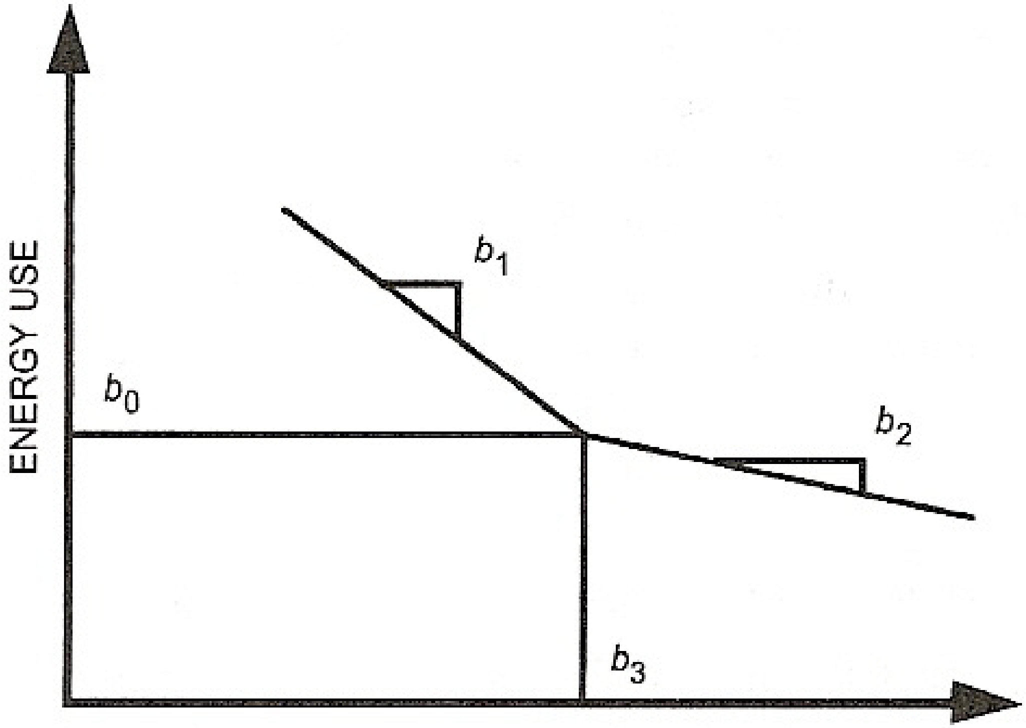
Baseline + Cooling w/ Change Point



D. THREE-PARAMETER CHANGE-POINT, COOLING

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Baseline + 2 Heating w/ Change Point

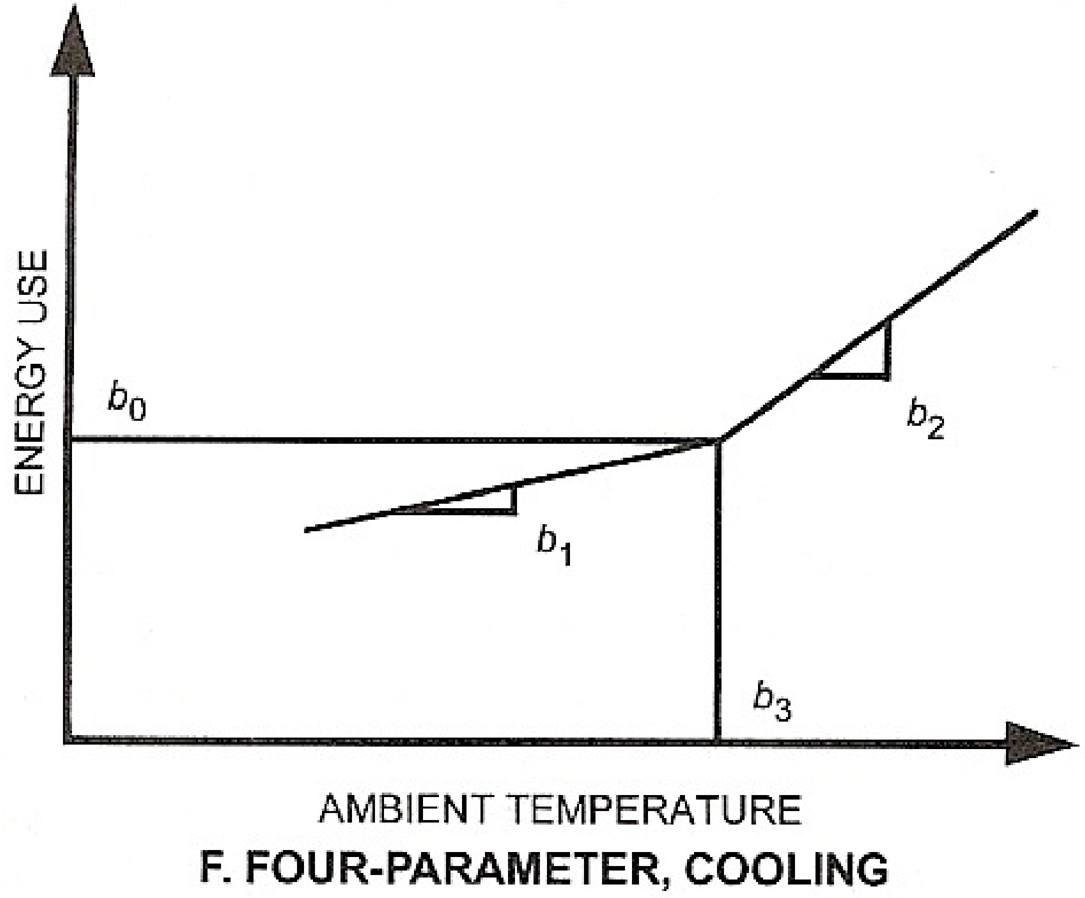


AMBIENT TEMPERATURE

E. FOUR-PARAMETER, HEATING

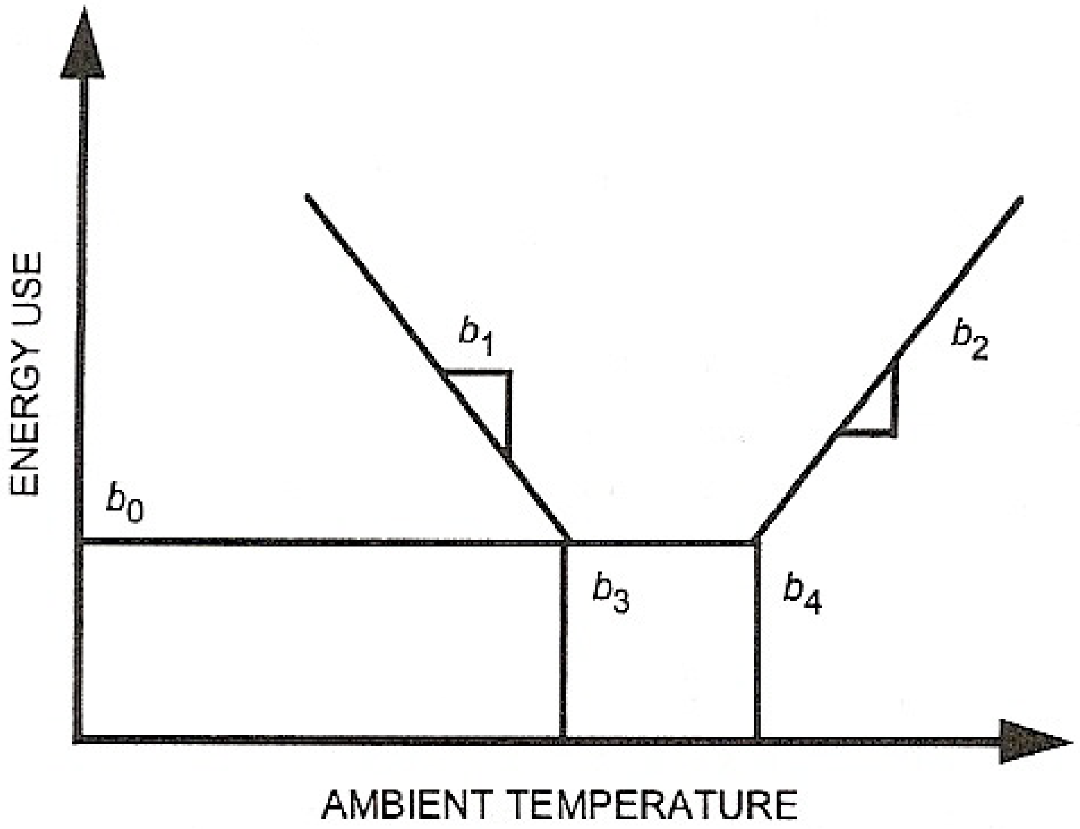
Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Baseline + 2 Cooling w/ Change Point



Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Baseline + Heating + Cooling w/ 2 Change Points



G. FIVE-PARAMETER

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Generalized Equations for the Previous Cases

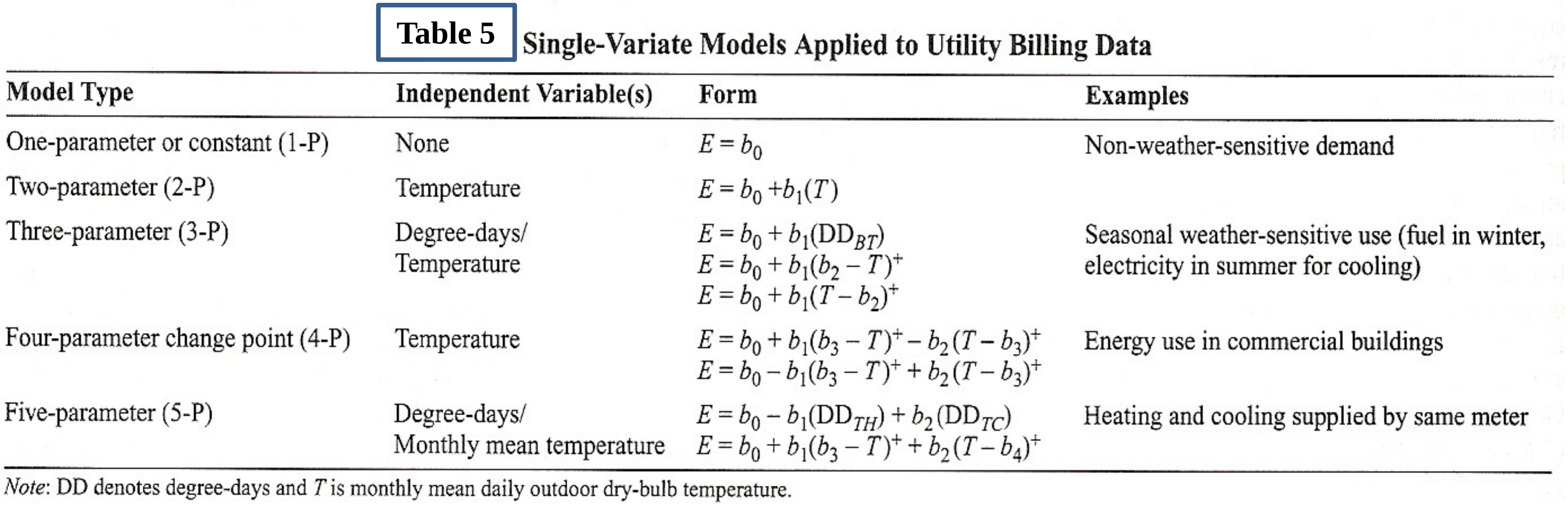


Table 5 **Single-Variate Models Applied to Utility Billing Data**

Model Type	Independent Variable(s)	Form	Examples
One-parameter or constant (1-P)	None	$E = b_0$	Non-weather-sensitive demand
Two-parameter (2-P)	Temperature	$E = b_0 + b_1(T)$	
Three-parameter (3-P)	Degree-days/ Temperature	$E = b_0 + b_1(\mathrm{DD}_{BT})$ $E = b_0 + b_1(b_2 - T)^+$ $E = b_0 + b_1(T - b_2)^+$	Seasonal weather-sensitive use (fuel in winter, electricity in summer for cooling)
Four-parameter change point (4-P)	Temperature	$E = b_0 + b_1(b_3 - T)^+ - b_2(T - b_3)^+$ $E = b_0 - b_1(b_3 - T)^+ + b_2(T - b_3)^+$	Energy use in commercial buildings
Five-parameter (5-P)	Degree-days/ Monthly mean temperature	$E = b_0 - b_1(\mathrm{DD}_{TH}) + b_2(\mathrm{DD}_{TC})$ $E = b_0 + b_1(b_3 - T)^+ + b_2(T - b_4)^+$	Heating and cooling supplied by same meter

Note: DD denotes degree-days and T is monthly mean daily outdoor dry-bulb temperature.

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.24

Comparison of Various Energy Models

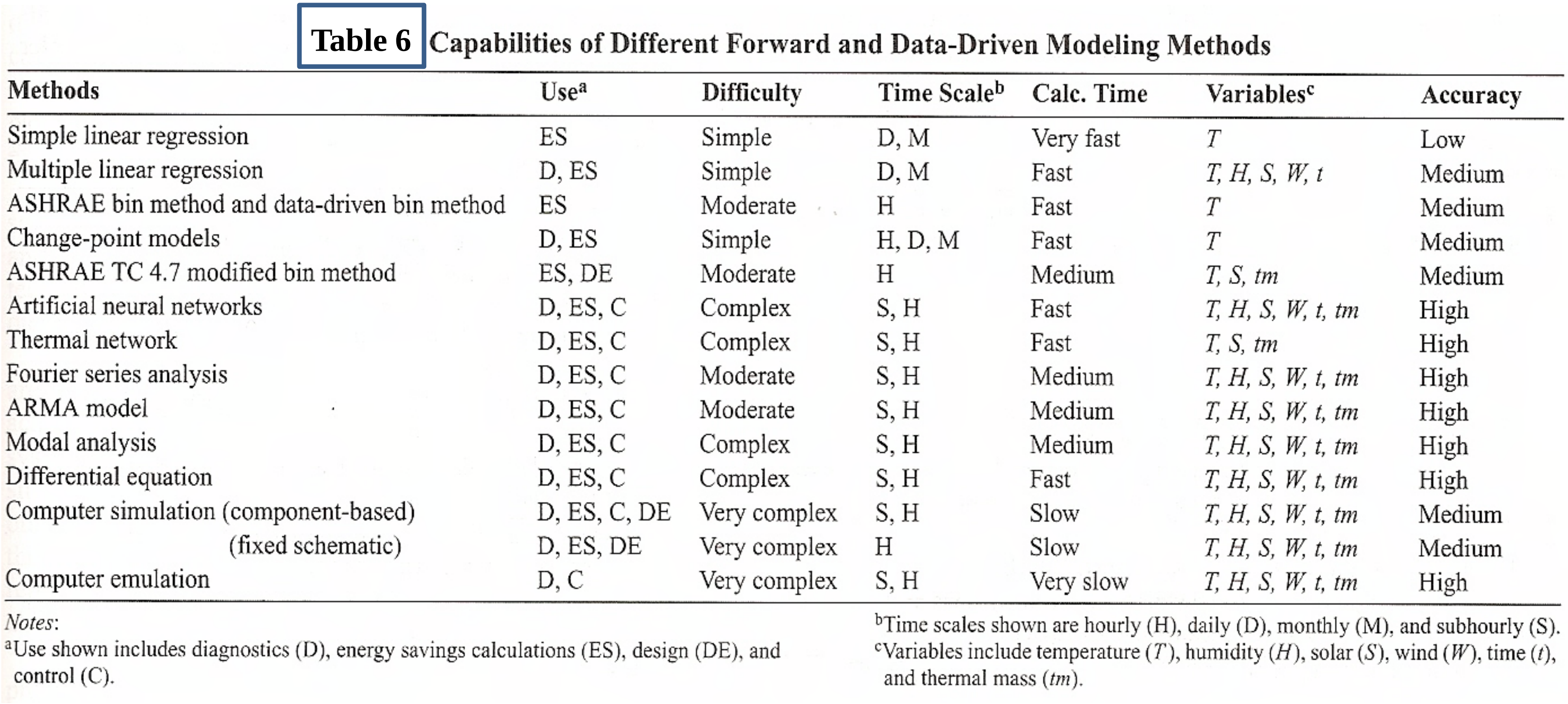


Table 6 Capabilities of Different Forward and Data-Driven Modeling Methods

Methods	Use[a]	Difficulty	Time Scale[b]	Calc. Time	Variables[c]	Accuracy
Simple linear regression	ES	Simple	D, M	Very fast	T	Low
Multiple linear regression	D, ES	Simple	D, M	Fast	T, H, S, W, t	Medium
ASHRAE bin method and data-driven bin method	ES	Moderate	H	Fast	T	Medium
Change-point models	D, ES	Simple	H, D, M	Fast	T	Medium
ASHRAE TC 4.7 modified bin method	ES, DE	Moderate	H	Medium	T, S, tm	Medium
Artificial neural networks	D, ES, C	Complex	S, H	Fast	T, H, S, W, t, tm	High
Thermal network	D, ES, C	Complex	S, H	Fast	T, S, tm	High
Fourier series analysis	D, ES, C	Moderate	S, H	Medium	T, H, S, W, t, tm	High
ARMA model	D, ES, C	Moderate	S, H	Medium	T, H, S, W, t, tm	High
Modal analysis	D, ES, C	Complex	S, H	Medium	T, H, S, W, t, tm	High
Differential equation	D, ES, C	Complex	S, H	Fast	T, H, S, W, t, tm	High
Computer simulation (component-based)	D, ES, C, DE	Very complex	S, H	Slow	T, H, S, W, t, tm	Medium
(fixed schematic)	D, ES, DE	Very complex	H	Slow	T, H, S, W, t, tm	Medium
Computer emulation	D, C	Very complex	S, H	Very slow	T, H, S, W, t, tm	High

Notes:

[a] Use shown includes diagnostics (D), energy savings calculations (ES), design (DE), and control (C).

[b] Time scales shown are hourly (H), daily (D), monthly (M), and subhourly (S).

[c] Variables include temperature (T), humidity (H), solar (S), wind (W), time (t), and thermal mass (tm).

Source: ASHRAE Handbook Fundamentals 2013, Chapter 19.39

In Summary

Questions and Discussion

Next Class

- General Mechanical & Heating Systems
  - General mechanical considerations
  - Combustion
  - Residential heating equipment

- Readings
  - HF Chapter 28.1 to 28.12
  - Supplemental Handout