Annotated Guide to Load Calculation Models and Algorithms

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About the Author

Jeffrey D. Spitler, Ph.D., P.E. is an Associate Professor in the School of Mechanical and Aerospace Engineering at Oklahoma State University, where he teaches classes and performs research in the areas of heat transfer, thermal systems, HVAC and ground-source heat pump systems. He received his Bachelor's, Master's, and Ph.D. degrees in mechanical engineering from the University of Illinois at Urbana-Champaign.

He is active in ASHRAE, where he serves on the energy calculation and geothermal systems technical committees, a standards project committee, and the Society's Student Activities Committee. He has worked on several ASHRAE research projects and co-authored the *ASHRAE Cooling and Heating Load Calculation Manual*.

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Jeffrey D. Spitler

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1. INTRODUCTION

1.1 Objective

In the 1970s ASHRAE (1975a, 1975b) published two books containing models and algorithms for energy analysis. Demand for these has remained strong, despite the numerous advances made in the field during the intervening years.

In order to meet this demand with more current and usable information, ASHRAE TC 4.7, the Energy Calculations technical committee, recently began development of a series of energy analysis software toolkits for use by engineers or software developers. Three different toolkits will be developed: primary HVAC components, secondary HVAC components, and building loads. The secondary HVAC components toolkit (Brandemuehl 1993) has been completed. The primary HVAC components toolkit is currently under development. Their development was preceded by an exhaustive literature search and development of an annotated bibliography related to HVAC equipment (ASHRAE 1990).

The objective of this project is to develop a similar annotated guide to building load calculation algorithms and models. The intended audience is developers of design load calculation software and energy analysis software.

Because building load calculations are important both to energy analysis and design analysis, this project is cosponsored by TC 4.1 (Design load calculations) and TC 4.7. Historically, the two committees have tended to work separately because they have different objectives. However, many of the methodologies used are the same in both areas, although the terminology tends to be slightly different.

1.2 Terminology

Load Calculations

Building load calculations are of interest to at least two groups of people—engineers sizing HVAC systems are interested in "design load calculations" (usually obtaining peak cooling and heating loads based on a hot summer day and a cold winter day); engineers and architects performing building energy analysis are interested in determining the loads placed on the HVAC system. Both groups are interested in heat transfer rates in buildings, and therefore the two tasks tend to overlap quite a bit. However, because both groups have had different interests, they have developed different methods and they tend to have different connotations for words such as "loads."

For design cooling load calculations, three types of heat transfer rates have been defined (McQuiston and Spitler 1992):

1. Heat gain—The instantaneous rate at which heat enters the space or is generated within the space. (Heat losses are negative heat gains.)
2. Cooling load—The space cooling load is the rate at which heat must be removed from the space to maintain a constant temperature in the space. This is different from the heat gain because of energy stored in the space's thermal mass. Usually, this is calculated on an hourly basis, though the cooling load is actually the instantaneous heat transfer rate at a specific time. (It is not the heat transfer rate integrated over a one-hour period. However, this distinction is probably not important to most practitioners.)

3. Space heat extraction rate—The heat extraction rate is the actual rate of heat removal from the space by the system. This would be the same as the cooling load if only the space temperature is held constant. The heat extraction rate is found at the same time as the zone temperature.

Designers are often only interested in determining the peak cooling load, in which case they do not calculate the space heat extraction rate. These definitions make the most sense in the framework of a weighting-factor-based method.[1] In this guide, "heat gain" models and algorithms will be found in Chapters 2 through 4. Cooling load and space heat extraction rate models and algorithms will be found in Chapter 5.

For energy analysis, the term "load calculations" refers to determining the load that the building imposes on the HVAC system. This is equivalent to the space heat extraction rate, or the cooling load if the space air temperature is held constant. Depending on the context, the "loads" is generally considered to be the heat transfer rate integrated over an hour's time. In many cases, it is calculated as an instantaneous rate and is taken to be representative of the hour. Also of interest is the zone temperature, particularly in cases where the temperature is allowed to float.

For the purposes of this guide, "load calculations" include methods for calculating either the instantaneous rate of heat transfer or the rate of heat transfer integrated over a one-hour time period in buildings and the zone temperature, whether or not an HVAC system is providing heating or cooling. The types of heat transfer include all of the heat transfer rates discussed above for design load calculations and energy analysis.

Both design load calculations and energy analysis have spawned a number of "simplified" methods. For design load calculations, these include the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) method, and the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) method. Simplified energy analysis methods include degree-day methods and bin methods. In both cases, the simplified methods were intended to be performed manually, or with a programmable calculator or early microcomputer. This guide does not cover models or algorithms useful only with the simplified methods. However, many of the models and algorithms in the guide may be suitable for use with simplified methods.

Readers interested in a more detailed description of simplified design load calculation methods should consult Chapters 25 and 26 of the *ASHRAE Handbook of Fundamentals* (1993) or the *ASHRAE Cooling and Heating Load Calculation Manual* (McQuiston and Spitler 1992). Readers interested in a more detailed description of simplified energy analysis methods should consult Chapter 28 of the *ASHRAE Handbook of Fundamentals* (1993) or Knebel (1983).

Models and Algorithms

The models and algorithms described in this guide are the basis for computer programs that perform load calculations. There a number of different connotations associated with each word. For this guide, the following definitions are assumed:

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[1] Weighting factor methods are described by references in section 5.3. Weighting factors use transfer functions to relate the current hour's cooling load to the current hour's heat gain and past values of heat gain and cooling load.

Model—A model is a mathematical description of a process. It can be reduced to a set of equations, although in many descriptions, not all of the equations will be given explicitly. A model would not generally specify inputs and outputs. In practice, many models are developed with specific inputs and outputs in mind.

Algorithm—An algorithm is a computational procedure for solving the equations of one or more models.

Theoretically, there is a sharp demarcation between models and algorithms. In practice, the descriptions of each tend to be intertwined, so some models described in the guide will have certain inputs specified. Also, many model descriptions will indicate which algorithm was used to solve the model equations.

1.3 Scope

There is a very large body of literature dealing with different aspects of load calculations—weather, solar radiation, ground temperature data, convection heat transfer, radiation heat transfer, conduction heat transfer, airflow around buildings, infiltration, ventilation, moisture transport, simulation methods, etc. The vast majority of the published works pertaining to these topics do **not** describe models or algorithms.

In order to make this a useful guide, an attempt has been made to critically evaluate whether or not each reference contains a reasonably complete model or algorithm description. References that do contain such a description are listed immediately after the discussion in each section.

In addition, many sections contain a brief list of "Related References." Generally speaking, the related references discuss various aspects of modeling, describe experimental validation, or compare different models. The reader should be aware that these lists are by no means exhaustive or complete lists of related references. The "Related References" have either a very brief annotation or no annotation, if the title serves as an adequate description.

In addition to the above criteria, several other criteria governed which models and algorithms are included and which are not included. The following is a list of additional criteria used to decide whether or not an item is included.

1. Models and algorithms included are generally ones that are currently suitable from the standpoint of computational requirements for either design load calculations or hourly energy analysis. Generally speaking this precludes certain models with excessive computational requirements such as detailed finite difference or finite element models of conductive heat transfer or airflow. There are some cases where relatively simple finite difference or finite element models may be appropriate, and some of these references have been included.

   On the other extreme, certain models which have as their chief advantage minimal computational time have also been excluded. These include models intended for manual use or intended for use with programmable calculators. Also excluded are models not intended to represent specific buildings, but rather are intended for such use as estimating utility load profiles.

   The reader should understand that this is a subjective process. In several cases, the discussion points the interested reader to a review paper which covers a class of models not covered in this guide.

2. Generally, models which **require** experimental calibration are not included here. Many models are included that can be improved with experimental calibration. As an example, infiltration models, which require tracer gas measurements, are not included. (However, some models, which are intended for use after experimental determination of an effective leakage area, are included because they can be used with a user-estimated effective leakage area.) As another example, references that describe experimental methods for obtaining conduction transfer function coefficients are not included either.
3. Many times, research is published in more than one form or more than one source. Generally, if the research was published in several papers, with the last paper summarizing everything and referencing past papers, or the last paper covering the most refined version of the model or algorithm, only the last paper is included here.
4. Generally, for work performed by students and published in theses, or performed by research labs and published in research reports, the work is also published in condensed form in the open literature where it is peer-reviewed. When that is the case, only the open literature form is included in the reference.
5. There are several areas which might be considered peripheral to load calculations. These include daylighting, thermal comfort, and indoor air quality. These areas are not included in this guide.
6. Only English-language works were considered.

1.4 Organization of this Guide

This guide is organized into five chapters, plus a reference section:

1. Introduction
2. Fundamentals—This primarily includes models and algorithms pertaining to the environmental conditions surrounding the building. Also included is a section on psychrometrics.
3. Building Envelope Surface Loads—This chapter covers heat transfer to and from the exterior of the building and heat transfer through the exterior building envelope (walls, roofs, foundation elements). Heat transfer to and from the inside surfaces of the envelope is covered in Chapter 5.
4. Other Building Loads—This chapter covers other types of heat transfers from the outside and internal heat generation.
5. Room Heat Transfer Models—This chapter covers heat transfer to and from the interior surfaces of the building, and determination of the required heat transfer rate from the HVAC system.
6. References—This section lists only the references cited in the narrative.

1.5 Methodology

This section briefly describes the methodology used to find the references contained in this guide. As this was not a "step-by-step" procedure, the various sources of references are listed below. In total, 1576 references were obtained and reviewed. A commercial bibliographic database was used to store all of the references and annotations.

1. Original database of approximately 700 papers that had previously been collected—two comprehensive literature searches related to design load calculations had been previously performed as part of ASHRAE research projects RP-359 and RP-626.
2. General sources—several sources that covered a wide range of building load calculation models and algorithms were reviewed. These include the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993), the *Thermal Analysis Research Program Manual* (Walton 1983), the *DOE-2 Engineers Manual* (York and Cappiello 1981), and *Energy Simulation in Building Design* (Clarke 1985).
3. Electronic databases were used to search for articles on all topics. The databases consulted include:
    a. Compendex, the electronic version of Engineering Index;
    b. Applied Science and Technology Index;
    c. the ASHRAE database, which references ASHRAE Transactions and many ASHRAE-sponsored conferences; and
    d. AIRBASE, a database of infiltration, ventilation, and airflow references (AIRBASE is available from the Air Infiltration and Ventilation Center).[2]
4. The ASHRAE electronic database only goes back to 1980. The years 1959-1976 are covered by the *ASHRAE Multiyear Composite Index of Technical Articles 1959-1976*. The years 1977-1979 are covered by annual indexes. These indexes were reviewed for pertinent references.
5. References cited by papers obtained—this is probably obvious to most readers, but is included here for sake of completeness. The literature review process is somewhat recursive—papers obtained will cite additional references which are then obtained, and which in turn cite additional references. A number of review papers were especially helpful.
6. Conference proceedings—a number of conference proceedings were obtained and reviewed for pertinent references. A partial list follows.
    a. Building Simulation '89 and '91, sponsored by the International Building Performance Simulation Association.
    b. Thermal Performance of the Exterior Envelopes of Buildings I(1979), II(1982), III(1985), IV(1989), and V(1992), sponsored by ASHRAE and DOE.
    c. Air Infiltration and Ventilation Center Conferences: 3rd(1982), 4th(1983), 5th(1984), 9th(1988), 12th(1991), and 13th(1992) AIVC Conferences.
    d. National Passive Solar Conferences: 4th(1979), 5th(1980), 7th(1982), 8th(1983), 9th(1984), and 10th(1985).
    e. Proceedings of the USER 1 Working Conference, 1988.
    f. Advances in Solar Energy Technology, 1987.
    g. 4th International Symposium on the Use of Computers for Environmental Engineering Related to Buildings, 1983.

[2] Address: University of Warwick, Science Park Limited, Barclays Venture Centre, Sir William Lyons Road, Coventry CV4 7EZ, Great Britain.

h. An ASTM Symposium on the Measured Air Leakage of Buildings, 1984.

i. 4th Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates, 1987.

j. 3rd International Congress on Building Energy Management, 1987.

k. International Daylighting Conferences, 1986 and 1989.

l. 21st Symposium of the International Center for Heat and Mass Transfer, 1989.

m. Clima 2000 (1985).

7. Survey. A survey was sent to 75 researchers world wide who had previously published papers on load calculation models and algorithms. Each survey contained a list of references, authored by that researcher, that had already been obtained. The researcher was requested to respond if there were any additional references related to building load calculation models and algorithms that had been missed. A total of 44 survey responses were received.