# ORIGINS OF ANALYSIS METHODS IN ENERGY SIMULATION PROGRAMS USED FOR HIGH PERFORMANCE COMMERCIAL BUILDINGS

A Thesis

by

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## ABSTRACT

Current designs of high performance buildings utilize hourly building energy simulations of complex, interacting systems. Such simulations need to quantify the benefits of numerous features including: thermal mass, HVAC systems and, in some cases, special features such as active and passive solar systems, photovoltaic systems, and lighting and daylighting systems. Unfortunately, many high performance buildings today do not perform the way they were simulated. One potential reason for this discrepancy is that designers using the simulation programs do not understand the analysis methods that the programs are based on and therefore they may have unreasonable expectations about the system performance or use.

The purpose of this study is to trace the origins of a variety of simulation programs and the analysis methods used in the programs to analyze high performance buildings in the United States. Such an analysis is important to better understand the capabilities of the simulation programs so they can be used more accurately to simulate the performance of an intended design. The goal of this study is to help explain the origins of the analysis methods used in whole-building energy simulation, solar system analysis simulation or design, and lighting and daylighting analysis simulation programs. A comprehensive history diagram or genealogy chart, which resolves discrepancies between the diagrams of previous studies, has been provided to support the explanations for the above mentioned simulation programs.

## DEDICATION

***To***

***My Loving God, Wife and Family***

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# CHAPTER I

# INTRODUCTION

## 1.1 Background

Numerous methods are used to calculate building energy use in today's simulation programs[1] (Gough, 1999; Crawley et al., 2008). Currently, a list of the various simulation programs for estimating the energy use in buildings is maintained and updated by the U.S. Department of Energy (US DOE) (EERE, 2013a). However, simulation results from two different programs listed at this site often show significant differences for similar buildings, even when experts simulate the exact same buildings (Huang et al., 2006; Versage et al., 2010; Tupper et al., 2011). In addition, most people who use simulation programs do not understand the analysis methods that the programs are based upon (Tupper et al., 2011; RMI, 2011), and previous attempts to trace the history or ancestry of the analysis methods sometimes yielded different origins. These misunderstandings can lead to simulations being applied to features in buildings that a program cannot simulate, producing incorrect results or worse.

Therefore, the purpose of this study is to trace the history of simulation programs and the analysis methods used to analyze high performance buildings in the United States. The expectation is that if simulation users knew more about the origins of the analysis methods in the simulation programs they used, some of the current problems

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[1] Simulation programs are mathematical computer models based on physical and engineering fundamentals (IBPSA, 2011).

and obstacles in applying the building simulation program might be resolved (Tupper et al., 2011).

To accomplish this goal, approximately 20 of the most widely used simulation programs were studied, including both the analysis methods contained in the programs and the source of those analysis methods. This study covered programs that simulate hourly whole-building energy use, solar photovoltaic (PV), solar thermal, passive solar, lighting, and daylighting systems. The programs that were studied were selected for the following reasons: (a) the simulation program is most widely used in the U.S., (b) the program and its documentation are available in the U.S., (c) the simulation program or a derivative of the program is still presently in use and supported, and (d) the analysis method used in the simulation program has made a significant contribution toward the development of the simulation analysis area.

## 1.2 Objectives and Scope

This study identifies the origins of the analysis methods in simulation programs used in high performance buildings. The simulation programs studied analyze whole-building energy use, solar PV, solar thermal, passive solar, lighting, and daylighting systems. This research has four objectives:

1. Review and analyze the previous literature in order to trace the origins of the analysis methods contained in widely used simulation programs in the U.S.;
2. Develop a consistent, comprehensive history diagram that corrects problems in the previous diagrams;

3. Identify the key roles of individuals and organizations that have contributed significantly to the development of simulation programs; and
4. Identify the important analysis methods of the most widely used programs, including where the analysis methods came from.

Using these the four objectives, the simulation programs analyzed were selected with the following criteria: (a) the simulation program is widely used in the U.S., (b) the program and its documentation are available in the U.S. in English, (c) the simulation program, or a derivative of the program is still presently in use and supported, and (d) the analysis method used in the simulation program has made a large contribution toward the development of simulation in this area.

Even though the analysis methods of simulation programs cover many aspects of building energy use, this study is primarily focused on a subset of analysis methods. For example, in the case of whole-building analysis programs, this study focuses on heat transfer methods for the exterior building envelope.

**1.3 Significance of the Study**

This study investigates the history of simulation programs and their analysis methods, which are used to analyze high performance buildings in the United States. Such an analysis is significant because it will help users to better understand the capabilities of today's most widely used simulation programs based on an analysis of the origins of their analysis methods. Currently, there have been only a few previous studies that explained only a limited segment of the origins of the most important analysis methods used in building simulation programs. Unfortunately, even today, most users do not achieve the same modeling results on the same building, even when they use the same simulation programs to simulate the same building using the same weather data (RMI, 2011).

This study is intended to give readers a better understanding of where the analysis methods of the simulation programs came from, who developed them, and why they were developed through the comprehensive genealogy chart.

### 1.4 Limitations of the Study

The proposed study is conducted with the following limitations:

1. The study is focused on the origins of the calculation methods used in simulation programs, not on the future directions of existing programs.
2. The study does not cover the origins of the analysis methods and simulation programs used in Building Information Modeling (BIM), HVAC system performance analysis, building water use, indoor air quality (IAQ), thermal comfort, acoustics or structural/earthquake simulations of buildings.
3. The study does not cover simulation programs developed outside the U.S. although many of the programs reviewed are used outside the U.S.
4. The study does not analyze the program source codes or the specific equations in the simulation programs with the exception of the equations shown in the references that were reviewed. Ultimately, a more detail analysis would investigate the algorithms used in building simulation programs by studying the source code (i.e., FORTRAN) of the simulation programs. This would be a logical next step of a future study.

## 1.5 Organization of the Thesis

This study has six chapters. Chapter I introduces the background, objectives and scope, significance, and limitations of this study as well as the organization of this study.

Chapter II is the literature review. This chapter defines high performance buildings using building standards and reviews the history of the methodologies and simulations used in high performance buildings regarding the development of computer technology. This chapter also reviews previous studies that attempted to trace the history of: whole-building energy simulation; solar photovoltaic (PV), active solar and passive solar system simulation; and lighting and daylighting simulation programs.

Chapter III explains the method, used in this study, including the identification and review of different classes of simulation programs and explains methods used to develop and analyze a new comprehensive history diagram.

Chapter IV contains the results of this study. This chapter describes the new comprehensive diagram.

Chapter V provides an analysis of the new comprehensive history diagram, including: an analysis by time period, a tracing of specific analysis methods, a tracing of specific simulation programs and a tracing of the influence of specific individuals and organizations.

Chapter VI summarizes this study and describes what has been learned from this study. In addition, this chapter suggests future work based on features or facts that were discovered during the course of the study but were left unresolved.

# CHAPTER II

# LITERATURE REVIEW

This literature review covers: (a) the definition of high performance buildings and (b) a review of the previous studies of the history of the analysis methods and simulation programs used for high performance buildings. The sources of literature include the publications from: National Bureau of Standards or NBS, now National Institute of Standards and Technology (NIST); American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE); National Research Council (NRC), Rocky Mountain Institute (RMI); Energy Systems Laboratory (ESL) at Texas A&M University; and national laboratories of the U.S. Department of Energy (US DOE), including: National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL); the proceedings of the 1970 and 1985 building energy simulation conferences; and the proceedings of the International Building Performance Simulation Association (IBPSA), as well as various theses and dissertations from which many of the analysis methods originated.

## 2.1 Defining High Performance Buildings

High performance commercial buildings are significantly more energy efficient than standard commercial buildings (Cho and Haberl, 2006). However, in order to understand high performance commercial buildings, we have to understand the minimum energy efficiency standards for common commercial buildings.

In order to make buildings energy efficient, minimum energy efficiency standards have been developed in recent decades to both buildings under construction and existing buildings. ASHRAE Standard 90.1-2010 is the current, minimum energy efficiency standard for commercial buildings in the U.S (ASHRAE, 2010). Figure 2.1 shows the history of ASHRAE Standard 90.1 for commercial buildings.

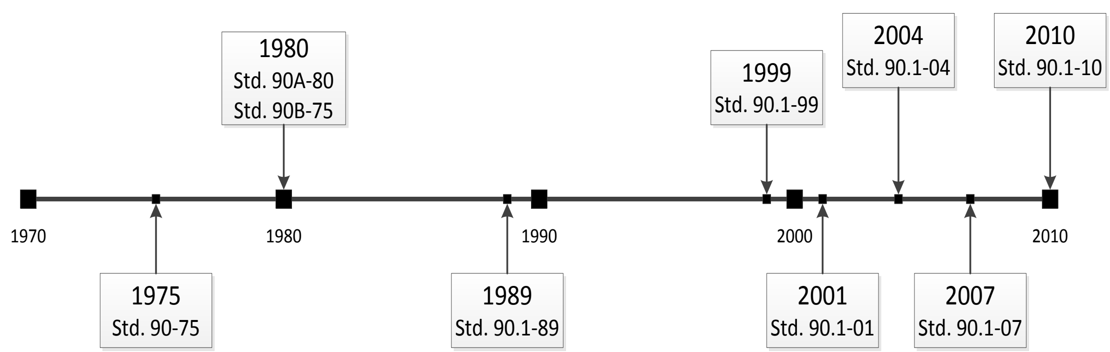


*Figure 2.1.* ASHRAE standard 90.1 timeline. Adapted from "Thermal Mass Provisions in ASHRAE Standard 90.1 and the IECC" by S. Skalko, 2012. Copyright 2012 by American Concrete Institute (ACI). Reprinted with permission.

While ASHRAE Standard 90.1-2010 is used extensively as the baseline for minimum energy efficiency in commercial buildings, high performance buildings are being designed and built today that are more efficient than ASHRAE Standard 90.1-2010 (Holness, 2011).

One standard for high performance buildings is ASHRAE Standard 189.1-2009, which has been jointly developed by the ASHRAE, the U.S. Green Building Council (USGBC) and the Illuminating Engineering Society (IES). ASHRAE Standard 189.1-2009 covers all important areas of the Leadership in Energy and Environmental Design

(LEED) rating system developed by USGBC. This standard is approximately 32% more efficient than ASHRAE Standard 90.1-2004 (Holness, 2011). In addition, ASHRAE Standard 189.1-2009 covers "…site sustainability, water use efficiency, energy efficiency, indoor environmental quality (IEQ), and the building's impact on the atmosphere, materials and resources." (ASHRAE, 2009, p. 4). ASHRAE Standard 189.1-2011, which is the revised version of 189.1-2009, was released in February 2012 (Stanke, 2012). ASHRAE Standard 189.1-2011 provides substantial improvements over the previous version, including reference to ASHRAE Standard 90.1-2010, which has more stringent requirements than ASHRAE Standard 90.1-2007 (ASHRAE, 2011; Stanke, 2012). For example, ASHRAE Standard 90.1-2010 has more stringent requirements for sidelights and skylights, which ASHRAE Standard 90.1-2007 does not have. ASHRAE Standard 189.1-2011 also includes a detailed prescriptive option with respect to a minimum sidelighting effective aperture and a skylight effective aperture, which ASHRAE Standard 189.1-2009 did not have.

The International Green Construction Code (IGCC), developed by the International Code Council (ICC), is another standard for high performance commercial buildings. In addition, the IGCC covers conservation of natural resources, materials, energy and water. It also has requirements concerning indoor environmental air quality and owner education. The IGCC can cross-reference ASHRAE Standard 189.1 if a local jurisdiction adopts it (ICC, 2012).

Net zero energy buildings (NZEBs) are buildings that need energy equal to or less than the amount of renewable energy provided on-site annually. However, the definition of NZEBs can vary, based on one of the following: (a) net zero site energy, (b) net zero source energy, (c) net zero energy costs, and (d) net zero energy emissions (Torcellini et al., 2006, p. 4). The net zero site energy definition means site energy used in a building should be offset by renewable energy generated on-site in one year; whereas in the net zero source energy definition, the concept of energy is extended to the primary energy source that provides the energy for the site, including all source energy consumed to produce electricity. The use of the net zero energy costs definition uses the cost of energy exported to the grid equal to the amount of annual energy cost to be paid in the utility bill for energy use and services in one year. The net zero energy emissions definition assumes that the renewable energy generated on-site makes up for the building's energy sources that have emissions associated with production. Each definition has limitations even though the definitions cover the features that can effectively express NZEBs. Therefore, reliable and consistent definitions of the NZEBs are required for designers, engineers, researchers, and policy makers (Torcellini et al., 2006).

NZEBs must incorporate energy efficiency, renewable energy and environmental factors into a wholly integrated design (Holness, 2011). The integrated design, as defined by ASHRAE and the American Institute of Architects (AIA), is a collaborative process that improves project results through the participation of all project members.

Holness (2011) lists the integral aspects of the integrated design:

> building orientation to suit climate zone; coordinated siting, landscaping and building location; highly insulated building envelope; optimized high performance fenestration; optimized use of daylighting; low density ambient lighting (electronic dimmable); high efficiency task lighting

> (occupancy control); control of plug and process loads; dedicated outdoor air systems with enthalpy recovery and demand control; super efficient heating, ventilation, air conditioning (HVAC) systems; expanded use of heat pumps; radiant heating and cooling systems; high performance packaged systems, including variable refrigerant flow (VRF) systems; consideration of renewable energy; and ongoing commissioning, operation and maintenance. (p. 57)

All in all, high performance buildings are not currently defined in a uniform fashion. In addition, many building energy standards have been developed to save energy in buildings. These standards are becoming more stringent with each new edition. In summary, there is more and more evidence that architects and engineers are beginning to move toward the design, construction and operation of net zero buildings.

### 2.2 Review of Previous Attempts to Trace the Methods Used in Simulation Programs and the History of Simulation Programs

Several events and trends have focused attention on reducing building energy use over the last 50 years. In 1973, the Arab oil embargo raised oil prices worldwide, which raised overall energy prices and motivated the development of calculation procedures for improved thermal performance with respect to energy use in buildings, including commercial building energy codes (i.e., ASHRAE Standard 90 in 1975 (Hydeman, 2006) and the model energy code (MEC, now IECC) in 1983 (US DOE, 1999)) (Ayres and Stamper, 1995). More recently, growing concerns about climate change have led to an effort to reduce $CO_2$ emissions from fossil fuel-fired electricity plants that supply electricity to buildings. As a result, renewable energy is once again increasing in use because it produces no $CO_2$ in comparison to electricity produced from fossil fuels (IPCC, 2011).

Analysis by hourly computer simulation programs is one way that energy use can be reduced in buildings at the design stage (ASHRAE TGER, 1975). According to Kusuda (1999), in 1959, the ASHRAE Journal published the first paper that addressed how a digital computer could be used to simulate an HVAC system component (Soumerai et al., 1959). In this study, a Bendix G-15 computer that used assembly language was used at the Worthington air conditioning company to calculate the cylinder pressure of a refrigeration compressor. The authors had to work hard for the calculation because the programming language for the Bendix G-15 was very tedious and limited by today's standards. Shortly afterwards in the 1950s, an IBM 7094 computer using FORTRAN, which was a more powerful programming language, was used for building simulations at the National Bureau of Standards (NBS). The availability of the IBM 7094 computer using FORTRAN enabled a numerical simulation to be developed that analyzed the interior thermal environment of fallout shelters in 1964 at NBS even though the simulation running time was quite long. This simulation achievement using a digital computer encouraged other engineers including Metin Lokmanhekim, who played an important role in creating the DOE-2 program at LBNL, to develop the beginnings of today's building simulation programs (Kusuda, 1999).

As computers became more powerful, engineers were able to use more detailed calculation methods, which had previously not been used due to the limited computer memory for earlier building energy simulations. In addition, with the development of computers using FORTRAN, which allowed the simulation developers to develop a program on one computer to be run on another computer, many new programs for simulation were developed that had more flexibility, including programs that allowed the user to manage varying loads, with different HVAC systems. Eventually, better user interfaces were also developed (Sowell and Hittle, 1995).

This section discusses the previous studies that traced energy analysis simulation programs and their analysis methods with respect to whole-building energy use, solar PV, active solar, passive solar, and lighting and daylighting simulation programs. This section reviews studies from the 1950s to the present, which roughly follows the evolution of FORTRAN. The previous studies include: the proceedings of the first symposium on use of computers for environmental engineering related to buildings held in 1970 (NBS, 1971); the report funded by the Electric Power Research Institute (EPRI) for computer programs with solar heating and cooling systems (Feldman and Merriam, 1979); the proceedings of the building energy simulation conference held in 1985 (US DOE, 1985); the bibliography of available computer programs of HVAC, which is provided by ASHRAE (Degelman and Andrade, 1986); and ASHRAE 1995 publications celebrating the 100$^{th}$ anniversary of ASHRAE (Ayres and Stamper, 1995; Sowell and Hittle, 1995; Shavit, 1995). Also covered are the previous studies regarding ASHRAE's annotated guides (1990, 1996), Kusuda's IBPSA paper (1999), Haberl and Cho's paper (2004), Kota and Haberl's paper (2009), and a recent report by the Rocky Mountain Institute (Tupper et al., 2011).

### *2.2.1 Proceedings of the first symposium on use of computers for environmental engineering related to buildings (Kusuda ed., 1971)*

The first symposium with respect to the use of computers for building energy simulation was held at the National Bureau of Standards (NBS) in Gaithersburg, Maryland in 1970. This symposium, entitled "Use of Computers for Environmental Engineering Related to Buildings", attracted approximately 400 architects, engineers, and scientists from 12 countries. NBS, ASHRAE, and the Automated Procedures for Energy Consultants (APEC) sponsored this symposium. The 59 technical papers of this symposium addressed a wide variety of issues including computer applications for building heat transfer analysis, loads and energy calculations, HVAC system simulations, weather data, and computer graphics (Kusuda ed., 1971). Many of the papers contained detailed listings of the equations and algorithms that were used.

The majority of these proceedings was related to the cooling and heating load calculations because these were popular topics among building environmental engineers in the late 1960s (Kusuda ed., 1971). The application of computers to the dynamic thermal load calculations allowed building engineers to work with more accurate solutions and methods that better represented a building's time-varying loads (Tull, 1971; Lokmanhekim, 1971).

In these proceedings, significant historical facts regarding the application of the computer to building environmental engineering were mentioned several times such as the ASHRAE algorithms and the Post Office program. However, these proceedings did not include timeline diagrams that helped readers more easily understand the historical development of building simulation programs and the analysis methods used in the simulation programs that were discussed.

### *2.2.2 Building energy analysis computer programs with solar heating and cooling system capabilities (Feldman and Merriam, 1979)*

The 1979 Electric Power Research Institute (EPRI) report by Feldman and Merriam concluded that several organizations had developed computer analysis programs for solar heating and cooling systems. The report focused on the available programs for electric utilities and their customers. Scott Feldman and Richard Merriam at Arthur D. Little, Inc. investigated 31 computer programs that they selected based on the criteria outlined in their report. For example, Feldman and Merriam chose programs that were not merely duplicated from another program; provided detailed information describing the program; and did not analyze building loads only (i.e., programs that included a solar system analysis). In general, the characteristics of these programs were different because they used different analysis methods, system component types and data requirements. Only a few of the programs reviewed by Feldman and Merriam remain in use today; many of the programs are no longer in use or have been combined with other programs. The report is significant because it referenced many studies that contained detailed information about the computer models and their applications, performance analyses of solar systems, and the ASHRAE methods used in the computer simulation models (Feldman and Merriam, 1979). The report also included diagrams and summary matrices to help readers better understand the capabilities and background of the simulation programs that were surveyed.

In summary, the 1979 Feldman and Merriam report explained the capability and history of each program available in 1979 with 12 tables and a history diagram (see Figure 2.2).

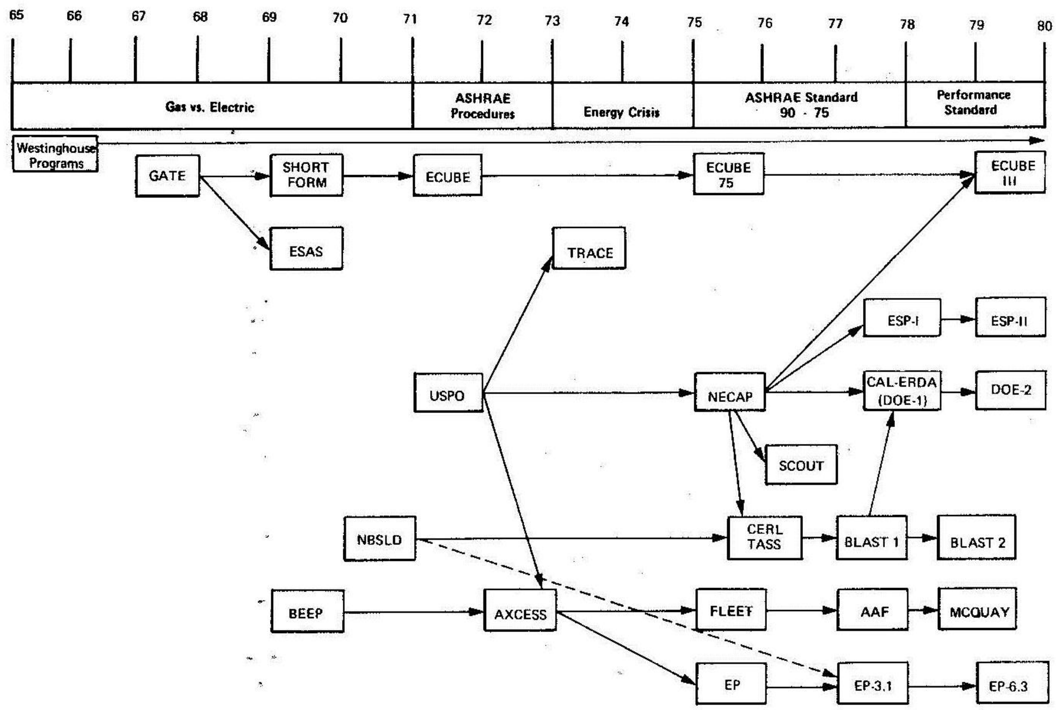


*Figure 2.2.* History of energy analysis computer programs. *Note.* From "Building Energy Analysis Computer Programs With Solar Heating and Cooling System Capabilities," by S. J. Feldman and R. L. Merriam, 1979. Copyright 1979 by EPRI. Reprinted with permission.

The clearly presented information in the report was exceptional among all other historical treatments of building simulation programs. However, the history diagram and its explanations did not describe the detailed connections between the programs and their analysis methods, nor did it name all the key individuals involved in the program development. In addition, the diagram contained only energy analysis programs to compare the background of solar heating and cooling programs. In other words, the diagram did not show solar heating and cooling programs. Finally, the report was written in 1979 and only covered computer programs created before then. It was never updated by EPRI.

#### *2.2.3 Proceedings of the building energy simulation conference (US DOE, 1985)*

The Building Energy Simulation Conference held in Seattle, Washington, in 1985 was sponsored by the Passive Solar Group of the United States Department of Energy (US DOE, 1985). The conference was unique because it was one of the first U.S. conferences that focused on building energy simulation since the first symposium at National Bureau of Standards (NBS) in 1970. The proceedings of the conference focused on effective simulation applications, microcomputer techniques and program development. Out of a total of 59 papers in the proceedings, 11 papers were about applications of building energy simulation, 13 papers about the microcomputer simulation techniques and 22 papers about simulation program development.

The proceedings of the conference also provided an explanation about how building energy simulation was developed and conducted from the late 1960s until 1985 in a variety of locations, including: North America (Kusuda, 1985), Europe (Sornay and Clarke, 1985), Asia (Matsuo, 1985) and Oceania (i.e., Australia and New Zealand) (Mason, 1985). The proceedings also included papers that explained microcomputer programs such as ECAP (Jansen, 1985) and ESPRE (Merriam, 1985), which contributed to opportunities for further developing many of today's energy simulation programs (Kusuda, 1985). The microcomputer programs referenced in the proceedings used a number of different calculation techniques to calculate energy use in buildings, including: the Cooling Load Temperature Difference (CLTD) Method (Rudoy and Duran, 1975); a Resistor-Capacitor (RC) Network Model (Paschkis, 1942); and Response Factor (Mitalas and Stephenson, 1967) / Weighting Factor (Stephenson and Mitalas, 1967) Method. Other papers in the proceedings discussed related program developments for passive solar systems (Gratia 1985; Hayashi et al., 1985; Ishizuka et al., 1985; Emery et al., 1985). There was also a paper by Winkelmann and Selkowitz that discussed a daylighting simulation program that was combined into a whole-building energy simulation program (i.e., DOE-2) (Winkelmann and Selkowitz, 1985).

In summary, the proceedings of this conference covered many of the historical aspects for building energy simulation and solar simulation programs (i.e., daylighting and passive solar programs). However, although the proceedings did contain historical papers, they did not include any papers that contained timeline diagrams to help readers graphically visualize the sequence and inter-connection of the historical process of building energy simulation.

#### *2.2.4 A bibliography of available computer programs in the area of heating, ventilating, air conditioning, and refrigeration (Degelman and Andrade, 1986)*

This bibliography described general abstracts and annotated software abstracts of various simulation programs, including areas of acoustics, computer-aided building design, mechanical equipment design, energy and economic analysis, heating and cooling load calculations, lighting, solar systems, psychrometrics, weather data analysis, and other related areas. This bibliography included information that had been collected until November 1986, which was from domestic and foreign journals, all U.S. universities, national laboratories, and known software companies. There are two main sections; Section 1 presents the abstracts categorized by the areas of the simulation programs, and Section 2 includes cross-reference indices by keyword, computer type, price category, program name, and author or vendor, which are used for searching the simulation programs (Degelman and Andrade, 1986).

This bibliography contained the abstracts, operating environment, program availability and authors of 36 heating and cooling load calculations, 52 energy analysis, nine solar system analysis, and 18 lighting design and analysis simulation programs. The abstracts and subsections provided the features, computer types such as microcomputer, minicomputer, or mainframe computer, source code type, and author of each simulation program. In addition, some abstracts of these simulation programs explained the analysis methods used in these simulation programs. However, this bibliography did not explain the historical development of the analysis methods used in the simulation programs, and most of the abstracts did not describe which analysis method was used in the simulation program.

#### *2.2.5 An annotated guide to models and algorithms for energy calculations relating to HVAC equipment (Yuill, 1990) and annotated guide to load calculation models and algorithms (Spitler, 1996)*

By the 1990s, engineers and researchers had developed many simulation models that contained thousands of different algorithms to simulate hourly envelope loads and HVAC system loads for building simulation programs. To help researchers sift through the different programs, ASHRAE sponsored several annotated guides. For example, in 1975, the ASHRAE Task Group on Energy Requirements (TGER) published two books (ASHRAE, 1975a, 1975b) that included algorithms for load calculation and modeling methods for HVAC systems and plants in order to computerize building energy analysis. These ASHRAE annotated guide books were developed because many simulation program developers spent much of their time searching ASHRAE literature for technical information to help them write their algorithms. Such demand for this information directly motivated ASHRAE to develop and publish the annotated guides. The ASHRAE annotated guides provided explanations and references to help simulation program developers better understand the algorithms and models used in building computer programs. The annotated guide book relating to HVAC equipment (Yuill, 1990) included algorithms relating to the air-handling, refrigeration, heating, unitary and solar heating equipment, while the annotated guide book for load calculation (Spitler, 1996) covered building envelope models, entire building loads models and other room heat transfer models.

In summary, the two ASHRAE annotated guides thoroughly reviewed the previous references and provided detailed information about the historical development of the previous algorithms and models for HVAC equipment and load calculations. However, the guides did not contain detailed timeline diagrams (i.e., family trees or genealogy charts) that help trace the interconnections of the algorithms and models in order to better grasp their significance.

### *2.2.6 Historical development of building energy calculations (Ayres and Stamper, 1995)*

During the 1970s, companies and government organizations created dozens peak-load and annual energy use simulation programs. The energy calculation methodologies used in these simulation programs varied from detailed hourly simulations to simple steady-state equations. Many of these simulation programs are no longer in use because of a lack of support, poor documentation, limited technical upgrades, or discontinuance of the program. A few programs were re-released, updated and improved over time and included detailed documentation. By 1980, there were approximately ten major hourly energy analysis programs for large commercial buildings. However, by 1995, only the proprietary energy simulation programs developed by Trane, Carrier, the Automated Procedures for Energy Consultants (APEC), and a few others had survived because their software documentation and support were satisfactory. Some companies with proprietary software did not want to share the algorithms of their simulation programs, which often contributed to the demise of the software. On the other hand, there have been many advances in public domain energy analysis programs because the shared algorithms made the programs more available to users, and as a result, received a wider acceptance.

During this period, the government financially supported only a few of the public programs, which contributed to their success, while at the same time, making it difficult for private companies to continue to support their programs because of the competition from the publically-funded programs. In recent years, the U.S. national laboratories, selected educational institutions and a few private companies have focused more on developing new interfaces for the existing energy simulation programs rather than developing new calculation methods in order to meet increasing demands for ease-of-use (Ayres and Stamper, 1995).

Ayres and Stamper used tables and diagrams to help explain the history of the manual and automated energy calculation methods as well as energy simulation programs. Their explanations included information about the basic analysis methods, the historical background of why simulation programs became important, and which organizations developed or supported the simulation programs. The paper concluded that many proprietary energy analysis programs had difficulty surviving, while only a few public domain building energy simulation programs survived beyond 1995.

In summary, the Ayres and Stamper paper showed that today's energy analysis programs for buildings were developed from only a few peak-load and annual energy calculation computer programs. The paper also contained a useful family tree type diagram for the public domain programs (see Figure 2.3).

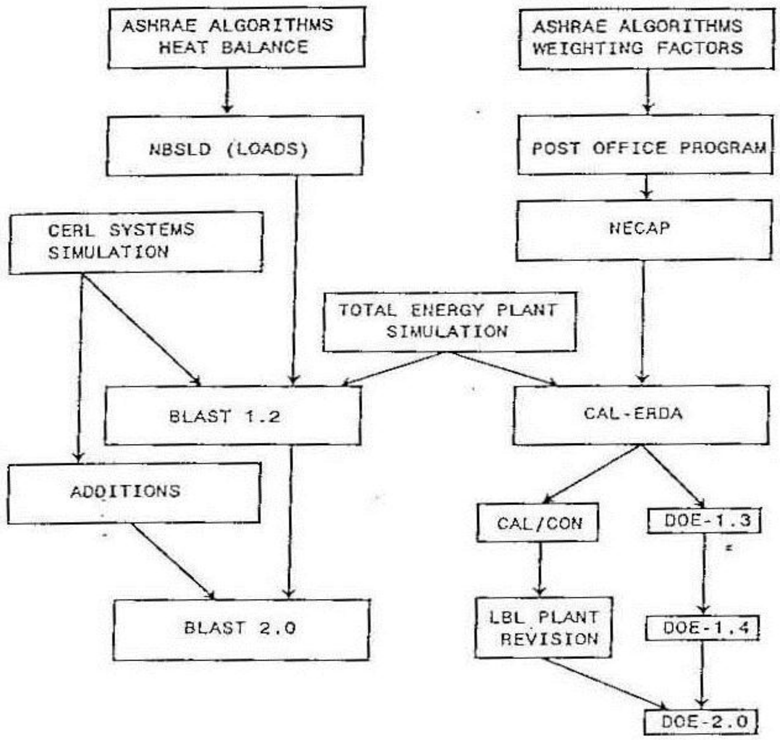


*Figure 2.3.* Family trees of public domain programs. *Note.* From "Historical Development of Building Energy Calculations," by J. M. Ayres and E. Stamper, 1995, *ASHRAE Transactions, 37*, p.847. Copyright 1995 by ASHRAE[2] (www.ashrae.org). Reprinted with permission.

However, there were few explanations about the diagram and no details that explained the connections between the public domain programs and the earlier energy analysis programs in terms of the analysis methods used to analyze building energy use, or the authors of the earlier analysis methods.

### *2.2.7 Evolution of building energy simulation methodology (Sowell and Hittle, 1995)*

According to the paper by Sowell and Hittle (1995), the generally available public domain energy analysis programs for buildings use one of two methods to

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[2] ASHRAE address: 1791 Tullie Circle, N.E. Altlanta, GA 30329

calculate the heating and cooling loads in buildings. One method, called the weighting factor method (Mitalas and Stephenson, 1967), calculates cooling or heating loads with pre-calculated weighting factors or custom weighting factors. Weighting factors are used to convert heat gains through walls or roofs to heating or cooling loads in a zone. The other method is the heat balance method that uses a conductive, convective, and radiative heat balance for all room surfaces in the thermal zone. These two methods for calculating a building's hourly heating and cooling loads have been applied in most major public domain programs. Each method has advantages and limitations, which affect the performance of the energy programs. For example, the weighting factor method does not require repeated calculations for simulation, and the heat balance method does not need the assumptions of constant convection conditions (Sowell and Hittle, 1995).

Sowell and Hittle explained the development of the load, system, plant, and economics (LSPE) simulation sub-programs. They also compared the two main public domain programs that existed prior to 1995 (i.e., DOE-2 and BLAST) that used the two methods (i.e., the weighting factor method for DOE-2 and the heat balance method for BLAST). However, the paper did not have a historical diagram or complete explanations of all the references in the development process of the LSPE algorithms in the two methods. Finally, since the paper was written in 1995, it did not cover analysis methods written since then that are contained in today's public domain programs (i.e, EnergyPlus).

### *2.2.8 Short-time-step analysis and simulation of homes and buildings during the last 100 years (Shavit, 1995)*

Short-time-step analysis and hourly simulation programs for buildings have been under development for the last 100 years, which has included three time periods: pre-World War II, from World War II (1945) to the second energy crisis (1973), and a period representing the post-second energy crisis. In contrast to the hourly energy simulation programs, the short-time-step analysis programs were designed to evaluate building heating and cooling loads on a minute-by-minute basis for use when simulating the performance of a building's HVAC controls simulation. Such an analysis using a short-time-step was able to simulate short-time-steps for thermal systems in almost real time. However, hourly whole-building programs were used to analyze an entire building's annual energy use because of the long computing time required by the short-time-step programs (Shavit, 1995).

Shavit explained the pre-1960s historical aspects of the analysis methods that contributed to the development of building simulation programs. Shavit's paper made an important contribution because it is difficult to find detailed explanations about any pre-1960s analysis methods in other papers. Before digital computers were used for building analysis in the 1960s, engineers used analog computers, which used an electric circuit analogy (i.e., actual resistors and capacitors), to simulate the time-dependent thermal behavior (Willcox et al., 1954; Buchberg, 1955; Buchberg 1958). The electric circuit analogy greatly influenced the thermal analysis calculations in all succeeding simulation programs, including short-time-step and whole-building simulation programs.

Shavit’s paper also provided comparisons between the short-time-step programs and whole-building simulation programs. Finally, this paper provided useful information about short-time-step programs and their uses in control simulations. In addition, the paper provided a timeline diagram that included both short-time-step programs and hourly whole-building simulation programs from 1967 to 1986 (see Figure 2.4). Like the diagram of the 1979 EPRI report, Shavit’s diagram included the lineage of several additional privately developed programs (i.e., TRACE and ECUBE). However, the diagram did not explain from where the analysis methods in these programs originated. Unfortunately, Shavit did not provide sufficient explanations and references necessary for a complete understanding of the history diagram in the paper.

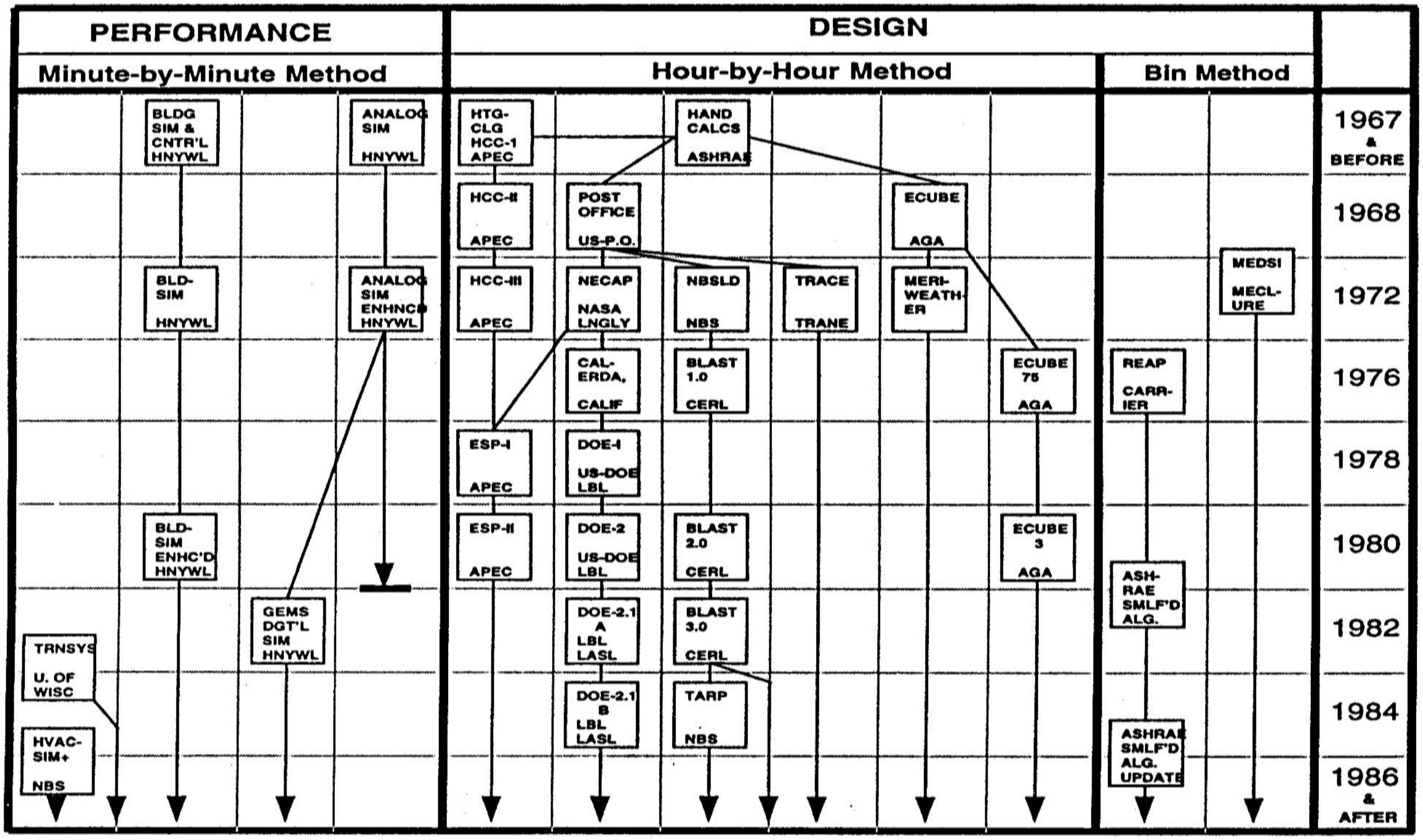


*Figure 2.4.* Development timeline of simulation programs. *Note.* From "Short-Time-Step Analysis and Simulation of Homes and Buildings During the Last 100 Years," by G. Shavit, 1995, *ASHRAE Transactions, 101,* p. 864. Copyright 1995 by ASHRAE (www.ashrae.org). Reprinted with permission.

### *2.2.9 Early history and future prospects of buildings system simulation (Kusuda, 1999)*

According to Kusuda (1999), in the early 1960s, the U.S. government developed the first computerized thermal simulations to analyze fallout shelters to determine what interior conditions would be like in the heavy underground concrete structures. Around this same time, gas and electric companies such as the Westinghouse Electric Company and a group of gas industry companies, called Gas Application to Total Energy (GATE), also started producing general-purpose thermal simulations for buildings based on hourly calculations. This trend motivated ASHRAE to form the Task Group on Energy Requirements (TGER) in 1967 to develop a public-domain, whole-building energy simulation program with hourly load calculations. Also, in 1967, the Automated Procedure for Engineering Consultants (APEC) developed a loads calculation program (HCC) that used the Total Equivalent Temperature Differential (TETD)/Time Averaging (TA) method, which was better-suited to run on the small computers that had limited memory, which were used by HVAC engineers at that time (Kusuda, 1999).

In his paper, Kusuda also discussed his experience with the detailed development of thermal simulation analysis methods, including specific analysis methods for psychometric calculations, room air motion using Computational Fluid Dynamics (CFD) and heating and cooling load calculations. In each of these discussions, Kusuda also discussed the historical aspects of each method and provided references to organizations or individuals that contributed to the development of the analysis methods. Kusuda also provided his view of future prospects for building simulation programs based on his more than 30 years of experience and knowledge writing simulation programs.

In summary, Kusuda's paper covered his personal simulation experience from the 1950s to the 1970s including the detailed development of analysis methods and their historical significance. The information in this paper was also based in part on his experience, which is important because he contributed significantly to the development of many of the original analysis methods that are still used in simulation programs today. However, his paper did not have a historical diagram to help the reader visually understand the hierarchy and genealogy of the analysis methods he discussed. Also, even though the paper was published in 1999, Kusuda did not include the most recent state-of-the-art programs (i.e., EnergyPlus) and their analysis methods in his discussion.

***2.2.10 Literature review of uncertainty of analysis methods (F-Chart, PV F-Chart , and DOE-2 program) (Haberl and Cho, 2004a, 2004b, 2004c)***

Haberl and Cho wrote three reports in 2004. Haberl and Cho's first report in 2004 traced the lineage of the F-Chart method, which originated from Sanford Klein's Ph.D. dissertation (Klein, 1976). The F-Chart program uses the F-Chart method, also developed by Klein, which estimates the fraction F of heating loads generated from solar energy (Klein, 1993). Correlations using data from many TRNSYS simulation runs, which analyzed specific solar heating systems, were used to create the F-Chart equations (Klein et al., 1976). The F-Chart program can be used to design solar heating systems by deciding what size and type of solar collectors are best for a given heating load and the domestic hot water (DHW) system of a building (Haberl and Cho, 2004a). The second report traced the roots of the PV F-Chart program that can be used to analyze photovoltaic systems, utility interface, and battery storage systems. Klein and Beckman

(1983; 1985) developed the PV F-Chart method that uses the utilizability concept (Haberl and Cho, 2004b). The utilizability concept, developed by Whillier (1953a, 1953b), calculates the useful fraction of the solar radiation reached to a surface over a critical amount (Duffie and Beckman, 2006). In a third report, the analysis methods in DOE-2 were traced back to their roots. The DOE-2 program is a whole-building, hourly energy simulation program that can analyze energy use and operating costs in most residential and commercial buildings (Haberl and Cho, 2004c). The Lawrence Berkeley National Laboratory (LBNL) developed DOE-2 beginning in 1978 (Leighton et al., 1978).

In summary, the three reports by Haberl and Cho explained many of the origins of the analysis methods used in simulation programs for active solar systems, PV systems and the overall building energy systems. The reports included historical family tree type diagrams (see Figure 2.5 to 2.7).

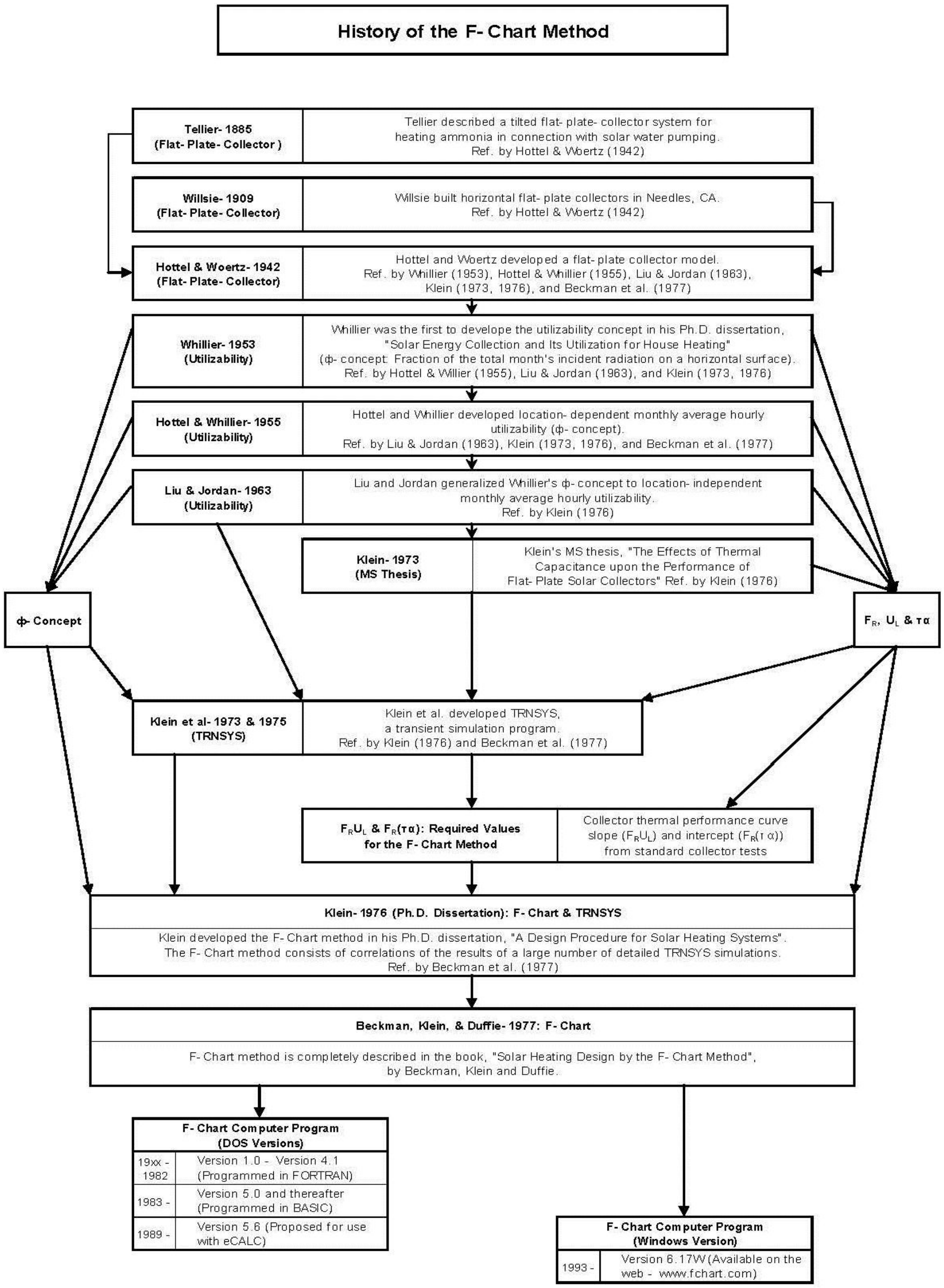


*Figure 2.5.* History diagram of the F-Chart program. *Note.* From “Literature Review of Uncertainty of Analysis Methods (F-Chart Program),” by J. S. Haberl and S. Cho, 2004a. Copyright 2004 by the ESL. Reprinted with permission.

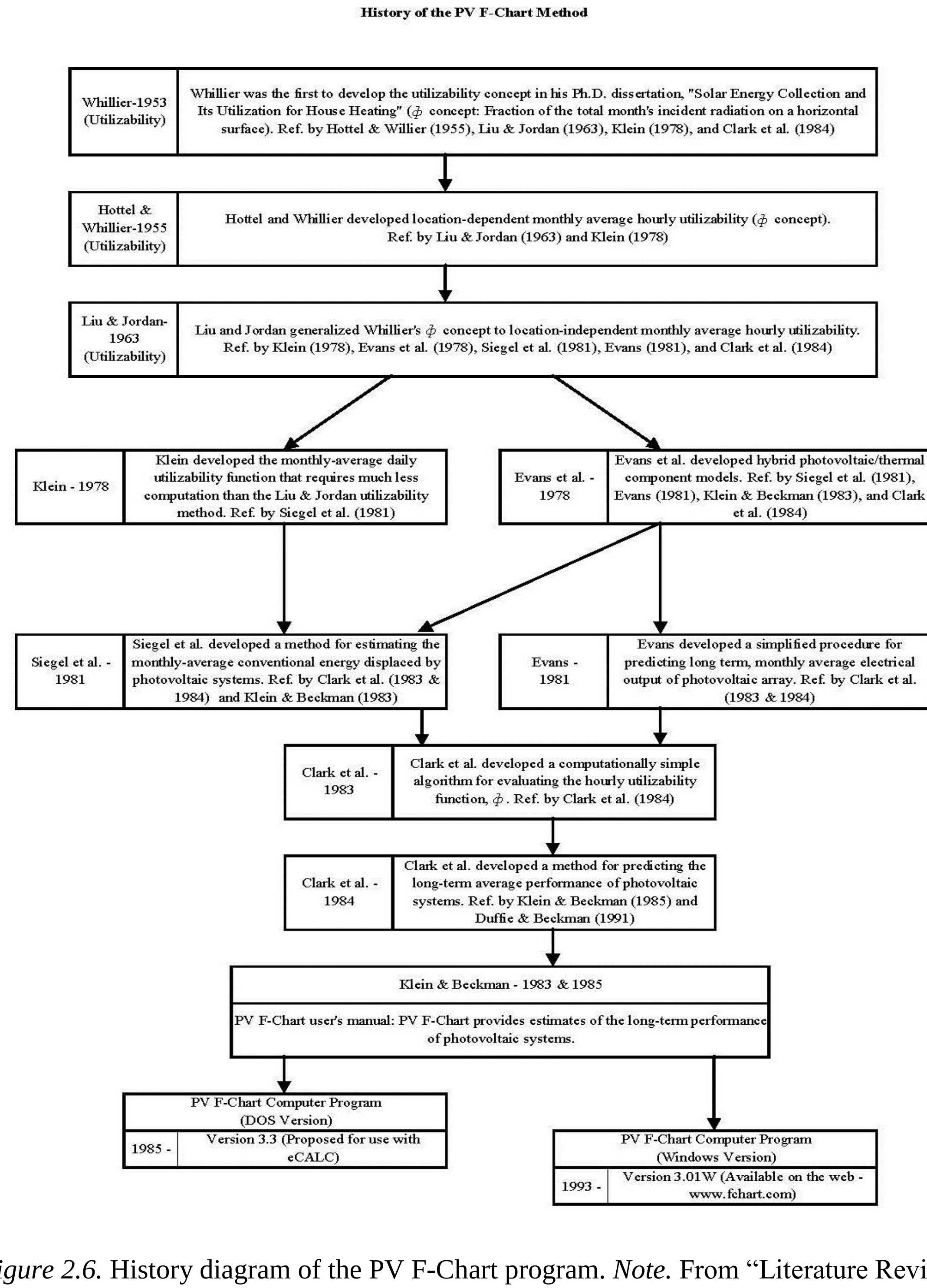


*Figure 2.6.* History diagram of the PV F-Chart program. *Note.* From "Literature Review of Uncertainty of Analysis Methods (PV F-Chart Program)," by J. S. Haberl and S. Cho, 2004b. Copyright 2004 by the ESL. Reprinted with permission.

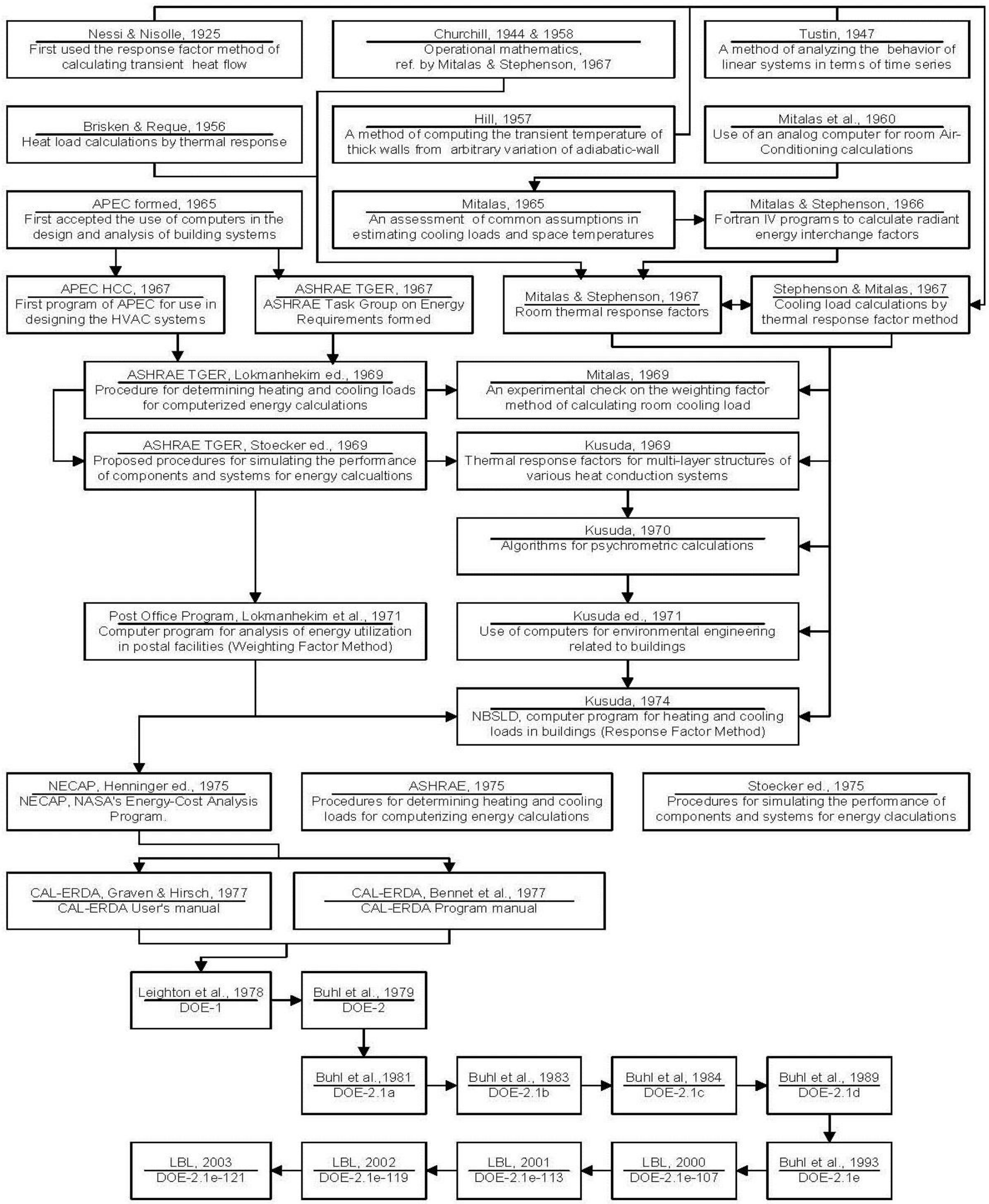


*Figure 2.7.* History diagram of the DOE-2 simulation program. *Note.* From "Literature Review of Uncertainty of Analysis Methods (DOE-2 Program)," by J. S. Haberl and S. Cho, 2004c. Copyright 2004 by the ESL. Reprinted with permission.

These three historical diagrams provided detailed information about the analysis methods in a straightforward and clear diagram that used a branching, family tree format. However, each report only treated the analysis methods of the specific program (i.e., F-Chart, PV F-Chart and DOE-2 program) and did not provide any linkage between the programs. In other words, the first report covered only the F-Chart program, the second report only the PV F-Chart program and the third report only the DOE-2 program. In addition, the three reports did not cover other programs in use today (i.e., EnergyPlus), nor have they been updated since they were published.

#### *2.2.11 Contrasting the capabilities of building energy performance simulation programs (Crawley et al., 2005)*

Various whole-building simulation programs have been developed to use in saving energy in buildings since the 1970s. In 2005, Crawley et al.'s paper reviewed the features of 20 whole-building simulation programs including: BLAST (Hittle, 1977), BSim , DeST (Chen and Jiang, 1999), DOE-2.1e (Winkelmann et al., 1993), ECOTECT (Marsh, 1996), Ener-Win (Degelman, 1990), Energy Express (Moller, 1996), Energy-10, EnergyPlus (Crawley et al., 2001), eQUEST (LBNL and JJH, 1998), ESP-r (Energy Systems Research Unit, 2002; Clarke, 1982, 2001), IDA ICE (Sahlin et al, 2003), IES <VE>, HAP (Carrier, 2003), HEED (Milne, 2004), PowerDomus (Mendes et al., 2003), SUNREL (Deru et al, 2002), Tas, TRACE (Trane, 1992), and TRNSYS (Klein et al., 1976). In the paper, overviews of 20 simulation programs were described and 14 tables were presented to compare the specific areas of 20 programs including: general modeling features; zone loads; building envelope and daylighting; infiltration, ventilation and multizone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; economic evaluation; climate data availability; results reporting; validation; user interface, links to other programs, and availability (Crawley et al., 2005).

Among the many comparative papers and surveys for building simulation programs, this paper provided the most comprehensive comparisons for specific features using 14 tables and their footnotes. However, the tables utilized information provided by vendors, which may not have had an adequate peer-review (Crawley et al., 2005). In addition, even though the overviews and tables of 20 simulation programs describe analysis methods used in the programs, they did not explain where the analysis methods originated, and who or which organization contributed to the development of the analysis methods.

#### *2.2.12 Historical survey of daylighting calculation methods and their use in energy performance simulation (Kota and Haberl, 2009)*

The report by Kota and Haberl (2009) provided a historical development of daylighting analysis methods. Numerous daylighting calculation methods have been developed over the past 100 years, with many important ideas introduced during the last twenty years. Selected analysis methods have also been incorporated into whole-building energy simulation programs (Kota and Haberl, 2009). This paper covered daylighting calculation factors such as sky models, daylight performance indicators and daylighting tools. It also explained many of the daylighting analysis methods used in the whole-building energy simulation programs.

In summary, this paper traced the origins of the methods used in the daylighting simulation programs and the development process of the daylighting calculations methods. This paper also included a detailed historical family tree diagram (see Figure 2.8). Although the historical diagram seemed to be the only known analysis that provided such detailed information, it was presented in a somewhat confusing diagram with several parallel paths, different line types crossing back and forth between paths and, unfortunately, used a very small font that made the diagram difficult to read. Finally, the report has also not been updated since it was published.

#### *2.2.13 Pre-read for Building Energy Modeling (BEM) innovation summit (Tupper et al., 2011)*

RMI, ASHRAE, IBPSA, USGBC, and the Institute for Market Transformation (IMT) recognized the need for collaboration among stakeholders in the field of building energy modeling. In the spring of 2011, RMI hosted the first BEM Innovation Summit with other organizations in Boulder, Colorado to work together to develop widespread use of BEM solutions for analysis of high performance buildings. This report was published with the purpose of explaining the history and present situation of the BEM industry in the U.S to all participants of the BEM innovation summit (Tupper et al., 2011).

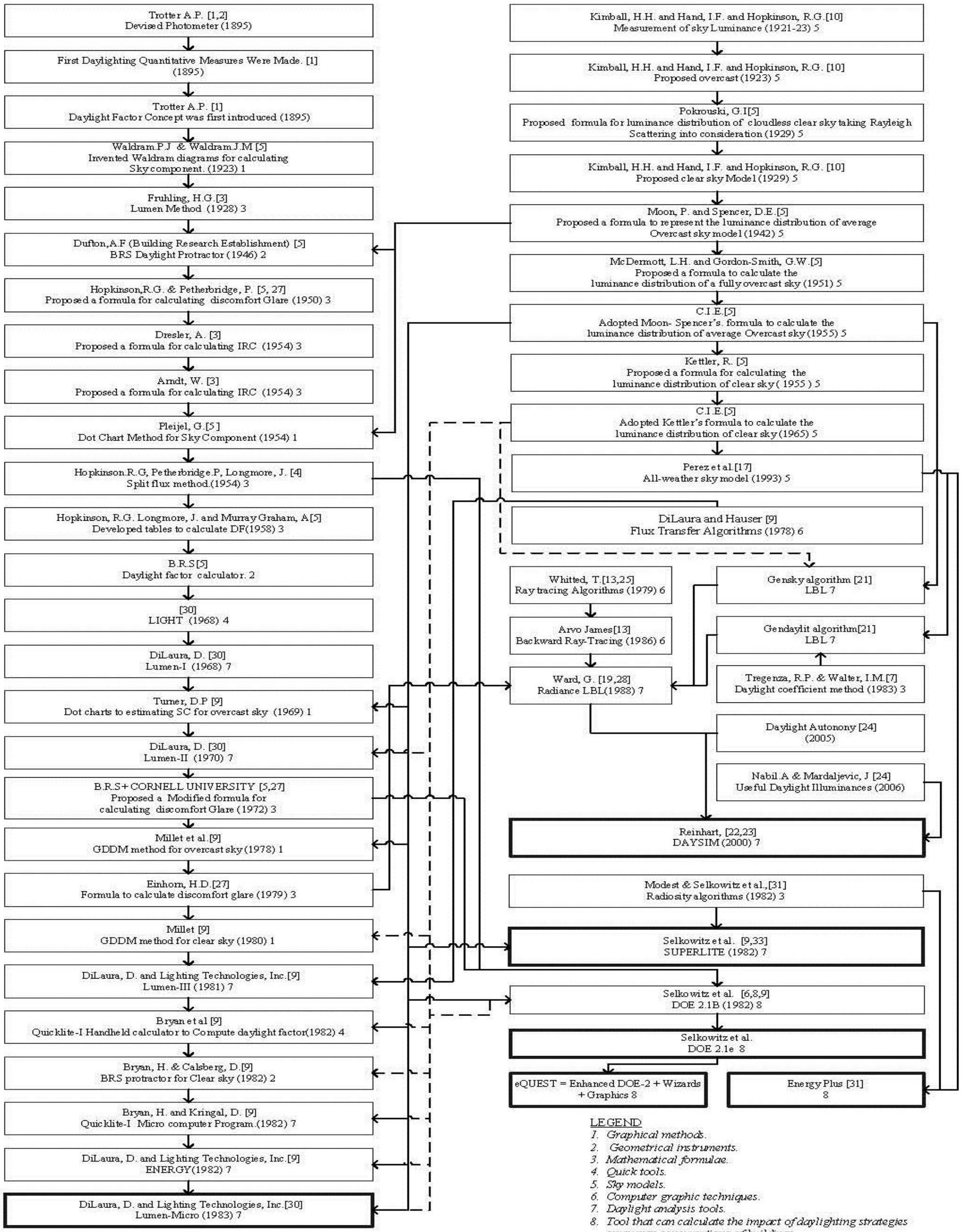


**Figure1: Chronological Development of Daylight Calculations.**

*Figure 2.8.* History diagram of the daylighting calculation methods and the daylighting simulation programs. *Note.* From "Historical Survey of Daylighting Calculations Methods and Their Use in Energy Performance Simulations," by S. Kota and J. S. Haberl, 2009. Copyright 2009 by the ESL. Reprinted with permission.

In this pre-read report, there was a section that discussed the history of BEM. This section provided a historical explanation and a historical flow chart that graphically displayed the evolution of BEM. The flow chart highlighted the development of many different building energy software programs including their release date and also indicated key organizations that contributed to the simulation development along the timeline. Much of the flow chart and accompanying explanation was adapted from Haberl and Cho's (2004c) third report with additional information provided by personal communications with selected building simulation experts.

In summary, the history section of the RMI report explained the history of selected analysis methods, simulation programs, and organizations from the pre-1960s to the present using a timeline diagram (see Figure 2.9). However, it did not discuss the different analysis methods in each simulation program, and the boxes in the flow chart contained inconsistent content. For example, some boxes had explanations of building simulation programs and funding organizations, whereas other boxes only marked the names of the simulation programs and organizations. In addition, the boxes of the flow chart were cluttered and not as well organized as other historical diagrams. Finally, the flowchart was based on Haberl and Cho's diagram (see Figure 4), which did not trace all the programs in the RMI report. The RMI report also did not have all the references for the flow chart. Therefore, a more detailed diagram or flow chart with additional information still needs to be developed.

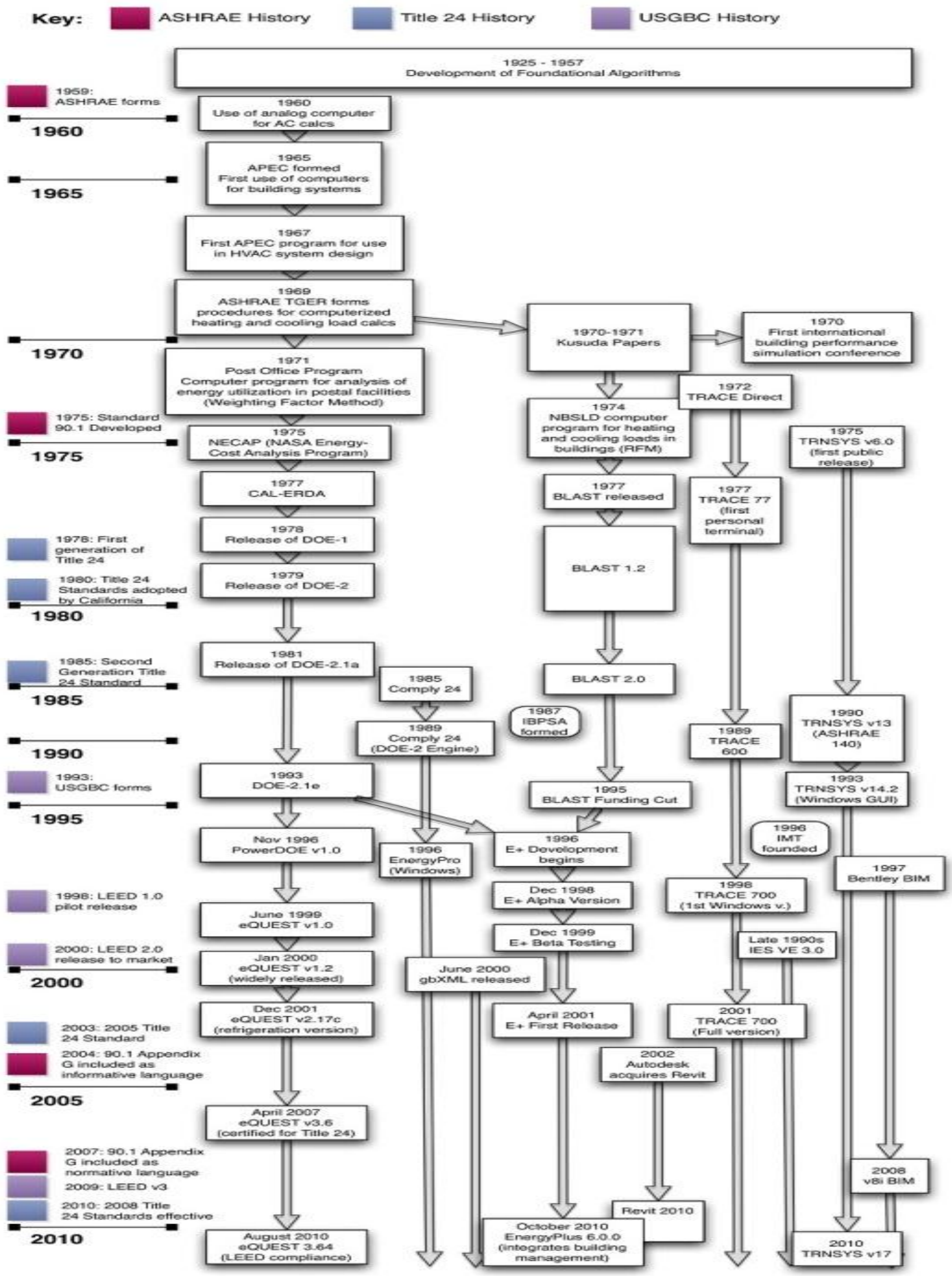


*Figure 2.9.* History diagram of energy simulation programs. *Note.* From "Pre-Read Building Energy Modeling (BEM) Innovation Summit," by K. Tupper et al., 2011. Copyright 2011 by the RMI. Reprinted with permission.

## 2.3 Summary of Literature Review

This literature review included a review of the different definitions of high performance buildings using the most widely used standards, a review of the history of the methodologies and simulations used to analyze high performance buildings with respect to the development of computer technology, and a review of the previous studies that investigated the methods used in simulation programs and traced the history of simulation programs. The previous studies reviewed included: historical traces of whole-building energy simulation; solar PV, active solar and passive solar system simulation; and lighting and daylighting simulation programs. Table 2.1 shows the areas covered by the previous studies. Table 2.2 shows which previous literature had historical diagrams and the features of the historical diagrams that were reviewed. Each of areas of the previous studies is summarized as follows:

- Whole-Building Energy Simulation: Several of the previous studies covered the history of whole-building energy simulations and their analysis methods. Fifteen studies discussed the history of whole-building energy simulations among the sixteen studies that were reviewed. Five history diagrams were provided among the fifteen studies. These history diagrams varied in format and included timelines and family tree-type diagrams to help readers better understand the relationship and development of the analysis methods in the simulation programs. However, some history diagrams had no connections between simulation programs and their analysis methods, while others had connection but presented little about what analysis methods were shared. Many have not been updated since the studies were written, some of which are now 17 years old. Other history diagrams did not have detailed information about the relevant individual boxes in the history diagrams. One of most insightful discussions had no diagram to accompany the discussions (i.e., Kusuda's paper in 1999).

- Solar System Simulation: Four literature (i.e., EPRI report in 1979, Proceedings of the building energy simulation conference in 1985, and Haberl and Cho's reports in 2004) covered the history of solar system simulations. Two literature contained history diagrams of the solar system simulations (i.e., Haberl and Cho's reports in 2004). The history diagrams showed detailed information including brief explanations and references. However, the diagrams did not compare many solar simulation programs and their analysis methods. Also, the diagrams did not include information about organizations supporting the development of the solar system simulation programs.
- Lighting & Daylighting Simulation: Only one of the previous papers included a history diagram of lighting and daylighting simulation programs (i.e., Kota and Haberl's report in 2009). This historical diagram presented brief explanations and references from 1895 to 2006. However, the diagram was constructed with somewhat confusing parallel paths with several line types crossing back and forth between the paths and, unfortunately, used a very small font that was difficult to read.

Table 2.1. *Catalog of previous studies that identified the analysis methods used in simulation programs for high performance commercial buildings.*

| **Paper Title** | **Author / Year** | **Whole-Building Energy** | | **Solar Systems** | | | **Lighting & Daylighting** |
|---|---|---|---|---|---|---|---|
| | | **Load Calculation** | **HVAC Systems** | **PV System** | **Active Solar System** | **Passive Solar System** | |
| Proceedings of the first symposium on use of computers for environmental engineering related to buildings | Kusuda, T. (Ed.) / 1971 | • | • | | | | |
| Building Energy Analysis Computer Programs with Solar Heating and Cooling System Capabilities | Feldman & Merriam / 1979 | • | • | • | • | • | |
| Building Energy Simulation Conference Notebook | US DOE / 1985 | • | • | | | • | |
| A bibliography of available computer programs in the area of heating, ventilating, air conditioning, and refrigeration | Degelman & Andrade / 1986 | • | • | • | • | • | • |

Table 2.1. *Continued*

| Paper Title | Author / Year | Whole-Building Energy | | Solar Energy | | | Lighting & Daylighting |
|---|---|---|---|---|---|---|---|
| | | Load Calculation | HVAC Systems | PV System | Active Solar System | Passive Solar System | |
| An Annotated Guide to Models and Algorithms for Energy Calculations Relating to HVAC Equipment | Yuill & Associates LTD / 1990 | | • | | | | |
| Historical Development of Building Energy Calculations | Ayres & Stamper / 1995 | • | • | | | | |
| Evolution of Building Energy Simulation Methodology | Sowell & Hittle / 1995 | • | • | | | | |
| Short-Time-Step Analysis and Simulation of Homes and Buildings During the Last 100 Years | Shavit / 1995 | • | • | | | | |
| Annotated Guide to Load Calculation Models and Algorithms | Spitler / 1996 | • | | | | | |
| Early History and Future Prospects of Building System Simulation | Kusuda / 1999 | • | • | | | | |

Table 2.1. *Continued*

| Paper Title | Author / Year | Whole-Building Energy | | Solar Energy | | | Lighting & Daylighting |
|---|---|---|---|---|---|---|---|
| | | Load Calculation | HVAC Systems | PV System | Active Solar System | Passive Solar System | |
| Literature Review of Uncertainty of Analysis Methods (F-Chart, PV F-Chart, DOE-2 Program) | Haberl & Cho / 2004a, 2004b, 2004c | • (2004c) | | • (2004b) | • (2004a) | • (2004a) | |
| Contrasting the capabilities of building energy performance simulation programs | Crawley et al. / 2005 | • | • | • | • | • | • |
| Historical Survey of Daylighting Calculation Methods and Their Use in Energy Performance Simulation | Kota & Haberl / 2009 | | | | | | • |
| Pre-Read for BEM Innovation Summit | Tupper et al. / 2011 | • | • | | | | |

Table 2.2. *Coverage of the previous literature including features of the diagram found in the previous studies.*

| Paper Title | Author / Year | Literature Covered Year | Literature Topic | History Diagram Existence | History Topic | History Diagram Features | |
|---|---|---|---|---|---|---|---|
| | | | | | | Advantages | Disadvantages |
| Proceedings of the first symposium on use of computers for environmental engineering related to buildings | Kusuda, T. (Ed.) / 1971 | Pre-1971 | Whole-Building Simulation | No | Whole-Building Simulation | Mentioned significant historical facts regarding the application of the computer to building environmental engineering several times such as the ASHRAE algorithms and the Post Office program. | Did not include timeline diagrams that helped readers more easily understand the historical development of building simulation programs and the analysis methods used in those simulation programs. |
| Building Energy Analysis Computer Programs with Solar Heating and Cooling System Capabilities | Feldman & Merriam / 1979 | 1960s - 1970s | Whole-Building Simulation | Yes | Whole-Building Simulation | Displayed various whole-building simulation programs. | Did not explain the connections between the programs and their algorithms. Not updated after 1980. Not explained in detail. |
| Building Energy Simulation Conference Notebook | US DOE / 1985 | 1960s - 1985 | Whole-Building Simulation / Solar Systems Simulation | No | Whole-Building Simulation | Covered many of the historical aspects for building energy simulation and solar simulation programs (i.e., daylighting and passive solar programs). | Did not include any papers that contained timeline diagrams to help readers graphically visualize the sequence and inter-connection of the historical process of building energy simulation. |
| A bibliography of available computer programs in the area of heating, ventilating, air conditioning, and refrigeration | Degelma & Andrade / 1986 | Pre-1987 | Whole-Building / Solar Systems / Lighting & Daylighting Simulations | No | No | Contained the abstracts, operating environment, program availability and authors of 36 heating and cooling load calculations, 52 energy analysis, nine solar system analysis, and 18 lighting design and analysis simulation programs. The abstracts and subsections provided the features, computer types such as microcomputer, minicomputer, or mainframe computer, source code type, and author. | Did not explain the historical development of the analysis methods used in the simulation programs, and most of the abstracts did not describe which analysis method was used in the simulation program. |

Table 2.2. *Continued*

| Paper Title | Author / Year | Literature Covered Year | Literature Topic | History Diagram Existence | History Topic | History Diagram Features | |
|---|---|---|---|---|---|---|---|
| | | | | | | Advantages | Disadvantages |
| An Annotated Guide to Models and Algorithms for Energy Calculations Relating to HVAC Equipment | Yuill & Associates LTD / 1990 | 1958 - 1990 | Whole-Building Simulation | No | Whole-Building Simulation | Reviewed the previous references and provided detailed information about the historical development of the previous algorithms and models for load calculations. | Did not contain detailed timeline diagrams (i.e., family trees or genealogy charts) that help trace the interconnections of the algorithms and models in order to better grasp their significance, nor has ASHRAE updated these guides since its publication. |
| Historical Development of Building Energy Calculations | Ayres & Stamper / 1995 | 1965 - 1995 | Whole-Building Simulation | Yes | Whole-Building Simulation | Provided the algorithm information of simulation programs and explained when programs had new functions. | No dates and no detailed boxes for explaining connections between the public domain programs and the earlier proprietary energy analysis programs in terms of algorithms. |
| Evolution of Building Energy Simulation Methodology | Sowell & Hittle / 1995 | 1960s - 1995 | Whole-Building Simulation | No | Whole-Building Simulation | Explained the development of the load, system, plant, and economics (LSPE) sub-programs. Also, compared the two main public domain programs that existed in 1995 (i.e., DOE-2 and BLAST) that used the two methods (i.e., the weighting factor method and the heat balance method). | Did not have a historical diagram or complete explanations of all the references in the development process of the LSPE algorithm in the two methods. |
| Short-Time-Step Analysis and Simulation of Homes and Buildings During the Last 100 Years | Shavit / 1995 | 1868 - 1995 | Whole-Building Simulation | Yes | Whole-Building Simulation | Provided a timeline diagram of short-time-step programs and hourly whole-building simulation programs from 1967 to 1986. | Did not explain where the analysis methods in either program came from. |

Table 2.2. *Continued*

| Paper Title | Author / Year | Literature Covered Year | Literature Topic | History Diagram Existence | History Topic | History Diagram Features | |
|---|---|---|---|---|---|---|---|
| | | | | | | Advantages | Disadvantages |
| Annotated Guide to Load Calculation Models and Algorithms | Spiter / 1996 | 1958 - 1996 | Whole-Building Simulation | No | Whole-Building Simulation | Reviewed the previous references and provided detailed information about the historical development of the previous algorithms and models for HVAC equipment. | Did not contain detailed timeline diagrams (i.e., family trees or genealogy charts) that help trace the interconnections of the algorithms and models in order to better grasp their significance, nor has ASHRAE updated these guides since its publication. |
| Early History and Future Prospects of Building System Simulation | Kusuda / 1999 | 1950s - 1970s | Whole-Building Simulation | No | Whole-Building Simulation | Covered Kusuda's personal simulation experience from the 1950s to 1970s including the detailed development of analysis methods and their historical significance. The information in this paper was also based in part on his experience, which is significantly important because he contributed significantly to the development of many of the original analysis methods that are still used in simulation programs today. | Did not have a historical diagram to help the reader visually understand the hierarchy and genealogy of the analysis methods he discussed. Also, even though the paper was published in 1999, Kusuda did not include the most recent state-of-the-art programs (i.e., EnergyPlus) and their analysis methods in his discussion. |
| Literature Review of Uncertainty of Analysis Methods (F-Chart Program) | Haberl & Cho / 2004a | 1885 - 1993 | Solar Thermal Systems | Yes | Solar Thermal Systems | Provided detailed information and straightforward diagram paths. | Did not compare other similar programs and their analysis methods. The diagram covered only the F-Chart program. |
| Literature Review of Uncertainty of Analysis Methods (PV F-Chart Program) | Haberl & Cho / 2004b | 1953 - 1993 | Solar PV Systems | Yes | Solar PV Systems | Same as above. | Did not compare other similar programs and their analysis methods. The diagram covered only the PV F-Chart program. |

Table 2.2. *Continued*

| Paper Title | Author / Year | Literature Covered Year | Literature Topic | History Diagram Existence | History Topic | History Diagram Features | |
|---|---|---|---|---|---|---|---|
| | | | | | | Advantages | Disadvantages |
| Literature Review of Uncertainty of Analysis Methods (DOE-2 Program) | Haberl & Cho / 2004c | 1925 - 2003 | Whole-Building Simulation | Yes | Whole-Building Simulation | Same as above. | Did not compare other similar programs and their analysis methods. The diagram covered only the DOE-2 program. |
| Contrasting the capabilities of building energy performance simulation programs | Crawley et al. / 2005 | Pre-2006 | Whole-Building / Solar Systems / Lighting & Daylighting Simulations | No | No | Provided the comparisons in the most specific areas using 14 tables and their footnotes among many comparative papers and surveys for building simulation programs. | Utilized information provided by vendors, which may not have had an adequate review (Crawley et al., 2005). Did not explain where the analysis methods originated, and who or which organization contributed to the development of the analysis methods. |
| Historical Survey of Daylighting Calculation Methods and Their Use in Energy Performance Simulation | Kota & Haberl / 2009 | 1895 - 2007 | Lighting & Daylighting | Yes | Lighting & Daylighting | Provided detailed information including references and explanations. | Presented in a somewhat confusing diagram flow with several line types and footnotes, as well as a small font that was difficult to read in the diagram. |
| Pre-Read for BEM Innovation Summit | Tupper et al. / 2011 | 1925 - 2011 | Whole-Building Simulation | Yes | Whole-Building Simulation | Explained several simulation programs and organizations from pre 1960s to present. | Did not compare the analysis methods of each simulation program. Also, the boxes of the diagram contained inconsistent content. The boxes of the diagram were cluttered. Finally, this diagram was based on Haberl and Cho's partially developed diagram; therefore, more detailed information should be added. |

In summary, although there have been many attempts at tracing the history of analysis methods used in whole-building, solar, and lighting and daylighting simulation programs, all of the previous attempts have some limitations. Therefore, there is a need for a more comprehensive and improved history diagram, which includes origins and brief explanations of the important analysis methods in the simulation programs for whole-building, solar PV, active solar, passive solar, lighting and daylighting simulation programs. Such comprehensive analysis is needed because if simulation users knew more about the analysis methods in the simulation programs and their origins, some of the current problems and obstacles in applying the building simulation program might be resolved (Tupper et al., 2011). For example, today, different building simulation users do not achieve the same modeling results, even when they use the same programs to simulate the same building, using the same weather data. Also, in general, simulation users who did not create the simulation program usually do not completely comprehend what the simulation program can simulate without an extensive review of all the program analysis methods, defaults and calculation logic (RMI, 2011).

# CHAPTER III

# METHODOLOGY

## 3.1 Overview of Methodology

The methodology of this study is provided in this chapter. The objectives of this study are as follows: (a) to review and analyze the previous literature in order to trace the origins of the analysis methods contained in widely-used simulation programs in the U.S.; (b) to develop a consistent, comprehensive historical diagram that resolves discrepancies in the previous diagrams; (c) to identify the key roles of individuals and organizations that have contributed significantly to the development of simulation programs; and (d) to identify the important analysis methods of the most widely used programs, where the analysis methods came from, who developed the methods, and how the programs use the capabilities of the analysis methods to simulate high performance buildings. With these objectives, the following tasks were performed:

1. Identify the major groups of simulation programs that are used to analyze high performance buildings in the U.S. Review each group of simulation programs and trace the origins of the simulation programs to the original source of the key analysis methods.
2. Develop a new comprehensive history diagram (i.e., genealogy chart).
    - 2.1. Identify the analysis methods used in the simulation programs.
    - 2.2. Accurately analyze the historical facts of the previous studies.
    - 2.3. Add relevant historical information about the analysis methods to identify from where the analysis methods originated.

3. Review the new comprehensive genealogy chart with key experts of each program group.

4. Complete and analyze the new genealogy chart by time period, by specific organization or funding, by specific analysis method, and by specific simulation program.

In order to better describe the origins of analysis methods used in today's simulation programs, a new comprehensive history diagram was created. Figure 3.1 shows the steps involved with this methodology. The following sections explain the details of each procedure. 15 simulation programs which are divided into three groups are studied in this research (Section 3.2). The overall features of each program are briefly described in the summary table of Section 3.2.4. A description about how each group of simulation programs was reviewed is explained in Section 3.2. The procedures used to create the new comprehensive history diagram are presented in Section 3.4. Finally, an analysis of the history diagram using four approaches (i.e., time period, specific analysis methods, specific simulation programs, and specific organizations or funding) is presented in Section 3.5.

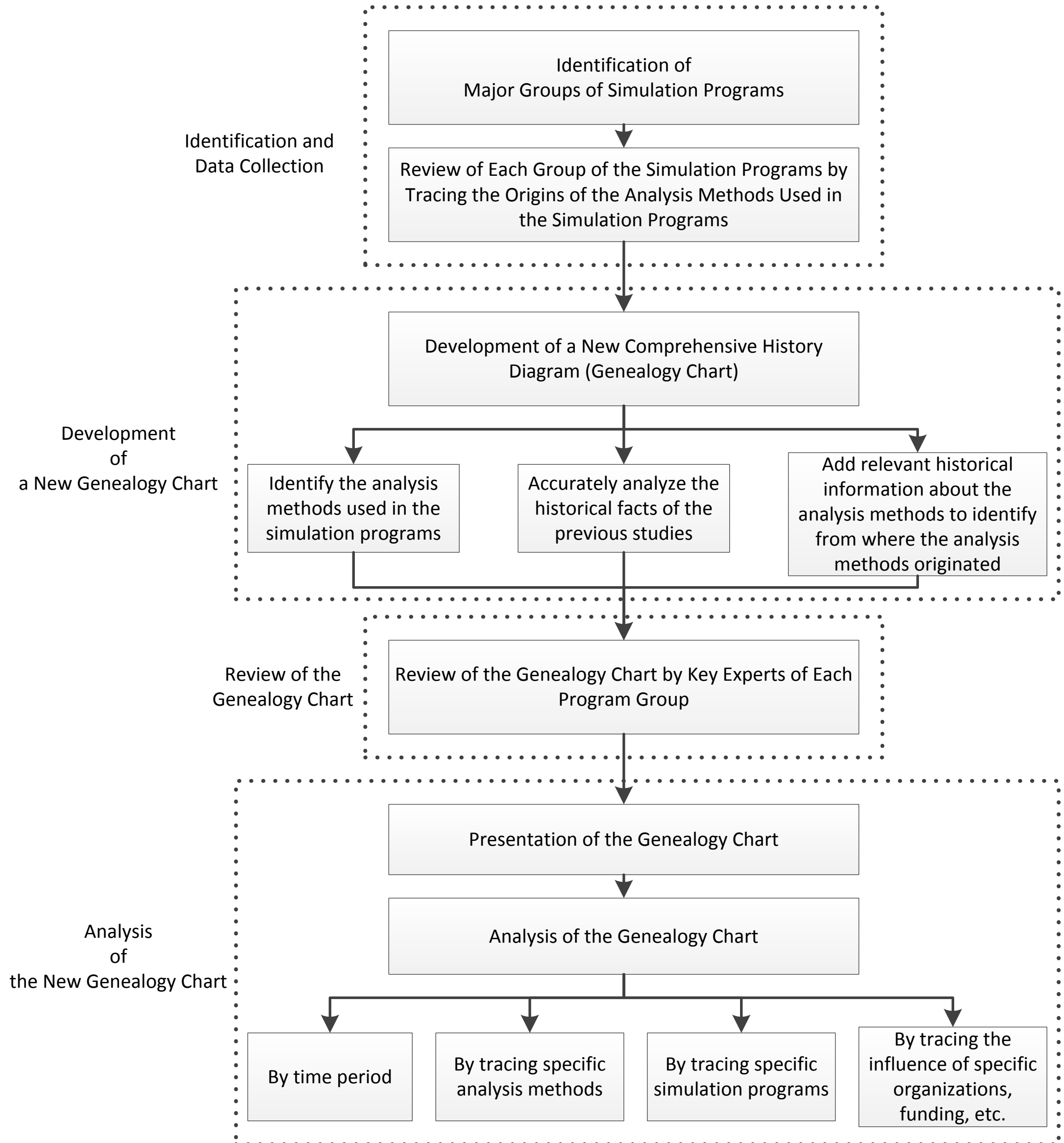


*Figure 3.1*. Procedures for developing and discussing the new comprehensive genealogy chart.

## 3.2 Identification of Major Groups of Simulation Programs

There are numerous simulation programs for analyzing high performance buildings (EERE, 2013a). These simulation programs can be categorized by three groups (i.e., whole-building analysis, solar energy analysis, and lighting and daylighting analysis) that are seen in Figure 3.2. These three groups were chosen primarily because of the different organizations that supported them. Some of the simulation programs appear in more than one group.

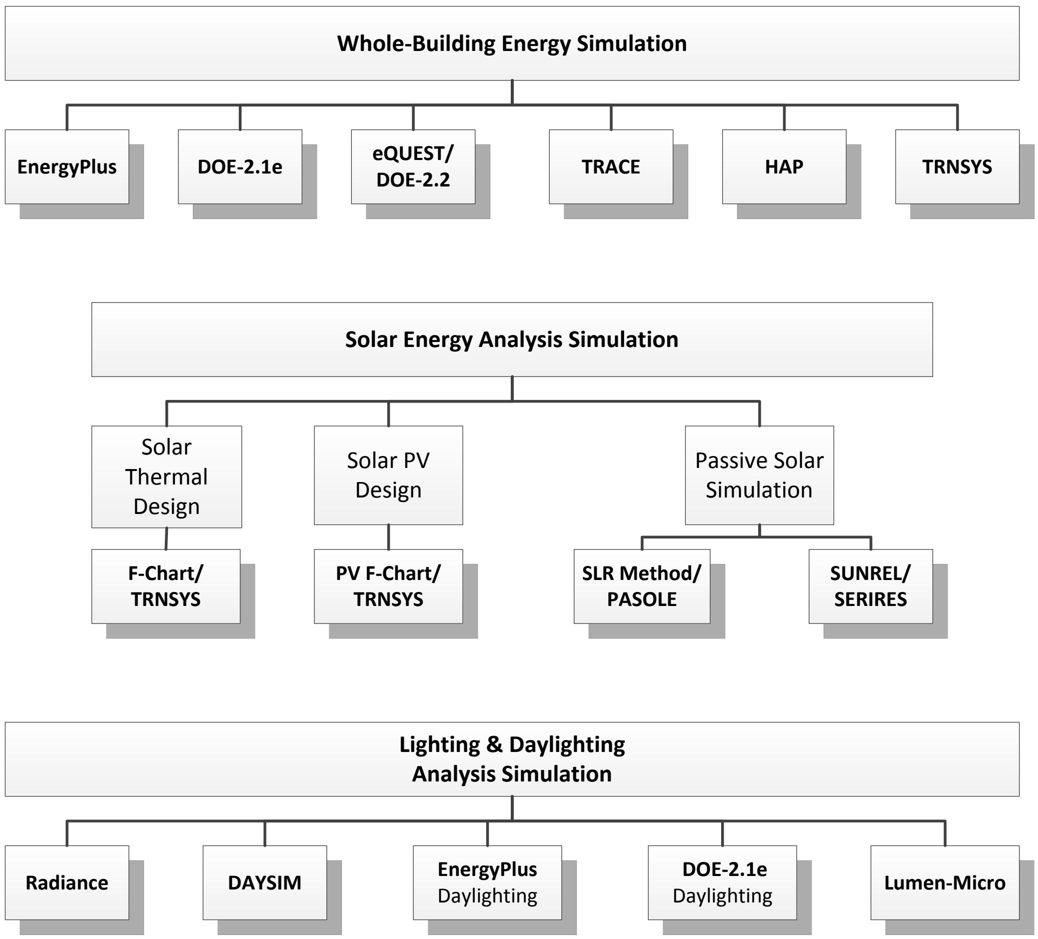


*Figure 3.2.* Three groups of simulation programs by different organizations.

The major U.S. organization that has contributed significantly to the development of whole-building energy simulation programs is the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). In addition to

ASHRAE, several national institutes such as the National Institute of Standards and Technology or NIST (formerly the National Bureau of Standards or NBS) and the U.S. Postal Service (USPS), national laboratories – the Lawrence Berkeley National Laboratory or LBNL (foremerly the Lawrence Berkeley Laboratory or LBL), Argonne National Laboratory (ANL), and Los Alamos National Laboratory or LANL (formerly Los Alamos Scientific Laboratory or LASL) contributed to the development of the whole-building energy simulation programs. Several consulatants and academic institutes also contributed the development. These include the Computational Consultants Bureau (CCB), GARD Analytics (formerly known as the General American Research Division (GARD) of the General American Transportation Corporation (GATX)), the University of Illinois at Urbana-Champaign (UIUC), and Oklahoma State University (OSU). The first symposium at the NBS in 1970 successfully continues to the present time as the IBPSA conference. Most of the financial support of the whole-building simulation development has come from the U. S. Department of Energy (US DOE).

The major U.S. contributors to the development of solar energy analysis programs include: the American Society of Mechanical Engineers (ASME) Solar Energy Division (SED) and the American Solar Energy Society (ASES) of the International Solar Energy Society (ISES). The US DOE financially supported the simulation development of solar energy systems since 1972. Several national laboratories and universities conducted studies for simulation development under the sponsorship of the US DOE. The national laboratories include LASL (now, LANL), the Solar Energy

Research Institute (SERI) (now, the National Renewable Energy Laboratory or NREL), and the Sandia National Laboratory (SNL). The universities include the University of Wisconsin-Madison (UWM) and Colorado State University (CSU).

The major U.S. contributor to the development of lighting and daylighting analysis programs is the Illuminating Engineering Society of North America (IESNA). The LBL (now LBNL) has been the major developer for lighting and daylighting simulations in the U.S. since 1976 when there was strong national interest for employing daylighting strategies into new energy efficient building design.

These three different groups appear to have worked separately due to their different stated objectives even though the end result contributed to integrated high performance building simulations. Therefore, the simulation programs in this study were classified by the three different groups. Six whole-building analysis simulation programs, four solar energy analysis programs, and five lighting and daylighting simulation programs were studied, and the results presented on the new chart.

### *3.2.1 Whole-building energy simulation programs*

In general, hourly whole-building analysis programs calculate all the hourly energy that is consumed or generated by an entire building over the period of one year. These whole-building simulation programs take into account the effects of weather, internal loads and occupants' energy-use patterns to calculate how different HVAC systems meet the heating and cooling loads. In this study, EnergyPlus (Crawley et al., 2001), DOE-2.1e (Winkelmann et al., 1993), eQUEST/DOE2.2 (Hirsch, 1998), TRACE

(Trane, 1992), HAP (Carrier, 2003), and TRNSYS (Klein et al., 1976) were studied as whole-building analysis simulation programs.

### *3.2.2 Solar energy simulation programs*

Solar energy can be used to heat air or water using various solar systems, or it can be used to generate electricity. In this study, the following types of solar energy design or simulation programs were studied: solar thermal, solar PV, and passive solar.

#### *3.2.2.1 Solar thermal design program*

Solar thermal simulation programs are used to analyze solar thermal systems such as active solar thermal systems (i.e., solar collectors and thermal storage units) and solar domestic hot water (SDHW) systems. In this study, one solar thermal design program, which is called the F-Chart program (Klein and Beckman, 2001a), was traced and analyzed. This program uses the F-Chart method, which was created by correlations of many simulation runs using TRNSYS, a simulation program (Klein et al., 1976).

#### *3.2.2.2 Solar Photovoltaic (PV) design program*

Solar PV, also called solar cells, converts sunlight (i.e., solar radiation) directly into electricity. The PV F-Chart program (Klein and Beckman, 2001b), which is based on the F-Chart method and Clark et al.'s method (Clark et al., 1984), can be used to evaluate the long-term performance of PV systems. This program was traced and analyzed as the solar PV design program in this study.

#### *3.2.2.3 Passive solar simulation program*

Passive solar houses use solar heating directly (i.e., without pumps, blowers, etc.) and sometimes include natural passive cooling. For example, solar direct gain, sunspaces, Trombe walls, and passive down-draft cooltowers[3] are passive solar strategies. SUNREL (Deru et al., 2002) currently can be used to calculate the effectiveness of different types of passive solar buildings. SUNREL based on SERIRES uses the solar geometry equations by McFarland in 1979 and the solar declination equation by Duffie and Beckman in 1991 (Deru et al., 2002). PASOLE, which was introduced in 1978, analyzes passive solar buildings. A correlation using results from over hundred simulation runs through PASOLE (i.e., the detailed simulation program) created the Solar Load Ratio (SLR) method, which is a method for estimating the required solar collector array size for space heating without active solar systems (Balcomb, 1992). In this study, these programs were traced and analyzed as passive solar simulation programs. In addition, the F-Chart program, previously classified as a solar thermal simulation program, can also be used to analyze selected passive solar systems, such as passive direct gain and a passive storage wall.

### *3.2.3 Lighting and daylighting simulation program*

Daylighting strategies use natural light to reduce the electricity loads of artificial electric lighting systems. A proper daylighting design can provide improved illumination for occupants and can reduce a building's energy use. Building orientation, window size, and shading (i.e., overhangs and fins) are used to calculate the lighting levels at specific points in a space. Such programs can also keep track of how much artificial lighting is

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[3] The passive down-draft cooltower uses the evaporation of water to cool the incoming air at the top of a tower (i.e., chimney). The incoming air, cooled by the evaporation effect, becomes heavier and falls down through the tower and cools inside of a building. This passive design has been applied to the visitor center of Zion National Park, designed by NREL (Torcellini, 2000).

needed to supplement the daylighting illumination to meet predetermined lighting levels. The simulation programs for lighting and daylighting analysis used in this study are DAYSIM (Reinhart and Herkel, 2000; Reinhart and Walkenhorst, 2001), Radiance (Ward, 1994), the daylighting model in EnergyPlus (i.e., DElight) (Crawley et al, 2001), the daylighting routines in DOE-2.1e (Winkelmann and Selkowitz, 1985), and the daylighting routines in Lumen Micro (DiLaura, 1982)[4].

***3.2.4 Scope and summary table of each simulation program***

In this study, the simulation programs in each group were selected based upon the following criteria: (a) the simulation program is widely used in the U.S., (b) the program and its documentation are publically available in English throughout the U.S., (c) the simulation program or a derivative of the program is still presently in use and supported, and (d) the analysis method used in the simulation program has made a large contribution toward the development of simulation (i.e., building thermal, solar thermal, solar PV, passive solar, or daylighting).

The features of each simulation program are summarized in Table 3.1. The authors and sponsoring agencies are also included in the table. The abstract column contains the capabilities and other features. The historical significance column provides a discussion of why the simulation program is important regarding the development of simulation programs of each area. This column also presents how a simulation program affects other simulation programs.

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[4] Information about the development of the lighting and daylighting simulation programs was reviewed based on Kota's doctoral proposal in 2011.

Table 3.1. *Characteristics of the programs in three major groups.*

| Category | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|
| Whole-Building Energy Simulation Program | EnergyPlus | Pedersen, C.O., Fisher, D.E., Liesen, R.J., Strand, R.K., & Taylor, R.D. (University of Illinois at Urbana-Champaign, UIUC), Buhl, W.F. & Winkelmann, F.C. (LBNL), Lawrie, L.K (U.S. Army Construction Engineering Research Laboratories, CERL), and Crawley, D.B. (US DOE) / US DOE | • Intro: Currently, the most actively studied whole-building simulation program in U.S. EnergyPlus incorporates the best features and capabilities of BLAST and DOE-2.<br>• Capabilities: whole-building analysis, including: heating and cooling loads, solar and daylighting analysis, HVAC equipment, and economic analysis. Also, additional analysis, including: multizone airflow, fuel cells, and water management.<br>• Other: The structures of EnergyPlus are adjusted for third-party developers to promote the development of new simulation modules or user interfaces of EnergyPlus. | EnergyPlus is the newest whole-building energy simulation program sponsored by US DOE. EnergyPlus has improved features from the previous building simulation programs, which were discussed in the community of the building simulation specialists. EnergyPlus has optimized the features and capabilities of several previous programs, including BLAST and DOE-2. |
| | DOE-2.1e | Birdsall, B.E., Buhl, W.F., Ellington, K.L., Erdem, A.E., Winkelmann, F.C., & Rosenfeld, A.H. (NBNL), Hunn, B.D. (Los Alamos Scientific Laboratory (LASL), now Los Alamos National Laboratory, (LANL), Hirsch, J.J., & Gates, S.D. (James J. Hirsch and Associates (JJH)), Roschke, M.A., Cumali, Z.O, Graven, R.M., Lokmanhekim, M., , Davis, P.K., Kaganove, J.J., & Smith, R.L. / US DOE | • Intro: The most actively used public domain program before EnergyPlus. DOE-2.1e can analyze hourly building loads, energy use, and operating cost. Energy saving measures can be determined by using DOE-2.1e.<br>• Capabilities: whole-building analysis, including: heating and cooling loads, daylighting analysis, HVAC equipment, and economic analysis.<br>• Other: This program is used to develop code-compliant simulation certified by the Residential Energy Services Network (RESNET). | DOE-2.1e was the main public domain program of the US DOE before EnergyPlus. Many national laboratories and academic institutes developed DOE-2 to become a refined and comprehensive simulation program. This program has significantly contributed to the development of the energy saving standards and the design and analysis of buildings. |

Table 3.1. *Continued*

| Category | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|
| Whole-Building Energy Simulation Program | eQUEST/ DOE-2.2 | eQuest: James J. Hirsch and Associates (JJH) / non-Government funding<br><br>DOE-2.2: Simulation Research Group at LBNL & James J. Hirsch and Associates (JJH) / US DOE, the Electric Power Research Institute (EPRI), & JJH | • Intro: The most widely used whole-building simulation program that has a user-friendly graphical user interface including a building creation wizard, 3D building geometry display, a graphical HVAC layout, and graphical simulation results.<br>• Capabilities: whole-building analysis, including: heating and cooling loads, solar and daylighting analysis, HVAC equipment, and economic analysis.<br>• Other: The simulation engine of eQUEST is DOE 2.2 developed from the DOE 2.1e version 087, which was released in 1995. This DOE 2.2 engine analyzes window, lighting, and HVAC systems more accurately and flexibly than the DOE 2.1e version 087. | eQUEST is the proprietary version of DOE-2.1e, owned by JJH, developed in 1999. eQUEST is only an existing version of DOE-2 series. This program uses DOE 2.2 developed from the DOE 2.1e version 087, which was released in 1995. DOE 2.1e has not been worked on since 2003. |
| | TRNSYS | Klein, S. A., Beckman, W. A., & Duffie, S. A. (Solar Energy Laboratory, Univ. of Wisconsin-Madison) / US DOE | • Intro: Flexible, modular simulation program that has a library of models of system components written as FORTRAN subroutines. A module includes algebraic or differential equations that can be modified by users.<br>• Capabilities: whole-building analysis, including HVAC analysis and sizing, multizone airflow, electric power simulation, solar design, building thermal performance, and analysis of control schemes.<br>• Other: TRNSYS was used to develop the F-Chart method and PV F-Chart method. | TRNSYS is a widely used modular or component-based program since 1975. This program has made a major contribution to building energy simulation programs, solar thermal simulations, and PV analysis. |
| | TRACE | Trane Company | • Intro: Load and energy calculation program by the Trane company.<br>• Capabilities: TRACE can evaluate several alternatives to save building energy, including: building envelopes, HVAC systems and equipment, and economic combinations.<br>• Other: TRACE provides the choice of eight cooling load methods and the algorithms developed by ASHRAE. | A proprietary program for load and energy calculations since 1980. |

Table 3.1. *Continued*

| Category | | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|---|
| Whole-Building Energy Simulation Program | | HAP | Carrier Company | • Intro: Hourly analysis program by the Carrier company.<br>• Capabilities: HAP can calculate building loads and system sizes.<br>• Other: HAP uses ASHRAE's Transfer Function Method (TFM) for thermal loads and the System-Based Design concept, which is based on ASHRAE's Heat Extraction Method, for system sizes. Graphical user interface is used. | A proprietary program for load and energy calculations since 1980. |
| Solar Energy Analysis Simulation or Design Program | Solar Thermal Analysis | F-CHART / TRNSYS | Klein, S. A. & Beckman, W. A. (Solar Energy Laboratory, Univ. of Wisconsin-Madison) | • Intro: Comprehensive solar system analysis and design program.<br>• Capabilities: The system options contain: water and building storage heating, domestic hot water, integral collector-storage DHW, passive direct-gain, passive collector-storage wall, pebble bed storage heating, indoor and outdoor pool heating. The collector options include flat-plates, evacuated types, compound parabolic concentrating (CPC) collectors, and 1or 2 axis tracking types. F-CHART also provides thermal performance and economic analysis.<br>• Other: F-Chart uses utilizability methods to analyze active solar heating systems and un-utilizability method to estimate passive direct-gain systems and storage wall systems. | Proven long-term analysis program for active and passive solar systems. The analysis method of this program originated from Whillier in1953. |
| | Solar PV Analysis | PV F-CHART / TRNSYS | Klein, S. A. & Beckman, W. A. (Solar Energy Laboratory, Univ. of Wisconsin-Madison) | • Intro: Comprehensive photovoltaic (PV) system analysis and design program.<br>• Capabilities: PV F-CHART analyzes: monthly estimates of utility interface systems, battery storage systems, and stand-alone systems. The tracking options include fixed, 1or 2 axis tracking, and concentrators. Also, it provides economic analysis.<br>• Other: PV F-CHART uses utilizability methods to estimate the weather variation effect regarding the long-term average performance of PV systems. | Proved long-term analysis program for PV systems. The analysis method of this program originated from Whillier in1953. |

Table 3.1. *Continued*

| Category | | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|---|
| Solar Energy Analysis Simulation or Design Program | Passive Solar Analysis | Solar Load Ratio (SLR) Method / PASOLE | PASOLE: McFarland, R. D. (LASL (now LANL))<br><br>SLR Method: Balcomb, J. D., & McFarland, R. D. (LASL (now LANL)) | • Intro: A research program that incorporates a thermal network solution by specifying nodes that represent finite regions.<br>• Capabilities: PASOLE analyzes passive solar heated structures and contains models and algorithms for calculating solar sources in a general framework. Provides simulation support for a design method related to passive solar heating.<br>• Other: SLR method uses a simplified monthly calculation procedure depending on correlations that are the ratio of solar gain to building load. The correlations are results from thousands of hourly simulations developed at LASL (i.e., PASOLE). | SLR method is a widely-used method to calculate passive solar buildings since 1978. PASOLE was used to provide the correlation parameters of the SLR method. |
| | | SUNREL | National Renewable Energy Laboratory (NREL) | • Intro: The whole-building simulation program, most suitable for passive solar buildings.<br>• Capabilities: SUNREL contains modeling of moveable insulation, interior shading control, Trombe walls, water walls, advanced glazings, schedulable window shading, active-charge/passive-discharge thermal storage, phase change materials, and natural ventilation.<br>• Other: SUNREL is used for the building physics and mathematics engine in Targeted Retrofit Energy Analysis Tool (TREAT), developed for single and multifamily building analysis software. | SUNREL is the upgraded version of SERIRES developed by SERI (now NREL) in 1983. Currently used program for passive solar strategies. |

Table 3.1. *Continued*

| Category | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|
| Lighting & Daylighting Analysis Simulation Program | Radiance | Ward, G. J. / LBNL | • Intro: Advanced and accurate lighting and daylighting simulation program based on the ray-tracing method.<br>• Capabilities: Radiance can predict illumination and visual environment using a synthetic imaging system. Calculates spectral radiance and spectral irradiance values.<br>• Other: Radiance can be used for other building simulation programs as a simulation engine in order to estimate architectural lighting and daylighting. | Radiance uses a more accurate method (i.e., the ray-tracing method) than the widely used method (i.e., the radiosity method) to analyze illumination parameters. This program was developed in 1988. |
| | DAYSIM | Reinhart, C. / National Research Council (NRC) and Fraunhofer Institute for Solar Energy Systems | • Intro: This program uses algorithms of Radiance and the daylight coefficients approach.<br>• Capabilities: DAYSIM can analyze the annual daylight metrics: such as daylight autonomy (DA) and useful daylight illuminance (UDI) for calculating annual glare and supplemental electric lighting energy use.<br>• Other: DAYSIM provides occupancy, electric lighting, and shading device hourly schedule, which can be used for an integrated lighting-thermal simulation of the whole-building energy simulation programs. | Radiance-based program for estimating annual lighting and daylighting illuminance distribution. This program was developed in 1998. |
| | EnergyPlus Daylighting | Winkelmann, F. C., Modest, M., & Selkowitz, S / LBNL | • Intro: The daylighting model and DElight (i.e., an alternative daylighting model) of EnergyPlus provide lighting and daylighting analysis.<br>• Capabilities: These two methods are combined with thermal loads and HVAC analysis like the DOE-2 program, so these methods can assess building energy use by daylighting strategies.<br>• Other: The daylighting model of EnergyPlus uses three calculation steps based on the DOE-2 program, which uses the split-flux method for inter-reflected light. DElight of EnergyPlus uses the radiosity method to calculate inter-reflected light. | Daylighting analysis was included in the first official EnergyPlus version in 2001. This program can estimate building energy use by daylighting strategies because EnergyPlus is a whole-building energy simulation program. |

Table 3.1. *Continued*

| Category | Program Name | Author / Sponsoring Agency | Abstract | Historical Significance |
|---|---|---|---|---|
| Lighting & Daylighting Analysis Simulation Program | DOE-2 Daylighting | Winkelmann, F. C. / LBNL | • Intro: The daylighting simulation model of DOE-2 is combined with thermal loads and HVAC analysis.<br>• Capabilities: This model can estimate building energy consumption by daylighting designs.<br>• Other: This daylighting calculation model, which uses the split-flux method for inter-reflected light, contributed to the daylighting calculation of EnergyPlus. | Daylighting analysis was included in the DOE-2 version of 1982. This program is also a whole-building simulation program, then the daylighting analysis for building energy use is possible. |
| | Lumen Micro | DiLaura, D. / Lighting Technologies, Inc. | • Intro: Widely used program to design and analyze electric lighting and daylighting.<br>• Capabilities:Lumen Micro provides numerical data and several display options.<br>• Other: Lumen Micro first added a daylighting analysis in the late 1980s. A radiosity approach is used in this program. | Widely used design program for lighting and daylighting. The original program was developed in 1968. |

In general, many of the authors are staff at the national laboratories, and they were sponsored by the U.S. DOE. The development of most of simulation programs began around or just before 1970 or 1980.

### 3.3 Review of Each Group of the Simulation Programs by Tracing the Origins of the Analysis Methods Used in the Simulation Programs

Fifteen studies that discussed whole-building energy simulations were reviewed. Five history diagrams were provided among the fifteen studies. Four pieces of literature (i.e., EPRI report in 1979, Proceedings of the building energy simulation conference in 1985, and Haberl and Cho’s reports in 2004a, 2004b) covered the history of solar system simulations. Two reports contained history diagrams of the solar energy simulations (i.e., Haberl and Cho's reports in 2004a, 2004b). Only one of the previous papers included a history diagram of lighting and daylighting simulation programs (i.e., Kota and Haberl's report in 2009).

Unfortunately, the previous studies and diagrams did not provide the connections between the analysis methods and the simulation programs. Therefore, there is a need for a more comprehensive and improved history diagram, which includes origins and brief explanations of the important analysis methods in the simulation programs for whole-building, solar PV, active solar, passive solar, lighting and daylighting simulation programs. In addition, none of diagrams have been updated since the studies were written. The limitations could be resolved by analyzing the original references cited in all the previous studies as well as the new published studies.

### 3.4 Development of a New Comprehensive History Diagram

After analyzing the original references cited in all the previous studies, a new comprehensive history diagram was created. This new diagram included the three different groups of simulation programs and included key analysis methods and their authors as well as institutions. In order to display all the information in this new diagram, the diagram was oriented horizontally, running across several pages. In this new diagram, special attention has been paid to connect the analysis methods to the simulation programs that codified the original analysis methods.

#### *3.4.1 Identify the analysis methods used in the simulation programs*

Several analysis methods are used in today's whole-building energy, solar energy, and lighting and daylighting simulation programs. Table 3.2 indicates which analysis methods were traced in this study. The primary types of analysis methods can be categorized by the type of building parameters. Therefore, this table was designed to aid in describing the new comprehensive history diagram. In this study, a selection of the primary analysis methods was chosen for analyzing the origins of the simulation programs.

Table 3.2. *Analysis methods of the simulation programs.*

| Group | Selected Parameter | Analysis Method | Program Name |
|---|---|---|---|
| Whole-Building Energy Simulation Program | Zone Thermal Loads | Heat Balance Method | EnergyPlus |
| | | Weighting Factor Method | DOE-2.1e |
| | | Weighting Factor Method | eQUEST/DOE-2.2 |
| | | Finite-Difference and Network Approach / Heat Balance Method | TRNSYS |
| | | Weighting Factor Method, Cooling Load Temperature Difference / Cooling Load Factor Method, Total Equivalent Temperature Differential / Time Averaging Method, or Radiant Time Series Method | TRACE |
| | | Weighting Factor Method | HAP |
| Solar Energy Analysis Program | Solar Heating Load Performance | Utilizability Method, Un-Utilizability Method, and F-Chart Method | F-CHART / TRNSYS |
| | | Utilizability Method and PV Design Method | PV F-CHART / TRNSYS |
| | | Thermal Network Method | SLR Method / PASOLE |
| | | Thermal Network Method | SUNREL |
| Lighting & Daylighting Analysis Simulation Program | Internal Reflected Component | Ray-Tracing Method | Radiance |
| | | Ray-Tracing Method | DAYSIM |
| | | Split-Flux Method or Radiosity Method | EnergyPlus Daylighting Module |
| | | Split-Flux Method | DOE-2 Daylighting Model |
| | | Radiosity Method | Lumen Micro |

The different analysis methods for calculating the zonal thermal loads used in the whole-building energy simulation programs are the Heat Balance method, the Weighting Factor Method, the Cooling Load Temperature Difference/Cooling Load Factor Method, the Total Equivalent Temperature Difference/Time Averaging Method, or the Radiant Time Series Method. The analysis methods for estimating the solar heating load performance used in the solar energy analysis programs are the Utilizability Method, the Un-utilizability Method, the F-Chart Method, the PV Design Method, or the Thermal Network Method. The internal reflected component analysis methods for the lighting and daylighting analysis programs are the Ray-Tracing Method, the Radiosity Method, or the Split-Flux Method.

***3.4.2 Accurately analyze the historical facts of the previous studies***

In general, the previous literature did not accurately express the contributors that developed the analysis methods used in the simulation programs. In addition, several of the previous papers had errors or discrepancies regarding selected historical origins of the simulation programs and their analysis methods. In this study the errors contained in the previous history studies were identified by studying the literature referenced in the simulation manuals or listed in other historical papers. Therefore, the new comprehensive history diagram presents a more comprehensive history diagram that expresses the contributors and corrects the previous errors.

### *3.4.3 Add relevant historical information about the analysis methods to identify from where the analysis methods originated*

In most cases, in the previous history diagrams, no explanation was provided about the source of the analysis methods used in the simulation programs. In order to find the connections between the analysis methods and the simulation programs, several sources were studied including the simulation program manuals and personal communications.

## 3.5 Review of the New Comprehensive Genealogy Chart by Key Experts of Each Program Group

The new comprehensive genealogy chart was reviewed by the experts in each program area: the whole-building energy simulation, solar energy analysis simulation or design, and lighting and daylighting analysis simulation programs.

The reviewers of the new chart include: Zulfikar O. Cumali, Edward F. Sowell, Dennis R. Landsberg, and Larry O. Degelman, who reviewed the whole-building simulations part of the genealogy chart; Juan-Carlos Baltazar-Cervantes who reviewed the solar energy analysis part of the chart; and Richard R. Perez who reviewed the lighting and daylighting analysis part of the chart. The expert review of the diagram found some errors in the original chart and provided useful information for the final chart. Table 3.3 shows the list of reviewers.

Table 3.3. *List of reviewers.*

| Group | Reviewer | Organization | Expertise |
|---|---|---|---|
| Whole-Building Energy Simulation | Zulfikar O. Cumali | President at Computation Consultants Bureau (CCB), now President at Optens, LLC | Weighting Factor Method used in DOE-2.1e |
| | Edward F. Sowell | Emeritus of Computer Science and Mechanical Engineering at California State University, Fullerton | Analysis Methods used in DOE-2.1e |
| | Dennis R. Landsberg | President at L&S Energy Services, Inc. | Whole-Building Simulation Programs developed in the 1980s |
| | Larry O. Degelman | Emeritus of Architecture at Texas A&M University | Whole-Building Simulation Programs developed in the 1980s. |
| | Daniel E. Fisher | Professor at Oklahoma State University | Cooling Load Calculation Procedure used in EnergyPlus |
| Solar Energy Simulation | Juan-Carlos Baltazar-Cervantes | Manager of the Energy Analysis Group at Energy Systems Laboratory | Solar Energy Simulation Programs |
| Lighting and Daylighting Simulation | Richard R. Perez | Professor at State University of New York at Albany | Sky Models used in Lighting & Daylighting Simulation Programs |

## 3.6 Presentation and Analysis of the New Comprehensive History Diagram (Genealogy Chart)

The new comprehensive genealogy chart developed in this study was analyzed by the following four sections: time period, analysis method, simulation program, and organization or support funding.

### *3.6.1 Discuss the new simulation genealogy chart by time period*

In this analysis, the simulation genealogy chart was examined according to the time period. In general, each time period spans 10 years, exclusive of the pre-1950 period. This discussion includes relevant background or events when the simulation programs were being developed.

### *3.6.2 Discuss the new simulation genealogy chart by tracing specific analysis method*

All simulation programs have specific analysis methods. For example, the whole-building analysis simulation programs have analysis methods for calculating the dynamic hourly heat transfer through multilayer walls and for calculating the zonal heating and cooling loads. In this section, the simulation genealogy chart was traced according to the key analysis methods used in the simulation programs, which were discussed in Section 3.4.1.

### *3.6.3 Discuss the new simulation genealogy chart by tracing specific simulation programs*

In this section, the simulation genealogy chart was analyzed by tracing the roots of each simulation program. In the chart, 15 computer programs that are currently in use were analyzed.

### *3.6.4 Discuss the new simulation genealogy chart by tracing the influence of specific organizations or support funding*

In this section, the simulation genealogy chart was analyzed by tracing the influence of the organizations which funded the development of the simulation programs. The organizations were classified by three different groups mentioned in Section 3.2, which include: whole-building analysis, solar energy analysis, and lighting and daylighting analysis.

## 3.7 Summary of Methodology

This chapter has presented the methodology to be used to discuss and analyze the new comprehensive simulation history diagram (i.e., simulation genealogy chart). To accomplish this, four tasks were conducted as follows: 1) Identification of different groups of simulation programs, 2) Review of each group of the simulation programs by tracing the origins of the analysis methods used in the simulation programs, 3) Development of the new comprehensive simulation genealogy chart, and 4) Analysis of the new simulation genealogy chart. The results of these procedures will be discussed in Chapter IV.

# CHAPTER IV

# RESULTS

This chapter explains the results of this study in three sections, using the methodology discussed in Chapter III. Section 4.1 describes the new comprehensive genealogy chart, and includes the significance of both the horizontal and vertical axes in the chart as well as the components of the chart. Section 4.2 presents the four approaches to most effectively use the chart.

## 4.1 Description of the New Comprehensive Genealogy Chart

The new comprehensive genealogy chart was created based on the methodology described in Chapter III. This chart was designed to help readers better understand the origins of the analysis methods in the simulation programs used for high performance commercial buildings. Detailed discussion about this chart (i.e., by time period, by analysis method, by simulation program, and by organization) will be included in Chapter V. In this chapter, the general features of the new chart are described. This chart is horizontally oriented to include as much information as possible, which currently measures eight pages in length. Each page is presented in Figure A.2 in Appendix A. A legend of the genealogy chart is presented in Figure A.1.

### *4.1.1 Features of the genealogy chart*

In the new genealogy chart, there are connections drawn between the analysis methods used in the simulation programs and the simulation programs. The connections are an important feature in this study because this feature can help resolve some of the problems found from the previous literature reviewed in Chapter II. In order to better understand this chart, Table 4.1 shows the eight components of the chart.

Table 4.1. *Components of the new comprehensive genealogy chart.*

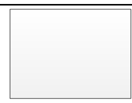
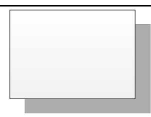
| Component | Description |
|---|---|
|  | An arrow indicates connections between boxes that contain events related to analysis methods or simulation programs. In some cases, two or three boxes affect only one box. The box connected to the starting point of an arrow is affected by the box at the end point of an arrow. |
|  | A box contains an event connected to analysis methods, which happened in one year. Such boxes will be called event boxes. |
|  | A shaded box contains an event related to simulation programs other than analysis methods, which happened in one year. Such a box will be called a shaded event box. |
|  | Time periods from 1950 to the present are divided into individual years by the dashed vertical lines. In the years prior to 1950, the dashed line signifies a period of ten years. |
|  | A small, rounded box marks the abbreviation of an organization that contributed to the development of an analysis method or a simulation program. The rounded box is usually located on the bottom left of the event or shaded event box of the chart. A legend of the genealogy chart explains the abbreviations in Figure A.1. |
|  | A small, rectangular box indicates the abbreviation of an analysis method. A small box is usually located on the bottom right of the event or shaded event box of the chart. Readers can easily know which event or shaded event box contains which analysis method using the small box. A legend of the genealogy chart explains the abbreviation in Figure A.1. |
|  | A dashed box is the indicator of an event box in the next page or previous page. This dashed box, which shows the year and author of the next or previous event box, is located at the start or end of the arrowed line in each page. |
|  | A diamond box represents the legend for the analysis methods for lighting and daylighting simulation. The number inside a diamond box distinguishes the legend classification as followings: 1. Graphical methods, 2. Geometrical instruments, 3. Sky models, 4. Mathematical formulae, 5. Computer graphic techniques, 6. Daylight analysis tools; and 7. Tools that can calculate the impact of daylighting strategies on energy consumption of buildings. |

Table 4.1 *Continued*

| Component | Description |
|---|---|
|  | A big, rounded box marks an analysis method or simulation program that does not meet the criteria used in this study. In some cases, this box is used for indicating an important historical event. |

Each component will be described in detail from Section 4.1.2 to 4.1.4. The small, rectangular boxes located on the bottom right of the event boxes allow readers to quickly determine which simulation program uses which analysis methods by following the solid arrow that connects the event box with the shaded event box.

### *4.1.2 Description of the horizontal axis of the chart*

The horizontal axis of each page of the chart presents a time period of ten years, exclusive of pre-1950 entries. The pre-1950 selection contains the origins of the development of the time period in one page of the chart since there were very few events during this period of more than 50 years.

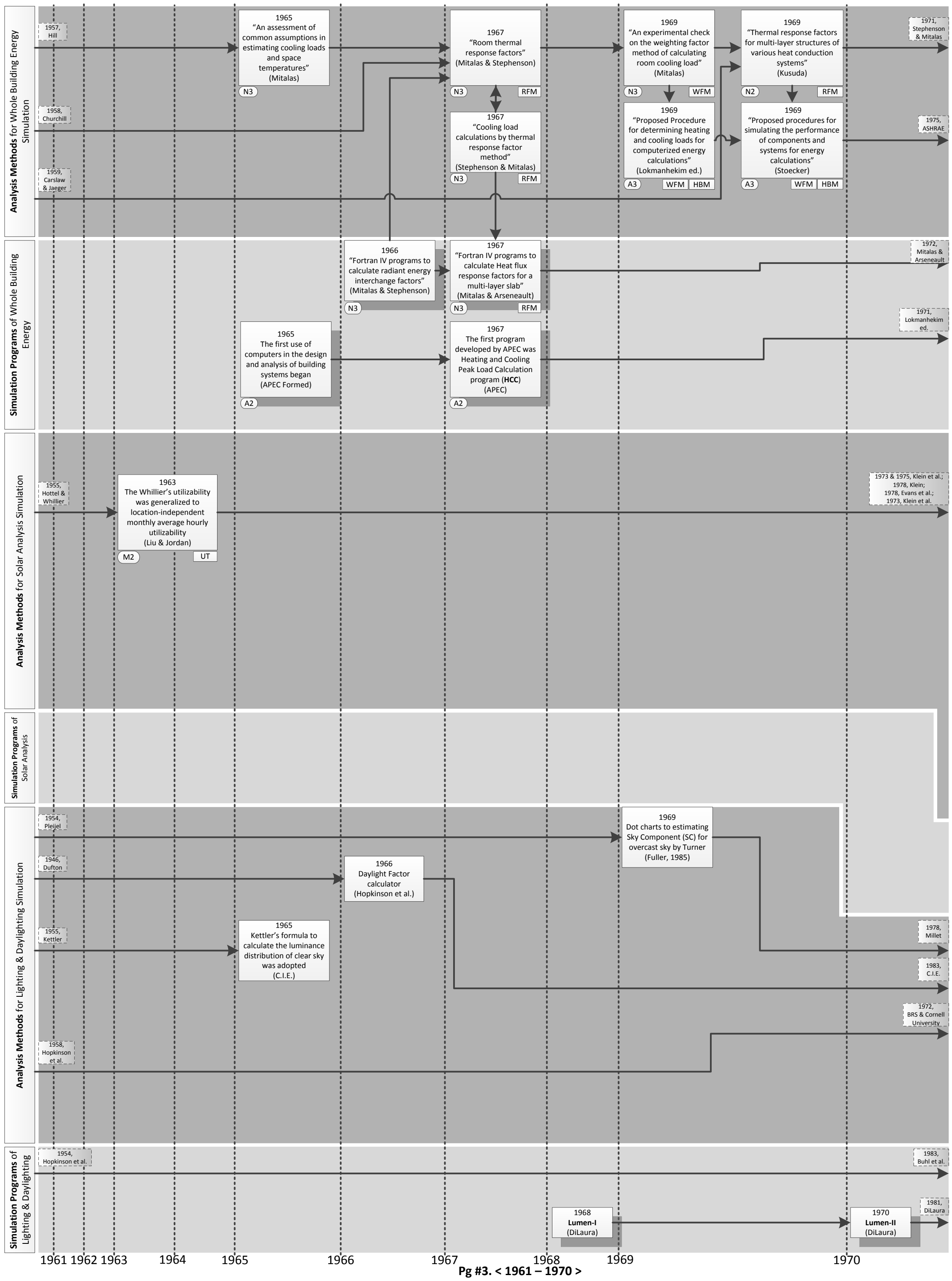



*Figure 4.1*. Example: 1961-1970 selection of the new comprehensive genealogy chart.

Figure 4.1 shows an example section of the chart from 1961 to 1970. Each year of the horizontal axis has a vertical dashed line. The distance between two vertical dashed lines is not to scale. The distance varies by the length of space required for the explanations in the boxes contained in a given year. The dashed line for each year is to the left of each event or shaded event boxes to divide the boxes into years.

### *4.1.3 Description of the vertical axis of the chart*

The vertical axis of the chart is divided into groups according to the selected simulation programs and the analysis methods used in each. In the current version of the chart, the vertical axis for the whole chart is divided into six areas.

The six titles of the vertical axes are (starting at the top of the chart): analysis methods for whole-building energy simulation, simulation programs of whole-building energy; analysis methods for solar analysis simulation, simulation programs of solar analysis; and analysis methods for lighting and daylighting, simulation programs of lighting and daylighting.

### *4.1.4 Description of shaded areas of the chart*

Each of the three groups is divided into two shaded areas along the horizontal axis: the top area for the analysis methods and the bottom area for simulation programs. The areas indicating the analysis methods are darker shaded, and the areas indicating the simulation programs are lighter shaded. Figure 4.2 shows a portion of the chart showing the two shaded areas of whole-building energy simulation.

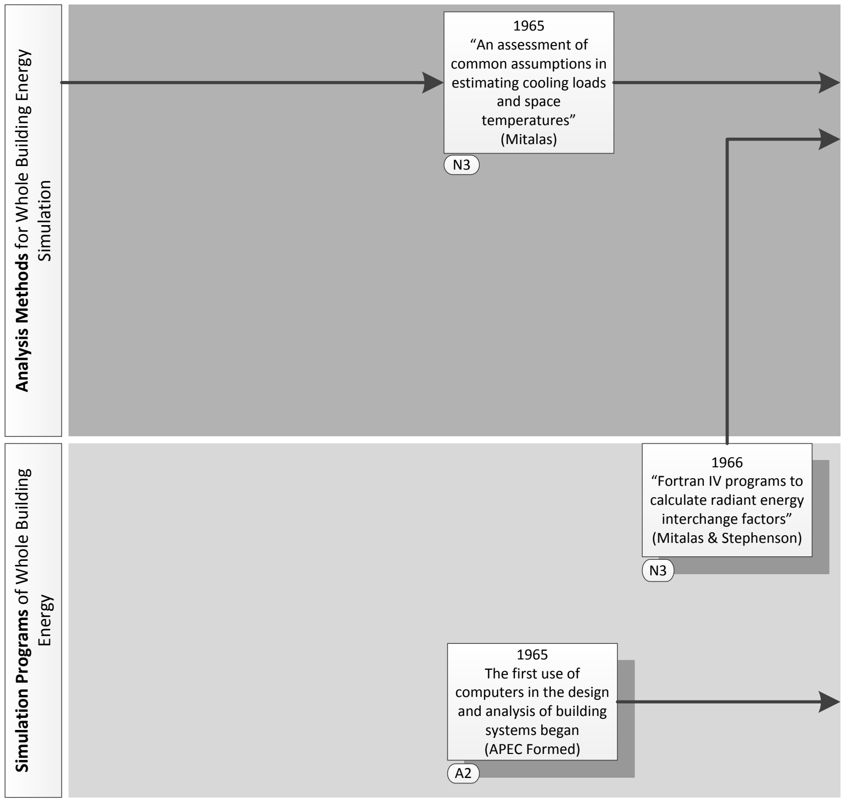



*Figure 4.2.* Example: a portion of the chart showing the two shaded areas of whole building energy simulation.

The shaded event boxes have shadows to clearly indicate that these boxes explain simulation programs. The sizes of the shaded areas are dependent on the number of the event boxes during each period. The event or the shaded event boxes in the chart may have a small rounded box, a small rectangular box, or both types at the bottom of the event boxes. The explanations of the small boxes are included in Table 4.1.

In the case of Figure 4.2, the event box in the dark area (i.e., the analysis method section) indicates Mitalas evaluated the assumptions for cooling load calculations in 1965. Mitalas was a researcher at N3 (i.e., National Research Council Canada). This study was related to RFM (i.e., response factor method). The shaded event boxes in the light area (i.e., the simulation program section) indicate that the Automated Procedures for Energy Consultants (APEC) started to use digital computers for designing and analyzing building systems in 1965. In addition, in 1966, Mitalas and Stephenson, who were researchers at N3, developed Fortran IV programs to calculate interchange factors of radiant energy.

Figure 4.3 shows one example of an event box that has both a small, rounded box and a small, rectangular box at the bottom.

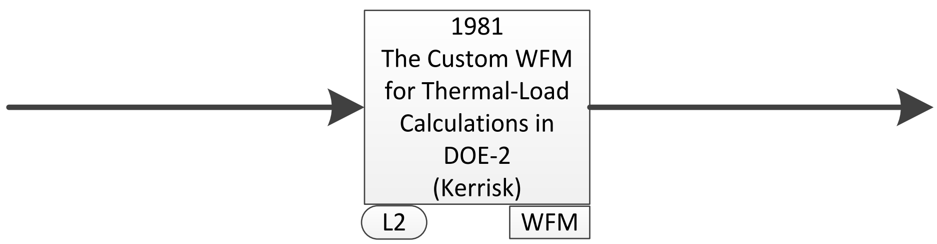



*Figure 4.3.* Example: small, rounded and rectangular boxes at the bottom of the event box.

The small, rounded box in the lower left is labeled L2 to indicate Los Alamos Scientific Laboratory or LASL (now Los Alamos National Laboratory or LANL). The small, rectangular box at the lower right indicates Weighting Factor Method (WFM).

Figure 4.4 shows an arrow that connects two event boxes. The arrow between event boxes indicates that the events, which are explained in the boxes, are related to each other.


*Figure 4.4.* Example: event boxes connected by a line with an arrow.

The event box connected to the left side of the arrow affects the event box at the right of the arrow. For example, Hottel and Whillier's study of 1955 was based on Whillier's study conducted in 1953.

Figure 4.5 shows dashed boxes. In the case that an arrow is continued on to the next page, a dashed box is used to indicate which event box it will be connected to. A left dashed box indicates an event box from the previous page, and a right dashed box identifies an event box of the next page.

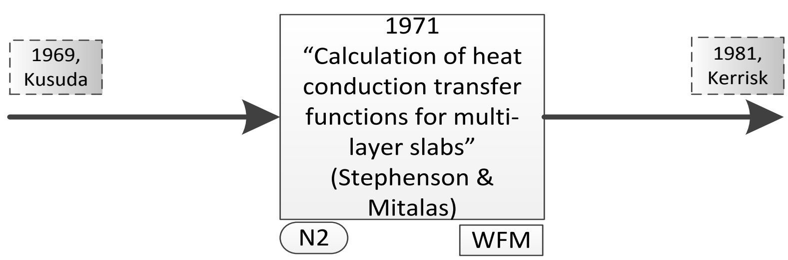



*Figure 4.5.* Example: dashed boxes on the arrow lines.

In Figure 4.5, Stephenson and Mitalas's study in 1971 shows the connections with Kusuda's study in 1969 that was described in the previous page and Kerrisk's study in 1981 that was described in the next page.

Figure 4.6 shows the example of a diamond-shaped box. A diamond-shaped box with a number signifies the classification of the analysis methods for lighting and daylighting simulation.

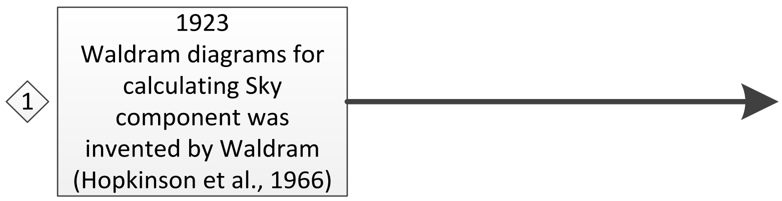



*Figure 4.6.* Example: a diamond box with a number on the left of the event box.

The number inside the diamond box is categorized as follows: 1. Graphical methods; 2. Geometrical instruments; 3. Sky models; 4. Mathematical Formulae; 5. Computer graphic techniques; 6. Daylight analysis tools; and 7. Tools that can calculate the impact of daylighting strategies on energy consumption of buildings. These categories were based on Kota and Haberl's classification (Kota and Haberl, 2009). In Figure 4.6, the diamond box with number one indicates Waldram's diagram developed in 1923 was one of graphical methods.

Figure 4.7 shows an example of a big, rounded box.

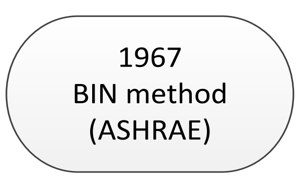



*Figure 4.7.* Example: a big, rounded box.

An example of a big, rounded box indicates an analysis method or simulation program that does not meet the criteria used in the scope of this study. The criteria are: (a) the simulation program is widely used in the U.S., (b) the program and its documentation are available in the U.S. in English, (c) the simulation program or a derivative of the program is still presently in use and supported, and (d) the analysis method used in the simulation program has made a large contribution toward the development of simulation in this area. In Figure 4.7, for example, the BIN method introduced by ASHRAE in 1967 is not presently in use and supported for simulation.

#### ***4.1.5 Errors or discrepancies found from the previous studies or previous history diagrams***

Some of the historical facts from previous studies or previous history diagrams have errors or discrepancies. Table 4.2 shows several of the errors or discrepancies found from the previous studies.

Table 4.2. *Errors or discrepancies from the previous studies.*

| Title | Year | Author | Inaccurate Information | Corrected Information | Reference Used for Correction |
|---|---|---|---|---|---|
| Early history and future prospects of building system simulation | 1999 | Kusuda, T. | APEC developed HCC using the True Mean Temperature Difference (TMTD) method. | APEC developed HCC using the Total Equivalent Temperature Differential (TETD) / Time Averaging (TA) method. | Ayres, J. M. and Stamper, E., 1995 |
| | | | Gas Application to Total Energy (GATE) | The gas industry established the Group to Advance Total Energy (GATE) | Ayres, J. M. and Stamper, E., 1995 |
| Historical Development of Building Energy Calculations | 1995 | Ayres & Stamper | NECAP renamed CAL-ERDA | The Systems program of CAL-ERDA utilized the equations of the ASHRAE algorithms and the NECAP program (i.e., NASA's Energy Cost Analysis Program) for developing the simulation procedure. | Graven and Hirsch, 1977/ Cumali, 2012 |
| State-of-the-art review of whole building, building envelope, and HVAC component and system simulation and design tools. | 2002 | Jacobs & Henderson | HAP is only available as a DOS program (version 3.2) while Trane just recently (March 2001) introduced the full MS Windows version of TRACE 700 that does calculations for 8,760 hours (Jacobs and Henderson). | In 1999, HAP Version 4.0 was released as a MS Windows version. | Carrier, 2013/ Farzad, 2012 |

The incorrect information was modified using the cited references show in Table 4.2. Some of the errors were found in the history diagrams of the previous studies. Others were located during the review of the report or the review from the experts as described in Section 3.5. Both cases were corrected and the corrected version is reflected in the new chart.

## 4.2 Four Methods to Utilize the New Comprehensive Genealogy Chart

This section describes four approaches or methods to effectively utilize the new comprehensive genealogy chart. The approaches are divided by time period, analysis method, simulation program, and organization or funding source.

### *4.2.1 Analysis by time period*

The analysis by time period helps readers understand when the simulation programs and their analysis methods were developed and includes selected background or additional information about the simulation programs or the analysis methods created.

### *4.2.2 Analysis by analysis method*

The analysis by analysis method presents the key analysis methods used in the simulation programs. This approach explains why the analysis methods were developed, who developed them, and how the analysis methods were developed.

### *4.2.3 Analysis by simulation program*

The analysis by simulation program describes when the simulation programs were developed, who developed them, why the simulation programs were developed, and which analysis methods were used in the simulation programs.

### *4.2.4 Analysis by organization*

The analysis by the organization or funding explains which organizations funded, or contributed to the development of simulation programs, including their objectives and conferences.

A more detailed description and discussion of the genealogy chart using the four approaches will be presented in the next chapter.

### 4.3 Summary of Results

In this chapter, the format of new comprehensive genealogy chart was described. The chart has six components, vertical and horizontal axes, and different shaded areas. These features were explained in Sections 4.1.1 to 4.1.4. Errors and inaccurate information discovered in the previous studies with respect to building simulation programs and their analysis methods were presented in Section 4.1.5. The errors were corrected, and these corrected errors were used in the new genealogy chart. Section 4.2 described the four methods to utilize the new comprehensive genealogy chart. The next chapter, Chapter V, will include the analysis discussions and references for the chart.

# CHAPTER V

# DISCUSSION OF THE NEW GENEALOGY CHART

In this chapter, the new comprehensive genealogy chart is discussed using the four approaches discussed in Chapter IV including: by time period, by analysis method, by simulation program, and by organization. Figure 5.1 outlines these approaches.

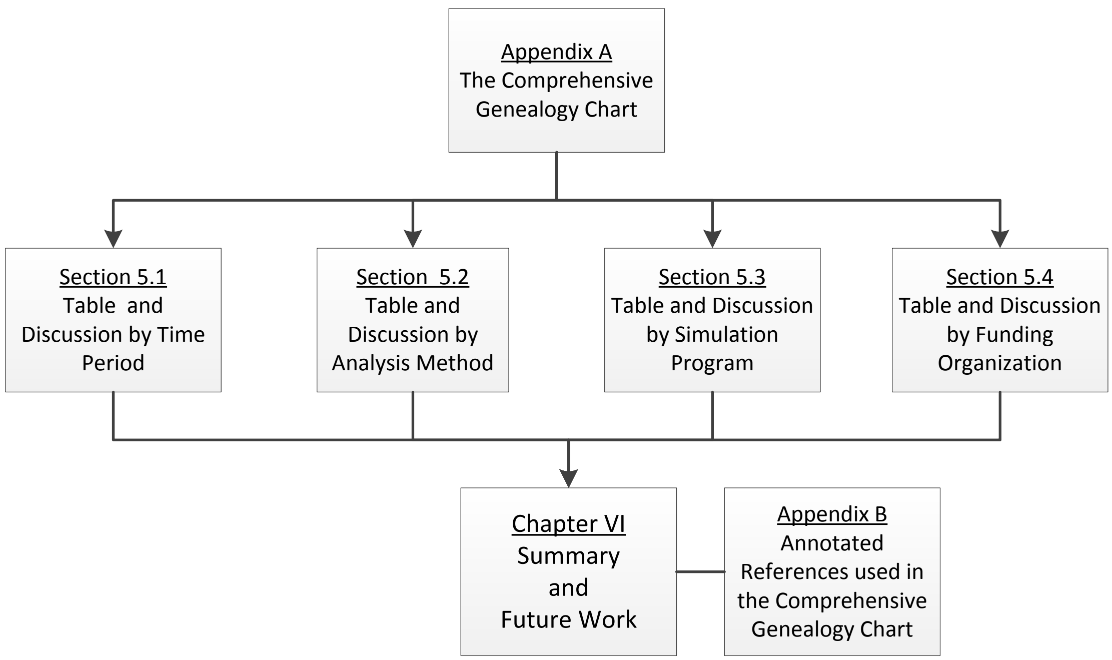



*Figure 5.1*. Structure of discussion of the comprehensive genealogy chart.

Each section is characterized using a summary table categorized by time period, by specific analysis method, by specific simulation program, and by organization. The summary tables are presented to help readers better understand the genealogy chart shown in Appendix A.

In Section 5.1, the origins of the selected key analysis methods and computer programs are described by time period. The historical background of the origins and additional analysis methods are also noted. Table 5.1 presents the matrix of the development of the selected analysis methods and computer programs, which are classified by time period. The year indicates when the analysis methods or simulation programs were first released. Section 5.2 explains the origins of the analysis methods used in the selected simulation programs by the three groups (i.e., whole-building analysis, solar energy analysis, and lighting and daylighting analysis simulation programs). Table 5.2 shows the analysis methods classified by the three groups, the parameters of the analysis methods, and the years when the analysis methods were developed. Section 5.3 describes the origins of the simulation programs by the three groups. The years when the simulation programs were released are indicated in Table 5.3. Section 5.4 historically explains the key organizations that contributed to the development of the analysis methods or the simulation programs. Table 5.4 shows which organization supports which simulation program or analysis method and the years when the organizations were founded.

Appendix B provides major annotated references used in the chart. The references are classified by the three groups and the analysis methods of each group.

### 5.1 Discussion of the Chart by Time Period

This section reviews when the simulation programs and their analysis methods were developed. In some cases historical backgrounds are contained in this discussion as well. Table 5.1 shows when the analysis methods or the simulation programs were created or released. The selected analysis methods and the selected simulation programs of Table 5.1 came from the event boxes and the shaded event boxes of the genealogy chart shown in Appendix A.

Table 5.1. *Major development of analysis method or simulation program by year*.

| Group | Year | Analysis Method or Simulation Program |
|---|---|---|
| Whole-Building Energy Simulation | 1925 | The Response Factor Method (RFM) was proposed in France (Nessi & Nisolle) |
| | 1937 | A method of the electrical analogy was first conceived in Europe (Beuken). |
| | 1939 | The idea of the Equivalent Temperature Differential (ETD) method was first introduced (Alford, Ryan, & Urban) |
| | 1942 | The concept of the electrical circuitry analogy for analyzing heat transfer of buildings was first introduced (Paschkis) |
| | 1947 | The RFM was introduced in the U.S. (Tustin) |
| | 1958 | The accuracy of thermal network on analog computer for calculating the cooling load was demonstrated (Buchberg). |
| | 1963 | The HVAC loads using a digital computer were first analyzed (Kusuda & Achenbach). |
| | 1967 | The detailed RFM, also called the Weighting Factor Method (WFM), for a digital computer was developed (Mitalas & Stephenson). |
| | 1967 | HCC that calculated peak cooling and heating loads, which was based on the TETD method, was developed by APEC (Tupper et al., 2011). |
| | 1971 | The z-transform that was more efficient than the RFM was proposed (Stephenson & Mitalas) |
| | 1971 | The U.S. post office program that used the WFM was developed by GARD/GATX (USPS, 1971) |
| | Early 1970 | NBSLD, which was based on the RFM and the Heat Balance Method (HBM) using the thermal network concept, was developed (Kusuda) |
| | 1972 | TRACE that used the WFM was released (Sowell & Hittle, 1995) |
| | 1977 | BLAST based on the HBM was developed by the U.S. Army Construction Engineering Research Laboratory (Hittle). |

Table 5.1. *Continued*

| Group | Year | Analysis Method or Simulation Program |
|---|---|---|
| Whole-Building Energy Simulation | 1979 | DOE-2 that used the WFM was released (LBL). |
| | 1981 | The custom WFM used in DOE-2 was described (Kerrisk, 1981). |
| | 1987 | HAP that used the WFM was released (Farzad, 2012). |
| | 2001 | EnergyPlus, which was based on the best algorithms from BLAST and DOE-2.1, was first released (Crawley et al.) |
| Solar Energy Analysis Simulation | 1942 | The first quantitative study for analyzing a flat-plate collector was conducted (Hottel & Woertz). |
| | 1953 | The utilizability concept for analyzing active solar systems was first introduced (Whillier). |
| | Early 1970 | The National Science Foundation and the United States Energy Research and Development Administration begun to support the development of solar energy technologies (Beckman, 1993). |
| | 1975 | TRNSYS, a detailed solar simulation program, was publically released (Klein, 1976; Tupper et al., 2011) |
| | 1976 | The F-Chart method, a simplified solar energy calculation method, was developed by using TRNSYS as a part of Klein's PhD dissertation (Klein). |
| | 1978 | The PV array efficiency estimating method was suggested (Evans et al.) |
| | 1978 | The Passive Solar Energy (PASOLE) program using a thermal network method was developed (McFarland). |
| | 1978 | The Solar Load Ratio (SLR) method, a simplified passive solar calculation method, was developed by using PASOLE (Balcomb & McFarland) |
| | 1980 | The un-utilizability method for analyzing passive solar systems was developed (Monsen & Klein). |
| | 1982 | The F-Chart software, which was widely used to estimate the long term performance of active and passive solar systems, was released (Klein & Beckman; Haberl & Cho, 2004a). |
| | 1983 | The PV F-Chart software, which was widely used to estimate the long term performance of PV systems (Klein & Beckman; Haberl & Cho, 2004b). |
| | 1983 | The Solar Energy Research Institute Residential Energy Simulator (SERIRES) version 1.0 was released to analyze passive solar strategies of buildings (Palmiter & Wheeling) |
| | 1996 | SUNREL was developed as an upgraded version of SERIRES (Deru). |
| Lighting & Daylighting Analysis Simulation | 1911 | First daylight factor (DF) concept (Trotter) |
| | 1928 | The Lumen method for calculating the Daylight Factor (DF) was developed by using an empirical formula (as cited in Dresler, 1954). |
| | 1954 | The split flux method, the improved method of the Lumen method, was developed for calculating an Internal Reflected Component (IRC) of daylighting (Hopkinson et al.) |

Table 5.1. *Continued*

| Group | Year | Analysis Method or Simulation Program |
|---|---|---|
| Lighting & Daylighting Analysis Simulation | 1966 | The radiosity concept was introduced for calculating the IRC (Sparrow & Cess) |
| | 1967 | The concept of the ray-tracing method was first introduced (Appel) |
| | 1968 | The electric lighting analysis computer program, called Lumen-I, was developed (Kota & Haberl, 2009). |
| | 1982 | SUPERLITE that used the radiosity method was developed (Selkowitz et al., 1982). |
| | 1983 | Lumen Micro that used the radiosity method was developed (Kota, 2011). |
| | 1983 | The DOE 2.1 daylighting model that used the split flux method was added to the DOE 2.1b version (LBNL). |
| | 1986 | The backward ray-tracing method, the improved method of the ray-tracing method, was developed (Arvo). |
| | 1989 | Radiance that used a backward ray-tracing method to estimate IRC was developed (Ward). |
| | 1998 | DAYSIM that used the Radiance algorithms was developed to estimate annual daylight profiles (Reinhart, 2013). |

Even though the development of several analysis methods for whole-building simulation, solar energy design or simulation, and lighting and daylighting simulation started in the pre-1950s period, the development of simulation programs did not begin until the 1960s because the digital computers had not been widely used yet. The development of the computer and its programming language has affected the development of the simulation programs and their analysis methods from 1960 to the present. In this study, the selected analysis methods (i.e., key analysis methods) used for computer simulation programs were investigated even if various analysis methods were developed to analyze high performance buildings.

### *5.1.1 Pre-1950s*

In the pre-1950s period, specifically from 1600 and 1900, most fundamentals (i.e., gas laws, heat properties, and thermodynamics) of HVAC systems were studied. They scientifically contributed to the development of technology. Gas laws explained the relations of temperature, volume, and pressure, and thermodynamics described the relations of heat, work, and energy. The fundamental understanding allowed engineers to create more efficient systems and predict energy performance (Donaldson et al., 1994). In 1836 and 1850, Thomas Tredgold and Eugéne Péclet introduced heat transfer theory for ventilating and heating systems through their books (Donaldson et al., 1994; Mao et al., 2013). In 1894, Hermann Rietschel, a professor at the Technical University of Berlin – Charlottenburg, proposed general procedures for the design of HVAC systems based on the scientific fundamentals. The title of the published book was Guide to Calculating and Design of Ventilating and Heating Installations (Donaldson et al., 1994).

The most important social issues in the pre-1950s period were World War I and II, which spanned each from 1914 to 1918 and from 1939 to 1945. World War I and II forced governments to promote energy conservation. People tried to save resources due to the war, and it motivated engineers to create efficient methods to save energy (Shavit, 1995).

The development of a computer was also important event in the pre-1950s. In 1834, Charles Babbage designed a computing machine (i.e., called the Analytical Engine) that became the basis of a current computer framework (Steitz, 2006; CHM, 2008). During World War I, mechanical calculators were developed to help engineers better calculate the trajectory of artillery shells, whereas World War II saw the development of punched-cards, the electronic calculators (i.e. ENIAC and EDVAC) and the development of the first computers (i.e., COLOSSUS and MANIAC), which were the foundation for all computers that followed (McCartney, 1999; Copeland, 2006). In 1946, John Mauchly and John Presper Eckert at the University of Pennsylvania developed the Electrical Numerical Integrator And Calculator (ENIAC) sponsored by the U.S. Army. The first digital calculator for a general purpose, ENIAC, was originally developed for enhancing artillery target accuracy. However, ENIAC was used for estimating weather prediction and wind tunnel calculations as well as military experiments because World War II ended in 1945 (Bellis, 2013).

*5.1.1.1 Discussion of Pre-1950s whole-building simulation*

In order to estimate whole-building energy use, the fundamentals and essential concepts for calculating cooling and heating loads were developed in the pre-1950s period.

In 1897, Rolla Carpenter discussed time-dependent temperature to select a radiator size in the American Society of Heating and Ventilating Engineers (ASHVE, now ASHRAE) Transactions (Carpenter, 1897). This was the first study to be published in the ASHVE Transactions for considering time-dependent temperature (Shavit, 1995). In 1907, he used the Peclet equation developed in 1868 to estimate material conduction by temperature difference with the coefficient of conductivity and the thickness of the material (Carpenter, 1907). In 1913, Ralph C. Taggart first published the differential equation in the ASHVE Transactions to estimate the required time to heat rooms by using steam radiators. The differential equation was solved by an explicit approach (Taggart, 1913; Shavit, 1995). The use of air conditioning increased the importance of calculating heat gain and loss in buildings (Shavit, 1995). In 1935, F. Faust, L. Levine, and F. Urban, engineers at the General Electric Corporation, calculated the cooling load by using a time lag effect in a paper, titled "A rational heat gain method for the determination of air conditioning cooling loads" (Faust et al., 1935). The time lag accounted for the effect of wall's thermal storage capacity. In other words, the time lag concept accounted for time delay and heat amplitude reduction between an outer surface and an inter surface of a wall (Faust et al., 1935; Alford et al., 1939). In 1939, J. Alford, J. Ryan, and F. Urban, engineers at the General Electric Corporation, proposed a decrement factor to visualize the wall's thermal storage capacity (Alford et al., 1939).

Through World War II (1939-1945), people recognized the importance of available resources. Researchers started to develop new methods for the building performance computation (Shavit, 1995). In 1942, the concept of the electrical circuitry analogy for analyzing heat transfer in buildings was first introduced by Victor Paschkis, a research engineer at Columbia University (Paschkis, 1942; Paschkis and Baker, 1942; Shavit, 1995). C. Beuken first conceived a method of the electrical analogy in Europe in 1937 and 1938 (as cited in Paschkis and Baker, 1942).

After World War II, researchers used analog computers[5] for solving various engineering problems. In 1948, Harold Johnson, a professor at University of California – Berkeley, used this technology (i.e., analog circuitry) to analyze transient thermal performance at inner surfaces of building walls (Johnson, 1948). The weighting factor concept for the transient thermal behavior was introduced in his study (Johnson, 1948; Shavit, 1995). In the same year, Charles Leopold, a consulting engineer, developed a hydraulic analogue based on the electric analogy approach to accurately estimate conduction, convection, radiation, and thermal storage behavior used for calculating a cooling load (Leopold, 1948).

The most widely-used concept for calculating instantaneous heat gain through walls and roofs was the Response Factor Method (RFM), first used by André Nessi and Léon Nisolle, engineers at Ėcole Centrale Paris, in France in 1925 (Nessi and Nisolle, 1925; Haberl and Cho, 2004c). The RFM was first introduced in the U.S. in 1947 by Arnold Tustin, who was a British professor at the University of Birmingham. This method was published in an Electrical Engineering Journal (Tustin, 1947; Haberl and Cho, 2004c).

Another transient heat gain calculation method, called the Equivalent Temperature Differential (ETD) method, which was later used in the Total Equivalent Temperature Differential (TETD)/Time Averaging (TA) method (Rees et al., 2000), was

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[5] Analog computers use continuous inputs (i.e., electrical circuits) to calculate problem variables described using electrical voltages, whereas digital computers use discrete inputs using symbols such as numbers and letters, which are described in programming languages (i.e., FORTRAN) (Dooijes and Peek, 2013; Collins, 2013).

proposed by James Stewart at the Carrier Corporation in 1948 (Stewart, 1948). This ETD method was based on the concept of the sol-air temperature method developed in 1944 by C. Mackey and L. Wright, professors at Cornell University (Mackey and Wright, 1944, 1946). Mackey and Wright's study referenced the solution of J. Alford, J. Ryan, F. Urban proposed in 1939 (Alford et al., 1939; Mackey and Wright, 1944). Mackey and Wright's study assumed periodic cycles of steady state temperature on a one-day basis for calculating heat gain through walls and roofs. This assumption caused one of the limitations to accurately estimate heat gain of buildings (Kusuda, 1969).

*5.1.1.2 Discussion of Pre-1950s solar energy analysis simulation*

In this study, the origins of today's solar thermal, solar PV, and passive solar simulation programs were also investigated. In the pre-1950s period, active solar thermal systems included solar collectors, storage units, and solar domestic hot water (SDHW) systems. In terms of solar collectors, a flat-plate collector was widely used because this type of collector is easier to build than other types of collectors. In 1885, Charles Tellier set up and introduced the concept of a tilted, flat-plate collector, which heated ammonia, with a solar water pumping system (Tellier, 1885). In 1909, H. Willsie developed a horizontal, flat-plate collector that used a working fluid of sulphur dioxide to collect heat for a heat engine operation (Willsie, 1909). In order to analyze a flat-plate collector, Hoyt Hottel and B. Woertz first conducted a quantitative study in 1942 (Hottel and Woertz, 1942). This method was the basis of the utilizability method introduced by Austin Whillier in 1953 (Whillier, 1953a, 1953b).

*5.1.1.3 Discussion of Pre-1950s lighting and daylighting simulation*

In the pre-1950s period, sky models for calculating sky luminance and daylighting analysis methods for calculating daylight illuminance in buildings started being developed. These studies became the key methods of lighting and daylighting simulation programs.

A sky model is one of important factors to estimate daylighting in a building because both direct and diffuse daylight from the sun and sky come into a building. In 1921, Herbert Kimball and Irving Hand at the Weather Bureau in Washington D.C. first measured sky luminance distribution (Kimball and Hand, 1921; Kota, 2011). In 1929, Pokrowski developed a formula for calculating the luminance distribution of a cloudless clear sky using Rayleigh scattering[6]. In 1942, P. Moon and D. Spencer developed an empirical formula for calculating sky luminance distribution of an overcast sky (as cited in Hopkinson et al, 1966; Kota, 2011).

Most daylightling calculation methods used in today's simulation tools are divided into a daylight factor (DF) method, a daylight coefficient (DC) method, and a ray-tracing technique (Kota, 2011). The first study using the daylight factor was conducted by Alexander Trotter in 1989 (as cited in Walsh, 1951). In 1928, H. G. Fruhling developed the Lumen method to calculate the DF using an empirical formula (as cited in Dresler, 1954).

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[6] Light's elastic scattering. This was discovered by Lord Rayleigh who was an English physicist. This is caused by the electric polarizability of particles. Diffuse radiation of sky is generated from this phenomenon of sunlight in the sky (Rayleigh Scattering, 2013).

The methods for finding components of the daylight factor (DF) can be divided into graphical and non-graphical methods. In 1923, P. Waldram developed the Waldram diagram, which is a graphical method used for estimating the overall DF or a single DF component (as cited in Hopkinson et al., 1966). In 1946, A. Dufton proposed daylight protractors as a non-graphical method to calculate the DF (as cited in Hopkinson et al., 1966).

### *5.1.2 1950s*

In the 1950s, analog computers became widely used for building energy analysis. The key analysis methods for solar, lighting and daylighting simulation programs were also developed in the 1950s, which were based on selected methods developed prior to this time.

In the 1950s, a programming language for digital computers was developed that became widely used in the 1960s. In 1954, the International Business Machines Corporation (IBM) developed FORmula TRANslator (FORTRAN), which was the first high level programming language. This language was commercially released in 1957 (CHM, 2008). FORTRAN positively affected the availability of a digital computer in the 1960s because FORTRAN allowed the simulation developers to create a program on one computer to be run on another computer, so multiple programs for simulation were soon developed.

#### *5.1.2.1 Discussion of 1950s whole-building simulation*

In the 1950s, analog computers were widely used to study cooling and heating loads. In 1954, H. Nottage and G. Parmelee, research engineers at the American Society of Heating and Ventilating Engineers (ASHVE) Research Laboratory, used thermal circuits on analog computers to analyze cooling and heating loads (Nottage and Parmelee, 1954). In the same year, T. Willcox, C. Oergel, S. Reque, C. ToeLaer, and W. Brisken, who were engineers at the General Electric Corporation, studied cooling loads used in residential buildings using analog computers (Willcox et al., 1954). In 1955, Harry Buchberg used an analog computer approach to study thermal behavior in simple dwelling houses. His original study was his Master of Science thesis at University of California – Los Angeles (UCLA) sponsored by the American Society of Heating and Air-Conditioning Engineers (ASHAE, formerly ASHVE and now ASHRAE) (Buchberg, 1955). In 1958, Buchberg extended his previous study that was conducted in 1955 as an associate professor at UCLA, which was also sponsored by the ASHAE. In the second study, he demonstrated the accuracy of thermal network on analog computer for calculating the cooling load (Buchberg, 1958).

In 1956, the RFM using rectangular pulses was developed by W. Brisken and S. Reque who were engineers at the General Electric Corporation after the RFM was first introduced in the U.S. by A. Tustin in 1947. In the next year, Paul R. Hill at the Langley Aeronautical Laboratory of the National Adivosry Committee for Aeronautics (NACA, now National Aeronautics and Sapce Administration (NASA)) first proposed the RFM that uses triangular pulses more accuracy than rectangular pulses (Hill, 1957).

*5.1.2.2 Discussion of 1950s solar energy analysis simulation*

In 1953, the key analysis method for solar simulation program was developed. Austin Whillier first proposed the utilizability concept for analyzing the ratio of the incident solar radiation that reaches the surface of a solar system, thorough his Ph.D. dissertation at the Massachusetts Institute of Technology (MIT), under Prof. Hoyt Hottel's direction (Whillier, 1953b). In 1955, Hottel and Whillier used Whillier's utilizability concept to develop the location-dependent, monthly-average hourly utilizability concept (Hottel and Whillier, 1955; Beckman, 1993; Haberl and Cho, 2004a).

*5.1.2.3 Discussion of 1950s lighting and daylighting simulation*

In order to have a designated sky model, in 1955 the International Commission on Illumination (CIE) selected Moon and Spencer's formula as the standard to calculate the overcast sky luminance distribution. This formula was developed in 1942 for luminance distribuition of an average overcast sky (as cited in Hopkinson et al, 1966).

In order to develop a daylighting calculation method in buildings, A. Dresler (1954) extended the Lumen method, developed by Fruhling in 1928, and especially improved the method to calculate an Internal Reflected Component (IRC) of daylight (Dresler, 1954). In the same year, R. Hopkinson, J. Longmore, and P. Petherbridge at the Building Research Station in the U.K. developed the split flux method based on A. Dresler, W. Arndt, and G. Pleijel (Hopkinson et al., 1954). This method calculated the IRC using an empirical formula. In 1958, Hopkinson et al. created tables to calculate DFs (Hopkinson et al., 1966).

***5.1.3 1960s***

In the 1960s, digital computers began to be substituted for analog computers because digital computers were more convenient to program new problems and digital computers using FORTRAN made it easier to describe the governing equations and driving functions than the configurations required by analog computers. The scientific application of digital computers was considerably improved by FORTRAN, the high level programming language that was commercially released in 1957 by IBM.

In the early 1960s, the Union of Soviet Socialist Republics (USSR) intimidated the U.S. with their nuclear weapon. As a response, researchers at the Building Research Division (BRD) of the National Bureau of Standards (NBS) (now the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST)) studied the indoor, thermal environmental conditions in high occupancy fallout shelters using an IBM 7094 with FORTRAN (Kusuda, 1999). This study was one of the first studies to use a digital computer to study the dynamic heat transfer in a building.

The Stanford Research Institute (SRI) reported building space heating and cooling energy accounted for approximately 20% of the end-use consumption in 1968 in the U.S (as cited in ASHRAE, 1975a). This report helped engineers recognize the importance of energy saving in buildings, which helped motivate ASHRAE to begin its research efforts in building energy simulations (ASHRAE, 1975a).

*5.1.3.1 Discussion of 1960s whole-building simulation*

In the early 1960s, analog computers were still used to analyze cooling and heating loads in buildings like during the 1950s. In 1962, D. G. Stephenson and G. P. Mitalas studied solar heat gain using an analog computer (Stephenson and Mitalas, 1962). In 1965, L. Nelson published one of the first detailed studies regarding the interaction between envelope, equipment, and control systems of a building using an analog computer (Nelson, 1965; Shavit, 1995).

In the 1960s, researchers started to use digital computers for estimating the HVAC applications in buildings. In 1963, Tasami Kusuda and P. Achenbach's study at the NBS was one of the first to analyze the HVAC loads using a digital computer (Kusuda and Achenbach, 1963). In 1967, G. P. Mitalas and D. G. Stephenson at the National Research Council (NRC) Canada improved their own previous work that used an analog computer in 1962 (Stephenson and Mitalas, 1962). Their study developed the response factors for digital computers that became the basis for today's instantaneous heat gain analysis through walls and roofs of buildings (Mitalas and Stephenson, 1967; Shavit, 1995).

Stephenson and Mitalas's Response Factor Method (RFM) for calculating heat gain through walls and roofs and Weighting Factor Method (WFM) for calculating cooling loads (Mitalas and Stephenson, 1967; Stephenson and Mitalas, 1967) became the important foundations toward the thermal performance development of whole-building simulation computer programs (Shavit, 1995).

In 1967, Mitalas and J. G. Arseneault developed a FORTRAN IV program to calculate heat gain through multi-layered slabs using the RFM of Mitalas and Stephenson (Mitalas and Arseneault 1967; Kusuda, 1969). Mitalas and Arseneault used a Laplace transform matrix introduced by Louis A. Pipes in 1957 (Pipes, 1957; Mitalas and Arseneault 1967; Kusuda, 1969). Previously, Mackey and Wright's study in 1944 employed Fourier series rather than the Laplace transform to calculate heat conduction equations due to the low speed of computers (Mackey and Wright, 1944; Kusuda, 1969).

In 1969, Kusuda extended the RFM for calculating the response factors (RFs) for curvatures of multi-layers (Kusuda, 1969). In the same year, Mitalas compared the calculated results of the WFM with the measured data (Mitalas, 1969). Using the RFM and the WFM, researchers and engineers could analyze the dynamic heat gain and cooling loads through multi-layered walls and roofs to better design envelope and HVAC systems in buildings.

In 1965, ASHRAE founded a Presidential Committee on Energy Consumption to specifically address the calculations of heating and cooling loads with more accurate computer methods. This committee reviewed the issues surrounding the development of more accurate methods in detail and suggested further assignments to a task group, called Task Group on Load Profiles, also founded in 1965. From 1965 to 1966, the initial Task Group researched accurate methods and developed a diagram for calculating building load profiles (Tull, 1971; Stamper, 1995). In 1966, the Task Group voted for the ASHRAE budgets to fund energy calculation research projects and a new renamed Task Group (Stamper, 1995). In 1967, the new Task Group known as the ASHRAE Task Group on Energy Requirements (TGER) for Heating and Cooling Buildings held its first meeting. Robert Tull, who was a previous ASHRAE president, became the first chairman of the ASHRAE TGER (Tull, 1971; Stamper, 1995; Kusuda, 1999). In 1968 and 1969, ASHRAE TGER first presented two booklets that contained the computer algorithms for the dynamic, hourly cooling and heating loads calculation methods and methods for modeling secondary systems and plants. The first booklet on the loads calculation was narrowly distributed to approximately 150 researchers and engineers at the ASHRAE annual meeting in 1968 to receive comments from them (Lokmanhekim ed., 1971; Tull, 1971). The final form of the booklet that contained the algorithms for the pre-calculated WFM and the custom WFM was published in 1971 (Lokmanhekim ed., 1971). The 3$^{rd}$ edition of the booklet that included the algorithms for the WFM and the HBM was presented in 1975 (ASHRAE, 1975a).

In the 1960s, the development of computer programs for calculating building thermal performance began. In 1966 and 1967, Mitalas, Stephenson, and Arseneault who were researchers at the NRC Canada developed FORTRAN IV programs to analyze building thermal performance (Mitalas and Stephenson, 1966; Mitalas and Arseneault, 1967). FORTRAN IV was released by the IBM in 1962. In 1967, the group of consulting engineers, called the Automated Procedures for Energy Consultants (APEC), developed a computer program (i.e., HCC) that calculated peak cooling and heating loads for a building. This program was based on the TETD/TA method introduced in ASHRAE Guide and Data Book published in 1961 (ASHRAE, 1961; as cited in Ayres and Stamper, 1995; Mao et al., 2013), which used the sol-air temperature method of Mackey and Wright in 1944 and 1946 (Mackey and Wright, 1944, 1946). Many of the same APEC members who developed the HCC program also participated in the formation of the ASHRAE TGER (Tupper et al., 2011).

*5.1.3.2 Discussion of 1960s solar energy analysis simulation*

In 1963, the key analysis method (i.e., the utilizability method) for solar simulation program was further developed (Liu and Jordan, 1963). Benjamin Liu and Richard Jordan, professors at the University of Minnesota, developed the location-independent, monthly average hourly utilizability method using Whillier's utilizability concept, developed in 1955 (Whillier, 1953a, 1953b).

*5.1.3.3 Discussion of 1960s lighting and daylighting simulation*

For a sky model, in 1965, R. Kettler developed a formula for luminance distribution of a clear blue sky. The CIE selected Kettler's formula for luminance distribution of a clear blue sky as the standard for luminance distribution of a clear blue sky with sun (as cited in Hopkinson et al., 1966).

For daylighting calculation methods in buildings, in 1966, E. Sparrow at the University of Minnesota and R. Cess at the State University of New York at Stony Brook introduced the radiosity concept in their book, entitled Radiation Heat Transfer (Sparrow and Cess, 1966). In 1967, Arthur Appel at the IBM Research Center first proposed the concept of ray tracing (Appel, 1967; Weghorst et al., 1984). These two methods, the radiosity method and the ray tracing method became the basis of today's lighting and daylighting simulation programs.

For the simulation of lighting and daylighting, in 1968, the electric lighting analysis computer program, called Lumen-I, was developed by David DiLaura, which was based on point-by-point calculations. In 1970, DiLaura developed Lumen II that improved the existing capabilities of Lumen I by adding the calculations for daylighting, glare, and visual comfort (as cited in Kota and Haberl, 2009).

### *5.1.4 1970s*

As a result of the oil crises (i.e., 1973 and 1979), the development of FORTRAN, and the increasing availability of digital computers, more and more engineers began to develop building thermal calculation methods and eventually whole-building simulation programs (Ayres and Stamper, 1995). Engineers and researchers were finally able to more easily apply the laws of thermodynamics to complex whole-building simulation programs using mainframe computers with FORTRAN (Pedersen, 2009).

In 1970, the first symposium with respect to the use of computers for building energy simulation was held at the National Bureau of Standards (NBS) in Gaithersburg, Maryland. This symposium, entitled “Use of Computers for Environmental Engineering Related to Buildings”, attracted approximately 400 architects, engineers, and scientists from 12 countries. The NBS, ASHRAE, and the Automated Procedures for Energy Consultants (APEC) sponsored this symposium. The 59 technical papers of this symposium addressed issues including computer applications for building heat transfer analysis, loads and energy calculations, HVAC system simulations, weather data, and computer graphics (Kusuda ed., 1971).

#### *5.1.4.1 Discussion of 1970s whole-building simulation*

Several significant events occurred in the 1970s. First, in 1971, Stephenson and Mitalas proposed the z-transform method that was more efficient than the Response Factor Method (RFM) regarding speed and memory space of digital computers

(Stephenson and Mitalas, 1971). In 1975, the ASHRAE TGER published the 3rd editions of "Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations" and "Procedures for Simulating the Performance of Components and Systems for Energy Calculations", which were originally published in 1968 and 1969 (ASHRAE, 1975a, 1975b). These publications helped researchers and engineers quickly learn the basic knowledge of whole-building simulation programs, which accelerated the development of whole-building energy simulation (Sowell and Hittle, 1995).

In the late 1960s, the NBS used the state-of-the-art digital computer to estimate heat conduction of fallout shelters in underground. Based on this work, in the early 1970s, Kusuda at the NBS proposed the National Bureau of Standards Load Determination (NBSLD) program that used the RFM and the Heat Balance Method (HBM) to analyze building thermal performance (i.e., heating and cooling loads) (Stamper, 2001; Wright, 2003). This NBSLD program was developed for calculating cooling loads, excluding HVAC systems and plants. Later, this program was improved for calculating annual energy use with simple HVAC systems in one zone (Kusuda, 1999). In 1976, the FORTRAN algorithms of NBSLD were publically released to help engineers develop their own simulation programs according to their needs. Some of the algorithms that came from ASHRAE TGER's book (ASHRAE, 1975a) were corrected in the NBSLD algorithms book (Kusuda, 1976). The U.S. Army Construction Engineering Research Laboratory (CERL) used these algorithms including the HBM to develop CERL's first building simulation program, called as TASS. In 1977, CERL developed the Building Load Analysis and System Thermodynamics (BLAST) program using the modifications to CERL's first simulation program (i.e., TASS) and a new FORTRAN code. In 1979, BLAST 2.0 was released. The HBM concept of NBSLD and BLAST is now the basis for today's public domain program, EnergyPlus (Walton, 2001).

In 1971, the U.S. Post Office released the post office program to analyze, design, or remodel U.S. Post Office facilities (Lokmanhekim, 1971; USPS, 1971). Researchers at the General American Research Division (GARD) of the General American Transportation Corporation (GATX), which was a subcontractor of Post Office facilities, developed a building shadow calculation program under the direction of Metin Lokmanhekim. The GARD/GATX developed the U.S. Post Office program based on the ASHRAE TGER report about the shadow program and the ASHRAE TGER algorithms that used the weighting factor method (WFM) (USPS, 1971; Ayres and Stamper, 1995; Kusuda, 1999). As a result, the U.S. Post Office program became the first public domain program for whole-building simulation accounting for cooling and heating loads, HVAC systems, plants, and economic analysis (USPS, 1971; Haberl and Cho, 2004c).

In the late 1970s, Zulfikar O. Cumali and the Computation Consultants Bureau (CCB) developed the CAL-ERDA code based on the loads sub-program code used in the Post Office Program (Cumali, 2013). The name of the CAL-ERDA program came from the names of the sponsors: the California (CAL) Energy Commission and the United States Energy Research and Development Administration (ERDA). CAL-ERDA was an improvement over the Post Office program because the code of the Post Office program was a monolithic that required recompilation for each subroutine, whereas CAL-ERDA was speed up by recompiling the code. The CCB also developed the Building Description Language (BDL) for CAL-ERDA, which was the first user-friendly computer input language (i.e., familiar terminology), for controlling the load, systems, plant, and economic sub-programs of the program (Graven and Hirsch, 1977; Cumali, 2013). The Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory (LBNL)), the Argonne Nation Laboratory (ANL), and the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) also contributed to the development of CAL-ERDA (Graven and Hirsch, 1977).

In 1976, CAL-ERDA was released. In the same year, the California Energy Commission (CEC) and the ERDA sponsorship for CAL-ERDA ended and the ERDA was integrated into the U.S. Department of Energy (US DOE) (Birdsall et al., 1990). About this same time when M. Lokmanhekim moved from the GARD/GATX in Illinois to the LBL in California, he brought his skills from the development of the Post Office program to the LBL to accelerate the development of CAL-ERDA (Kusuda, 1999). The LOADS program of CAL-ERDA was developed based on the ASHRAE algorithms published in 1975. The SYSTEMS program of CAL-ERDA utilized the equations of the ASHRAE algorithms and the NECAP[7] program (i.e., the National Aeronautics and Space Administration (NASA)'s Energy Cost Analysis Program) for developing the simulation procedure (Graven and Hirsch, 1977).

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[7] NECAP was developed by the GARD/GATX under the sponsorship of the NASA in 1975 by improving the Post Office program (Henninger ed., 1975; Sowell and Hittle, 1995). NECAP consisted of six computer programs: Response Factor Program, Data Verification Program, Thermal Load Analysis Program, Variable Temperature Program, System and Equipment Simulation Program, and Owning and Operating Cost Program (Henninger ed., 1975).

In 1978, DOE-1, a slightly enhanced version of CAL-ERDA, was released by CCB, LBL (now LBNL), LASL (now LANL), and ANL (ANL, 1978 as cited in LASL, 1980; Cumali, 2013). The US DOE Office of Buildings and Community Systems supported the development of DOE-1 (Birdsall et al., 1990). Zulfikar Cumali, Ender Erdem, Robert Grave, and Metin Lokmanhekim led the development of the BDL of DOE-1 (LASL, 1980). In 1979, LBL improved the central plant algorithms of DOE-1 and released DOE-2 (Ayres and Stamper, 1995). In 1979 and 1980, DOE-2.0a and DOE-2.1a were released by LBL and LASL. In the new programs, a new BDL had been created for the DOE-2 series to more easily control the LOADS analysis program, the SYSTEMS program, the PLANT program, and the ECONOMICS analysis program. Frederick Buhl, James Hirsch, and Mark Roschke helped design the BDL of the DOE-2 series. Frederick Buhl was the principal researcher for the LOADS program, James Hirsh for the SYSTEMS program, Steven Gates for the PLANT program, Frederick Winkelmann for the ECONOMICS and LOADS programs, and Mark Roschke for the DOE-2 Solar Simulator, which was called the Component Based Simulator (CBS) for active solar systems (LASL, 1980).

In terms of the proprietary programs regarding whole-building simulation in the 1970s, in 1972, the Trane company released Trane Air Conditioning Economics (TRACE) direct version. TRACE was derived from the post office program developed in 1971 (Sowell and Hittle, 1995). In 1977, TRACE 77 version was released (Tupper et al., 2011).

In addition to the hourly whole-building simulation programs, performance-based (i.e., minute-by minute) simulation programs were also developed. In the early 1960s, Nelson at Honeywell, Inc. started the effort to study dynamic performance of buildings, HVAC systems, and control systems within them, using an analog computer (Nelson, 1965). In 1978, Gideon Shavit at Honeywell, Inc. developed the performance-based simulation program, BLDSIM, using a digital computer (as cited in Shavit, 1995). Digital computers made it possible to solve any ordinary differential equations and non-linear relationship to better analyze the high-frequency dynamic performance of HVAC control systems in a building (Shavit, 1995).

*5.1.4.2 Discussion of 1970s solar energy analysis simulation*

In the early 1970s, the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison (UWM) and the Solar Energy Applications Laboratory (SEAL) at Colorado State University (CSU) began to study solar energy technologies supported by the National Science Foundation and the United States Energy Research and Development Administration (ERDA) (now the U.S. Department of Energy (US DOE)) (Beckman, 1993; Tupper et al., 2011). The CSU team planned to build a solar energy test house, and needed a flexible simulation program to find the various design options before the test house was built. Therefore, the UWM suggested a modular program for flexible analysis, called the Transient Systems Simulation (TRNSYS) program (Klein, 1976; Beckman, 1993). Sanford A. Klein, a graduate student at the University of Wisconsin-Madison, introduced the FORTRAN program, TRNSYS, through his PhD study (Klein, 1976; Beckman, 1993). In 1975, TRNSYS was publically released, and

Klein finished his dissertation in 1976 (Tupper et al., 2011). Since then TRNSYS has become a widely used modular or component-based program. Originally, TRNSYS was developed for solar thermal simulations, but has also made a major contribution to building energy simulation programs, PV analysis, and other analysis such as hydrogen production analysis (Athienitis, et al., 2012).

For simplified solar energy calculations, in 1977, William. A. Beckman, Sanford. A. Klein, and John. A. Duffie published the F-Chart method, which was a simplified set of correlations based on thousands of simulations using TRNSYS (Klein, 1976; Beckman et al., 1977).

In 1978 to further develop the utilizability method suggested in 1953 by Whillier (Whillier, 1953a, 1953b), Klein developed the monthly-average daily utilizability function that improved upon Liu and Jordan's daily utilizability study in 1963 (Klein, 1978). In 1979, Manual Collares-Pereira at the University of Chicago and Ari Rabl at the Solar Energy Research Institute (SERL, now National Renewable Energy Laboratory (NREL)) developed long term average energy models using the daily utilizability correlations in order to estimate different types of solar collectors such as flat-pate collectors, compound parabolic concentrators (CPC), and tracking collectors for east-west, polar, and two-axis tracking axis (Collares-Pereira and Rabl, 1979). Collares-Pereira and Rabl's study was supported by the US DOE. In 1980, J. C. Theilacker and Klein proposed a new correlation method that simplified and improved the accuracy of Klein's correlation method that was developed in 1978. This method was also applicable to surfaces facing the equator like Klein's method, and it added more correlations for surfaces shaded by overhangs and vertical surfaces facing east and west orientations (Theilacker, 1980; Klein and Beckman, 1984; Theilacker and Klein, 1980; Jones and Wray, 1992).

For photovoltaic (PV) system analysis, in 1978, D. L. Evans, W. A. Facinelli, and R. T. Otterbein studied hybrid / PV thermal component models. A PV array efficiency estimating method was suggested in this study (Evans et al., 1978; Klein and Beckman, 1984).

For passive solar system analysis, in 1978, Robert D. McFarland at Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) developed the Passive Solar Energy (PASOLE) program using a thermal network method (McFarland, 1978). In the same year, the Solar Load Ratio (SLR) method was proposed by John Douglas Balcomb and R. D. McFarland (Balcomb and McFarland, 1978). The Solar Load Ratio (SLR) method, a simplified passive solar calculation method, used correlation parameters generated from thousands of runs with PASOLE, which is similar to the relationship of the F-Chart method and TRNSYS. In 1980, another passive solar method for estimating the useful amount of solar energy for passive solar heating loads in building structure, called the un-utilizability method, was developed by W. A. Monsen and Klein (Monsen and Klein, 1980).

In summary, during the 1970s, major solar energy analysis studies were conducted under the US DOE’s support. The most widely used solar simulation program, TRNSYS, was developed in 1975 based on a modular approach for flexibility. The simplified solar energy calculation method, the F-Chart method, was developed in

1977 using TRNSYS. The previously developed utilizability method for estimating the ratio of the incident solar radiation that reaches the surface of a solar system was further developed in 1978, 1979, and 1980. A PV array efficiency estimating method was developed in 1978. In the same year, the passive solar energy analysis program, PASOLE, was developed. The simplified passive solar energy calculation method, the SLR method, was also developed in 1978 using PASOLE. Another passive solar energy calculation method, called the un-utilizability method for estimating the solar energy amount above the critical solar level for calculating heating loads stored in building structure, was developed in 1980.

*5.1.4.3 Discussion of 1970s lighting and daylighting simulation*

Graphical methods for calculating the DF were continuously developed after P. Waldram developed the Waldram diagram in 1923. In 1979, Millet proposed the Graphic Daylight Design Method (GDDM) to estimate the overall DF regarding the standard CIE overcast sky. In 1980, Millet extended the study to include a clear sky (as cited in Moore, 1985).

For glare analysis, in 1972, the Building Research Station (BRS) in the U.K. and Cornell University proposed the Daylight Glare Index (DGI) to estimate glare, which was an improvement on the BRS glare equation from 1950 (as cited in Kota, 2011). In 1979, H. D. Einhorn proposed a formula that contributed to the development of the CIE Glare Index (CGI) (Einhorn, 1979; Wienold and Christoffersen, 2006).

For lighting and daylighting computation methods, in 1975 and 1976, DiLaura who previously developed Lumen I and Lumen II in 1968 and 1970, respectively, proposed efficient computation methods for calculating direct and reflected component illuminance and visual comfort, which were used for Equivalent Sphere Illumination (ESI) (DiLaura 1975, 1976). In 1980, DiLaura established Lighting Technologies Inc. This company later released Lumen III in 1981 (Moore, 1985; Kota and Haberl, 2009).

#### *5.1.5 1980s*

In the 1980s, microcomputers became widely used for building energy simulation programs. Unfortunately, the accuracy of simulation results using microcomputers was less than the accuracy of simulation results using mainframe computers. The main reason for this was that microcomputers used simplified calculation methods compared to the detailed methods of the mainframe computers. Even though microcomputers had lower accuracy, engineers preferred to use microcomputers because mainframe computers were expensive and difficult to use and engineers had trouble understanding the complete operating systems of mainframe computers (Kusuda, 1985). Eventually, by the late 1980s, microcomputers (i.e., personal computers) became powerful enough to run mainframe computer-based simulation programs such as DOE-2 and BLAST.

Another trend of the 1980s was that existing the whole-building simulation programs were updated and revised, rather than developing new analysis methods for simulation programs (Tupper et al., 2011). On the other hand, the analysis methods for solar simulation programs, lighting and daylighting simulation programs were continuously developed.

*5.1.5.1 Discussion of 1980s whole-building simulation*

The weighting factor method (WFM), which was developed in the mid-1960s, was improved for use in various room types in a building. In 1979, Zulfikar O. Cumali and his associates (i.e., the CCB) developed the mathematical method of an upgraded WFM, called a custom WFM (Cumali et al., 1979; Cumali, 2013). In 1981, the custom WFM method used in the DOE-2.1 program was described in detail (Kerrisk, 1981; Kerrisk et al., 1981). The original WFM (i.e., precalculated WFM) used precalculated input data representing typical buildings (i.e., light, medium, and heavy construction), whereas the custom WFM employed actual input data representing various buildings (Kerrisk et al., 1981).

In the 1980s, there were also updates and improvements to whole-building simulation programs[8]. In 1981, BLAST 3.0, which was the upgraded version of BLAST 2.0 from 1979, was released (Herron et al., 1981). In addition, DOE-2.1a was released in 1981 (LASL, 1981). During the remainder of the 1980s new versions of DOE-2 were released including: DOE-2.1b in 1982, DOE-2.1c in 1984, and DOE-2.1d in 1989 (LBL, 1982, 1984, 1989). The details of new versions will be further discussed in Section 5.3.1.1 and 5.3.1.2.

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[8] In the 1980s, many engineering offices did not have mainframe computers, and the speed of personal computers was slow. Therfore, A Simplified Energy Analysis Method (ASEAM), which was a public domain program, was widely used during the period because ASEAM could run on small and slow computers (PNNL, 1990; Jacobs and Henderson, 2002; Landsberg, 2013). ASEAM used a modified bin method for loads calculation and the system and plant algorithms of DOE-2 for system energy calculation (Cane, 1979; Knebel, 1983; PNNL, 1990; Landsberg, 2013). W. S. Fleming & Associates, Inc. developed ASEAM. The US DOE's Federal Energy Management Program (FEMP) supported the development of ASEAM (PNNL, 1989, 1990).

In terms of the development of the proprietary programs for whole-building simulation, in 1989, TRACE 600, which was the upgraded version of TRACE 77 (originally released in 1977) was released (Tupper et al., 2011). Another proprietary whole-building energy simulation program developed by the Carrier Company was the Hourly Analysis Program (HAP). In 1987, HAP version 1.0 was released, which was a new enhanced version of the Commercial Load Estimating and Bin Opcost analysis programs, which were developed by the Carrier Company. In 1989, HAP version 2.0 was released which used ASHRAE's load calculation methods (Farzad, 2012).

To improve the documentation of whole-building energy calculation methods, in the late 1980s, ASHRAE developed the annotated guide book for HVAC systems and equipment that updated the previous ASHRAE book, "Procedures for Simulating the Performance of Components and Systems for Energy Calculations" (Yuill, 1990). This new annotated guide included new literature about mathematical models and computer algorithms for HVAC systems and equipment.

In summary, in the 1980s, public domain (i.e., BLAST and DOE-2.1) and proprietary whole-building simulation programs (i.e., TRACE and HAP) were improved and updated. The upgraded WFM, called the custom WFM, was developed and used in DOE-2.1. The mathematical theory and computer algorithms of this method were introduced in 1979 and 1981. ASHRAE published the annotated guide book in 1990, including mathematical models and computer algorithms for HVAC systems and equipment.

*5.1.5.2 Discussion of 1980s solar energy analysis simulation*

For analyzing the performance of direct gain solar heating system, in 1981, W. A. Monsen, S. A. Klein, and W. A. Beckman at the SEL of the UWM used the un-utilizability method, which was previously proposed by Monsen and Klein in 1980, to calculate the performance of thermal storage walls. In the same year, Klein, Monsen, and Beckman also proposed a simplified procedure for analyzing the performance of thermal storage walls using correlation parameters and tabulated weather data (Jones and Wray, 1992). For further developing the utilizability method suggested in 1953, Clark, Klein, and Beckman developed a simplified algorithm in 1983 for digital computers to calculate the hourly utilizability function for analyzing the solar radiation of active solar heating systems. Also, in 1983, the F-Chart program, a simplified solar energy analysis program, was released for use as a FORTRAN program. This program adopted the utilizability and un-utilizability concepts for designing and analyzing active and passive solar heating systems (Klein and Beckman, 2001a).

For analyzing the performance of PV systems, in 1980, D.L. Evans, W. A. Facinelli, and L. P. Koehler at Arizona State University proposed a simplified, non-computer based procedure to size PV arrays and battery storage to satisfy electrical loads (Evans et al., 1980). In 1981, M. D. Siegel, Klein, and Beckman at the SEL of the UWM also proposed a simplified method to analyze PV system performance using monthly-average calculation (Siegel et al., 1981). Finally, in 1984, D. R. Clark, Klein, and Beckman at the SEL of the UWM developed a method to analyze the long-term average performance of PV systems (Clark et al., 1984). This method was used in the PV F-

Chart program to calculate the annual performance of PV systems. The user manual of the program, which detailed the analysis of the method developed by Clark, Klein, and Beckman in 1984, was published in 1985 (Klein and Beckman, 2001b).

In the 1980s, two simplified solar energy analysis programs (i.e., long-term, monthly analysis programs), the F-Chart software and the PV F-Chart software, were released. The F-Chart software is widely used to calculate the long term performance of active and passive solar systems, and the PV F-Chart software is widely used to calculate the long term performance of PV systems. In 1982, F-Chart versions 1.0 through 4.1 were released for mainframe computers using the FORTRAN programming language. In 1983, F-Chart version 5 was released for microcomputers, which was programmed in BASIC. In the same year, the PV F-Chart computer program was first released. In 1985, PV F-Chart version 3.3 was released for microcomputers that used Disk Operating System (DOS). All the F-Chart and PV F-Chart programs were developed by the SEL of the UWM (Haberl and Cho, 2004a, 2004b).

For passive solar system analysis, in 1983, Larry Palmiter and Terry Wheeling at the Ecotope Group developed the Solar Energy Research Institute Residential Energy Simulator (SERIRES) Version 1.0, a FORTRAN program, to analyze passive solar strategies used in residential and small commercial. The development of SERIRES was founded through a contract with the Solar Energy Research Institute (SERI) (now the National Renewable Energy Laboratory, (NREL)). Ron Judkoff, Bob O'Doherty, David Simm, and David Wortman were technical monitors of SERI. SERIRES was released for mainframe computers programmed in FORTRAN 66 in 1983 buildings (Palmiter and Wheeling, 1983).

In summary, the utilizability and un-utilizability methods were further developed in 1983 and 1981 respectively, and a simplified analysis method for the performance of PV systems was developed in 1984. The two simplified solar energy analysis programs (i.e., long-term, monthly analysis programs), the F-Chart software for active and passive solar strategies and the PV F-Chart software for PV strategies, were released in 1983 and 1985. The SERIRES simulation program for analyzing passive solar strategies used in residential and small commercial buildings was released in 1983.

*5.1.5.3 Discussion of 1980s lighting and daylighting simulation*

In regards to daylighting calculation methods in buildings, in 1982, the radiosity computer algorithms, which were based on the radiosity concept introduced in 1966, were developed to calculate the Internal Reflected Component (IRC) in buildings (Modest, 1982; Selkowitz et al., 1982; Kim et al., 1986). In addition, the lighting and daylighting simulation program, SUPERLITE (Selkowitz et al., 1982) that used the radiosity algorithms was also developed (Hitchcock and Carroll, 2003).

Other daylighting calculation methods in buildings were also developed during this period. In 1983, P. R. Tregenza and I. M. Waters developed the concept of a Daylight Coefficient (DC) method (Tregenza and Waters, 1983). The DC method was used to calculate the illuminance distributions inside buildings according to the sky luminance conditions present at a given moment. In 1986, James Arvo developed a backward ray-tracing method following the concept of ray-tracing, which was originally developed by Arthur Appel in 1967 (Appel, 1967). The backward ray tracing method provided an improved solution for exactly calculating the indirect diffuse reflection, which had not been previously solved (Arvo, 1986).

In terms of a sky model for a daylighting model, in 1987, K. Matsuura developed a new formula for the sky model. This formula was used for calculating luminance distribution of a clear turbid sky and for an intermediate sky condition (as cited in Kota, 2011).

In the 1980s, several new versions of lighting and daylighting analysis programs were developed. In 1981, David L. DiLaura and Lighting Technologies, Inc. developed Lumen III, which was upgraded from the previous Lumen II program (Moore, 1985; Kota, 2011). In Lumen III, flux transfer algorithms were provided, which were previously developed by D. L. DiLaura and Gregg A. Hauser in 1978 (DiLaura and Hauser, 1978; Moore, 1985). In 1982, DiLaura and Lighting Technologies, Inc. developed a new daylighting program for microcomputers named Energy, which was also marketed by Lighting Technologies, Inc. (Moore, 1985). In 1983, DiLaura and Lighting Technologies, Inc. developed the Lumen Micro program that used radiosity algorithms (Kota, 2011). Also, in 1983, the DOE-2.1b version was released, which added a daylighting analysis model using the split flux method. In the early 1980s, SUPERLITE was developed at the Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory (LBNL)), which used the radiosity algorithms to analyze the IRC (Selkowitz et al., 1982). In 1989, Radiance was first released by Gregory J. Ward at the LBL (Ward, 1994). Radiance, which was developed on the UNIX platform is an advanced lighting and daylighting simulation program for analyzing color (i.e., renderings) and illuminance of building inside and outside light (EERE, 2011c). Radiance used a backward ray-tracing method to estimate the IRC. In 1990, Radiance versions 1.2 and version 1.3 were released (LBNL, 2013).

In summary, for daylighting calculations in buildings, radiosity algorithms were developed in 1982. Advanced daylighting calculation methods, including the DC method and the backward ray-tracing method, were introduced in 1983 and 1986. In the 1980s, several new versions of the previously developed and new programs for lighting and daylighting simlation were developed (i.e., Lumen III, Lemen Micro, DOE-2.1 daylighting model, SUPERLITE, and Radiance).

***5.1.6 1990s***

In the 1990s, as personal computers continued to improve, the decreased price and improved speed and memory of the computers made it possible for engineers to use detailed engineer programs on their personal computers in their offices (Ayres and Stamper, 1995). Also, in 1985, Microsoft (MS) Windows, which added a graphical user interface (GUI) to the underlying DOS operating system, was released. In a similar fashion to the Apple’s GUI, MS Windows GUI also helped to accelerate the use of personal computers by the general public.

The improvement and enhancement of existing simulation programs also continued during the 1990s. Most of the improvements were focused on the development of the graphical user interface and more sophisticated analysis procedures (Ayres and Stamper, 1995; Sowell and Hittle, 1995). These improvements added new algorithms to better integrate existing procedures, and in some cases, provided optimized solution schemes (Sowell and Hittle, 1995).

*5.1.6.1 Discussion of 1990s whole-building simulation*

For more efficient and rigorous cooling load calculation, in 1997, Jeffrey D. Spitler, Daniel E. Fisher, and Curtis O. Pedersen at University of Illinois at Urbana-Champaign (UIUC) proposed the Radiant Time Series (RTS) method for calculating peak cooling load. This new method was an improvement over the previous CLTD/SCL/CLF, TETD/TA, and TFM methods (Spitler et al., 1997; ASHRAE, 2001).

In terms of the development of simulation programs, the first version of DOE 2.1e and DOE-2.1e-087 were released by LBL in 1993 and 1995 (Winkelmann et al.; 1993; LBNL and JJH, 1998). In the early 1990s, engineers of James J. Hirsch and Associates (JJH), LBNL (the new name of LBL from 1995 to the present), and the Electric Power Research Institute (EPRI) began to develop DOE-2.2, a new version of DOE-2.1. In 1996, PowerDOE, the first graphical interface program using DOE-2.2, was created by JJH. In 1999, eQUEST version 1.0, another graphical interface program using DOE 2.2 was released by JJH. While the development of PowerDOE stopped in 2001 due to funding difficulty, eQUEST has been continuously developed until today (as cited in Tupper et al., 2011).

In 1996, the U.S. Department of Energy (US DOE) and the U.S. Department of Defense (US DOD) started to develop a new whole-building simulation program, called EnergyBase, later designated as EnergyPlus (Crawley et al., 1997). EnergyPlus combined the best features of DOE-2 released by LBNL in 1979, BLAST and IBLAST released by U.S. Army Construction Engineering Research Laboratory (CERL) and University of Illinois in 1977 and 1994 (Crawley et al., 1999). The alpha version of EnergyPlus was developed and tested internally in 1998, and a beta version of EnergyPlus was released to be tested by engineers outside the development circle in 1999 (Crawley et al., 1999). Due to the development of the new simulation program (i.e., EnergyPlus), the funding for further improvements to BLAST and DOE-2.1 was discontinued (Tupper et al., 2011).

The development of the two most widely used proprietary whole-building simulation programs, TRACE and HAP, continued. The Carrier Company released HAP version 3.0 in 1993 and version 4.0 in 1999. HAP version 4.0 was the first version to be developed for the Microsoft Windows (Farzad, 2012). The Trane Company released TRACE 700 in 1998, which was their first Windows version (Tupper et al., 2011).

In respect to whole-building energy calculation methods documentation, in 1996, ASHRAE, who recognized the importance of documentation for building energy analysis methods, published another annotated guide for load calculation models and algorithms, following the previously published annotated guide for HVAC equipment published in 1990 (Spitler, 1996). In 1993 and 1998, ASHRAE issued two new toolkits for secondary and primary HVAC systems (Brandemuehl et al., 1993; ASHRAE 1998). These new toolkits contained algorithms, models and executable FORTRAN code to help simulation software developers better understand and create new programs (Spitler, 1996; Pedersen et al., 2003). The toolkits replaced the earlier ASHRAE book, named “Procedures for Simulating the Performance of Components and Systems for Energy

Calculations" published by the ASHRAE TGER in 1975 (ASHRAE, 1975b; Spitler, 1996)). The new toolkits also included updates based on ASHRAE's literature search, which was conducted in the annotated guide for HVAC equipment issued in 1990 (Spitler, 1996).

In summary, regarding whole-building energy calculation methods documentation, ASHRAE, who recognized the importance of documentation for building energy analysis methods, published in 1966 an updated annotated guide for load calculation models and algorithms, following the previously published annotated guide for HVAC equipment that was published in 1990. In the 1990s, the development of the whole-building simulation programs continued. The first version of DOE 2.1e and The 087 version of DOE-2.1e were released by LBL in 1993 and 1995. In 1996, the U.S. Department of Energy (US DOE) and the U.S. Department of Defense (US DOD) started to develop a new whole-building simulation program, called EnergyBase, later designated as EnergyPlus. The development of the two most widely used proprietary whole-building simulation programs, TRACE and HAP, continued as well. The Carrier Company respectively released HAP versions 3.0 and 4.0 in 1993 and 1999. The Trane Company released TRACE 700 in 1998.

*5.1.6.2 Discussion of 1990s solar energy analysis simulation*

In 1993, Klein and Beckman released the F-Chart program version 6.17W and the PV F-Chart program version 3.01W. Both versions were now compatibly with the MS Windows operating system (Haberl and Cho, 2004a, 2004b). In 1996, the SEL of the

UWM also released TRNSYS version 14.2, which was the first MS Windows compatible version (as cited in Tupper et al., 2011).

In 1996, the SERIRES version 1.0, which was originally developed by the Ecotope Group under the contract with the Solar Energy Research Institute (SERI) (now the National Renewable Energy Laboratory (NREL)) in 1983, was upgraded and released as SUNREL by Colorado State University and NREL (Deru, 1996). One of upgrades was to make the format of the program more flexible with respect to future improvements and to be compatible with visual user interfaces (Deru et al., 2002).

*5.1.6.3 Discussion of 1990s lighting and daylighting simulation*

From 1991 to 1997, the Radiance program was updated each year (i.e., version 2.0 in 1991, version 2.1 in 1992, version 2.3 in 1993, version 2.4 in 1994, version 2.5 in 1995, version 3.0 in 1996, and version 3.1 in 1997) (LBNL, 2013). In 1998, Reinhart proposed DAYSIM using the Radiance algorithms as a lighting and daylighting analysis simulation program that can estimate annual daylight profiles (Reinhart, 2013).

In terms of a sky model for a daylighting model, Richard Perez, R. Seals, and J. Michalsky at the State University of New York developed a new sky model for all weather conditions in 1993 (Perez et al., 1993). This model was adopted shortly after by the Radiance and DAYSIM programs (Kota, 2011).

***5.1.7 From 2001 to present***

Recently, growing concerns about climate change have led to an effort to reduce $CO_2$ emissions from fossil fuel-burning power plants that supply electricity to buildings. Therefore, building standards and codes, for example, ASHRAE Standard 189.1-2009 and ASHRAE Standard 189.1-2011 published in 2009 and 2011 respectively, and the International Green Construction Code (IGCC) issued in 2012, have been created for high performance buildings to reduce energy use and $CO_2$ emissions from fossil fuel-fired power plants. In such standards and codes, building energy simulation is one of severed compliance paths for a user to prove their proposed design consumes less energy annually than a similar building built to the prescriptive cod standards (Tupper et al., 2011).

The improvement and enhancement of existing simulation programs also continued. Fixing existing bugs and having new simulation features were the main reasons for further development of the simulation programs.

*5.1.7.1 Discussion of whole-building simulation from 2001 to present*

In 2001, the first version of EnergyPlus was released after the alpha and beta testing of EnergyPlus was completed in the late 1990s (Crawley et al., 1999). EnergyPlus is a public domain program, which was designed to be a modular, well-structured code. EnergyPlus is based on the best algorithms from several of the previous building simulation programs (i.e., BLAST, IBLAST, and DOE-2.1). After the first release, EnergyPlus was improved and updated by the national laboratories and third-party developers, under sponsorship by the US DOE. EnergyPlus version 1.1 was released in 2003, version 1.2 in 2004, version 1.3 and 1.4 in 2006, version 2.0 and 2.1 in 2007, version 2.2 and 3.0 in 2008, version 3.1 and 4.0 in 2009, version 6.0 in 2010, version 7.0 in 2011, version 7.1 and 7.2 in 2012, and version 8.0 in 2013(EERE, n.d.;

EERE, 2010; EERE, 2011e; EERE, 2012; EERE, 2013b). The details of all the different versions will be noted in Section 5.3.1.1.

Due to the focus on the development of EnergyPlus, funding for improving DOE-2.1 was terminated. Instead of the US DOE funding for improvements to DOE-2.1, DOE-2.2, a new proprietary version of DOE-2.1 developed in the late 1990s, has been continuously improved for the capabilities and fixing bugs of DOE-2.2 until today. eQUEST, the graphic interface version of DOE-2.2, also has been upgraded by James J. Hirsch and Associates (JJH). In 2001, 2003, 2005, 2007, and 2010, eQUEST versions 2.17c, 3.4, 3.55, 3.61b, and 3.64 were respectively released (as cited in Tupper et al., 2011; JJH, 2009). The details of the different versions will be described in Section 5.3.1.3.

The two most popular proprietary whole-building simulation programs, TRACE and HAP were also widely used in the 2000s. TRACE and HAP can be used to calculate building loads, building energy use, and size HVAC systems (Jacobs and Henderson, 2002; Farzad, 2012). TRACE, developed by the Trane Company in 1972, has been continuously updated and released until today (i.e., Trace 700 full version in 2001, Trace 700 version 4.1 in 2002, Trace 700 version 6.0 in 2006, Trace 700 version 6.2 in 2008, and Trace 700 version 6.2.10 in 2013) (Tupper et al., 2011; Trane, 2013). HAP, developed by the Carrier Company in 1987, also has been continuously improved until today (i.e., version 4.1 in 2002, version 4.2 in 2003, version 4.3 in 2006, version 4.4 in 2008, version 4.5 in 2010, version 4.6 in 2012, and version 4.7 in 2013) (Carrier, 2013).

The details of TRACE and HAP versions will be described in Section 5.3.1.4 and 5.3.1.5.

TRNSYS, which was released by Klein and the SEL in 1975, was originally developed to analyze active solar heating systems. TRNSYS can be also used to simulate HVAC systems using its component-based or modular approaches. The solution algorithms of TRNSYS were more rigorous than the solution algorithms of whole-building energy simulation programs such as BLAST and DOE-2.1. However, the models of whole-building simulation programs for calculating conventional cooling and heating loads were more detailed (Sowell and Hittle, 1995). TRNSYS was updated and widely used in the U.S (i.e., version 15 in 2001, version 16 in 2004, version 17 in 2010, and version 17.1 in 2012). The details of TRNSYS versions will be further discussed in Section 5.3.1.6.

To improve the documentation of whole-building energy calculation methods, in 2002, ASHRAE published a toolkit for building load calculations, developed by C. O. Pedersen, D. E. Fisher, R. J. Liesen, and R. K. Strand (Pedersen et al., 2003). The ASHRAE toolkit for building loads replaced the ASHRAE TGER's book about procedures for determining heating and cooling loads issued in 1975 (ASHRAE, 1975a; Pedersen et al., 2003). In additon, the new toolkit was based on the more recent literature research from ASHRAE's annotated guide for load calculation models and algorithms written by Spitler in 1996 (Spitler, 1996).

In summary, from 2001 to the present, improvements and enhancements to existing simulation programs were conducted to mostly fix existing bugs and bring in new features. In 2001, the first version of EnergyPlus was released after the alpha and beta testing of EnergyPlus were completed in the late 1990s. After the first release, EnergyPlus was improved and updated. eQUEST, TRACE, HAP, and TRNSYS were also upgraded and enhanced by their developers.

*5.1.7.2 Discussion of solar energy analysis simulation from 2001 to present*

Since 2001, the user manuals of the F-Chart program and the PV F-Chart program, published in 1983, were updated. New Windows versions of the F-Chart program and the PV F-Chart program were also released in 2001 (Klein and Beckman, 2001b).

In 2002, Michael Deru, Ron Judkoff, and Paul Torcellini of NREL publically released a new version of SUNREL. In 2004, SUNREL version 1.14 was released. SUNREL is used almost exclusively to simulate passive solar technologies in small buildings (Deru et al., 2002). SUNREL can be used to design "…moveable insulation, interior shading control, energy-efficient windows, thermochromatic glazings, Trombe walls, water walls, phase change materials, and rockbins." (Deru et al., 2002, p.1).

*5.1.7.3 Discussion of lighting and daylighting simulation from 2001 to present*

After 2001, new methods for estimating daylighting performance, the Daylight Autonomy (DA) and the Useful Daylight Illuminance (UDI) index, were developed (Nabil and Mardaljevic, 2006). These methods were then used in DAYSIM to estimate daylight profiles.

Since 2001, Radiance and DAYSIM that use the Radiance algorithms have been continuously improved until today (i.e., DAYSIM version 1.3 in 2002, version 2.0 in

2003, version 2.1 in 2005, and version 3.X in 2010; Radiance version 3.4 in 2002, version 3.5 in 2003, version 3.7 in 2005, version 3.9 in 2008, version 4.0 in 2010, and version 4.1 in 2011) (LBNL, 2013; Reinhart, 2013). The details of Radiance and DAYSIM versions will be further discussed in Section 5.3.3.1.1 and 5.3.3.1.2.

In 2004, DElight, a lighting and daylighting simulation program, was added to EnergyPlus version 1.2. The DElight version 1.x series used the daylighting algorithms of DOE-2.1. DElight version 2.0 was updated to use the radiosity algorithms of SUPERLITE. The 2.0 version of DElight was included with EnergyPlus version 1.2, which was released in 2004 (Hitchcock and Carroll, 2003; EERE, n.d.). The DElight version 2.0 included algorithms to estimate complex fenestration systems (CFS) (Hitchcock and Carroll, 2003).

#### *5.1.8 Summary*

Section 5.1 discussed the development of the analysis methods and the simulation programs (i.e., whole-building energy simulation, solar energy analysis simulation, and lighting and daylighting analysis simulation) by period: pre-1950s, 1960s, 1970s, 1980s, 1990s, and from 2001 to present. Appendix A shows the comprehensive genealogy chart that is referenced in the discussions of Section 5.1.

Significant historical events such as World War I (1914-1918) and World War II (1939-1945), the development of digital computers and computer programming language (1950s), and repeated oil crises (1967, 1973, and 1979) have had a major impact on the development of key analysis methods and the origins of the simulation programs that are now used to simulate annual building energy use.

In the pre-1950s period, most of the fundamentals (i.e., gas laws, heat transfer properties, and thermodynamics) of HVAC systems were studied and published that significantly contributed to the development of today's technology. Also, during this same period, researchers and engineers developed the essential methods for: calculating dynamic heat gain and building loads (i.e., cooling and heating loads) used in whole-building energy simulation programs; calculating solar heating performance prediction used in solar energy analysis design and simulation programs; and for analyzing internally reflected illuminance used in lighting and daylighting simulation programs.

During the 1950s, analog computers became widely used to study the behavior of dynamic heat gain/loss and the response of heating, ventilating, and air conditioning (HVAC) systems. From the 1960s to the present, advanced digital computers and analysis methods suitable for the digital computers were developed and became widely used. Digital computers were substituted for analog computers because the digital computer is more convenient to program, and the methods used in digital computers made it easier and quicker to describe the governing equations and driving functions than the methods used in analog computers. Finally, the scientific application of the digital computer was considerably improved by the FORTRAN programming language, a high level programming language that was commercially released in 1957 by IBM. FORTRAN also allowed computer codes written on one computer to be run on another computer by a different analyst, which accelerated the availability of simulation programs. As a result, the concept of analog computers and the capabilities of digital computers significantly contributed to the development of whole-building, solar energy, lighting and daylighting simulation programs. Currently, almost all computer simulation programs in use today continued to be written in the FORTRAN programming language.

Section 5.2, which follows, will discuss the comprehensive genealogy chart shown in Appendix A by analysis method.

### 5.2 Discussion of the Chart for Tracing Specific Analysis Methods

A multitude of analysis methods are used in today's whole-building simulation, solar analysis simulation, and lighting and daylighting simulation programs. One way to discuss these methods is to trace each method according to analysis type.

In general, whole-building simulation programs such as DOE-2 and BLAST were composed of four major sections: loads, systems, plants, and economics (Sowell and Hittle, 1995). In this study, the analysis methods for calculating building cooling loads used in whole-building simulation programs are the main focus, with less of an emphasis on systems, plant and economics.

Solar energy analysis programs evaluate the performance of systems that are designed to collect and use solar radiation for thermal or electricity conversion. In this study, the methods for estimating the solar heating performance prediction are the main focus, with less of an emphasis on passive cooling methods or solar-driven cooling simulations.

Historically, lighting and daylighting simulation programs have used three components in order to calculate the daylight coming through a window or skylight: the Sky Component (SC), the External Reflected Component (ERC), and the Internal Reflected Component (IRC). For this study, the methods for IRC are primarily traced and analyzed, with less of an emphasis on methods used to calculate the SC or the ERC. Table 5.2 indicates the selected analysis methods and the year the analysis methods were developed.

Table 5.2. *Development of the analysis methods used in the simulation programs.*

| Group | Building Parameter | Analysis Method (Applied Program) | Year Developed |
|---|---|---|---|
| Whole-Building Energy Simulation | Zone Thermal Loads | Total Equivalent Temperature Differential / Time Averaging method (HCC) | Began in 1942 |
| | | Transfer Function Method or Weighting Factor Method (DOE-2.1e, eQUEST/DOE-2.2, TRACE, and HAP) | Began in 1925 in France |
| | | CLTD/CLF method (TRACE) | 1975 |
| | | Heat Balance Method (EnergyPlus and TRNSYS) | Began in 1850 in Germany |
| | | Radiant Time Series Method (TRACE and L) | 1997 |
| Solar Energy Analysis Simulation | Solar Heating Performance Prediction | Utilizability Method (F-Chart Program and PV F-Chart Program) | 1953 |
| | | Un-Utilizability Method (F-Chart Program) | 1980 |
| | | Thermal Network Method (TRNSYS and SUNREL, basically the concept of the thermal network method was used for all the whole-building and solar simulation programs excluding lighting and daylighting simulation programs) | Began in 1942 |
| | | F-Chart Method (F-Chart Program) | 1976 |
| Lighting & Daylighting Analysis Simulation | Internal Reflected Component of Daylighting | Split-Flux Method (DOE-2.1&2.2 and EnergyPlus) | 1954 |
| | | Radiosity Method (Lumen Micro and EnergyPlus) | 1966 |
| | | Ray-Tracing Method (Radiance and DAYSIM) | 1968 (Original Ray-Tracing Method), 1986 (Backward Ray-Tracing Method) |

In the 1920s, the most widely used method for calculating the dynamic heat gain through walls and roofs for whole-building energy simulation (i.e., the Response Factor Method (RFM)) was developed and published by André Nessi and Léon Nisolle at Ėcole Centrale Paris (French University) in France. The RFM concept is used in most of today’s cooling and heating loads calculations such as with the Weighting Factor

Method or the Transfer Function Method for DOE-2.1e, DOE 2.2/eQUEST, TRACE, and HAP, the CLTD/CLF method for TRACE, the Heat Balance method for EnergyPlus and TRNSYS, and the Radiant Time Series Method for TRACE.

In the 1940s, the origin of the Resistance-Capacitance (RC) network analysis method (i.e., the thermal network method) used in solar and whole-building simulation programs was first introduced by Victor Paschkis, a research engineer at Columbia University. This thermal network concept is used in all solar energy simulation programs, as well as whole-building energy simulation programs. In the 1950s, the most important method (i.e, the utilizability method) for calculating the performance of solar heating systems used in solar energy design or simulation programs was developed by Austin Whillier at the MIT. The utilizability method is used today in detailed solar energy simulation programs such as TRNSYS and in simplified solar energy design programs such as the F-Chart and the PV F-Chart program.

In the 1950s and 1960s, the origins of the Inter Reflected Component (IRC) calculation method (i.e., the split flux method, the radiosity method, and the ray tracing method) for daylighting simulation were developed. In 1954, the split flux method was proposed by R. Hopkinson, J. Longmore, and P. Petherbridge at the Building Research Station in the U.K. In 1966, E. Sparrow at the University of Minnesota and R. Cess at the State University of New York at Stony Brook introduced the radiosity concept in their book, entitled Radiation Heat Transfer. In 1967, Arthur Appel at the IBM Research Center first proposed the concept of ray tracing.

Today, the split flux method is used in whole-building energy simulation programs such as DOE-2.1e, DOE 2.2/eQUEST, and EnergyPlus as a daylighting model. The radiosity method is used in Lumen Micro and in EnergyPlus as a daylighting module. The ray tracing method is also used in a detailed lighting and daylighting simulation program including rendering such as Radiance.

***5.2.1 The analysis methods of whole-building energy simulation***

In Section 5.2.1, the origins of cooling load calculations used in building simulation programs were described. Various methods for calculating commercial (i.e., non-residential) building cooling and heating loads[9] have been developed (Mao et al., 2013). However, in order to more rigorously calculate building loads over long periods such as one year, rigorous hourly approaches were required that used digital computers (ASHRAE, 1997).

In this study, the analysis methods for cooling load calculations used in today's whole-building energy simulation programs were included: The Total Equivalent Temperature Difference (TETD) / Time Averaging (TA) method, the Cooling Load Temperature Difference (CLTD) / Cooling Load Factor (CLF) method, the Transfer Function Method (TFM), and the Radiant Time Series (RTS) method for calculating peak cooling load; the Weighting Factor Method (WFM) and the Heat Balance Method (HBM) for calculating time-varying cooling load for energy analysis (ASHRAE, 1997, 2009; Rees et al., 2000; Smith, 2011).

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[9] In this study, the origins of the analysis methods for cooling loads were analyzed rather than heating loads. Procedures for calculating cooling loads are basically the same to those for calculating heating loads with some exceptions (ASHRAE, 2009).

Cooling load calculations are mainly categorized by four variables: heat gain, cooling load, heat extraction rate, and cooling coil load. Heat gain means the entered or generated instantaneous heat gain in a space through walls, roofs, and windows. Cooling load indicates the instantaneous heat that has to be removed in a space to keep constant air temperature and humidity. Cooling load is affected by a time delay effect (i.e., the thermal storage effect). Heat extraction rate is the same to the space cooling load if the space air temperature is constant. The space heat extraction rate covers the effect of a slight cyclic variation or swing of space temperature. Finally, cooling coil load is the instantaneous heat removal from the cooling coil and additional system loads such as heat gain due to fan, duct, outdoor air heat, and outdoor air moisture (ASHRAE, 2009). In this study, the origins of heat gain and cooling loads were analyzed. Figure 5.2 and Figure 5.3 show the diagrams of the ASHRAE handbook published in 1997 and 2009. The diagram (see Figure 5.2) of the past ASHRAE handbook published in 1997 contains the TETD/TA method (ASHRAE, 1961), the TFM (McQuiston and Spitler, 1992), and the CLTD/CLF method (Rudoy and Duran, 1975).

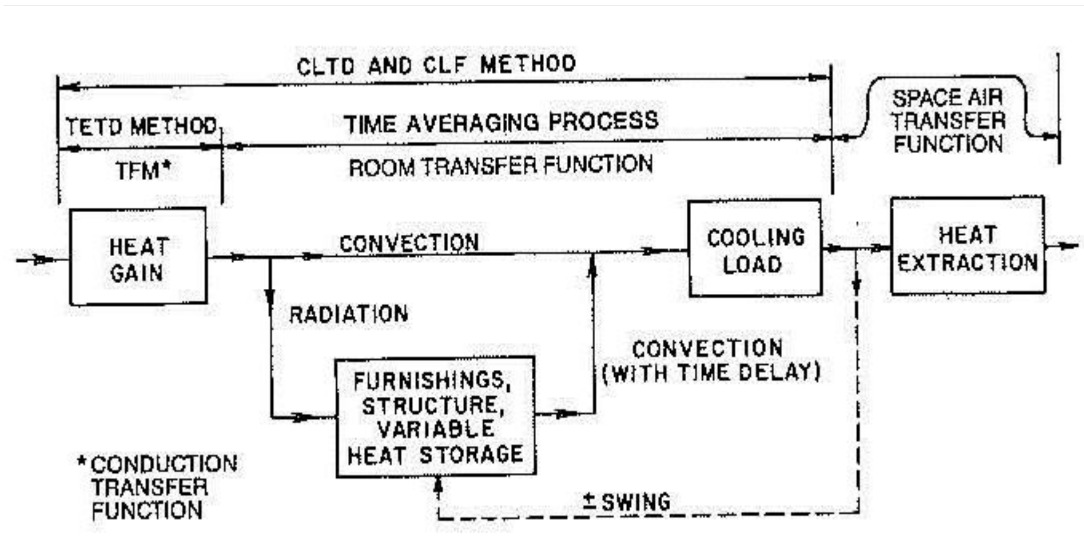


*Figure 5.2.* Origin of difference between magnitude of instantaneous heat gain and instantaneous cooling load. *Note.* From “Nonresidential Cooling and Heating Load Calculations,” by Technical Committee 4.1, 1997, *ASHRAE Handbook of Fundamentals*, p. 28.2. Copyright 1997 by ASHRAE (www.ashrae.org). Reprinted with permission.

The diagram (i.e., Figure 5.3) of the recent ASHRAE handbook published in 2009 contains the HBM (Pedersen et al., 1997) and the RTS method (Spitler et al., 1997).

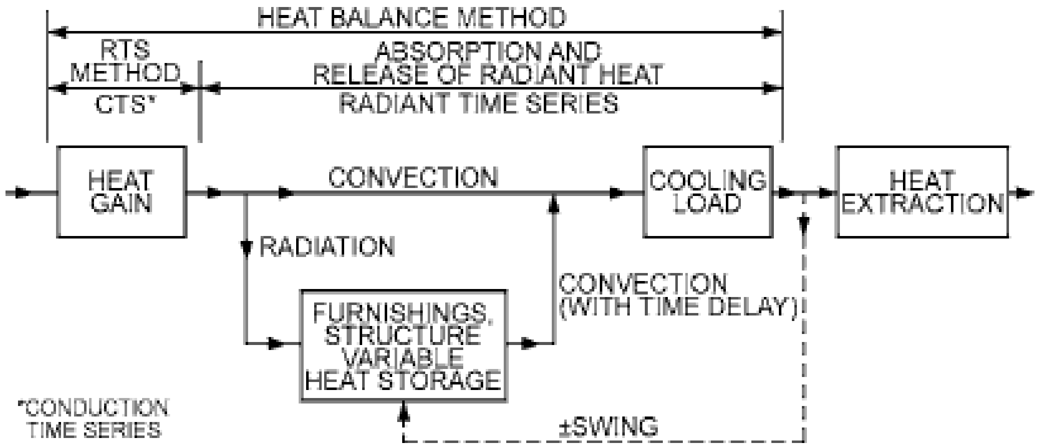


*Figure 5.3.* Origin of difference between magnitude of instantaneous heat gain and instantaneous cooling load. *Note.* From "Nonresidential Cooling and Heating Load Calculations," by Technical Committee 4.1, 2009, *ASHRAE Handbook of Fundamentals,* p. 18.2. Copyright 2009 by ASHRAE (www.ashrae.org). Reprinted with permission.
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Figure 5.2 and Figure 5.3 also indicate which analysis method is categorized in the variable. The TETD method of the TETD/TA method, the Conduction Transfer Functions (CTFs) of the WFM or the TFM, and the Conduction Time Series (CTS) of the RTS method are used to calculate the heat gain. The TA method of the TETD/TA method, the Weighting Factors (WFs) of WFM or TFM, and the Radiant Time Factors (RTFs) of the RTS method are used for calculating the cooling load. The CLTD/CLF method and HBM are used for calculating the heat gain and the cooling load at the same time. Air temperature WFs of WFM or TFM is used for calculating the heat extraction rate.

*5.2.1.1 Total equivalent temperature difference (TETD) / Time averaging (TA) method*

The TETD/TA[10] method allowed building engineers to estimate approximate heat gains by using tabulated TETD values of walls and roofs, or near equivalents (ASHRAE, 1997). This method was first developed to analyze the transient aspects of solar radiation and time delay by the thermal storage effect (McQuiston and Spitler, 1992). The heat gain using the TETD/TA method is obtained from the overall heat transfer coefficient, U, and the equivalent temperature difference known as TETD calculated by the sol-air temperature variation, decrement factors, and time lags according to the type of construction of the walls and roofs (Threlkeld, 1970; McQuiston and Spitler, 1992; ASHRAE, 1997). This heat gain method is considered a first order Response Factor Method (i.e., decrement factors and delay factors) (McQuistion and Spitler, 1992).

In the TETD/TA method, cooling load is calculated by using a Time Averaging (TA) method in order to convert heat gain to cooling load. The TA method accounts for a thermal storage effect or the radiant effect of heat gain (McQuiston and Spitler, 1992). A thermal storage effect accounts for interior surfaces of a room that absorb and store some radiation portion of heat gain. The absorbed and stored heat is later released to the air in a room with the effect of time delay as convective heat unless the room surfaces perfectly absorb or release heat (Kusuda and Powell, 1972). One of the limitations of the TETD/TA method is that the TETD/TA does not provide a rigorous technique for defining the TA period (i.e., time delay for cooling load). When the users of the

[10] The TETD is used for calculating heat gain, and the TA is used for calculating cooling load.

TETD/TA method decide the TA period, the decision is based on users' experience (McQuiston and Spitler, 1992).

The development of TETD/TA is shown in the first shaded area from the top in Figure A.2. An abbreviation, TT, in the small, rectangular boxes indicates the TETD/TA method at the bottom of the event boxes. In 1944, C. Mackey and L. Wright, professors at Cornell University, used the concept of sol-air temperature (called equivalent temperature in England), decrement factors, and time lag to calculate periodic heat transfer for homogeneous walls dealing with solar heat gain (Mackey and Wright, 1944). This study was later extended to composite walls (Mackey and Wright, 1946). Mackey and Wright's studies were based on the studies proposed by F. Faust et al. and J. Alford at al. at the General Electric Corporation in 1935 and 1939 (Faust et al., 1935; Alford et al., 1939; Mackey and Wright, 1942). In 1935, F. Faust et al. calculated heat gain through walls by considering a time lag and solar effect in their paper (Faust et al., 1935). The time lag accounted for the effect of wall's thermal storage capacity. In other words, time lag concept accounted for time delay and heat amplitude reduction between an outer surface an inter surface of a wall (Faust et al., 1935; Alford et al., 1939). In 1939, J. Alford et al. proposed a decrement factor to visualize the wall's thermal storage capacity (Alford et al., 1939).

The TETD method of the TETD/TA method was outlined and tabled for calculating heat gain of practical walls by J. Stewart at the Carrier Corporation in 1948 based on Mackey and Wright's study in 1944 (Stewart, 1948; Threlkeld, 1970). Finally, the TETD/TA method using the TA was introduced to calculate cooling load in the

ASHRAE Guide and Data Book (now ASHRAE Handbook of Fundamentals) published in 1961 (ASHRAE 1961; Mao et al., 2013). Even though the TETD/TA was developed as a manual method at first, this method has also been used as a computer procedure (McQuiston and Spitler, 1992). For example, the HCC program developed by APEC in 1967 used the TETD/TA method (Ayres and Stamper, 1995).

*5.2.1.2 Transfer function method (TFM) or weighting factor method (WFM)*

The TFM or the WFM was derived from the Heat Balance Method (HBM). In other words, energy balance equations are used to determine weighting factors (Cumali et al., 1979; Kerrisk, 1981). The transfer function concept is utilized in this method to connect heat gain to cooling load and to connect cooling load to heat extraction rate, so it is called the Transfer Function method (Mitalas, 1972). The TFM or the WFM uses two steps to calculate cooling loads like the TETD/TA method. The first step is to calculate all types of heat gain within a room. The second step converts heat gain to cooling load (ASHRAE, 1997). In the process of converting heat gain into cooling load, the TFM or the WFM uses each transfer function with respect to the past values of heat gain while the TETD/TA method uses a simple average weighted value (i.e., the TA method) in terms of the previous values of heat gain (Mitalas, 1972; McQuiston and Spitler, 1992).

Response Factors (RFs) and later Conduction Transfer Functions (CTFs) are used to calculate instantaneous heat gain, which accounts for the effect of time delay, through walls and roofs. RFs are also called thermal response factors (Mitalas and Stephenson, 1967; ASHRAE, 1997). RFs are time series coefficients with respect to the current instantaneous heat gain, which relates the current and past values of exterior and interior temperatures. CTFs use a heat flux history in place of a temperature history using the z-transform functions (Stephenson and Mitalas, 1971; Spitler, 2011). The computer procedure for calculating instantaneous heat gain using CTFs is more efficient than the procedure using RFs because it calculates faster and uses less memory space (Stephenson and Mitalas, 1971).

Weighting Factors (WFs), also called room transfer function coefficients, are used to convert the various types of the instantaneous heat gain into cooling loads. The basic concept of RFs was extended to cooling load and room air temperature using WFs as transfer functions (Kusuda, 1985). WFs can be obtained using the DOE-2 program by converting RFs to transfer functions (McQuiston and Spitler, 1992). In this way, WFs represent the properties of all elements thermal storage in a room, which defines the characteristics of time-varying heat gain in a room (Mitalas, 1972).

In the TFM or the WFM, room surface temperatures and cooling loads for typical constructions such as schools and offices, which are categorized by light, medium, and heavy constructions, are first obtained using the strict and lengthy HBM. In these processes, triangular pulses of unit heat gain are used to simulate solar heat gain, conduction heat gain, lighting heat gain, equipment heat gain or occupants heat gain. The sum of the input excitation pulses are then used to calculate the transfer function coefficients (i.e., WFs) for a room as numerical constants indicating time-varying cooling load (McQuiston and Spitler, 1992; ASHRAE, 1997). In this way, the calculated WFs can be assumed to be independent of the input pulses. Therefore, this method can reduce the time involved compared to the more strict and lengthy HBM (Sowell and

Hittle, 1995; ASHRAE, 1997). Instead of a lengthy calculation, the TFM or WFM simply multiplies the WFs by the heat gain in keeping with the time series and later sums the products (ASHRAE, 1997).

The development of the TFM or the WFM is shown in the first and second shaded areas from the top in Figure A.2. An abbreviation, WFM, in the small, rectangular boxes indicates the TFM or the WFM at the bottom of the event boxes. Another abbreviation, RFM, in the small, rectangular boxes represents the RFM that was used for the TFM or WFM as a heat gain calculation. The origin of the TFM or WFM began from the study of the RFM by A. Nessi and L. Nisolle at Ėcole Centrale Paris (French University) in France in 1925 (Nessi and Nisolle, 1925). Nessi and Nisolle first used the Response Factor Method (RFM) to calculate transient heat gain by applying unit step functions for the RFM (Stephenson and Mitalas, 1967). Nessi and Nisolle used infinite solution for the RFM, which required considerable calculation time (Stephenson and Mitalas, 1971; Fisher, 2013). In 1947, A. Tustin, who was a British professor at the University of Birmingham, introduced the time-series concept that was used in the RFM through an Electrical Engineering Journal (Tustin, 1947). Tustin showed that ordinary arithmetic operations can be applied to time-series calculations (Tustin, 1947; Stephenson and Mitalas, 1967). In 1954, T. Willcox, C. Oergel, S. Reque, C. ToeLaer, and W. Brisken, who were engineers at the General Electric Corporation, showed an electrical resistance-capacitance (RC) circuit that can be used to calculate transient heat gain and cooling load in a room (Willcox et al., 1954). Figure 5.4 shows a RC thermal circuit with five main branches that are linked to voltages representing temperature.

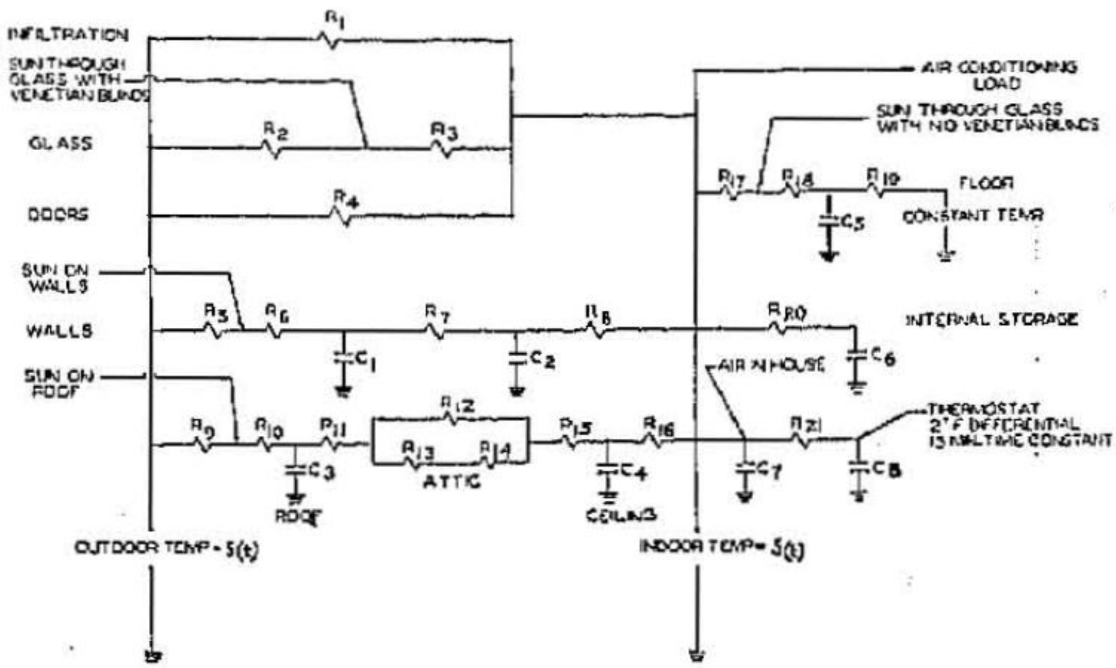


*Figure 5.4.* Resistance-capacitance thermal circuit. *Note.* From "Analogue Computer Analysis of Residential Cooling Loads," by T. N. Willcox, C. T. Oergel, S. G. Reque, C. M. ToeLaer, W. R. Brisken, 1954, *ASHVE Transactions*, *60*, p. 509. Copyright 1954 by ASHVE (now, ASHRAE (www.ashrae.org)). Reprinted with permission.

In 1956, W. Brisken and S. Reque at the General Electric Corporation further refined the previous study by Willcox et al. for calculating cooling load by using the RFM with rectangular pulses, which was developed by Nessi and Nisolle. They found the exclusive features of the RFM (Brisken and Reque, 1956; Stephenson and Mitalas, 1967). In 1957, Paul R. Hill at the Langley Aeronautical Laboratory first applied triangular pulses of surface temperature to the RFM rather than rectangular pulses in order to increase the accuracy of the RFM (Hill, 1957; Stephenson and Mitalas, 1967). Figures 5.5 and 5.6 show the examples of rectangular temperature pulses and triangular temperature pulses (i.e., $V_{1,i}$ and $V_{n,i}$ = pulse heights; time t = i δ where δ is the discrete time interval of pulses) (Kusuda, 1969). Time-series by triangular pulses show a more smooth function by straight-line parts rather than time-series by rectangular pulses (Mitalas and Stephenson, 1967).

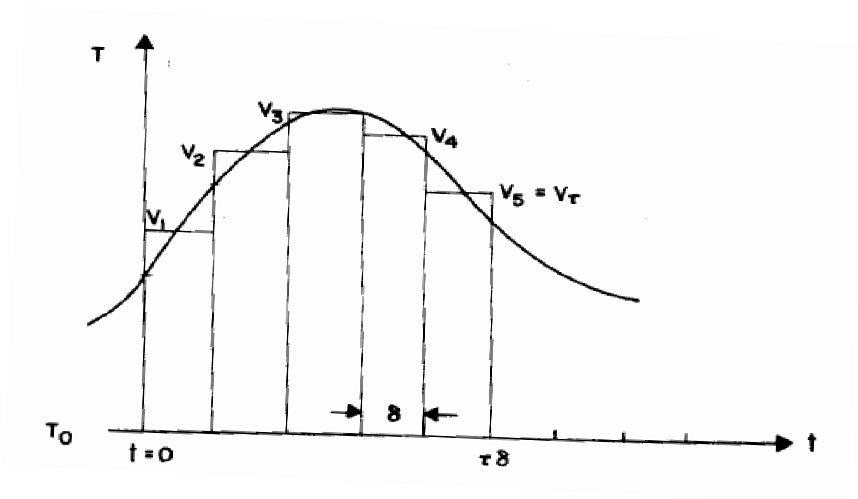


*Figure 5.5.* Rectangular temperature pulses. *Note.* From "Thermal Response Factors for Multi-Layer Structures of Various Heat Conduction Systems," by T. Kusuda, 1969, *ASHRAE Transactions*, *75*, p. 249. Copyright 1969 by ASHRAE (www.ashrae.org). Reprinted with permission.

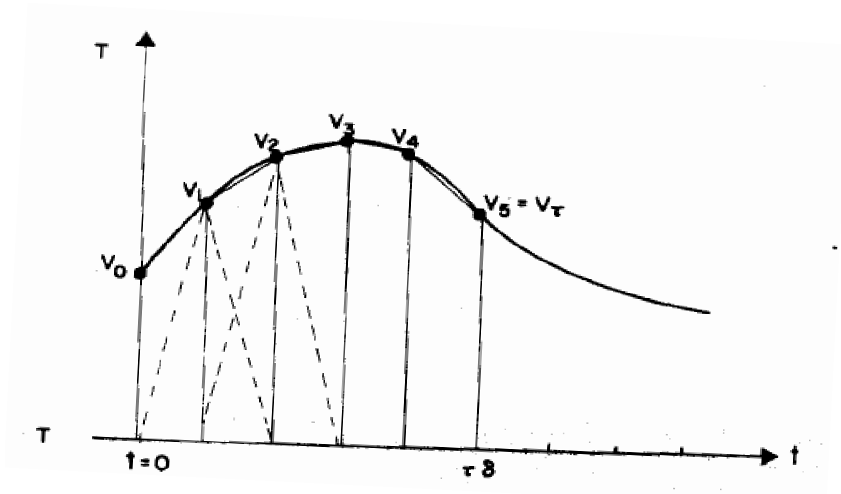


*Figure 5.6.* Triangular temperature pulses. *Note.* From "Thermal Response Factors for Multi-Layer Structures of Various Heat Conduction Systems," by T. Kusuda, 1969, *ASHRAE Transactions*, *75*, p. 249. Copyright 1969 by ASHRAE (www.ashrae.org). Reprinted with permission.

In 1965, G. Mitalas at the National Research Council (NRC) Canada proved that linear mathematical models could be applicable for estimating the thermal behavior in air conditioned rooms (Mitalas, 1965). This study was important because engineers can only use the RFM and the WFM when systems can be expressed by linear equations (Stephenson and Mitalas, 1967).

In 1967, G. Mitalas and D. Stephenson at the NRC Canada developed a new RFM that used P. Hill's triangular pulses for digital computers that applied the RFM for the transient thermal analysis of buildings. G. Mitalas and D. Stephenson's method provided a more accurate analysis than W. Brisken and S. Reque's method that used an analog model of lumped resistances and capacitances (RC) and rectangular pulses (Brisken and Reque, 1956; Mitalas and Stephenson, 1967; Kusuda, 1969). The most important difference is that Mitalas and Stephenson's method can separately estimate convection and radiation rather than combined convection and radiation in a room (Mitalas and Stephenson, 1967). In the same year, a related paper of D. Stephenson and G. Mitalas introduced the application of the RFM for estimating cooling load and surface temperature (i.e., the WFM) (Stephenson and Mitalas, 1967).

Also, in 1967, G. Mitalas and J. Arseneault created a FORTRAN IV program for an IBM-360 computer to calculate RFs for multi-layer walls or roofs. In their program, the heat flux of the multi-layer systems was able to be calculated numerically by inverting a matrix of Laplace transforms, which was introduced by L. A. Pipes in 1957 (Pipes, 1957), with the help of the digital computer when triangular pulses were used to simulate the temperature profile of the transient boundary condition (Mitalas and Arseneault, 1967; Kusuda, 1969). This Laplace transform approach was able to improve the calculation accuracy by the lumped RC approach of Brisken and Reque. (Kusuda, 1969).

In 1969, T. Kusuda utilized G. Mitalas and J. Arseneaults' method to calculate the RFs for analyzing curved exterior surfaces such as cylindrical, spherical buildings, underground pipes, tunnels, and storage tanks (Kusuda, 1969). In 1971, D. Stephenson and G. Mitalas further developed the RFM using CTFs (i.e., finite approach) that was more efficient than the previous RFM regarding speed and memory space of digital computers (Stephenson and Mitalas, 1971; Fisher, 2013).

Finally, in 1971, the RFM using CTFs was adopted by the ASHRAE Task Group on Energy Requirements (TGER) (Lokmanhekim ed., 1971). The ASHRAE TGER recommended the RFM using CTFs and further developed from the RFM to the WFM using another transfer functions (Lokmanhekim ed., 1971; Kusuda, 1985). The RFM could be used to calculate time-varying heat gain using wall RFs and surface temperatures, and the WFM could be used to calculate time-varying cooling load using WFs and heat gain (Lokmanhekim ed., 1971). In the 1970s, engineers preferred the WFM over the more time consuming HBM because the speed and memory of digital computers was limited at the time. (Kusuda, 1985). In 1988, a new method for deciding

CTFs[11] and WFs was suggested through ASHRAE research projects (Harris and McQuistion, 1988; Sowell 1988a, 1988b, 1988c; Spitler and Fisher, 1999).

The original WFs developed in 1967 and 1971, called the pre-calculated WFs, were pre-calculated for typical rooms such as light, medium, and heavy weight constructions to be used to calculate hourly cooling load. The ASHRAE Handbook of Fundamentals contained the pre-calculated WFs in the table (Sowell and Hittle, 1995). The use of pre-calculated WFs reduced the calculation time with a modest loss in rigorousness of the HBM. In 1979, the deficiency of the pre-calculated WFs was improved by Z. Cumali, A. Sezgen, and R. Sullivan at the CCB (Cumali et al., 1979). The new WFs, called the custom WFs, used the actual description data of rooms for calculating cooling load. The algorithms of the custom WFM were included in the whole-building energy simulation program, DOE-2.1 (Kerrisk, 1981; Kerrisk et al., 1981). In the DOE-2.1 program, the custom WFs were generated for time-varying cooling load in each zone (Kerrisk, 1981; Cumali, 2012). The custom WFs consist of heat gain WFs and air temperature WFs. Heat gain WFs are the transfer functions for converting transient heat gains to space cooling load. Air temperature WFs are WFs that are used to calculate the heat extraction rate and air temperature from the net energy load including the cooling load of rooms (ASHRAE, 2009). While the pre-calculated WFs showed some inaccuracy regarding heaving constructed rooms (i.e., lots of thermal mass)

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[11] CTFs procedure, which was described by H. T. Ceylan and G. E. Myers in 1980, John E. Seem in 1987, and Kunze Ouyang and Fariborz Haghighat in 1991, was used for the Heat Balance Method (HBM) of EnergyPlus (Ceylan and Myers, 1980; Seem, 1987; Ouyang and Haghighat, 1991; UIUC and LBNL, 2012).

and rooms affected by a large amount of solar load, the custom WFs showed an improved accuracy for heaving constructed rooms, solar load driven rooms, and even direct gain passive solar rooms (Schnurr et al., 1979; Kerrisk et al., 1980; Kerrisk, 1981). In 2012, Z. Cumali proposed improved algorithms based on the custom WFM, which used a numerical Green's functions (NGFs) solution, to improve the speed of the time-varying load calculations in EnergyPlus (Cumali, 2012).

The TFM or WFM explained in this section is currently used for DOE-2.1e, eQUEST/DOE-2.2, TRACE, and HAP which will be described in Section 5.3.1.2 through 5.3.1.5.

*5.2.1.3 Cooling load temperature difference (CLTD)/solar cooling load (SCL)/cooling load factor (CLF) method*

The CLTD/SCL/CLF method is based on the TFM to calculate the cooling load. This method is a hand calculation with a one-step procedure that does not require the two steps (i.e., the heat gain and cooling load steps such as the TETD/TA method and the TFM or the WFM) (ASHRAE, 1997). The CLTD is used to calculate the conductive cooling loads of walls, roofs, and windows. The Solar Cooling Load (SCL) is used to determine solar radiation cooling load, and CLF is used to calculate internal cooling load of lights, peoples, appliances and equipment (McQuiston and Spitler, 1992).

The CLTD/CLF method was developed by William Rudoy and Fernando Duran at the University of Pittsburg in 1975 (Rudoy and Duran, 1975). This method simplified the TETD/TA and TFM methods by removing the step that converts radiant heat gain to cooling load (ASHRAE, 2001). In 1993, this method was modified to become the

CLTD/SCL/CLF method by J. D. Spitler, F. C. McQuiston, and K. I. Lindsey as ASHRAE Research Project-626 (Spitler et al., 1993). The concept of the Solar Cooling Load (SCL) replaced the CLF for calculating solar radiation cooling load through fenestration. The SCL reduced the unnecessary step of the CLF and enhanced the accuracy for estimating the solar radiation load (McQuiston and Spitler, 1992; Spitler et al., 1993). In addition, the new CLTD/SCL/CLF method improved the effects of zone response due to zone types using the new WFs and CTFs developed by ASHRAE Research Project-472 in 1988 (Spitler et al., 1993). Before ASHRAE Research Project-472, ASHRAE Research Project-359 conducted in 1984 discovered the effects of the zone response (Sowell and Chiles, 1985).

In the genealogy chart, the original CLTD/CLF method and the new CLTD/SCL/CLF method are shown in the big rounded boxes. The TRACE program uses the CLTD/CLF method to size cooling loads.

*5.2.1.4 Heat balance method (HBM)*

The HBM , also called the thermal balance method, is the scientifically strictest method to calculate building cooling loads when compared to the TETD/TA method, the TFM or WFM, and the CLTD/CLF method. The heat balance model has five major assumptions: constant air temperature in a zone, constant surface temperatures, constant long and shortwave irradiation, diffuse radiating surfaces, and one-dimensional heat conduction at the surfaces of the room. In conjunction with these assumptions, the four processes of the heat balance were analyzed: outside surface heat balance, wall conduction, inside surface heat balance, and air heat balance (Pedersen et al., 1997). Figure 5.7 shows the connections between the four processes.

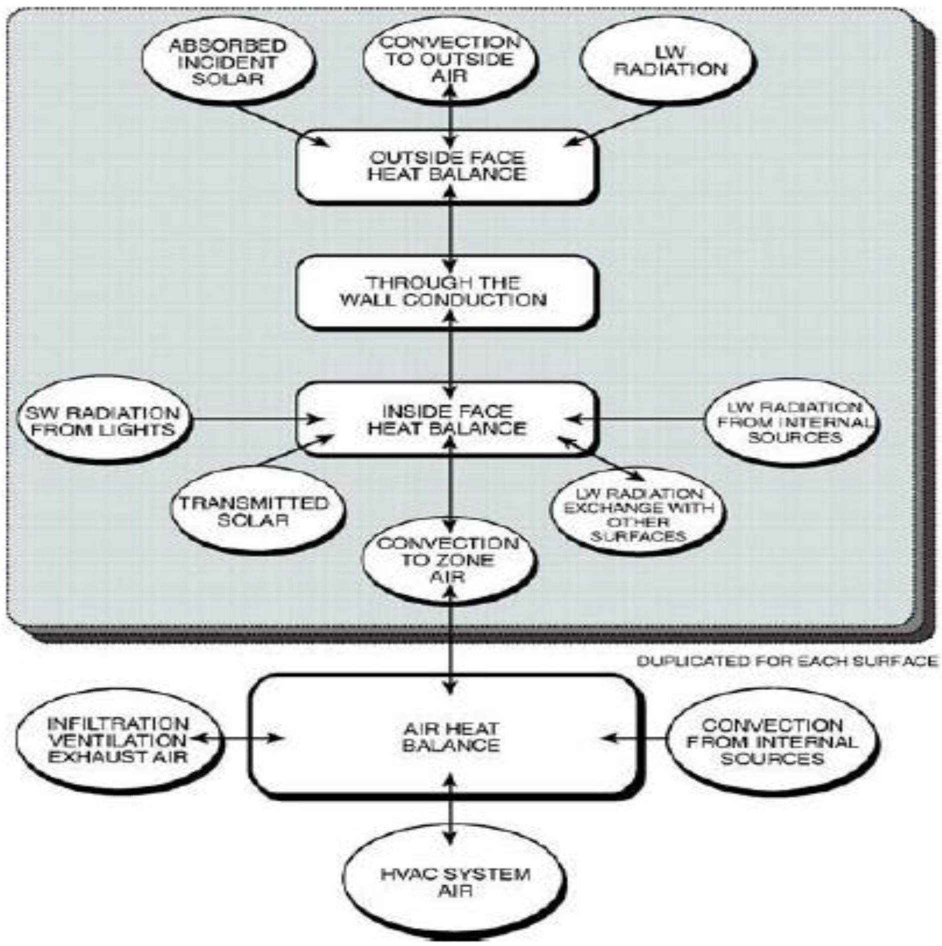


*Figure 5.7.* Schematic of heat balance processes in zone. *Note.* From "Nonresidential Cooling and Heating Load Calculations," by Technical Committee 4.1, 2009, *ASHRAE Handbook of Fundamentals*, p. 18.16. Copyright 2009 by ASHRAE (www.ashrae.org). Reprinted with permission.

Three processes of the outside surface heat balance, the wall conduction, and the inside face heat balance are calculated for each surface in the zone at the same time. For the wall conduction, the Conduction Transfer Functions (CTFs), which was previously described in Section 5.2.1.2, are used to calculate the instantaneous heat gain through walls. The air heat balance procedure interacts with the heat convection to zone air obtained from the three processes for each surface in the zone. The cooling load is provided by the air heat balance procedure (ASHRAE, 2009).

The advantages of the HBM are that it does not require the simplifying assumptions of the linear superposition that were used for the WFM or TFM, and the HBM can analyze changing parameters such as heat convection coefficients at the surfaces in the zone and transient solar variables that reach into the zone or room (Sowell and Hittle, 1995). Above all, the procedures in the HBM do not hide the fundamental processes for accurately calculating each step without risky errors (Pedersen et al., 1997).

The development of the HBM is shown in the first shaded area from the top in Figure A.2. An abbreviation, HBM, in the small, rectangular boxes indicates the HBM at the bottom of the event boxes. The original fundamentals of the HBM were established by N. Carnot, R. Clausius, and E. F. Obert. One of the fundamentals of the HBM was the first law of thermodynamics, developed by Clausius in 1851. This principle was based on Carnot's study about cycles relating heat and work (Donaldson et al., 1994; Pedersen, 2009). Clausius divided the cycles into minute parts and additionally proposed internal energy. Inexact differentials were used for heat and work, and an exact differential was used for energy in the first law. In 1960, this concept was modified by Obert. He developed a new concept for the first law by introducing time as the independent variable. Thus, in the first law of Obert, heat and work were also considered as exact differentials. In other words, Obert defined the first law based on time of the independent variable (Obert, 1960; Pedersen, 2009). Aerospace and other types of engineers have widely used general heat balance models in their research (Sowell and Hittle, 1995). The first application for buildings that used a complete method form of the HBM was developed by Kusuda for the National Bureau of Standards Load Determination (NBSLD) program (Kusuda, 1976; Sowell and Hittle, 1995; Pedersen et al., 1997). Kusuda studied the thermal network approach proposed by Buchberg in 1958 to improve the HBM (Kusuda, 1999). The ASHRAE Task Group on Energy Requirements (TGER) outlined the heat balance algorithm for computer programs in 1975 (ASHRAE, 1975a). Following the development of the NBSLD, in 1977 and 1983, BLAST[12] and TARP[13] also employed the HBM. Finally, in 1997, ASHRAE Research Project-875, sponsored by Technical Committee 4.1, organized the current HBM for the cooling load calculation and procedure (Pedersen et al., 1997). In the HBM, an improved CTFs procedure, which was described by H. T. Ceylan and G. E. Myers in 1980, John E. Seem in 1987, and Kunze Ouyang and Fariborz Haghighat in 1991, was used to calculate dynamic heat gain through walls and roofs (Ceylan and Myers, 1980; Seem, 1987; Ouyang and Haghighat, 1991; UIUC and LBNL, 2012). The origins of the CTFs were described in Section 5.2.1.2. The HBM[14] was used for calculating cooling load in

[12] In 1977, the U.S. Army Construction Engineering Research Laboratory (CERL) developed the Building Load Analysis and System Thermodynamics (BLAST) program using the modifications of CERL’s first simulation program (i.e., TASS) and new program code.

[13] In 1983, National Bureau of Standards (NBS, now NIST) developed Thermal Analysis Research Program (TARP) using the heat balance algorithms proposed by ASHRAE in 1975.

[14] The HBM calculates heat gain and cooling load at the same time (i.e., no break), whereas the TFM and the RTS method have a break between heat gain and cooling load calculation (Fisher, 2013).

EnergyPlus, the whole-building energy simulation program, released in 2001 (Crawley et al., 2002).

*5.2.1.5 Radiant time series (RTS) method*

The RTS method is directly simplified from the HBM and is therefore more rigorous than other simplified (i.e., non-heat-balance based methods) cooling load calculations (i.e., the TETD/TA method, the TFM or WFM, and the CLTD/SCL/CLF method). The RTS method does not need iterative calculations such as the TFM or WFM. Also, engineers can easily inspect the coefficients of the radiant time series (i.e., the radiant time factors) for various zone types (Spitler et al., 1997).

The RTS method consists of two series of calculations, as is case for the TFM or WFM and the TETD/TA method. The first is to calculate time-varying heat gain and the second is to calculate cooling load using the heat gain. The RTS method uses conduction time series (CTS) for calculating time-varying heat gain through walls and roofs and radiant time factors (i.e., the RTS coefficients) for calculating the radiant part of the cooling load. The convective part of the cooling load that does not require the radiant time factors (RTFs) is later combined with the radiant part of the cooling load to generate the total cooling load for a particular hour (ASHRAE, 2009).

The development of the RTS method is shown in the first shaded area from the top in the 1991-2000 section and the 2001-2010 section of Figure A.2. An abbreviation, RTS, in the small, rectangular boxes indicates the RTS method at the bottom of the event boxes. In 1997, Jeffrey D. Spitler, Daniel E. Fisher, and Curtis O. Pedersen proposed the RTS method as the part of the ASHRAE Research Project-875 (Spitler et al., 1997). In

2001, the ASHRAE Fundamentals Handbook adopted the RTS method with the HBM instead of the TETD/TA method, the TFM or WFM, and the CLTD/SCL/CLF method (ASHRAE, 2001). As mentioned above in this section, the RTS method uses CTS and RTFs for calculating each heat gain and cooling load. The origins of CTS started from the development of response factors (RFs) and conduction transfer functions (CTFs). The origins of RFs and CTFs were described in Section 5.2.1.2. The RFs were changed to periodic response factors (PRFs) in the RTS method. PRFs are a simplified version of response factors, which use a set of 24, for a steady periodic input (Spitler et al., 1997). In 1999, Spitler and Fisher showed the PRFs can be generated from CTFs using the assumptions of steady periodic heat input conditions (Spitler and Fisher, 1999). Finally, the CTS were formed from the further simplification of the 24 periodic response factors, divided by the overall U factor of walls or roofs (ASHRAE, 2001).

In 1997, the RTFs for calculating the radiant cooling load were described by J. Spitler, D. Fisher, and C. Pedersen (Spitler et al., 1997). The RTFs was directly generated by the HBM as the purpose of the RTS method that was to offer the simplified method from the HBM (ASHRAE, 2001). In 1998, Pedersen et al. developed a computer program based on the HBM, called Hbfort, to generate the RTFs (Pedersen et al., 1998). The approach for creating RTFs is similar to the approach for generating the custom weighting factors using the DOE-2.1 program (ASHRAE, 2001).

#### *5.2.2 The analysis methods of solar system analysis simulation or design*

Solar energy analysis programs evaluate the performance of solar systems that are designed to collect and use solar radiation for thermal or electricity conversion.

These programs are used for simulations and design methods: Computer simulations estimate the time-dependent short-term and long-term performance of solar energy systems in detail, and design methods analyze the long-term average performance of solar energy systems with less calculation work than simulations (Klein, 1993). Design methods are useful for engineers to choose and size solar systems when input data and solar irradiation have high uncertainty (Evans et al., 1982).

In this study, the solar design methods were mainly investigated. The analysis methods for detailed solar simulation programs are described in Section 5.2.2.1, and the design methods for solar design programs (i.e., simplified programs) are explained from Section 5.2.2.2 to 5.2.2.4. The development of the analysis methods and the design methods for solar energy programs is shown in the third shaded area from the top in the pre-1950 section to the 1981-1990 section of Figure A.2 in Appendix A. In Figure A.2, the abbreviations explained by Figure A.1 in the small, rectangular boxes indicate the analysis method represented in the event box.

*5.2.2.1 The analysis method of detailed simulation programs*

In 1972, due to a national direction toward solar energy employment, the first solar energy simulation programs under U.S. government funding were developed with the sponsorship of the National Science Foundation (NSF) and the U.S. Energy Research and Development Administration (ERDA, now the U. S. Department of Energy (US DOE)). The simulation programs included TRNSYS developed by the University of Wisconsin-Madison and several programs by the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) (Kusuda, 1985; Beckman, 1993). In 1975, the TRNSYS program, which was initially developed as a public domain program, was first publically released by the Solar Energy Laboratory (SEL) at the University of Wisconsin. The LASL programs were not fully documented and were used as research tools (Beckman 1993). One of the LASL programs was PASOLE, which stands for PAssive SOLar Energy. The PASOLE program was used for developing the Solar Load Ratio (SLR) method, a design method, for passive solar heating applications (McFarland, 1978; Feldman and Merriam, 1979).

These simulation programs for solar energy applications used a thermal network approach to solve the time-varying heat transfer problem. This is because the analysis of a solar heating system on a building requires both an analysis of the time-varying conditions of the house and the time-dependent solar radiation being collected by the solar system, including the heat storage effect (Kusuda, 1985). Also, the use of thermal networks had been shown to be useful in accounting for transient time variation or temperature dependent values (Niles, 1992). However, the thermal network approach had limitations for calculating the heat balance in rooms and estimating HVAC systems used in large-size commercial buildings (Kusuda, 1985).

Before researchers used digital computers to analyze buildings that also have solar energy systems with the thermal network approach, electrical components were used in analog circuits because the building thermal components were similar to electrical circuit components in the thermal network method (Niles, 1992). In 1974, Peikari explained the electrical network fundamentals (Peikari, 1974). In 1977, Kimura also discussed the thermal networks for buildings (Kimura, 1977). After the advent of the digital computers, numerical methods were used for thermal network programs to enhance analysis accuracy. The finite difference method of the numerical approach can algebraically use the equations to simultaneously or iteratively solve them (Niles, 1992). In 1979, the PASOLE program, which was introduced by McFarland used the implicit method of the finite difference method; and in 1983, the SERIRES program (now, SUNREL), which was developed by Larry Palmiter and Terry Wheeling, used the explicit method of the finite difference method (McFarland, 1978; Palmiter and Wheeling, 1983; Niles, 1992).

*5.2.2.2 Active solar system design method*

Active solar systems consist of solar collectors, storage components, fluid transport equipment, loads, heat exchangers, auxiliary systems, and other devices (Duffie, 1993). Domestic water heating systems are typical examples of the active solar systems. In this study, the development of analysis methods used in the F-Chart program, which is based on TRNSYS simulation, was summarized and traced.

5.2.2.2.1 Utilizability method

The utilizability method was developed to analyze the incident solar radiation that reaches the surface of a solar system. The utilizability method was first proposed by Whillier in 1953 to analyze flat-plate solar collectors (Whillier, 1953a, 1953b). The method was later extended to estimating concentrating collectors, passive and photovoltaic systems (Klein, 1993). The solar radiation that reaches a collector can be expressed in Figure 5.8. Sequence A represents three average days, while sequence B indicates a clear, an overcast, and an average day. $I_{c,1}$ is the critical level which is used to calculate the daily utilizability. $I_{c,2}$ would be a higher critical level that might represent a thermal use with a higher temperature. The utilizable incident solar radiation on the collectors is indicated as the area above the critical level. The solar radiation area below the critical level represents the thermal losses of solar collectors, and the area above the critical level represents the "utilizable" part of the absorbed solar radiation (Klein, 1978; Klein, 1993).

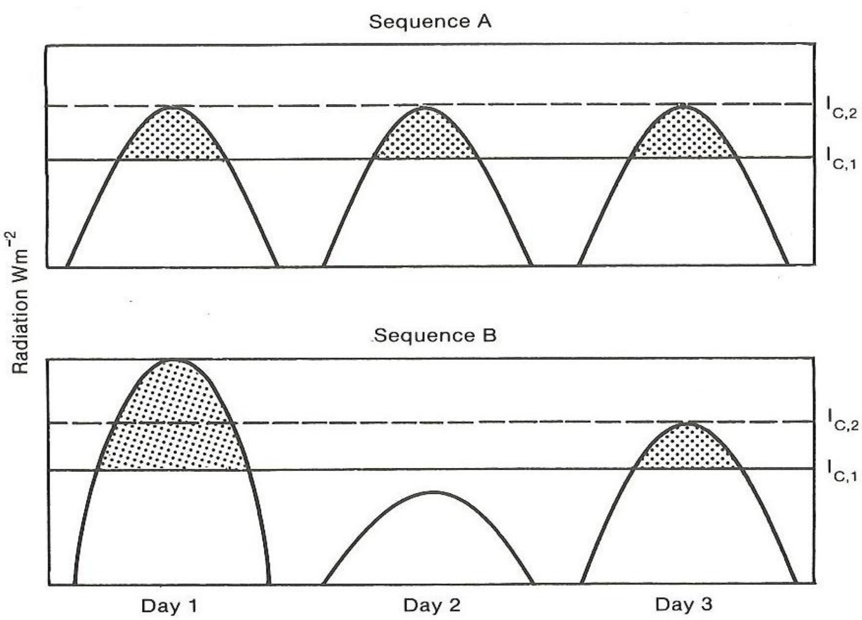


*Figure 5.8.* Effect of radiation distribution on the monthly average daily utilizability. *Note.* From "Calculation of Flat-Plate Collector Utilizability," by S. A. Klein, 1978, *Solar Energy*, p. 395. Copyright 1978 by Elsevier. Reprinted with permission.

The utilizability method considers the critical insolation level as a constant level. However, usually most active solar systems have variable critical levels due to the effects of their thermal storage units and the ambient temperature. Thus, correction factors for compensating for the errors generated by assuming a constant critical level were developed, and correlations for the correction factors were obtained by TRNSYS simulation results. The correlation method improved the utilizability method and enhanced the accuracy of the F-Chart method, which will be explained in the next section, 5.2.2.2.2.

The development of the utilizability method is shown in the third shaded area from the top from the pre-1950 section continuing over to the 1981-1990 section of Figure A.2. An abbreviation, UT, in the small, rectangular boxes indicates the utilizability method at the bottom of the event boxes. In 1953, Whillier proposed the first utilizability concept for evaluating flat-plate solar collectors to shorten the calculation for analyzing the collectors, as part of his Ph.D. dissertation, at the Massachusetts Institute of Technology (MIT), under Prof. Hottel's direction (Whillier, 1953b). Before this study, Hottel and Woertz developed the fundamental equations for flat-plate solar collectors (Hottel and Woertz, 1942; Hottel, 1950). In 1955, Hottel and Whillier presented their work (i.e., equations for solar collectors and the utilizability method for the solar radiation incident) at a conference on the use of solar energy (Hottel and Whillier, 1955). The equations they used for collectors represented how much useful solar energy could be collected according to the collector and operating variables. The variables they used for the collectors are $F_R(\tau\alpha)$ and $F_RU_L$ (where $F_R$ = heat removal efficiency, $\tau\alpha$ = suitable mean value of the product of the effective transmittance of the glass cover plates and the absorptivity of the blackened receiver, $U_L$ = overall collector heat loss coefficient) (Whillier, 1953b). The critical level for determining the utilizable part of the solar radiation incident on the collectors was defined using the variables for the collectors. Finally, the utilizability ($\emptyset$) equation was obtained from a function of the critical level if the solar radiation data is sufficiently available (Klein, 1993).

In 1963, Liu and Jordan generalized Whillier's utilizability method (Liu and Jordan 1963). In Whillier's utilizability curves, introduced in his dissertation in 1953, he indicated that the plots of utilizability could be expressed as the calculated utilizability obtained from the utilizability equation versus the ratio of the critical level to the long-term average hourly radiation. Whillier also showed utilizability could be determined for each hour from solar noon because it symmetrically divided the distribution of solar radiation as shown in Figure 5.8. The limitation of this simplification was that the utilizability method could not be applied to locations where there was morning fog or large mountains (i.e., location-dependent utilizability) (Whillier, 1953b; Haberl and Cho, 2004a). Using Whillier's utilizability curve method, Liu and Jordan's studies proposed a cloudiness index in order to create a location-independent utilizability curve method (Klein, 1993). The cloudiness index depended on the turbidity and cloudiness of an atmosphere. Liu and Jordan's study in 1960 proved that the cloudiness index was the main parameter that affected the sum of the distribution of daily solar radiation upon a horizontal surface (Liu and Jordan, 1960). Also, Liu and Jordan studied the effects of collectors that have tilted surfaces using the utilizability curves (Liu and Jordan, 1963). In 1980 and 1981, Theilacker and Bendt et al. validated Liu and Jordan's studies with advanced computers and enough solar radiation data because Liu and Jordan's studies were conducted during a period when the capabilities of computers were more limited and they use insufficient solar radiation data (Theilacker, 1980; Bendt et al., 1981).

The disadvantages of Liu and Jordan's utilizabiliy curves were that there were no analytical methods to express the utilizability curves, and the utilizability curves were focused only on surfaces of collectors facing the equator. In 1983, Hollands and Huget developed an analytical equation for utilizability (Hollands and Huget, 1983). Even though the algebra of their calculations was complicated, a computerized calculation for any orientation surfaces was developed from the algebra (Klein and Beckman, 1984). In the same year, Clark et al. developed a correlation method for utilizability, which was used for any array orientation (Clark et al., 1983). This computerized method was algebraically simpler than Hollands and Huget's method with similar accuracy (Klein and Beckman, 1984).

In addition to the hourly utilizability method, there was also a daily utilizability method. While the hourly utilizability represented the utilizable part of the solar radiation during an hourly period of a specific day, a daily utilizability represented the average utilizable part of the solar radiation from the sunrise and sunset period for a month (i.e., this is often called the monthly-average daily utilizability). In other words, the daily utilizability represented the average solar radiation for each month beyond the critical level during the period between the rise and fall of sun. In order to use the daily utilizability concept, the critical level of the solar radiation distribution was considered as an hourly constant during the entire day. These improved methods for estimating the daily utilizability were developed even though there was an equation for evaluating the daily utilizability using the radiation-weighted average of the hourly utilizability values during all daylight hours (Klein and Beckman, 1984). In 1978, Klein proposed a correlation method for the daily utilizability, where he used curve-fitted values to develop the daily utilizability correlation and hourly radiation data obtained from Liu and Jordan's statistical data, which was given by their study in 1960, instead of using actual radiation data. Klein's daily utilizability chart reduced the calculation efforts and was easily implemented in automated computer programs. The limitation of this method was that it could be applied to only surfaces headed for the equator (Klein, 1978). In 1979, Collares-Pereira and Rabl developed long-term average energy models using the daily utilizability correlations to estimate the utilizable solar radiation on flat-pate collectors, compound parabolic concentrator (CPC), and tracking collectors for east-west, polar, and two-axis tracking axis. In order to analyze all these collectors, the models considered the operating temperature used in the solar collectors (Collares-Pereira and Rabl, 1979).

In 1980, Theilacker proposed a new correlation method that simplified and improved the accuracy of Klein's correlation method developed in 1978. This new method was also applicable to surfaces facing the equator like Klein's method, but it added new correlations for surfaces shaded by overhangs and vertical surfaces facing east and west (Theilacker, 1980; Theilacker and Klein, 1980).

In 1981, Klein et al. developed new tables for vertical surfaces facing south by using the monthly utilizability obtained from Theilacker's correlation method (Klein et al., 1981; Klein and Beckman, 1984). Then, in 1982, Evans et al. developed a new method that used the actual collector parameters instead of using the critical level. This method used an empirical approach for the monthly average utilizability to analyze flat-plate collectors, especially for tilted collectors facing south, and the collector efficiency. This empirical approach could quickly determine the results according to the changes of location, design and inlet temperature of collectors (Evans et al., 1982).

The utilizability concept explained in this section is currently used for the F-Chart program developed in 1982, which will be described in Section 5.3.2.1.1.

5.2.2.2.2 F-Chart method

The f-chart method is used to estimate active solar space heating systems and solar domestic hot water systems. The F-Chart method is a correlation that uses results from over hundreds of simulation runs using TRNSYS, which is a detailed transient thermal simulation program, to create the fraction, f (Beckman et al., 1977). The fraction of the heating load for each month, which will be provided by solar energy, represents f. The f was developed for defined solar heating systems. The process for gaining the f values is parallel to the approach of other engineer fields that make correlations of multiple physical measurements. The f-chart method is usually presented as two dimensionless variables that are important parameters of solar heating systems (Figure 5.9): The X variable represents the ratio of reference collector energy loss during a month to total heating load during the same month, and the Y variable represents the ratio of total energy absorbed on the solar collector during a month to the total heating load during the same month (Klein, 1993). Figure 5.9 and Figure 5.10 show the interrelation between f, X, and Y of the solar heating systems using liquid fluids or air fluids.

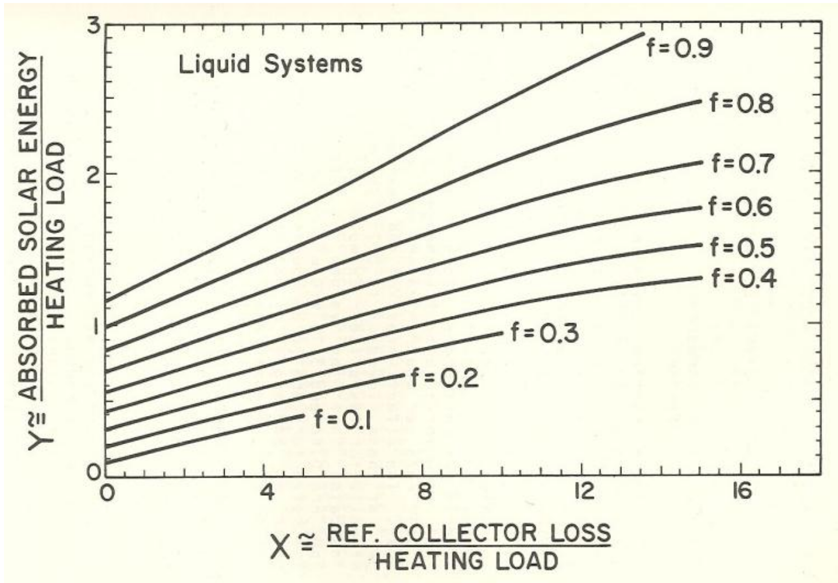


Figure 5.9. F-chart for liquid systems. *Note.* From “Chapter 5. Long-Term Performance of Solar heating Systems,” by W. A. Beckman, S. A. Klein, and J. A. Duffie, 1977, Solar Heating Design by the F-Chart Method, p. 59. Copyright 1977 by John Wiley & Sons, Inc. Reprinted with permission.

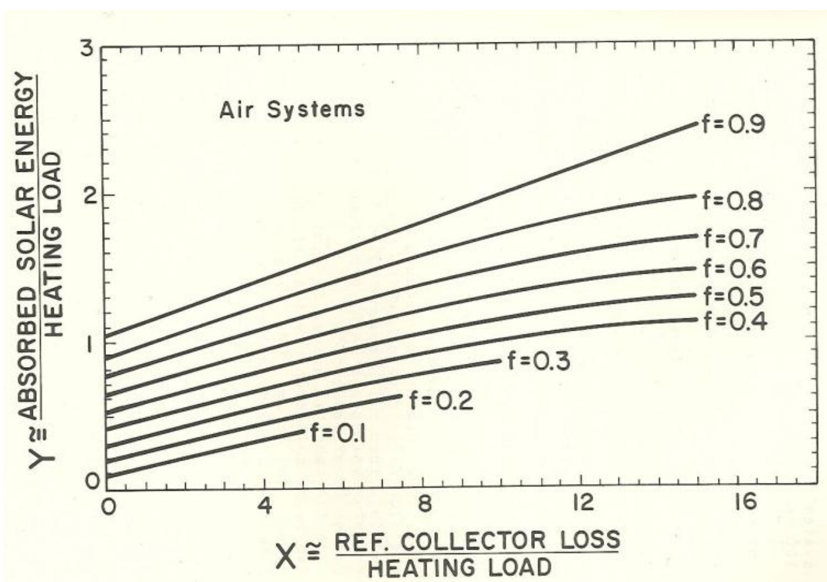


*Figure 5.10.* F-chart for air systems. Adapted from “Chapter 5. Long-Term Performance of Solar heating Systems,” by W. A. Beckman, S. A. Klein, and J. A. Duffie, 1977, Solar Heating Design by the F-Chart Method, p. 75. Copyright 1977 by John Wiley & Sons, Inc. Reprinted with permission.

In order to gain the fraction of the annual heating load generated from solar energy, F (i.e., F indicates the annual heating load fraction by solar energy, and f means the monthly heating load fraction by solar energy), X and Y are obtained for each month. The value of f, then, is determined by the location of the intersection of the X variable and Y variable for each month. Finally, the value of F is calculated by a function of f and the sum of the monthly total (i.e., space and water) heating loads. In the f-chart method, the fluid flow rate of the collector, the capacity of the thermal storage, and the size of the load heat exchanger are considered as constant values (Klein, 1993).

The solar energy community used the f-chart method widely in order to design new systems and analyze the performance of existing systems. However, the f-chart method has the following disadvantages: a) erroneous results may be produced when the f-chart method is used for solar systems other than the standard type of systems for which the f-chart method was initially developed, b) the f-chart method was basically developed for an ideal system performance estimation and therefore cannot predict the performance of actual systems that have system characterizations that vary from the original simulations, c) the f-chart method does not account for small amounts of energy use required to run controllers, pumps, and fans, and d) ambient solar radiation and monthly solar radiation are only inputs for the f-chart method in term of the meteorological information. Therefore, for sites where the input data are not available, data from nearby sites must be used. The utilizability method, introduced in Section 5.2.2.2.1, more generally accounts for the solar radiation data in detail rather than the f-chart method (Klein, 1993).

The development of the f-chart method is shown in the third shaded area from the top in the 1971-1980 section of Figure A.2. In 1976, Klein developed the f-chart method (Klein, 1976; Beckman et al., 1977). The f-chart method was further developed for customary types of active solar systems such as active domestic hot water systems (i.e., two-tank domestic water heating systems), pebble bed storage space and domestic water heating systems, and water storage space and domestic water heating systems.

In 1979, Klein and Beckman developed the monthly utilizability, f-chart method to extend the f-chart concept to other applications such as concentrating solar collectors (Klein and Beckman, 1979). To accomplish this, they used the monthly utilizability concept introduced in the previous section to generalize the f-chart method. In 1981, Klein and Theilacker proposed a method to estimate radiation data for the tilted surface of collectors using horizontal solar radiation data because the solar radiation incident on the collector plane was only for horizontal data (Klein and Theilacker, 1981). In 1983, Braun et al. expanded the monthly utilizability, f-chart method for close-loop solar energy systems, developed by Klein and Beckman in 1979, to the monthly utilizability, f-chart method for open-loop systems (Braun et al., 1983).

Even though the f-chart method was developed to reduce computational effort compared to the detailed simulation programs, this method still required substantial computational efforts due to the repetition for the correlation. Thus, various researchers developed simpler correlation methods that used the results of the f-chart method (Klein, 1993). In 1976, Ward developed a new correlation for solar space heating systems with water storage that used three collector types (Ward, 1976). In 1978, Barley and Winn proposed a correlation that calculated the annual solar fraction for varying to space and domestic water heating systems (Barley and Winn, 1978). In the same year, Lameiro and Bendt proposed a new correlation method, called as the GFL method, for analyzing the annual solar fraction. In 1980, Wright developed four graphs obtained from the results of a correlation by the f-chart method in order to further simplify the analysis of actual solar domestic hot water system performance (Wright, 1980). In 1982, Kreider et al. also developed a correlation of the annual solar fraction using the f-chart method that was similar to the previous correlation methods. This correlation method was called as the W-Chart method (Kreider et al., 1982). These correlation methods, which were based on the f-chart method, became restrictive because, after the mid-1980s, advanced personal computers were able to quickly calculate the models of the f-chart method (Klein, 1993).

Other researchers extended the f-chart method because it was initially developed for only three types of active solar systems as earlier mentioned. In 1979, Jurinak and Abdel-Khalik performed simulations for air-based solar heating systems using the TRNSYS program, which led to correlations for air type systems. In their study, a correction factor obtained from the simulation results was then applied to the f-chart method for estimating phase change energy storage systems (Jurinak and Abdel-Khalik, 1979). In 1980, Buckles and Klein developed a modified f-chart method to analyze domestic hot water systems that used for a single tank system. Originally, the f-chart method was proposed for domestic hot water systems with two tank systems (Buckles and Klein, 1980). In the same year, Anderson et al. conducted a study concerning parallel solar heat pump systems. They used the results of simulations to propose a design method for the systems. This design method utilized the f-chart method to calculate the fraction of the monthly solar energy load (Anderson et al., 1980). In 1985, Evans et al. performed simulations for active-passive hybrid space heating systems using the TRNSYS program. Their simulation results developed a new correction factor that could be applied to the f-chart method for analyzing the hybrid active-passive space heating systems (Evans et al., 1985).

The F-Chart method explained in this section is currently used for the F-Chart program developed in 1982, which will be described in Section 5.3.2.1.1.

*5.2.2.3 Passive solar system design method*

Passive solar systems use solar heating directly (i.e., without pumps, blowers, etc.) and sometimes include natural passive cooling. Passive solar systems require simpler and less expensive equipment than that of active solar systems. However, passive systems for heating need large areas that receive and store solar energy, and the systems may not be able to effectively store solar energy for long periods (Evans et al., 1985). In this study, the development of design methods related to the PASOLE program and the F-Chart program was summarized and traced.

5.2.2.3.1 Solar Load Ratio (SLR) method

The SLR method was developed to use for passive solar systems in a condition without an active solar system. The SLR method was initially developed for estimating the required solar collector array size for space heating by Balcomb and Hedstrom in 1976 (Balcomb and Hedstrom, 1976). They correlated the results from a detailed simulation program, PASOLE, which will be discussed in Section 5.3.2.2.2. This correlation method was divided into a detailed and a simplified type. The detailed method used the simulation results of system performance for each month, such as the approach for the development of the f-chart method (Klein, 1993). The SLR was determined using simulations as the ratio of the solar radiation incident on the collectors to the building load for each month. After calculating the SLR, the monthly solar fraction was obtained as a function of the SLR. Also, an annual solar fraction could be calculated using the load-weighted average of the monthly solar fractions, similar to the procedure of the f-chart method (Klein, 1993). The simplified method, the SLR method, used an annual calculation, which used a table that contains the ratio of the heating load to the collector for annual solar fractions. These tabulated values were obtained from the results of the detailed hourly simulations using PASOILE (Balcomb and Hedstrom, 1976). However, the SLR method was applicable only for standardized systems (Klein, 1976; Klein 1993).

The development of the SLR method is shown in the third shaded area from the top in the 1971-1980 section of Figure A.2. An abbreviation, SLR, in the small, rectangular boxes indicates the SLR method at the bottom of the event boxes. In 1976, Balcomb and Hedstrom developed the SLR method for estimating the required solar collector array size for space heating. In 1978, Balcomb and McFarland proposed the SLR method for passive solar heated walls (Balcomb and McFarland, 1978). In 1981, Schnurr et al. proposed an extension to the SLR method. This extended method was used for estimating space and water heating systems used in commercial buildings. In the use of the results from the DOE-2 detailed simulation program, new correlations were developed for these space and water heating systems (Schnurr et al., 1981). In the same year, Arney et al. proposed the P-Chart, which is a simplified method of the SLR method, to optimize passive system size and predict annual solar fraction (Arney et al., 1981). In 1984 and 1988, Balcomb et al. defined a new SLR method to specifically analyze passive solar systems (Balcomb et al., 1984; Balcomb and Wray, 1988).

In general, the SLR method was widely received, and tabulated SLR values can still be seen in popular textbooks such as the Mechanical and Electrical Equipment for Buildings (Grondzik et al., 2010). However, another new method, called the un-utilizability method that will be described in the next section, was developed because the SLR method had limitations.

5.2.2.3.2 Un-utilizability method

The un-utilizability method utilizes the monthly utilizability concept to measure the solar energy amount that does not reduce ancillary heating load for calculating heating loads stored in a building structure (i.e., passive solar system) (Monsen and Klein, 1980; Monsen et al., 1981). The un-utilizability method improved the limitations of the SLR method, explained in the previous section, in terms of direct gain systems and collector-storage walls. This is because the SLR method could not account for the building capacitance effects, interior temperature fluctuation, or alternating room temperatures, night insulation, and solar absorptance (Monsen et al., 1982).

The development of the un-utilizability method is shown in the third shaded area from the top in the 1981-1990 section of Figure A.2. An abbreviation, Un-UT, in the small, rectangular boxes indicates the un-utilizability method at the bottom of the event boxes. The roots of the un-utilizability are the same as those of the utilizability method for estimating active solar heating systems, which began with the studies of Whillier, Liu and Jordan, and were then expanded and modified by Klein, and Theilacker and Klein between 1953 and 1980. These studies were summarized in section 5.2.2.2.1.

In 1980, Monsen and Klein developed the un-utilizability method for passive solar systems (Monsen and Klein, 1980; Monsen et al., 1981). In this method, they applied the un-utilizability concept to estimate the performance of direct solar gain systems. In 1981, Monsen et al. further developed the un-utilizability method to analyze collector-storage walls (i.e., thermal storage walls). In the same year, Klein et al. proposed tables for simplifying the un-utilizability procedure (Klein et al., 1981). In addition, Theilacker et al. extended this method for estimating vertical surfaces with an overhang, facing south (Theilacker et al., 1981; Jones and Wray, 1992).

The un-utilizability method explained in this section is currently used for the F-Chart program developed in 1982, which will be described in Section 5.3.2.1.1.

*5.2.2.4 Solar photovoltaic (PV) design method*

Solar PV, also called solar cells, converts sunlight (i.e., solar radiation) directly into electricity. The PV F-Chart program (Klein and Beckman, 2001b), which is based on the utilizability method, the F-Chart method, and Clark et al.'s method (Clark et al., 1984), can be used to evaluate the monthly performance of PV systems. In this study, the development of the design method used in the PV F-Chart program is summarized and traced in the following section.

A detailed method provides a short-term (i.e., hourly or less than an hour) analysis with short-term weather and specific location data, but a simplified method (i.e., a design method) achieves a long-term (i.e., monthly average) estimation.

5.2.2.4.1 PV design method

The design method used in the PV F-Chart program also makes use of the utilizability method, and is generally based on Siegel et al. and Clark et al.'s methods (Klein and Beckman, 2001b). The detailed origins of the development of the utilizability method were explained in section 5.2.2.2.1.

The development of the design methods of the PV-F Chart program is shown in the third shaded area from the top in the 1981-1990 section of Figure A.2. An abbreviation, PV, in the small, rectangular boxes indicates the PV design method at the bottom of the event boxes. In 1981, Siegel et al. developed a simplified method to analyze the monthly-average PV performance. The methods for estimating monthly average daily PV array output (i.e., electrical output), excess array capacity, and battery storage were presented in this study. Siegel et al's method used the TRNSYS compatible subroutines developed by Evans et al. in 1978 to estimate PV performance data, which were then compared to the results of the TRNSYS simulations (Evans et al., 1978; Siegel et al., 1981). Before this study, a method for the long term, monthly average PV array output was proposed by Evans in 1980 (Evans, 1980). Also, a method for the excess array capacity was developed by Gupta and Young. Gupta and Young predicted the excess capacity of the array by using Liu and Jordan's utilizabilty method developed in 1963 (Gupta and Young, 1980; Siegel et al., 1981). However, Siegel et al's method for the excess capacity used Klein's utilizability method developed in 1978 that used the monthly average daily utilizability because Klein's utilizability method had more computation efficiency than Liu and Jordan's original utilizability method (Klein, 1978; Siegel et al., 1981). For estimating the battery charge/discahrge, Siegel et al. used Shepherd's battery model proposed in 1965 as well as the model of a 2-V battery cell explained by Evans et al. in 1978 (Shepherd, 1965; Evans et al., 1978; Siegel et al., 1981).

In 1984, Clark et al. presented a design method for estimating PV systems to improve the design methods developed by Evans and Evans et al. in 1980 (Clark et al., 1984). Evans's method accounted for the average PV array output without energy storage capacity using a computational method and graphs. Evans et al.'s method considered the effect of energy storage capacity for estimating the solar load fraction of PV systems by using graphs (Evans, 1980; Evans et al., 1980).

In preparation for the coming wide-spread availability of personal computers (i.e., microcomputers), Clark et al's design method presented a proper computational method by an analytical method for predicting PV systems with or without storage capacity (Clark et al., 1984). Clark et al.'s method adopted their previous study in 1983 in order to estimate the PV system performance without battery storage capacity. The previous study presented the algorithm of the hourly utilizability function rather than the daily utilizability function used in Siegel et al's method. The hourly utilizability function allowed Clark et al.'s method to be used for analyzing hourly loads in the PV systems (Clark et al., 1983; Clark et al., 1984).

The PV design method explained in this section is currently used for the PV F-Chart program developed in 1983, which will be described in Section 5.3.2.3.1.

### *5.2.3 The analysis methods of lighting and daylighting analysis simulation*

Historically, daylighting analysis programs have used three components in order to calculate the daylight coming through a window or skylight: the Sky Component (SC), the External Reflected Component (ERC), and the Internal Reflected Component (IRC). For this study, the methods for IRC were traced and analyzed. In particular, the development of the IRC methods used in DAYSIM, Radiance, EnergyPlus, DOE-2, and Lumen Micro was summarized and traced.

#### *5.2.3.1 Split flux method*

The Split flux method is used for calculating the IRC, which is one of the components of the daylight factor (DF) method (Bryan and Clear, 1980). According to Bryan and Robert, "… the daylight factor is defined as the ratio between the daylight illumination at a point in the interior and the simultaneous exterior illumination available on a horizontal surface from an unobstructed sky (excluding direct sunlight) expressed as a percentage" (Bryan and Clear, 1980, p.1).

Figure 5.11 shows three paths of light that reach a point on a horizontal work surface: the sky light (the Sky Component (SC)), the reflected light from external obstacles (the External Reflected Component (ERC)), and the reflected light from internal roofs, floors, or walls (the Internal Reflected Component (IRC)). The daylight factor method accounts for all three components (Bryan and Clear, 1980).

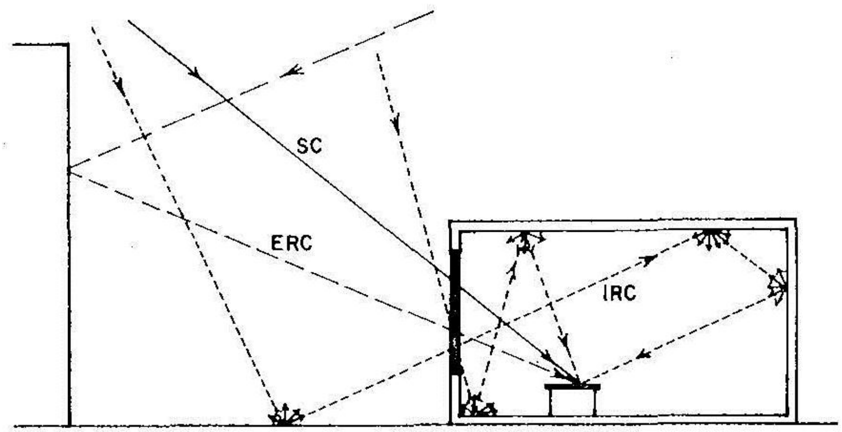


*Figure 5.11.* Components of the daylight factor. *Note.* From "A Procedure for Calculating Interior Daylight Illumination with a Programmable Hand Calculator," by H. J. Bryan and R. D. Clear, 1980, *LBL Report*, *LBL-11186 C.2*, p. 2. Copyright 1980 by the LBNL.

The split flux method is used to calculate the average IRC, which is the ratio between the inter-reflected illumination at a point on a horizontal work surface and the simultaneous sky illumination on an external flat ground. The split flux method uses two calculations to estimate the IRC: the entering light from the sky and the entering light from the ground (Bryan and Clear, 1980).

Figure 5.12 indicates the concept of the split flux method:

> The light from the sky on entering the room is considered to be modified by the average reflectance of the floor and those parts of the walls below the mid-height of the window. The light from the ground is considered to be modified by the average reflectance of the ceiling and those parts of the walls above the mid-height of the window. $f_s$ = window factor due to the light incident on the window from sky, $R_{fw}$ = average reflectance of the floor and those parts of the walls, below the plane of the mid-height of the window (excluding the window-wall), $f_g$ = window factor due to the light incident on the window from ground, $R_{cw}$ = average reflectance of the ceiling and those parts of the walls, above the plane of the mid-height of the window (excluding the window-wall) (Bryan and Clear, 1980, p.3)

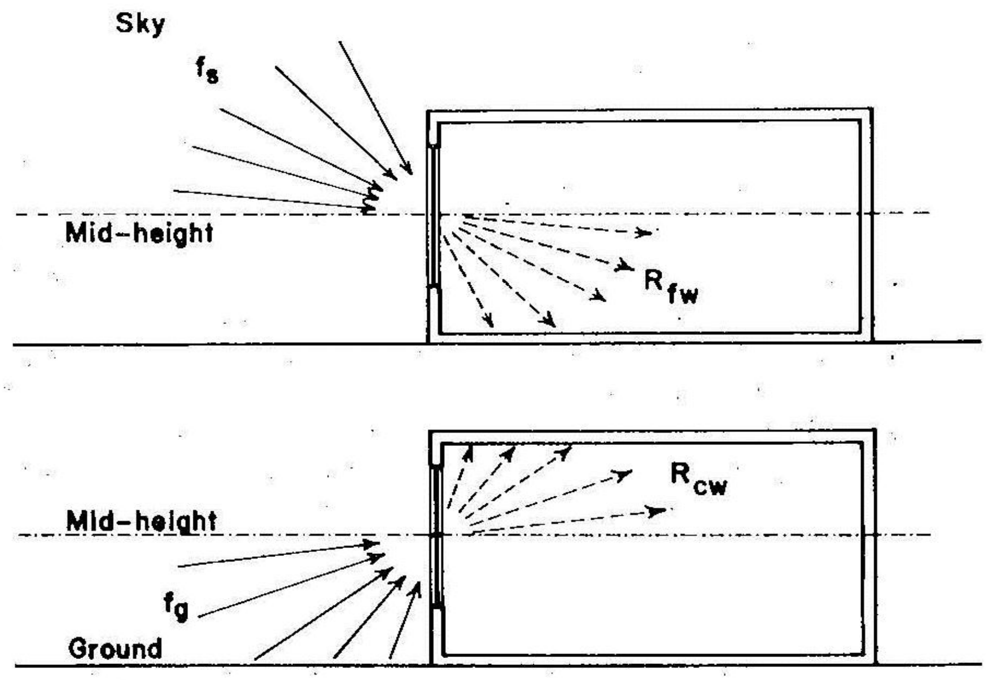


*Figure 5.12.* The split flux concept. *Note.* From "A Procedure for Calculating Interior Daylight Illumination with a Programmable Hand Calculator," by H. J. Bryan and R. D. Clear, 1980, *LBL Report, LBL-11186 C.2,* p. 3. Copyright 1980 by the LBNL.

The development of the split flux method is shown in the fifth shaded area from the top in the pre-1950 section and the 1951-1960 section of Figure A.2. An abbreviation, SF, in the small, rectangular boxes indicates the split flux method at the bottom of the event boxes. In order to trace the development of the split flux method, the origins of the DF method were also traced because the split flux method was used for the IRC of the DF method.

In 1895, the daylight factor method was proposed to measure daylighting performance in a condition that did not account for the instantaneous effect of sky luminance (as cited in Love, 1992). In 1928, Fruhling proposed an empirical formula, called the Lumen method, to produce the DF. The empirical formula was used for calculating a utilization coefficient, which Fruhling used to create a table of the utilization factors. Unfortunately, Fruhling's method did not account for the ERC and the IRC (as cited in Dresler, 1954). In 1954, Dresler extended Fruhling's method to calculate the IRC using the Ulbricht unit sphere principle (Dresler, 1954). About this same time, Arndt developed a method for calculating the IRC. Arndt's method adopted a simpler approach compared to Dresler's method for calculating the first lighting flux that reaches an inside surface through a window (as cited in Dresler, 1954).

Finally, also in the same year, Hopkins et al. presented the split flux method based on Arndt's method. The split flux method was used to estimate the IRC using an empirical formula (Hopkinson et al., 1954). The split flux method assumes interior surfaces of a room are a connected sphere shape and perfectly diffuse with no inner obstacles, so it works best when a room is shape as a cube and does not have internal partitions. Due to these reasons, the internally reflected illuminance at the back side of a room may be over-predicted when the ceiling height of a room is much less than the depth of the window-wall (Winkelmann and Selkowitz, 1985). In 1989, Tregenza presented a modified method of the split flux method to account for large external obstacles such as overhang (Tregenza, 1989).

*5.2.3.2 Radiosity method*

The radiosity method is an advanced approach used to accurately calculate the IRC. This procedure uses the energy balance concept for analyzing radiative heat transfer, which thermal engineers widely use (Goral et al., 1984).

Figure 5.13 shows the radiosity method. The term radiosity embodies reflected or transmitted incident light plus self-emitted light. All the reflection and emission light is assumed to be ideally diffuse (i.e., Lambertian surfaces or reflectors), and the inner surface of a room is divided into patches. The reflected light indicates the light leaving a patch multiplied by the rate of the radiant light leaving a patch which was reached from the previous patch (i.e., the form-factor (F)) and the reflectivity of a patch. The form-factor accounts for effect of the geometry. The total reflected and self-emitted light of each patch is the radiosity of the patch (Greenberg et al., 1986). The radiosity approach provides a view-independent analysis, which can be used for pre-estimating dynamic sequences of illumination. In addition, the diffuse reflection as calculated by the radiosity method can later include surface reflections, which have a small amount of specular areas with negligible error (Goral et al., 1984).

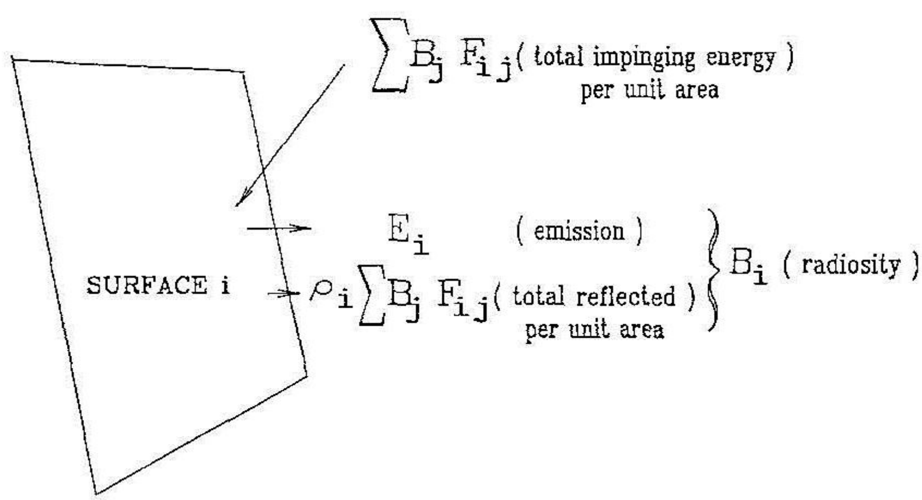


*Figure 5.13.* Total radiosity. *Note.* From “Radiosity: A Method for Computing Global Illumination,” by D. P. Greenberg, M. F. Cohen, and K. E. Torrance, 1986, *The Visual Computer,* 2, p. 292. Copyright 1986 by Springer. Reprinted with permission.

Radiosity (B) = the total rate of energy leaving a surface (i.e., sum of emitted and reflected energy); Emission (E) = The rate of energy (light) emitted from a surface; Reflectivity ($\rho$) = the fraction of incident light which is reflected back into the environment; Form-factor (F) = the fraction of the energy leaving one surface which lands on another surface; i or j = 1 to N; N = the number of discrete surfaces of "patches".

The development of the radiosity method is shown in the fifth shaded area from the top in the 1971-1980 section and the 1981-1990 section of Figure A.2. An abbreviation, RS, in the small, rectangular boxes indicates the radiosity method at the bottom of the event boxes. In In 1966, Sparrow and Cess introduced the radiosity concept in their book (Sparrow and Cess, 1966). In 1982, Modest utilized the radiosity method to develop the algorithm for digital computers to calculate the daylighting effects inside rooms in buildings (Modest, 1982). In 1984, Cindy Goral, Kenneth Torrance, Donald Greenberg, and Bennett Battaile at Cornell University first used the radiosity method for computer graphics. At this time, the existing computer graphics did not use reflection models that considered the reflection effects between diffuse surfaces. Therefore, the radiosity method, which accounted for reflection s, provided a more accurate analysis rather than the existing models for the global illumination (Goral et al., 1984).

The radiosity method was used in the SUPERLITE and DElight programs (Hitchcock and Carroll, 2003). Version 2.0 of DElight has been integrated into Version

1.2 of EnergyPlus, which was released in 2004, as well as the following versions of EnergyPlus (EERE, n.d.). EnergyPlus will be discussed in Section 5.3.3.2.2.

*5.2.3.3 Ray tracing method*

Ray tracing is a method of creating computer graphics images with high quality. The ray tracing method is also used for analyzing inter-reflections between both diffuse and specular surfaces (Ward et al., 1988). The ray tracing method uses the approach of tracing the rays of light generated from a source of light to the eye of the viewer (Kuchkuda, 1988). Figure 5.14 shows the concept of the original ray tracing method.

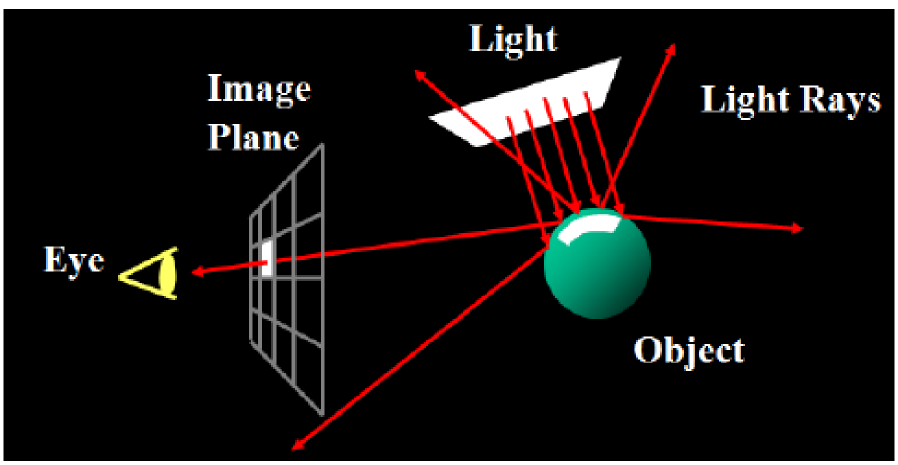


*Figure 5.14.* The concept of the ray tracing method. *Note.* From "COEN 290 Computer Graphics I," by B. Grantham, 2008. Reprinted with permission.

In the ray tracing method, the rays of a light source are distributed in all directions in a room. Among the rays, some rays are reflected and refracted by an object. Finally, some of these rays reach a viewpoint through an image plane. The idea of the original ray tracing method was to follow all the paths of the rays from a light source to the viewer. Unfortunately, this approach is wasteful because most of the rays of a light source do not strike the viewpoint (i.e., image plane) (Kuchkuda, 1988).

Figure 5.15 shows the concept of the improved ray tracing method.

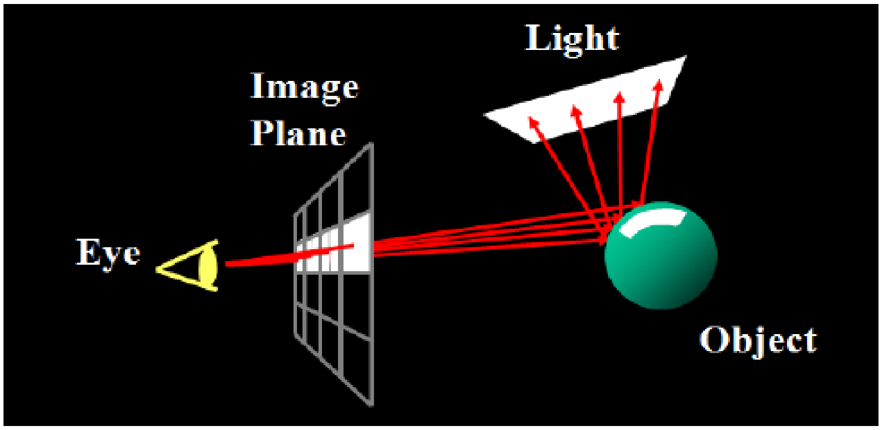


*Figure 5.15.* The concept of the improved ray tracing method. *Note.* From “COEN 290 Computer Graphics I,” B. Grantham, 2008. Reprinted with permission.

The improved ray tracing method (i.e., light-backwards ray tracing method) traces a ray of each point (i.e., each pixel) backwards from the viewer through the image plane to the object (Arvo, 1986; Kuchkuda, 1988; Ward, 1994). In other words, the paths of the rays are traced in reversed from a viewpoint to an object in contrast to the original ray tracing method which followed all of the paths of light.

The development of the improved ray tracing method is shown in the fifth shaded area from the top in the 1961-1970 section through the 1981-1990 section of Figure A.2. An abbreviation, RT, in the small, rectangular boxes indicates the ray tracing method at the bottom of the event boxes. In 1967, Arthur Appel at the IBM Research Center first proposed the concept of ray tracing (Appel, 1967; Weghorst et al., 1984). In 1971, Robert A. Goldstein and Roger Nagel at Mathematical Applications Group, Inc. used the ray tracing method to introduce image production software developed by MAGI (Goldstein and Nagel, 1971; Weghorst et al., 1984). In 1980, Turner Whitted at Bell Laboratories extended the ray tracing method in order to account for global illumination in terms of rendering computer graphics images (Whitted, 1980). In 1984, Robert L. Cook, Thomas Porter, and Loren Carpenter at Lucasfilm Ltd. improved the ray tracing method by using an analytical function. The unsolved problems of the original ray tracing method such as motion blur, fuzzy reflections, and depth of field were resolved by this analytical approach (Cook et al., 1984). In the same year, Hank Weghorst, Gary Hooper, and Donald Greenberg at Cornell University proposed computational procedures to reduce the process time for making images by the ray tracing method (Weghorst et al., 1984). In 1986, James Arvo at Apollo Computer, Inc. described the backward ray tracing method. The backward ray tracing method provided a solution for exactly calculating indirect light's diffuse reflection, which had not been solved (Arvo, 1986).

The advanced ray tracing method (i.e., the backward ray tracing method) has been used in the Radiance program, developed by Ward in 1988, to analyze the effects of lighting and daylighting in buildings (Ward et al., 1988; Ward, 1994). The most recent version of Radiance (i.e., Version 4.2) is currently used (IBPSA USA, 2013). Radiance will be discussed in Section 5.3.3.1.1.

## 5.3 Discussion of the Chart for Tracing Specific Programs

In this section, six whole-building energy simulation programs, four solar energy analysis simulation and design programs, and five lighting and daylighting analysis simulation programs are historically traced and discussed based on the new comprehensive genealogy chart. Table 5.3 shows when the simulation or design programs were released and which analysis method discussed in the previous section was used for each program.

Table 5.3. *Development of the simulation or design programs*

| Group | Selected Parameter | Simulation Program or Design Program (Applied Analysis Method) | Publically Released Year (Reference) |
|---|---|---|---|
| Whole-Building Energy Simulation | Zone Thermal Loads | EnergyPlus (Heat Balance Method) | 2001 (Crawley et al., 2002) |
| | | DOE-2.1e (Transfer Function Method (i.e., Weighting Factor Method)) | 1979 (LASL, 1980) |
| | | eQUEST/DOE-2.2 (Transfer Function Method (i.e., Weighting Factor Method)) | 1999 (Tupper et al., 2011) |
| | | TRACE (Transfer Function Method or Radiant Time Series Method) | 1972 (Schwedler, 2012) |
| | | HAP (Transfer Function Method (i.e., Weighting Factor Method)) | 1987 (Tupper et al., 2011) |
| | | TRNSYS (Heat Balance Method) | 1975 (Klein, 1976; Tupper et al., 2011) |
| Solar Energy Analysis Design or Simulation | Solar Heating Load Performance | F-Chart Program (f-Chart Method, Utilizability Method, and Un-Utilizability Method) | 1982 (Klein & Beckman, 2001a; as cited in Haberl and Cho, 2004a) |
| | | PV F-Chart Program (PV Design Method and Utilizability Method) | 1983 (Klein & Beckman, 2001b) |
| | | SUNREL (Thermal Network Method) | 1996 (Deru, 1996) |
| Lighting & Daylighting Analysis Simulation | Internal Reflected Component | DAYSIM (Ray-Tracing Method) | 1998 (Reinhart, 2013) |
| | | Radiance (Ray-Tracing Method) | 1989 (Ward, 1994) |
| | | EnergyPlus Daylighting Module (Split-Flux Method or Radiosity Method) | 2004 (EERE, 2012) |
| | | DOE-2 Daylighting Model (Split-Flux Method) | 1982 (Selkowitz et al., 1982; LBL, 1982; Winkelmann, 1983) |
| | | Lumen-Micro (Radiosity Method) | 1983 (as cited in Kota and Haberl, 2009) |

All the simulation or design programs currently used in the U.S. were released after 1970 due to the increased availability of powerful computers and improved compliers. Even though various programs have been developed, some of the programs have used the same analysis method.

### *5.3.1 Whole-building energy simulation programs*

Whole-building energy simulation programs[15] are used to simulate energy use in buildings, which account for the variation of weather, HVAC system performance, and occupants in the buildings. Whole-building energy simulation programs are used to fulfill building energy code or standard compliance, measurement and verification (M&V), and energy budget conformance as well as determining design phase building performance, HVAC systems performance, and long-term energy costs (PNNL, 1990; Higgins, 2012).

#### *5.3.1.1 EnergyPlus*

EnergyPlus is the newest whole-building energy simulation program sponsored by the US DOE. EnergyPlus improved many of the features of previous building simulation programs, which were discussed in the community of building simulation specialists (Pedersen et al., 1997). EnergyPlus is a modular structured program that consists of two basic modules: a heat and mass balance simulation and a building systems simulation (Crawley et al., 2005). EnergyPlus integrated existing models,

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[15] This study did not analyze the origins of simulation programs for analyzing the dynamic performace of mechanical systems in buildings (i.e., BLDSIM, HVACSIM+, and SPARK). BLDSIM was developed by Shavit in 1978 (as cited in Shavit, 1995). HVACSIM+ and SPARK are component-based simulation progams like TRNSYS, and they provide improved analysis for HVAC systems in comparison with whole-building simulation programs (Park et al., 1985; Buhl et al., 1993; Sowell and Hittle, 1995; Wright, 2003).

algorithms, or programs in the two modules. The heat and mass balance simulation module includes the DOE-2 daylighting model (Winkelmann and Selkowitz, 1985) and DELight2 developed by the Lawrence Berkeley National Laboratory (LBNL), the window performance analysis of WINDOW developed by the LBNL, and the airflow network model based on AIRNET developed by Walton at the National Institute of Standards and Technology (NIST) (Walton, 1989). The building systems simulation module includes the system and plant models of DOE-2 and BLAST (Pedersen et al., 1997; UIUC and LBNL, 2012). DOE-2 was released in 1979 by the Lawrence Berkeley Laboratory (LBL, now LBNL) and the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL) under the U.S. Department of Energy (US DOE)'s support for the development. The Building Load Analysis and System Thermodynamics (BLAST) was released in 1977 by the U.S. Army Construction Engineering Research Laboratory (CERL) under the U.S. Department of Defense (US DOD)'s support. The development of DOE-2 and BLAST was described in Section 5.1.4.1.

The two modules are managed by the simultaneous solution method based on IBLAST, which was a research version of BLAST (Crawley et al., 2004; UIUC and LBNL, 2012).

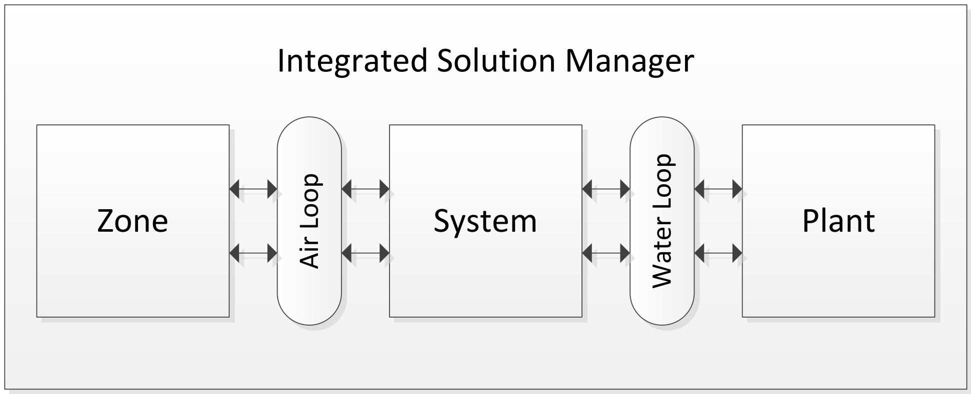


*Figure 5.16.* Schematic of simultaneous solution scheme. Adapted from "Integrated Solution Manager," by UIUC and LBNL, 2012, EnergyPlus Engineering Reference, p. 7. Copyright 2012 by UIUC and LBNL.

Figure 5.16 shows the simultaneous approach used in EnergyPlus. The integrated solution manager integrates and controls all the components of the models by using calculation loops. This integrated solution method between the building loads analysis and HVAC systems analysis, which includes central plant systems, allows more accurate estimations for space temperature than the estimations of the sequential simulations without feedback, which were used in the DOE-2 and BLAST programs. The exact space temperature analysis through the integrated simulation skill provides a more physically realistic result to size and control HVAC systems as well as estimate the occupants' comfort (Pedersen et al., 1997; Crawley et al., 2005).

The development of EnergyPlus is shown in the second shaded area from the top in the 1991-2000 section to the 2011-present section of Figure A.2. The origins of EnergyPlus can be traced from DOE-2.1e and BLAST, including IBLAST. The genealogy chart of DOE-2.1e and BLAST starts from the 1971-1980 section of Figure

A.2., because most of capabilities used in EnergyPlus were obtained from these two programs. The development of DOE-2.1E will be discussed in the next section.

In terms of the development of BLAST, which is one of the programs that contributed to EnergyPlus, the National Bureau of Standards Load Determination (NBSLD) program developed by the National Bureau of Standards (NBS, now the National Institute of Standards and Technology (NIST)) was an important starting point to trace BLAST. In 1976, the algorithms used in NBSLD, including the heat balance method (HBM) or RMTMP (Kusuda and Powell, 1972), were officially released to help engineers develop their own building simulation programs according to their requests. The algorithms that came from ASHRAE Task Group on Energy Requirements (TGER)'s book were corrected and included in the NBSLD algorithms book (Kusuda, 1976). The U.S. Army Construction Engineering Research Laboratory (CERL) used the NBSLD algorithms to develop CERL's first building simulation program, called TASS. In 1977, CERL developed BLAST using the modifications of TASS and a new program code (Walton, 2001). BLAST was an integrated program including: NBS's NBSLD (i.e., the building load calculation program using HBM), the Computation Consultants Bureau (CCB)'s total energy plant simulation (TEPS), and CERL's own system simulation (Ayres and Stamper, 1995). In 1979 and 1981, BLAST 2.0 and 3.0 were released (Walton, 2001). In 1994, IBLAST was developed by the University of Illinois at Urbana-Champaign (UIUC). The HBM concept of BLAST and the simultaneous solution method of IBLAST significantly impacted the development of EnergyPlus (Crawley et al., 2005). In the meantime, in 1983, George Walton developed Thermal

Analysis Research Program (TARP) at the NIST (Walton, 1983). TARP was derived from BLAST (Sowell and Hittle, 1995). TARP was able to simultaneously solve heat balance formulae for multiple rooms in conjunction with air pressure balance formulae. This unique solution was used for evaluating the movement of natural air, contaminant, and humidity in multiple rooms (Kusuda, 1985). The one algorithm of the TARP is used for calculating inside and outside surface convection for EnergyPlus (UIUC and LBNL, 2012).

In 1995, the development of EnergyPlus started because of the need to merge two simulation programs sponsored by the US DOE and US DOD: DOE-2 and BLAST (Crawley et al., 1997). In 1997, EnergyPlus was first publically introduced as EnergyBase (Pedersen  et al., 1997). In 1998 and 1999, the alpha and beta version tests of EnergyPlus were conducted (Crawley et al., 1999). Finally, in 2001, the first version of EnergyPlus was released (Crawley et al., 2001). In 2003, in Version 1.1, EnergyPlus incorporated TRNSYS, which will be discussed in Section 5.3.1.6, to calculate PV systems. From Version 1.2 in 2004, the model, based on the Duffie and Beckman's equivalent one-diode model, was used for PV calculations (Duffie and Beckman, 2006; UIUC and LBNL, 2012). In addition, from Version 1.2, EnergyPlus used DELight 2 developed by LBNL to analyze the effects of lighting and daylighting (UIUC and LBNL, 2012). In 2006, Version 1.3 was released. The existing Airflow Network models (i.e., COMIS and ADS) were replaced by a new model with the integrated features from both models.

In 2007, Version 2.0 replaced the existing materials data of DOE-2 and BLAST with new data from the 2005 ASHRAE Handbook of Fundamentals. In 2008, new models were added to version 3.0: ventilated slab model, thermal chimney model, and a cooltower model. In 2009, beginning with version 4.0, users can control the parameters of window glazing by changing the U factor, solar heat gain coefficient (SHGC), and visible transmittance (VT) (EERE, n.d.). In 2010, in Version 6.0, the execution time of EnergyPlus was significantly reduced by approximately 25 to 40% (EERE, 2010). In 2012 and 2013, Versions 7.2 and 8.0 further improved the calculation speed and fixed previous bugs (EERE, 2012; EERE, 2013b).

*5.3.1.2 DOE 2.1e*

DOE-2.1e was the main public domain program of the US DOE before EnergyPlus. Several national laboratories and institutes developed DOE-2.1e to become a refined and comprehensive simulation program. This program significantly contributed to the development of the energy saving standards and the design and analysis of buildings. DOE-2.1e can analyze hourly building loads, energy use, and operating cost. It can also conduct daylighting analysis, HVAC equipment analysis, and economic analysis. Currently, DOE-2 based programs are the only programs used to develop code-compliant simulations certified by the Residential Energy Services Network (RESNET).

Figure 5.17 shows the sequential simulation used in the DOE-2.1e program without feedback from the previous step. DOE-2.1e consists of four sub-programs: Loads Analysis, Systems Analysis, Plant Analysis, and Economic Analysis. For the first step, the Load Analysis sub-program (LOADS) is simulated by using building descriptions and weather data. For the next step, the System Analysis sub-program (SYSTEMS) uses the results of the LOADS as the input. Likewise, the Plant Analysis sub-program (PLANT) uses the results of the SYSTEMS as the input. For the last step, the Economic Analysis sub-program (ECONOMICS) estimates energy cost based on the demands of electricity and fuel used in PLANT (Crawley et al., 2005).

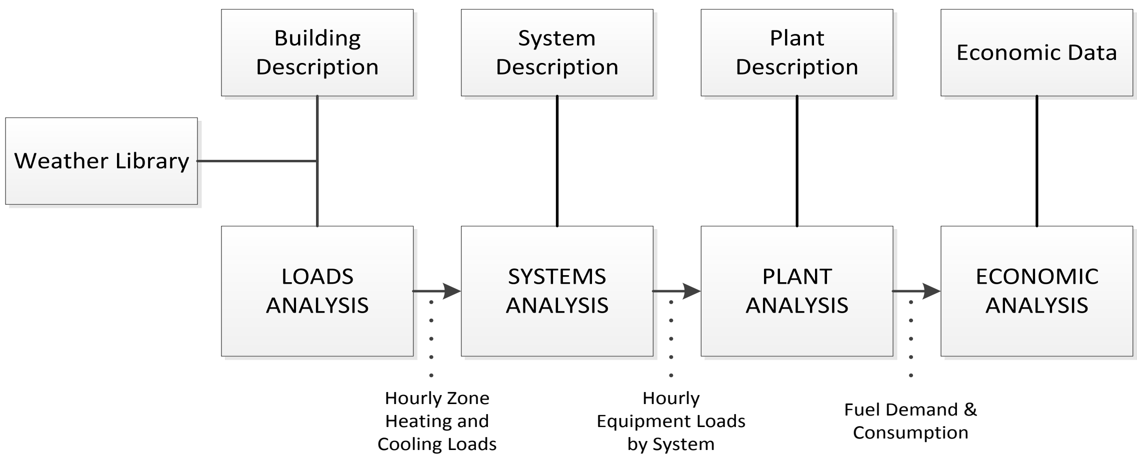


*Figure 5.17*. Building simulation sequence. Adapted from “Historical Development of Building Energy Calculations,” by J. M. Ayres and E. Stamper, 1995, *ASHRAE Transactions*, *37*, p. 844. Copyright 1995 by ASHRAE (www.ashrae.org). Reprinted with permission.

The development of DOE-2.1e is shown in the second shaded area from the top in the 1971-1980 section through the 2001-2010 section of Figure A.2. The origin of DOE-2.1e can be traced to the Post Office Program because the program significantly influenced CAL-ERDA before DOE-1.0. On the other hand, the HCC program, a peak load calculation program, was developed by the Automated Procedures for Energy Consultants (APEC) in 1967 (Ayres and Stamper, 1995). This program could be the previous program of the Post Office Program because the load calculation is the significant part with respect to the development of the whole-building simulation program even though they do not have a direct connection.

In the late 1960s, the General American Research Division (GARD) of the General American Transportation Corporation (GATX), which was a subcontractor for the Post Office facilities division, developed the loads program (i.e., computational procedures) for the Post Office Program (Stamper 1995; Cumali, 2013). In 1971, the U.S. post office introduced the post office program (USPS, 1971) to help analyze building and remodeling efforts for the U.S. Post Office facilities. To accomplish this, the GARD/GATX engineers developed a building shadow calculation program under the direction of Metin Lokmanhekim (Kusuda, 1999). The GARD/GATX developed the U.S. post office program with the ASHRAE TGER report regarding the GARD/GATX shadow program and the ASHRAE TGER algorithms that used the weighting factor method (WFM) (USPS, 1971; Kusuda and Powell, 1972; Kusuda, 1999).

In the late 1970s, the Computation Consultants Bureau (CCB) developed the CAL-ERDA code based on the loads sub-program code used in the Post Office Program. The name of the CAL-ERDA program was from the name of the sponsors: the California (CAL) Energy Commission and the United States Energy Research and Development Administration (ERDA). The code of the Post Office program was a monolithic and required recompilation for each subroutine. The speed of the CAL-ERDA was improved by recompiling the code. CCB also developed the Building Description Language (BDL), which is a user-friendly computer input language (i.e., familiar terminology), for controlling the load, systems, plant, and economic sub-programs of the program (Cumali, 2013; Graven and Hirsch, 1977). The Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory (LBNL)), The Argonne Nation Laboratory (ANL), and Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) also contributed to the development of CAL-ERDA (Graven and Hirsch, 1977). In 1976, CAL-ERDA was produced. In the same year, the California Energy Commission (CEC) and ERDA sponsorship for CAL-ERDA ended and ERDA was integrated into the U.S. Department of Energy (US DOE) (Birdsall et al., 1990). When Metin Lokmanhekim moved from GARD to LBL, he brought the skill of the Post Office program to LBL to develop CAL-ERDA (Kusuda, 1999). The LOADS program of CAL-ERDA was developed based on the ASHRAE algorithms published in 1975. The SYSTEMS program of CAL-ERDA utilized the equations of the ASHRAE algorithms and the NECAP program (i.e., NASA's Energy Cost Analysis Program) for developing the simulation procedure (Graven and Hirsch, 1977).

In 1978, DOE-1, a slightly enhanced version of CAL-ERDA, was released by CCB, LBL (now LBNL), LASL (now LANL), and ANL (ANL, 1978 as cited in LASL, 1980; Cumali, 2013). The US DOE Office of Buildings and Community Systems supported the development of DOE-1 (Birdsall et al., 1990). Zulfikar Cumali, Ender Erdem, Robert Grave, and Metin Lokmanhekim contributed to the development of the BDL of DOE-1 (LASL, 1980). In 1979 and 1980, DOE-2.0a and DOE-2.1a were released by LBL and LASL. In the new program, a new BDL had been created for the

DOE-2 series to more easily control the LOADS analysis program, the SYSTEMS program, the PLANT program, and the ECONOMICS analysis program. Frederick Buhl, James Hirsch, and Mark Roschke designed the BDL of the DOE-2 series. Frederick Buhl was the principal researcher for the LOADS program, James Hirsh for the SYSTEMS program, Steven Gates for the PLANT program, Frederick Winkelmann for the ECONOMICS and LOADS programs, and Mark Roschke for the DOE-2 Solar Simulator, which was called the Component Based Simulator (CBS) for active solar systems (LASL, 1980).

In 1982, DOE-2.1b was released by LBL and LANL (LBL, 1982). From this version, users could use metric inputs for the simulation and could choose metric or English units for the output result reports. Also, in DOE-2.1b, a simulation method for daylighting calculation using the split flux method, explained in Section 5.2.3.1, was installed.

In 1984, DOE-2.1c was released by LBL (LBL, 1984). The funding from the US DOE had been quickly reduced at ANL and LASL, so LBL became the main national laboratory for developing new versions of DOE-2 (Ayres and Stamper, 1995). In this version, algorithms for analyzing sunspaces were added. In 1989, DOE-2.1d was released by LBL, which included an improved calculation method for diffuse solar radiation shading (LBL, 1989). In 1993, DOE-2.1e was introduced by LBL and James J. Hirsch and Associates (JJH). In this version, the models for water loop heat pump systems, water-cooled condenser option for packaged units, electric and fuel meters, packaged variable volume temperature (PVVT) system, and gas heat pumps were developed. In 1995, 2000, 2001, 2002, and 2003, DOE-2.1e-Version 087, DOE-2.1e-107, DOE-2.1e-113, DOE-2.1e-119, and DOE-2.1e-121 were released (LBNL and JJH, 1998; Haberl and Cho, 2004c; Crawley et al., 2005). DOE-2.1e can be categorized two versions: the standard DOE-2.1e and the enhanced DOE-2.1e. The standard DOE-2.1e series, which indicates the versions before Version e-110, were developed by LBNL and JJH. The enhanced DOE-2.1e series, which means the versions after Version e-110, were developed by JJH and were improved by fixing existing bugs and having new features. The features of the enhanced DOE-2.1e contributed to the development of DOE-2.2 (JJH, 2012).

In 2003, DOE-2.1e-136 was last released as the legacy version (JJH, 2009). In 2005, the development of DOE-2.1e was terminated due to the change of the US DOE's funding priorities. The US DOE now focused on developing EnergyPlus, which is discussed in Section 5.3.1.1. However, the DOE 2.1e based programs such as Visual DOE and Energygauge developed by each Eley Associates and Florida Solar Energy Center (FSEC) are currently used (Jacobs and Henderson, 2002; as cited in Tupper et al., 2011).

*5.3.1.3 eQUEST / DOE 2.2*

eQUEST or called Quick Energy Simulation Tool is a Graphical User Interface (GUI) version that uses the DOE-2.2 simulation program. This program is owned by James J. Hirsch and Associates (JJH) and was first released in 1999 (Jacobs and Henderson, 2002; as cited in Tupper et al., 2011). DOE 2.2 was developed using the DOE 2.1e version released in 1994 (LBNL and JJH, 1998). DOE 2.1e has not been further developed since 2003 (JJH, 2009). This new DOE 2.2 program with updated models can analyze window, lighting, and HVAC systems more accurately and flexibly than the DOE 2.1e program even though these programs have similar fashions to estimate whole-building energy use. However, the significant difference between DOE-2.1e and DOE-2.2 is related to a simulation sequence. Figure 5.18 shows the simulation sequence of DOE-2.2. The HVAC subprogram of DOE-2.2 integrated the previously SYSTEMS and PLANT subprograms of DOE-2.1e. Also, DOE-2.2 uses an hour loop to simulate the LOADS and HVAC subprograms together (LBNL and JJH, 1998). The different simulation sequence of DOE-2.2 improved the connectivity for loads calculation (JJH, 1997).

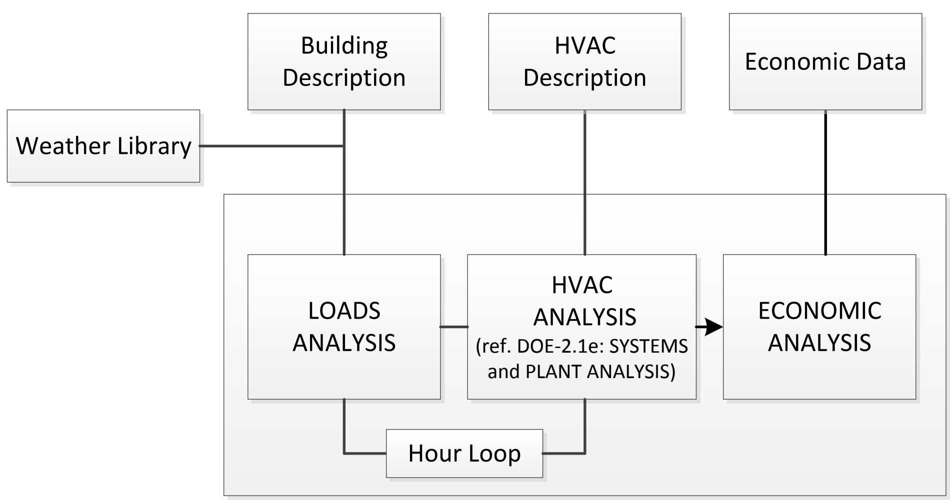


*Figure 5.18.* DOE-2.2 simulation sequence. Adapted from "DOE-2.2 Changes and New Features," by LBNL and JJH, 1998, Overview of DOE-2.2, p. 6. Copyright 1998 by LBNL and JJH.

eQUEST based on the DOE-2.2 program is a freeware program, although its source code is privately owned. It allows users to perform detailed building energy analysis even though users do not have extensive experience with respect to the DOE-2.1e simulation program. The user-friendly GUI has a building creation wizard and an energy efficiency measure (EEM) wizard as well as a graphical module based on DOE-2.2. Two input options are provided in eQUEST: a wizard option and a detailed input option. The wizard option works with reduced input data to describe the building such as building geometry and HVAC systems. The detailed input option allows users to access and control the full input data of DOE-2.2 (Jacobs and Henderson, 2002).

The development of eQUEST is shown in the second shaded area from the top in the 1991-2000 section and the 2010-Present section of Figure A.2. The origin of eQUEST begins DOE 2.1e, which is one of versions of the DOE-2.1 program, developed in 1993. The DOE 2.1e and DOE-2.1e-087 versions were released by LBL in 1993 and 1995 (LBNL and JJH, 1998; Haberl and Cho, 2004c). Engineers of James J. Hirsch and Associates (JJH), LBNL (the new name of LBL from 1995), and the Electric Power Research Institute (EPRI) began to develop DOE-2.2, a new version of DOE-2.1e, in the early 1990s.

In 1996, PowerDOE, the first GUI program that used DOE-2.2, was created by JJH along with several partners, under sponsorship by the electric power industry through EPRI. During the development period for PowerDOE, ownership issues regarding the DOE-2.2 source code caused a conflict between LBNL and JJH. This dispute caused LBNL to focus on developing a new whole-building simulation program (i.e., EnergyPlus), which is described in Section 5.3.1.1. During this time, JJH commercialized and further developed DOE-2.2 using sponsorship from mainly non-government institutes (i.e., non-US DOE funding) (as cited in Tupper et al., 2011).

In 1999, the eQUEST version 1.0, another GUI program that used DOE 2.2, was released by JJH. While the development of PowerDOE stopped in 2001 due to funding difficulty, eQUEST continues to be developed today. In 2000, Version 1.2 of eQUEST was widely released on the internet. In 2001, Version 2.17c, which included a refrigeration simulation for grocery stores, was released. In 2007, Version 3.6 was released and certified for Title 24[16]. In 2009, Version 3.63b was released and the US DOE allowed the version to be the qualified simulation program for the commercial building tax deductions of the Energy Policy Act of 2005[17] (EPACT 2005, now the Emergency Economic Stabilization Act of 2008 (EESA 2008)). In 2010, Version 3.64 was released, which provided a feature to generate the compliance models for LEED baselines (as cited in Tupper et al., 2011; JJH, 2009). The major funding source (i.e., approximately 90%) for the recent eQUEST development was obtained from California's Public Goods Charge (PGC), which was an additional charge on electricity sales (Tupper et al., 2011).

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[16] The Title 24 code began in 1980 and is the building energy code of the California Energy Commission (CEC). eQUEST received the qualification for the performance requirement for Title 24 (Tupper et al., 2011).

[17] EPACT 2005 allows the benefit of a tax reduction to building owners who save more than 50% building energy cost when it compared to the energy cost, meeting ASHRAE Standard 90.1-2001. Energy simulation programs must be approved by the Internal Revenue Service and US DOE in order to calculate building energy savings (Tupper et al., 2011).

*5.3.1.4 TRACE*

The Trane Air Conditioning Economics (TRACE) program is a widely used program among practicing architects and engineers for building loads and energy calculations. TRACE was developed by the Trane Company. The first version of TRACE was released in 1972 (as cited in Tupper et al., 2011; Schwedler, 2012). TRACE has its own calculation engine and Graphical User Interface (GUI). TRACE is widely used by practicing architects and engineers because the Trane Company strongly supports TRACE. In 2001, a MS Windows version was developed to simulate hourly building loads and energy use (Jacobs and Henderson, 2002). TRACE provides users with several options for calculating cooling loads, including: the Transfer Function method (TFM) or the Weighting Factor Method (WFM), the Total Equivalent Temperature Difference / Time Averaging (TETD/TA) method, the Cooling Load Temperature Difference / Cooling Load Factor (CLTD/CLF) method, and the Radiant Time Series (RTS) method. These methods were previously discussed in Section 5.2.1.

The development of TRACE is shown in the second shaded area from the top in the 1971-1980 section to the 2011-Present section of Figure A.2. In 1972, Trane released the TRACE direct version. TRACE was derived from the Post Office program developed in 1971 (Sowell and Hittle, 1995). In 1977, the TRACE 77 version was released, and in 1989, TRACE 600 was released, which was the upgraded version of TRACE 77 (as cited in Tupper et al., 2011).

The Trane Company released TRACE 700 in 1998, which was the first MS Windows version of the program (Tupper et al., 2011). Since 2000, engineers and architects have widely used both the TRACE program and the HAP program from the Carrier company. Both programs are used to calculate building loads, size of HVAC systems, and annual energy use (Jacobs and Henderson, 2002). TRACE has continued to be released and updated until now (i.e., TRACE 700 Windows full Version in 2001, TRACE 700 Version 4.1 in 2002, TRACE 700 Version 6.0 in 2006, TRACE 700 Version 6.2 in 2008, and TRACE 700 Version 6.2.10 in 2013) (Tupper et al., 2011; Trane, 2013). TRACE 700 Version 6.2 added the RTS method, which was described in Section 5.2.1.5, to calculate peak cooling loads. The RTS method was not a feature available in the 600 version.

*5.3.1.5 HAP*

The Hourly Analysis Program (HAP) was developed by the Carrier Company. The first version of HAP was released in 1987 (Tupper et al., 2011). HAP has its own calculation engine and GUI based on the MS Windows platform (Jacobs and Henderson, 2002; EERE, 2011a). Practicing engineers and architects widely use the HAP program because the Carrier Company strongly supports HAP (Jacobs and Henderson, 2002). Dynamic heat gain, design peak loads, HVAC system sizing and design, and annual hourly energy use can be simulated by HAP (EERE, 2011a).

The development of HAP is shown in the second shaded area from the top in the 1981-1990 section through the 2011-Present section of Figure A.2. In 1960, the System Design Manual of Carrier was published to help engineers learn the HVAC system design method. This book contained manual calculation procedures for estimating dynamic heat gain and design peak loads (Carrier, 1960). In 1981, Carrier released the

Commercial Load Estimating program Version 1.0, which was a Personal Computer (PC) based program, for automatically estimating the building design peak loads (Tupper et al., 2011; Farzad, 2012). The program provided engineers with a time-saving, cost effective way to calculate the design peak loads. The program was well-received since engineers were spared the tedious hand calculations needed for calculating the design peak loads. Shortly after the Commercial Load Estimating program Version 1.0, the Bin Opcost analysis program Version 1.0 was developed for estimating the annual energy use in buildings that used ASHRAE's Bin method (Farzad, 2012).

In 1987, HAP Version 1.0 was released, which was a follow-up program to Carrier's Commercial Load Estimating and Bin Opcost analysis programs. HAP Version 1.0 combined the functions of calculating the design peak loads, HVAC system design, and hourly energy analysis. By 1987, the development of PCs had improved enough that the accuracy of energy analysis using an hour by hour procedure was possible. Therefore, in 1989, HAP Version 2.0 was released. This version applied ASHRAE's Transfer Function Method (TFM) to calculate building loads (Farzad, 2012; EERE 2012). In 1993 and 1999, Version 3.0 and Version 4.0 were respectively released. Version 4.0 moved HAP from the MS DOS platform to the MS Windows platform (Farzad, 2012). Version 4.0 included a MS Windows-based Graphical User Interface (GUI) to more easily faciliate input data (Farzad, 2012; Carrier, 2013).

HAP has continued to be released and updated until now. In 2002, Version 4.1 added the capabilities to calculate the energy use and cost regarding air-side system and plant operations. In 2006, Version 4.3 implemented the option for importing gbXML building information format, which is a new data format to connect data between building design and information programs and building energy simulation programs. Also, Version 4.3 provided a Building Wizard program to provide useful schematic or preliminary design options. In 2008, Version 4.4 provided useful options to help users achieve the LEED Energy and Atmosphere Credit 1. In addition, Version 4.4 updated new Wizard features, which were based on the Wizard options of Version 4.3, to help users more quickly enter the needed input data for a simulation. In 2012, Version 4.6 added more new HVAC models such as variable refrigerant flow (VRF) equipment and condensing and non-condensing boilers, which were based on customer surveys (Carrier, 2013).

HAP currently uses ASHRAE's Transfer Function Method (TFM) or Weighting Factor Method (WFM) to calculate dynamic heat gains and building loads, which was explained Section 5.2.1.2 (Farzad, 2012; EERE 2012).

*5.3.1.6 TRNSYS*

TRNSYS is a widely used modular or component-based program. Originally, the program was called TRANsient SYStems (TRANSYS), which was later changed to TRNSYS because only six letters were permitted in early version of FORTRAN compilers (Beckman, 1993). This program was developed to simulate solar systems with the transient variation as the program name indicates. The first publically available version of TRNSYS was released at the University of Wisconsin-Madison in 1975 (Tupper et al., 2011). This program originally was developed for solar thermal simulations, but has extended a major contribution to building energy simulation, passive solar, photovoltaic (PV), and even hydrogen production analysis (Athienitis, et al., 2012).

TRNSYS uses connecting modular subroutines to perform an analysis. The subroutines (i.e., models) contain mathematical equations (i.e., ordinary differential or algebraic equations) and all necessary aspects for calculating each system. This connective solution approach has been shown to be more rigorous and accurate than other whole-building simulation programs that must estimate solar heating and cooling systems used in buildings (Kusuda, 1985; Sowell and Hittle, 1995). However, the solution approach is limited for large-size buildings because large-size buildings simultaneously have the heating and cooling loads, and high internal loads occur in these types of buildings. For large-size buildings, the whole-building simulation programs, which are previously described in Section 5.3.1.1 through 5.3.1.5, are more proper (ASHRAE, 1981). The algorithms of the whole-building simulation programs were more detailed for calculating conventional cooling and heating loads (Sowell and Hittle, 1995).

The development of TRNSYS is shown in the second shaded area from the top in the 1971-1980 section through the 2011-Present section of Figure A.2. In the early 1970s, the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison (UWM) started to study solar energy technologies, under the sponsorship of the US DOE (as cited in Tupper et al., 2011). Sanford Klein, then a graduate student at the University of Wisconsin-Madison, proposed the methods for accounting for the thermal storage effect of solar collectors as his MS thesis. He later developed a multi-node collector model for analyzing the transient effect of thermal storage (Klein, 1973). In the same year, Klein and SEL proposed TRNSYS using Klein's method for solar collectors as one of the components of TRNSYS (as cited in Klein, 1976). In 1975, TRNSYS was publically released, and Klein finished his dissertation in 1976 (Klein, 1976; Tupper et al., 2011). In 1977, William Beckman, Sanford Klein, and John Duffie completely described the F-Chart method that was introduced by Klein's PhD dissertation (Beckman et al., 1977). The F-Chart method consists of correlations based on thousands of the simulation results using TRNSYS.

In 1993, the SEL released TRNSYS Version 14.2, which was the first MS Windows version (Tupper et al., 2011). Unfortunately, the algorithms in TRNSYS required a lot of computing time to simulate complete system. However, although a program initially, this problem was resolved as more powerful Personal Computers (PCs) became available. In the late 1990s, the US DOE decided to stop supporting TRNSYS and to focus on developing a new whole-building simulation program (i.e., EnergyPlus), which is described in Section 5.3.1.1. From that time, the main funding source for the development of TRNSYS has been reinvestment through the TRNSYS sales revenue (Tupper et al., 2011).

Since 1975, TRNSYS has been updated and widely used in the U.S. (i.e., Version 15 in 2001, Version 16 in 2004, Version 17 in 2010, and Version 17.1 in 2012). TRNSYS uses the finite difference and network approach (i.e., the connecting approach by using models that contain differential equations) to analyze solar heating and cooling systems used in buildings (Kusuda, 1985). In addition, TRNSYS uses the Conduction

Transfer Function (CTF) method explained in Section 5.2.1.2 to analyze transient heat gain through walls and roofs (SEL, 2010; Delcroix et al, 2012). TRNSYS uses the Heat Balance Method (HBM) described in Section 5.2.1.4 to estimate cooling loads (SEL, 2010).

***5.3.2 Solar analysis simulation or design programs***

Solar energy analysis programs evaluate the performance of systems that are designed to collect and use solar radiation for thermal or electrical conversion. The programs are used for simulations and design methods (i.e., simplified methods). Detailed simulation programs estimate the time-dependent short-term and long-term performance of solar energy systems in detail, and design programs (i.e., simplified programs) analyze the long-term average performance of solar energy systems with less calculation work than simulations (Klein, 1993). Detailed simulation programs are used to create the most accurate results. On the other hand, design programs are used to make quick results as a design step because an iterative process is required at the design step (Athienitis, et al., 2012). In addition, design programs are useful for engineers to choose and size solar systems when input and solar irradiation data has high uncertainty (Evans et al., 1982).

*5.3.2.1 Active solar system analysis*

Active solar heating and cooling systems contain unpredictable variables such as nonlinear reaction parameters of systems with respect to solar radiation, weather data, and transient variation (Duffie, 1993). In order to simulate solar systems, two types of simulation programs were developed: the detailed simulation and the design analysis programs. TRNSYS, the detailed simulation program, was explained in Section 5.3.1.6. In terms of the design analysis program for active solar system analysis, F-Chart program was selected in this study.

5.3.2.1.1 F-Chart program

The F-Chart program was proposed by SEL at the University of Wisconsin-Madison. The F-Chart method used in the F-Chart program was first introduced in Klein's PhD dissertation (Klein, 1976). The utilizability method and the F-Chart method, explained in Section 5.2.2.2.1 and 5.2.2.2.2, are used to analyze active solar space heating systems and solar domestic hot water systems. A correlation using results from over hundred simulation runs through TRNSYS, which is the detailed transient thermal simulation program, create the fraction, f (Beckman et al., 1977). The F-Chart program was originally created in the BASIC platform (i.e., now in the Windows platform). This computer program reduces tedious work, such as controlling of solar radiation data of the F-Chart method by utilizing a computer speed. This program also provides economic analysis such as costs, life cycle, and cash flow of the solar systems (Klein and Beckman, 2001a; Athienitis, et al., 2012). The F-Chart program uses the F-Chart method to estimate active domestic hot water system, pebble bed storage space and domestic water heating systems, water storage space and/or domestic water heating systems, and building storage systems. The F-Chart program also uses the utilizability, F-Chart method, explained in Section 5.2.2.2.2 to analyze general solar heating systems. In addition, the F-Chart program uses the un-utilizability method, explained in Section

5.2.2.3.2, to estimate passive direct-gain system and storage wall systems (Klein and Beckman, 2001a).

The development of the F-Chart program is shown in the fourth shaded area from the top in the 1981-1990 section through the 2001-2010 section of Figure A.2.

The F-Chart program was first developed for mainframe computers using the FORTRAN platform. Until 1982, the F-Chart program (i.e., Version 1.0 through 4.1) had been developed in FORTRAN. From 1983 to1992, the versions of the F-Chart program (i.e. Version 5.0 series) were written in BASIC for microcomputers. Since 1993, the F-Chart program has been developed in the Windows platform (as cited in Haberl and Cho, 2004a; Klein and Beckman, 2001a).

*5.3.2.2 Passive solar system analysis*

Passive solar heating and cooling systems contain unpredictable variables such as nonlinear reaction parameters of systems with respect to solar radiation, weather data, and transient variation (Duffie, 1993). In order to simulate passive solar systems, two types of simulation programs were developed: the detailed simulation and the design analysis programs. In the following sections, 5.3.2.2.1 and 5.3.2.2.2, the detailed simulation programs (i.e., SUNREL and PASOLE) were discussed. In terms of the design analysis program for passive solar system analysis, the F-Chart program was explained in the previous section, Section 5.3.2.1.1.

5.3.2.2.1 SUNREL

SUNREL is the whole-building simulation program for small-size buildings, but suitable for the buildings that have passive solar systems (EERE, 2011b). This is because the thermal network method used in SUNREL had limitations for calculating the heat balance in rooms and estimating HVAC systems used in large-size commercial buildings (Kusuda, 1985). SUNREL is an upgraded version of SERIRES developed by the Solar Energy Research Institute (SERI, now called the National Renewable Energy Laboratory, NREL) in 1983 (Palmiter and Wheeling, 1983). SUNREL can be used to calculate the effectiveness of different types of passive solar buildings. SUNREL is used as the building physics and mathematics engine in Targeted Retrofit Energy Analysis Tool (TREAT), which was developed for single and multifamily building analysis software (NREL, 2005; EERE, 2011b).

The development of the SUNREL program is shown in the fourth shaded area from the top in the 1971-1980 section through the 2001-2010 section of Figure A.2. In 1980, SUNCAT Version 2.4 was developed by Larry Palmiter and Terry Wheeling at Ecotope Group, a non-profit organization for energy research and education (as cited in Palmiter and Wheeling, 1983). The SUNCAT program was one of a series of programs developed by Palmiter and Wheeling over four years. In 1983, the SERIRES version 1.0 developed by the same authors under contract to SERI (now NREL). SERIRES stands for Solar Energy Research Institute Residential Energy Simulator (Palmiter and Wheeling, 1983). In 1996, SERIRES was upgraded to SUNREL by Colorado State University and NREL (Deru, 1996). One of the upgrades was to make the format of the program flexible with respect to future improvements and visual user interfaces, using the FORTRAN language. SUNREL uses the solar geometry equations by McFarland in

1979 and the solar declination equation by Duffie and Beckman in 1991 (Deru, 1996; Deru et al., 2002).

SUNREL used a thermal network approach to solve the time-varying heat transfer problem. This is because the analysis of a solar heating system on a building requires both an analysis of the time-varying conditions of the house as well as the time-dependent solar radiation being collected by the solar system (Kusuda, 1985). Also, the use of thermal networks had been shown to be useful in accounting for transient time variation or temperature dependent values. The SERIRES program, developed by Larry Palmiter and Terry Wheeling in 1983, used the explicit approach of the finite difference method (Niles, 1992).

5.3.2.2.2 PASOLE

In 1972, due to the national scheme for solar energy employment, the first solar energy simulation programs funded by the U.S. government were developed under the sponsorship of the National Science Foundation (NSF) and the U. S. Energy Research and Development Administration (ERDA, now the U. S. Department of Energy (US DOE)) (Kusuda, 1985; Beckman, 1993). One of the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) programs is PASOLE, which stands for PAssive SOLar Energy. PASOLE was introduced by McFarland at LASL in 1978. This simulation program was created to simulate detailed analyses for passive solar systems. Users were able to manipulate a thermal network model used in PASOLE by utilizing nodes, connections of nodes, and parameters between nodes and connections. The nodes and parameters were created in FORTRAN subroutines (McFarland, 1978; Feldman and Merriam, 1979).

The development of the PASOLE program is shown in the fourth shaded area from the top in the 1971-1980 section of Figure A.2. In 1978, PASOLE was introduced by R. D. McFarland at the LASL (McFarland, 1978). John Douglas Balcomb proposed the simulation type idea of creating PASOLE. J. C. Hedstrom developed a one-mass-node simulation program, which contributed to the development of PASOLE (McFarland, 1978). The LASL utilized PASOLE to develop passive solar models for Trombe walls, direct-gain systems, and sunspaces. A correlation using results from over hundred simulation runs through PASOLE (i.e., the detailed simulation program) created the Solar Load Ratio (SLR) method (Balcomb, 1992). The SLR method, the design method for a monthly backup heat analysis, was discussed in Section 5.2.2.3.1.

After the advent of digital computers, numerical methods were used for thermal network based computer programs to enhance analysis accuracy. The finite difference method of the numerical approach can algebraically use equations to simultaneously or iteratively solve the equations. The thermal network approach program, PASOLE, used the implicit approach of the finite difference method (Niles, 1992).

*5.3.2.3 Solar photovoltaic (PV) analysis*

PV analysis programs estimate the electrical output of PV systems, including PV panels, energy inverters, and energy storage. The analysis is based on geometric locations and weather data (Klise and Stein, 2009). In this study, the PV F-Chart program that uses a simplified method (i.e., design method) will be discussed. Detailed

PV programs (i.e., simulation programs), such as PV-DesignPro developed from Maui Solar and PVWatt developed from NREL, were not discussed in this study. Most detailed programs in the U.S. use the PVFORM model (i.e., detailed model) developed in 1985 at the Sandia National Laboratory (Menicucci, 1985, 1986). Simulation programs provide a short-term (i.e., hourly or less than an hour) analysis with short-term weather and specific location data, but the PV F-Chart program achieves a long-term (i.e., monthly average) estimation of PV systems (Klein and Beckman, 2001b).

5.3.2.3.1 PV F-Chart program

The PV F-Chart program was developed by SEL at the University of Wisconsin in 1983 (Haberl and Cho, 2004b). This program is used for estimating the long-term PV system analysis. In addition, this program provides the economic analysis for life cycle costs. The PV F-Chart program consists of major four algorithms: monthly average PV array output, monthly average excess energy, effect of load variability, and battery storage systems. The PV design method, explained in Section 5.2.2.4.1, is largely used for the four algorithms. In addition, the utilizability method, explained in Section 5.2.2.2.1, is employed for the monthly average excess energy and effect of load variability algorithms (Klein and Beckman, 2001b). For a plane of array radiation analysis, a simple isotropic sky model of Liu and Jordan developed in 1963 is used in the PV-F Chart program (Klise and Stein, 2009).

The development of the PV F-Chart program is shown in the fourth shaded area from the top in the 1981-1990 section through the 2001-2010 section of Figure A.2. The PV F-Chart program was first developed for mainframe computers using the FORTRAN platform. Since 1993, the PV F-Chart program has been developed in the Windows platform (as cited in Haberl and Cho, 2004a; Klein and Beckman, 2001b).

### *5.3.3 Lighting and daylighting analysis simulation programs*

In order to analyze the daylight or natural light effect, several methods were developed: rules of thumb, graphical methods, and methods of utilizing physical models (as cited in Ubbelohde and Humann, 1998). Lighting designers wanted to estimate interior illumination in buildings with one of methods above. Several calculation methods were developed to accurately analyze the interior light. Many lighting designers assumed computer simulation programs were able to be used for estimating interior light with the most accurate approach (Ubbelohde and Humann, 1998).

Daylighting strategies use natural light to reduce the loads of artificial electrical lighting systems. A proper daylighting design can provide improved illumination for occupants and can reduce a building's energy use. Building orientation, window size, shading (i.e., overhangs and fins), and the use of artificial lighting systems are involved in a daylighting simulation. Daylighting analysis simulation programs are primarily used to calculate the lighting levels at specific points in a space. They can also keep track of how much artificial lighting is needed to supplement the illumination to meet predetermined lighting levels. The simulation programs for lighting and daylighting analysis used in this study are the following: Radiance, DAYSIM, and Lumen Micro as an independent program; the daylighting model in EnergyPlus (i.e., DElight) and the daylighting routines in DOE-2.1e as an integrated program.

*5.3.3.1 Independent program*

Daylighting analysis programs can be used to estimate building energy use by daylighting strategies. However, in this independent program section, lighting and daylighting design or visualization programs are discussed. The independent programs are not connected to building energy use analysis accounting for electric lighting and building loads related to HVAC system analysis.

5.3.3.1.1 Radiance

Radiance developed in the UNIX platform is an advanced lighting and daylighting simulation program for analyzing color (i.e. renderings) and illuminance of building inside and outside light (EERE, 2011c). Rendered images generated from Radiance are significantly beneficial to evaluate lighting distribution and aesthetics (Papamichael et al., 1998). Radiance uses the light-backwards ray tracing method discussed in Section 5.2.3.2 in order to analyze inter-reflections between both diffuse and specular surfaces (Ward et al., 1988; Ward, 1994). A Monte Carlo method (i.e., a numerical method) also was used in Radiance to estimate indirect illuminance (Howell and Perlmutter, 1964; Ward et al., 1988). Radiance adopted all weather sky model developed by Perez, Seals, and Michalsky to account for room illuminance under sky conditions (Kota, 2011).

Radiance is an integrated program with different programs (Papamichael et al., 1998). For generating sky models, the GENSKY and GENDAYLIT programs are used in Radiance: A sky scene description of the CIE standard sky distribution is generated by GENSKY, a sky scene description by using Perez’s all weather sky model is produced by GENDAYLIT (Mardaljevic, 2000). Also, the RAD program helps users manage input control parameters (Papamichael et al., 1998).

The development of the Radiance program is shown in the sixth shaded area from the top in the 1981-1990 section through the 2011-Present section of Figure A.2. Radiance was developed by Gregory Ward at the LBL and the Ecole Polytechnique Federal de Lausanne (EPFL, Swiss institute). The development of this program was initiated by studying ray tracing algorithms discussed in Section 5.2.3.2. US DOE and later the Swiss federal government decided to support this study after they found energy saving opportunities through lighting and daylighting strategies. In 1989, Radiance was first released (Ward, 1994). In 1990, Version 1.2 and 1.3 were released. Luminaire data of the Illuminating Engineering Society (IES) format was added to Version 1.3 using conversion utility. In 1991, Version 2.0 was released. An option for estimating irradiance in lieu of radiance was added to this Version 2.0. In 1992, 1993, 1994, and 1995, Version 2.1, Version 2.3, Version, 2.4, and Version 2.5 were released. For Version 2.5, a new item for the Materials and Geometry (MGF) format was added (LBNL, 2013). In 1996 and 1997, Version 3.0 and 3.1 were released (LBNL, 2013). For Version 3.0, the RANIMATE program that handles walk-through animations for multiple processing was installed (Ward and Shakespeare, 1998; Papamichael et al., 1998; LBNL, 2013). For Version 3.1, the PCOND program that adjusts the exceeded range of images to be visible was added (Ward et al., 1997; Papamichael et al., 1998; LBNL, 2013). These programs helped users understand the daylight properties applied in buildings (Papamichael et al., 1998).

In 2002, Version 3.4 was released. An improved command was added for calculating specified ray origins and its directions. In 2003, Version 3.5 was released, and this version enhanced the accuracy for estimating irradiance gradient adjacent to specular surfaces. In 2005, Version 3.7 that contained the RTCONTRIB program was released. The new program was used to calculate ray contribution coefficients. In 2006, Version 3.8 was released. The RAN2TIFF program was added in Version 3.8 to control animation sequences, incorporated with the PCOND program. In 2008, 2010, and 2011, Version 3.9, 4.0, and 4.1 were released. The DCTIMESTEP program was added to Version 4.0. This program using the daylight coefficient (DC) method was used to generate a combined picture for a specific time as well as sensor values (NBNL, 2013).

5.3.3.1.2 DAYSIM

DAYSIM is an advanced lighting and daylighting simulation program for estimating the annual daylight and electric light effects (EERE, 2011d; Reinhart, 2013). State-of-the-art façade systems can be analyzed in DAYSIM. Also, complex systems and controls for electric lighting equipment can be modeled. In order to calculate the global illumination, DAYSIM adopted the algorithms of Radiance discussed in the previous section. Radiance uses the backward ray tracing method discussed in Section 5.2.3.2 to analyze inter-reflections between both diffuse and specular surfaces (Ward et al., 1988; Ward, 1994). DAYSIM provides the annual illuminance analysis by combining the ray tracing method with a Daylight Coefficient (DC) method proposed by Tregenza and Waters in 1983 (Tregenza and Waters 1983; Versage et al., 2010). The DC method is used to estimate the illuminance distributions inside buildings according to sky luminance conditions. A celestial hemisphere divided by small parts (i.e., patches) is utilized in the DC method. Each part of the sky model provides the illuminance to a reference point on a surface in a building (i.e., a room or space). This approach easily estimates the total illuminace of a reference point according to a sky condition. In DAYSIM, the DC approach enables the annual daylighting analysis (i.e., hourly analysis) with a sky condition to avoid long simulation time (Versage et al., 2010). Also, an advanced model based on a Lightswitch algorithm is incorporated with DAYSIM. This model provides sub-hourly simulation for the behavior of occupants in order to estimate an accurate lighting and daylighting use for dynamic situations including lighting controls and window blinds (Reinhart et al., 2003; Bourgeois et al., 2006). DAYSIM provides occupancy, electric lighting, and shading device hourly schedules. The hourly schedules can be used for an integrated lighting-thermal simulation of the whole-building energy simulation programs (i.e., eQUEST, EnergyPlus, and TRNSYS) (Reinhart, 2013). DAYSIM can analyze the annual daylight metrics, such as daylight autonomy (DA) and useful daylight illuminance (UDI) for estimating annual glare and supplemental electric lighting (Reinhart, 2013). DA is the percent of daylighting occupied time that meets a minimum illuminance boundary for one year at a reference point on a surface in a building. UDI indicates the valuable daylighting levels avoiding too bright or dark (i.e., 100-2000 lux) (Nabil and Mardajevic, 2005). DAYSIM adopted all weather sky model developed by Perez, Seals, and Michalsky to account for room illuminance under sky conditions (Kota, 2011).

The development of the DAYSIM program is shown in the sixth shaded area from the top in the 1991-2000 section through the 2011-Present section of Figure A.2. In 1998, Christoph Reinhart led the development of DAYSIM. The National Research Council (NRC) Canada, Fraunhofer Institute for Solar Energy Systems (FISE), Harvard University, and Massachusetts Institute of Technology (MIT) contributed the development of DAYSIM. In 2001, the FISE developed an advanced simulation module for daylighting analysis to estimate annual illuminance. Also, the FISE proposed a subprogram for predicting short-time interior illuminance (Reinhart, 2013). In the same year, Christoph Reinhart improved the DA method used for DAYSIM, which was originally suggested by the Association Suisse des Electriciens in 1989 (as cited in Reinhart et al., 2006).

In 2003, a JAVA graphical interface of DAYSIM was developed at the NRC. In 2004, the NRC created and combined the occupant behavior model based on Lightswitch with DAYSIM. In addition, the FISE measured field data for the occupant behavior model. In 2006, MIT and the NRC validated translucent glazing simulations of DAYSIM with measured data. In 2009, Harvard University compared the five façade simulation results of DAYSIM and 3dsMax based on measured data from the NRC. In 2010, the FISE developed a new subprogram (i.e., gen_dgp_profile) to simulate annual glare levels by using a probability concept. In 2012, various independent groups for shading and lighting were added in a ds_electric_lighting subprogram of DAYSIM at MIT. The improved subprogram provided system simulations for complex façades and lighting controls used for multi-zones (Reinhart, 2013).

5.3.3.1.3 Lumen Micro

Lumen Micro, which was developed at Lighting Technologies Inc. in 1983, was widely used for designing electric lighting systems in industry (Ubbelohde and Humann, 1998; as cited in Kota and Haberl, 2009). Lumen Micro uses the radiosity method discussed in 5.2.3.2 (Ubbelohde and Humann, 1998). Lumen-micro has limitations compared to Radiance and DAYSIM because the radiosity method used in Lumen Micro cannot estimate spectral properties of inside surfaces or complex geometries, compared to the ray tracing method used in Radiance and DAYSIM (Papamichael et al., 1998; Versage et al., 2010).

The development of the Lumen Micro program is shown in the sixth shaded area from the top in the 1961-1970 section through the 2001-2010 section of Figure A.2. In 1968, David L. DiLaura proposed Lumen I which can estimate artificial lighting systems based on point-by-point calculations. In 1970, DiLaura developed Lumen II with the Smith, Hinchman, and Grylls Group, an architectural engineering firm. This program improved the existing capabilities of Lumen I by adding the estimation options of daylighting, glare, and visual comfort (Kota and Haberl, 2009). In 1975 and 1976, DiLaura proposed efficient computation methods for calculating direct and reflected component illuminance and visual comfort, for equivalent sphere illumination (ESI) (DiLaura 1975, 1976). In 1980, DiLaura established Lighting Technologies Inc., and Lumen III was developed at Lighting Technologies Inc. in 1981 (Kota and Haberl, 2009). Lumen III was used for estimating daylight illuminance in a room with the flux transfer computer algorithms proposed byDiLaura and Gregg A. Hauser, which was based on

DiLaura's previous studies in 1975 and 1976 (DiLaura and Hauser, 1978; Moore, 1985; Kota and Haberl, 2009). Overcast and clear sky models were used for calculating the daylight illuminance in a room of Lumen III (Kota and Haberl, 2009).

In 1983, Lighting Technologies Inc. released the first version of Lumen Micro, which was the next version of the Lumen series (i.e., Lumen I, II, and III). The name of Lumen Micro reflected the use of a microcomputer (as cited in Kota and Haberl, 2009). In the late 1980s, Lighting Technologies Inc. added a daylighting component to Lumen Micro. In 1996 and 1998, Lumen Micro Version 7.1 and Version 7.5 were released (Ubbelohde and Humann, 1998). Lumen Micro 2000 was released as a recent version (Kota and Haberl, 2009). For calculating the Internal Reflected Component (IRC), Lumen Micro 2000 used the finite element flux transfer method that was known as the radiosity method. The International Commission on Illumination (CIE) sky models were used for calculating daylight illuminance in Lumen Micro 2000 (Ubbelohde and Humann, 1998; Kota and Haberl, 2009).

Also, Lumen Designer was developed at Lighting Technologies Inc. Lumen Designer adopted a Computer Aided Design (CAD) approach, integrated with the Lumen Micro algorithms (Estes et al., 2004). Lumen Micro and Lumen Designer are not available for sale after Musco Sports acquired Lighting Technologies Inc. (LTI, 2006).

*5.3.3.2 Integrated program*

Lighting and daylighting programs integrated in the whole-building energy simulation programs can assess building energy use by daylighting strategies (Versage et al., 2010). In this section, the integrated module and program within DOE-2 and EnergyPlus (i.e., whole-building energy simulation programs) are discussed.

5.3.3.2.1 DOE-2 daylighting module

A daylighting simulation module was combined with the DOE-2.1b program released in 1982 (Selkowitz et al., 1982; LBL, 1982). This module has been applied to the DOE-2.1 program series since 1982. This module can be used for estimating whole-building energy consumption by daylighting strategies because it is combined with DOE-2.1 (i.e., the whole-building energy simulation program). This daylighting calculation module of DOE-2 uses the split-flux method discussed in 5.2.3.1 for estimating inter-reflected light. EnergyPlus also adopted and improved the daylighting module of DOE-2.1 as one of two options (UIUC and LBNL, 2012). Another program is discussed in the next section.

Three main steps are applied to the daylighting module of DOE-2.1. Daylight factors are first decided based on clear sky statuses or an overcast status. The clear sky statuses depend on 20 different positions of the sun. After daylight factors are calculated, hourly room illuminance is determined by utilizing the pre-estimated daylight factors. The pre-estimated daylight factors are interpolated by the hourly sky and sun conditions as well as outside horizontal illuminance in order to calculate the hourly room illuminance. This approach decreases the daylighting simulation time of DOE-2.1. Finally, the requirements for electric lighting systems are calculated based on the difference between the hourly daylighting room illuminance and a required (i.e., design) room illuminance (Selkowitz et al., 1982; Winkelmann and Selkowitz, 1984).

The development of the DOE-2.1 daylighting module is shown in the sixth shaded area from the top in the 1981-1990 section of Figure A.2. In 1954, Hopkins et al. presented the split flux method used for calculating the inter-reflected light. The daylighting module of DOE-2.1 was based on the split flux method to calculate room illuminance. In 1982, the daylighting module was included in the DOE-2.1b version (Selkowitz et al., 1982; LBL, 1982; Winkelmann, 1983). This module has been applied to the DOE-2.1 program series since 1982. In 2001, the first official EnergyPlus version adopted and improved the daylighting module of DOE-2.1 (Crawley et al., 2002; UIUC and LBNL, 2012). The improved aspects of the EnergyPlus daylighting module provide four different types of sky and hourly positions of the sun whereas that of DOE-2.1 used two sky types and 20 positions of the sun that cover annual range (UIUC and LBNL, 2012). However, in 2010, it was found that the EnerglyPlus daylighting module represented a limitation for estimating zone illuminance in a long shape zone. The illuminance levels at spots that were long distance from a window were overestimated. This study showed the daylighting analysis results through DAYSIM that used the ray tracing method, which was discussed in 5.2.3.2, provided higher accuracy in a long shape zone than the results of the EnergyPlus daylighting module (Versage et al., 2010).

5.3.3.2.2 EnergyPlus daylighting program

Daylighting analysis has been included in EnergyPlus since the first official the EnergyPlus version released in 2001 (Crawley et al., 2002; EERE, n.d.). Two daylighting calculation approaches of EnergyPlus can be used for estimating whole-building energy use by daylighting strategies because EnergyPlus is a whole-building energy simulation program. The two approaches are the daylighting module and DElight (i.e., an alternative daylighting program). The EnergyPlus daylighting module, the upgraded module of DOE-2.1, was explained in the previous section. Another daylighting program of EnergyPlus, which is called DElight that uses the radiosity method to calculate inter-reflected light, is discussed in this section. Basically, the EnergyPlus daylighting module and DElight have the same process for energy analysis by the daylighting strategies. The DElight program has more advantages than the EnergyPlus daylighting module because DElight can estimate complex fenestration systems (CFS) and use the radiosity method that estimates the inter-reflected light more accurately than the split flux method used in the EnergyPlus daylighting module, including more accurate estimation for internal obstacles (UIUC and LBNL, 2012).

The development of the EnergyPlus daylighting program is shown in the sixth shaded area from the top in the 1981-1990 section through the 2001-2010 of Figure A.2. In 1982, Modest proposed the algorithms of SUPERLITE that use the radiosity method (Modest, 1982; Selkowitz et al., 1982). In the same year, the SUPERLITE program was developed at LBNL (Selkowitz et al., 1982). SUPERLITE Version 2.0 was the last version in the perspective of active development (Estes et al., 2004). LBNL also developed DElight, the next level program for a lighting and daylighting analysis. The DElight version 1.x series used the daylighting algorithms of DOE-2.1, and the DElight version 2.0 used the daylighting algorithms of SUPERLITE. The DElight version 2.0 contained the algorithms to estimate complex fenestration systems (CFS) (Hitchcock and

Carroll, 2003). In 2004, DElight that uses the radiosity method was added to the EnergyPlus version 1.2 and the following versions of EnergyPlus (EERE, n.d.).

## 5.4 Discussion of the Chart Tracing the Influence of Specific Organizations or Funding Sources

Many organizations have contributed to the development of simulation programs with funding from several government agencies and industry sponsors. The major federal funding agency that has supported simulation is the U.S. Department of Energy (US DOE). In the past, US DOE funding has usually been allocated to specific institutes according to the government priorities, economic conditions, and importance of research (Tupper et al., 2011). As well as the US DOE, selected industry associations sponsored the development of the simulation programs. With these funding sources, various developers or institutes have developed new or improved methods for simulation programs.

The following sections discuss key developers or institutes including which funding sources contributed to the development of specific simulation programs. Table 5.1 shows key developers, institutes, or meetings (i.e., symposium or conference) by funding source and started year as well as developed computer programs by the patron.

Table 5.4. *The summary of major organizations and funding sources.*

| Group | Key Developer, Organization, or Meeting (i.e., Symposium or Conference) | Sponsor or Funding Source / Year Started | Computer Program Developed |
|---|---|---|---|
| Whole-Building Energy Simulation | Organization: The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) | Various Source / 1959 | Developed analysis methods for building energy simulation |
| | Organization: The ASHRAE Task Group on Energy Requirements (TGER) | The National Bureau of Standards (NBS, now NIST), the U.S. Postal Service (USPS) and the National Research Council of Canada (NRC) / 1967 | Developed algorithms for building energy simulation |
| | Symposium: The Use of Computers for Environmental Engineering Related to Buildings | NBS, ASHRAE, and Automated Procedures for Engineering Consultants (APEC) / 1970 | N/A |
| | Organization: The U.S. Postal Service and the General American Research Division (GARD) of the General American Transportation Corporation (GATX)<br>Symposium: U.S. Postal Service Symposium - Computer Program for Analysis of Energy Utilization | USPS and National Security Industrial Association / 1971 | The Post Office Program |
| | Organization: The Energy Research and Development Administration (ERDA) (now, the U.S. Department of Energy (US DOE)), the Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory (LBNL)), the Computation Consultants Bureau (CCB), the Argonne Nation Laboratory (ANL), and the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) | US DOE / 1976 | CAL-ERDA / DOE-1&2 Versions |
| | Organization: The U.S. Army Construction Engineering Research Laboratory (CERL) and University of Illinois at Urbana-Champaign (UIUC) | US DOD / 1977 | BLAST (Later, IBLAST) |
| | Organization: CERL, UIUC, LBNL, Oklahoma State University (OSU), GARD Analytics, and Florida Solar Energy Center | US DOE / 1996 | EnergyPlus |
| | Organization: CERL, UIUC, LBNL, Oklahoma State University (OSU), GARD Analytics, and Florida Solar Energy Center | US DOE / 1996 | EnergyPlus |

Table 5.4. *Continued*

| Group | Key Developer, Organization, or Meeting (i.e., Symposium or Conference) | Sponsor or Funding Source / Year Started | Computer Program Developed |
|---|---|---|---|
| Whole-Building Energy Simulation | Conference: The International Building Performance Simulation Association (IBPSA) Conference | IBPSA / 1989 | N/A |
| | Organization: ASHRAE Technical Committee (TC) 4.7 | ASHRAE / 1981 | Developed algorithms and energy estimating methods for building energy simulation |
| Solar Energy Analysis Design or Simulation | Organization: The American Society of Mechanical Engineers (ASME) | Various Sources / 1880 | N/A |
| | Organization: The ASME Solar Energy Division (SED) | ASME / 1966 | N/A |
| | Organization: The American Solar Energy Society (ASES) of the International Solar Energy Society (ISES) | Various Sources / 1954 | N/A |
| | Developer: N.Sheridan and K. Bullock at the University of Queensland in Australia J. Duffie at the University of Wisconsin – Madison (UW - Madison) | N/A / 1967 | First Simulation Study using an Analog Computer |
| | Developer: H. Buchberg and J. Roulet at the University of California – Los Angeles (UCLA) | N/A / 1968 | First Simulation Study using an Digital Computer |
| | Developer: L. Butz, W. Beckman, and J. Duffie at the UW – Madison | ERDA (now US DOE) / 1974 | First Simulation Study sponsored by the ERDA (now, the US DOE) |
| | Organization: The Solar Energy Laboratory (SEL) at the UW – Madison | National Science Foundation (NSF) and ERDA / 1975 | TRNSYS |
| | Conference: The Passive Solar Heating and Cooling Conference | ERDA / 1976 | N/A |
| | Organization: The Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) | NSF and ERDA / 1975 & 1978 | PASOLE |
| | Organization: The Solar Energy Laboratory (SEL) at the UW – Madison | N/A / 1982 | F-Chart Software |
| | Organization: The Solar Energy Laboratory (SEL) at the UW – Madison | N/A / 1983 | PV F-Chart Software |
| | Organization: The Solar Energy Research Institute (SERI, now the National Renewable Energy Laboratory (NREL)) | US DOE / 1983 | SERIRES |

Table 5.4. *Continued*

| Group | Key Developer, Organization, or Meeting (i.e., Symposium or Conference) | Sponsor or Funding Source / Year Started | Computer Program Developed |
|---|---|---|---|
| Solar Energy Analysis Design or Simulation | Organization: The Sandia National Laboratory (SNL) | US DOE / 1985 | PVFORM model |
| | Organization: The CSU and NREL (i.e., formerly SERI) | US DOE / 1996 | SUNREL |
| Lighting & Daylighting Analysis Simulation | Organization: The Illuminating Engineering Society of North America (IESNA) of the Illuminating Engineering Society (IES) | Various Sources / 1906 | N/A |
| | Developer: R. Hopkinson, J. Longmore, and P. Petherbridge at the Building Research Station in the U.K. | N/A / 1954 | Split Flux Method, later Used for the DOE-2 Daylighting Model |
| | Developer: E. Sparrow at the University of Minnesota and R. Cess at the State University of New York at Stony Brook | N/A / 1966 | Radiosity Method, later Used for SUPERLITE and DElight Version 2.0 (i.e. the EnergyPlus Daylighting Module) |
| | Developer: Arthur Appel at the IBM Research Center | N/A / 1967 | Ray Tracing Method, later Used for Radiance |
| | Developer: David DiLaura at Wayne State University | N/A / 1968 | Lumen I (later became Lumen Micro) |
| | Conference: The Association for Computing Machinery (ACM)'s Special Interest Group on Graphics and Interactive Techniques (SIGGRAPH) Conference | ACM / 1974 | N/A |
| | Organization: LBL (now LBNL) | US DOE / 1982 | The DOE-2 Daylighting model |
| | Organization: LBL | US DOE / 1982 | SUPERLITE |
| | Developer: Gregory Ward at the LBL and the Ecole Polytechnique Federal de Lausanne (EPFL, Swiss institute) | US DOE and the Swiss government / 1989 | Radiance |
| | Organization: LBNL (formerly LBL) | US DOE / 2003 or 2004 | DElight Version 2.0 (i.e., the EnergyPlus Daylighting Module) |

In this section, the key developers or institutes are categorized by organization for the whole-building energy simulation programs, solar energy analysis programs, and the lighting and daylighting analysis programs.

### *5.4.1 The organizations for developing whole-building simulation programs*

The most important engineering organization that contributed to the development of whole-building simulation programs in the U.S. is the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

In 1889, the Master Steam and Hot Water Fitters Association of the United States (i.e., the antecedent of the American Society of Heating and Ventilating engineers (ASHVE)) was organized and opened the first convention of the Master Fitters Association. In 1894, ASHVE was started by the contribution of Hugh Barron who wanted to improve the convention by focusing on technical issues other than business of interest. In 1904, another engineering association, the American Society of Refrigerating Engineers (ASRE), was established by William Ross. He organized ASRE under the idea caused from an industry journal, the Cold Storage and Ice Trade Journal (Donaldson et al., 1994; ASHRAE, 2013).

In 1954, the name of ASHVE was changed to the American Society of Heating and Air Conditioning Engineers (ASHAE). In 1958, the members of ASHAE and ASRE voted to merge the two organizations. Finally, in 1959, the merged organization was officially launched with a new name, ASHRAE (ASHRAE, 2013).

Until the 1960s, most engineers estimated heating and cooling energy used in a building by using approximate methods from experience such as the heating degree day method, the bin method, and the cooling degree day method (i.e., equivalent full-load hour method) (Tull, 1971; Stamper, 1995). However, accurate methods were required to calculate heating and cooling energy because the heating and cooling energy cost accounts for the substantial amount of the total energy cost in a building. In addition, the use of a computer was necessary because an accurate energy estimation was complicated due to the effects of the varying weather data, HVAC system performance, and HVAC operating schedules (Tull, 1971).

In 1965, ASHRAE founded a Presidential Committee on Energy Consumption according to the significance of calculating heating and cooling energy with accurate methods. This committee checked the issues of developing accurate methods in detail and suggested assignments to a task group, called Task Group on Load Profiles, founded in 1965. From 1965 to 1966, the initial Task Group researched the accurate methods and developed a diagram for estimating building load profiles (Tull, 1971; Stamper, 1995). In 1966, the Task Group voted for the budgets for energy calculation research projects and a new renamed Task Group (Stamper, 1995). In 1967, the new Task Group known as the ASHRAE Task Group on Energy Requirements (TGER) for Heating and Cooling Buildings held the first meeting. Robert Tull, who was a previous ASHRAE president, became the chairman of the ASHRAE TGER (Tull, 1971; Stamper, 1995; Kusuda, 1999). In the mid-1960s, other engineering groups such as Westinghouse Electric Company, a group of gas industry companies called Group to Advance Total Energy (GATE), and Automated Procedures for Engineering Consultants (APEC) also developed computer procedures to calculate building energy. The ASHRAE TGER decided to utilize the computer procedures developed from other engineering groups to develop new computer algorithms (Tull, 1971; Stamper, 1995). At the time, engineers needed open source algorithms because some existing procedures of the groups were proprietary (Stamper, 1995). The National Bureau of Standards (NBS, now NIST), the U.S. Postal Service (USPS) and the National Research Council of Canada (NRC) also have contributed to the Task Group's project (Tull, 1971).

The ASHRAE TGER consisted of four subcommittees. Subcommittee #1 on Heating and Cooling Load Requirements was in charge of developing building loads calculation procedures. Subcommittee #2 on System and Equipment Energy was responsible for creating a new method to calculate energy requirements of HVAC systems and plants by utilizing the building loads. Subcommittee #3 on the Overall Logic Pattern worked for integrating other affecting variables, such as weather, operation schedule, and system auxiliaries, with the building loads and energy requirements calculations. Subcommittee #4 on Field Validation Studies was in charge of validating the developed procedures (Tull, 1971).

The ASHRAE TGER developed algorithms for calculating building loads that implemented a non-steady state heat calculation method developed by Stephenson and Mitalas in 1967 instead of the Total Equivalent Temperature Difference (TETD) / Time Averaging (TA) method described in the 1967 ASHRAE fundamental handbook. Stephenson and Mitalas's method, called the Thermal Response Factor Method, was used for calculating the instantaneous heat conduction through walls and roofs. This method discussed in Section 5.2.1.2 was also used for approximately calculating the thermal storage effect for walls and roofs. In 1968 and 1969, ASHRAE TGER first released two books that contained the algorithms of the building loads calculation methods of buildings and the energy calculation methods of HVAC systems and plants.

The loads calculation book was restrictively distributed to researchers and engineers at the ASHRAE annual meeting in 1968. The system simulation book was released in 1969. This book also was narrowly distributed (Tull, 1971).

In 1970, the first symposium regarding the use of computers for building energy simulation was held at the National Bureau of Standards (NBS) in Gaithersburg, Maryland, titled "Use of Computers for Environmental Engineering Related to Buildings" (Kusuda ed., 1971). This symposium attracted approximately 400 architects, engineers, and scientists from 12 countries. The 59 technical papers of this symposium addressed issues including computer applications for building heat transfer analysis, loads and energy calculations, HVAC system simulations, weather data, and computer graphics. The majority of these proceedings was related to cooling and heating load calculations because these were popular topics among building environmental engineers in the late 1960s (Kusuda ed., 1971). The application of computers to dynamic thermal load calculations allowed building engineers to work with more accurate solutions and methods (Tull, 1971; Lokmanhekim, 1971).

In 1971, the USPS held a symposium to introduce a Post Office computer program (USPS, 1971). The USPS developed the Post Office program, called Computer Program for Analysis of Energy Utilization in Postal Facilities, to calculate building energy savings for increasing post office branches. In the 1970s, the USPS was the second ranking institute that built many buildings in the U.S. (USPS, 1971; Stamper, 1995). The General American Research Division (GARD) of the General American Transportation Corporation (GATX), which was a subcontractor for the Post Office facilities division, developed the loads program (i.e., computational procedures) for the Post Office Program (Stamper 1995; Cumali, 2013).

In 1973, oil crisis from an Arab embargo as well as advanced computers triggered progressive improvements of developing computer procedures that analyze building thermal behavior and energy consumption (Ayres and Stamper, 1995). U.S. government funding was moved to the building energy simulation program area from the nuclear and aerospace technology area (Kusuda, 1999). The Energy Research and Development Administration (ERDA) (now, the USDOE) and Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory (LBNL)) developed CAL-ERDA in 1976 based on the analysis method (i.e., the Weighting Factor Method (WFM)) of the Post Office program. The Computation Consultants Bureau (CCB), the Argonne Nation Laboratory (ANL), and the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)) also contributed to the development of CAL-ERDA (Graven and Hirsch, 1977). In 1979, CAL-ERDA became the DOE-2 version. In the mid-1980s, the funding from the US DOE had been quickly reduced at ANL and LASL, so LBL became the main national laboratory for developing new versions of DOE-2 (Ayres and Stamper, 1995).

The U.S. Department of Defense (DOD) supported and the U.S. Army Construction Engineering Research Laboratory (CERL) issued BLAST in 1977 based on the analysis method (i.e., the Heat Balance Method (HBM)) of the NBSLD program developed at the NBS in the late 1960s (Stamper, 1995). In the meantime, proprietary sectors also developed building energy simulation programs. The utility industry released Gas for the Advancement of Total Energy (GATE) (later E-CUBE) in 1967 and AXCESS in 1971, and APEC issued HCC and ESP in 1967 and 1978. The Trance Company developed TRACE in 1972 (PNNL, 1990; Stamper, 1995; Ayres and Stamper, 1995). In 1996, DOE-2 and BLAST started to be combined as EnergyPlus by the efforts of LBNL, CERL, University of Illinois at Urbana-Champaign (UIUC), Oklahoma State University (OSU), GARD Analytics (formerly, GARD/GATX), and Florida Solar Energy Center, which are sponsored by the US DOE (Crawley et al., 2002).

In 1974, 1978, and 1983, building energy simulation symposiums following the first symposium for the use of computers for building energy simulation that was held in 1970 at the NBS were opened in Paris, Banff, and Tokyo. This is because the first symposium at the NBS was successfully held and attracted substantial interest (Kusuda ed., 1971; Kusuda, 1999). In 1985, the Building Energy Simulation Conference, sponsored by the Passive Solar Group of the US DOE, was held in Seattle, Washington (US DOE, 1985). The previous four symposiums and the one conference were considered as the origins of the International Building Performance Simulation Association (IBPSA) conference, which has been now opened every two years since 1989 (Kusuda, 1999). The IBPSA was established in 1987 to develop and share practical and advanced knowledge for building energy simulation worldwide (Tupper et al., 2011).

The ASHRAE TGER became Technical Committee (TC) 4.7 (ASHRAE, 1981; Stamper, 1995). TC 4.7 has contributed to the development of building energy simulation and the building energy estimating methods for simulation such as EnergyPlus until now.

In summary, the ASHRAE TGER was the main contributor for developing the algorithms of building energy simulation. Currently, TC 4.7, formerly the ASHRAE TGER, is the main supplier for the algorithms and estimating methods of building energy simulation. The US DOE, US DOD, USPS, and NBS (now NIST) contributed to the development of simulation programs based on the algorithms of the ASHRAE TFGER. National laboratories (i.e., LBL, ANL, and LASL) and consultant and academic institutes (i.e., CCB, GARD Analytics, UIUC, and OSU) also contributed to the development. The first symposium at the NBS successfully continues to the present time as the IBPSA conference.

#### *5.4.2 The organizations for developing solar system analysis simulation programs*

The American Society of Mechanical Engineers (ASME) Solar Energy Division (SED) and the American Solar Energy Society (ASES) have been the major contributors for the development of solar system analysis simulation programs.

In 1880, the ASME was founded to enhance and to share mechanical technology (ASME, 2013a). In the mid-1950s, mechanical engineers at the Massachusetts Institute of Technology (MIT) started to study reliable solar energy systems. Hottel and Woertz published their paper in Transactions of ASME (Hottel and Woertz, 1942; Balcomb, 1992; Beckman, 1993). In 1960, the Journal of Solar Energy Engineering was started. This journal has allowed many solar engineers to be involved in solar technology and simulation development (ASME, 2013b). In 1966, the ASME SED was grouped from the ASME to effectively utilize mechanical systems for solar energy (ASME, 2013c). In addition, the ASME Solar Energy Conference was started in 1981 for sharing information between solar engineers. This conference was integrated by previous conferences (i.e., the System Simulation and Economic Analysis (SSEA) Conference and the Solar Heating and Cooling Operational Results (SHCOR) Conference) sponsored by US DOE. The SSEA conference, held in 1978 and 1980, dealt with the issues of system simulation and economics. The SHCOR, held in 1978 and 1979, covered active and passive solar systems (Reid, 1981).

The ASES was founded in 1954. The ASES has increased solar energy feasibility as one of the sections of the International Solar Energy Society (ISES) (ASES, 2012). Solar Energy has been a journal of the ISES since 1957 and this journal also allowed many solar engineers to be involved in solar technology and simulation development (ELSEVIER, 2013). The ISES conference has been held every two years since the 1950s for solar engineers (ISES, 2012).

In 1967, N. Sheridan and K. Bullock at the University of Queensland in Australia and J. Duffie at the University of Wisconsin – Madison first studied simulation for solar systems. The researchers studied a process between solar water heating system components by using an analog computer (Sheridan et al., 1967; Beckman, 1993). In the same year, Close at the UW – Madison extended the previous study using an analog computer to an improved study using a digital computer with an analog simulation program. He proposed a factorial design method for estimating the effects of solar water heaters (Close, 1967). Early studies were conducted by using analog simulation because electrical models were able to easily account for the physical systems. However, analytic weather data was used and annual analysis could not be studied by analog simulation due to high cost (Beckman, 1993). In 1968, H. Buchberg and J. Roulet at University of California – Los Angeles (UCLA) used real weather data for annual simulation by using digital computer programs for estimating the effects of solar collector, storage, and auxiliary systems in residential buildings. IBM 7094 (i.e., a digital computer) located at UCLA was used for all computations in this study (Buchberg and Roulet, 1968). In 1973, G. Löf at Ohio State University (OSU) and R. Tybout at Colorado State University (CSU) first studied solar heating systems with a practical "what if" approach. They selected eight cities in the U.S. and hourly analyzed solar heating systems with several parameters, such as house, collector, storage sizes, tilted angle of solar collectors, and collector thermal capacity, using the speed of a digital computer (Löf and Tybout, 1973; Beckman, 1993). All the papers above were published in Solar Engineering journals of ISES.

Before 1973, solar simulation research was conducted by different universities and institutes, showing a lack of coherence between researches. In 1972, the national scheme for solar energy employment was proposed by the National Science Foundation (NSF) (Beckman, 1993). In 1974, the first study for solar simulation under the sponsorship of the U. S. Energy Research and Development Administration (ERDA, now the U. S. Department of Energy (US DOE)) was conducted by L. Butz, W. Beckman, and J. Duffie at the UW – Madison for solar cooling and heating systems of residential buildings (Butz et al., 1974; Beckman, 1993). About the same time, CSU researchers tried to build a test house for estimating solar heating systems, supported by the NSF. The simulation code of the Butz et al.'s program showed the deficiency of analyzing the CSU's solar test house. This was because the flexibility of the simulation code was inefficient to analyze the design parameters of the test house even though the solar heating systems of Butz et al's study were parallel to those of the CSU's solar test house (Beckman, 1993). The need of a flexible program created a simulation program with a modular approach. The Solar Energy Laboratory (SEL) at the UW – Madison proposed this development plan of the simulation program to the NSF. In 1975, a new developed simulation code became the modular simulation program, TRNSYS under the sponsorship of the NSF and the ERDA (Klein, 1976; Beckman, 1993; Tupper et al., 2011).

Other simulation programs were developed at the Los Alamos Scientific Laboratory (LASL, now Los Alamos National Laboratory (LANL)), by the sponsorship of the NSF and the US DOE programs (Kusuda, 1985; Beckman, 1993). The LASL programs were not fully documented and used as research tools (Beckman 1993). One of the LASL programs was PASOLE, and the name was from PAssive SOLar Energy. This simulation program was used in aiding to create design methods for passive solar heating applications (McFarland, 1978; Feldman and Merriam, 1979).

In 1976, the first strong interest for passive solar systems was represented as the Passive Solar Heating and Cooling conference, which was held at the University of New Mexico (LASL, 1976; Balcomb, 1992). The ERDA sponsored this conference, and the LASL coordinated it in collaboration with the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the New Mexico Solar Energy Association (NMSEA) (LASL, 1976). In 1977 and 1978, the ASES of ISES also held a conference for passive solar systems, sponsored by the US DOE (Prowler ed., 1978).

In 1979, Arthur D. Little, Inc. engineers including Feldman and Merriam reviewed approximately 70 simulation programs. The report of Arthur D. Little, Inc. was sponsored by Electric Power Research Institute (EPRI). The Solar Energy Research Institute (SERI, now the National Renewable Energy Laboratory (NREL)) and the US DOE coordinated this review report due to mutual interests (Feldman and Merriam, 1979). The SERI published a brochure with the updated list of solar simulation programs based on EPRI's report (SERI, 1980).

In 1983, The SERI developed the SERIRES simulation program for buildings that have passive solar systems. SERIRES stands for Solar Energy Research Institute Residential Energy Simulator (Palmiter and Wheeling, 1983). In 1985, the Sandia National Laboratory (SNL) developed a PVFORM model (i.e., detailed model) for photovoltaic (PV) systems used in most detailed PV programs in the U.S. (Menicucci, 1985; Klise and Stein, 2009). In 1996, SERIRES was upgraded to SUNREL by CSU and NREL (i.e., formerly SERI) (Deru, 1996). In 2009, the SEL published a review report for PV simulation programs (Klise and Stein, 2009).

In summary, the SED of ASES and the ASES of ISES have been the major contributors in the U.S. for the development of solar energy technology and simulation programs. From 1972, the US DOE financially supported most of the simulation development of solar energy systems. National laboratories (i.e., LASL (now, LANL), SERI (now, NREL), and SNL), and universities (i.e., the UW – Madison and CSU), institutes (i.e., EPRI and NMSEA) conducted studies for the simulation development under the sponsorship of the US DOE.

### *5.4.3 The organizations for developing lighting and daylighting analysis simulation programs*

The Illuminating Engineering Society (IES) and the Illuminating Engineering Society of North America (IESNA), which were established in 1906, have contributed to the development of lighting and daylighting technology. In the same year, the Journal of the Illuminating Engineering Society was started and published every year since 1906 (DiLaura, 2006). The ASES and ISES have also enhanced lighting and daylighting technology. The journal of Solar Energy by the ISES was started in 1957 and this journal also allowed many lighting and daylighting engineers to be involved in lighting and daylighting technology and simulation development (ISES, 2012).

In 1954, 1966, and 1968, key methods for calculating internal reflected light were introduced. In 1954, the split flux method was proposed by R. Hopkinson, J. Longmore, and P. Petherbridge at the Building Research Station (BRS) in the U.K. (Hopkinson et al., 1954). In 1966, E. Sparrow at the University of Minnesota and R. Cess at the State University of New York at Stony Brook introduced the radiosity concept in their book (Sparrow and Cess, 1966). In 1967, Arthur Appel at the IBM Research Center first proposed the concept of ray tracing (Appel, 1967; Weghorst et al., 1984).

In 1968, David DiLaura at Wayne State University proposed the Lumen I program that can estimate artificial lighting systems based on point-by-point calculations. In 1970, DiLaura developed Lumen II. This program improved the existing capabilities of Lumen I by adding the estimation options of daylighting, glare, and visual comfort. In 1980, DiLaura established Lighting Technologies Inc., and Lumen III was developed at Lighting Technologies Inc. in 1981. In 1983, Lighting Technologies Inc. released the first version of Lumen Micro, which was the next version of the Lumen series (i.e., Lumen I, II, and III). The name of Lumen Micro reflected the use of a microcomputer (as cited in Kota and Haberl, 2009). In the late 1980s, Lighting Technologies Inc. added a daylighting module to Lumen Micro. In 1996 and 1998, Lumen Micro Version 7.1 and Version 7.5 were released (Ubbelohde and Humann, 1998).

In 1969, the Special Interest Group on Graphics and Interactive Techniques (SIGGRAPH) was grouped from the Association for Computing Machinery (ACM) established in1947 (Williams, 1998; ACM, 2013). In 1974, a SIGGRAPH conference was initiated and has been held every year since 1974 (Williams, 1998). The SIGGRAPH and conference have been an important role for the development of lighting and daylighting simulation because the simulation analysis was related to rendering issues (i.e., image generation) based on computer graphics (Ward, 1994).

In the U.S. around 1976, strong interest and effort for employing passive solar energy were initiated (Balcomb, 1992). In 1976, the Passive Solar Heating and Cooling conference, which was discussed in the previous section, was held by the coordination of the LASL and the sponsorship of the ERDA (LASL, 1976; Balcomb, 1992). The interest of passive solar energy stimulated daylighting utilization because daylighting could be employed as a major approach of passive solar technology. In addition, daylighting utilization was able to accomplish building energy savings due to the reduction of electrical light usage (Gordon et al., 1986).

In 1982, LBL (now LBNL) researchers developed a daylighting model using the split flux method introduced in 1954. They integrated the daylighting model with the DOE-2.1b program (i.e., the building loads analysis program) to analyze the energy effects of the daylighting utilization in buildings (Selkowitz et al., 1982; LBL, 1982; Winkelmann, 1983). This model has been applied to the DOE-2.1 program series since 1982. In the same year, Michael Modest at University of Southern California (USC) published a paper to describe computer algorithms using the radiosity method introduced in 1966. The algorithms for digital computers were developed to calculate the daylighting effects inside rooms in buildings (Modest, 1982). Also, in the same year, Stephen Selkowitz, Jong-Jin Kim, Mojtaba Navvab, and Frederick Winkelmann at LBL described and compared the DOE-2.1 daylighting model and SUPERLITE (Selkowitz et al., 1982). In 1984, Cindy Goral, Kenneth Torrance, Donald Greenberg, and Bennett Battaile at Cornell University first represented the radiosity method for computer graphics (Goral et al., 1984).

In around 2003, NBNL developed a DElight Version 2.0 program that was the next version of SUPERLITE using the radiosity method. Before Version 2.0, Version 1.X series adopted the daylighting algorithms of the DOE-2.1b using the split flux method (Hitchcock and Carroll, 2003). In 2004, University of Illinois at Urbana-

Champaign (UIUC) and LBNL researchers integrated the version 2.0 of DElight into the EnergyPlus Version 1.2. From 2004, the DElight has been combined with the following versions of EnergyPlus (EERE, n.d.).

In 1989, Radiance using the ray tracing method introduced in 1968 was first released by the effort of Gregory Ward at the LBL and the Ecole Polytechnique Federal de Lausanne (EPFL, Swiss institute) (Ward, 1994). In 1998, Christoph Reinhart led the development of DAYSIM based on the Radiance algorithms. The National Research Council (NRC) Canada, Fraunhofer Institute for Solar Energy Systems (FISE), Harvard University, and Massachusetts Institute of Technology (MIT) contributed the development of DAYSIM (Reinhart, 2013). Since the years, Radiance and DAYSIM have been widely used for lighting and daylighting analysis.

In summary, the Illuminating Engineering Society of North America (IESNA), which was established in 1906, was a main contributor for developing lighting and daylighting technology in the U.S. In the 1950s and 1960s, many researchers (i.e., Hopkinson, Longmore, Patherbridge, Sparrow, Cess, Appel, and DiLaura) developed key lighting and daylighting analysis methods that were later used for simulation programs. After 1976 when there was strong national interest for employing daylighting strategies, LBL (now LBNL) has been a major developer for lighting and daylighting simulation (i.e., the DOE-2.1 daylighting algorithms, SUPERLITE, DElight, and Radiance).

# CHAPTER VI

# SUMMARY

Throughout this study, the origins of the key analysis methods used in whole-building simulation programs, solar energy design and simulation programs, and lighting and daylighting simulation programs, which were developed in the U.S., were traced and analyzed. In addition, the origins of the selected simulation programs and the organizations who contributed to the development of the analysis methods and the simulation programs were traced and analyzed. As a result, a new comprehensive genealogy chart has been created as shown in Appendix A, which is discussed using four approaches: by time period, analysis method, simulation program, and funding or organization. This study is intended to give readers a better understanding of where the analysis methods of the simulation programs came from, who developed them, and why they were developed through tracing the origins of the simulation programs.

The observations and findings from this study are the following:

Summary by time period:

- Significant historical events such as World War I (1914-1918) and World War II (1939-1945), the development of analog and digital computers and programming languages (1950s), and repeated oil crises (1967, 1973, and 1979) had a major impact on the development of key analysis methods and the origins of the simulation programs that are now used to simulate annual building energy use.

- In the pre-1950s period, most fundamentals (i.e., gas laws, heat transfer properties, and thermodynamics) of HVAC systems were studied and published, which contributed significantly to the development of today's technology. Also, during this same period, researchers and engineers developed the essential methods for: calculating dynamic heat gain and building loads (i.e., cooling and heating loads) used in whole-building energy simulation programs; calculating solar heating performance prediction used in solar energy analysis design and simulation programs; and for analyzing internal reflected illuminance used in lighting and daylighting simulation programs.
- During the 1950s, analog computers were widely used to study the behavior of dynamic heat gain/loss and the response of heating, ventilating, and air conditioning (HVAC) systems.
- From the 1960s until the present, digital computers and analysis methods suitable for the digital computers were developed and became widely used. Digital computers were substituted for analog computers because the digital computer is more convenient to program, more flexible, and the methods used in digital computers made it easier and quicker to describe the governing equations and driving functions than the methods used in analog computers. Finally, the scientific applications of the digital computer was considerably improved by the FORTRAN programming language, a high level scientific programming language that was first commercially released in 1957 by IBM. FORTRAN also allowed computer codes written on one computer to be run on another computer

by a different analyst, which accelerated the availability of simulation programs. As a result, both analog and digital computers significantly contributed to the development of whole-building, solar energy, lighting and daylighting simulation programs.

Summary by analysis method:

- In the 1920s, one of the most important methods for calculating the dynamic heat gain through walls and roofs for whole-building energy simulation (i.e., the Response Factor Method (RFM)) was developed and published by André Nessi and Léon Nisolle at Ėcole Centrale Paris (French University) in France. The RFM concept is still used in most of today's cooling and heating loads calculations such as with the Weighting Factor Method or the Transfer Function Method for DOE-2.1e, DOE 2.2/eQUEST, TRACE, and HAP, the CLTD/CLF method for TRACE, the Heat Balance method for BLAST and EnergyPlus, and the Radiant Time Series Method for TRACE.
- In the 1940s, the origin of the Resistance-Capacitance (RC) network analysis method (i.e., the thermal network method) used in simulation programs for buildings was first introduced by Victor Paschkis, a research engineer at Columbia University. The thermal network concept is used today in whole-building simulation programs such as DOE-2.1e and EnergyPlus and detailed solar simulation programs such as TRNSYS and SUNREL.

- In the 1950s, the origin of the most important method (i.e, the utilizability method) for calculating the performance of solar heating systems for design or simulation programs was developed by Austin Whillier at MIT. The utilizability method is used today in both advanced solar energy simulation programs such as TRNSYS and simplified solar design programs such as the F-Chart and the PV F-Chart program.
- In the 1950s and 1960s, the origins of the Inter Reflected Component (IRC) calculation method (i.e., the split flux method, the radiosity method, and the ray tracing method) for daylighting simulation were developed. In 1954, the split flux method was proposed by R. Hopkinson, J. Longmore, and P. Petherbridge at the Building Research Station in the U.K. In 1966, E. Sparrow at the University of Minnesota and R. Cess at the State University of New York at Stony Brook introduced the radiosity concept in their book, entitled Radiation Heat Transfer. In 1967, Arthur Appel at the IBM Research Center first proposed the concept of ray tracing. Today, the split flux method method is used in whole-building energy simulation programs such as DOE-2.1e, DOE 2.2/eQUEST, and EnergyPlus as a daylighting module. The radiosity method is used in Lumen Micro and one of the dayligihtg modules of EnergyPlus. Finally, the ray-tracing method is used in an advanced lighting and daylighting simulation program such as Radiance.

Summary by simulation program

- During the 1970s, companies and government organizations created dozens of peak-load and annual energy use simulation programs due to the repeated energy crises (1967, 1973, and 1979), the availability of digital computers, and the development of FORTRAN. However, many of these simulation programs are no longer in use because of a lack of support, poor documentation, limited technical upgrades, or discontinuance of the program.
- Today's most widely used simulation programs are the following:
  - a) whole-building energy simulation: EnergyPlus, DOE-2.1e, DOE-2.2/eQUEST, TRNSYS, TRACE, and HAP;
  - b) detailed solar energy simulation: TRNSYS and SUNREL, simplified solar design analysis: the F-Chart program and the PV F- Chart program; and
  - c) Independent lighting and daylighting simulation programs: Radiance, DAYSIM, and Lumen Micro; Integrated lighting and daylighting simulation programs: the DOE-2 daylighting model and the EnergyPlus daylighting modules.

Summary by organization and conference

- Over the years, ASHRAE has led the development of the analysis methods and the algorithms for whole-building energy simulation in the U.S. Most developments of whole-building simulation programs have been conducted by governmental organizations (i.e., US DOE, US DOD, USPS, and NIST), engineering societies (i.e., ASHRAE and IBPSA), national laboratories (i.e., LBNL, ANL, and LANL), and consultant and academic institutes (i.e., CCB, GARD Analytics, UIUC, and OSU).

- In 1970, the first symposium regarding the use of computers for building energy simulation was held at the NBS (now, NIST) in Gaithersburg, Maryland. In 1985, the Building Energy Simulation Conference, sponsored by the Passive Solar Group of the US DOE, was held in Seattle, Washington (US DOE, 1985). Both of these events are considered as the origins of the International Building Performance Simulation Association (IBPSA) conference, which has been held every two years since 1989.
- The SED of ASES, established in 1966, and the ASES of ISES, established in 1954, have been the major organizers of conferences in the U.S. that reported on the development of solar energy technology and simulation programs. From 1972 onward, the ERDA (now, the US DOE) financially supported the development of simulation of solar energy systems. National laboratories (i.e., LANL, NREL, and SNL), and universities (i.e., the UW – Madison and CSU) conducted important studies that led to simulation development under the sponsorship of the US DOE.
- The Illuminating Engineering Society of North America (IESNA), established in 1906, was the main organizer of conferences that reported on the development of lighting and daylighting technology in the U.S. In the 1950s and 1960s, many

researchers (i.e., Hopkinson, Longmore, Patherbridge, Sparrow, Cess, Appel, and DiLaura) developed key lighting and daylighting analysis methods that were later used for simulation programs. After 1976 when there was a strong national interest for employing daylighting strategies, LBNL became the major developer for lighting and daylighting simulation.

Key analysis methods developed by specific individuals at a variety of organizations can be traced to today's most widely used simulation programs.

- The Total Equivalent Temperature Differential (TETD)/Time Averaging (TA) method, the Transfer Function Method (TFM), the Cooling Load Temperature Difference (CLTD)/Solar Cooling Load (SCL)/Cooling Load Factor (CLF) method, and the Radiant Time Series (RTS) method were developed to calculate peak cooling load for whole-building energy simulation programs. The Weighting Factor Method (WFM) and the Heat Balance Method (HBM) were developed to calculate time-varying cooling load for energy analysis for whole-building energy simulation programs.
- The thermal network method was developed and used to analyze the time-varying dynamic cooling load and to simulate solar energy systems.
- The utilizability method and the un-utilizability method were developed to analyze solar energy amount for use by solar energy design or simulation programs.

- The split flux method, the radiosity method, and the ray tracing method were developed to analyze the inter-reflected lighting and daylighting in buildings for lighting and daylighting simulation programs.

Currently, the most widely used computer simulation programs in the U.S. for whole-building energy simulations are DOE-2.1e, eQUEST/DOE2.2, TRACE, HAP, TRNSYS, and EnergyPlus. TRNSYS and SUNREL are the most popular programs used for detailed solar energy analysis in buildings. TRNSYS is used to estimate solar thermal, active and passive solar systems, while SUNREL is used to analyze passive solar systems. The F-Chart program and the PV F-Chart program are both widely used for simplified solar energy analysis. Daylighting models in EnergyPlus, DOE-2.1e, and eQUEST/DOE2.2 are widely used to analyze daylighting in buildings and to estimate reduced lighting by daylighting. Radiance and Lumen Micro are used to simulate lighting and daylighting of buildings and render images for lighting and daylighting. DAYSIM is used to analyze annual lighting and daylighitng in buildings.

These prevalent simulation programs have adopted the key analysis methods, including the weighting factor method (WFM), the heat balance method (HBM), the thermal network method, the utilizability method, the un-utilizability method, the split flux method, the radiosity method, and the ray tracing method. The WFM is used in DOE-2.1e, eQUEST/DOE2.2, TRACE, and HAP. The HBM is used in EnergyPlus. The thermal network method is used in all whole-building and solar energy simulation programs, excluding lighting and daylighting simulation programs. The utilizability method and un-utilizability method are used in the F-Chart program, and the utilizability method is used in the PV F-Chart program. The split flux method is used in the daylighting model in DOE 2.1e, eQUEST/DOE2.2, and EnergyPlus. The radiosity method is used in the daylighting model of EnergyPlus and Lumen Micro. The ray tracing method is used in Radiance and DAYSIM. DAYSIM uses the algorithms of Radiance.

Some simulation programs have adopted the same analysis methods because these methods have proved to be reliable. These analysis methods all have strength and weaknesses- some have detailed solutions at slower computation speeds, and while others have simplified solutions at higher speeds.

In this study, the origins of the analysis methods and the simulation programs as well as the developers and the organizations who contributed to or funded the development of the analysis methods and the simulation programs have been discussed in order to better understand the simulation programs based on the comprehensive genealogy chart. The discussions based on the comprehensive genealogy chart provide detailed information to identify and comprehend the simulation programs, their analysis method, developers, and organizations. The new comprehensive genealogy chart can be used to better understand the analysis methods and capabilities of the selected simulation programs.

## REFERENCES


Alford, J. S., Ryan, J. E., & Urban, F. O. (1939). Effect of heat storage and variation in outdoor temperature and solar intensity on heat transfer through walls. *ASHVE Transactions, 45*, 369-396.

American Solar Energy Society (ASES). (2012). *About the American solar energy society*. Retrieved from http://www.ases.org/about-ases/

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1961). *ASHRAE guide and data book 1961 fundamentals and equipment.* New York, NY: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1975a). *Procedure for determining heating and cooling loads for computerizing energy calculations - Algorithms for building heat transfer subroutines.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1975b). *Procedures for simulating the performance of components and systems for energy calculations. W.F. Stoecker, (Ed.).* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1981). *ASHRAE Handbook: 1981 Fundamentals.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1997). *ASHRAE Handbook: 1997 Fundamentals.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (1998). *A toolkit for primary HVAC system energy calculations*. Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2001). *ASHRAE Handbook: 2001 Fundamentals.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2009). *ASHRAE Handbook: 2009 Fundamentals.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2010). *ANSI/ASHRAE/IESNA standard 90.1-2010, Energy standard for buildings except low-rise residential buildings.* Atlanta, GA: Author

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2011). *ANSI/ASHRAE/USGBC/IES standard 189.1-2011, Standard for the design of high-performance green buildings except low-rise residential buildings.* Atlanta, GA: Author.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2013). *The ASHRAE centennial: 100 years of progress.* Retrieved from www.ashrae.org/file%20library/doclib/public/200511311142_347

American Society of Mechanical Engineers (ASME). (2013a). *About ASME.* Retrieved from https://www.asme.org/about-asme

American Society of Mechanical Engineers (ASME). (2013b). *All issues.* Retrieved from http://solarenergyengineering.asmedigitalcollection.asme.org/issues.aspx

American Society of Mechanical Engineers (ASME). (2013c). *Solar energy division.* Retrieved from http://divisions.asme.org/solar/

Anderson, J. V., Mitchell, J. W., & Beckman, W. A. (1980). A design method for parallel solar-heat pump systems. *Solar Energy, 25,* 155-163.

Appel, A. (1967). The notion of quantitative invisibility and the machine rendering of solids. *Proceedings of the ACM National Conference, New York, NY,* 387-393.

Arney, M., Seward, P., & Kreider, J. F. (1981). P-chart – a passive solar design method. *Energy Engineering, 78*(3), 41-50.

Arvo, J. (1986). Backward ray tracing. *SIGGRAPH '86 Developments in Ray Tracing Course notes, volume 12.* Retrieved from http://www.cs.washington.edu/education/courses/cse457/06au/projects/trace/extra/Backward.pdf

Association for Computing Machinery (ACM). (2013). *History.* Retrieved from http://www.acm.org/about/history?searchterm=acm+established+1947

Athienitis, A., Kalogirou, S. A., & Candanedo, L. (2012). Modeling and simulation of passive and active solar thermal systems. In A. Sayigh (Ed.), *Comprehensive Renewable Energy Volume III* (pp. 357-417). New York, NY: ELSEVIER.

Ayres, J. M., & Stamper, E. (1995). Historical development of building energy calculations. *ASHRAE Transactions, 37*(2), 841-849.

Balcomb, J. D. (1992). Introduction. In J. D. Balcomb (Ed.), *Passive solar buildings* (pp. 1-37). Cambridge, MA: The MIT Press.

Balcomb, J. D., & Hedstrom, J. C. (1976). A simplified method for calculating required solar collector array size for space heating. *Proceedings of ISES Annual Meeting, Winnipeg, Canada, August 15-20,* 280-294.

Balcomb, J. D., Jones, R. W., McFarland, R.D., & Wray, W. O. (1984). *Passive solar heating analysis: a design manual.* Atlanta, GA: ASHRAE.

Balcomb, J. D., & McFarland, R. D. (1978). A simple empirical method for estimating the performance of a passive solar heated building of the thermal storage wall type. *Proceedings of 2nd National Passive Solar Conference, Philadelphia, PA, March 16-18,* 1-13.

Balcomb, J. D., & Wray, W. O. (1988). *Passive solar heating analysis. Supplement one: thermal mass effects and additional SLR correlations.* Atlanta, GA: ASHRAE.

Barley, C. D., & Winn, C. B. (1978). Optimal sizing of solar collectors by the method of relative areas. *Solar Energy 21*(4), 279-289.

Beckman, W. A. (1993). Detailed simulation methods and validation. In G. Löf (Ed.), *Active solar systems* (pp. 19-38). Cambridge, MA: The MIT Press.

Beckman, W. A., Klein, S. A., & Duffie, J. A. (1977). *Solar heating design by the f-chart method.* NY: John Wiley & Sons.

Bellis, M. (2013). *The history of the ENIAC computer.* Retrieved from http://inventors.about.com/od/estartinventions/a/Eniac.htm

Bendt, P., Collares-Pereira, M., & Rabl, A. (1981). The frequency distribution of daily insolation values. *Solar Energy, 27*(1), 1-5.

Birdsall, B., Buhl, W. F., Ellington, K. L., Erdem, A. E., & Winkelmann, F. C. (1990). *Overview of the DOE-2 building energy analysis program version 2.1 D* (LBL-19735, Rev. 1). Berkeley, CA: Lawrence Berkeley Laboratory.

Bourgeois, D., Reinhart, C. F., & Macdonald, I. (2006). Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control. *Energy and Buildings, 38(7)*, 814-823.

Brandemuehl, M. J., Gabel, S., & Andresen, I. (1993). A tookit for secondary HVAC system energy calculations. Atlanta, GA: ASHRAE.

Braun, J. E., Klein, S. A., & Pearson, K. A. (1983). An improved design method for solar water heating systems. *Solar Energy, 31(6)*, 597-604.

Bryan, H. J., & Clear, R. D. (1980). *A procedure for calculating interior daylight illumination with a programmable hand calculator* (LBL-11186). Retrieved from http://ec2-54-235-160-58.compute-1.amazonaws.com/fedora/repository/ir%3A81470

Buchberg, H. (1955). Electric analogue prediction of the thermal behavior of an inhabitable enclosure. *ASHVE Transactions 61,* 339-386.

Buchberg, H. (1958). Cooling load from thermal network solutions. *ASHVE Transactions 64,* 111-128.

Buchberg, H., & Roulet, J. R. (1968). Simulation and optimization of solar collection and storage for house heating. *Solar Energy, 12*, 31-50.

Buckles, W. E., & Klein, S. A. (1980). Analysis of solar domestic hot water heaters. *Solar Energy, 25*, 417-424.

Buhl, W. F., Erdem, A. E., Winkelmann, F. C., & Sowell, E. F. (1993). Recent improvements in SPARK: Strong component decomposition, multivalued objects, and praphical interface. *Proceedings of Building Simulation '93, Adelaide, Australia, August 16-18,* 283-290.

Butz, L. W., Beckman, W. A., & Duffie, J. A. (1974). Simulation of a solar heating and cooling system. *Solar Energy, 16,* 129-136.

Cane, R. L. D. (1979). *A "modified" bin method for estimating annual heating energy requirements of residential air source heat pumps* (DBR No. 910). Ottawa, Canada: National Research Council Canada.

Carpenter, R. C. (1897). Method of proportioning direct radiation. *ASHRAE Transactions 3*, 73-90.

Carpenter, R. C. (1907). Derivation of constants for building losses. *ASHRAE Transactions 13*, 90-102.

Carrier Corporation. (1960). *Handbook of air conditioning system design.* NY: McGraw – Hill.

Carrier Corporation. (2003). *HAP Quick Reference Guide.* Syracuse, NY: Carrier Corporation.

Carrier Corporation. (2013). *What's new with HAP*. Retrieved from http://www.commercial.carrier.com/commercial/hvac/general/0,3053,CLI1_DIV12_ETI3944,00.html.

Ceylan, H. T., & Myers, G. E. (1980). Long-time solutions to heat-conduction transients with time-dependent inputs. *Journal of Heat Transfer, 102*(1), 115-120.

Chen, F., & Jiang, Y. (1999). Introduction of building environment designer's simulation toolkit (DeST). *Proceedings of Building Simulation '99, Kyoto, Japan*, 1165-1172.

Cho, S., & Haberl, J. S. (2006). A survey of high-performance office buildings in the United States. *Proceedgins of Symposium on Improving Building Systems in Hot and Humid Climates, Orlando, FL, July 24-26*.

Clark, D. R., Klein, S. A., & Beckman, W. A. (1983). Algorithm for evaluating the hourly radiation utilizability function. *Journal of Solar Energy Engineering, 105*(3), 281-287.

Clark, D. R., Klein, S. A., & Beckman, W. A. (1984). A method for estimating the performance of photovoltaic systems. *Solar Energy, 33*(6), 551-555.

Clarke, J. A. (1982). *Documentation of the ESP-r system final grant report to SERC.* Glasgow, Scotland: University of Strathclyde.

Clarke, J. A. (2001). *Energy simulation in building design.* Oxford, England: Butterworth and Heineman.

Close, D. J. (1967). A design approach for solar processes (A 1966 conference paper). *Solar Energy, 11*(2), 112-122.

Collares-Pereira, M., & Rabl, A. (1979). Simple procedure for predicting long term average performance of nonconcentrating and of concentrating solar collectors. *Solar Energy, 23(3)*, 235-253.

Collins. (2013). *Digital computer.* Retrieved from http://www.collinsdictionary.com/dictionary/english/digital-computer

Computer History Museum (CHM). (2008). *The Babbage engine.* Retrieved from http://www.computerhistory.org/babbage/history/

Cook, R. L., Porter, T., & Carpenter, L. (1984). Distributed ray tracing. *Computer Graphics, 18*(3), 137-145.

Copeland, B. J. (Ed.). (2006). *COLOSSUS – the secrets of Bletchley Park's codebreaking computers.* NY: Oxford University Press.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2005). *Contrasting the capabilities of building energy performance simulation programs.* Retrieved from http://gundog.lbl.gov/dirpubs/2005/05_compare.pdf

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment, 43*(4), 661-673.

Crawley, D. B., Lawrie, L. K., Pedersen, C. O., Liesen, R. J., Fisher, D. E., Strand, R. K., Taylor, R. D., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., & Erdem, A. E. (1999). EnergyPlus: A new generation building energy simulation program. *Proceedings of Renewable and Advanced Energy Systems for the 21st Century, Maui, Hawaii, April 11-15*.

Crawley, D. B., Lawrie, L. K., Pedersen, C. O., Winkelmann, F. C., Witte, M. J., Strand, R. K., Liesen, R. J., Buhl, W. F., Huang, Y. J., Hnninger, R. H., Glazer, J., Fisher, D. E., & Shirey, D. (2002). EnergyPlus: New, capable, and linked**.** *Proceedings of the 2002 International Green Building Conference, Austin, TX.*

Crawley, D. B., Lawrie, L. K., Pedersen, C. O., Winkelmann, F. C., Witte, M. J., Strand, R. K., Liesen, R. J., Buhl, W. F., Huang, Y. J., Henninger, R. H., Glazer, J., Fisher, D. E., Shirey, D. B., Griffith, B. T., Ellis, P. G., & Gu, L. (2004). EnergyPlus: An update**.** *Proceedings of the SimBuild 2004 Conference, Boulder, CO, August 4-6.*

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Erdem, A. E., Pedersen, C. O., Liesen, R. J., & Fisher, D. E. (1997). What next for building energy simulation – A glimpse of the future. *Proceedings of Building Simulation '97, Prague, Czech Repunblic, September 7-10, Volume II,* 395-402.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., & Pedersen, C. O. (2001). EnergyPlus: New capabilities in a whole-building energy simulation program**.** *Proceedings of Building Simulation 2001*, *Rio de Janeiro, Brazil, August*, 51-58.

Cumali, Z. O. (2012). *Fast algorithms for EnergyPlus acceleration Phase I – 2012.* Unpublished manuscript, Optens, LLC, CA.

Cumali, Z. O. (February 12, 2013). Personal communication.

Cumail, Z. O., Sezgen, A. O., & Sullivan, R. (1979). Final report - passive solar calculation methods (Report under Contract EM-78-C-01-5221 to US Department of Energy). Oakland, CA: CCB/Cumali Associates.

Degelman, L. O. (1990). ENERCAL: A weather and building energy simulation model using fast hour-by-hour algorithms. *Proceedings of the 4th National Conference on Microcomputer Applications in Energy, Tucson, AZ,* 15-22.

Degelman, L. O., & Andrade, G. (1986). *A bibliography of available computer programs in the area of heating, ventilating, air conditioning, and refrigeration.* Atlanta, GA: ASHRAE.

Delcroix, B., Kummert, M., Daoud, A., & Hiller, M. (2012). Conduction transfer functions in TRNSYS multizone building model: Current implementation, limitations and possible improvements. *Proceedings of the Fifth National Conference of IBPSA-USA, Madison, WI,* 219-226.

Deru, M. P. (1996). *Improvements to the SERIRES/SUNREL building energy simulation program.* (Master's thesis). Fort Collins, CO: Colorado State University.

Deru, M. P., Judkoff, R., & Torcellini, P. (2002). *SUNREL, Technical reference manual* (NREL/BK-550-30193). Golden, CO: National Renewable Energy Laboratory.

DiLaura, D. L. (1975). On the computation of equivalent sphere illumination. *Journal of the Illuminating Engineering Society, 4,* 129-149.

DiLaura, D. L. (1976). On the computation of visual comfort probability. *Journal of the Illuminating Engineering Society, 5,* 207-217.

DiLaura, D. L. (2006). *A history of light and lighting: in celebration of the centenary of the Illuminating Engineering Society of North America.* New York, NY: The Illuminating Engineering Society of North America.

DiLaura, D. L., & Hauser, G. A. (1978). On calculating the effects of daylighting in interior spaces. *Journal of the Illuminating Engineering Society, 7,* 2-14.

Donaldson, B., Nagengast, B., & Meckler, G. (1994). *Heat & cold: Mastering the great indoors.* Atlanta, GA: ASHRAE.

Dooijes, E. H., & Peek, H. Z. (2013). *Analog computers.* Retrieved from http://www.science.uva.nl/museum/AnalogComputers.php

Dresler, A. (1954). The "reflected component" in daylighting design. *Transactions of the Illuminating Engineering Society, 19*(2), 50-60.

Duffie, J. A. (1993). Overview of modeling and simulation. In G. Löf (Ed.), *Active solar systems* (pp. 3-18). Cambridge, MA: The MIT Press.

Duffie, J. A., & Beckman, W.A. (2006). *Solar engineering of thermal processes.* (3rd ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Einhorn, H. D. (1979). Discomfort glare: a formula to bridge differences. *Lighting Research and Technology, 11*(2), 90-94.

ELSEVIER. (2013). *Solar energy.* Retrieved from http://www.sciencedirect.com/science/journal/0038092X/1

Emery, A. F., Garbini, J. L., Heerwagen, D. R., Kunkle, R. D., & Kippenhan, C. J. (1985). The measured performance and computer simulation of two unheated passive solar test cells in the Pacific Northwest. *Proceedings of Building Energy Simulation Conference, Seattle, WA,* 368-375.

Energy Efficiency & Renewable Energy (EERE). (n.d.). *New features by EnergyPlus version.* Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/pdfs/featurehighlights.pdf

Energy Efficiency & Renewable Energy (EERE). (2010). *EnergyPlus energy simulation software.* Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/

Energy Efficiency & Renewable Energy (EERE). (2011a). *Building energy software tools directory: HAP.* Retrieved from http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=385/pagename=alpha_list_sub

Energy Efficiency & Renewable Energy (EERE). (2011b). *Building energy software tools directory: SUNREL.* Retrieved from http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=457/pagename=alpha_list_sub

Energy Efficiency & Renewable Energy (EERE). (2011c). *Building energy software tools directory: Radiance.* Retrieved from http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=66/pagename=alpha_list_sub

Energy Efficiency & Renewable Energy (EERE). (2011d). *Building energy software tools directory: DAYSIM.* Retrieved from http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=428/pagename=alpha_list_sub

Energy Efficiency & Renewable Energy (EERE). (2011e). *EnergyPlus energy simulation software.* Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/

Energy Efficiency & Renewable Energy (EERE). (2012). *EnergyPlus energy simulation software.* Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/

Energy Efficiency & Renewable Energy (EERE). (2013a). *Building energy software tools directory*. Retrieved from http://apps1.eere.energy.gov/buildings/tools_directory/

Energy Efficiency & Renewable Energy (EERE). (2013b). *EnergyPlus energy simulation software.* Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/

Energy Systems Research Unit. (2002). *The ESP-r system for building energy simulation, user guide version 10 series.* Glasgow, Scotland: University of Strathclyde.

Estes, J. M., Schreppler, S., & Newsom, T. (2004). *Daylighting prediction software: comparative analysis and application. Proceedgins of the Fourteenth Symposium on Improving Building Systems in Hot and Humid Climates, Richardson, TX, May 17-20*, 259-267.

Evans, B. L., Klein, S. A., & Duffie, J. A. (1985). A design method for active-passive hybrid space heating systems. *Solar Energy, 35(2)*, 189-197.

Evans, D. L. (1980). Simplified method for predicting photovoltaic array output. *Proceedings of American Section Meeting of the International Solar Energy Society, Phoenix, AZ, June 2-6*.

Evans, D. L., Facinelli, W. A., & Koehler, L. P. (1980). *Simulation and simplified design studies of photovoltaic systems* (SAND 80-7013). Albuquerque, NM: Sandia National Laboratories.

Evans, D. L., Facinelli, W. A., & Otterbein, R. T. (1978). *Combined photovoltaic/thermal system studies* (SAND 78-7031). Albuquerque, NM: Sandia National Laboratories.

Evans, D. L., Rule, T. T., & Wood, B. D. (1982). A new look at long term collector performance and utilizability. *Solar Energy, 28*(1), 13-23.

Farzad, M. (2012, January 13). Personal communication.

Faust, F. H., Levine, L., & Urban, F. O. (1935). A rational heat gain method for the determination of air conditioning cooling loads. *ASHVE Transactions, 41*, 327-354.

Feldman, S. J., & Merriam, R. L. (1979). *Building energy analysis computer programs with solar heating and cooling System capabilities* (Research Report No. EPRI ER-1146 to the Electric Power Research Institute). Cambridge, MA: Arthur D. Little, Inc.

Fisher, D. E. (January 29, 2013). Personal communication.

Goldstein, R. A., & Nagel, R. (1971). 3-D visual simulation. *Simulation*, *16*, 25-31.

Goral, C. M., Torrance, K. E., Greenberg, D. P., Battaile, B. (1984). Modeling the interaction on light between diffuse surfaces. *Proceedings of the 11th Annual Conference on Computer Graphics and Interactive Techniques SIGGRAPH '84, New York, NY,* 213-222.

Gordon, H. T., Rittelman, P. R., Estoque, J., Hart, G. K., & Kantrowitz, M. (1986). Passive solar energy for non-residential buildings. In K. W. Böer (Ed.), *Advances in solar energy – an annual review of research and development volume 3* (pp. 171-206). Boulder, CO: American Solar Energy Society (ASES), Inc.

Gough, M. A. (1999). *A review of new techniques in building energy and environmental modelling.* Final Report BRE Contract No. BREA-42. Garston, Watford, UK: Building Research Establishment.

Grantham, B. (2008). *COEN 290 Computer Graphics I – Santa Clara University.* Retrieved from www.plunk.org/COEN-290/Notes/Week8.ppt

Gratia, E. (1985). The Sunspace: Computation and in-situ measures. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 338-345.

Graven, R. M., & Hirsch, P. R. (1977). *CAL-ERDA users manual* (ANL/ENG-77-03). Argonne, IL: Argonne National Laboratory.

Greenberg, D. P., Cohen, M. F., & Torrance, K. E. (1986). Radiosity: A method for computing global illumination. *The Visual Computer, 2,* 291-297.

Grondzik, W. T., Kwok, A. G., Stein, B., & Reynolds, J. S. (2010). *Mechanical and electrical equipment for buildings*. Hoboken, NJ: John Wiley & Sons, Inc.

Gupta, Y., & Young, S. (1980). Method of predicting long-term average performance of photovoltaic systems. *Proceedings of Systems Simulation and Economic Analysis Conference, San Diego, CA.*

Haberl, J. S., & Cho, S. (2004a). *Literature review of uncertainty of analysis methods (F-Chart program)* (ESL-TR- 04-08-04). Retrieved from Texas A&M University, Energy Systems Laboratory website: http://www.esl.tamu.edu/docs/terp/2004/ESL-TR-04-08-04.pdf

Haberl, J. S., & Cho, S. (2004b). *Literature review of uncertainty of analysis methods (PV F-Chart program)* (ESL-TR-04-10-02). Retrieved from Texas A&M University, Energy Systems Laboratory website: http://www.esl.tamu.edu/docs/terp/2004/ESL-TR-04-10-02.pdf

Haberl, J. S., & Cho, S. (2004c). *Literature review of uncertainty of analysis methods (DOE-2 program)* (ESL-TR- 04-11-01). Retrieved from Texas A&M University, Energy Systems Laboratory website: http://www.esl.tamu.edu/docs/terp/2004/ESL-TR-04-11-01.pdf

Harris, S. M., & McQuiston, F. C. (1988). A study to categorize walls and roofs on the basis of thermal response. *ASHRAE Transactions*, *94*(2), 688-714.

Hayashi, T., Urano, Y., Watanabe, T., & Ryu, Y. (1985). Passive system simulation program "PSSP" and its applications. *Proceedings of the Building Energy Simulation Conference, Seattle, WA*, 346-353.

Henninger, R. H. (Ed.). (1975). *NECAP – NASA's energy-cost analysis program: Part II – engineering manual.* NASA CR-2590 Part II. Washington, DC: National Aeronautics and Space Administration (NASA).

Herron, D., Walton, G., & Lawrie, L. (1981). *Building loads anlaysis and system thermodynamics (BLAST) program users manual. Volume one. Supplement (Version 3.0).* Illinois, IL: U.S. Army Construction Engineering Research Laboratory (CERL).

Higgins, J. A. (2012). Energy modeling basics. *ASHRAE Journal*, *54*(12), 26-30.

Hill, P. R. (1957). *A method of computing the transient temperature of thick walls from arbitrary variation of adiabatic-wall temperature and heat-transfer coefficient.* (Technical Notes No. 4105). Hampton, VA: Langley Aeronautical Laboratory.

Hitchcock, R. J., & Carroll, W. L. (2003). DElight: A daylighting and electric lighting simulation engine. *Proceedings of Building Simulation 2003, Eindhoven, The Netherlands,* 483-489.

Hittle, D. C. (1977). *The building loads analysis and system thermodynamics program (BLAST).* Illinois, IL: U.S. Army Construction Engineering Research Laboratory (CERL).

Hollands, K. G. T., & Huget, R. G. (1983). A probability density function for the clearness index, with applications. *Solar Energy, 30(3)*, 195-209.

Holness, G. (2011). On the path to net zero, how do we get there from here?. *ASHRAE Journal*, *53*(6), 50-60.

Hopkinson, R. G., Longmore, J., & Petherbridge, P. (1954). An empirical formula for the computation of the indirect component of daylight factor. *Transactions of the Illuminating Engineering Society, 19*(7), 201-219.

Hopkinson, R. G., Petherbridge, P., & Longmore, J. (1966). *Daylighting*. London, England: Heinemann.

Hottel, H. C. (1950). Performance of flat-plate solar energy collectors. *Proceedings of a Course-Symposium Held at MIT, Cambridge, MA*, 58-71.

Hottel, H. C. (1954). Radiant-heat transmission. In W. H. McAdams (Ed.), *Heat transmission* (3d ed., chapter 4). NY: McGraw-Hill.

Hottel, H. C., & Whillier, A. (1955). Evaluation of flat-plate solar collector performance. *Transaction of the Conference on the Use of Solar Energy: The Scientific Basis, Tucson, AZ, Vol. 2., Part I, Secton A*, 74-104.

Hottel, H. C., & Woertz, B. B. (1942). Performance of flat-plate solar collectors. *ASME Transactions, 64*, 91-104.

Howell, J. R., & Perlmutter, M. (1964). Monte Carlo solution of thermal transfer through radiant media between gray walls. *Journal of Heat Transfer, 86*(1), 116-122.

Huang, J., Bourassa, N., Buhl, F., Erdem, E., & Hitchcock, R. (2006). Using energyplus for California title-24 compliance calculations. *Proceedings of 2nd National IBPSA-USA Conference SimBuild 2006, Cambridge, MA.*

Hydeman, M. (2006). A tale of two codes. *ASHRAE Journal, 48*, 46-53.

International Building Performance Simulation Association - USA Affiliate (IBPSA USA). (2011). *Overview of simulation.* Retrieved from http://www.labeee.ufsc.br/sites/default/files/disciplinas/ECV4202_Overview_Simulation.pdf

International Building Performance Simulation Association - USA Affiliate (IBPSA USA). (2013). *Radiance.* Retrieved from http://www.bembook.ibpsa.us/index.php?title=Radiance

International Code Council (ICC). (2012). *International green construction code* [PowerPoint]. Retrieved from http://www.iccsafe.org/cs/IGCC/Documents/Media/IGCC-PPT.ppsx

Intergovernmental Panel on Climate Change (IPCC). (2011). Renewable energy and climate change. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds.), *IPCC special report on renewable energy sources and climate change mitigation* (pp.l61-208). New York, NY: Cambridge University Press.

International Solar Energy Society (ISES). (2012). *ISES conferences.* Retrieved from http://www.ises.org/index.html

Ishizuka, M., Kobashi, K., & Nakamura, T. (1985). Validation of energy simulation program for passive solar house. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 360-367.

Jacobs, P., & Henderson, H. (2002). *State-of-the-art review of whole building, building envelope, and HVAC component and system simulation and design tools.* Retrieved from http://www.engineering.ucsb.edu/~mgroup/wiki/images/a/ae/30010.30020-final.pdf

James J. Hirsch & Associates (JJH) (1997). *Converting DOE-2.1E input files for use with DOE-2.2 and PowerDOE.* Retrieved from www.doe2.com/download/Docs/cnvrt21e.pdf

James J. Hirsch & Associates (JJH) (2009). *DOE-2 building energy use and cost analysis tool.* Retrieved from http://doe2.com/DOE2/#doe21edocs

James J. Hirsch & Associates (JJH) (2012). *Comparison of DOE-2.1E, DOE-2.2, eQUEST and PowerDOE.* Retrieved from http://www.doe2.com/compare.html

Jansen, S. J. (1985). ECAP - An energy and cost analysis program for microcomputers. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 104-111.

Johnson, H. A. (1948). Periodic heat transfer at the inner surface of a homogeneous wall. *ASHVE Transactions 54,* 143-164.

Jones, G. F., & Wray, W. O. (1992). Simplified methods. In J. D. Balcomb (Ed.), *Passive solar buildings* (pp. 181-197). Cambridge, MA: The MIT Press.

Jurinak, J. J., & Abdel-Khalik, S. I. (1979). Sizing phase-change energy storage units for air-based solar heating systems. *Solar Energy, 22*, 355-359.

Kerrisk, J. F. (1981). *Weighting factors in the DOE-2 computer program* (LA-8886-MS). Los Alamos, NM: Los Alamos Scientific Laboratory.

Kerrisk, J. F., Hunn, B. D., Schnurr, N. M., & Moore, J. E. (1981). *The custom weighting-factor method for thermal-load calculations in the DOE-2 computer* *program* (LA-UR-81-1559). Los Alamos, NM: Los Alamos Scientific Laboratory.

Kerrisk, J. F., Moore, J. E., Schnurr, N. M., & Hunn, B. D. (1980). Passive solar design calculations with the DOE-2 computer program. *Proceedings of the Fifth National Passive Solar Conference, Amherst, MA, October 19-26*, 116-120.

Kim, J. J., Papamichael, K. M., Selkowitz, S., Spitzglas, M., & Modest, M. (1986). Determining daylight illuminance in rooms having complex fenestration systems. *Proceedings of the International Daylighting Conference, November 5-7, Long Beach, CA.*

Kimball, H. H., & Hand, I. F. (1921). Sky-brightness and daylight-illumination measurements. *Monthly Weather Review, 49*(9), 481-488.

Kimura, K. (1977). *Scientific basis of air-conditioning.* London, England: Applied Science Publishers.

Klein, S. A. (1973). *The effects of thermal capacitance upon the performance of flat-plate solar collectors.* (Master's thesis). Madison, WI: University of Wisconsin-Madison.

Klein, S. A. (1976). *A design procedure for solar heating systems.* (Doctoral dissertation). Madison, WI: University of Wisconsin-Madison.

Klein, S. A. (1978). Calculation of flat-plate collector utilizability. *Solar Energy*, *21*(5), 393-402.

Klein, S. A. (1993). Design methods for active solar systems. In G. Löf (Ed.), *Active solar systems* (pp. 39-80). Cambridge, MA: The MIT Press.

Klein, S. A., & Beckman, W. A. (1979). A general design method for closed-loop solar energy systems. *Solar Energy, 22*(3), 269-282.

Klein, S. A., & Beckman, W. A. (1984). Review of solar radiation utilizability. *Journal of Solar Energy Engineering, 106*, 393-402.

Klein, S. A., & Beckman, W. A. (2001a). *F-Chart user's manual: F-Chart software.* Retrieved from www.fchart.com.

Klein, S. A., & Beckman, W. A. (2001b). *PV F-Chart user's Manual: DOS version: F-Chart Software.* Retrieved from www.fchart.com.

Klein, S. A., Beckman, W. A., & Duffle, J. A. (1976). TRNSYS - A transient simulation program. *ASHRAE Transactions 82*(1), 623-633.

Klein, S. A., Monsen, W. A., & Beckman, W. A. (1981). Tabular data for the unutilizability passive solar design method. *Proceedings of 6th National Passive Solar Conference, Portland, OR, September 8-12,* 282-332.

Klein, S. A., & Theilacker, J. C. (1981). An algorithm for calculating monthly-average radiation on inclined surfaces. *Journal of Solar Energy Engineering, 103*(1), 29-33.

Klise, G. T., & Stein, J. S. (2009). *Models used to assess the performance of photovoltaic systems* (Sandia Report SAND2009-8258). Retrieved from http://prod.sandia.gov/techlib/access-control.cgi/2009/098258.pdf

Kota, S. (2011). *Developing and testing an improved thermal and daylighting model to study high performance commercial office buildings.* (Unpublished doctoral proposal). Texas A&M University, College Station, TX.

Kota, S., & Haberl, J. S. (2009). Historical survey of daylighting calculation methods and their use in energy performance simulations. *Proceedings of the 9th International Conference for Enhanced Building Operation, Austin, TX.*

Kreider, J. F., Cowing, T., & Lohner, T. (1982). Direct calculation of cost-optimal solar DHW system size for the United States. *Proceedings of ASME Solar Energy Division 4$^{th}$ Annual Meeting, Albuquerque, NM,* 115-118.

Kuchkuda, R. (1988). An introduction to ray tracing. In R. A. Earnshaw (Ed.)., *Theoretical foundations of computer graphics and CAD* (pp. 1039-1060). London, England: Springer-Verlag.

Kusuda, T. (1969). Thermal response factors for multi-layer structures of various heat conduction systems. *ASHRAE Transactions, 75*(1), 246-271.

Kusuda, T. (Ed.). (1971). *Use of computers for environmental engineering related to buildings.* (National Bureau of Standards Building Science Series 39). Washington, DC: Government Printing Office.

Kusuda, T. (1976). *NBSLD, the computer program for heating and cooling loads in buildings.* (National Bureau of Standards Building Science Series 69). Washington, DC: Government Printing Office.

Kusuda, T. (1985). Summary of recent activities on building energy simulation analysis in North America. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 1-14.

Kusuda, T. (1999). Early history and future prospects of building system simulation. *Proceedings of Building Simulation* 1999*, Kyoto, Japan, 1,* 3-16.

Kusuda, T., & Achenbach, P. R. (1963). Numerical analyses of the thermal environment of occupied underground spaces with finite cover using a digital computer. *ASHRAE Transactions, 69*, 439-447.

Kusuda, T. & Powell, F. J. (1972). Use of modern computer programs to evaluate dynamic heat transfer and energy use processes in buildings. In B. E. Foster (Ed.), *National Bureau of Standards Special Publication 361: Vol.1. Performance Concept in Buildings* (pp. 407-418). Washington, DC: Government Printing Office.

Lameiro, G. F., & Bendt, P. (1978). *The GFL method for sizing solar energy space and water heating systems* (SERI-30). Golden, CO: Solar Energy Research Institute (now NREL).

Landsberg, D. R. (January 30, 2013). Personal communication.

Lawrence Berkeley Laboratory (LBL). (1982). *DOE-2 supplement version 2.1B* (LBL-8706, Rev.3.Suppl.). Berkeley, CA: Author.

Lawrence Berkeley Laboratory (LBL). (1984). *DOE-2 supplement version 2.1C* (LBL-8706, Rev.4.Suppl.). Berkeley, CA: Author.

Lawrence Berkeley Laboratory (LBL). (1989). *DOE-2 supplement version 2.1D* (LBL-8706, Rev.5.Suppl.). Berkeley, CA: Author.

Lawrence Berkeley National Laboratory (LBNL). (2013). *Radiance release notes*. Retrieved from http://radsite.lbl.gov/radiance/refer/Notes/ReleaseNotes.html

Lawrence Berkeley National Laboratory (LBNL) & James J. Hirsch & Associates (JJH). (1998). *Overview of DOE-2.2.* Retrieved from http://www.doe2.com/download/Docs/22_Oview.pdf

Leighton, G. S., Ross, H. D., Lokmanhekim, M., Rosenfeld, A. H., Winkelmann, F. C., & Cumali, Z. O. (1978). *DOE-1: A new state-of-the-art computer program for the energy utilization analysis of buildings* (LBL-7836). Berkeley, CA: Lawrence Berkeley Laboratory.

Leopold, C. S. (1948). Hydraulic analogue for the solution of problems of thermal storage, radiation, convection and conduction. *ASHVE Transactions 54,* 389-406.

Lighting Technologies Inc. (LTI) (2006). *Some changes.* Retrieved from http://www.lighting-technologies.com/announce/anc_apd.html

Liu, B. Y. H., & Jordan, R. C. (1960). The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy, 4(3),* 1-19.

Liu, B. Y. H., & Jordan, R. C. (1963). A rational procedure for predicting the long-term average performance of flat-plate solar-energy collectors. *Solar Energy, 7(2),* 53-74.

Löf, G. O. G., & Tybout, R. A. (1973). Cost of house heating with solar energy. *Solar Energy, 14,* 253-278.

Lokmanhekim, M. (1971). Calculation of energy requirements with the proposed ASHRAE algorithms for U.S. postal buildings. In T. Kusuda (Ed.), *Building Science Series: Vol. 39. Use of Computers for Environmental Engineering Related to Buildings* (pp. 279-287). Atlanta, GA: ASHRAE.

Lokmanhekim, M. (Ed.). (1971). *Procedure for determining heating and cooling loads for computerized energy calculations – algorithms for building heat transfer subrouties.* Atlanta, GA: ASHRAE.

Los Alamos Scientific Laboratory (LASL). (1976). *Passive solar heating and cooling - conference and workshop proceedings* (LA-6637-C). Los Alamos, NM: Author.

Los Alamos Scientific Laboratory (LASL). (1980). *DOE-2 reference manual part 1 (version 2.1).* Los Alamos, NM: Author.

Love, J. A. (1992). The evolution of performance indicators for the evaluation of daylighting systems. *Proceedings of Industry Applications Society Annual Meeting, Houston, TX*, 1830-1836.

Mackey, C. O., & Wright, L. T. (1942). Summer comfort factors as influenced by the thermal properties of building materials. *Heating, Piping, and Air Conditioning, 14*(12), 750-757.

Mackey, C. O., & Wright, L. T. (1944). Periodic heat flow – homogeneous walls or roofs. *Heating, Piping, and Air Conditioning, 16*(9), 546-555.

Mackey, C. O., & Wright, L. T. (1946). Periodic heat flow – composite walls or roofs. *ASHVE Transactions, 52,* 283-296.

Malhotra, M. (2009). *An analysis of off-grid, off-pipe housing in six U.S. climates.* (Doctoral Dissertation). Retrieved from http://www-esl.tamu.edu/docs/publications/thesis_dissertations/esl-th-09-12-02.pdf

Mao, C., Haberl, J. S., & Baltazar, J. C. (2013). Peak heating/cooling load design methods: how we got to where we are today in the U.S. *Proceedings of 13$^{th}$ International Conference of the IBPSA, France,* In Preparation (August).

Mardaljevic, J. (2000). Simulation of annual daylighting profiles for internal illuminance. *Lighting Research and Technology, 32*(3), 111-118.

Marsh, A. J. (1996). Integrating performance modeling into the initial stages of design. *Proceedings of ANZAScA Conference, Hong Kong, China.*

Mason, M. (1985). Survey of simulation technology in Australia and New Zealand. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 31-40.

Matsuura, K. (1987). *Luminance Distributions of Various Reference Skies.* CIE Technical Report TC 3-09. Vienna, Austria: International Commission on Illumination (CIE).

Matsuo, Y. (1985). Survey of simulation technology in Japan and Asia. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 23-30.

McCartney, S. (1999). *ENIAC - the triumphs and tragedies of the world's first computer.* New York, NY: Walker.

McFarland, R. D. (1978). PASOLE: A general simulation program for passive solar energy (LA-7433-MS). Los Alamos, NM: Los Alamos National Laboratory.

McQuiston, F. C., & Spitler, J. D. (1992). *Cooling and heating load calculation manual.* (2$^{nd}$ ed.). Atlanta, GA: ASHRAE.

Mendes, N., Oliveira, R. C., & Santos, G. H. (2003). Domus 2.0: A whole-building hygrothermal simulation program. *Proceedings of Building Simulation 2003, Eindhoven, The Netherlands,* 863-870.

Menicucci, D. F. (1985). PVFORM- A new approach to photovoltaic system performance modeling. *Proceedings of the 18th IEEE Photovoltaic Specialists Conference, Las Vegas, NV, October 21.*

Menicucci, D. F. (1986). Photovoltaic array performance simulation models. *Solar Cells, 18,* 383-392.

Merriam, L. R. (1985). ESPRE 1.2: A microcomputer program for residential hourly energy use Analysis. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 144-149.

Milne, M., Barnett, J., Gomez, C., Leeper, D., & LaRoche, P. (2004). Customizing HEED for a small utility district. *Proceedings of the American Solar Energy Society 2004, Portland, OR.*

Mitalas, G. P. (1965). An assessment of common assumptions in estimating cooling loads and space temperatures. *ASHRAE Transactions, 71,* Pt. 2, 72-80.

Mitalas, G. P. (1968). Calculation of transient heat flow through walls and roofs. *ASHRAE Transactions, 74,* Pt. 2, 182-188.

Mitalas, G. P. (1969). An experimental check on the weighting factor of calculating room cooling load. *ASHRAE Transactions, 75,* Pt. 2, 222-232.

Mitalas, G. P. (1972). Transfer function method of calculating cooling loads, heat extraction and space temperature. ASHRAE Journal, 14*(12)*, 54-56.

Mitalas, G. P., & Arseneault, J. G. (1967). *Fortran IV program to calculate heat flux response factors for a multi-layer slab.* DBR Computer Program No. 26. Ottawa, Canada: National Research Council of Canada – Division of Building Research.

Mitalas, G. P., & Arseneault, J. G. (1972). *Fortran IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs*. DBR Computer Program No. 33. Ottawa, Canada: National Research Council of Canada – Division of Building Research.

Mitalas, G. P., & Stephenson, D. G. (1966). *Fortran IV programs to calculate radiant energy interchange factors.* DBR Computer Program No. 25. Ottawa, Canada: National Research Council of Canada – Division of Building Research.

Mitalas, G. P., & Stephenson, D. G. (1967). Room thermal response factors. *ASHRAE Transactions, 73,* Pt.1, 1-10.

Modest, M. F. (1982). A general model for the calculation of daylighting in interior spaces. *Energy and Buildings, 5,* 69-79.

Moller, S. K. (1996). BUNYIP – A major upgrade. *Proceedings of the Annual Conference of the Australian and New Zealand Solar Energy Society, Darwin, Australia.*

Monsen, W. A., & Klein, S.A. (1980). Prediction of direct gain solar heating system performance. *Proceedings of American Section of the International Solar Energy Society, Phoenix, AZ, June, 1980,* 865-869.

Monsen, W. A., Klein, S.A., & Beckman, W. A. (1981). Prediction of direct gain solar heating system performance. *Solar Energy, 27(2),* 143-147.

Monsen, W. A., Klein, S.A., & Beckman, W. A. (1981). The unutilizability design method for collector-storage walls. *Proceedings of Annual Meeting, American Section of the International Solar Energy Society, Philadelphia, PA, May 1981. American Section of the International Solar Energy Society.* 862-866.

Monsen, W. A., Klein, S.A., & Beckman, W. A. (1982). The un-utilizability design method for collector-storage walls. *Solar Energy, 29(5)*, 421-429.

Moore, F. (1985). *Concepts and practice of architectural daylighting.* New York, NY: Van Nostrand Reinhold Company.

Nabil, A., & Mardaljevic, J. (2005). Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research and Technology, 37*(1), 41-59.

Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings, 38*(7), 905-913.

National Renewable Energy Laboratory (NREL). (2005). R&D 100 award – TREAT with SUNREL Energy Analysis Software. *NREL-FS-550-38989.* Retrieved from http://bld-specialists.com/documents/PVFORM_sol_cells_sm.pdf

Nelson, L. W. (1965). The analog computer as a product design tool. *ASHRAE Journal 7*(11), 37-45.

Nessi, A., & Nisolle, N. (1925). *Regimes variables de fonctionnement dans les installations de chauffage central.* Paris, France: Dunod.

Neymark, J., & Judkoff, R. (2002). *International energy agency building energy simulation test and diagnostic method for heating, ventilating, and air-*

*conditioning equipment models (HVAC BESTEST); Volume 1: Cases E100-E200.* Retrieved from http://www.nrel.gov/docs/fy02osti/30152.pdf

Niles, P. W. B. (1992). Simulation analysis. In J. D. Balcomb (Ed.), *Passive solar buildings* (pp. 111-179). Cambridge, MA: The MIT Press.

Nottage, H. B., & Parmelee, G. V. (1954). Circuit analysis applied to load estimating. *ASHVE Transactions 60,* 59-102.

Obert, E. F. (1960). *Concepts of thermodynamics.* NY: McGraw-Hill.

Ouyang, K., & Haghighat, F. (1991). A procedure for calculating thermal response factors of multi-layer walls – State space method. *Building and Environment, 26*(2), 173-177.

Pacific Northwest National Laboratory (PNNL). (1989). *Architect's and engineer's guide to energy conservation in existing buildings Volume 2 – Energy conservation opportunities* (PNL-7105, Vol. 2). Richland, WA: Author.

Pacific Northwest National Laboratory (PNNL). (1990). *Architect's and engineer's guide to energy conservation in existing buildings Volume 1 – Energy use assessment and simulation methods* (PNL-7105, Vol. 1). Richland, WA: Author.

Palmiter, M. L. (1992). *SUNCAT version 2.4 user notes.* Butte, MT: National Center for Appropriate Technology.

Palmiter, M. L., & Wheeling, T. (1983). *Solar energy research institute residential energy simulator (Version 1.0).* Golden, CO: Solar Energy Research Institute (now NREL).

Papamichael, K., Hitchcock, R., Ehrlich, C., & Carroll, B. (1998). New tools for the evaluation of daylighting strategies and technologies. *Proceedings of the International Daylighting Conference'98, Ottawa, ON, Canada.* 37-44.

Park, C., Clark, D. R., & Kelly, G. E. (1985). An overview of HVACSIM+, a dynamic building/HVAC/control systems simulation program. *Proceedings of the 1st annual building energy simulation conference, Seattle, WA, August 21-22.*

Paschkis, V. (1942). Periodic heat flow in building walls determined by electrical analogy method. *ASHVE Transactions 48,* 75-90.

Paschkis, V., & Baker, H. D. (1942). A method for determining unsteady-state heat transfer by means of an electrical analogy. *ASME Transactions 64*, 105-112.

Pedersen, C. O. (2009). *Building simulation* [PowerPoint slides]. Retrieved from IBPSA-USA 2009 Meeting: http://www.ibpsa.us/pub/meetings/2009-06-curtis-pedersen-NOTES.pdf

Pedersen, C. O., Fisher, D. E., & Liesen, R. J. (1997). Development of a heat balance procedure for calculating cooling loads. *ASHRAE Transactions, 103*, 459-468.

Pedersen, C. O., Fisher, D. E., Liesen, R. J., & Strand, R. K. (2003). ASHRAE toolkit for building load calculations. *ASHRAE Transactions, 109*(1), 583-589.

Pedersen, C. O., Fisher, D. E., Spitler, J. D., & Liesen, R. J. (1998). *Cooling and heating load calculation principles.* Atlanta, GA: ASHRAE.

Peikari, B. (1974). *Fundamentals of network analysis and synthesis.* NJ: Prentice-Hall.

Perez, R., Seals, R., & Michalsky, J. (1993). All-weather model for sky luminance distribution-Preliminary configuration and validation. *Solar Energy, 50*(3), 235-245.

Pipes, L. A. (1957). Matrix analysis of heat transfer problems. *Journal of the Franklin Institute, 263*(3), 195-206.

Pokrowski, G. I. (1929). Uber die Helligkeitsverteilung am Himmel', Phys. Z., 30, 697. (English Translation: The brightness distribution of the sky, Building Research Station Library Communication No. 487, 1953)

Prowler, D. (Ed.). (1978). *Proceedings of the 2nd national passive solar conference (proceedings of the American section of ISES).* Philadelphia, PA: Mid-Atlantic Solar Energy Association.

Rayleigh Scattering. (2013). In *Wikipedia.* Retrieved June 15, 2013, from http://en.wikipedia.org/wiki/Rayleigh_scattering

Rees, S. J., Spitler, J. D., Davies, M. G., & Haves, P. (2000). Qualitative comparison of North American and U.K. cooling load calculation methods. *HVAC&R Research, 6*(1), 75-99.

Reid, R. L. (1981). Editorial. *Journal of Solar Energy Engineering, 103*(3), 1.

Reinhart, C. F. (2013). *DAYSIM: Advanced daylight simulation software.* Retrieved from http://daysim.ning.com/page/credits

Reinhart, C. F., & Herkel, S. (2000). The simulation of annual daylight illuminance distributions- a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings 32*(1), 167-187.

Reinhart, C. F., & Mardaljevic, J., & Rogers, Z. (2006). Dynamic daylight performance metrics for sustainable building design. *Leukos, 3*(1), 7-31.

Reinhart, C. F., & Morrison, M., & Dubrous, F. (2003). The lightswitch wizard – reliable daylight simulation for initial design investigation. *Proceedings of the Buildings Simulation 2003, Eindhoven, The Netherlands*, 1093-1100.

Reinhart, C. F., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings, 33*(7), 683-697.

Rocky Mountain Institute. (2011). *Post-Report from the BEM innovation summit.* Retrieved from Rocky Mountain Institute website: http://rmi.org/Content/Files/BEM_Report_FINAL.pdf

Rudoy, W., & Duran, F. (1975). ASHRAE RP-138 development of an improved cooling load calculation method. *ASHRAE Transactions, 81*(2), 19-69.

Sahlin, P., Eriksson, L., Grozman, P., Johnsson, H., Shapovalov, M., & Vuolle, M. Will equation-based building simulation make it? – experiences from the introduction of IDA indoor climate and energy. *Proceedings of Building Simulation 2003, Eindhoven, The Netherlands,* 1147-1154.

Schnurr, N. M., Hunn, B. D., & Williamson, K. D. (1981). The solar load ratio method applied to commercial building active solar system sizing. *Proceedings of ASME Solar Energy Division 3rd Annual Meeting, Reno, NV.*

Schnurr, N. M., Kerrisk, J. F., Moore, J. E., Hunn, B. D., & Cumail, Z. O. (1979). Applications of DOE-2 to direct-gain passive solar systems: Implementation of a weighting-factor calculative technique. *Proceedings of the Fourth National Passive Solar Conference, Kansas City, MO, October 3-5,* 182-186.

Schwedler, M. (January 13, 2012). Personal communication.

Seem, J. E. (1987). *Modeling of heat transfer in buildings.* (Doctoral dissertation). Madison, WI: University of Wisconsin-Madison.

Selkowitz, S., Kim, J. J., Navvab, M., & Winkelmann, F. (1982). The DOE-2 and superlite daylighting programs. *Proceedings of the 7$^{th}$ National Passive Solar Conference, Knoxville, TN.*

Shavit, G. (1995). Short-time-step analysis and simulation of homes and buildings during the last 100 years. *ASHRAE Transactions, 101*(1), 856-868.

Shepherd, C. M. (1965). Design of primary and secondary cells: II. An equation describing battery discharge. *Journal of the Electrochemical Society, 112*(7), 657-664.

Sheridan, N. R., Bullock, K. J., & Duffie, J. A. (1967). Study of solar processes by analog computer. *Solar Energy, 11*(2), 69-77.

Siegel, M. D., Klein, S. A., & Beckman, W. A. (1981). A simplified method for estimating the monthly-average performance of photovoltaic systems. *Solar Energy, 26,* 413-418.

Siegel, R., & Howell, J. R. (1972). *Thermal radiation heat transfer.* NY: McGraw – Hill.

Skalko, S. V. (2012). *Building code treatment of thermal mass in energy modeling* [PowerPoint slides]. Retrieved from America Concrete Institute (ACI) 2012 Spring Conference: http://www.concrete.org/Convention/spring-

Convention/PresenterHandouts.asp?SessionID=00003875&CurrentDay=3%2F19%2F2012

Smith, B. (2011). *HVAC peak load calculation methods – History and comparisons.* Retrieved from http://www.elitesoft.com/web/newsroom/loadcalcs.html

Solar Energy Laboratory (SEL). (2010). *TRNSYS 17 manual*. Madison, WI: Author.

Solar Energy Research Institute (SERI). (1980). *Analysis methods for solar heating and cooling applications – passive and active systems.* (3rd ed.). Washington, DC: Government Printing Office.

Sornay, J., & Clarke, J. (1985). Recent developments of building energy simulation tools in Europe. *Proceedings of the Building Energy Simulation Conference, Seattle, WA,* 15-22.

Soumerai et al. (1959). Digital computer applied to compressor design analysis. *ASHRAE Transactions, 1*(7), 43-49.

Sowell, E. F. (1988a). Classsification of 200,640 parametric zones for cooling load calculations. *ASHRAE Transactions*, *94*(2), 754-777.

Sowell, E. F. (1988b). Cross-check and modification of the DOE-2 program for calculation of zone weighting factors. *ASHRAE Transactions*, *94*(2), 737-753.

Sowell, E. F. (1988c). Load calculations for 200,640 zones. *ASHRAE Transactions, 94*(2), 716-736.

Sowell, E. F., & Hittle, D. C. (1995). Evolution of building energy simulation methodology. *ASHRAE Transactions, 101*(1), 850-855.

Sparrow, E. M., & Cess, R. D. (1966). *Radiation heat transfer*. Belmont, CA: Brooks/Cole.

Spitler, J. D. (1996). *Annotated guide to load calculation models and algorithms.* Atlanta, GA: ASHRAE.

Spitler, J. D. (2011). Thermal load and energy performance prediction. In J. L. M. Hensen & R. Lamberts (Eds.), *Building performance simulation for design and operation* (pp. 84-142). New York, NY: Spon Press.

Spitler, J. D., & Chiles, D. C. (1985). Characterization of zone dynamic response for CLD /CLTD tables. *ASHRAE Transactions, 91*(2A), 162-178.

Spitler, J. D., & Fisher, D. E. (1999). On the relationship between the radiant time series and transfer function methods for design cooling load calculations. *HVAC&R Research, 5*(2), 123-136.

Spitler, J. D., Fisher, D. E., & Pedersen, C. O. (1997). The radiant time series cooling load calculation procedure. *ASHRAE Transactions, 103*(2), 503-515.

Spitler, J. D., McQuistion, F. C., & Lindsey, K. L. (1993). The CLTD/SCL/CLF cooling load calculation method. *ASHRAE Transactions, 99*(1), 183-192.

Stamper, E. (1995). ASHRAE's development of computerized energy calculations for buildings. *ASHRAE Transactions, 101*(1), 768-772.

Stamper, E. (2001). The role of the National Institute of Standards and Technology in development of energy calculation programs. *ASHRAE Transactions, 107*(2), 684-687.

Stanke, D. (2012). 189.1 revised. *ASHRAE Insights, 27*(1), 3.

Steitz, B. (2006). *A brief computer history.* Retrieved from http://people.bu.edu/baws/brief%20computer%20history.html

Stephenson, D. G., & Mitalas, G. P. (1962). An analog evaluation of methods for controlling solar heat gain through windows. *ASHRAE Transactions, 4*(2), 41-46.

Stephenson, D. G., & Mitalas, G. P. (1967). Cooling load calculations by thermal response factor method. *ASHRAE Transactions, 73*(1), 1-7.

Stephenson, D. G., & Mitalas, G. P. (1971). Calculation of heat conduction transfer functions for multi-layer slabs. *ASHRAE Transactions, 77* Part II, 117-126.

Stewart, J. P. (1948). Solar heat gain through walls and roofs for cooling load calculations. *ASHVE Transactions 54,* 361-388.

Taggart, R. C. (1913). Time analysis in starting heating apparatus. *ASHVE Transactions, 19*, 292-308.

Tellier, C. (1885). The utilization of solar heat for the elevation of water. Reprinted from *La Nature*. *Scientific American, 53,* 214.

Theilacker, J. C. (1980). *An investigation of monthly-average utilizability for flat-plate collectors.* (Master's thesis). Madison, WI: University of Wisconsin-Madison.

Theilacker, J. C., & Klein, S. A. (1980). Improvements in the utilizability relationships. *Proceedings of American Section of the ISES Annual Meeting, Phoenix, AZ, June 2-6,* 271-275.

Theilacker, J. C., Klein, S. A., & Beckman, W. A. (1981). Solar radiation utilizability for south-facing vertical surfaces shaded by an overhang. *Proceedings of American Section of the ISES Annual Meeting, Philadelphia, PA, May 27-30,* 853-856.

Threlkeld, J. L. (1970). *Thermal environmental engineering.* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall, Inc.

Torcellini, P. (2000). *Highlighting high performance: Zion National Park visitor center – a sustainable building for the future.* Retrieved from http://www.nrel.gov/docs/fy00osti/29315.pdf

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). *Zero energy buildings: a critical look at the definition.* To be presented at ACEEE Summer Study, Pacific Grove, *CA.* Preprint retrieved from http://www.nrel.gov/docs/fy06osti/39833.pdf

Trane. (1992). *TRACE 600 Engineering Manual.* La Crosse, WI: Trane Company.

Trane. (2013). *TRACE 700 version information.* Retrieved from http://www.trane.com/Commercial/dna/view.aspx?i=2067#release6210

Tregenza, P. R. (1989). Modification of the split-flux formulae for mean daylight factor and internal reflected component with large external obstructions. *Lighting Research and Technology, 21,* 125-128.

Tregenza, P. R., & Waters, I. M. (1983). Daylight coefficients. *Lighting Research and Technology*, *15*(2), 65-71.

Tull, R. H. (1971). The program of the ASHRAE task group on the determination of energy requirements heating and cooling buildings. In T. Kusuda (Ed.), *Building Science Series: Vol. 39. Use of Computers for Environmental Engineering Related to Buildings* (pp. 199-203). Washington, DC: Government Printing Office.

Tupper, K., Franconi, E., Chan, C., Fluhrer, C., Jenkins, M. & Hodgin, S. (2011). *Pre-Read for BEM innovation summit.* Retrieved from Rocky Mountain Institute website: http://www.rmi.org/Content/Files/Summit_PreRead_Apr-19-2011(2).pdf

Tustin, A. (1947). A method of analyzing the behavior of linear systems in terms of time series. *J. Inst. Elec. Engineers, 94*, Pt. 2A, 130-142.

Ubbelohde, M. S., & Humann C. (1998). Comparative evaluation of four daylighting software programs. *Proceedings of ACEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.*

University of Illinois at Urbana-Champaign (UIUC) & Lawrence Berkeley National Laboratory (LBNL). (2012). *EnergyPlus engineering reference.* Berkeley, CA: Author.

U.S. Department of Energy (US DOE). (1985). *Building energy simulation conference notebook.* Golden, CO: The Solar Energy Research Institute. The Passive Solar Group of the U.S. Department of Energy (now, NREL).

U.S. Department of Energy (US DOE). (1999). *Codes* & *standards: The model energy code* (Report No. DOE/GO-10099-934). Retrieved from http://www.gwssi.com/learning/images/modelcode.pdf

U. S. Postal Service (USPS). (1971). *USPS symposium: Computer program for analysis of energy utilization.* Washington, DC: Author.

Versage, R., Melo, A. P., & Lamberts, R. (2010). Impact of different daylighting simulation results on the prediction of total energy consumption. *Proceedings of 4th National IBPSA-USA Conference SimBuild 2010, New York, NY.*

Walsh, J. W. T. (1951). The early years of illuminating engineering in Great Britain. *Transactions of the Illuminating Engineering Society, 16*(3), 49-60.

Walton, G. N. (1983). *Thermal anlaysis research program reference manual* (NBSSIR 83-2655). MD: National Bureau of Standards (now, NIST).

Walton, G. N. (1989). *AIRNET – A computer program for building airflow network modeling* (NISTIR 89-4072). MD: National Institute of Standards and Technology.

Walton, G. N. (2001). Computer program for heating and cooling loads in buildngs. *A Century of Excellence in Measurements, Standards, and Technology. A Chronicle of Selected NBS/NIST Publications 1901-2000. Special Publication 958.* pp 266-269. MD: National Institute of Standards and Technology.

Ward, G. J. (1994). The RADIANCE Lighting Simulation and Rendering System. *Proceedings of '94 SIGGRAPH Conference, Orlando, FL,* 459-472.

Ward, G. J., & Rubinstein, F. M. (1988). A new technique for computer simulation of illuminated spaces. *Journal of the Illuminating Engineering Society, 17*(1), 80-91.

Ward, G. J., & Rubinstein, F. M., & Clear, R. D. (1988). A ray tracing solution for diffuse interreflection. *Computer Graphics, 22*(4), 85-92.

Ward, G. J., Rushmeier, H., & Piatko, C. (1997). *A visibility matching tone reproduction operator for high dynamic range scenes* (LBL-39882). Berkeley, CA: Lawrence Berkeley National Laboratory.

Ward, G. J., & Shakespeare, R. (1998). *Rendering with Radiance: The art and science of lighting visualization.* Burlington, MA.

Ward, J. C. (1976). Minimum cost sizing of solar heating systems. *Proceedings of ASES/ISES Annual Meeting, Winnipeg, Canada*, 336-346.

Weghorst, H., Hooper, G., & Greenberg, D. P. (1984). Improved computational methods for ray tracing. *ACM Transactions on Graphics, 3*(1), 52-69.

Whillier, A. (1953a). The utilization of solar energy in South Africa. *Journal of South Africa Institute of Mechanical Engineers, 2*(9), 260-266.

Whillier, A. (1953b). *Solar energy collection and its utilization for house heating.* (Doctoral Dissertation). Cambridge, MA: MIT.

Whitted, T. (1980). An improved illumination model for shaded display. *Communications of the ACM, 23,* 343-349.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings 38*(7), 743-757.

Willcox, T. N., Oergerl, C. T., & Reque, S. G. (1954). Analogue computer analysis of residential cooling loads. *ASHVE Transactions 60,* 505-524.

Williams, R. (1998). *SIGGRAPH and the SIGGRAPH conference: The early days.* Retrieved from www.siggraph.org/publications/newsletter/v32n3/contributions/williams.html

Willsie, H. E. (1909). Experiments in the development of power from the sun's heat. *Engineering News*, *61*(19), 511-514.

Winkelmann, F. C. (1983). *Daylighting calculation in DOE-2* (LBL-11353). Berkeley, CA: Lawrence Berkeley Laboratory.

Winkelmann, F. C., Birdsall, B. E., Buhl, W. F., Ellington, K. L., Erdem, A. E., Hirsch, J. J., & Gates, S. (1993). *DOE-2 supplement version 2.1E* (LBL-34947). Berkeley, CA: Lawrence Berkeley Laboratory.

Winkelmann, F. C., & Selkowitz, S. (1984). *Daylight simulation in the DOE-2 building energy analysis program* (LBL-18508). Berkeley, CA: Lawrence Berkeley Laboratory.

Winkelmann, F. C., & Selkowitz, S. (1985). Daylighting simulation in DOE-2: Theory, validation, and applications. *Proceedings of the Building Energy Simulation Conference*, *Seattle, WA*, 326-337.

Wright, R. N. (2003). *Building and fire research at NBS/NIST 1975-2000* (NIST BSS 179). Washington, DC: Government Printing Office.

Wright, W. A. (1980). A method for generating graphic solar design tools. *Proceedings of ASES/ISES Annual Meeting, Phoenix, AZ,* 286-290.

Yuill, G. K., & Associates Ltd. (1990). *An annotated guide to models and algorithms for energy calculations relating to HVAC equipment.* Atlanta, GA: ASHRAE.

# APPENDIX A


*Figure A.1*. The legend of the new comprehensive genealogy chart.

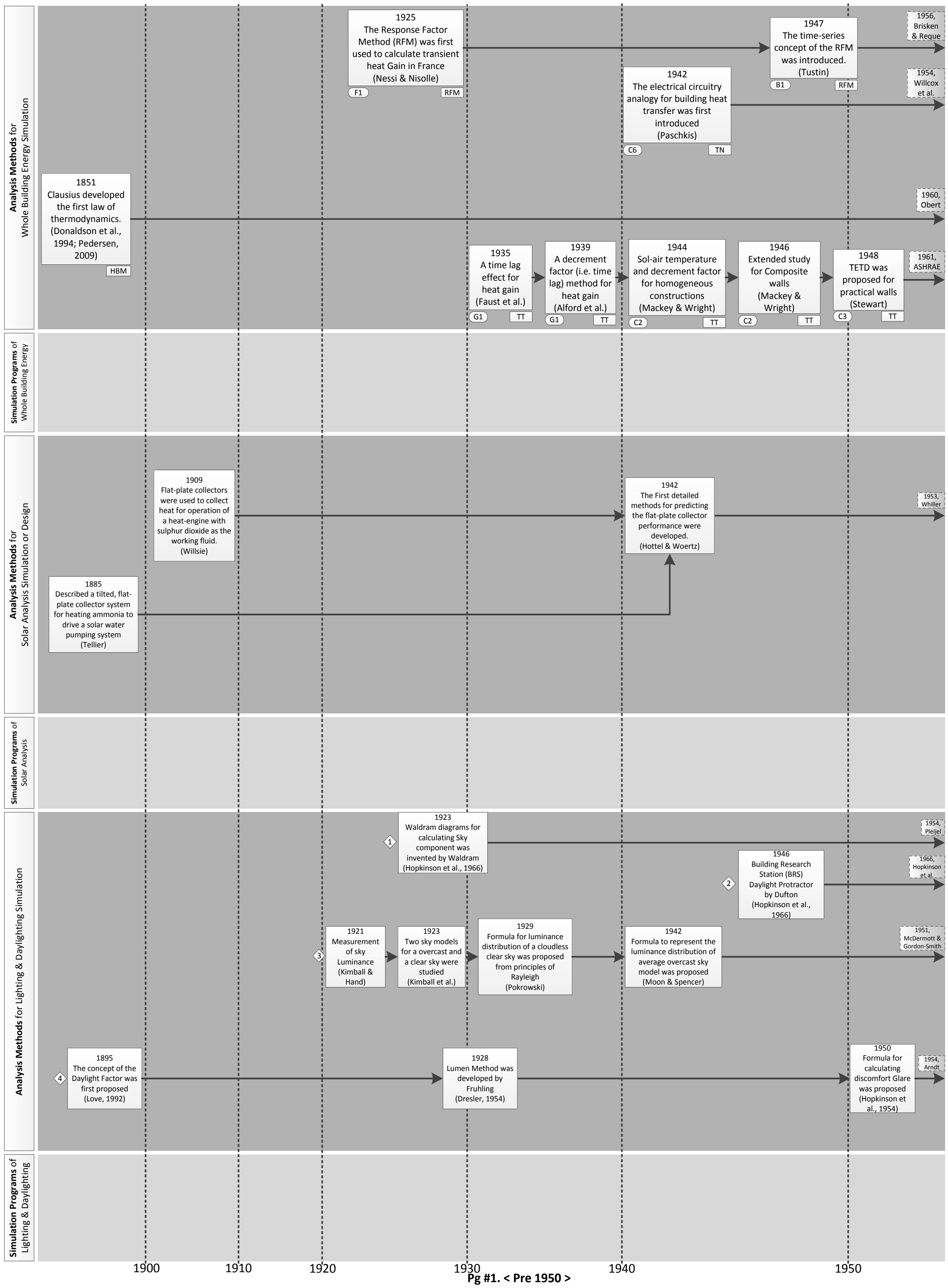


*Figure A.2.* The new comprehensive genealogy chart.

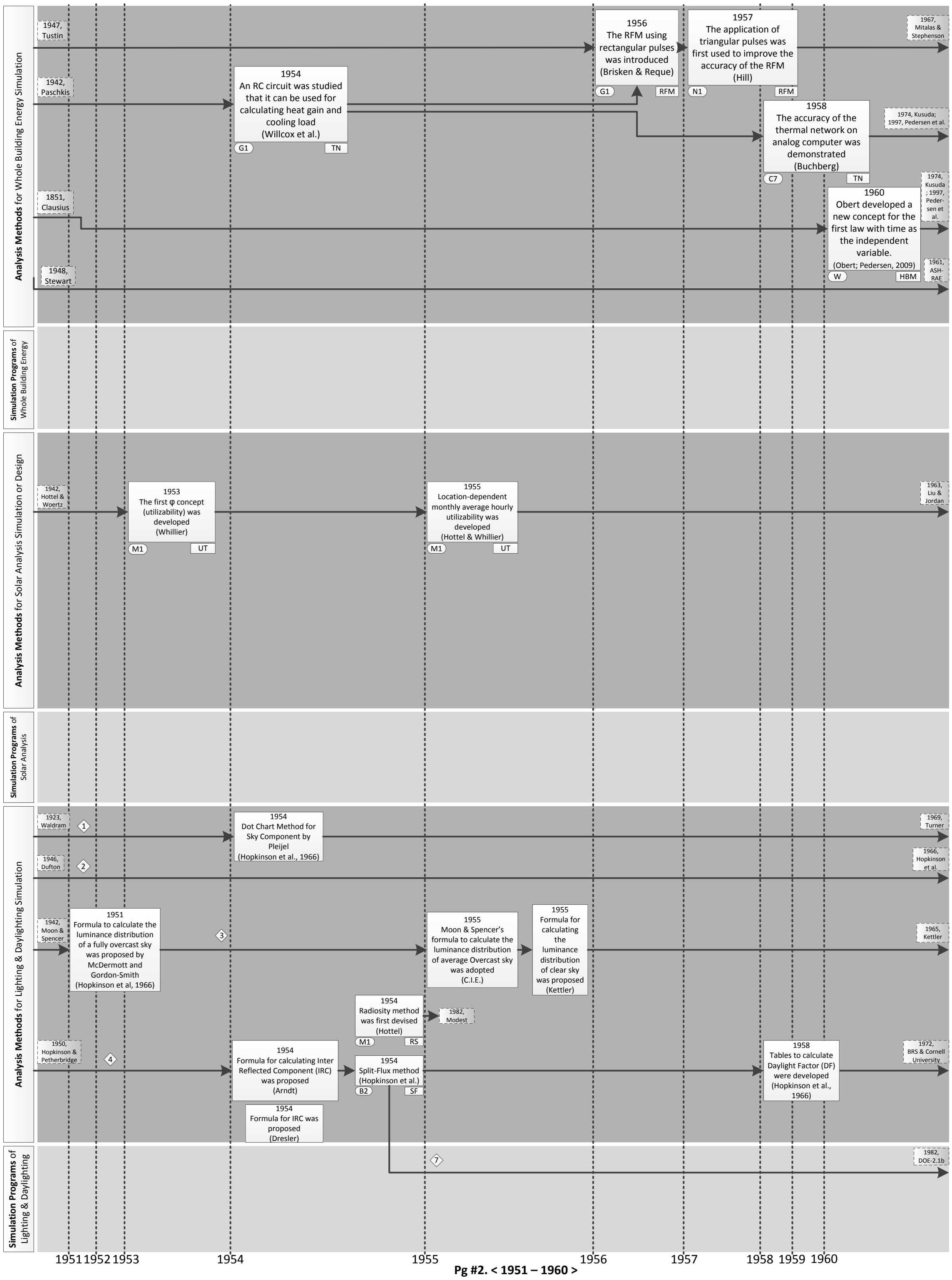


*Figure A.2.* Continued

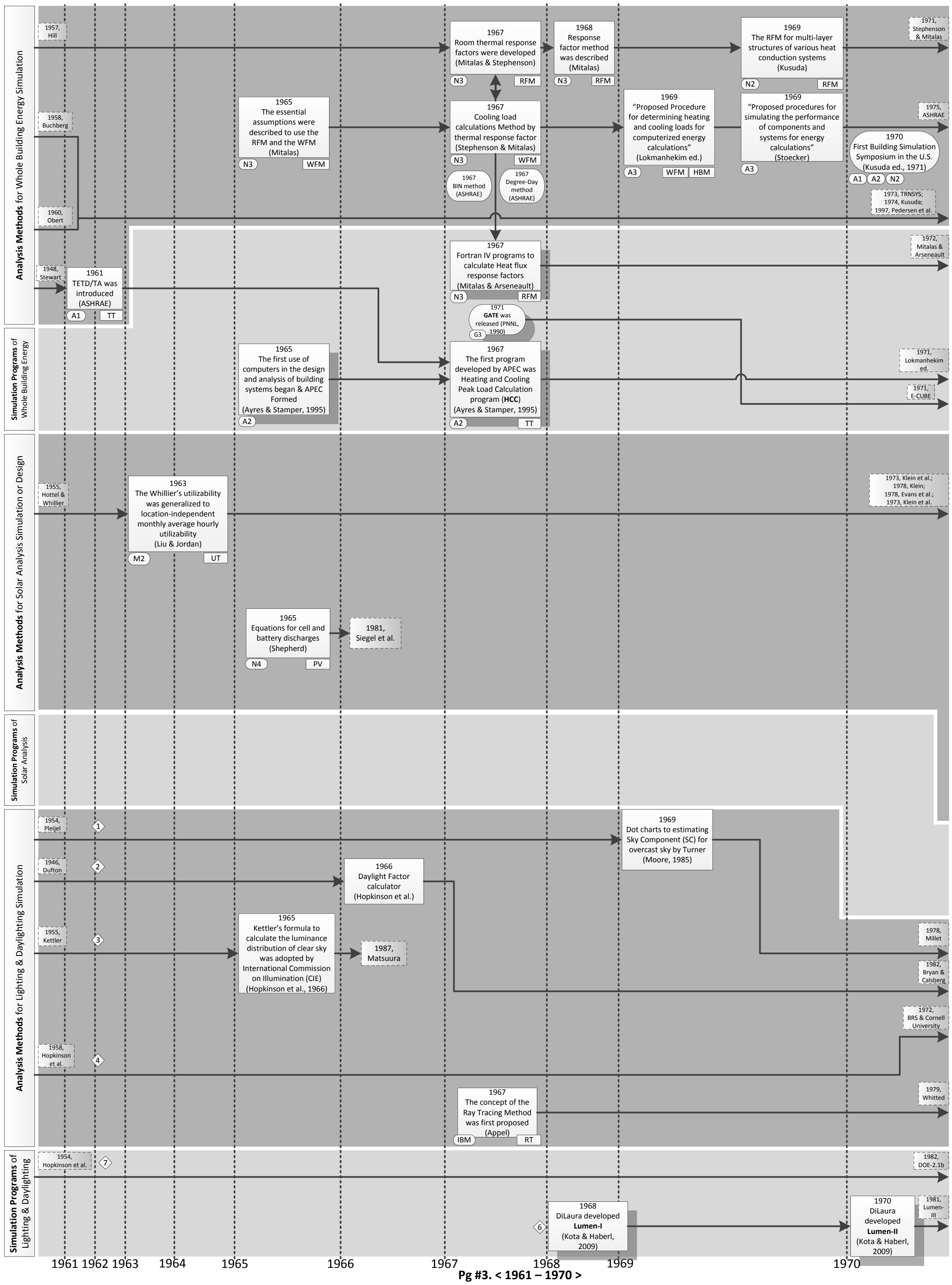


*Figure A.2.* Continued

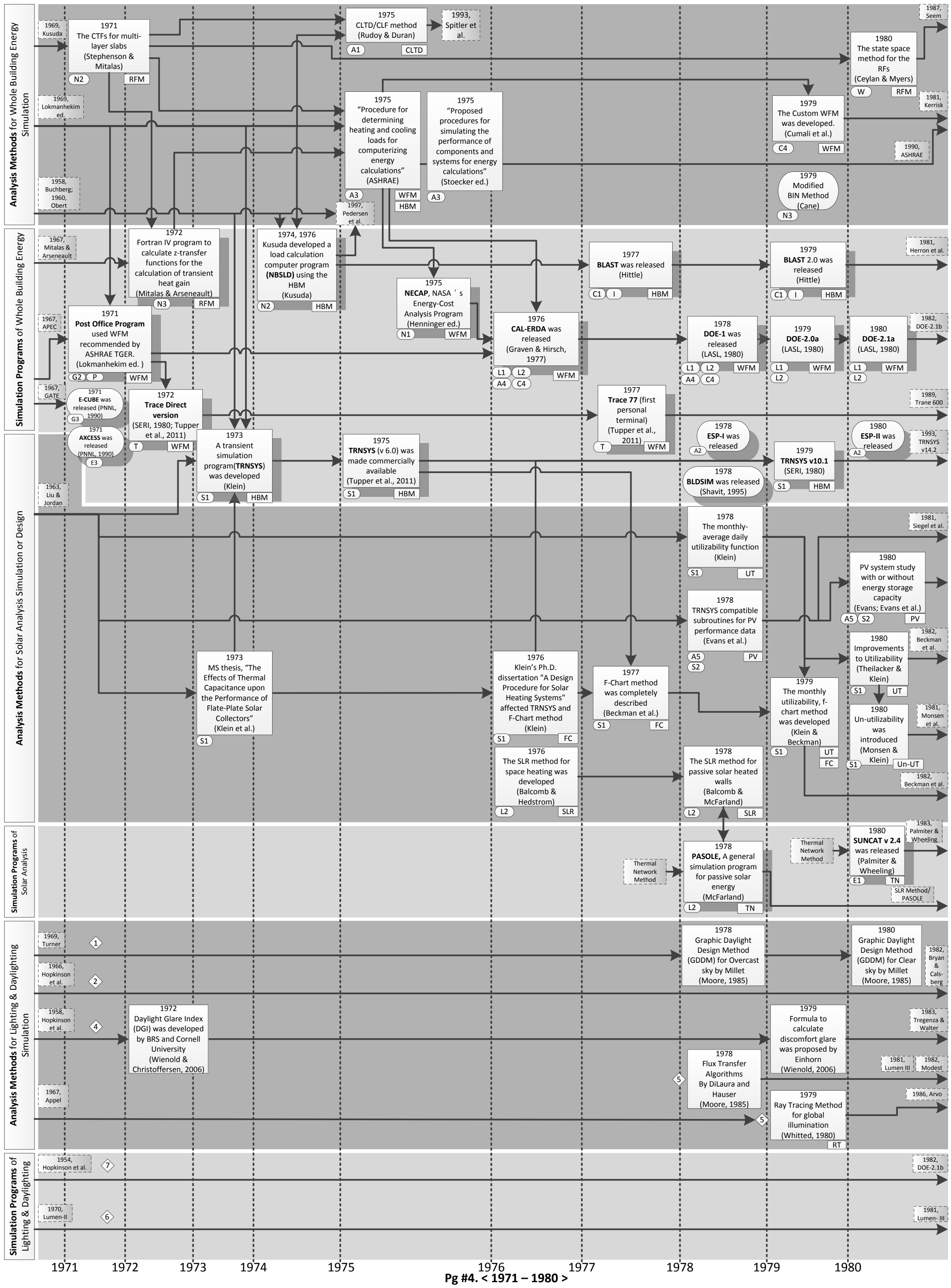


*Figure A.2.* Continued

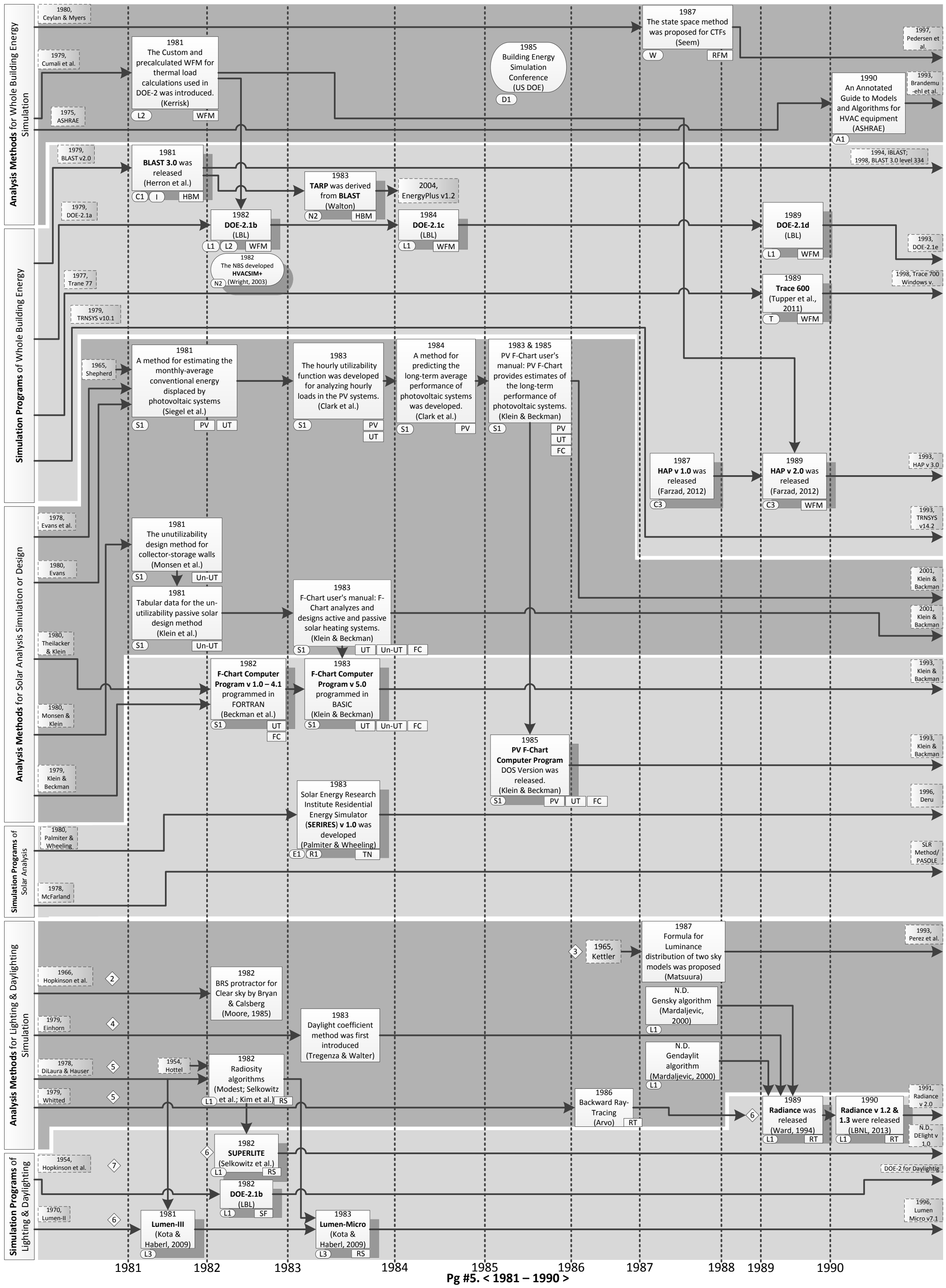

*Figure A.2.* Continued

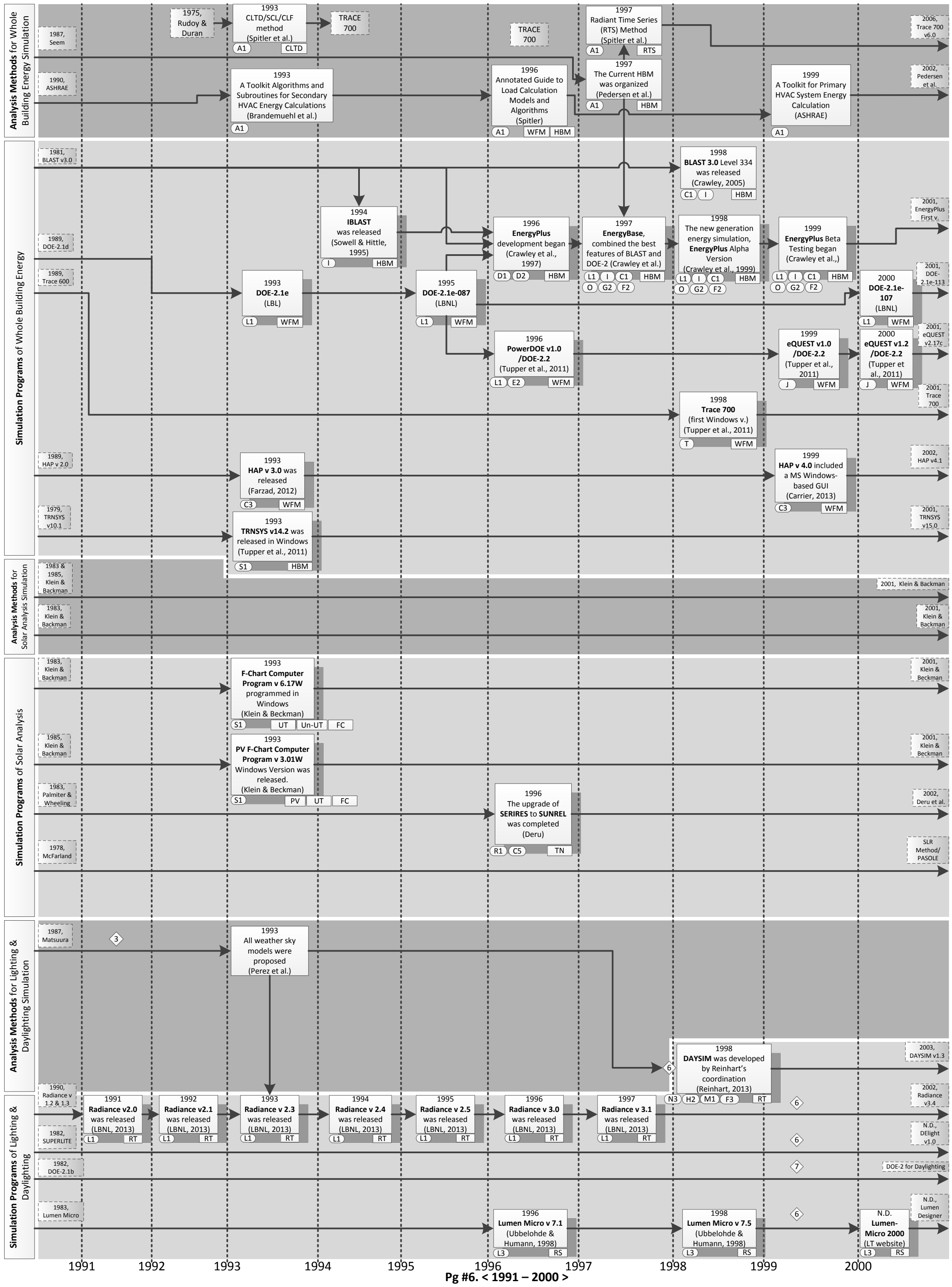

*Figure A.2.* Continued

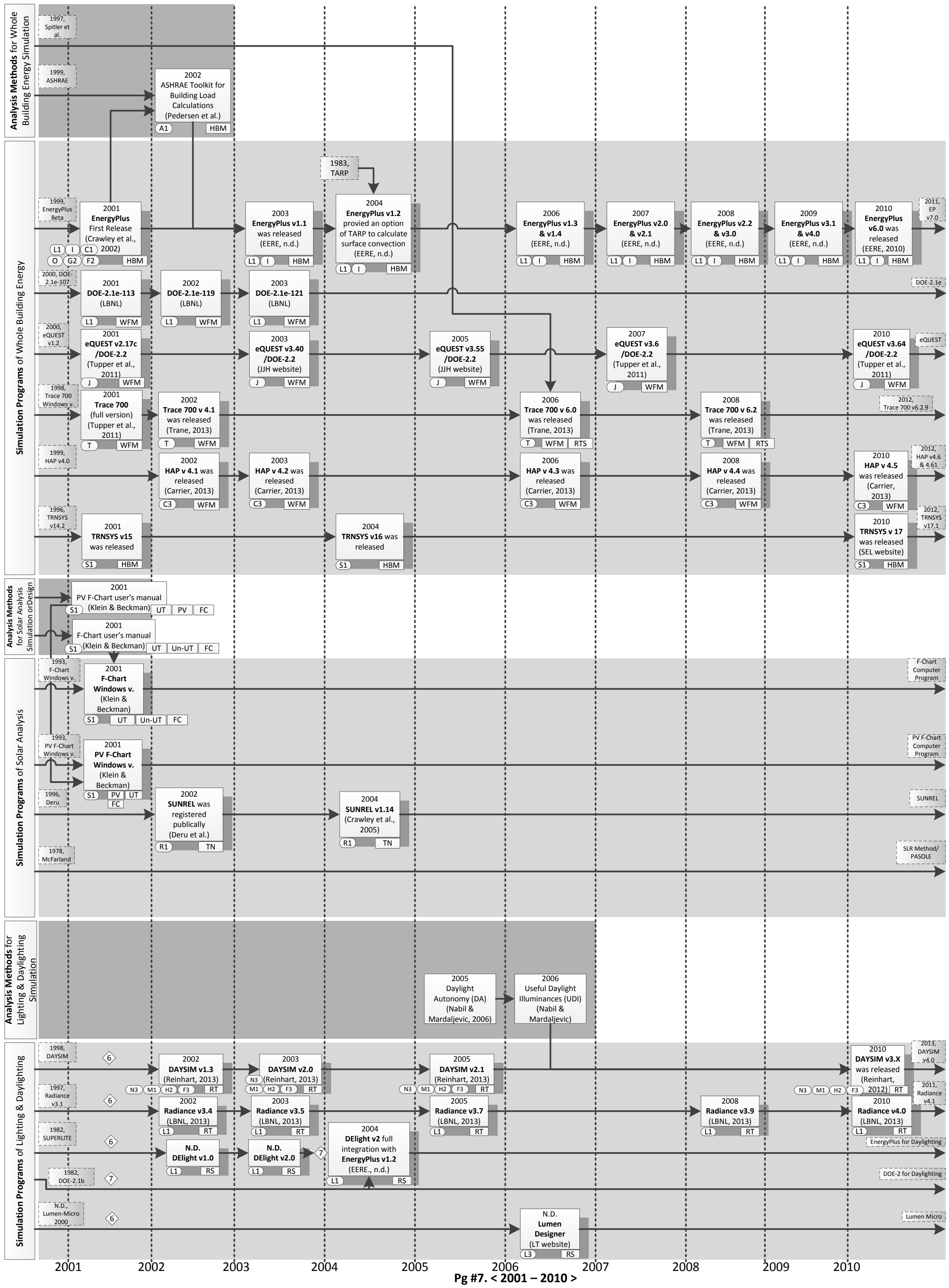


*Figure A.2.* Continued

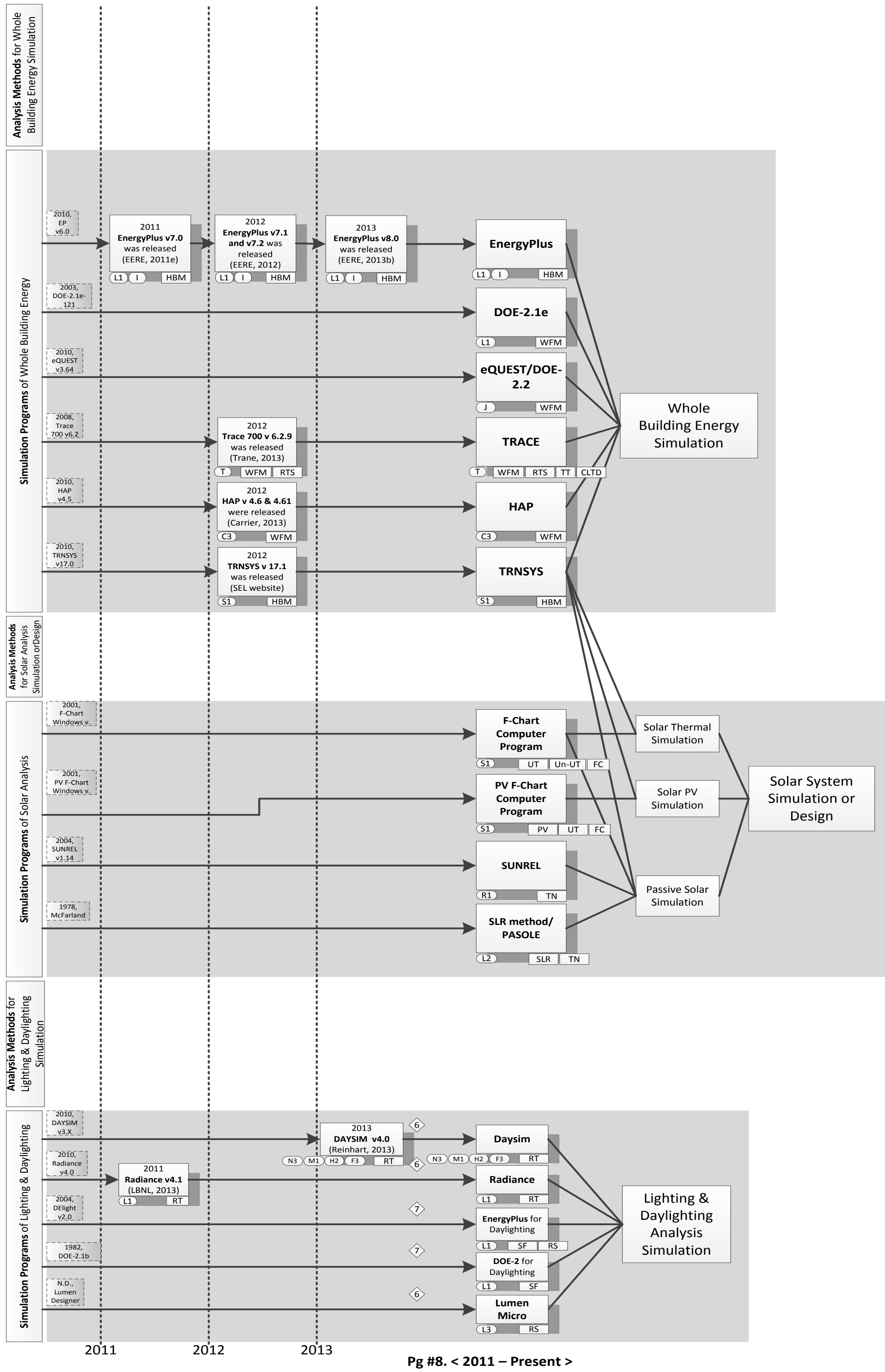


*Figure A.2.* Continued

# APPENDIX B

Table B.1. *Annotated references of the analysis methods of the whole-building energy simulation programs.*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Time Equivalent Tempera-ture Difference (TETD)/ Time Averaging (TA) Method | 1935 | Faust, F., Levine, L., & Urban, F. | Engineers at the General Electric Corporation | A rational heat gain method for the determination of air conditioning cooling loads | Faust et al. calculated the cooling load using a time lag effect of walls. | The time lag accounted for the effect of wall's thermal storage capacity. In other words, the time lag concept accounted for time delay and heat amplitude reduction between an outer surface and an inter surface of a wall (Faust et al., 1935; Alford et al., 1939). |
| | 1939 | Alford, J., Ryan, J., & Urban, F. | Engineers at the General Electric Corporation | Effect of heat storage and variation in outdoor temperature and solar intensity on heat transfer through walls | Alford et al. proposed a decrement factor to visualize the wall's thermal storage capacity. | The concept of a decrement factor was used for Mackey and Wright's study (Mackey and Wright, 1944). |
| | 1944 | Mackey, C. O. & Wright, L. T. | Professors at Cornell University | Periodic heat flow – homogeneous walls or roofs. | Mackey and Wright's study assumed periodic cycles of steady state temperature on a one-day basis for calculating heat gain through walls and roofs (Kusuda, 1969). | They employed Fourier series rather than the Laplace transform to calculate heat conduction equations due to the low speed of computers (Mackey and Wright, 1944; Kusuda, 1969). |
| | 1946 | Mackey, C. O. & Wright, L. T. | Professors at Cornell University | Periodic heat flow – composite walls or roofs. | Previous study was extended to composite walls. | This study contributed to the development of the ETD method. |
| | 1948 | Stewart, J. | Engineer at the Carrier Corporation | Solar heat gain through walls and roofs for cooling load calculations | The ETD method (later the TETD method) was outlined and tabled for calculating heat gain of practical walls. | This study contributed to the development of the TETD method. |
| | 1961 | ASHRAE | ASHRAE | ASHRAE Guide and Data Book | The TETD/TA method using the TA was introduced to calculate cooling load. | Even though the TETD/TA was developed as a manual method at first, this method has also been used as a computer procedure (McQuiston and Spitler, 1992). For example, the HCC program developed by APEC in 1967 used the TETD/TA method (Ayres and Stamper, 1995). |

Table B.1. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Response Factor Method (RFM)/ Conduction Transfer Function (CTF) Method | 1925 | Nessi, A. & Nisolle, L. | Engineers, Ėcole Centrale Paris (French University) | Regimes variables de fonctionnement dans les installations de chauffage central (Regime variables of operation in the installations of central heating) | Nessi and Nisolle employed the superposition of unit step functions rather than triangular pulses (Stephenson, D. G. & Mitalas, G. P., 1967). | The response factor method of calculating transient heat flow was used first (Stephenson, D. G. & Mitalas, G. P., 1967). |
| | 1947 | Tustin, A. | British engineer, professor of engineering at the University of Birmingham | A method of analyzing the behavior of linear systems in terms of time series | Prof. Tustin showed that time-series are very similar to polynomials in that they can be added, subtracted, multiplied and divided. The commutative and distributive laws of ordinary arithmetic also apply for time-series (Stephenson, D. G. & Mitalas, G. P., 1967). | The concept of a time-series was first presented by Tustin, in 1947 (Stephenson, D. G. & Mitalas, G. P., 1967). |
| | 1956 | Brisken, W. R. & Reque, S. G. | Manager, commercial and industrial air conditioning department, General Electric Co. / Systems analysis engineer, electrical engineering laboratory, GE Co. | Heat load calculations by thermal response | Steady-state load factors were modified to include transient effects and special allowances were recommended for internal heat storages of the buildngs. This procedure, the thermal response method was further developed in this study (Brisken, W. R. & Reque, S. G.). | Unique features of the thermal response method were found in this study. However, the response factors due to rectangular pulses were still used (Stephenson, D. G. & Mitalas, G. P., 1967). |
| | 1957 | Hill, P. R. | Researcher, National Advisory Committee for Aeronautics (NACA) | A method of computing the transient temperature of thick walls from arbitrary variation of adiabatic-wall temperature and heat-transfer coefficient | Formulas to facilitate the determination of the transient surface temperatures of thick walls from an arbitrary variation of adiabatic-wall temperature and heat-transfer coefficient have been developed. Formulas to facilitate the determination of heat flow from an arbitrary variation of wall surface temperature were also obtained (Hill, P. R., 1957). | A simple method is developed for the calculation of the temperature history of the surfaces of a thick wall or of any plane within the wall (Hill, P. R., 1957). The first application of triangular pulses was used (Stephenson, D. G. & Mitalas, G. P., 1967). |

Table B.1. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Response Factor Method (RFM)/ Conduction Transfer Function (CTF) Method | 1967 | Mitalas, G. P. & Stephenson, D. G. | Researchers, Building Services Section, Division of Building Research, National Research Council, Canada | Room thermal response factors | Room thermal response factors were developed for improving previous response factors of Brisken and Reque. | This paper presented a method of computing the factors for any room. It differs from the earlier work by Brisken and Reque. |
| | 1967 | Mitalas, G. P. & Arseneault, J. G. | Researchers, Division of Building Research, National Research Council, Canada | Fortran IV program to calculate heat flux response factors for a multi-layer slab | Mitalas and J. G. Arseneault developed a FORTRAN IV program to calculate heat gain through multi-layered slabs using the RFM of Mitalas and Stephenson. | This Laplace transform approach was able to improve the calculation accuracy by the lumped RC approach of Brisken and Reque. |
| | 1971 | Stephenson, D. G.& Mitalas, G. P. | Researchers, Building Services Section, Division of Building Research, National Research Council, Canada | Calculation of heat conduction transfer functions for multi-layer slabs | CTFs use a heat flux history in place of a temperature history using the z-transform functions. | The computer procedure for calculating instantaneous heat gain using CTFs is more efficient than the procedure using RFs because it calculates faster and uses less memory space. |
| | 1971 | Lokmanhekim ed. | ASHRAE Task Group on Energy Requirements (TGER) | Procedure for determining heating and cooling loads for computerized energy calculations – algorithms for building heat transfer subrouties. | ASHRAE TGER adopted the RFM that uses CTFs. This booklet shows the computer algorithms for the RFM. | These publications helped researchers and engineers quickly learn the basic knowledge of whole-building simulation programs, which accelerated the development of whole-building energy simulation (Sowell and Hittle, 1995). |
| | 1980 | Ceylan, H. & Myers, G. | Graduate student and professor at the University of Wisconsin-Madison | Long-time solutions to heat-conduction transients with time dependent inputs | They compared the state space method with other solution procedures (UIUC and LBNL, 2012). | Without applying z-transform, this study suggested a method to calculate response factors. |
| | 1987 | Seem, J. E. | Graduate student at the University of Wisconsin-Madison | Modeling of heat transfer in buildings | Seem shows the procedures to calculate the CTFs using the state space method. | This study showed the state space method reduced the calculation time to estimate the CTFs rather than the Laplace transform approach. |

Table B.1. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Response Factor Method (RFM)/ Conduction Transfer Function (CTF) Method | 1991 | Ouyang, K. & Haghighat, F. | Researchers at China Academy of Building Research, China and Concordia University, Canada | A procedure for calculating thermal response factors of multi-layer walls-state space method | They compared the state space method with the Laplace transform method. | The differences of response factors obtained from the two mehods were almost zero.<br>In the HBM, an improved CTFs procedure, which was described by H. T. Ceylan and G. E. Myers in 1980, John E. Seem in 1987, and Kunze Ouyang and Fariborz Haghighat in 1991, was used to calculate dynamic heat gain through walls and roofs (Ceylan and Myers, 1980; Seem, 1987; Ouyang and Haghighat, 1991; UIUC and LBNL, 2012). |
| Weighting Factor Method (WFM) | 1965 | Mitalas, D. G. | Researcher, Building Services Section, Division of Building Research, National Research Council, Canada | An assessment of common assumptions in estimating cooling loads and space temperatures | This paper recorded an analytical study that was carried out to determine the errors associated with various simplifying assumptions as well as to evaluate the significance of the various room construction features. | This study provided the essential assumptions to use the RFM and WFM for calculating cooling loads. |
| | 1967 | Stephenson, D. G.& Mitalas, G. P. | Researchers, Building Services Section, Division of Building Research, National Research Council, Canada | Cooling load calculations by thermal response factor method | Room thermal response factors were applied to cooling load calculations. | This method required less arithmetic than finite difference calculations. Response Factors are used when governing functions are linear. |
| | 1969 | Mitalas, G. P. | Researcher, Building Services Section, Division of Building Research, National Research Council, Canada | An experimental check on the weighting factor method of calculating room cooling load | The calculated values of the WFM were compared to the measured values of the WFM. | This study proved the accuracy of the WFM in real situations. However, one type of rooms was used for this study. |
| | 1979 | Culmali, Z. O., Sezgen, A. O., & Sullivan, R. | Consultant engineers at the Computation Consultants Bureau | Passive solar calculation methods | The analytical procedures of the custom weighting factors, which are parameters used in z-transfer functions, were introduced. | The custom weighting factors were developed to improve original weighting factors, also called pre-calculated weighting factors. |

Table B.1. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Weighting Factor Method (WFM) | 1981 | Kerrisk, J. F. | Researcher, Los Alamos Scientific Laboratory | Weighting factors in the DOE-2 computer program | The custom weighting factors used in DOE-2.1 were described. | The procedures and assumptions of the load calculation methods of DOE-2.1 were described. |
| Thermal Network Method | 1942 | Paschkis, V. | Research Engineer at Columbia University | Periodic heat flow in building walls determined by electrical analogy method | The concept of the electrical circuitry analogy for analyzing heat transfer in buildings was first introduced. | The concept of the electrical circuitry analogy for analyzing heat transfer in buildings was first introduced. |
| | 1954 | Nottage, H. & Parmelee, G. | Research Engineers at the American Society of Heating and Ventilating Engineers (ASHVE) Research Laboratory | Circuit analysis applied to loas estimating | They used thermal circuits on analog computers to analyze cooling and heating loads. | They used thermal circuits on analog computers to analyze cooling and heating loads. |
| | 1954 | Willcox, T., Oergel, C., Reque, S., ToeLaer, C., & Brisken, W. | Engineers at the General Electric Corporation | Analogue computer analysis of residential cooling loads | They studied cooling loads used in residential buildings using analog computers. | They studied cooling loads used in residential buildings using analog computers. |
| | 1955 | Buchberg, H. | Graduate Student at University of California – Los Angeles (UCLA) | Electric analogue prediction of the thermal behavior of an inhabitable enclosure | He used an analog computer approach to study thermal behavior in simple dwelling houses. | He used an analog computer approach to study thermal behavior in simple dwelling houses. |
| | 1958 | Buchberg, H. | Professor at UCLA | Cooling load from thermal network solutions | He demonstrated the accuracy of thermal network on analog computer for calculating the cooling load. | He demonstrated the accuracy of thermal network on analog computer for calculating the cooling load.<br>The thermal network approach was also used for simulation programs for solar energy application (Kusuda, 1985).<br>Kusuda studied the thermal network approach proposed by Buchberg in 1958 to improve the HBM (Kusuda, 1999). |

Table B.1. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Heat Balance Method (HBM) | 1851 | Clausius, R. | German physicist and mathematician | (as cited in Donaldson et al., 1994) | Clausius divided the cycles into minute parts and additionally proposed internal energy. Inexact differentials were used for heat and work, and an exact differential was used for energy in the first law (Pedersen, 2009). | In 1960, this concept was modified by Obert. |
| | 1960 | Obert, E. F. | Professor at the University of Wisconsin-Madison | Concepts of thermodynamics | Obert developed a new concept for the first law by introducing time as the independent variable. In the first law of Obert, heat and work were also considered as exact differentials. In other words, Obert defined the first law based on time of the independent variable (Pedersen, 2009). | Aerospace and other types of engineers have widely used general heat balance models in their research (Sowell and Hittle, 1995). |
| | 1976 | Kusuda, T. | Researcher at the National Bureau of Standards (NBS) | NBSLD, the computer program for heating and cooing loads in buildings | The HBM was used in the National Bureau of Standards Load Determination (NBSLD) program. Kusuda studied the thermal network approach proposed by Buchberg in 1958 to improve the HBM (Kusuda, 1999). | The first application for buildings that used a complete method form of the HBM was developed by Kusuda for the NBSLD program (Kusuda, 1976; Sowell and Hittle, 1995; Pedersen et al., 1997). |
| | 1997 | Pedersen, C. O., Fisher, D. E., & Liesen, R. J. | Professor and Researchers at the University of Illinois at Urbana-Champaign | Development of a heat balance procedure for calculating cooling loads | ASHRAE Research Project-875, sponsored by Technical Committee 4.1, organized the current HBM for the cooling load calculation and procedure. | The HBM , also called the thermal balance method, is the scientifically strictest method to calculate building cooling loads when compared to the TETD/TA method, the TFM or WFM, and the CLTD/CLF method. |

Table B.2. *Annotated references of the analysis methods of the solar analysis programs.*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Utilizability Method | 1942 | Hottel, H. C. & Woertz, B. B. | Professor and Researcher at the MIT | Performance of flat-plate solar collectors | Hottel and Woertz developed the fundamental equations for flat-plate solar collectors. | This study contributed to the development of the utilizability method. |
| | 1953 | Whillier, A. | PhD at the MIT | Solar energy collection and its utilization for house heating | Whillier proposed the first utilizability concept for evaluating flat-plate solar collectors to shorten the calculation for analyzing the collectors. | This utilizability concept was widely used for analyzing the incident solar radiation that reaches the surface of a solar system. |
| | 1963 | Liu, B. Y. H. & Jordan, R. C. | Professors at the University of Minnesota | A rational procedure for predicting the long-term average performance of flat-plate solar-energy collectors | Using Whillier's utilizability curve method, Liu and Jordan's studies proposed a cloudiness index in order to create a location-independent utilizability curve method (Klein, 1993). Also, Liu and Jordan studied the effects of collectors that have tilted surfaces using the utilizability curves. | Liu and Jordan generalized Whillier's utilizability method. |
| | 1978 | Klein, S. A. | Professor at the University of Wisconsin - Madison | Calculation of flat-plate collector utilizability | Klein proposed a correlation method for the monthly average daily utilizability, where he used curve-fitted values to develop the daily utilizability correlation and hourly radiation data obtained from Liu and Jordan's statistical data, which was given by their study in 1960, instead of using actual radiation data. | Klein's monthly average daily utilizability chart reduced the calculation efforts and was easily implemented in automated computer programs. |
| | 1979 | Collares-Pereira, M. & Rabl, A. | Researchers at the University of Chicago and Solar Energy Research Institute | Simple procedure for predicting long term average performance of nonconcentrating and of concentrating solar collectors | Collares-Pereira and Rabl developed long-term average energy models using the daily utilizability correlations to estimate the utilizable solar radiation on flat-pate collectors, compound parabolic concentrator (CPC), and tracking collectors for east-west, polar, and two-axis tracking axis. In order to analyze all these collectors, the models considered the operating temperature used in the solar collectors. | This study applied Liu and Jordan's method to concentrating and nonconcentrating solar collectors. |
| | 1980 | Theilacker, J. C., & Klein, S. A. | Researcher and Professor at the University of Wisconsin - Madison | Improvements in the utilizability relationships. | Theilacker proposed a new correlation method that simplified and improved the accuracy of Klein's correlation method developed in 1978. | This new method was also applicable to surfaces facing the equator like Klein's method, but it added new correlations for surfaces shaded by overhangs and vertical surfaces facing east and west. |

Table B.2. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Utilizability Method | 1982 | Evans, D. L., Rule, T. T., & Wood, B. D. | Professors at Arizona State University | A new look at long term collector performance and utilizability | Evans et al. developed a new method that used the actual collector parameters instead of using the critical level. This method used an empirical approach for the monthly utilizability to analyze flat-plate collectors, especially for tilted collectors facing south, and the collector efficiency. | This empirical approach could quickly determine the results according to the changes of location, design and inlet temperature of collectors. |
| F-Chart Method | 1976 | Klein, S. A. | Professor at the University of Wisconsin - Madison | A design procedure for solar heating systems | Klein suggested the f-chart method. | The f-chart method was further developed for customary types of active solar systems such as active domestic hot water systems (i.e., two-tank domestic water heating systems), pebble bed storage space and domestic water heating systems, and water storage space and domestic water heating systems. |
| | 1979 | Klein, S. A., & Beckman, W. A. | Professors at the University of Wisconsin - Madison | A general design method for closed-loop solar energy systems. | Klein and Beckman developed the monthly utilizability, f-chart method. | This study extended the f-chart concept to other applications such as concentrating solar collectors. |
| | 1979 | Jurinak, J. J., & Abdel-Khalik, S. I. | Researcher and Professor at the University of Wisconsin - Madison | Sizing phase-change energy storage units for air-based solar heating systems | Jurinak and Abdel-Khalik performed simulations for air-based solar heating systems using the TRNSYS program, which led to correlations for air type systems. | In their study, a correction factor obtained from the simulation results was then applied to the f-chart method for estimating phase change energy storage systems. |
| | 1980 | Buckles, W. E., & Klein, S. A. | Researcher and Professor at the University of Wisconsin - Madison | Analysis of solar domestic hot water heaters | Buckles and Klein developed a modified f-chart method. | This study analyzed domestic hot water systems that used for a single tank system. Originally, the f-chart method was proposed for domestic hot water systems with two tank systems. |
| | 1980 | Anderson, J. V., Mitchell, J. W., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | A design method for parallel solar-heat pump systems | Anderson et al. conducted a study concerning parallel solar heat pump systems. They used the results of simulations to propose a design method for the systems. | This design method utilized the f-chart method to calculate the fraction of the monthly solar energy load. |
| | 1983 | Braun, J. E., Klein, S. A., & Pearson, K. A. | Researchers and Professor at the University of Wisconsin - Madison | An improved design method for solar water heating systems | Braun et al. developed the monthly utilizability, f-chart method for open-loop systems. | This study expanded the monthly utilizability, f-chart method for close-loop solar energy systems, developed by Klein and Beckman in 1979. |

Table B.2. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| F-Chart Method | 1985 | Evans, B. L., Klein, S. A., & Duffie, J. A. | Researcher and Professors at the University of Wisconsin - Madison | A design method for active-passive hybrid space heating systems | Evans et al. performed simulations for active-passive hybrid space heating systems using the TRNSYS program. | Their simulation results developed a new correction factor that could be applied to the f-chart method for analyzing the hybrid active-passive space heating systems |
| SLR Method | 1976 | Balcomb, J. D., & Hedstrom, J. C. | Researchers at Los Alamos Scientific Laboratory | A simplified method for calculating required solar collector array size for space heating | Balcomb and Hedstrom developed the SLR method for estimating the required solar collector array size for space heating. | The SLR method was developed to use for passive solar systems in a condition without an active solar system. They correlated the results from a detailed simulation program, PASOLE. |
| | 1978 | Balcomb, J. D., & McFarland, R. D. | Researchers at Los Alamos Scientific Laboratory | A simple empirical method for estimating the performance of a passive solar heated building of the thermal storage wall type | Balcomb and McFarland proposed the SLR method for passive solar heated walls. | The SLR method was extended. |
| | 1981 | Schnurr, N. M., Hunn, B. D., & Williamson, K. D. | Researchers at Los Alamos Scientific Laboratory | The solar load ratio method applied to commercial building active solar system sizing | Schnurr et al. proposed an extension to the SLR method. | This extended method was used for estimating space and water heating systems used in commercial buildings. In the use of the results from the DOE-2 detailed simulation program, new correlations were developed for these space and water heating systems. |
| | 1984 | Balcomb, J. D., Jones, R. W., McFarland, R.D., & Wray, W. O. | Researchers at Los Alamos Scientific Laboratory | Passive solar heating analysis: a design manual. | Balcomb et al. defined a new SLR method to specifically analyze passive solar systems. | The SLR method of this study is the present definition (Jones and Wray, 1992). |

Table B.2. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Un-tilizability Method | 1980 | Monsen, W. A., & Klein, S.A. | Researcher and Professor at the University of Wisconsin - Madison | Prediction of direct gain solar heating system performance | Monsen and Klein developed the un-utilizability method for passive solar systems. | In this method, they applied the un-utilizability concept to estimate the performance of direct solar gain systems. |
| | 1981 | Monsen, W. A., Klein, S.A., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | The unutilizability design method for collector-storage walls | Monsen et al. further developed the un-utilizability method to analyze collector-storage walls (i.e., thermal storage walls). | The un-utilizability method was extended. |
| | 1981 | Klein, S. A., Monsen, W. A., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | Tabular data for the unutilizability passive solar design method. | Klein et al. proposed tables for simplifying the un-utilizability procedure. | The simplified approach for the un-utilizability method was proposed. |
| PV Design Method | 1965 | Shepherd, C. M. | Researcher at the U. S. Naval Research Laboratory | Design of primary and secondary cells: II. An equation describing battery discharge | This study explained an equation for cell and battery discharges. | Siegel et al. (1981) used the battery model of this study. |
| | 1978 | Evans, D. L., Facinelli, W. A., & Otterbein, R. T. | Professors at Arizona State University and Researchers at the Sandia National Laboratories | Combined photovoltaic/thermal system studies | Evans et al. developed the TRNSYS compatible subroutines to estimate PV performance data. | Siegel et al's method (1981) used the TRNSYS compatible subroutines and a 2-V battery cell model of this study. |
| | 1980 | Evans, D. L. | Professor at Arizona State University | Simplified method for predicting photovoltaic array output | A method for the long term, monthly average PV array output was proposed. | Evans's method accounted for the average PV array output without energy storage capacity using a computational method and graphs. |
| | 1980 | Evans, D. L., Facinelli, W. A., & Koehler, L. P. | Professors at Arizona State University | Simulation and simplified design studies of photovoltaic systems | TRNSYS simulations were conducted to study PV systems with electrical storage. | Evans et al.'s method considered the effect of energy storage capacity for estimating the solar load fraction of PV systems by using graphs. |
| | 1980 | Gupta, Y., & Young, S. | Science Applications, Inc. | Method of predicting long-term average performance of photovoltaic systems. | A method for the excess array capacity was developed. | Gupta and Young predicted the excess capacity of the array by using Liu and Jordan's utilizabilty method developed in 1963. |

Table B.2. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| PV Design Method | 1981 | Siegel, M. D., Klein, S. A., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | A simplified method for estimating the monthly-average performance of photovoltaic systems | Siegel et al. developed a simplified method to analyze the monthly-average PV performance. | The methods for estimating monthly average daily PV array output (i.e., electrical output), excess array capacity, and battery storage were presented. Siegel et al's method for the excess capacity used Klein's utilizability method developed in 1978 that used the monthly average daily utilizability because Klein's utilizability method had more computation efficiency than Liu and Jordan's original utilizability method. |
| | 1983 | Clark, D. R., Klein, S. A., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | Algorithm for evaluating the hourly radiation utilizability function. | This study presented the algorithm of the hourly utilizability function rather than the daily utilizability function used in Siegel et al's method. | The hourly utilizability function allowed Clark et al.'s method to be used for analyzing hourly loads in the PV systems. |
| | 1984 | Clark, D. R., Klein, S. A., & Beckman, W. A. | Researcher and Professors at the University of Wisconsin - Madison | A method for estimating the performance of photovoltaic systems. | Clark et al's design method presented a proper computational method by an analytical method for predicting PV systems with or without storage capacity. | Clark et al.'s method adopted their previous study in 1983 in order to estimate the PV system performance without battery storage capacity. |

Table B.3. *Annotated references of the analysis methods of the lighting and daylighting analysis programs.*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Split Flux Method | 1954 | Hopkin-son, R. G., Longmore, J., & Pether-bridge, P. | Researchers at the Building Research Station, UK | An empirical formula for the computation of the indirect component of daylight factor | Hopkins et al. presented the split flux method based on Arndt's method (1954). | The split flux method was used to estimate the IRC using an empirical formula. The split flux method assumes interior surfaces of a room are a connected sphere shape and perfectly diffuse with no inner obstacles, so it works best when a room is shape as a cube and does not have internal partitions. Due to these reasons, the internally reflected illuminance at the back side of a room may be over-predicted when the ceiling height of a room is much less than the depth of the window-wall (Winkelmann and Selkowitz, 1985). |
| | 1989 | Tregenza, P. R. | Professor at the University of Nottingham, UK | Modification of the split-flux formulae for mean daylight factor and internal reflected component with large external obstructions. | Tregenza presented a modified method of the split flux method. | Tregenza presented a modified method of the split flux method to account for large external obstacles such as overhang. |
| Radiosity Method | 1954 | Hottel, H. C. | Professor at the MIT | Radiant-heat transmission | Hottel first devised the radiosity method (Siegel and Howell, 1972). | This study was the first introduction of the radiosity method. |
| | 1966 | Sparrow, E. M., & Cess, R. D. | Professor at the University of Minnesota and Professor at State University of New York – Stony Brook | Radiation heat transfer | Sparrow and Cess introduced the radiosity concept in their book. | They described the radiosity concept in detail. |
| | 1982 | Modest, M. F. | Professor at the University of Southern California – Los Angeles | A general model for the calculation of daylighting in interior spaces. | Modest develop the algorithm for digital computers to calculate the daylighting effects inside rooms in buildings. | The radiosity method was used for the algorithm. |
| | 1984 | Goral, C. M., Torrance, K. E., Greenberg, D. P., Battaile, B. | Professors and graduate students at Cornell University | Modeling the interaction on light between diffuse surfaces. | Goral et al. first used the radiosity method for computer graphics. | At this time, the existing computer graphics did not use reflection models that considered the reflection effects between diffuse surfaces. Therefore, the radiosity method, which accounted for reflection s, provided a more accurate analysis rather than the existing models for the global illumination. |

Table B.3. *Continued*

| Sorter | Year | Author | Who were they? | Literature Title | What did the literature do? | Why was it important? |
|---|---|---|---|---|---|---|
| Ray Tracing Method | 1967 | Appel, A. | Researcher at the IBM Research Center | The notion of quantitative invisibility and the machine rendering of solids | Appel first proposed the concept of ray tracing method (Weghorst et al., 1984). | This study was the first introduction of the ray tracing method. |
| | 1971 | Goldstein, R. A., & Nagel, R. | Engineers at Mathematical Applications Group, Inc | 3-D visual simulation | Goldstein and Nagel used the ray tracing method to introduce image production software developed by MAGI. | The ray tracing method was used for producing images. |
| | 1980 | Whitted, T. | Researcher at Bell Laboratories | An improved illumination model for shaded display | A shading model was studied to estimate intensities with global illumination information. | This study extended the ray tracing method in order to account for global illumination in terms of rendering computer graphics images. |
| | 1984 | Cook, R. L., Porter, T., & Carpenter, L. | Engineers at Lucasfilm Ltd. | Distributed ray tracing | Cook et al. improved the ray tracing method by using an analytical function. | The unsolved problems of the original ray tracing method such as motion blur, fuzzy reflections, and depth of field were resolved by this analytical approach. |
| | 1984 | Weghorst, H., Hooper, G., & Greenberg, D. P. | Graduate Students and Professor at Cornell University | Improved computational methods for ray tracing | Weghorst et al. proposed computational procedures to reduce the process time for making images by the ray tracing method. | The improved computational procedures were suggested for producing images by the ray tracing method. |
| | 1986 | Arvo, J. | Apollo Computer, Inc | Backward ray tracing | Arvo described the backward ray tracing method. | The backward ray tracing method provided a solution for exactly calculating indirect light’s diffuse reflection, which had not been solved by the original ray tracing method. |