IMPROVEMENTS AND APPLICATIONS OF THE METHODOLOGY FOR POTENTIAL ENERGY SAVINGS ESTIMATION FROM RETRO-COMMISSIONING/RETROFIT MEASURES

A Thesis

by

JINGJING LIU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Mechanical Engineering

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Approved by:

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Committee Members, Charles Culp
Warren Heffington
Head of Department, Dennis L. O'Neal

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ABSTRACT

Improvements and Applications of the Methodology for Potential Energy Savings Estimation from Retro-commissioning/Retrofit Measures. (May 2010)

Jingjing Liu, B.A., Tsinghua University;

M.S., Tsinghua University

Chair of Advisory Committee: Dr. David E. Claridge

This thesis has improved Baltazar's methodology for potential energy savings estimation from retro-commissioning/retrofits measures. Important improvements and discussions are made on optimization parameters, limits on optimization parameter values, minimum airflow setting for VAV systems, space load calculation, simulation of buildings with more than one type of system, AHU shutdown simulation, and air-side simulation models. A prototype computer tool called the Potential Energy Savings Estimation (PESE) Toolkit is developed to implement the improved methodology and used for testing.

The implemented methodology is tested in two retro-commissioned on-campus buildings with hourly measured consumption data. In the Sanders Corps of Cadets Center, the optimized profiles of parameter settings in single parameter optimizations can be explained with engineering principles. It reveals that the improved methodology is implemented correctly in the tool. The case study on the Coke Building shows that the improved methodology can be used in buildings with more than one system type.

The methodology is then used to estimate annual potential energy cost savings for 14 office buildings in Austin, TX with very limited information and utility bills. The methodology has predicted an average total potential savings of 36% for SDVAV systems with electric terminal reheat, 22% for SDVAV systems with hot water reheat, and 25% for DDVAV systems. The estimations are compared with savings predicted in the Continuous Commissioning® assessment report. The results show it may be helpful to study the correlation by using generalized factors of assessment predicted energy cost savings to estimated potential energy cost savings. The factors identified in this application are 0.68, 0.66, and 0.61 for each type of system. It is noted that one should be cautious in quoting these factors in future projects.

In the future, it would be valuable to study the correlation between measured savings and estimated potential savings in a large number of buildings with retro-commissioning measures implemented. Additionally, further testing and modifications on the PESE Toolkit are necessary to make it a reliable software tool.

To my Zhiqin and Jason,

my parents and grandparents.

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This thesis was completed with guidance, contribution, support, and love from my committee, colleagues, friends and family.

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1. INTRODUCTION

1.1 Background and Problem Statement

The importance of improving energy efficiency and reducing operating cost of buildings first gained nationwide attention during the oil embargo of 1973 (Claridge, 1998). Commercial buildings use a significant fraction of all energy use, accounting for 18.4% of the total energy use in the United States (EIA, 2007), and this fraction is increasing. Building owners/operators are showing more interest in saving energy as a result of increasing energy prices. A significant volume of literature suggests that retro-commissioning typically reduces annual energy consumption by 5% to 20%, with higher values (up to 30%) in some buildings (TIAX LLC., 2005). The Energy Systems Laboratory personnel at Texas A&M University have retro-commissioned, or improved operating efficiency in more than 300 buildings during the last 20 years; the average measured utility savings are about 20%, with simple paybacks typically occurring in less than two years (Energy Systems Laboratory, 2009).

On-site maintenance personnel play an important role in daily building mechanical system operation and trouble-shooting. However, in order to optimize the energy efficiency in a building as much as possible, the owner/operator usually needs to resort to companies or specialists that have expertise in existing building/facility energy savings for a retro-commissioning or energy retrofit project. At the beginning of such a project, some form of screening is often applied to determine whether there is sufficient

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This thesis follows the style of *ASHRAE Transactions.*

potential for savings to justify a retro-commissioning assessment or an energy audit (also referred to as an energy assessment). If screening results are positive, the assessment is performed and the potential for energy savings in the building is evaluated before the owner/operator decides that further work is likely to produce significant energy savings meeting the owner's economic criteria. A popular technique that is used to screen for savings potential in a building is to compare its energy use per square foot of gross area to a group of buildings of similar type in the same climate. This technique is also known as conventional energy benchmarking. Although this technique is very easy to use when a satisfactory database is available and gives some idea about the relative efficiency of the building, buildings are not always as similar as they appear. The buildings used for comparison are not necessarily energy efficient in general, and it gives no indication of energy conservation measures (ECMs) that merit consideration in the next step. Some of the improved energy benchmarking methods found in recent studies (Mills et al., 2008; Mathew and Mills, 2008; Yalcintas, 2006 and Cipriano et al., 2009) show potential in suggesting ECMs, but the other limitations still apply. There are also various energy simulation tools available to energy engineers. They can be used to predict savings from implementation of certain ECMs by changing inputs and comparing results. However, they are not designed to project the potential of savings in a building without detailed information about the building and the built-in system plus they are usually complicated to use. Consequently, it would be desirable to have a methodology which is capable of predicting the opportunities for savings independent from the energy performance of other buildings. And yet, this methodology should be easy enough to use in the early phase of retro-commissioning assessments or energy audits to help decide if a comprehensive assessment should be carried out to identify commissioning measures and/or ECMs for further analysis.

Baltazar (2006) proposed such a methodology for estimating the potential energy savings in commercial buildings. At its core is the procedure for obtaining the minimum energy use cost required to maintain indoor thermal comfort. Baltazar used a model based on the modified bin method (Knebel, 1983) to represent the built-in HVAC system and used a numerical procedure for energy cost minimization. The total energy cost includes the electrical cost for lighting, equipment, and fans, as well as cooling and heating cost. All components of energy use are optimized except for electrical cost for lighting and equipment use. Sequential exhaustive search in the designated range of values for all the independent parameters commonly controlled for a specific type of HVAC system was employed to carry out the optimization. The potential savings in each bin of outside air dry-bulb temperature is determined as the difference between the actual energy cost and the minimum energy cost. The savings in each bin is then accumulated to yield the total potential energy cost savings during the period being evaluated (preferably a whole year). This methodology was applied to several buildings that have been retrofitted and/or retro-commissioned in Texas. The measured savings in the Zachry Engineering Center at Texas A&M University was about 85% of the estimated potential savings, which was considered a close agreement.

This methodology is promising, yet in order to make it a useful tool in retro-commissioning assessments or energy audits, further testing and improvement of the methodology is required. In addition, development of a computer tool will make the testing much easier. Although Baltazar's implementation in Microsoft® Excel VBA codes fulfilled the scope of the methodology tested in his thesis, it is not designed as a tool to be readily used by others. Therefore, re-development of a computer tool with user-friendly interface including more simulation and optimization options is essential for testing of the methodology.

1.2 Objectives

The objectives of this study are to improve Baltazar's methodology for potential energy savings estimation and to test the predictions of the improved methodology by comparison with savings predicted in retro-commissioning assessment reports. This study will fulfill these objectives in three steps:

(1) A prototype computer tool called the Potential Energy Savings Estimation (PESE) Toolkit is developed to implement the improved methodology for potential energy savings estimation in early retro-commissioning assessments or energy audits. This tool is designed for the purpose of testing of the methodology.

(2) A preliminary test of the methodology implemented is conducted in two retro-commissioned buildings with hourly measured consumption data and retro-commissioning implementation information. The optimized profiles of parameter settings versus bin temperature are analyzed in single parameter optimizations in the first building.

(3) The methodology is then used to estimate potential savings for 14 office buildings with very limited information and utility bills. It is expected that this

methodology will predict an upper limit to the potential savings that can be achieved. The use of a generalized factor or factors to improve the correlation between potential savings identified in retro-commissioning assessment reports and those identified by this methodology is investigated.

2. LITERATURE REVIEW

2.1 Energy Audit

Today, as energy prices increase, saving money on energy bills through a commissioning and/or retrofit project is more attractive to commercial building owners. The typical process of a Continuous Commissioning® (CC®) project and an energy retrofit project as described by Liu et al. (2002) and Wendes (1994) are depicted individually in Figure 2.1. Both processes use an energy audit (or similarly a CC® assessment) as one of the first tasks to be performed as the basis of the following steps. In an energy audit, modifications that will reduce the energy cost of operating a building are identified and developed, and the results are presented appropriately for an owner/operator to decide if any, some, or all of the recommended modifications should be implemented. The modifications recommended by an energy audit generally involve equipment replacement or upgrades. According to the ASHRAE Technical Committee 7.6 Systems Energy Utilization (ASHRAE, 2004), an energy audit process should follow the six steps illustrated in Figure 2.2. In addition, depending on the purpose for which the results may be used, different levels of energy analysis can be performed on a given building, as shown in Figure 2.3. Each succeeding level of analysis builds upon the previous level, although there are no sharp boundaries between these levels.

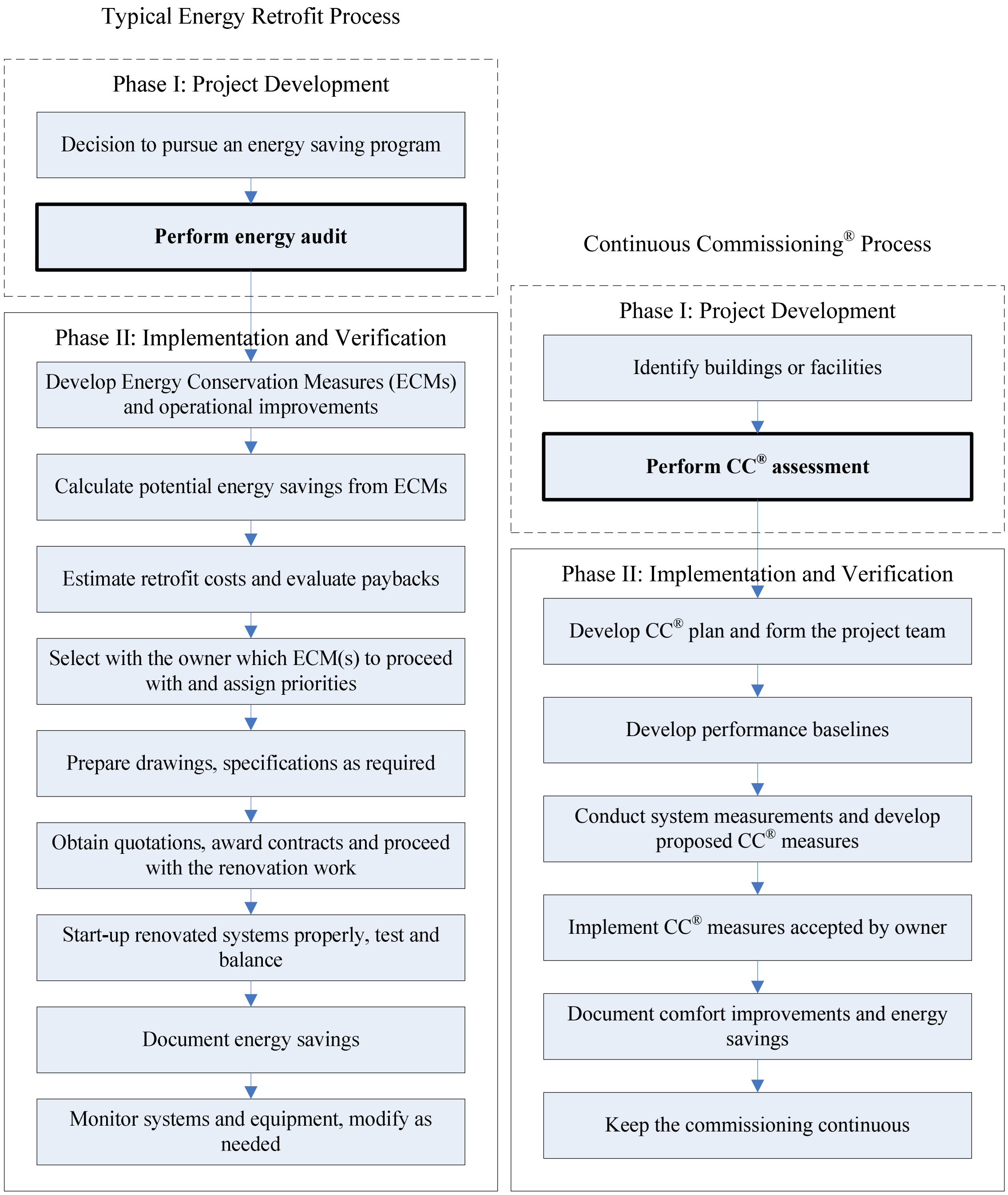


Figure 2.1 Diagram of commercial building retrofit/retro-commissioning processes

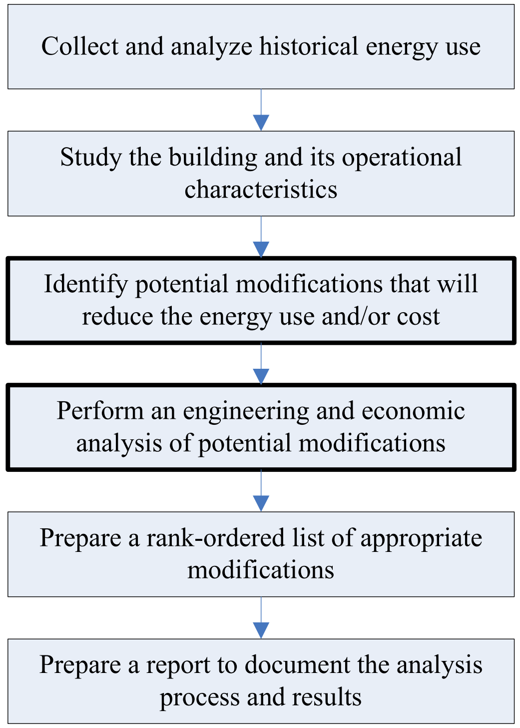


Figure 2.2 Diagram of commercial building energy audit steps

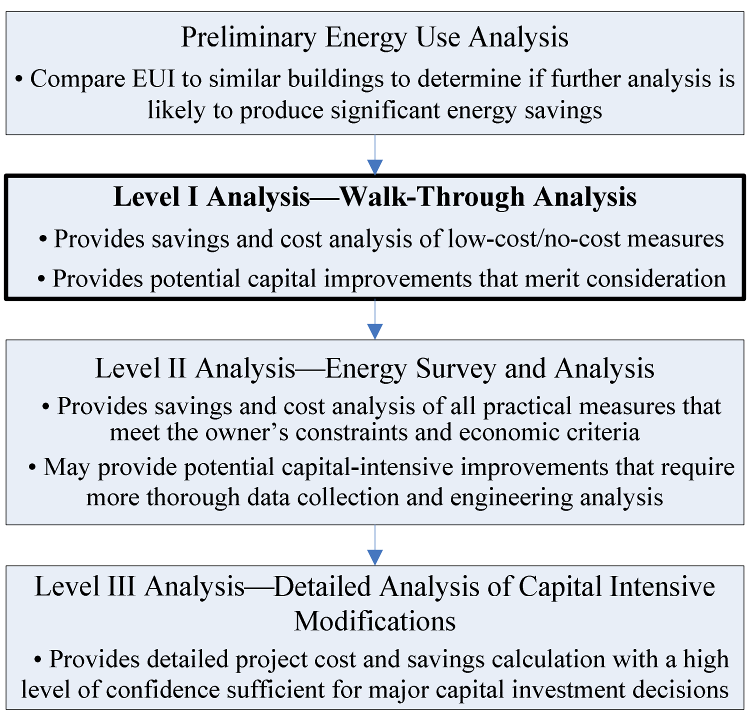


Figure 2.3 Level of effort in commercial building energy audit

In an energy audit, ECMs for different building systems can be recommended including, but not limited to the building envelope (insulation and air leakage issues), electrical system (lighting and office equipment), cooling and heating plant (chiller and boiler efficiency), HVAC system and the domestic water system. However, this study only discusses energy savings within the HVAC system. Various energy analysis methods/tools are available to the engineers for estimating energy savings incurred from ECMs applied to the HVAC system. These methods/tools vary widely in complexity and accuracy. In order to select an appropriate method/tool, one should consider the purpose and required level of effort in the current analysis. The following section, 2.2-2.4 will discuss the features and applications of each method by category: energy benchmarking, forward modeling and inverse modeling.

In general, energy benchmarking methods are conventionally used as the major tool for analyzing the building's historical energy use in preliminary level analysis, whereas recent studies show that they also have potential in identifying ECMs. Forward modeling methods are widely used in engineering and economic analysis of potential modifications, and the variety of options can fit the need from level I to level III analysis. The inverse modeling methods are most valuable in the determination of savings achieved after modifications are implemented;sometimes they can also be used with forward modeling to determine uncertain system parameters.

2.2 Energy Benchmarking

At the beginning of an energy audit process, historical energy use data is collected and analyzed. Energy benchmarking (comparing a building's normalized energy consumption to that of other buildings) is widely used in the preliminary level of energy analysis as a first measurement of energy efficiency to determine whether a building is a good candidate for a retro-commissioning and/or retrofit process. Relative energy use is commonly expressed in terms of an energy use index (EUI) and a cost use index (CUI), in which building gross floor area is used as the normalizing factor. Comparing a building's energy use index with that of comparable buildings in the same region is a good way to check its relative efficiency. While local energy consumption data may be available from local utility companies or energy offices, the DOE/EIA Commercial Buildings Energy Consumption Survey (CBECS) is a public source of benchmarking data for U.S. buildings with the most recent survey completed in 2003.

Most energy consulting companies and other organizations responsible for energy-efficiency of buildings use the mean or median value of the EUI for the kind of building being investigated as a benchmark (Federspiel, 2002), which is considered conventional benchmarking. Current studies of improved energy benchmarking methods utilize three different approaches: the distributional model-based approach, the regression-based approach and the artificial neural network (ANN)-based approach.

2.2.1 Distributional Model-based Approach

The Cal-Arch model is a simplistic web-based distributional benchmarking tool developed by Lawrence Berkeley National Laboratory (LBNL), which is based on the data from California's 1992 Commercial End-Use Survey (CEUS). Building location, building type, floor area and energy use are required input. The EUIs for a subset of buildings in the Cal-Arch database are plotted as a histogram with the evaluated building's EUI noted with an arrow, and the percent of buildings in the database that have lower EUIs is reported. The data displayed are actual EUIs and are not adjusted for weather or any other factors. The user can compare his/her building's EUI to that of similar buildings in the same climate zone or statewide (Matson and Piette, 2005).

Recognizing that conventional energy benchmarking can inspire action but provides no practical guidance, recent research at LBNL developed a new action-oriented benchmarking system based on the latest 2006 CEUS survey with a web-based interface called EnergyIQ. It is considered as a major advancement beyond Cal-Arch in that it is aimed to fill the need for a benchmarking tool that enables users to identify potential energy-efficiency options and prioritize areas for more detailed analysis and full-scale assessments (Mills et al., 2008). Action-oriented benchmarking extends traditional whole-building energy benchmarking in three ways: end-use benchmarking, features benchmarking and correlating features with end-use energy intensities, which can help assess the approximate savings potential from specific actions (Mathew and Mills, 2008). However, the effectiveness and widespread application of action-oriented benchmarking is contingent on the availability of reliable end-use data for buildings. Currently, end-use metering is still relatively rare, and no other states have databases like CEUS.

2.2.2 Regression-based Approach

While conventional benchmarking attempts to normalize energy use relative to a primary determinant - building floor area - it ignores many other factors. Sharp (1996) used the 1992 CBECS database to develop distributions of electric EUIs in office buildings for the nine U.S. census divisions, and concluded that both census division average and median EUIs are not reliable indicators for more localized EUIs. Consequently, he proposed a benchmarking method which identifies significant determinants with stepwise linear regression modeling. Beyond floor area, the number of workers, personal computers, owner-occupancy, operating hours, and the presence of an economizer or chiller are also found to be dominant variables. The resulting performance models can predict EUIs that are much better benchmarks than simple census division statistics. Sharp's method has been modified slightly and used as the basis of the Energy Star® benchmark, which is a web-based national tool based on building characteristic and energy use data from the CBECS survey. Rather than using census location as a proxy for weather, the Energy Star® benchmark explicitly compensates for weather. The Energy Star® benchmark is the 25th percentile of the EUI distribution, because this rating system is based on the assumption that 25% of the national building stock can achieve an Energy Star® rating of 75 or higher – these buildings are eligible for an Energy Star® label if the building also meets the indoor environment criteria.

2.2.3 ANN-based Approach

Yalcintas (2006) and Cipriano et al. (2009) presented a promising application of ANN techniques in building energy benchmarking. The foremost feature of their ANN method is that the benchmarking algorithm will renew itself if new building data is entered in the database. In the study developed by Yalcintas (2006), the ANN model specifically focuses on predicting a weighted EUI by taking into consideration various building variables, such as plug load density, lighting type and hours of operation, air conditioning equipment type and efficiency, etc. Data collected from laboratory, office and classroom-type buildings and mixed use buildings in Hawaii are used to present this technique and make successful predictions. Additionally, the use of the ANN benchmark model for predicting potential energy savings from retrofit projects was evaluated for the first time. In the study of Cipriano et al. (2009), a prediction model is developed for calculating the relationship between climate-adjusted EUIs and the significant characteristic factors of a building. An application to schools in Catalonia (Spain) is presented to validate the methodology and potential energy savings from retrofit projects are evaluated. The method shows promising features in order to be an easy-to-use tool for first identifying a building with higher energy consumption when compared with similar buildings, secondly identifying the most important parameters that can cause this high energy consumption and finally modeling energy performance and predicting energy savings by retrofit measures.

2.2.4 Benchmarking Summary

Within its current capabilities, an energy benchmarking method does not provide detailed results about the building's energy usage characteristics when compared with an energy simulation method or an ECM feasibility analysis, but is the least expensive method, and it serves as preliminary energy information and a support aid decision system. Significant advances in energy benchmarking have been achieved in recent studies; new tools and methods are extending the function of energy benchmarking from giving only a rough idea of building energy efficiency to helping identify potential energy-efficiency options. The distributional model-based approach and ANN-based approach have both proven to have potential in this direction. The former demands a much more sophisticated database than is generally available; the latter seems to have better application potential. However, there are two limitations inherent with energy benchmarking methods. The first is that they require a database which includes a statistically significant number of buildings that are comparable to the building being evaluated. Although similar climate and the use of the building are minimal requirements for comparison, other factors such as floor area, occupancy, construction, and HVAC system type are also significant factors. The second is that the comparable buildings are not necessarily energy efficient, which can lead to under-estimation of energy savings potential. In a final analysis, a building's energy efficiency and energy-saving potential does not depend on the performance of other buildings, but on the characteristics of the built-in system and operation strategy which only can be represented by system modeling methods.

2.3 Forward Modeling Methods

There are two broad but distinct approaches to modeling: forward modeling and inverse modeling. Forward modeling of building energy use begins with a physical description of the building system or component of interest. The peak and average energy use of such a building can then be predicted or simulated by the forward simulation model. The main advantage of this approach is that the system need not be physically built to predict its behavior. Thus, this approach is ideal in the preliminary design and analysis stage. Since it is based on sound engineering principles, it has gained widespread acceptance by the design and professional community. (ASHRAE, 2005)

2.3.1 Steady-state Methods

Steady-state energy analysis methods using the forward modeling approach are usually easy to perform by hand or using spreadsheet programs. Two types of steady-state forward methods can be distinguished: degree-day methods and bin methods.

The variable-base degree-day method has replaced the traditional degree-day method in general. Annual degree-days are computed at the balance point temperature of the particular building to predict heating and cooling energy uses. It is the simplest method for energy analysis and provides generally good predictions for buildings dominated by transmission loads with constant HVAC equipment efficiency. Where efficiency or conditions of use vary with outdoor temperature, consumption can be calculated for different values of the outdoor temperature and multiplied by the corresponding number of hours in the temperature interval (bin) centered on that temperature. This approach is known as the bin method.

ASHRAE Technical Committee 4.7 developed the modified bin method (Knebel 1983) to fill the need for a simple yet comprehensive method which can be used to calculate energy use in commercial buildings. The modified bin method recognizes that the building and zone loads consist of time dependent loads and temperature dependent loads. In expressing building loads as a function of outdoor temperature, two major simplifying assumptions are made. One is that all exterior loads can be expressed as a linear function of outdoor temperature; the other is that on a daily basis, two calculation periods representing occupied and unoccupied hours are sufficient. In buildings dominated by internal loads or in low mass structures the method provides reasonable results. And the accuracy associated with this method should meet the requirement of most Level I and some Level II savings and cost analyses. The simplicity of this method also gives opportunity for an easy link with optimization algorithms in applications of potential energy savings estimation.

2.3.2 Dynamic Methods

Computer simulation programs such as DOE-2, Trace, and EnergyPlus using dynamic methods can calculate energy consumption in complex buildings with hourly or sub-hourly time steps. An important characteristic of these simulation programs is their capability to account for the effects of thermal inertia so they can be used in buildings with significant thermal mass, thermostat setbacks, or predictive control strategies. These programs require a high-level of expertise and are generally suitable to simulate large buildings with complex HVAC systems and involved control strategies that are difficult to model by simplified energy analysis tools. To adequately estimate energy savings from ECMs, the models have to be calibrated to measured energy use (Krarti, 2000). Since these programs are relatively complex and computationally intensive, it is difficult to link them with outside optimization tools. However, they are widely used in Level II analyses where savings from a particular ECM or a list of ECM(s) need to be determined. The following are some examples of application as such.

Yu and Chow (2007) selected a typical commercial building in Hong Kong, for detailed HVAC system energy use analysis. An energy signature was developed with three years of monthly energy consumption data and compared with simulation results using TRACE 600. Then a total of 20 ECMs were investigated with simulation for possible use in local commercial buildings. They showed that three measures can yield significant savings (up to 17%).

Yang et al. (2006) evaluated the major factors affecting the electricity use of HVAC systems with simulation using EnergyPlus. A model building was developed to represent the typical construction characteristics of commercial buildings in Hong Kong. It was concluded that up to 36.2% of electricity use can be saved from improving COP of chillers, setting appropriate spacing cooling temperature, lowering lighting intensity, running fans at their design operating point, etc.

2.4 Inverse Modeling Methods

Inverse modeling, also known as "data-driven modeling", relies on energy use data of existing buildings to identify a set of building system parameters. Inverse modeling often allows identification of system models that are not only simpler to use but also are more accurate predictors of future system performance than forward methods, although they are less flexible in evaluating energy consumption of different design and operational alternatives (ASHRAE, 2005). Based on the reviews of Rabl (1988), MacDonald and Wasserman (1989), and Claridge (1998), inverse modeling methods may be categorized as empirical or "black-box" approach, calibrated simulation approach and gray-box approach.

2.4.1 Empirical Approach

With this approach, a simple or multivariate regression model is identified between measured energy use and the various influential parameters (e.g., climatic variables, building occupancy). Single-variate, multivariate, change point, Fourier series, and artificial neural network (ANN) models fall under this category. A purely statistical approach for model identification is usually adequate for baseline model development in energy conservation Measurement and Verification (M&V) projects (ASHRAE, 2005).

2.4.2 Calibrated Simulation Approach

The calibrated simulation approach can make more reliable predictions, but it is usually labor-intensive and requires expertise in both simulation and practical building operation, which prevent it from being more widely used. Katipamula and Claridge (1993) and Liu and Claridge (1998a, 1998b) suggested the simplified systems models with only two zones, which allow calibration to be done much faster as there are fewer parameters to vary. They illustrated that this method based on ASHRAE Simplified Energy Analysis Procedure (Knebel 1983) is not only applicable for baseline model development for M&V purposes when the pre-retrofit consumption is not metered, but also for identifying potential operational problems and for estimating potential savings from optimized operating parameters, such as optimizing cold and hot deck reset schedules.

2.4.3 Gray-box Approach

The gray-box approach is a hybrid approach between forward modeling and inverse modeling methods. It first formulates a physical model to represent the configuration of the system, and then identifies important parameters by statistical analysis (Rabl and Rialhe, 1992). Thus, it requires expertise in both physical modeling and statistical analysis. This approach has limited applicability to whole-building energy use although it has great potential in fault detection and diagnosis (FDD).

2.5 Summary

There are three types of tools (energy benchmarking, forward modeling methods and inverse modeling methods) available for energy use analysis in an energy retrofit or retro-commissioning project. They vary widely in ease of use and accuracy, which makes them fitting for different purposes and levels of analyses. Forward modeling methods have been widely accepted and used by the professional community for identification of potential ECMs and corresponding energy savings estimation in an energy audit. Recent academic research on improved energy benchmarking methods also shows some potential for ECM identification. However, as discussed earlier, there are limitations inherent with energy benchmarking methods. Among the forward modeling methods, the dynamic simulation tools can be used in different levels of analyses. However, they are generally time-consuming to perform and require expertise in use to get reliable results. The modified bin method is competitive in both Level I and Level II analyses to identify low-cost/no-cost ECMs and provide savings and cost analysis. In some cases, it can also be used with the calibrated simulation approach in determining the values of certain system parameters.

The modified bin method is simple in calculation and yet accurate enough in general for early phase energy savings analysis, plus it gives opportunity for easy link with optimization routines in programming. Consequently, it is adopted in the implemented methodology in this thesis, which is aimed to estimate potential energy savings with only limited information of the building and the built-in HVAC system. The steps and level of effort in which this methodology is intended to help are highlighted in Figure 2.2 and Figure 2.3. It is expected to help engineers mainly in the Level I analysis in evaluating low-cost/no-cost measures such as resetting room temperatures set points, cold deck and hot deck leaving air temperatures, and outdoor air intake. In some cases, capital cost may be required in order to implement the identified measure(s), for instance, installing an economizer. As project develops, more accurate input information may be available, and this methodology could also assist in some Level II analysis as such. When a satisfactory database is not available for performing an energy benchmarking, this methodology can also fill in the preliminary level of analysis to determine if further analyses are likely to predict significant savings. This can be especially valuable in projects where energy audits will be applied to many buildings, and pre-screening to identify the buildings with the most potential is necessary.

3. METHODOLOGY

3.1 Baltazar's Methodology

This study adopted the methodology of potential energy savings estimation proposed by Baltazar (2006), which evaluates theoretical potential savings based on thermodynamic considerations. The methodology is based on the modified bin method and can be briefly summarized as follows.

The potential energy savings in each outside air temperature bin can be obtained as the difference between the actual energy cost during a particular period (preferably a whole year) and the minimum energy cost needed to maintain comfortable indoor conditions using the existing HVAC systems in the building under the same weather conditions (Equation 3.1). Here the minimized energy cost is comprised of electricity cost, cooling cost and heating cost. The electricity cost consists of two parts: (1) lighting and equipment consumption which is estimated from measured data and remains constant, and (2) fan power consumption which is simulated. (Equation 3.2)

$$\text{Potential Energy Savings} = \text{Energy Cost}_{\text{ACTUAL}} - \text{Energy Cost}_{\text{MINIMIZED}} \tag{3.1}$$

$$\text{Energy Cost} = (\text{ELE Cost}_{\text{LTEQ}} + \text{ELE Cost}_{\text{FANP}}) + \text{CHW Cost} + \text{HHW Cost} \tag{3.2}$$

Bin temperature, mean coincident humidity ratio and measured energy consumption are required to determine the potential savings in each bin. They can be prepared from hourly measured consumption data as well as hourly outside air dry-bulb temperature data and any one of the three humidity parameters - wet bulb temperature, dew point temperature or relative humidity. The humidity ratio during each hour is first calculated from the dry-bulb temperature and the chosen humidity parameter. Then all the hourly data are sorted into bins based on the dry-bulb temperature. The mean coincident humidity ratio for each bin is computed as the mean humidity ratio for the hours in each bin and energy consumption data for hours in each bin is summed to give the consumption for each bin.

The essence of this methodology is the procedure for determining the minimum energy use cost, which has two major components as Figure 3.1 demonstrates: the combined model which thermodynamically represents the performance of the built-in HVAC system and the numerical procedure for energy cost minimization. The combined model takes weather conditions into account through a load calculation procedure and it becomes part of the input for the air-side system simulation. Both the load calculation and system simulation follows the ASHRAE Simplified Energy Analysis Procedure. The numerical procedure generates and seeks the parameter values which will produce minimum total energy use cost while meeting the indoor thermal comfort requirements.

Sequential exhaustive search is employed as the optimization method and manages through representative equivalent ambient conditions obtained by “bin sorting”. Figure 3.2 illustrates the procedure of implementation of the methodology in determining the minimum energy cost for each bin. The total potential energy cost savings during the period evaluated are then the sum of savings found in each bin.

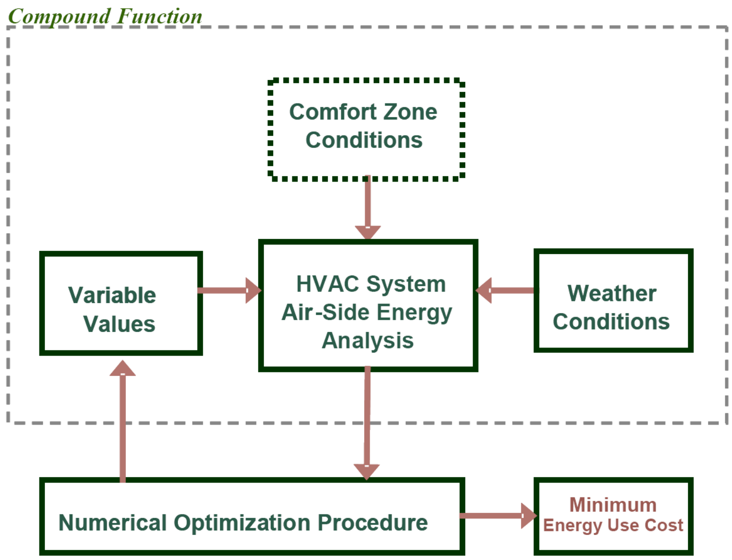


Figure 3.1 Block diagram of the methodology for potential energy savings determination (Baltazar, 2006)

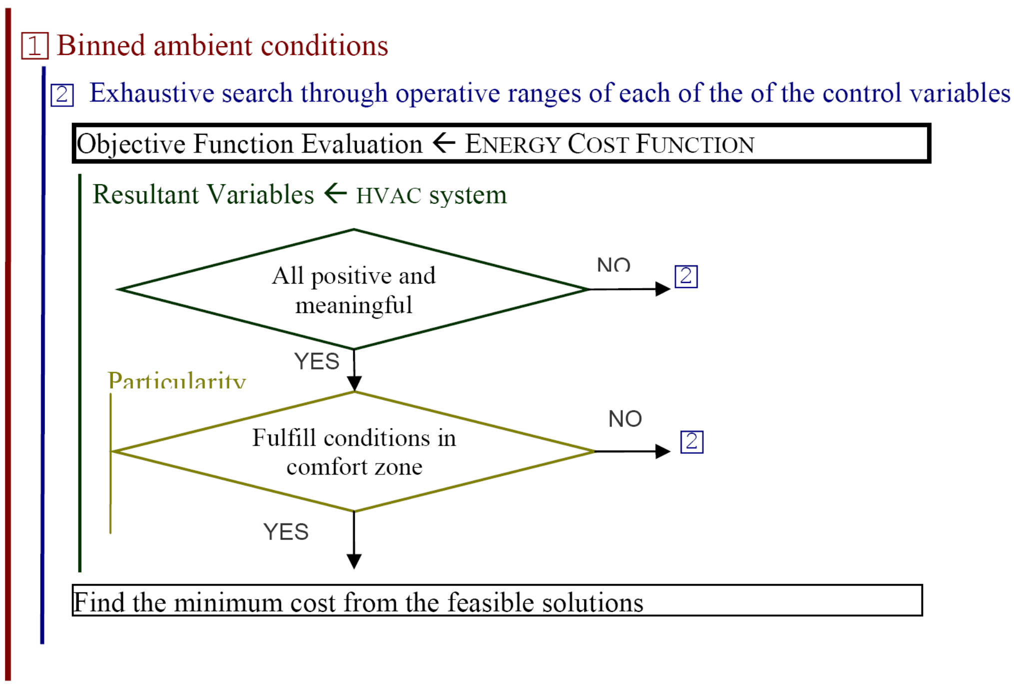


Figure 3.2 Flowchart of the methodology for evaluating potential energy savings in a building through binned ambient conditions. The total potential savings will be the sum of the individual products of the energy savings in each bin multiplied by its frequency. (Baltazar, 2006)

3.2 Improvements on Methodology

The following improvements on Baltazar's methodology have been incorporated in the PESE Toolkit.

3.2.1 Optimization Parameters

In Baltazar's implementation of the methodology, four parameters are selected for optimization: cold deck and hot deck (for dual duct systems) leaving air temperature set points; minimum supply airflow per square foot of floor area (for VAV systems); and the fraction of outside airflow in total design airflow. In this study, the volumetric outside airflow is optimized instead of optimizing outside air fraction because volumetric control is required in order to implement the optimization result; the minimum supply airflow is not optimized since the optimized value is always equal to the designated lower limit. In addition to the above changes, room temperature set points in the exterior and interior zones are included as additional optimization parameters, since space loads are dependent on these two parameters (refer to section 3.2.3).

In summary, five parameters are selected for optimization in this study: exterior and interior zone room temperature set points, cold deck and hot deck leaving air temperature set points, and outside air flow rate. In addition, in the implemented methodology in PESE Toolkit, options are provided to users for which of the five parameters will be activated. This is helpful in evaluating savings based on the existing control capability. For example, Baltazar concluded that his methodology seemed to over-estimate savings at lower outside air temperatures in buildings which do not have an economizer. In such a case, provided the option whether to optimize the outside air intake, one can choose either to estimate potential savings based on the current system setting, or to find out the extra savings achievable by installation of an economizer.

3.2.2 Limits on Optimization Parameter Values

In order to make the optimization result useful, it is important to set appropriate lower and upper limits on the values of optimization parameters. These limits should be determined based on the special requirements in each particular application. However, the considerations used to determine the limits in the case studies included in this thesis are given here for reference.

Room temperature set points: ASHRAE's general design criteria for commercial and public buildings can be adopted when there is no specific requirement for room temperature and relative humidity control. For example, 70-78°F and up to 60% RH are acceptable for offices (ASHRAE, 2007a) during occupied periods. According to the retro-commissioning practices at Texas A&M University, 65-85°F and up to 70% RH are commonly used for reset values during unoccupied periods.

Cold deck and hot deck leaving air temperature set points: Limits on these set points usually vary from project to project. Taking the practice of Texas A&M University as an example again, the reset range is usually 55-70°F for cold deck and 70-110°F for hot deck temperatures.

Outside air flow rate: Minimum outside air supply in breathing zone by ANSI/ASHRAE Standard 62.1-2007 (ASHRAE, 2007b) can be adopted as a lower limit. For example, 5 cfm/person and 0.06 cfm/ft^2 are generally required in design for offices;

however, this requirement can be as low as 7 cfm/person when a CO2 sensor is available to maintain a CO2 level of 1000ppm.

3.2.3 Minimum Airflow Setting

Exterior and interior zone minimum airflows are not parameters to be optimized by the methodology employed in this study. However, resetting minimum airflow is an important ECM in VAV systems and usually has significant influence on the energy use.

In retro-commissioning practice, the minimum airflow should be checked and reset if necessary for each individual VAV terminal box. This requires knowledge of the loads in each space as well as design information and terminal box details. Since this methodology is developed to assist in the early stage of a retro-commissioning or energy audit process, the above information is usually not available and not much effort can be expended to determine minimum airflow. Therefore, the following suggested procedure is intended to give an example how reasonable minimum airflows can be set with minimal effort while complying with related codes.

According to Taylor and Stein (2004), ANSI/ASHRAE Standard 62.1-2007 for ventilation and ANSI/ASHRAE Standard 90.1-2007 for energy (ASHRAE, 2007c), the minimum airflow during the occupied period can be reset to the largest of the following: (1) the airflow required to meet the design heating load at a supply air temperature that is not too warm (e.g. 85°F); (2) 30% of design airflow or 0.3 cfm/ft^2 if the design airflow is oversized; or (3) the minimum breathing zone outside air required by ANSI/ASHRAE Standard 62.1-2007. The minimum airflow during the unoccupied period can be reset to zero in most cases according to the practice at Texas A&M University.

3.2.4 Space Load Calculation

In Baltazar's implementation, space cooling and heating load are calculated based on fixed occupied period room temperature set points (e.g. 75°F). This can lead to inaccurate optimization results when the room temperatures are optimized using unoccupied resets and seasonal resets, because the conduction load makes up a significant fraction in the total space load and is proportional to the difference between the room temperature and the outside air temperature. Take office buildings for example. Room temperature can have a relatively wide acceptable range: 70-78°F during occupied periods and 65-85°F during unoccupied periods. Therefore, in this study, a space load calculation procedure is developed based on the Simplified Energy Analysis Procedure and linked with the optimization procedure, so that the space load will be re-calculated dynamically as room temperature set points change in the optimization process.

3.2.5 Simulation of Buildings with Multiple Types of Systems

Many buildings have more than one type of system. Therefore, the methodology should be made applicable to a large part of these buildings to be useful. In this study, two input parameters are introduced to account for this problem - the fractions of exterior and interior zone areas served by each type of system. They are applied to calculated whole-building exterior and interior zone space loads. Here, it is assumed that the space load is proportional to floor area. This assumption works fine with buildings having each type of system serving an entire floor or several floors, or buildings having two different types of systems serving the exterior zone and interior zone respectively.

3.2.6 AHU Shut-down Simulation

Shutting down the AHU(s) during unoccupied periods is a common and effective ECM. When the AHU is turned on before the building is occupied again, it has to bring the room temperature to set point in a short period. Observations of the measured consumption data in the Coke Building show that the cooling or heating energy consumption during the start-up period is usually significant. In addition, during the shut-down period, there is usually still a lower and upper limit on the room temperature to bring the AHU back to work. Therefore, the cooling and heating energy use during the unoccupied period needs to be estimated in a reasonable manner. This energy use can be estimated to be approximately equal to the sum of the largest two components of the space load: the internal heat gain and the conduction load.

During the AHU shut-down period, the room temperature changes under the influence of internal heat gain and conduction through the building envelope. As a result, the conduction load can be significantly different from that when the room temperature is kept at the occupied period set point. This challenges one of the major limitations of the modified bin method, which is based on time averaging techniques and does not take the thermal capacitance of the space into account.

However, based on the measured data in an office building on the Texas A&M University campus, where AHU shutdown has been implemented, it is found that the average room temperature during the unoccupied period has an approximate linear relationship with the average outside air temperature. This finding is used to estimate the average conduction load during the unoccupied period and is described in Appendix A.

It is noted that the relationship can vary from building to building depending on the building's size, construction, internal heat gain, etc. Nevertheless, the obtained relationship is made default in the implemented methodology in PESE Toolkit, which can be modified based on engineering considerations to make a best estimation.

3.2.7 Air-side Simulation Models

The air-side simulation models employed in Baltazar's methodology largely came from the SEAP, which was developed by ASHRAE TC4.7 and described in Knebel (1983). These models are inherited in this thesis. However, several significant modifications have been made in order to correctly represent the performance of the systems in optimization, because the SEAP models are developed to represent typical operating conditions.

For example, in dual duct systems, such a condition can occur in summer that the hot deck leaving air temperature is set back to as low as 70°F, while outside air is 90°F and room temperature is set at 75°F. The hot deck entering temperature (76.5°F assuming outside air fraction is 10%) is higher than the leaving air temperature set point. Using the SEAP models in such a case will lead to a mistake that the leaving air temperature equals the set point and thus hot deck has virtually cooled the air down from 76.5°F to 70°F; but in reality the leaving air temperature equals the entering temperature.

The SEAP models for SDVAV system only account for cooling mode. Therefore, model equations are added for heating mode with a limit (120°F) added for terminal box maximum supply temperature. With the modified model, minimum airflow during unoccupied period can be set to zero.

Additionally, since the value ranges of certain optimization parameters can overlap sometimes and lead to meaningless result, error handling equations are added in the modified models. For example, room temperature set points cannot be lower than cold deck leaving air temperature or higher than hot deck leaving air temperature, outside airflow cannot be larger than total airflow, total airflow cannot be larger than total design airflow, etc. The modified models for each type of system can be found in the following functions in Appendix G: f_CVTR, f_DDCV, f_SDVAV, and f_DDVAV.

4. PESE (Potential Energy Saving Estimation) TOOLKIT

4.1 Overview

The PESE Toolkit is a prototype computer tool designed for estimating potential energy use cost savings (including electricity cost, cooling cost and heating cost) theoretically achievable by optimizing certain control parameters in the HVAC system of a given commercial building. It is developed based on Baltazar's methodology with several major improvements explained in section 3.2. The tool is expected to help engineers mainly in the Level I analysis in a retro-commissioning assessment or an energy audit to identify no-cost/low-cost ECMs with corresponding savings estimated. For this purpose, only limited information about the building and its HVAC system is required to use the tool. It is developed with Visual Basic for Application (VBA) programming language, and the interface for input and output is based on Microsoft® Excel 2003 spreadsheets. The following is a list of important features included in the prototype version of the PESE Toolkit:

- Input interface to specify building and system parameters and optimization constraints.
- No separate calculation of space cooling and heating load is required. The user only needs to input information regarding building location and dimensions, internal heat gain, weather and thermal properties of the envelope in order to perform the load calculation procedure.

- A maximum of five optimization parameters are provided (refer to section 3.2.1). The user can decide which ones to activate for optimization depending on the system configuration (e.g. pneumatic control or DDC control, availability of a flow sensor for outside air intake). With none of the optimization parameters activated, a simulation without optimization will be executed, which can be used for the purpose of calibration to measured consumption data or checking the impact on energy use of changing certain parameters. This feature of simulation is not required in performing potential energy savings estimation.
- Air-side simulation models of four common HVAC systems are provided: Single Duct Constant Volume (SDCV) system, Dual Duct Constant Volume (DDCV) system, Single Duct Variable Air Volume (SDVAV) system, and Dual Duct Variable Air Volume (SDVAV) system.
- Common HVAC system configuration and control options are provided, such as preheat and reheat type (electric or using hot water), and control method of minimum outside air intake.
- Comprehensive output for each bin is provided to the user including energy costs and savings, energy consumption, space loads, system loads and parameters. Most of them are also illustrated in plots versus bin temperature for easy analysis.

4.2 Input

There is a worksheet named “Input” in PESE, where the user can type in all the necessary information about the building, the HVAC system and optimization options.

Required building information is categorized as general (location, orientation, dimensions, exterior and interior zone areas, etc.), internal heat gain (occupancy, lighting and equipment electricity use), weather (parameters for solar heat gain calculation) and envelope (window area fractions, U-values, SC-values, colors). Required HVAC system information comprises system type, preheat and reheat type, whether AHUs are shut down during unoccupied periods, fractions of exterior and interior zone area served by the system being evaluated, zone temperature set points, design supply air flows, cold deck and hot deck reset schedules, fan powers, and outside air control settings. For VAV systems, additional input for the VAV mechanism and minimum supply air flows are also necessary. Required optimization options are the parameters chosen to be activated for optimization, the range of values and grid division of these parameters during occupied and unoccupied period, energy prices and indoor relative humidity restraints for occupied period. It should be noted that for the parameters activated for optimization, the input of the current setting in the system information section is not required.

PESE also requires input of weather data and measured energy consumption data (electricity, chilled water and hot water) for each bin during occupied and unoccupied period respectively. The worksheet named “BinData” is for this part of the input. Since the required weather data including dry-bulb temperature and humidity ratio in the form of bins can rarely be found prepared, a “bin sorting” process is usually necessary. Appendix D gives an example of a bin sorting procedure. Examples of input interface can be found in the case studies in Section 5.

4.3 Output

The "BinData" worksheet holds not only the input but also the output for each bin during occupied and unoccupied periods. The output comprises several sections: energy costs (current and optimized), potential energy cost savings (in dollars and percentage), optimized energy consumption, space loads (including components), HVAC system loads (cooling, heating and fan power) and system parameters (temperatures, air flow rates and fractions, humidity ratios, etc.).

For easy interpretation and analysis of the results, PESE provides plots of most of the above results versus bin temperature. There are five chart sheets in PESE named "Savings", "OCP_Cons&Load", "OCP_SysPar", "UNOCP_Cons&Load" and "UNOCP_SysPar" representing the following categories of output: (1) energy cost and saving during occupied and unoccupied period; (2) consumption values, system and space loads during occupied period; (3) system parameters during occupied period; (4) consumption values, system and space loads during unoccupied period and (5) system parameters during unoccupied period. Detailed output parameters and examples of output chart sheets are provided in Appendix E.

4.4 Models and Program Structure

The load calculation procedure is described in Appendix B, and air-side simulation models can be found in Appendix G along with nomenclature explained in Appendix C. In addition, the program structure and flow charts are found in Appendix F, and the VBA codes implemented in the tool are enclosed in Appendix G.

5. CASE STUDIES

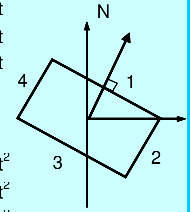
Preliminary testing of the improved methodology implemented in the PESE Toolkit is conducted in case studies of two buildings on the Texas A&M University campus, which have been retro-commissioned in the recent two years. The case of Sanders Corps of Cadets Center is studied to understand the optimization resulting from single parameter optimization; while the Coke Building is selected to show an example of how this methodology can be applied to buildings where the built-in HVAC system has more than one AHU type.

5.1 Sam Houston Sanders Corps of Cadets Center

The Sanders Corps of Cadets Center is a single story building located on the main campus of Texas A&M University with a total area of 19,363 square feet. The building consists of a large display hall, offices, a small library and conference room. It is generally open between 8:00 AM and 5:00 PM Monday through Friday except on holidays. The HVAC system is a single duct variable air volume (SDVAV) system with terminal reheat VAV boxes. There is only one air handling unit (AHU) to serve the whole building. Commissioning measures were implemented in this building by 11/2/2007.

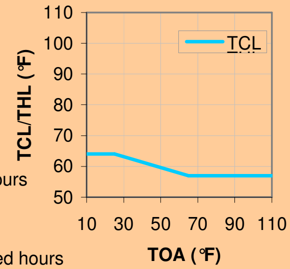
BUILDING INFORMATION

General		
Name	Sanders Corps of Cadets Center	
City	College Station	
Latitude	30	°
Orientation (Wall# 1)	NE	
Length	180	ft
Width	110	ft
Height	15	ft
Above ground floors	1	
Has Basement	FALSE	
Basement conditioned	FALSE	
A_{tot}	19,800	ft^2
A_e	7,800	ft^2
A_i	12,000	ft^2
Internal Heat Gain		
Ocp_e	20	pep
Ocp_i	20	pep
AveOcpFactor (Ocp)	1.00	
AveOcpFactor (Unocp)	0.10	
LTEQ (Ocp)	54	kW
LTEQ (Unocp)	25	kW
Weather		
FPS_July	0.72	
FPS_January	0.48	
Tpc	107	°F
Tph	27	°F
$T_{o,des}$	86	°F
Envelope		
U-wall	0.09	Btu/(h·ft²·°F)
U-window	1.00	Btu/(h·ft²·°F)
U-roof	0.05	Btu/(h·ft²·°F)
U-ground	0.05	Btu/(h·ft²·°F)
A_{win}/A_{wall} 1	25.0%	
A_{win}/A_{wall} 2	15.0%	
A_{win}/A_{wall} 3	25.0%	
A_{win}/A_{wall} 4	15.0%	
$A_{skylights}$	0	ft^2
SC 1	0.45	
SC 2	0.15	
SC 3	0.20	
SC 4	0.25	
SC skylights	0.00	
Wall color	Medium colored	
Roof color	Dark colored	



SYSTEM INFORMATION

System Type	SDVAV				
Reheat Type	Hot Water				
Preheat Type	Hot Water				
Has Economizer	FALSE				
AHU shut off	FALSE				
Fraction of A_e	100.0%				
Fraction of A_i	100.0%				
Zone T set point during occupied hours					
T_{e_ocp}	72	°F			
T_{i_ocp}	72	°F			
Zone T reset point during unoccupied hours					
T_{e_unocp}	72	°F			
T_{i_unocp}	72	°F			
V_{TD}	27,545	cfm			
V_e		cfm			
V_i		cfm			
T_{CL} (setpoint 1)	64	°F	@ $T_{OA}1=$	25	°F
T_{CL} (setpoint 2)	57	°F	@ $T_{OA}2=$	65	°F
T_{HL} (setpoint 1)		°F	@ $T_{OA}1=$		°F
T_{HL} (setpoint 2)		°F	@ $T_{OA}2=$		°F
$P_{SF\text{-}rated}$	30	hp	η_{SF}	1	
$P_{RF\text{-}rated}$	0	hp	η_{RF}	1	
OA controlled by	VOAmin		VOA_{max}	4,500	cfm
X_{OA,min_ocp}			X_{OA,min_unocp}		
V_{OA,min_ocp}	700	cfm	V_{OA,min_unocp}	500	cfm
VAV systems					
VAV mechanism	Variable Speed Drive				
V_{e,min_ocp}	7,200	cfm	V_{e,min_unocp}	6,370	cfm
V_{i,min_ocp}	11,080	cfm	V_{i,min_unocp}	9,800	cfm



OPTIMIZATION OPTIONS

Variables	Select	Ocp:range&grid				Unocp:range&grid			
Te	FALSE (°F)	70	–	78	9	65	–	85	11
Ti	FALSE (°F)	68	–	72	5	65	–	85	11
TCL	FALSE (°F)	55	–	70	16	55	–	70	16
THL	FALSE (°F)	80	–	115	16	80	–	115	16
VOA	FALSE (cfm)	600	–	4,500	11	0	–	4,500	12

ELE Price	0.092	$/kWh
CHW Price	9.602	$/MMBtu
HHW Price	13.099	$/MMBtu
RHz1	10	%
RHz2	60	%

Figure 5.1 Building information, system information and optimization options input in the calibrated simulation for Sanders Corps of Cadets Center

In the following sections, the energy use under current condition is first simulated without optimization and calibrated to measured energy use. Next, energy savings are estimated using single parameter optimizations, i.e. optimizing one applicable parameter at a time, for easy understanding of the optimized profile of parameters and energy uses. Finally, potential energy savings are estimated by performing multiple parameter optimization, i.e. optimizing all the applicable parameters together. It is noted that single parameter optimization and the calibration process are not necessary in regular potential savings estimations, because usually all the uncertain parameters that are significant to energy use are to be optimized or re-designated.

5.1.1 Simulation without Optimization

The basic information about the building required in the simulation with the PESE Toolkit is collected by on-site investigation, and information about the HVAC system is provided with some parameters remaining uncertain. The following single parameter optimization requires the value of these parameters determined, which leads to a brief calibration process with the method of calibrated signatures developed by Wei et al. (1998). The calibrated input used in the simulation is given in Figure 5.1. One year of hourly weather and measured consumption data during 12/1/2007-1/31/2008 (post-CC®) are sorted into 5°F bins with occupied and unoccupied period distinguished, as shown in Figure 5.2. No parameter is selected for optimization at this point.

The adequacy of calibration is evaluated with three statistical parameters: Root Mean Square Error (RMSE), Mean Bias Error (MBE) and Coefficient of Variation of the RMSE (CV-RMSE). By adjusting the exterior and interior zone minimum air flow rates, cold deck leaving air temperature reset schedule and minimum outside air flow rates, the statistical parameters are reduced to acceptable level (as shown in Table 5.1): during occupied period, the CV-RMSE is around 10% for electricity and chilled water and 45%

for hot water; the MBE is less than 2 kW for electricity, 25 kBtu/hr for chilled water and -63 kBtu/hr for hot water; the values for the unoccupied period are much smaller. The simulated annual energy use and costs after calibration are given in Table 5.2 as the baseline for optimization.

BIN DATA INPUTS — OCCUPIED PERIOD

Outside air temperature (°F) TOA	Outside air humidity ratio - wOA	Zone relative humidity (%) RHOA	Hours of occurrence (hr) HOURS	Measured ELE consumption (kWh) ELE_Meas	Measured CHW consumption (kBtu) CHW_Meas	Measured HHW consumption (kBtu) HHW_Meas
27	0.001948	65.2	2	89	241	410
32	0.002618	69.5	5	255	912	1,246
37	0.003551	77.1	33	1,998	6,122	7,843
42	0.004116	73.4	56	3,651	11,484	12,516
47	0.004348	64.1	110	7,204	25,093	21,783
52	0.005150	62.9	112	7,262	27,096	21,622
57	0.005589	56.8	163	10,795	41,775	29,424
62	0.006464	54.9	192	12,654	52,277	31,724
67	0.008619	61.3	290	19,161	85,079	42,959
72	0.010431	62.3	351	23,177	109,389	47,778
77	0.012683	63.9	382	25,705	130,655	44,621
82	0.014488	61.8	374	25,465	137,366	37,379
87	0.014880	54.0	290	20,511	116,138	25,384
92	0.014615	45.4	282	20,020	123,951	22,089
97	0.013313	35.5	140	10,176	66,872	11,207
102	0.012134	27.9	11	816	5,560	1,003
107	0.012752	25.2	1	75	494	106

BIN DATA INPUTS — UNOCCUPIED PERIOD

Outside air temperature (°F) TOA	Outside air humidity ratio - wOA	Zone relative humidity (%) RHOA	Hours of occurrence (hr) HOURS	Measured ELE consumption (kWh) ELE_Meas	Measured CHW consumption (kBtu) CHW_Meas	Measured HHW consumption (kBtu) HHW_Meas
27	0.002106	70.5	11	379	1,559	2,471
32	0.002643	70.1	76	2,742	13,073	18,875
37	0.003461	75.2	186	6,660	33,911	43,205
42	0.003995	71.3	303	10,867	59,504	63,529
47	0.004601	67.8	378	13,139	77,720	73,090
52	0.005675	69.3	428	14,643	93,132	78,959
57	0.007088	71.9	445	14,865	102,549	75,314
62	0.008834	74.8	538	18,285	132,524	81,251
67	0.010686	75.7	646	21,702	168,176	90,246
72	0.013023	77.5	813	27,466	231,191	95,715
77	0.015470	77.6	1,030	35,245	339,699	96,825
82	0.015346	65.3	532	17,628	190,299	47,773
87	0.014747	53.5	298	8,741	111,242	24,767
92	0.014614	45.3	205	5,884	78,678	16,114
97	0.012826	34.2	82	2,444	33,005	6,635
102	0.010645	24.5	10	302	4,001	846

Figure 5.2 Bin data input in the calibrated simulation for Sanders Corps of Cadets Center

Table 5.1 Statistical parameters representing simulation errors before (top) and after (bottom) calibration for Sanders Corps of Cadets Center

		ELE	CHW	HHW
RMSE	OCP	7.2 (kW)	55.8 (kBtu/hr)	65.5 (kBtu/hr)
	UNOCP	6.1 (kW)	68.9 (kBtu/hr)	66.5 (kBtu/hr)
MBE	OCP	2.9 (kW)	39.9 (kBtu/hr)	-54.9 (kBtu/hr)
	UNOCP	4.8 (kW)	50.4 (kBtu/hr)	50.6 (kBtu/hr)
CV-RMSE	OCP	11.0 %	17.8 %	42.9 %
	UNOCP	18.2 %	25.2 %	44.7 %

		ELE	CHW	HHW
RMSE	OCP	6.7 (kW)	32.1 (kBtu/hr)	69.5 (kBtu/hr)
	UNOCP	4.0 (kW)	27.8 (kBtu/hr)	31.0 (kBtu/hr)
MBE	OCP	1.8 (kW)	25.2 (kBtu/hr)	-62.6 (kBtu/hr)
	UNOCP	1.5 (kW)	0.4 (kBtu/hr)	14.9 (kBtu/hr)
CV-RMSE	OCP	10.3 %	10.2 %	45.5 %
	UNOCP	11.9 %	10.2 %	20.8 %

Table 5.2 Baseline annual energy use and costs for Sanders Corps of Cadets Center

	ELE (kWh)	**CHW (MMBtu)**	**HHW (MMBtu)**	**ELE ($)**	**CHW ($)**	**HHW ($)**	**TOTAL ($)**
Occupied	186,789	1,018	204	17,185	9,775	2,671	29,630
Unoccupied	204,418	1,696	969	18,806	16,289	12,686	47,782
Total	391,208	2,714	1,172	35,991	26,064	15,357	77,412

5.1.2 Reset Minimum Airflow

Following the procedure described in section 3.2.2, it is determined that the exterior and interior zone minimum airflow during the occupied period in Sanders Building is reset from 7,200 cfm and 11,080 cfm to 3,820 cfm and 3,600 cfm respectively, and the minimum airflow during the unoccupied period is reset from 6,370 cfm and 9,800 cfm to zeros. These reset values are used in the following single and multiple parameter optimizations. Figure 5.3 compares the cooling, heating and fan power energy use before and after resetting the minimum airflow. The result shows that the savings that can be achieved from this resetting alone are very significant: 20% and 54% in total during occupied and unoccupied periods respectively as shown in Table 5.3.

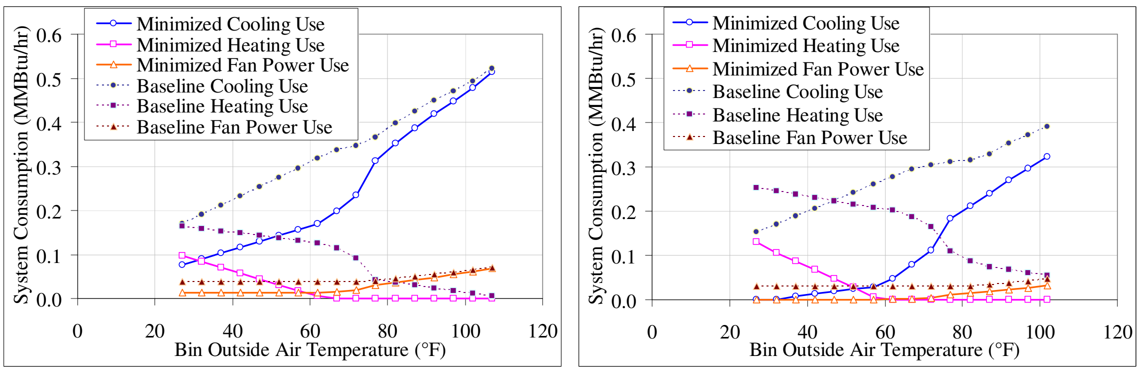


Figure 5.3 Cooling, heating and fan power consumption before and after resetting minimum airflow during occupied (left) and unoccupied (right) periods as a function of bin temperature for the Sanders Corps of Cadets Center

5.1.3 Single Parameter Optimization

Four out of the five available optimization parameters in PESE are applicable to this building. To better understand the effect on the energy use from each category of these parameters independently, they are grouped as follows to be activated for optimizations: exterior and interior zone temperature set points (T_e and T_i), cold deck leaving air temperature (T_{CL}), and outside airflow (V_{OA}). The lower and upper limiting values of each parameter as well as the number of grid division used in the optimization are given in Table 5.4. Savings achieved from each single parameter optimization and multiple parameter optimization are tabulated in Table 5.3 in comparison with resetting the minimum airflows; the same quantities are compared graphically in Figure 5.4. The profiles of optimized parameter settings as functions of ambient temperature during occupied and unoccupied periods are given in Figure 5.5. The optimized cooling, heating and fan power energy use in comparison with only resetting the minimum airflow is illustrated in Figure 5.6.

Table 5.3 Annual savings from resetting the minimum airflow, single parameter optimization and multiple parameter optimization for the Sanders Corps of Cadets Center

			ELE		CHW		HHW		TOTAL	
			($)	(%)	($)	(%)	($)	(%)	($)	(%)
Occupied	Only Reset Minimum Flow		1,166	7	2,199	22	2,432	91	5,796	20
	Single Parameter Optimization	T_e, T_i	1,782	10	2,909	30	2,536	95	7,228	24
		T_{CL}	1,494	9	2,334	24	2,516	94	6,344	21
		V_{OA}	1,166	7	2,795	29	2,431	91	6,392	22
	Multiple Parameter Optimization		1,964	11	3,525	36	2,565	96	8,054	27
Unoccupied	Only Reset Minimum Flow		3,990	21	9,962	61	11,651	92	25,603	54
	Single Parameter Optimization	T_e, T_i	4,932	26	13,502	83	12,235	96	30,669	64
		T_{CL}	4,169	22	10,030	62	11,729	92	25,928	54
		V_{OA}	3,990	21	10,943	67	11,634	92	26,567	56
	Multiple Parameter Optimization		4,875	26	14,381	88	12,306	97	31,562	66

Table 5.4 Optimization parameter setting limits for the Sanders Corps of Cadets Center

Opt. Parameter		Unit	Lower Limit	Upper Limit	Grid Division	Notes
Occupied	T_e	°F	70	78	9	ASHRAE design criteria for Office
	T_i	°F	68	72	5	ASHRAE design criteria for Museums and Galleries
	T_{CL}	°F	55	70	16	Commonly used on TAMU campus
	V_{OA}	cfm	600	4,500	11	Lower limit: Standard 62.1-2007 Upper limit: OA duct limit
Unoccupied	T_e	°F	65	85	11	Commonly used on TAMU campus
	T_i	°F	65	85	11	
	T_{CL}	°F	55	70	16	
	V_{OA}	cfm	0	4,500	12	Lower limit: Commonly used on TAMU campus

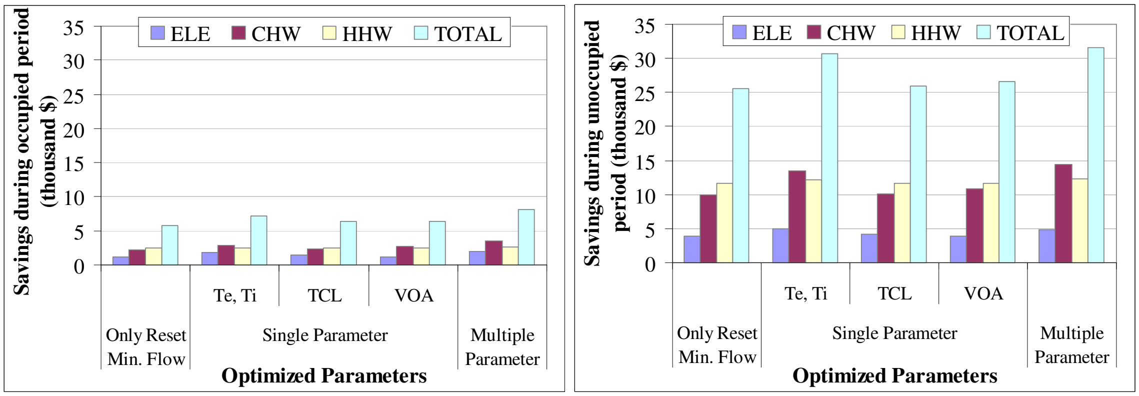


Figure 5.4 Comparison of annual savings from resetting the minimum airflow, single parameter optimizations and multiple parameter optimization for the Sanders Corps of Cadets Center

The results reveal that there are not significant extra savings (1%-4%) from each single parameter optimization during the occupied period in addition to that achieved from only resetting the minimum airflows. This also holds true for the unoccupied period except that an extra 10% of total savings is possible by optimizing the zone temperatures. This meets expectation because post-CC® data is used in the simulation, and these optimization parameters are among the typical CC® measures on campus. For both periods, greatest total savings come from optimizing the zone temperatures (24% for occupied and 64% for unoccupied). The savings from optimizing cold deck leaving air temperature (21% and 54%) and outside airflow (22% and 56%) are equivalent.

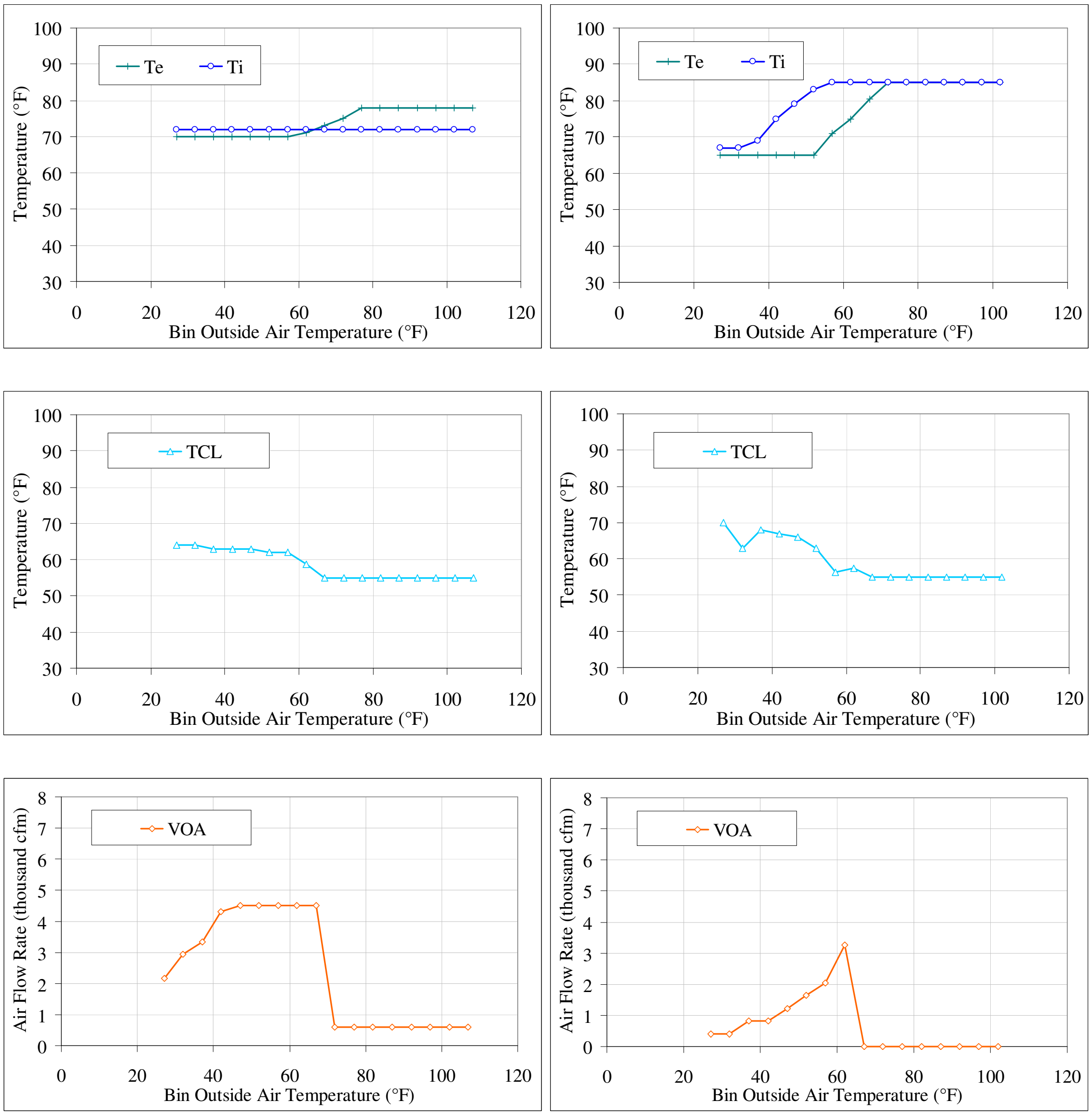


Figure 5.5 Optimized parameter settings from single parameter optimizations during occupied (left) and unoccupied (right) periods as a function of bin temperature for the Sanders Corps of Cadets Center

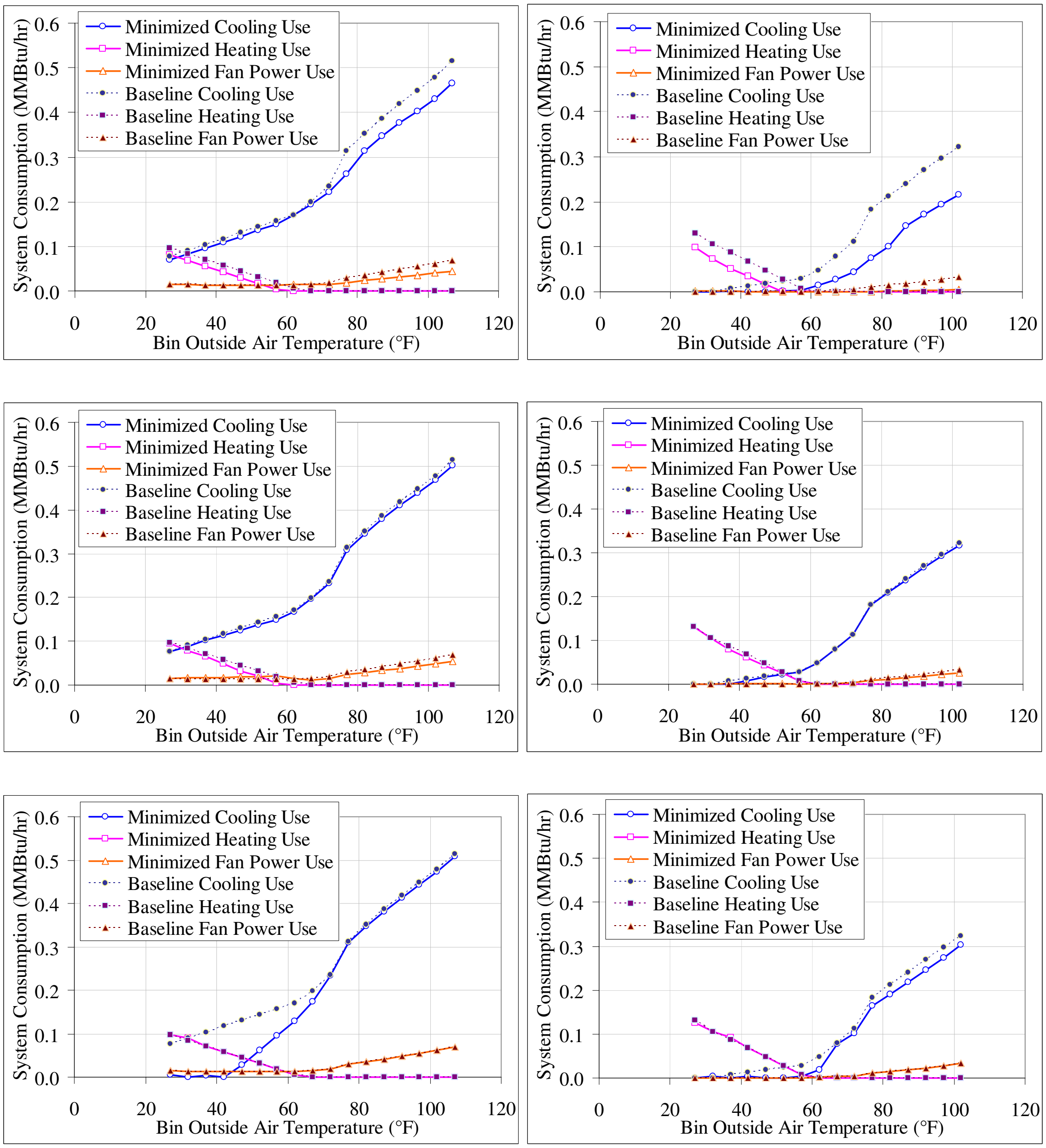


Figure 5.6 Cooling, heating and fan power consumption before (only resetting minimum airflows) and after single parameter optimizations during occupied (left) and unoccupied (right) periods as a function of bin temperature for the Sanders Corps of Cadets Center

5.1.3.1 Zone Temperature Set Points Optimization

There are two main ways in which the exterior and interior zone temperature set point could affect the total energy cost: (1) Minimizing indoor and outdoor temperature difference can significantly reduce space heating and sensible cooling loads. Figure 5.7 shows the comparison of space sensible heating and cooling load before and after optimizing zone temperature set points. (2) When supply airflow is higher than minimum value in cooling mode, a higher return air temperature requires smaller supply airflow and saves fan power on one hand; it increases cooling coil sensible load on the other hand. The former is more dominant in the range selected for optimization since the electricity price is nearly three times of the chilled water price for the same amount of energy.

The optimized exterior zone temperature set point stays at the lower limit (70°F), which reduces space heating load, when outside air temperature is lower than 57°F and 52°F during occupied and unoccupied periods respectively. It gradually rises to the upper limit (78°F) at the 82°F bin and the 72°F bin respectively. The increased exterior zone temperature at higher ambient temperatures has reduced space cooling load significantly.

The optimized interior zone temperature set point stays at its upper limit (72°F) constantly during the occupied period; it increases from 67°F at the 32°F bin to its upper limit (85°F) at the 57°F bin during the unoccupied period, and the space cooling load is significantly reduced. During both periods, the interior zone supply airflow is always higher than the minimum value. Consequently, a higher temperature set point is preferred to save fan power, except for a few low temperature bins during the unoccupied period where the cooling load is light. The effect of reducing cooling coil sensible load from a lower return air temperature more than offsets the slightly increased fan power.

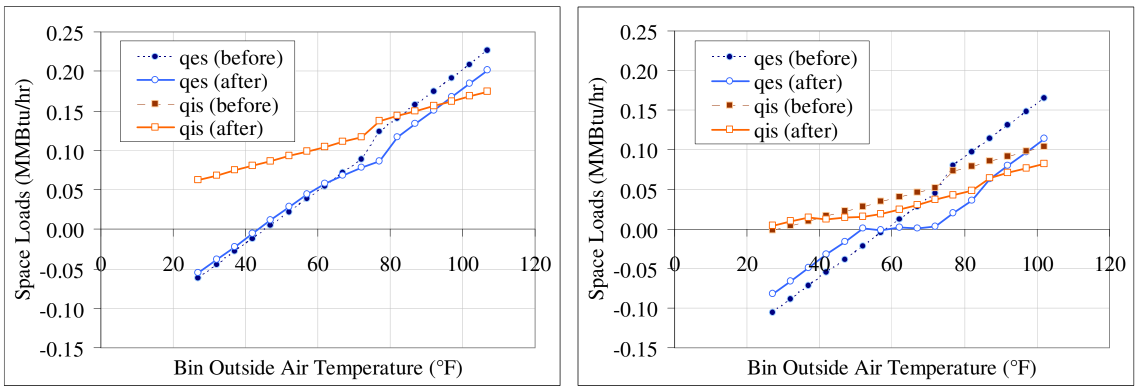


Figure 5.7 Exterior and interior zone sensible space loads before and after optimizing zone temperature set points during occupied (left) and unoccupied (right) periods as a function of bin temperature for the Sanders Corps of Cadets Center

5.1.3.2 Cold Deck Leaving Air Temperature Optimization

The optimized cold deck leaving air temperature (T_{CL}) decreases with increasing bin temperature in general during both occupied and unoccupied periods. There are three major principles driving this optimization result in both the exterior and interior zones: (1) In cooling mode at minimum airflow, reheating and sensible cooling energy could be saved if T_{CL} is set higher; (2) In cooling mode when airflow exceeds the minimum, fan power could be saved if T_{CL} is set lower; (3) In heating mode, reheating energy could be saved if T_{CL} is set higher.

The optimized T_{CL} reset profile during the occupied period gradually decreases from 64°F to the lower limit (55°F) at 67°F. At 62°F and lower, the exterior zone airflow stays at its minimum which favors a higher T_{CL}, while the interior zone airflow exceeds minimum which favors a lower T_{CL}. The optimized profile is the result of a balance between these two factors, and as the outside temperature goes lower the second factor becomes more dominant. At 67°F and higher, both exterior and interior zone airflows exceed their minimums, which lead to the optimized T_{CL} staying at its lower limit (55°F).

The optimized T_{CL} reset profile during the unoccupied period is also decreasing from lower to higher temperature bins in general. At 27°F, both the exterior and interior zones are in heating mode; thus the optimized T_{CL} goes to its upper limit (70°F). As the ambient temperature increases to 57°F, the exterior zone is still in heating while the interior zone is in cooling and its airflow exceeds the minimum flow. The optimized profile is the result of a balance between the two factors. At 62°F and higher, both zones are in the cooling mode which brings T_{CL} to its lower limit (55°F).

5.1.3.3 Outside Airflow Optimization

The optimization result shows that as the ambient temperature increases, the outside airflow drops to its lower limit at 72°F and 67°F during occupied and unoccupied periods respectively, where latent loads appear. It drops one bin earlier during the unoccupied period since the mean coincidental outside air relative humidity is higher than during the occupied period. At lower temperature bins, making use of outside air for free cooling can significantly reduce mixed air temperature and save cooling coil sensible load. However, as outside air temperature gets lower, preheating energy will be required when taking full outside air. As a result, during the occupied period, the optimized outside airflow reaches upper limit (4,500 cfm) from 47°F-67°F and decreases at lower temperatures to 2,160 cfm (at bin 27°F); during the unoccupied period, it gradually increases from 400 cfm (at 27°F) to 3,300 cfm (at 62°F) without ever reaching the upper limit, because the total airflow is much smaller than during the occupied period.

5.1.4 Multiple Parameter Optimization

A full fledged optimization with all of the above four parameters activated is performed with the same setting limits stated in Table 5.4. The potential savings obtainable from this multiple parameter optimization is listed in Table 5.3 and illustrated in Figure 5.4 in comparison with only resetting minimum airflow and the single parameter optimizations. An extra 7% and 12% total savings during occupied and unoccupied periods respectively are possible in addition to the savings achieved from resetting minimum airflow. For all of the energy use categories, the savings from multiple parameter optimization (ELE: 11% and 26%, CHW: 36% and 88%, HHW: 96% and 97%) are just slightly higher than the largest savings from single parameter optimizations, which in this case is by optimizing the zone temperatures. Figure 5.8 gives the profiles of optimized parameter settings during both the occupied and unoccupied periods. Figure 5.9 shows the optimized cooling, heating and fan power energy use compared with only resetting minimum airflow.

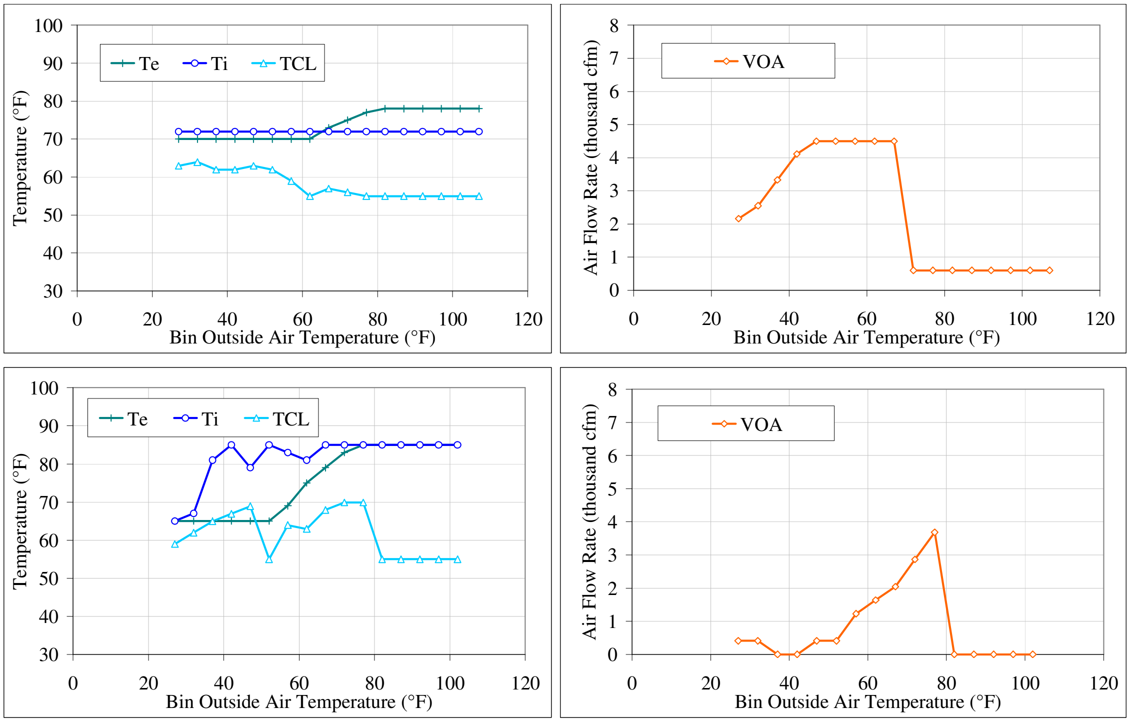


Figure 5.8 Optimized parameter settings from multiple parameter optimizations during occupied (top) and unoccupied (bottom) periods as a function of bin temperature for the Sanders Corps of Cadets Center

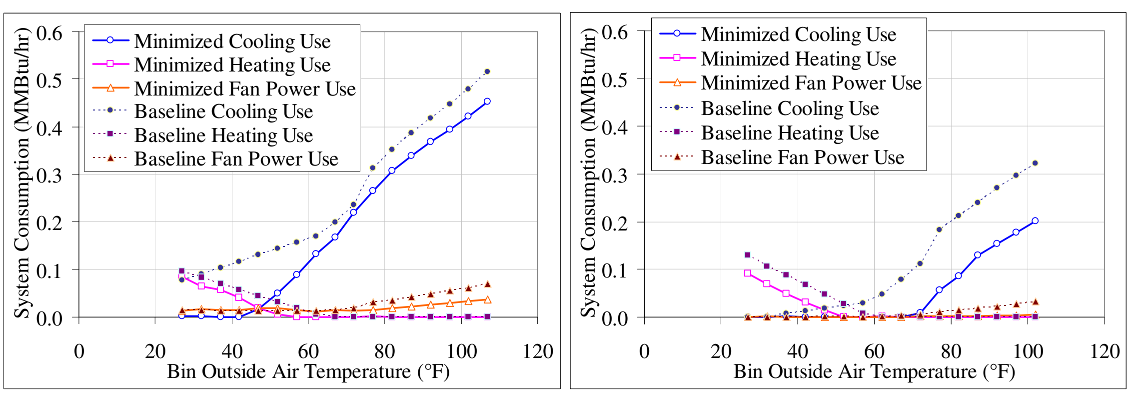


Figure 5.9 Cooling, heating and fan power consumption before (only resetting minimum airflows) and after multiple parameter optimizations during occupied (left) and unoccupied (right) periods as a function of bin temperature for the Sanders Corps of Cadets Center

5.2 Coke Building

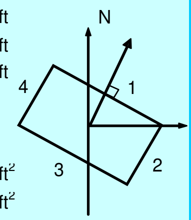
The Coke Building is located on the main campus of Texas A&M University with a total area of 24,446 square feet. It has three stories (including a half-underground basement) consisting of offices and conference rooms. The building is generally occupied weekdays from 8:00 AM to 5:00 PM. The HVAC system consists of one multizone unit (AHU1) serving the basement, one single duct VAV unit (AHU2) serving the first floor, two single duct VAV rooftop units (RTU1 and RTU 2) serving the second floor and one outside air pre-treat unit (OAHU) serving AHU1 and AHU 2. Electric strips are used as heaters in the terminal boxes associated with the SDVAV systems. Retro-commissioning measures have been implemented in this building since 7/15/2008. Since retro-commissioning, the HVAC system is turned off during the unoccupied period at 10:00 PM and turned on again around 6:00 AM the next morning.

5.2.1 Building Simulation

The simulation of the Coke Building is selected as an example of how to implement this methodology in buildings where more than one type of system is in place. In this case, simulation and optimization is required for each individual system. Therefore, the simulation for the Coke Building is divided into two parts: simulation of the multizone system and of the SDVAV system combining AHU2 and the two RTUs. In the implemented methodology, the space load is first calculated for the whole building and then divided according to the service area of each system. Calibration is only performed on the occupied period since the system is shut off at night and on weekends. The calibrated inputs used in both simulations are given in Figure 5.10.

BUILDING INFORMATION

General		
Name	Coke	
City	College Station	
Latitude	30	°
Orientation (Wall# 1)	NE	
Length	120	ft
Width	67	ft
Height	27	ft
Above ground floors	2	
Has Basement	TRUE	
Basement conditioned	TRUE	
A_{tot}	24,120	ft^2
A_e	11,736	ft^2
A_i	12,384	ft^2



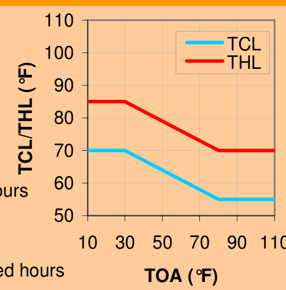
Internal Heat Gain		
Ocp_e	40	pep
Ocp_i	30	pep
AveOcpFactor (Ocp)	1.00	
AveOcpFactor (Unocp)	0.00	
LTEQ (Ocp)	32	kW
LTEQ (Unocp)	25	kW

Weather		
FPS_July	0.72	
FPS_January	0.48	
Tpc	107	°F
Tph	27	°F
$T_{o,des}$	86	°F

Envelope		
U-wall	0.09	Btu/(h·ft²·°F)
U-window	1.00	Btu/(h·ft²·°F)
U-roof	0.05	Btu/(h·ft²·°F)
U-ground	0.05	Btu/(h·ft²·°F)
A_{win}/A_{wall} 1	14.5%	
A_{win}/A_{wall} 2	10.5%	
A_{win}/A_{wall} 3	27.0%	
A_{win}/A_{wall} 4	13.0%	
$A_{skylights}$	0	ft^2
SC 1	0.65	
SC 2	0.70	
SC 3	0.45	
SC 4	0.70	
SC skylights	0.00	
Wall color	Medium colored	
Roof color	Dark colored	

SYSTEM INFORMATION

System Type	DDCV				
Reheat Type	Hot Water				
Preheat Type	Hot Water				
Has Economizer	FALSE				
AHU shut off	TRUE				
Fraction of A_e	33.3%				
Fraction of A_i	33.3%				



Zone T set point during occupied hours					
T_{e_ocp}	75 °F				
T_{i_ocp}	75 °F				
Zone T reset point during unoccupied hours					
T_{e_unocp}	°F				
T_{i_unocp}	°F				
V_{TD}	7,350 cfm				
V_e	3,575 cfm				
V_i	3,775 cfm				
T_{CL} (setpoint 1)	70 °F	@	$T_{OA}1=$	30 °F	
T_{CL} (setpoint 2)	55 °F	@	$T_{OA}2=$	80 °F	
T_{HL} (setpoint 1)	85 °F	@	$T_{OA}1=$	30 °F	
T_{HL} (setpoint 2)	70 °F	@	$T_{OA}2=$	80 °F	
$P_{SF\text{-}rated}$	10 hp				
$P_{RF\text{-}rated}$	0 hp				
OA controlled by	VOAmin		VOA_{max}	880 cfm	
X_{OA,min_ocp}			X_{OA,min_unocp}		
V_{OA,min_ocp}	600 cfm		V_{OA,min_unocp}	0 cfm	
VAV systems					
VAV mechanism	Variable Speed Drive				
V_{e,min_ocp}	cfm		V_{e,min_unocp}	cfm	
V_{i,min_ocp}	cfm		V_{i,min_unocp}	cfm	

OPTIMIZATION OPTIONS

Variables	Select	Ocp:range&grid				Unocp:range&grid			
Te	FALSE (°F)	70	–	78	9	65	–	85	11
Ti	FALSE (°F)	70	–	78	9	65	–	85	11
TCL	FALSE (°F)	55	–	70	16	55	–	70	16
THL	FALSE (°F)	70	–	110	21	70	–	110	21
VOA	FALSE (cfm)	600	–	880	4	0	–	880	10

ELE Price	0.092	\$/kWh
CHW Price	9.602	\$/MMBtu
HHW Price	13.099	\$/MMBtu
RHz1	10	%
RHz2	60	%

Figure 5.10 Building information, system information (first: multizone, second: SDVAV) and optimization options input in the calibrated simulation for the Coke Building

SYSTEM INFORMATION						
System Type	SDVAV					
Reheat Type	Electric					
Preheat Type	Electric					
Has Economizer	FALSE					
AHU shut off	TRUE					
Fraction of A_e	66.7%					
Fraction of A_i	66.7%					
Zone T set point during occupied hours						
T_{e_ocp}	73	°F				
T_{i_ocp}	73	°F				
Zone T reset point during unoccupied hours						
T_{e_unocp}		°F				
T_{i_unocp}		°F				
V_{TD}	20,615	cfm				
V_e	10,030	cfm				
V_i	10,585	cfm				
T_{CL} (setpoint 1)	60	°F	@	$T_{OA}1=$	40	°F
T_{CL} (setpoint 2)	55	°F	@	$T_{OA}2=$	80	°F
T_{HL} (setpoint 1)		°F	@	$T_{OA}1=$		°F
T_{HL} (setpoint 2)		°F	@	$T_{OA}2=$		°F
$P_{SF\text{-}rated}$	30	hp				
$P_{RF\text{-}rated}$	0	hp				
OA controlled by	VOAmin			VOA_{max}	3,180	cfm
X_{OA,min_ocp}				X_{OA,min_unocp}		
V_{OA,min_ocp}	2,500	cfm		V_{OA,min_unocp}	0	cfm
VAV systems						
VAV mechanism	Variable Speed Drive					
V_{e,min_ocp}	3,600	cfm		V_{e,min_unocp}		cfm
V_{i,min_ocp}	3,600	cfm		V_{i,min_unocp}		cfm

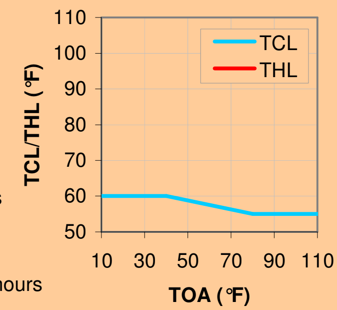


Figure 5.10 Continued

Additionally, a new method based on energy balance and the regression relationship between measured room temperature and outside temperature is used for the simulation of the unoccupied period. This method is developed as an approximation of the space load in the building and therefore does not allow for optimization of system parameters. It is incorporated in the PESE toolkit and explained in Appendix A. One year of hourly weather and measured consumption data from 7/16/2008-7/15/2009 (post-CC®) is used for bin sorting, as shown in Figure 5.11.

Several factors have contributed to the substantial amount of energy consumption during unoccupied period, as shown in Figure 5.11. (1) The significant hours included in unoccupied period in a year; (2) the consumption during start-up is included; (3) when room temperature reaches limiting setting (65°F and 85°F), the AHUs are turned back on; (4) during the last several months in the selected year, one of the AHUs was not shut off.

BIN DATA INPUTS — OCCUPIED PERIOD

Outside air temperature (°F) TOA	Outside air humidity ratio - wOA	Zone relative humidity (%) RHOA	Hours of occurrence (hr) HOURS	Measured ELE consumption (kWh) ELE_Meas	Measured CHW consumption (kBtu) CHW_Meas	Measured HHW consumption (kBtu) HHW_Meas
27	0.001246	41.8	1	84	41	28
32	0.002703	71.7	42	3,202	1,665	1,083
37	0.003146	68.3	65	4,824	3,744	1,981
42	0.003816	68.1	63	4,744	4,834	1,614
47	0.003599	53.1	83	5,330	5,531	1,344
52	0.004202	51.4	113	6,757	8,949	1,398
57	0.004694	47.8	157	8,588	14,287	1,487
62	0.006098	51.8	217	11,307	25,646	1,309
67	0.008071	57.4	313	15,329	45,095	1,167
72	0.009421	56.4	393	19,546	73,070	1,137
77	0.011322	57.2	434	21,694	113,882	689
82	0.013307	56.8	420	21,091	143,483	250
87	0.013848	50.3	373	19,112	145,362	89
92	0.014184	44.0	270	14,003	120,542	45
97	0.013191	35.2	192	10,015	90,958	28
102	0.011606	26.7	74	4,123	35,419	15
107	0.012752	25.2	1	56	600	0

BIN DATA INPUTS — UNOCCUPIED PERIOD

Outside air temperature (°F) TOA	Outside air humidity ratio - wOA	Zone relative humidity (%) RHOA	Hours of occurrence (hr) HOURS	Measured ELE consumption (kWh) ELE_Meas	Measured CHW consumption (kBtu) CHW_Meas	Measured HHW consumption (kBtu) HHW_Meas
27	0.002405	80.5	10	331	192	156
32	0.002694	71.5	110	3,391	2,130	1,245
37	0.002923	63.5	166	4,844	3,775	1,588
42	0.003406	60.8	262	7,320	6,242	1,524
47	0.004065	60.0	320	8,506	7,134	1,298
52	0.005160	63.0	350	9,184	10,017	857
57	0.006641	67.4	442	11,581	15,624	1,091
62	0.008425	71.4	560	14,297	22,448	839
67	0.010646	75.5	695	18,652	40,410	1,374
72	0.012719	75.7	710	19,523	55,586	836
77	0.014977	75.2	887	24,399	86,472	423
82	0.015146	64.5	523	14,499	53,039	93
87	0.014308	52.0	243	6,937	28,190	32
92	0.013931	43.3	148	4,325	21,026	27
97	0.012868	34.3	81	2,324	11,940	11
102	0.011502	26.4	42	1,274	7,278	9

Figure 5.11 Bin data input in the calibrated simulation for the Coke Building

By adjusting discharge air temperature reset schedules in both systems among a few other system parameters, the CV-RMSE for electricity, chilled water and hot water is reduced to 8.9%, 13.9% and 38% respectively, and the corresponding MBEs are -2.1 kW, 10.9 kBtu/hr and -1.7 kBtu/hr as shown in Table 5.5. The simulated annual consumption of each system during occupied and unoccupied periods is listed in Table 5.6 as the baseline for optimization.

Table 5.5 Statistical parameters representing simulation errors before (top) and after (bottom) calibration for the Coke Building during occupied period

	ELE	CHW	HHW
RMSE	8.5 (kW)	49.2 (kBtu/hr)	6.1 (kBtu/hr)
MBE	0.4 (kW)	23.7 (kBtu/hr)	1.4 (kBtu/hr)
CV-RMSE	14.4 %	21.5 %	63.1 %

	ELE	CHW	HHW
RMSE	5.3 (kW)	31.7 (kBtu/hr)	3.7 (kBtu/hr)
MBE	-2.1 (kW)	10.9 (kBtu/hr)	-1.7 (kBtu/hr)
CV-RMSE	8.9 %	13.9 %	38.0 %

Table 5.6 Baseline annual energy use and costs for the Coke Building

		ELE (kWh)	**CHW (MMBtu)**	**HHW (MMBtu)**	**ELE ($)**	**CHW ($)**	**HHW ($)**	**TOTAL ($)**
Occupied	Multizone	58,161	286	7	5,351	2,744	90	8,185
	SDVAV	111,898	631	0	10,295	6,055	0	16,350
	Total	170,059	916	7	15,645	8,799	90	24,535
Unoccupied	Multizone	49,117	122	15	4,519	1,174	192	5,885
	SDVAV	106,788	263	0	9,825	2,528	0	12,353
	Total	155,905	386	15	14,343	3,702	192	18,237
Total		325,964	1,302	22	29,989	12,502	282	42,772

5.2.2 Reset Minimum Airflow

Following the procedure described in section 3.2.2, it is determined that the exterior and interior zone minimum airflows within the SDVAV system during the occupied period in the Coke Building is reset from 3,600 cfm to 2,730 cfm and 2,480 cfm respectively. These reset values will be used in the following optimizations. Simulation results reveal that 14% of total energy use during the occupied period can be saved from this measure alone, as shown in Table 5.7. Figure 5.12 also gives the comparison of cooling, heating and fan power energy use bin profiles before and after the reset.

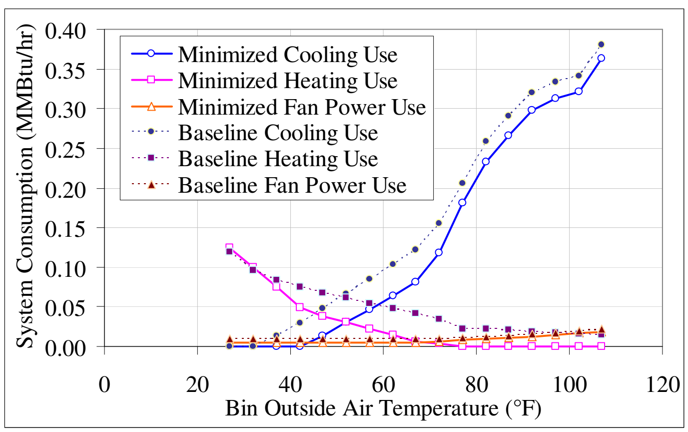


Figure 5.12 Cooling, heating and fan power consumption before and after resetting minimum airflow during the occupied period as a function of bin temperature for the Coke Building

5.2.3 Multiple Parameter Optimization

Multiple parameter optimization is performed on each system with the setting limits listed in Table 5.8. The savings obtained are given in Table 5.7 and compared with savings from only resetting the minimum airflow in the SDVAV system as shown in

Figure 5.13. It is observed that for the SDVAV system, there is 10% additional potential beyond the savings by resetting the minimum airflow (14%); however, for the multizone system, the room for potential savings is very limited (2%). Among the total savings predicted, an equivalent amount of money (around $3,200) is saved in electricity and chilled water use, and hot water use is all saved although the absolute amount is minimal. The profiles of optimized system parameter settings versus bin temperature are shown in Figure 5.14, and the profiles of optimized cooling, heating and fan power energy use compared with baseline energy use are given in Figure 5.15.

Table 5.7 Annual savings during occupied period from multiple parameter optimization compared with only resetting minimum airflow with the SDVAV system for the Coke Building

		ELE		**CHW**		**HHW**		**TOTAL**	
		($)	**(%)**	**($)**	**(%)**	**($)**	**(%)**	**($)**	**(%)**
Only Reset Minimum Flow		2,472	16	889	10	0	0	3,360	14
Multiple Parameter Optimization	Multizone	0	0	431	5	89	99	521	2
	SDVAV	3,219	21	2,789	32	0	0	6,009	24
	Total	3,219	21	3,221	37	89	99	6,529	27

Table 5.8 Optimization parameter setting limits for the Coke Building

Opt. Parameter		**Unit**	**Lower Limit**	**Upper Limit**	**Grid Division**	**Notes**
Multizone	T_e	°F	70	78	9	ASHRAE design criteria for Office
	T_i	°F	70	78	9	
	T_{CL}	°F	55	70	16	Commonly used on TAMU campus
	T_{HL}	°F	70	110	41	
SDVAV	T_e	°F	70	78	9	Commonly used on TAMU campus
	T_i	°F	70	78	9	
	T_{CL}	°F	55	70	16	
	V_{OA}	cfm	1,200	3,180	6	Lower limit: Standard 62.1-2007 Upper limit: OA duct limit

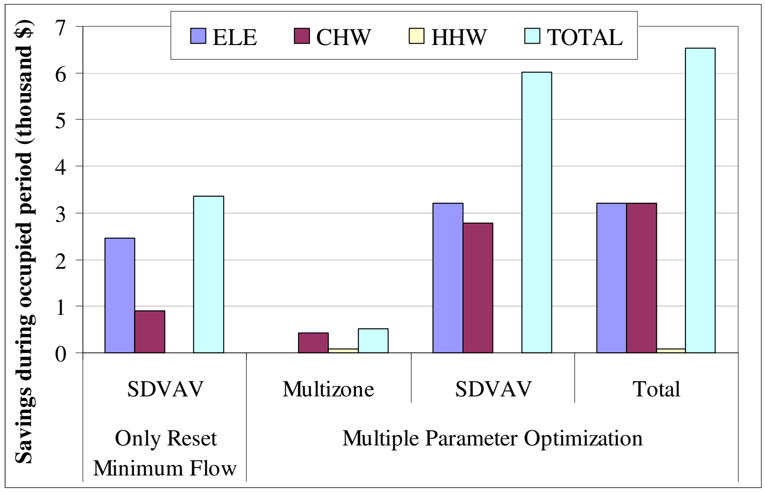


Figure 5.13 Comparison of annual savings during occupied period from multiple parameter optimization and only resetting minimum airflow with the SDVAV system for the Coke Building

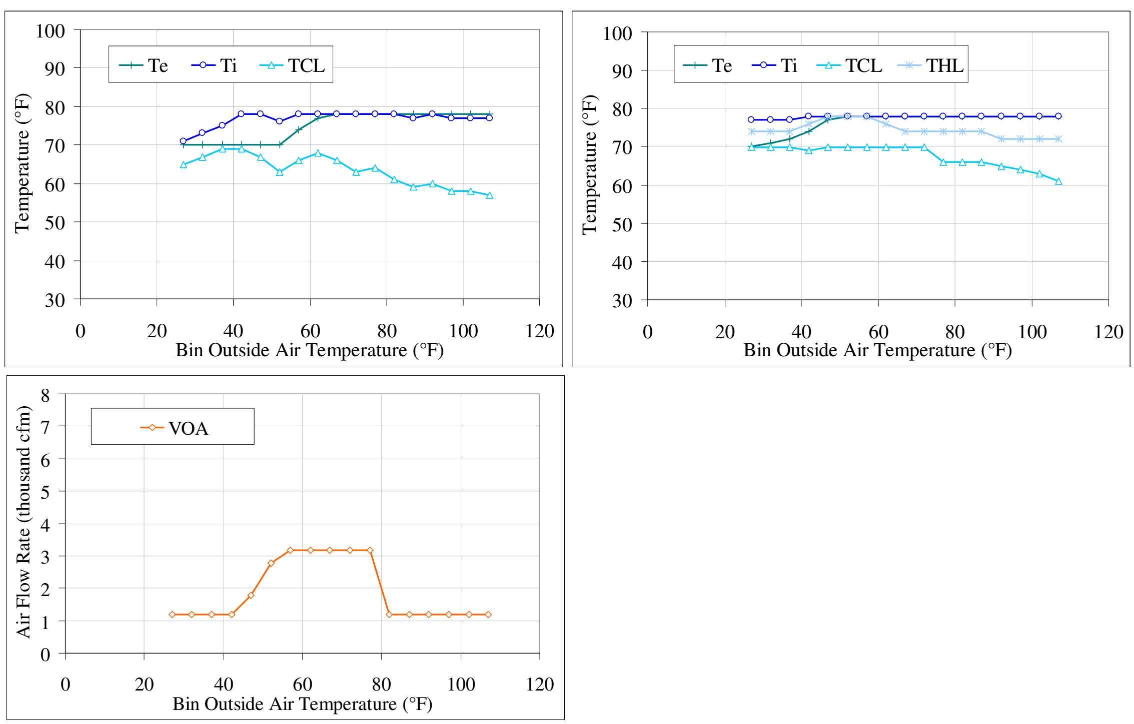


Figure 5.14 Optimized parameter settings for the SDVAV (left) and multizone (right) system as a function of bin temperature from multiple parameter optimization for the Coke Building

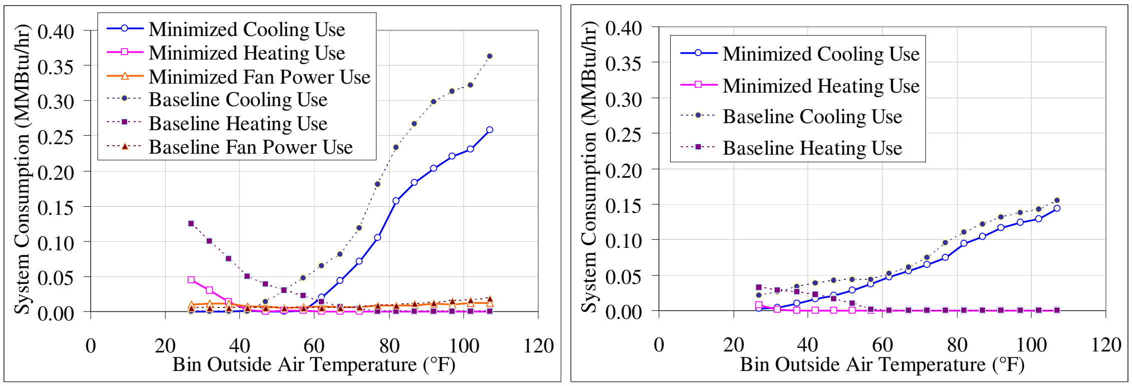


Figure 5.15 Cooling, heating and fan power consumption before (only resetting minimum airflows) and after multiple parameter optimizations during occupied period for the SDVAV (left) and multizone (right) system as a function of bin temperature for the Coke Building

6. APPLICATION IN TFC PROJECT

The methodology discribed in previous sections is expected to predict a theoretical upper limit to the potential energy savings in a building. However, in order to make the methodology useful in real projects, it is desirable to determine the fraction of the estimated potential savings that may be achievable in practice. In this section, the methodology is used to estimate potential savings in a real project for 14 state-owned office buildings with VAV systems. The results are compared with savings predicted in CC® assessment reports for these buildings, and the use of generalized factors to improve the correlation between potential savings identified by this methodology and those identified in retro-commissioning assessments is investigated.

6.1 Project Introduction

The Energy Systems Laboratory at Texas A&M University was contracted by the Texas Facilities Commission (TFC) to conduct Continuous Commissioning® assessments on the HVAC systems of a group of buildings managed by the TFC in Austin, Texas. 14 of these buildings are selected for the testing in this section. The two criteria used in the selection are: (1) the building is mainly used as offices; and (2) the type of HVAC system that serves most parts of the building is either single duct VAV or dual duct VAV systems.

Table 6.1 General information of selected TFC managed buildings

Building Name	Abbr.	Year	Floor	Gross Area	System Type	ELE Bill	NG Bill
John H. Winters Building	JHW	1984	7+1	502,500	SDVAV with electric terminal reheats	√	N/A
William P. Clements Building	WPC	1986	15+1	473,215	SDVAV with electric terminal reheat	√	N/A
Robert D. Moreton Building	RDM	1989	7	122,636	SDVAV with electric terminal reheat	√	N/A
Lorenzo De Zavala Archives & Library	ARC	1959	4+1	111,244	SDVAV	E.	E.
Tom C. Clark Building	TCC	1960	8+2	102,299	Mainly SDVAV	E.	E.
William B. Travis Building	WBT	1983	12+1	466,440	SDVAV	C.E.	E.
Lyndon B. Johnson Building	LBJ	1985	12+1	299,512	DDVAV	C.E.	√
Price Daniel, Sr. Building	PDB	1991	9+1	135,926	Mainly DDVAV	C.E.	E.
Robert E. Johnson Building	REJ	2000	5+1	307,091	Mainly DDVAV	√	√
Sam Houston Building	SHB	1959	10+2	170,967	Mainly DDVAV	E.	E.
Thomas J. Rusk Building	TJR	1976	6	99,971	DDVAV	C.E.	√
John H. Reagan Building	JHR	1961	5+1	161,787	Mainly DDVAV	E.	E.
Supreme Court Building	SCB	1961	4+2	69,253	Mainly DDVAV	E.	E.
Stephen F. Austin Building	SFA	1973	11+2	418,103	DDVAV	E.	E.

√ — consumption is metered and original bills are used to determine annual consumption
E.— consumption is estimated
C.E. — electricity consumption used to generate chilled water is estimated, while electricity for lighting and plug loads is metered

The basic information about the 14 buildings is listed in Table 6.1. The utility bills of electricity and natural gas are also provided for potential energy savings estimation. These buildings were built between 1959 and 2000 with gross areas between 70,000 to 500,000 ft^2. Six of these buildings are equipped with SDVAV systems, while the other eight buildings have DDVAV system as the main HVAC system type. Among the six buildings which have SDVAV systems, three of them use electricity for terminal reheat instead of hot water. Therefore, the buildings are grouped into three categories: three buildings with SDVAV systems with electric reheat, three with SDVAV systems with hot water reheat, and eight with DDVAV systems.

6.2 Potential Energy Savings Estimation

Unlike the two buildings selected for case studies in the previous section, hourly consumption of electricity, chilled water and hot water is not metered in the TFC managed buildings. Some of these buildings have on-site chillers and boilers, so that monthly electricity and natural gas bills for the year 2008 are available. The other buildings are provided chilled water and hot water from a central plant. Electricity for non-cooling/heating use is either purchased from a utility company or provided by the central plant as well. Since the amount of electricity, chilled water and hot water distributed to each building is not metered, electricity and natural gas bills are estimated for these buildings. The estimation of utility bills is based on the available consumption of similar buildings supplied by the same plant and the total consumption of the plant. It is assumed that energy consumption is proportional to building gross area. Table 6.1 gives a summary of the availability of utility bills.

Considering the situation stated above, energy consumption data will not be available in sorted bins for potential savings estimation per bin. Nevertheless, the methodology is still able to estimate annual potential savings in these buildings. The annual potential energy savings are determined as the difference between the measured or estimated annual consumption and the minimized annual consumption obtained with the methodology.

The current annual usage of electricity, natural gas and the total per square foot of gross area is given in Table 6.2. The average annual usage is 31.57 kWh/ft^2/yr for electricity, 25.74 kBtu/ ft^2/yr for natural gas, and 127.93 kBtu/ft^2/yr for the total (EUI). Before optimization, a simulation representing the current settings is conducted on each building with assumptions made on system operation parameters as in Table 6.3. The simulation parameters are adjusted so that the simulated annual consumption matches the annual total of utility bills. Then an optimization is performed with AHU shutdown, minimum airflow reset, and all applicable optimization parameters activated — room temperatures, cold deck and hot deck (only in DDVAV system) reset schedules and outside air intake. The optimized operation conditions are also listed in Table 6.3. Energy prices of \$0.0753/kWh for electricity and \$8.466/MMBtu for natural gas are used, which are the same as in the CC® assessment report. 1 kW/Ton is used as chiller plant overall efficiency, and 0.8 is used as boiler efficiency.

Table 6.2 gives the estimated potential energy and cost savings for electricity, natural gas and the total. It shows that the SDVAV systems with electric terminal reheat have the greatest potential for savings, with an average of 36%. The total potential energy savings for the SDVAV systems with hot water reheat (22% on average) and DDVAV systems (25% on average) are nearly as large. The potential savings on electricity use and natural gas use are 16% and 95% on average for SDVAV systems with hot water reheat, and 18% and 97% for DDVAV systems.

Table 6.2 Estimated potential electricity (a), natural gas (b) and total (c) savings in TFC managed buildings, and comparison with savings predicted in CC® assessment report

		Electricity					
		Annual Consumption (kWh)	Annual Usage (kWh/ft²/yr)	Potential Percent Savings	Potential Energy Cost Savings	Cost Savings Predicted in Assessment	Ratio of Cost Savings in Assessment to Potential Cost Savings
JHW	SDVAV E.R.	17,326,925	35.90	38%	$ 501,057	$ 267,062	0.53
WPC	SDVAV E.R.	14,119,500	29.84	36%	$ 379,123	$ 336,462	0.89
RDM	SDVAV E.R.	3,560,000	28.94	33%	$ 88,144	$ 54,573	0.62
ARC	SDVAV	3,513,528	31.58	14%	$ 36,166	$ 17,934	0.50
TCC	SDVAV	3,199,426	31.58	15%	$ 35,144	$ 19,019	0.54
WBT	SDVAV	12,778,819	27.40	21%	$ 202,163	$ 158,689	0.78
LBJ	DDVAV	10,552,877	35.23	17%	$ 138,415	$ 118,870	0.86
PDB	DDVAV	5,280,394	38.85	14%	$ 56,915	$ 24,818	0.44
REJ	DDVAV	8,382,000	27.29	27%	$ 172,329	$ 89,694	0.52
SHB	DDVAV	5,399,818	31.58	19%	$ 75,815	$ 44,134	0.58
TJR	DDVAV	2,920,094	29.21	13%	$ 29,007	$ 22,554	0.78
JHR	DDVAV	5,109,877	31.58	17%	$ 66,917	$ 29,280	0.44
SCB	DDVAV	2,187,285	31.58	20%	$ 33,078	$ 22,257	0.67
SFA	DDVAV	13,118,505	31.38	18%	$ 181,522	$ 113,871	0.63

(a)

		Natural Gas					
		Annual Consumption (MMBtu)	Annual Usage (kBtu/ft²/yr)	Potential Percent Savings	Potential Energy Cost Savings	Cost Savings Predicted in Assessment	Ratio of Cost Savings in Assessment to Potential Cost Savings
JHW	SDVAV E.R.	-	-	-	-	-	-
WPC	SDVAV E.R.	-	-	-	-	-	-
RDM	SDVAV E.R.	-	-	-	-	-	-
ARC	SDVAV	2,391	21.49	100%	$ 20,241	$ 11,937	0.59
TCC	SDVAV	3,007	29.68	100%	$ 25,394	$ 17,194	0.68
WBT	SDVAV	7,012	15.03	84%	$ 49,854	$ 57,577	1.15
LBJ	DDVAV	12,684	42.35	100%	$ 107,372	$ 49,687	0.46
PDB	DDVAV	2,921	21.49	100%	$ 24,731	$ 17,846	0.72
REJ	DDVAV	11,063	36.02	99%	$ 92,387	$ 41,873	0.45
SHB	DDVAV	3,674	21.49	100%	$ 31,094	$ 31,781	1.02
TJR	DDVAV	2,934	29.34	87%	$ 21,587	$ 6,129	0.28
JHR	DDVAV	3,477	21.49	100%	$ 29,437	$ 18,557	0.63
SCB	DDVAV	2,056	29.68	100%	$ 17,371	$ 13,029	0.75
SFA	DDVAV	6,286	15.03	95%	$ 50,330	$ 46,698	0.93

(b)

Table 6.2 Continued

		Total					
		Annual Energy Cost	**Annual Usage (kBtu/ft²/yr)**	**Potential Percent Savings**	**Potential Energy Cost Savings**	**Cost Savings Predicted in Assessment**	**Ratio of Cost Savings in Assessment to Potential Cost Savings**
JHW	SDVAV E.R.	1,304,717	122.51	38%	$ 501,057	$ 267,062	0.53
WPC	SDVAV E.R.	1,063,198	101.81	36%	$ 379,123	$ 336,462	0.89
RDM	SDVAV E.R.	268,068	98.74	33%	$ 88,144	$ 54,573	0.62
ARC	SDVAV	284,809	129.26	20%	$ 56,407	$ 29,871	0.53
TCC	SDVAV	266,373	137.45	23%	$ 60,538	$ 36,214	0.60
WBT	SDVAV	1,021,612	108.51	25%	$ 252,016	$ 216,267	0.86
LBJ	DDVAV	902,013	162.57	27%	$ 245,787	$ 168,557	0.69
PDB	DDVAV	422,345	154.04	19%	$ 81,646	$ 42,664	0.52
REJ	DDVAV	724,822	129.15	37%	$ 264,716	$ 131,567	0.50
SHB	DDVAV	437,714	129.26	24%	$ 106,909	$ 75,916	0.71
TJR	DDVAV	244,718	129.01	21%	$ 50,594	$ 28,683	0.57
JHR	DDVAV	414,211	129.26	23%	$ 96,354	$ 47,837	0.50
SCB	DDVAV	182,106	137.45	28%	$ 50,449	$ 35,287	0.70
SFA	DDVAV	1,041,038	122.09	22%	$ 231,853	$ 160,570	0.69

(c)

Table 6.3 Comparison of current and optimized operation in TFC managed buildings

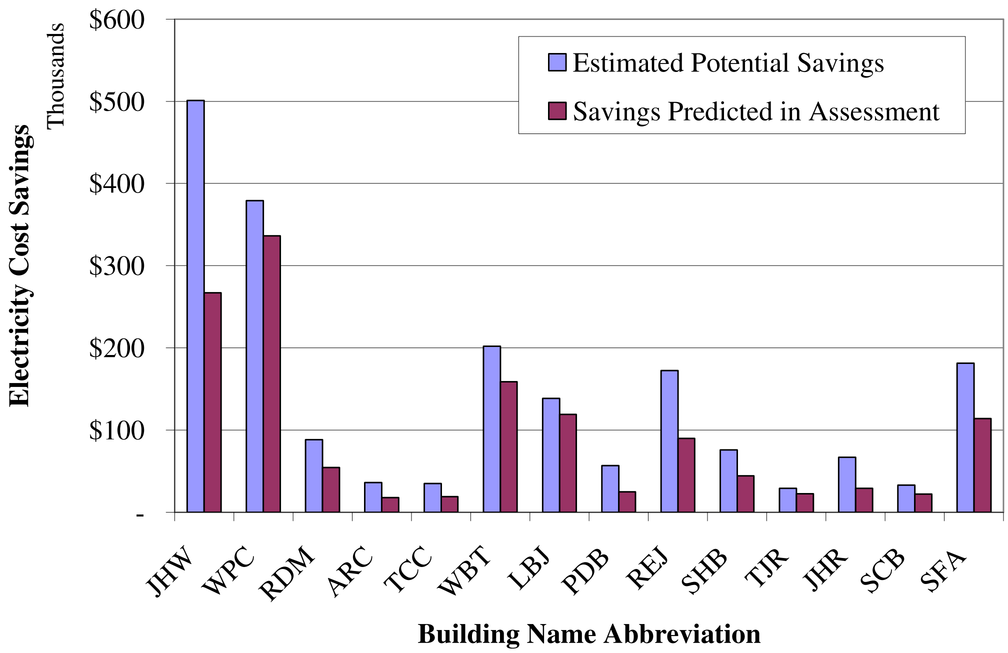
	Current Operation with Assumption	**Optimized Operation**
AHU operation	Run 24/7	AHU shutdown 10:00PM-5:00AM
Minimum supply airflow	40%-70% of total design airflow	0.3 cfm/ft²
Room temperature set point	Fixed set point, 72-75°F	Optimized with PESE
Cold deck leaving air temperature set point	Fixed set point, 53-55°F	Optimized with PESE
Hot deck leaving air temperature set point	Fixed set point, 85-95°F	Optimized with PESE
Outside air intake	10-15% of total design airflow	Optimized with PESE

6.3 Comparison with CC® Assessment

As a test of the methodology described in this thesis, the estimated potential energy cost savings in TFC managed buildings are compared with savings predicted in the CC® assessment report prepared by the Energy Systems Laboratory. For each of these buildings, the ratio between the predicted savings in the assessment report and the potential savings is determined. Then, a generalized factor for each type of system is obtained as an indicator of the fraction of the estimated potential energy cost savings that may be achieved in retro-commissioning assessments for office buildings with VAV systems in the future.

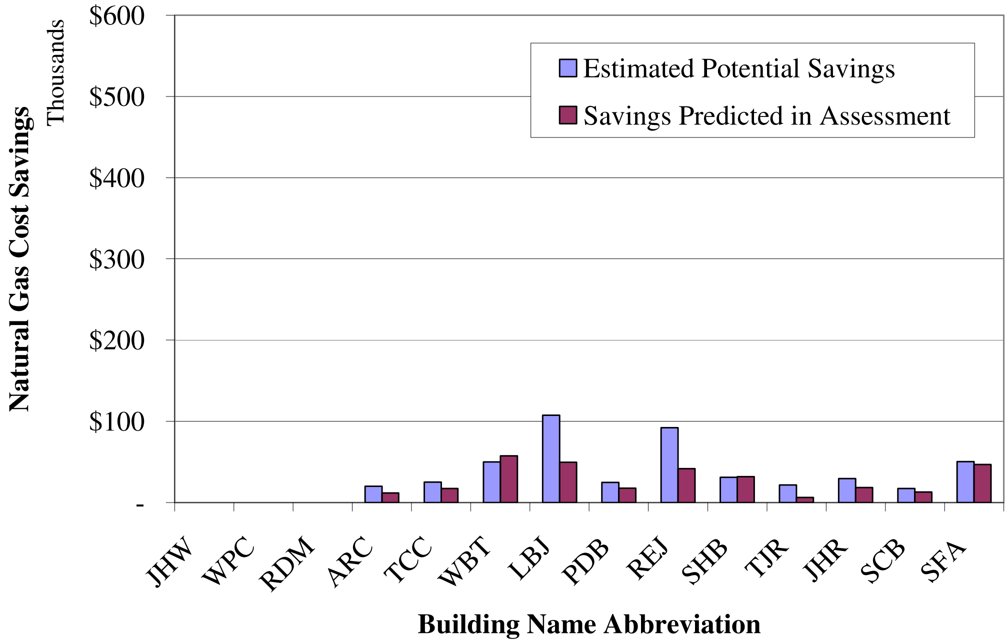
Figure 6.1 also illustrates comparisons of electricity, natural gas, and the total savings. It shows that the estimated potential savings is larger than the total savings predicted in the assessment report in each of the buildings. The amount of savings predicted in the assessment report is given in Table 6.2 with the ratio to estimated potential savings provided. The average ratios in each group of buildings are used as the generalized factors for each type of system, as shown in Table 6.4. The range of ratios in each group is also provided. The generalized factors of total energy savings are 0.68 for SDVAV systems with electric reheat, 0.66 for SDVAV systems with hot water reheat, and 0.61 for DDVAV systems. The generalized factors for electricity and natural gas are 0.61 and 0.81 for SDVAV systems with hot water reheat, and 0.61 and 0.66 for DDVAV systems. Larger variations are observed on the ratios for natural gas than those for electricity, because savings on electricity weight more in the optimization considering that its price (22.069/MMBtu) is much more expensive for the same amount of energy.

It should be noted that the savings predicted in the assessment report are largely based on simulations and include savings from improvement on water-side of the system as well as common retrofit savings, such as installing VFDs on chilled water and hot water pumps, DDC upgrade, etc. This explains the large values of ratios in building WPC and WBT, where significant retrofit measures are reported in the CC® assessment. Therefore, the ratios obtained above are expected to be smaller if only savings on the air-side are compared. Nevertheless, the predicted savings from AHU shutdown and improvements on the air-side dominate the total savings in the assessment report for most buildings.

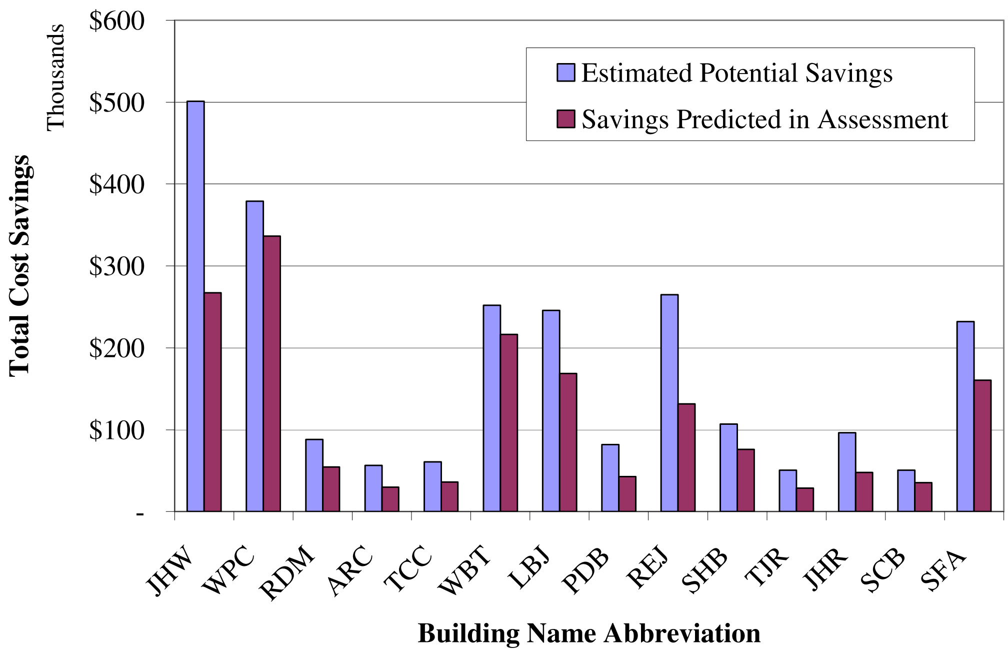


(a)

Figure 6.1 Comparison of estimated potential electricity (a), natural gas (b), and total (c) cost savings with savings predicted in the CC® assessment report in TFC managed buildings



(b)



(c)

Figure 6.1 Continued

Table 6.4 Averages and ranges of ratios of savings predicted in the CC® assessment report to estimated potential energy savings in TFC managed buildings

System Type	**Electricity**		**Natural Gas**		**Total**	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**
SDVAV with electric reheat	0.68	0.53-0.89			0.68	0.53-0.89
SDVAV with hot water reheat	0.61	0.50-0.78	0.81	0.59-1.15	0.66	0.53-0.86
DDVAV	0.61	0.44-0.86	0.66	0.28-1.02	0.61	0.50-0.71

7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions of Work

In this thesis, the methodology for potential energy savings estimation from retro-commissioning/retrofit measures proposed by Baltazar is improved in several important aspects and is implemented in a prototype computer tool for testing. The implemented methodology is tested in two retro-commissioned buildings. In the Sanders Corps of Cadets Center, the optimized profiles of parameter settings versus bin temperature are analyzed in single parameter optimizations. These profiles can be explained with engineering principles, which reveals that the improved methodology is implemented correctly. The case study on the Coke Building shows that the improved methodology can be used in buildings with more than one system type. Then the methodology is used to estimate annual potential energy savings in 14 TFC managed office buildings with VAV systems. The estimations of the improved methodology are compared with savings predicted in the CC® assessment report. The results show it may be helpful to study the correlation by using generalized factors of assessment predicted energy cost savings to estimated potential energy cost savings. The generalized factors identified in this application are 0.68 for SDVAV systems with electric reheat, 0.66 for SDVAV systems with hot water reheat, and 0.61 for DDVAV systems. It should be noted that one should be cautious in quoting these factors in future projects, since they are based on study of a limited number of buildings, specific energy prices, and various assumptions due to inadequate information.

7.2 Future Work

The generalized factors of energy cost savings in the assessment report to estimated potential energy cost savings are provided for VAV systems in this study. It would be useful to investigate the factors for other HVAC system types, such as single duct and dual duct constant volume systems. Additionally, it would be valuable to study on the correlations between measured savings and estimated potential savings in a larger number of buildings with retro-commissioning measures implemented. The PESE Toolkit is developed for the purpose of testing the methodology in this thesis. Further testing and modifications on the tool are necessary to make it a reliable software tool to be used among retro-commissioning engineers inside the Energy Systems Laboratory or to be made available to the public.

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APPENDIX A

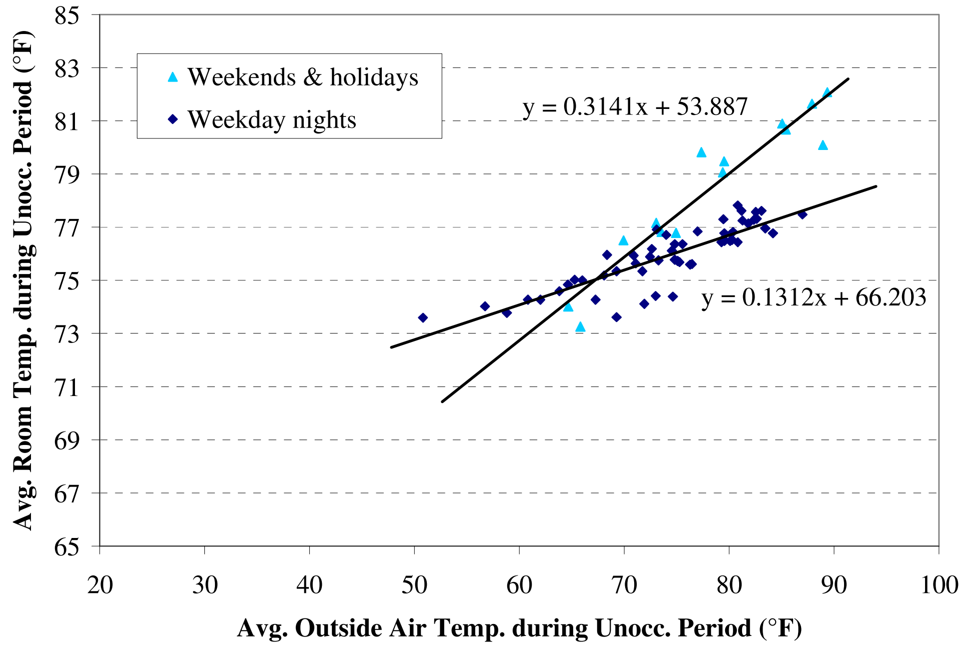
THE METHOD FOR AHU SHUTDOWN SIMULATION

AHU shutdown during the unoccupied period is one of the most common and effective energy saving measure used in retro-commissioning. However, the modified bin method has limited capability to accurately deal with highly time dependent problems and should be used with considerable judgment when the primary analysis deals with thermal capacitance dominated problems (Knebel, 1983). Obviously, the AHU shutdown is a problem of this kind, since the room temperature will gradually approach outside air temperature during the shutdown period. As a result, using the set point temperature during occupied period in calculation of conduction load during shutdown periods can lead to significant error.

It is proposed in this study to use the energy balance method for an approximate calculation of heating and cooling energy use during the AHU shutdown and start-up period. It is suggested to distinguish the “occupied” and “unoccupied” periods used in the bin sorting procedure by the AHU shutdown schedule with start-up included in the unoccupied period, because the heating or cooling load accumulated during the shutdown period will be removed mainly during the start-up period. By applying the energy balance method to the shutdown period, the heating or cooling energy use should approximately equal the total of lighting and equipment electricity use and conduction load.

The use of a linear regression relationship between the room temperature and the outside air temperature in the conduction load calculation during the unoccupied period with AHU shutdown is investigated. Based on the hourly measured data of room temperatures in the Coke Building on the TAMU campus with an AHU shutdown schedule implemented, it is found that the average room temperature during the unoccupied period follows an approximately linear regression relationship with the average outside air temperature during the same period, as shown in Figure A.1. The data during weekday nights and weekends & holidays are separated in the top figure, which shows that the slope in the regression relationship of weekends& holidays is about 2.4 times of the slope of weekday nights. Nevertheless, a linear regression relationship is determined for all unoccupied periods, shown in the bottom figure.

The necessity of using two separate regression relationships in computing conduction load during the unoccupied period is investigated. The result shows that the difference in the total heating and cooling load between using separate models for weekday nights and weekends & holidays and using one model for all is only about 10% or less for most bins and 1% for the annual total. Additionally, the difference between the annual total of heating and cooling loads computed with one model and the annual total of measured heating hot water consumption subtracted by chilled water consumption is only 2%. Therefore, it is decided that using one regression model for all unoccupied periods is sufficient. The model shown in the bottom figure is incorporated in the PESE Toolkit for AHU shutdown simulation.



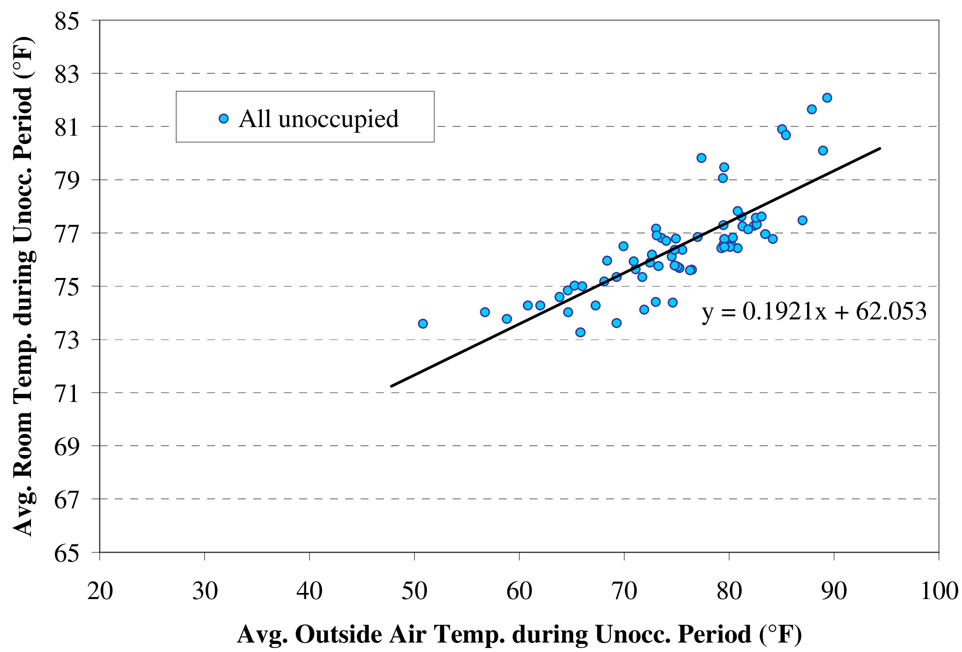


Figure A.1 Linear regression relationship between average room temperature and average outside air temperature during AHU shutdown period with weekday nights and weekends separated (top) or combined (bottom)

APPENDIX B

LOAD CALCULATION MODELS

The modified bin method is adopted for load calculation in PESE, which establishes the load as a linear function of outdoor dry-bulb temperature. Two calculation periods representing occupied and unoccupied hours are distinguished. The following equations show how each load component is linearized to the outdoor temperature.

Component 1: Conduction load

$$UA_{tot,e} = U_{wall}A_{wall} + U_{window}A_{window} + X_{Ae}(U_{roof}A_{roof} + U_{ground}A_{ground})$$

$$UA_{tot,i} = U_{skylights}A_{skylights} + U_{roof}(X_{Ai}A_{roof} - A_{skylights}) + X_{Ai}U_{ground}A_{ground}$$

$$QT_e = UA_{tot,e}(T_{OA} - T_e)$$

$$QT_i = UA_{tot,i}(T_{OA} - T_i)$$

Component 2: Solar heat gain through windows

$$QSOL_{Jul} = \sum(MSHGF_{Jul} \times A_{window} \times SC \times CLF_{tot} \times FPS_{Jul} / 24)$$

$$QSOL_{Jan} = \sum(MSHGF_{Jan} \times A_{window} \times SC \times CLF_{tot} \times FPS_{Jan} / 24)$$

For the exterior zone, sum the four orientations; for the interior zone, only the skylights.
FPS: fraction of possible sunshine (given in Table 3-1 in Knebel (1983)).

$$M\_QSOL = \frac{QSOL_{Jul} - QSOL_{Jan}}{T_{pc} - T_{ph}}$$

T_{pc} – peak summer bin temperature; T_{ph} – peak winter bin temperature.

$$QSOL_e = QSOL_{Jan,e} + M\_QSOL_e (T_{OA} - T_{ph})$$

$$QSOL_i = QSOL_{Jan,i} + M\_QSOL_i (T_{OA} - T_{ph})$$

Component 3: Transmission load solar component

$$CLTDs_{corr} = CLTDs_{LM} \times K + (78 - T_{zone}) + (T_{o,des} - 85)$$

T_{zone}: use T_e for exterior zone, T_i for interior zone
$T_{o,des}$: average outside temperature on design day
K_{wall}: dark colored-1, medium colored-0.83, light colored-0.65
K_{roof}: dark colored-1, light colored-0.5

$$QTS_{Jul} = \sum (U_{wall} \times A_{wall} \times CLTDs_{corr} \times FPS_{Jul})$$

$$QTS_{Jan} = \sum (U_{wall} \times A_{wall} \times CLTDs_{corr} \times FPS_{Jan})$$

For exterior zone, sum the four orientations plus part of the roof; For interior zone, only the other part of the roof.

$$M\_QTS = \frac{QTS_{Jul} - QTS_{Jan}}{T_{pc} - T_{ph}}$$

$$QTS_e = QTS_{Jan,e} + M\_QTS_e (T_{OA} - T_{ph})$$

$$QTS_i = QTS_{Jan,i} + M\_QTS_i (T_{OA} - T_{ph})$$

Transmission load solar component is only counted in the total load when $T_{OA} > T_{zone}$.

Component 4: Internal heat gain (sensible and latent) from occupants

$$\mathrm{AOF}_{\mathrm{CertainPeriod}} = \frac{\sum_{EachHour} OCP \times 1hr}{OCP_{FullOccupancy} \times Hours_{InThePeriod}}$$

$$QsOCP_e = 245 \times OCP_e \times AOF$$

$$QlOCP_e = 155 \times OCP_e \times AOF$$

$$QsOCP_i = 245 \times OCP_i \times AOF$$

$$QlOCP_i = 155 \times OCP_i \times AOF$$

AOF (Average Occupancy Factor): use AOF_{ocp} for occupied period and AOF_{unocp} for unoccupied period

Component 4: Internal heat gain from lighting and equipments

$$QLTEQ_e = 3412 \times X_{Ae} \times LTEQ$$

$$QLTEQ_i = 3412 \times X_{Ai} \times LTEQ$$

LTEQ (kW): use $LTEQ_{ocp}$ for occupied period and $LTEQ_{unocp}$ for unoccupied period

The MSHGF, CLF_{tot} and $CLTDs_{LM}$ values required in the solar heat gain and transmission load solar component calculation can be derived from 1989 *ASHRAE Handbook of Fundamentals*, which will be described in the following paragraphs. Note table names without section number refer to tables from Chapter 26 in 1989 *Fundamentals*.

Table 34 gives Maximum Solar Heat Gain Factors (MSHGF) according to latitude, month and directions. The MSHGF values for the months of July and January are picked out for the latitudes of interest and listed in Table B.1.

Table 36 and Table 39 give the CLF at 24 hours of solar time on each orientation for glass without or with interior shading respectively. By summing up CLF over 24 hours in each table (for Table 36 take values for medium construction), one can get

CLF_{tot} on each orientation in each situation. As Table B.2 revealed, on each orientation the CLF_{tot} values in both situations are very close. Hence, for the sake of simplification the values for glass with interior shading are used in PESE considering it is the case in most buildings.

Table B.1 Maximum Solar Heat Gain Factor for sunlit glass (Btu/h·ft^2)

		N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**
Jul	24°	45	116	176	210	213	185	129	65
	32°	40	111	167	204	215	194	150	96
	40°	38	102	163	198	216	203	170	129
	48°	37	96	156	196	214	209	187	158
Jan	24°	27	27	41	128	190	240	253	241
	32°	24	24	29	105	175	229	249	250
	40°	20	20	20	74	154	205	241	252
	48°	15	15	15	53	118	175	216	239

		S	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**
Jul	24°	46	65	129	185	213	210	176	116	278
	32°	72	96	150	194	215	204	167	111	273
	40°	109	129	170	203	216	198	163	102	262
	48°	146	158	187	209	214	196	156	96	244
Jan	24°	227	241	253	240	190	128	41	27	214
	32°	246	250	249	229	175	105	29	24	176
	40°	254	252	241	205	154	74	20	20	133
	48°	245	239	216	175	118	53	15	15	85

Table B.2 Comparison of CLF_{tot} for glass with and without interior shading

	N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**
Without Interior Shading	11.58	5.77	5.15	5.31	5.49	5.85	6.21	6.44
With Interior Shading	11.58	5.74	5.13	5.34	5.50	5.86	6.23	6.45
Absolute Difference	0.00	0.03	0.02	-0.03	-0.01	-0.01	-0.02	-0.01
Difference in Percentage (%)	0.0	0.5	0.4	-0.6	-0.2	-0.2	-0.3	-0.2

	S	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**
Without Interior Shading	6.41	6.43	6.24	5.84	5.46	5.36	5.14	5.76	8.23
With Interior Shading	6.44	6.48	6.20	5.83	5.47	5.33	5.15	5.77	8.21
Absolute Difference	-0.03	-0.05	0.04	0.01	-0.01	0.03	-0.01	-0.01	0.02
Difference in Percentage (%)	-0.5	-0.8	0.6	0.2	-0.2	0.6	-0.2	-0.2	0.2

Table 29 provides CLTDs at 24 hours of solar time for flat roofs with 13 different constructions when suspended ceiling is present or not. One can get CLTD 24-hour Average (CLTDs) for each construction type by averaging up CLTD over 24 hours in the table. Table B.3 shows that average values of CLTDs for different constructions are the same whether there is suspended ceiling or not, and CLTDs for all the constructions are close except for No.5, which is rare among the size of buildings this methodology deals with. Therefore, the average value is used in PESE regardless of roof construction.

Table B.3 Comparison of CLTDs for flat roofs with and without suspended ceiling

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**Avg.**
Without Suspended Ceiling	30	30	29	29	23	29	30	29	29	28	29	29	29	**29**
Difference from average (%)	2	2	2	1	-19	2	2	2	2	-2	1	2	2	
With Suspended Ceiling	30	30	29	29	23	29	30	29	29	28	29	29	29	**29**
Difference from average (%)	2	2	2	1	-19	2	2	2	2	-2	1	2	2	

Table B.4 Comparison of CLTDs for sunlit walls with different construction groups

	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Group A Walls	12	18	22	21	17	21	22	18
Group B Walls	12	17	22	21	17	20	22	17
Group C Walls	12	18	22	21	17	21	22	18
Group D Walls	12	18	22	21	17	21	22	18
Group E Walls	12	18	22	21	17	21	22	18
Group F Walls	12	18	23	21	17	21	22	18
Group G Walls	12	18	22	21	17	21	22	18
Average	12	18	22	21	17	21	22	18
Max Difference (%)	-2	-3	-3	-3	-3	-3	-3	-3

Table B.5 CLTD correction for latitude and month applied to walls and roofs

		N	NNE	NE	ENE	E	ESE	SE	SSE	
Jul	24°	1	2	2	0	0	-3	-3	-5	
	32°	1	1	1	0	0	-1	-1	-3	
	40°	0	0	0	0	0	0	0	0	
	48°	0	-1	0	0	1	1	3	3	
Jan	24°	-4	-6	-8	-9	-6	-3	9	3	
	32°	-5	-7	-9	-11	-8	-15	-4	2	
	40°	-5	-7	-10	-12	-9	-6	1	8	
	48°	-6	-8	-11	-13	-11	-8	-1	5	
		S	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**
Jul	24°	-6	-5	-3	-3	0	0	2	2	1
	32°	-3	-3	-1	-1	0	0	1	1	1
	40°	1	0	0	0	0	0	0	0	1
	48°	4	3	3	1	1	0	0	-1	0
Jan	24°	13	3	9	-3	-6	-9	-8	-6	-11
	32°	9	2	-4	-15	-8	-11	-9	-7	12
	40°	11	8	1	-6	-9	-12	-10	-7	-19
	48°	8	5	-1	-8	-11	-13	-11	-8	-24

Table 31 gives CLTD at 24 hours of solar time for sunlit walls on each orientation with 7 different construction type groups. Similarly with the case of roofs, one can get CLTDs on each orientation for each group. Table B.4 indicated that all groups of walls come very close on each orientation despite their construction difference. Thus, the average values are adopted in PESE.

Table 32 provides CLTD correction for latitude and month (LM) applied to walls and roofs. The CLTD correction values for the months of July and January are picked out for the latitudes of interest and listed in Table B.5. Since CLTD LM correction is available in 16 directions, CLTDs for sunlit walls are also expanded to 16 directions by average interpolation between the 8 existing directions in Table B.4. The expanded CLTDs including horizontal are provided in Table B.6. Latitude and month corrected

CLTDs ($CLTDs_{LM}$) can be obtained simply by adding the correction values in Table B.5 to them. The results are given in Table B.7.

Table B.6 CLTDs with expanded directions for sunlit walls and roofs

N	NNE	NE	ENE	E	ESE	SE	SSE	
12	15	18	20	22	21.5	21	19	
S	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**
17	19	21	21.5	22	20	18	15	29

Table B.7 CLTDsLM used in PESE Toolkit for sunlit walls and roofs

		N	NNE	NE	ENE	E	ESE	SE	SSE	
Jul	24°	13	17	20	20	22	18.5	18	14	
	32°	13	16	19	20	22	20.5	20	16	
	40°	12	15	18	20	22	21.5	21	19	
	48°	12	14	18	20	23	22.5	24	22	
Jan	24°	8	9	10	11	16	18.5	30	22	
	32°	7	8	9	9	14	6.5	17	21	
	40°	7	8	8	8	13	15.5	22	27	
	48°	6	7	7	7	11	13.5	20	24	
		S	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**
Jul	24°	11	14	18	18.5	22	20	20	17	30
	32°	14	16	20	20.5	22	20	19	16	30
	40°	18	19	21	21.5	22	20	18	15	30
	48°	21	22	24	22.5	23	20	18	14	29
Jan	24°	30	22	30	18.5	16	11	10	9	18
	32°	26	21	17	6.5	14	9	9	8	41
	40°	28	27	22	15.5	13	8	8	8	10
	48°	25	24	20	13.5	11	7	7	7	5

APPENDIX C

NOMENCLATURE OF AIR-SIDE MODELS

The air-side simulation models are inherited from Baltazar's (2006) dissertation with modifications explained in section 3.2.7. The implemented models for each type of system can be found in Appendix G. The notations used in the models are generally used within the Energy Systems Laboratory, which are listed as follows.

Symbols	**Variable**	**Unit**
P	Rated fan power	hp
PLR	Part load ratio	Dimensionless
q	Load	Btu/hr
dT	Temperature rise	°F
T	Temperature	°F
V	Air volume flow rate	ft^3/min
w	Humidity ratio	lb_w/lb_a
X	Air volume ratio	Dimensionless
Subscripts	**Variable**	**Combination**
C	Cold deck air	$\dot{V}$, X
CE	Cooling coil entering air	T, w
CL	Cooling coil leaving air	T, w
Cl	Cooling coil latent load	q
Cs	Cooling coil sensible load	q
CT	Cooling coil total load	q
e	Exterior zone air	T, $\dot{V}$, X
e,min	Minimum supply air for exterior zone in VAV systems	$\dot{V}$
eC	Exterior zone cold air	$\dot{V}$, X
eH	Exterior zone hot air	$\dot{V}$, X

el	Exterior zone latent load	q
eRH	Exterior zone reheat coil load	q
eS	Exterior zone supply air	T, w
es	Exterior zone sensible load	q
FT	Total fan power	q
H	Hot deck air	$\dot{V}$, X
HE	Heating coil entering air	T, w
HL	Heating coil leaving air	T, w
HT	Heating coil total load	q
i	Interior zone air	T, $\dot{V}$, X
i,min	Minimum supply air for interior zone in VAV systems	$\dot{V}$
iC	Interior zone cold air	$\dot{V}$, X
iH	Interior zone hot air	$\dot{V}$, X
il	Interior zone latent load	q
iRH	Interior zone reheat coil load	q
iS	Interior zone supply air	T, w
is	Interior zone sensible load	q
MA	Mixed air	T, w
OA	Outside air	T, $\dot{V}$, w, X
OA,max	Maximum outside air	$\dot{V}$, X
OA,min	Minimum required outside air	$\dot{V}$, X
PH	Preheat coil load or leaving air	q, T, w
R	Return air	T, w
Rw	Return air ("wet coil" condition)	w
Rd	Return air ("dry coil" condition)	w
RF	Return fan	ΔT, P
RF-rated	Rated return fan power	P
SF	Supply fan	ΔT, P
SF-rated	Rated supply fan power	P
T	Total air	$\dot{V}$
TD	Total designed air	$\dot{V}$

APPENDIX D

BIN SORTING

PESE requires input weather data (dry bulb temperatures and humidity ratios) and measured energy consumptions data sorted into bins and the number of hours in each bin. Generally, one year of measured hourly data is most desirable for the purpose of potential energy savings estimation. In order to obtain humidity ratios, any one of the three humidity parameters - wet bulb temperature, dew point temperature and relative humidity - is required besides dry bulb temperature. Additionally, since the ASHRAE SEAP suggests two calculation periods representing occupied and unoccupied hours on a daily basis, a Boolean parameter indicating whether the building is occupied during each hour is needed as well. In PESE the temperature difference between bins can be any value although 5°F and 3°F are common.

Figure D.1 gives an example of the bin sorting procedure developed by the author. With one year of hourly data as well as occupied hours on weekdays and weekends provided, the humidity ratios will be calculated for each hour, and then will be sorted into 5°F bins together with dry bulb temperature and measured consumption values. There is a drop list on the title line for one to choose from the three humidity parameters. The output follows the format of bin data input in PESE (shown in Figure 5.2). The structure of the bin sorting procedure is illustrated in the flow chart as shown in Figure D.2.

YEAR	MONTH	DAY	HOUR	IFOCP	TOA (°F)	ELE (kWh)	CHW (MBtu)	HHW (MBtu)	Tdp (°F)	wOA
2008	7	16	0	FALSE	79	23.40	95.00	0.00	72	0.016903
2008	7	16	1	FALSE	79	23.22	58.00	0.00	72	0.016903
2008	7	16	2	FALSE	79	22.61	81.00	0.00	72	0.016903
2008	7	16	3	FALSE	79	22.19	62.00	0.00	72	0.016903
2008	7	16	4	FALSE	77	22.80	62.00	0.00	72	0.016903
2008	7	16	5	FALSE	77	23.16	60.00	0.00	72	0.016903
2008	7	16	6	FALSE	77	25.54	58.00	0.00	72	0.016903
2008	7	16	7	TRUE	78	35.97	156.00	1.00	73	0.017500
2008	7	16	8	TRUE	83	35.18	395.00	0.00	74	0.018116
2008	7	16	9	TRUE	83	44.69	377.00	0.00	73	0.017500
2008	7	16	10	TRUE	86	46.80	368.00	0.00	71	0.016325
2008	7	16	11	TRUE	89	49.91	435.00	0.00	71	0.016325
2008	7	16	12	TRUE	90	48.74	441.00	0.00	70	0.015765
2008	7	16	13	TRUE	93	49.55	466.00	0.00	69	0.015222
2008	7	16	14	TRUE	96	50.92	460.00	1.00	68	0.014696
2008	7	16	15	TRUE	96	53.90	482.00	0.00	67	0.014186
2008	7	16	16	TRUE	90	54.20	520.00	0.00	67	0.014186
2008	7	16	17	TRUE	94	50.65	505.00	0.00	69	0.015222
2008	7	16	18	TRUE	95	38.54	439.00	0.00	66	0.013693
2008	7	16	19	TRUE	90	34.99	434.00	0.00	69	0.015222
2008	7	16	20	TRUE	87	34.03	401.00	0.00	67	0.014186
2008	7	16	21	FALSE	83	31.72	407.00	0.00	68	0.014696
2008	7	16	22	FALSE	82	31.09	234.00	0.00	69	0.015222
2008	7	16	23	FALSE	79	24.15	181.00	0.00	69	0.015222
2008	7	17	0	FALSE	79	24.18	102.00	0.00	70	0.015765
2008	7	17	1	FALSE	77	24.13	72.00	0.00	70	0.015765
2008	7	17	2	FALSE	76	23.68	90.00	0.00	70	0.015765
2008	7	17	3	FALSE	75	23.83	71.00	0.00	71	0.016325
2008	7	17	4	FALSE	74	23.37	69.00	0.00	71	0.016325
2008	7	17	5	FALSE	73	23.52	71.00	0.00	71	0.016325
2008	7	17	6	FALSE	73	24.12	69.00	0.00	71	0.016325
2008	7	17	7	TRUE	76	36.54	66.00	0.00	73	0.017500
2008	7	17	8	TRUE	79	37.83	425.00	0.00	74	0.018116
2008	7	17	9	TRUE	82	48.43	358.00	0.00	72	0.016903
2008	7	17	10	TRUE	85	50.80	398.00	0.00	70	0.015765
2008	7	17	11	TRUE	89	51.84	477.00	1.00	67	0.014186
2008	7	17	12	TRUE	92	49.93	456.00	0.00	63	0.012303
2008	7	17	13	TRUE	95	47.73	479.00	0.00	61	0.011449
2008	7	17	14	TRUE	95	48.96	454.00	0.00	60	0.011042
2008	7	17	15	TRUE	97	47.45	437.00	0.00	59	0.010648
2008	7	17	16	TRUE	97	48.46	444.00	0.00	60	0.011042
2008	7	17	17	TRUE	97	47.13	436.00	0.00	57	0.009898
2008	7	17	18	TRUE	96	36.95	424.00	0.00	55	0.009195
2008	7	17	19	TRUE	94	35.19	384.00	0.00	57	0.009898
2008	7	17	20	TRUE	90	34.92	374.00	0.00	60	0.011042
2008	7	17	21	FALSE	86	32.39	301.00	0.00	70	0.015765
2008	7	17	22	FALSE	84	31.69	203.00	0.00	70	0.015765
2008	7	17	23	FALSE	82	24.58	185.00	0.00	70	0.015765

INPUT OCCUPIED HOURS:
(0 TO 23: 12:00AM IS 0, 11:00PM IS 23)

WEEKDAYS	7	TO	20
WEEKENDS		TO	

INSTRUCTION: Columns with highlighted title are required inputs for bin sorting. The rest columns help to identify occupied / unoccupied hours. Humidity data could be Wet bulb, Dew point, or Relative humidity (choose from the title of column 13).
Please round up TOA to integer or 0.1°F

Figure D.1 Input of the bin sorting toolkit

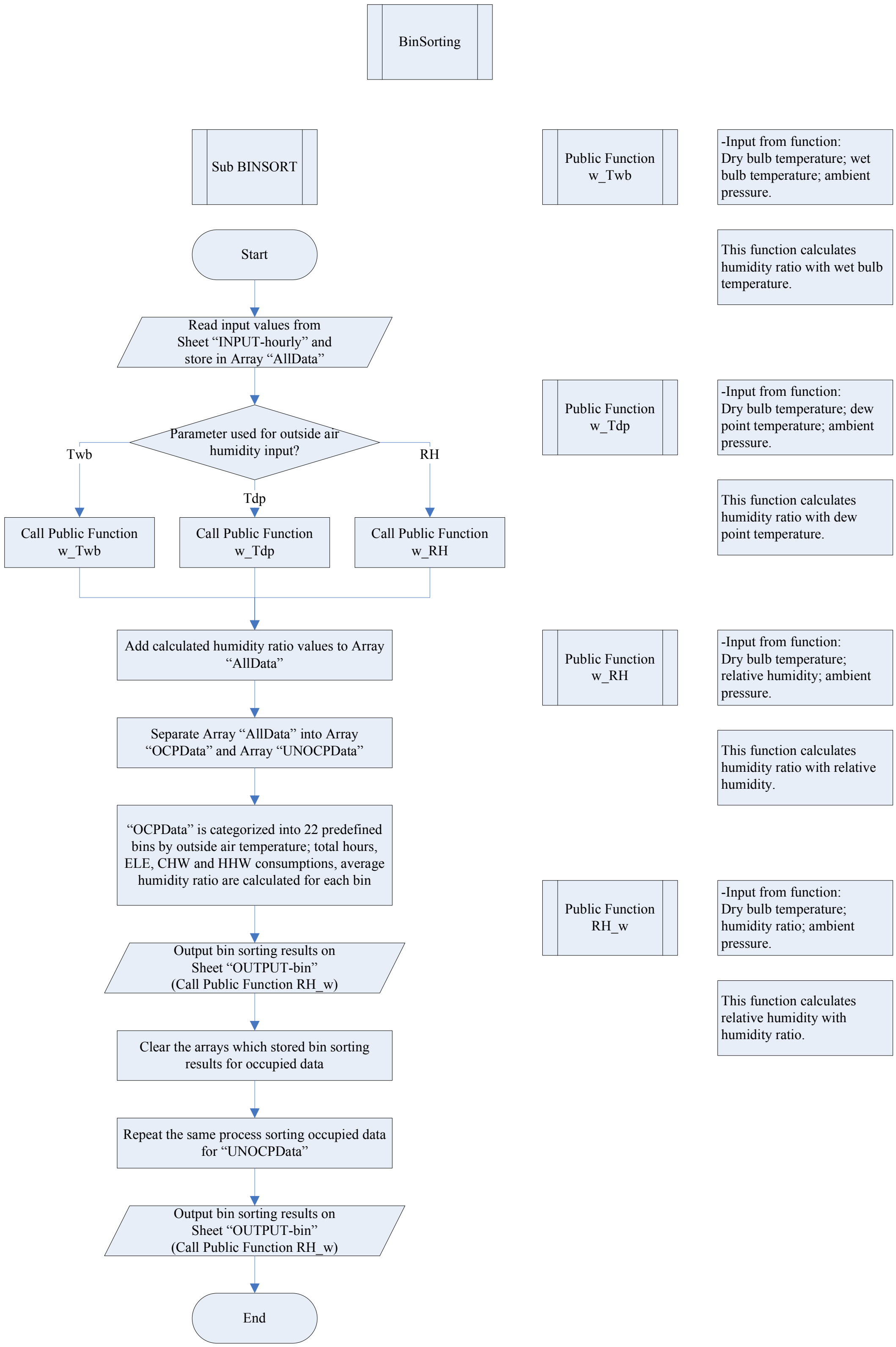


Figure D.2 Flow chart of the bin sorting toolkit

APPENDIX E

OUTPUT IN PESE TOOLKIT

The PESE Toolkit provides a comprehensive output of results by bin in the Sheet "BinData". These results are categorized into six major sections: current and optimized energy costs, potential energy cost savings, optimized energy consumption, space loads, system loads, and system parameters. The parameters included in each section are listed in Table E.1. Additionally, most of these output parameters are illustrated in the five chart sheets in the PESE Toolkit. Each chart sheet contains four plots, each of which represents certain categorized parameters. The criteria used to categorize the parameters in each plot are given in Table E.2. Figure E.1 shows the chart sheet No.1 – 3. Chart sheet No.4 and 5 are omitted since they are same in design with chart sheet No.2 and 3.

Table E.1 Output parameters in Sheet "BinData" in PESE Toolkit

Section	Output parameter	Symbol	Unit
Current bin energy cost	Current ELE cost	ELECost_Cur	$
	Current CHW cost	CHWCost_Cur	
	Current HHW cost	HHWCost_Cur	
	Current total cost	TotCost_Cur	
Optimized bin energy cost	Optimized ELE cost	ELECost_Opt	
	Optimized CHW cost	CHWCost_ Opt	
	Optimized HHW cost	HHWCost_ Opt	
	Optimized total cost	TotCost_ Opt	
Potential energy cost savings	ELE dollar savings	ELE_$Sav	$
	ELE percentage savings	ELE_%Sav	%
	CHW dollar savings	CHW_$Sav	$
	CHW percentage savings	CHW_%Sav	%
	HHW dollar savings	HHW_$Sav	$
	HHW percentage savings	HHW_%Sav	%
	Total dollar savings	Tot_$Sav	$
	Total percentage savings	Tot_%Sav	%
Optimized bin energy consumptions	Optimized ELE-LTEQ consumption	LTEQ_Opt	kWh
	Optimized ELE-FANP consumption	FANP_Opt	
	Optimized ELE consumption	ELE_Opt	
	Optimized CHW consumption	CHW_Opt	kBtu
	Optimized HHW consumption	HHW_Opt	
Optimized system parameter settings	Optimized exterior zone temperature	Te_Opt	°F
	Optimized interior zone temperature	Ti_Opt	
	Optimized cold deck temperature	TCL_Opt	
	Optimized hot deck temperature	THL_Opt	
	Optimized exterior zone minimum air flow	Vemin_Opt	cfm
	Optimized interior zone minimum air flow	Vimin_Opt	cfm
	Optimized minimum outside air flow ratio	XOAmin_Opt	-
	Optimized minimum outside air flow	VOAmin_Opt	cfm

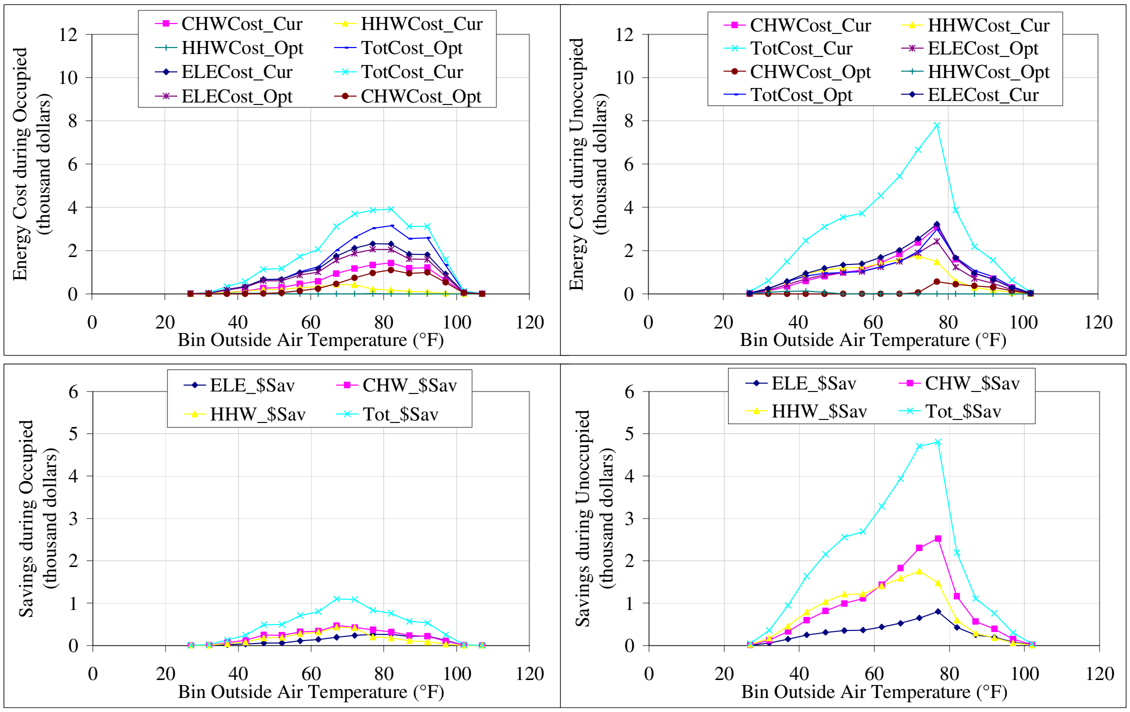
Loads	Exterior zone sensible load	qes	Btu/hr
	Interior zone sensible load	qis	
	Exterior zone latent load	qel	
	Interior zone latent load	qil	
Exterior zone sensible load components	Transmission load conduction	QTe	Btu/hr
	Solar heat gain through glass	QSOLe	
	Transmission load solar component	QTSe	
	Interior load - occupants	QsOCPe	
	Interior load - Lighting and equipment	QLTEQe	
Interior zone sensible load components	Transmission load conduction	QTi	Btu/hr
	Solar heat gain through glass	QSOLi	
	Transmission load solar component	QTSi	
	Interior load - occupants	QsOCPi	
	Interior load - Lighting and equipment	QLTEQi	
Simulated system loads	Cooling coil sensible load	qCs	Btu/hr
	Cooling coil latent load	qCl	
	Total cooling load	qCT	
	Preheat coil load	qPH	
	Heating coil load (dual duct)	qH	
	Exterior zone reheat load (single duct)	qeRH	
	Interior zone reheat load (single duct)	qiRH	
	Total heating load	qHT	
	Total fan power	qFT	
Simulated temperature parameters	Temperature rise across supply fan	dTSF	°F
	Temperature rise across return fan	dTRF	
	Exterior zone supply temperature	TeS	
	Interior zone supply temperature	TiS	
	Return air temperature	TR	
	Mixed air temperature	TMA	
	Preheat coil leaving temperature	TPH	
	Cooling/heating coil entering temperature	TCE	

Simulated air flow rate parameters	Exterior zone cold air flow (dual duct)	VeC	cfm
	Interior zone cold air flow (dual duct)	ViC	
	Exterior zone hot air flow (dual duct)	VeH	
	Interior zone hot air flow (dual duct)	ViH	
	Cold deck air flow (dual duct)	VC	
	Hot deck air flow (dual duct)	VH	
	Exterior zone supply air flow	Ve	
	Interior zone supply air flow	Vi	
	Outside air flow	VOA	
	Return air flow	VR	
	Total air flow	VT	
Simulated air flow fraction parameters	Exterior zone cold air flow ratio (dual duct)	XeC	-
	Interior zone cold air flow ratio (dual duct)	XiC	
	Exterior zone hot air flow ratio (dual duct)	XeH	
	Interior zone hot air flow ratio (dual duct)	XiH	
	Cold deck air flow ratio (dual duct)	XC	
	Hot deck air flow ratio (dual duct)	XH	
	Exterior zone supply air flow ratio	Xe	
	Interior zone supply air flow ratio	Xi	
	Outside air flow ratio	XOA	
	Return air flow ratio	XR	
Simulated fan power & humidity parameters	Partial load ratio (VAV)	PLR	-
	Supply fan power	PSF	hp
	Return fan power	PRF	
	Return air humidity ratio	wR	lb_w/lb_{da}
	Mixed air humidity ratio	wMA	
	Cooling coil leaving air humidity ratio	wCL	
	Whether cooling coil is wet	WetCoil	-
	Zone relative humidity	RH	%

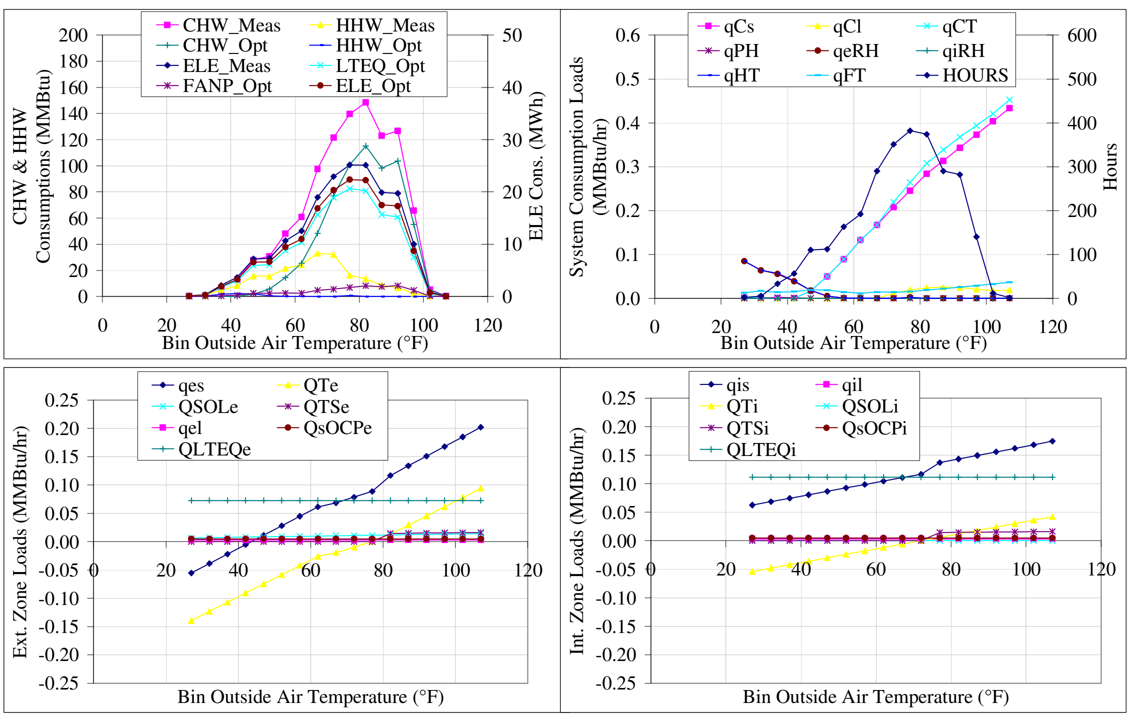
Table E.2 Component charts in each chart sheet in PESE Toolkit

Chart Sheet	Plot*	Unit
(1) energy cost and saving	(a) energy cost during occupied (b) energy cost during unoccupied (c) savings during occupied (d) savings during unoccupied	Thousand $
(2) consumptions and loads during occupied period	(a) measured and optimized energy use	MMBtu; MWh
	(b) system consumption loads and bin hours	MMBtu/hr; hours
	(c) exterior zone loads	MMBtu/hr
	(d) interior zone loads	MMBtu/hr
(3) system parameters during occupied period	(a) temperatures	°F
	(b) air flow rates	Thousand cfm
	(c) humidity ratios and relative humidity	Lbw/lbda
	(d) air flow ratios	%
(4) consumptions and loads during unoccupied period	(a) measured and optimized energy use	MMBtu; MWh
	(b) system consumption loads and bin hours	MMBtu/hr; hours
	(c) exterior zone loads	MMBtu/hr
	(d) interior zone loads	MMBtu/hr
(5) system parameters during unoccupied period	(a) temperatures	°F
	(b) air flow rates	Thousand cfm
	(c) humidity ratios and relative humidity	Lbw/lbda
	(d) air flow ratios	%

*In each chart sheet, (a), (b), (c), (d) refer to the upper left, upper right, lower left and lower right plot.

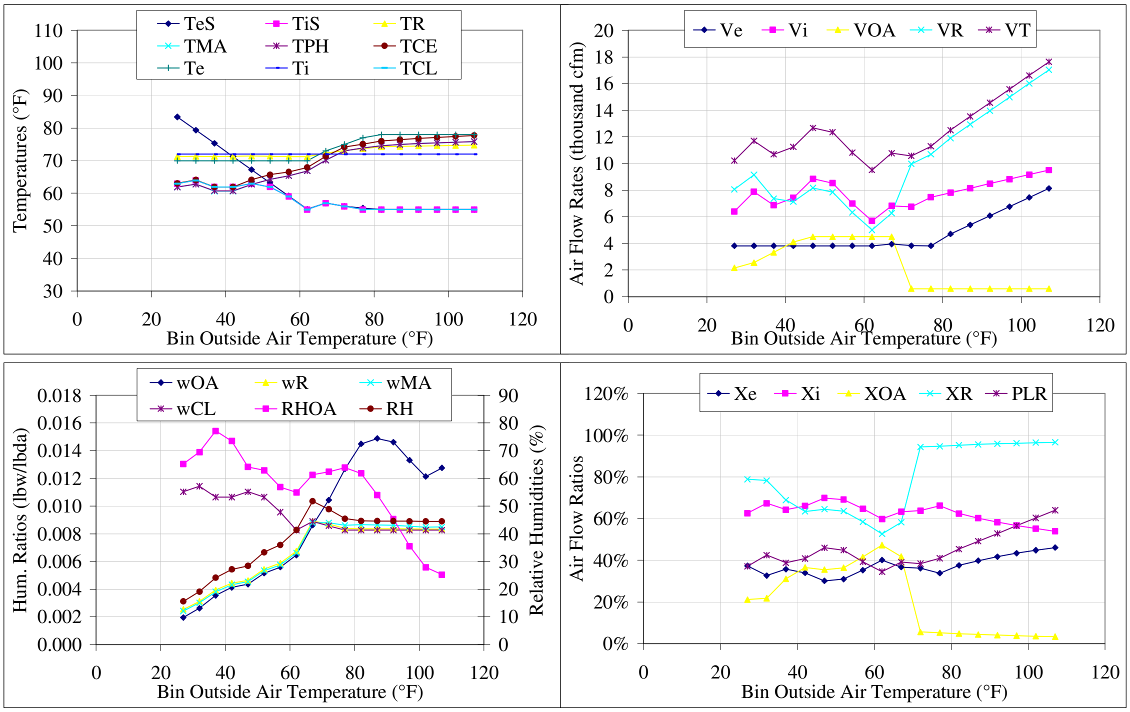


(a) Chart sheet No.1



(b) Chart sheet No.2

Figure E.1 Chart sheets in PESE Toolkit



(c) Chart sheet No.3

Figure E.1 Continued

APPENDIX F

FLOW CHARTS OF PESE TOOLKIT

There are 6 modules in the PESE program as listed in Table F.1. The structure of the program is illustrated with Figure F.1 at the module level and each module is further explored with individual flow charts (Figure F.2 to Figure F.7).

Table F.1 Main function of modules in PESE Toolkit

Module Name	**Main Function**
Main	Organizes the whole program: reads input from spreadsheet, executes optimization bin by bin for occupied and unoccupied periods, outputs results and plots.
Optimization	Performs exhaustive search for the combination of parameter settings which yields the minimum energy cost for a particular bin through air-side system simulation.
LoadCal	Calculates space loads with weather data for a particular bin.
SystemSim	Performs air-side system simulation given the system type and space loads.
OtherFun	Includes auxiliary functions for calculations of outside air flow, fan power and psychrometric parameters.
PlotNFormat	Includes subroutines which format data output on spreadsheet and generate plots.

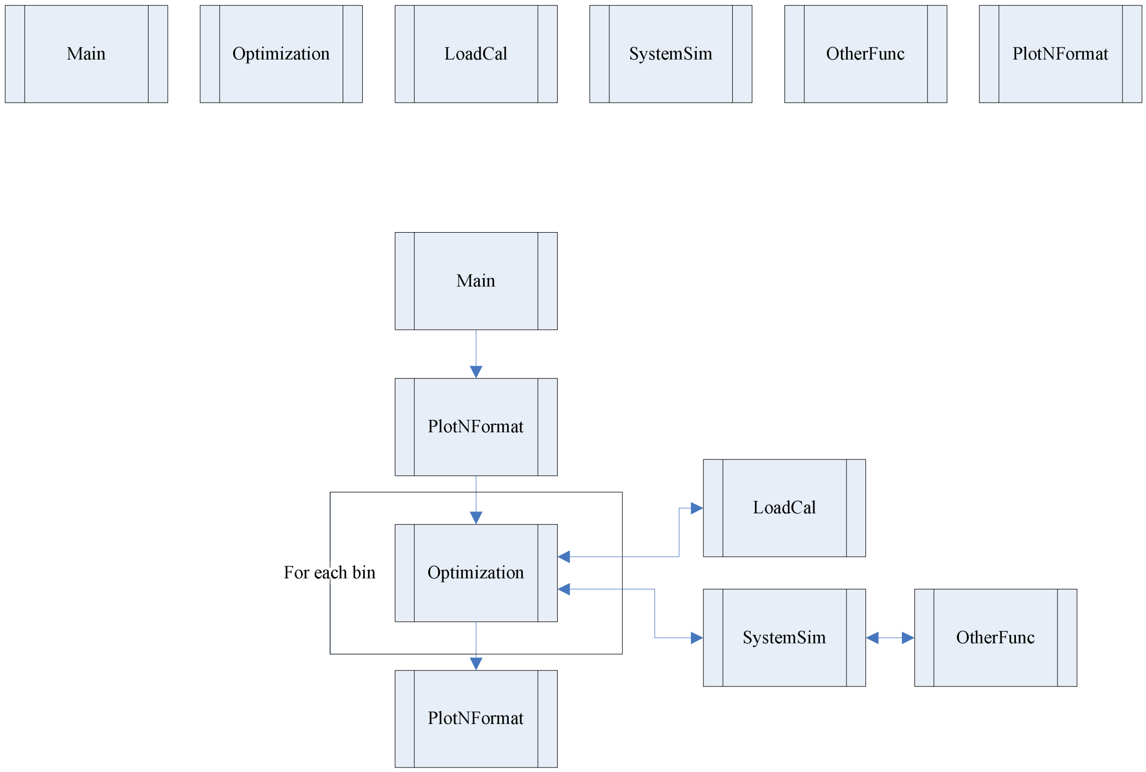


Figure F.1 Flow chart of modules in PESE Toolkit

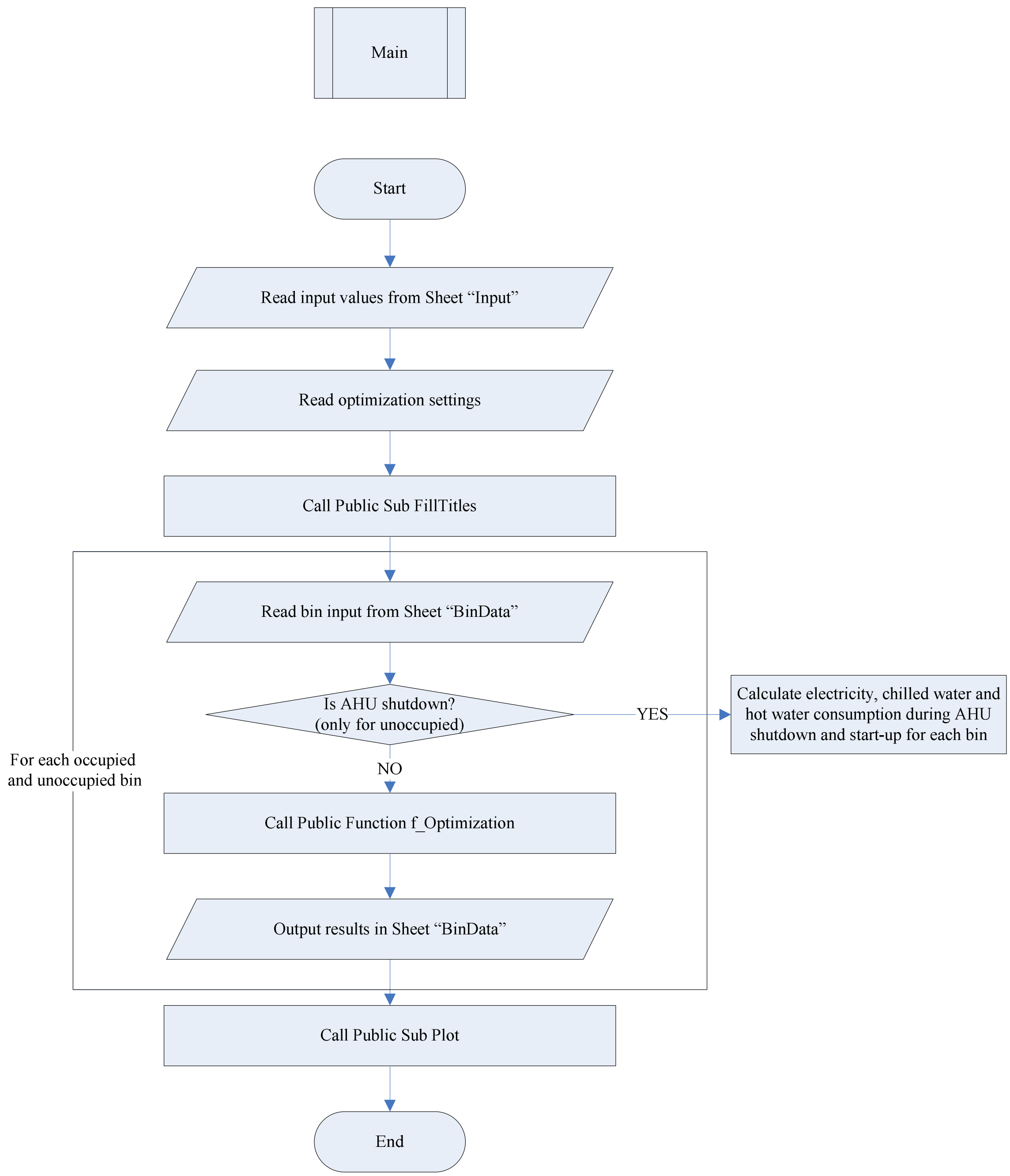


Figure F.2 Flow chart of module “Main”

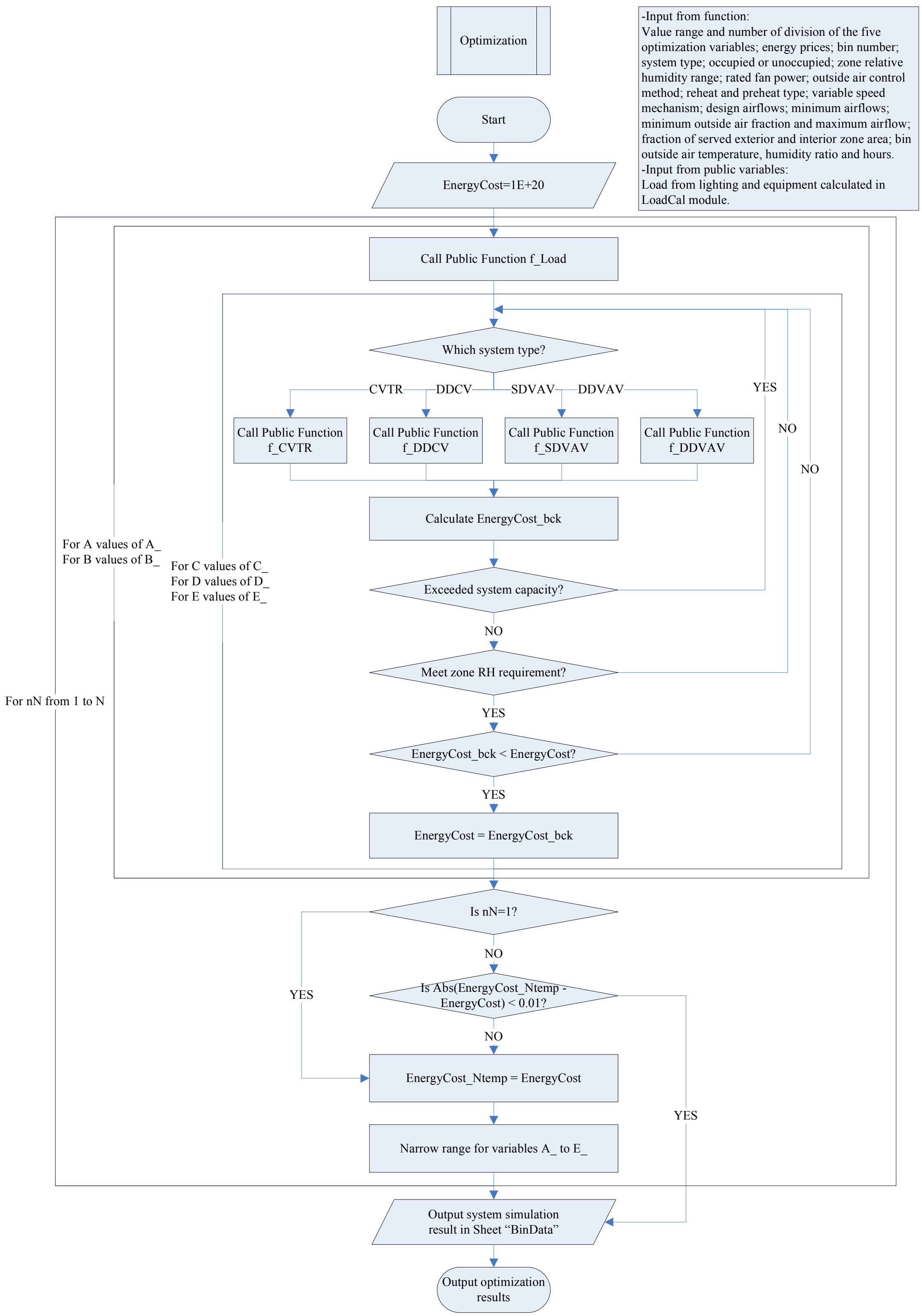


Figure F.3 Flow chart of module "Optimization"

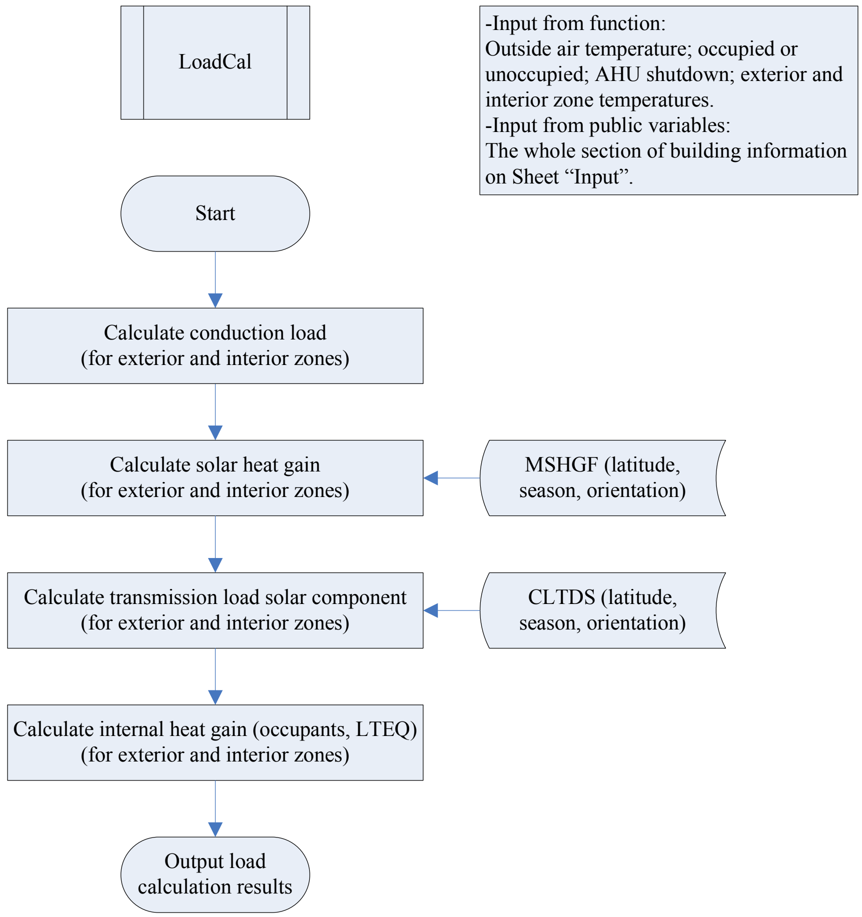


Figure F.4 Flow chart of module "LoadCal"

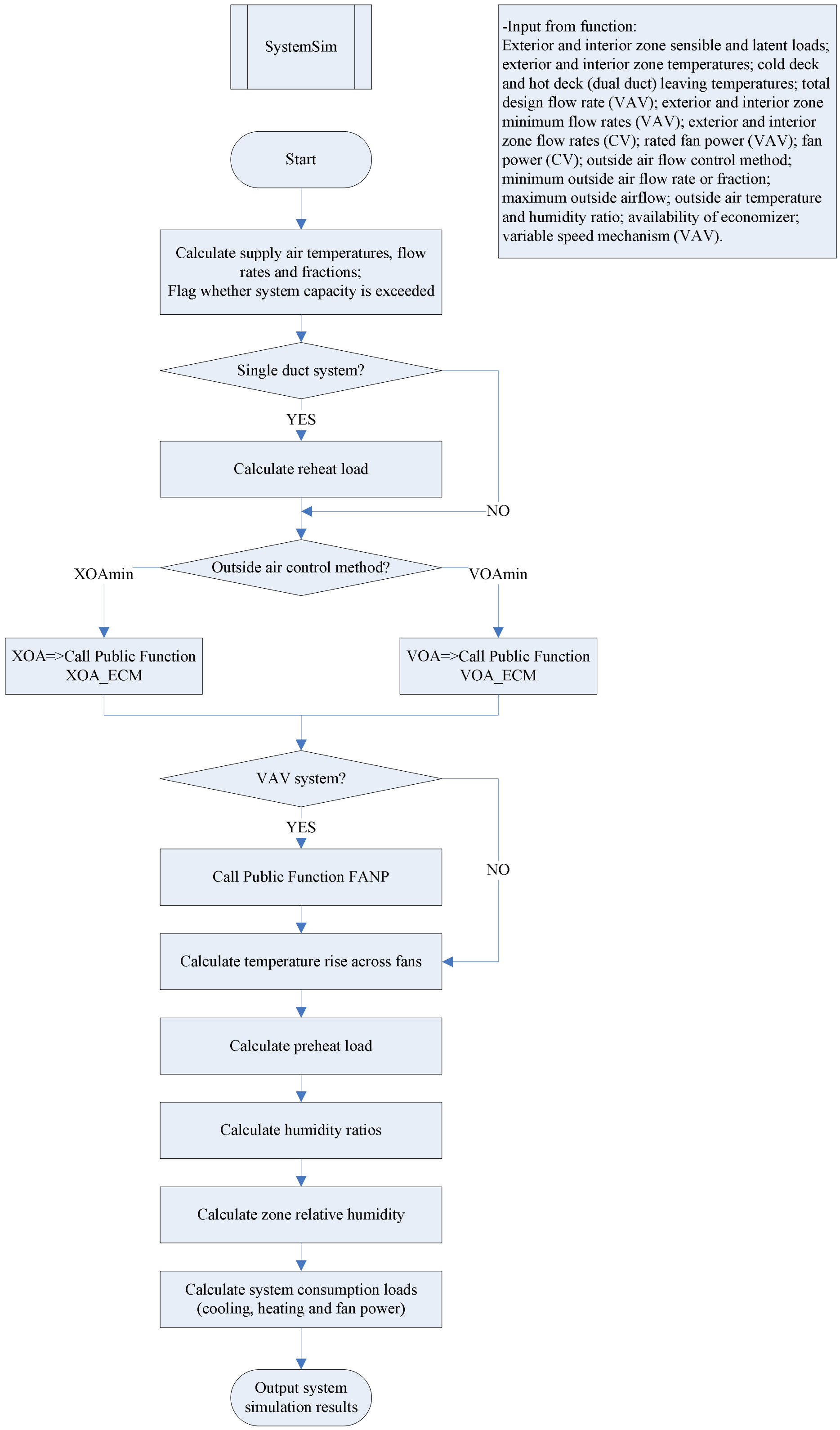


Figure F.5 Flow chart of module “SystemSim”

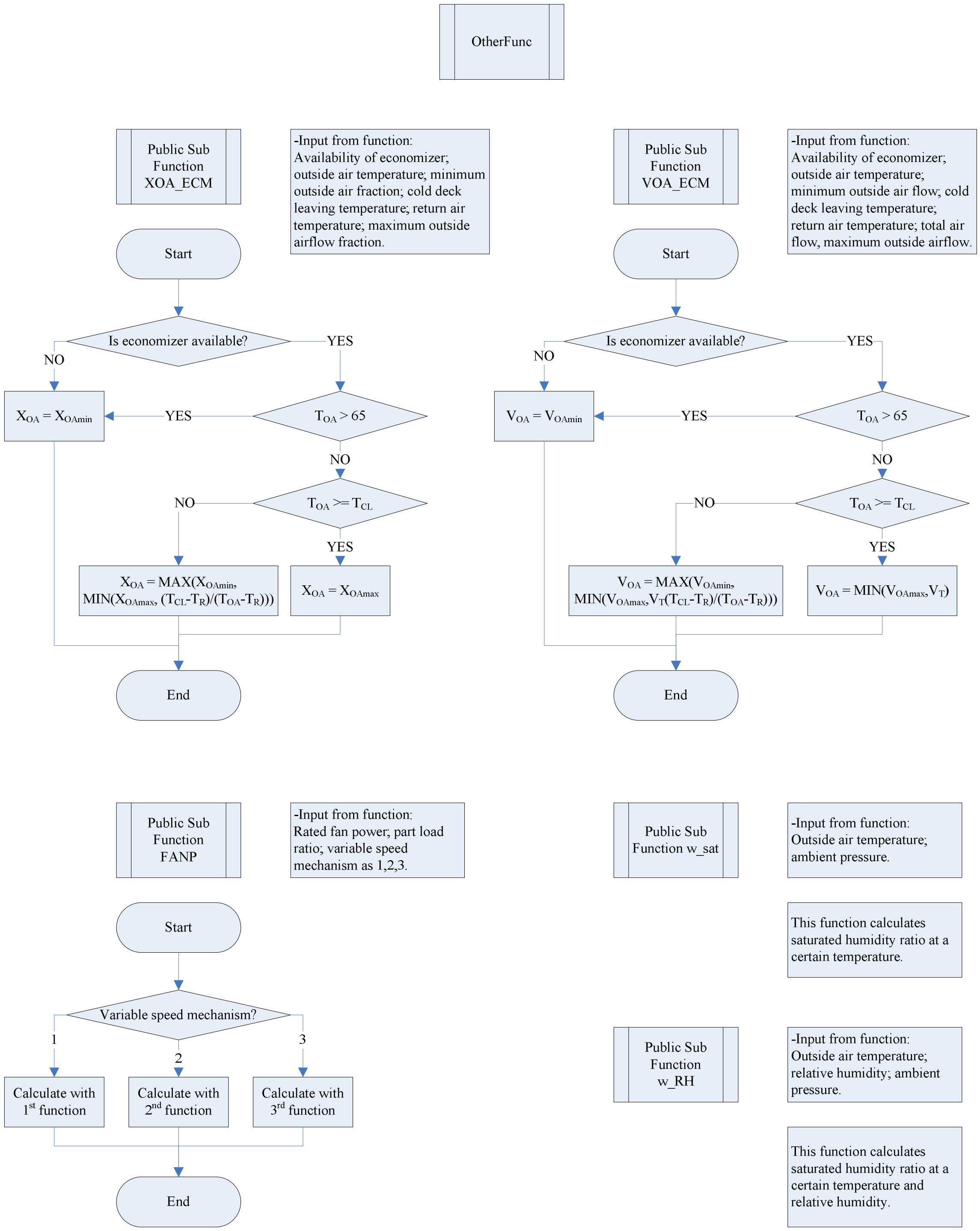


Figure F.6 Flow chart of module "OtherFun"

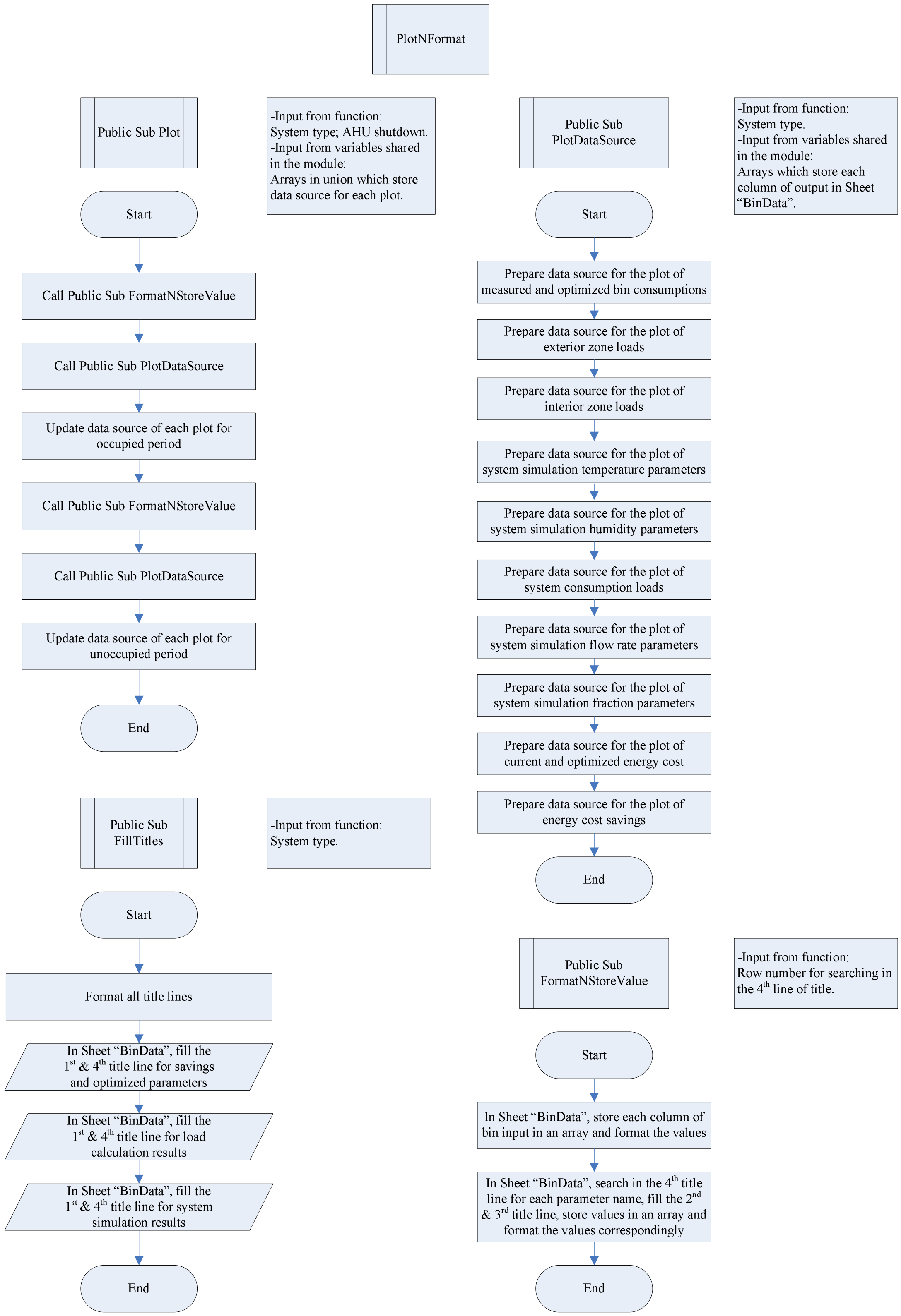


Figure F.7 Flow chart of module "PlotNFormat"

APPENDIX G

CODES IN PESE TOOLKIT

The VBA codes used in the PESE Toolkit are given in this appendix. It is helpful to refer the flow charts of the tool in Appendix C in reading the codes. In order to save space, only those closely related to algorithms and calculations are displayed. Codes are omitted for the module of PlotNFormat, and also inside the other modules, subroutines, and functions regarding definition of variables, reading input from spreadsheet, writing output to spreadsheet, formatting, etc.

```
Sub Main()

    'convert VAV method and OA control method to number as system simulation input
    If VAVM = "Variable Speed Drive" Then VAVM_n = 1
    If VAVM = "Inlet Vanes Control" Then VAVM_n = 2
    If VAVM = "Outlet Dampers" Then VAVM_n = 3
    If OACtrl = "XOAmin" Then OACtrl_n = 1
    If OACtrl = "VOAmin" Then OACtrl_n = 2
    If YN_VOA = True Then HasEcmz = False

    Call FillTitles(SysType)

    'settings of optimization variables during occupied period
    N = 3
    A = n_Te_ocp
    b_A1 = b_Te1_ocp
    b_A2 = b_Te2_ocp
    B = n_Ti_ocp
    b_B1 = b_Ti1_ocp
    b_B2 = b_Ti2_ocp
    C = n_TCL_ocp
    b_C1 = b_TCL2_ocp 'higher TCL is prefered
    b_C2 = b_TCL1_ocp
    D = n_THL_ocp
    b_D1 = b_THL1_ocp
    b_D2 = b_THL2_ocp
    E = n_VOA_ocp
    b_E1 = b_VOA1_ocp
    b_E2 = b_VOA2_ocp

    'MAIN SUB BIN BY BIN
    For i = 0 To 21
        'OCCUPIED BINS
        If ThisWorkbook.Worksheets("BinData").Cells(i + 5, 2) = "" Then
            ThisWorkbook.Worksheets("BinData").Cells(i + 5, 2).EntireRow.Hidden = True
        Else
            'Read TOA, wOA and hours from bin input
            TOAbin_ocp = ThisWorkbook.Worksheets("BinData").Cells(i + 5, 2)
            wOAbin_ocp = ThisWorkbook.Worksheets("BinData").Cells(i + 5, 3)
            Hrsbin_ocp = ThisWorkbook.Worksheets("BinData").Cells(i + 5, 5)

            'Cold and hot deck leaving temperatures
            If TOAbin_ocp <= TOA_TCL1 Then TCL_fTOA = TCL_1
            If TOAbin_ocp >= TOA_TCL2 Then TCL_fTOA = TCL_2
            If TOAbin_ocp > TOA_TCL1 And TOAbin_ocp < TOA_TCL2 Then _
                TCL_fTOA = TCL_1 + (TCL_1 - TCL_2) / (TOA_TCL1 - TOA_TCL2) * (TOAbin_ocp - TOA_TCL1)
```

```
        If TOAbin_ocp <= TOA_THL1 Then THL_fTOA = THL_1
        If TOAbin_ocp >= TOA_THL2 Then THL_fTOA = THL_2
        If TOAbin_ocp > TOA_THL1 And TOAbin_ocp < TOA_THL2 Then _
            THL_fTOA = THL_1 + (THL_1 - THL_2) / (TOA_THL1 - TOA_THL2) * (TOAbin_ocp - TOA_THL1)

        'for variables which are not selected for optimization
        If YN_Te = False Then
            A = 2
            b_A1 = Te_ocp
            b_A2 = Te_ocp
        End If

        If YN_Ti = False Then
            B = 2
            b_B1 = Ti_ocp
            b_B2 = Ti_ocp
        End If

        If YN_TCL = False Then
            C = 2
            b_C1 = TCL_fTOA
            b_C2 = TCL_fTOA
        End If

        If YN_THL = False Then
            D = 2
            b_D1 = THL_fTOA
            b_D2 = THL_fTOA
        End If

        If YN_VOA = False Then
            E = 2
            b_E1 = VOAmin_ocp
            b_E2 = VOAmin_ocp
        End If

        'calculate optimized energy cost and store in array
        Array_Optimization_ocp = f_Optimization(N, _
                                A, b_A1, b_A2, B, b_B1, b_B2, C, b_C1, b_C2, _
                                D, b_D1, b_D2, E, b_E1, b_E2, _
                                Price_ELE, Price_CHW, Price_HHW, i, SysType, True, _
                                RHz1, RHz2, PSF_rated, PRF_rated, _
                                OACtrl_n, HasEcmz, ReheatType, PreheatType, Ve, Vi, _
                                VAVM_n, VTD, Vemin_ocp, Vimin_ocp, XOAmin_ocp, VOAmax, FracAe, _
                                FracAi, TOAbin_ocp, , wOAbin_ocp, , Hrsbin_ocp)
    End If
Next i

'settings of optimization variables during unoccupied period
N = 3
A = n_Te_unocp
b_A1 = b_Te1_unocp
b_A2 = b_Te2_unocp
B = n_Ti_unocp
b_B1 = b_Ti1_unocp
b_B2 = b_Ti2_unocp
C = n_TCL_unocp
b_C1 = b_TCL2_unocp
b_C2 = b_TCL1_unocp
D = n_THL_unocp
b_D1 = b_THL1_unocp
b_D2 = b_THL2_unocp
E = n_VOA_unocp
b_E1 = b_VOA1_unocp
b_E2 = b_VOA2_unocp


For i = 0 To 21
    'UNOCCUPIED BINS
    If ThisWorkbook.Worksheets("BinData").Cells(i + 37, 2) = "" Then
        ThisWorkbook.Worksheets("BinData").Cells(i + 37, 2).EntireRow.Hidden = True
    Else
        TOAbin_unocp = ThisWorkbook.Worksheets("BinData").Cells(i + 37, 2)
        wOAbin_unocp = ThisWorkbook.Worksheets("BinData").Cells(i + 37, 3)
        Hrsbin_unocp = ThisWorkbook.Worksheets("BinData").Cells(i + 37, 5)

        If TOAbin_unocp <= TOA_TCL1 Then TCL_fTOA = TCL_1
        If TOAbin_unocp >= TOA_TCL2 Then TCL_fTOA = TCL_2
        If TOAbin_unocp > TOA_TCL1 And TOAbin_unocp < TOA_TCL2 Then _
            TCL_fTOA = TCL_1 + (TCL_1 - TCL_2) / (TOA_TCL1 - TOA_TCL2) * (TOAbin_unocp - TOA_TCL1)

        If TOAbin_unocp <= TOA_THL1 Then THL_fTOA = THL_1
        If TOAbin_unocp >= TOA_THL2 Then THL_fTOA = THL_2
        If TOAbin_unocp > TOA_THL1 And TOAbin_unocp < TOA_THL2 Then _
            THL_fTOA = THL_1 + (THL_1 - THL_2) / (TOA_THL1 - TOA_THL2) * (TOAbin_unocp - TOA_THL1)
```

```
        If YN_Te = False Then
            A = 2
            b_A1 = Te_unocp
            b_A2 = Te_unocp
        End If

        If YN_Ti = False Then
            B = 2
            b_B1 = Ti_unocp
            b_B2 = Ti_unocp
        End If

        If YN_TCL = False Then
            C = 2
            b_C1 = TCL_fTOA
            b_C2 = TCL_fTOA
        End If

        If YN_THL = False Then
            D = 2
            b_D1 = THL_fTOA
            b_D2 = THL_fTOA
        End If

        If YN_VOA = False Then
            E = 2
            b_E1 = VOAmin_unocp
            b_E2 = VOAmin_unocp
        End If

        If AHUoff = True Then
            Array_load_startup = f_Load(TOAbin_unocp, False, True, Te_ocp, Ti_ocp)
            'cooling coil load at design condition. This is also used as heating coil load
            'because design heating capacity is usually no larger than cooling.
            Qcoil_des = 1.08 * VTD * (Te_ocp - TCL_2)
            'how long the start up takes depends on time needed to remove exterior zone load
            Hrs_startup = Abs(Array_load_startup(0) * FracAe) * Hrsbin_unocp / Qcoil_des
            With ThisWorkbook.Worksheets("BinData")
                If Array_load_startup(0) < 0 Then  'heating required in exterior zone
                    'output start-up fan power, cooling and heating load
                    Startup_FANP = 0.7457 * (PSF_rated + PRF_rated) * Hrs_startup
                    If Array_load_startup(1) < 0 Then
                        Startup_CHW = 0
                        Startup_HHW = Abs(Array_load_startup(0) * FracAe + Array_load_startup(1) _
                        * FracAi) * Hrsbin_unocp / 1000
                    Else
                        Startup_CHW = Array_load_startup(1) * FracAi * Hrsbin_unocp / 1000
                        Startup_HHW = Abs(Array_load_startup(0) * FracAe) * Hrsbin_unocp / 1000
                    End If
                Else 'cooling required in exterior zone
                    Startup_FANP = 0.7457 * (PSF_rated + PRF_rated) * Hrs_startup
                    Startup_CHW = (Array_load_startup(0) * FracAe + Array_load_startup(1) _
                    * FracAi) * Hrsbin_unocp / 1000
                    Startup_HHW = 0
                End If
                If ReheatType = "Electric" Then
                    .Cells(i + 37, 25) = LTEQ_unocp * (Ae * FracAe + Ai * FracAi) / (Ae + Ai) * _
                    Hrsbin_unocp
                    .Cells(i + 37, 26) = Startup_FANP
                    .Cells(i + 37, 27) = .Cells(i + 37, 25)+ .Cells(i + 37, 26)+ Startup_HHW/3.412
                    .Cells(i + 37, 28) = Startup_CHW
                    .Cells(i + 37, 29) = 0
                Else
                    .Cells(i + 37, 25) = LTEQ_unocp * (Ae * FracAe + Ai * FracAi) / (Ae + Ai) _
                    * Hrsbin_unocp
                    .Cells(i + 37, 26) = Startup_FANP
                    .Cells(i + 37, 27) = .Cells(i + 37, 25) + .Cells(i + 37, 26)
                    .Cells(i + 37, 28) = Startup_CHW
                    .Cells(i + 37, 29) = Startup_HHW
                End If
            End With
        Else
            Array_Optimization_unocp = f_Optimization(N, _
                                    A, b_A1, b_A2, B, b_B1, b_B2, C, b_C1, b_C2, _
                                    D, b_D1, b_D2, E, b_E1, b_E2, _
                                    Price_ELE, Price_CHW, Price_HHW, i, SysType, False, _
                                    0, 70, PSF_rated, PRF_rated, _
                                    OACtrl_n, HasEcmz, ReheatType, PreheatType, Ve, Vi, _
                                    VAVM_n, VTD, Vemin_unocp, Vimin_unocp, XOAmin_unocp, VOAmax, _
                                    FracAe, FracAi,, TOAbin_unocp, , wOAbin_unocp, , Hrsbin_unocp)
        End If
    End If
Next i

Call Plot(SysType, AHUoff)

End Sub
```

```
Public Function f_Optimization(ByVal N As Integer, _
    ByVal A As Integer, ByVal b_A1 As Double, ByVal b_A2 As Double, _
    ByVal B As Integer, ByVal b_B1 As Double, ByVal b_B2 As Double, _
    ByVal C As Integer, ByVal b_C1 As Double, ByVal b_C2 As Double, _
    ByVal D As Integer, ByVal b_D1 As Double, ByVal b_D2 As Double, _
    ByVal E As Integer, ByVal b_E1 As Double, ByVal b_E2 As Double, _
    ByVal Price_ELE As Double, ByVal Price_CHW As Double, ByVal Price_HHW As Double, _
    ByVal BinNum As Integer, ByVal SysType As String, ByVal IFOCP As Boolean, _
    ByVal RHz1 As Double, ByVal RHz2 As Double, _
    ByVal PSF_rated As Double, ByVal PRF_rated As Double, _
    ByVal OACtrl_n As Integer, ByVal HasEcmz As Boolean, _
    ByVal ReheatType As String, ByVal PreheatType As String, _
    ByVal Ve As Double, ByVal Vi As Double, _
    ByVal VAVM_n As Integer, ByVal VTD As Double, _
    ByVal Vemin As Double, ByVal Vimin As Double, ByVal XOAmin As Double, ByVal VOAmax, _
    ByVal FracAe As Double, ByVal FracAi As Double, _
    Optional ByVal TOAbin_ocp As Double, Optional ByVal TOAbin_unocp As Double, _
    Optional ByVal wOAbin_ocp As Double, Optional ByVal wOAbin_unocp As Double, _
    Optional ByVal Hrsbin_ocp As Double, Optional ByVal Hrsbin_unocp As Double)
    'A-E are how to divide within the boundary of each variable

    EnergyCost = 1E+20
    Flag = False

    'Generate mesh for to be optimized variables
    For nN = 1 To N
        For nA = 1 To A
            A_ = b_A1 + (b_A2 - b_A1) / (A - 1) * (nA - 1)
            For nB = 1 To B
                B_ = b_B1 + (b_B2 - b_B1) / (B - 1) * (nB - 1)

                If IFOCP = True Then
                    'calculate load and store in an array
                    Array_Load_ocp = f_Load(TOAbin_ocp, True, False, A_, B_)
                    'apply factor to load components according to the area served by the system
                    Loadqes_ocp = Array_Load_ocp(0) * FracAe
                    Loadqis_ocp = Array_Load_ocp(1) * FracAi
                    Loadqel_ocp = Array_Load_ocp(2) * FracAe
                    Loadqil_ocp = Array_Load_ocp(3) * FracAi
                Else
                    Array_Load_unocp = f_Load(TOAbin_unocp, False, False, A_, B_)
                    Loadqes_unocp = Array_Load_unocp(0) * FracAe
                    Loadqis_unocp = Array_Load_unocp(1) * FracAi
                    Loadqel_unocp = Array_Load_unocp(2) * FracAe
                    Loadqil_unocp = Array_Load_unocp(3) * FracAi
                End If

                For nC = 1 To C
                    C_ = b_C1 + (b_C2 - b_C1) / (C - 1) * (nC - 1)
                    For nD = 1 To D
                        D_ = b_D1 + (b_D2 - b_D1) / (D - 1) * (nD - 1)
                        For nE = 1 To E
                            E_ = b_E1 + (b_E2 - b_E1) / (E - 1) * (nE - 1)
                            If IFOCP = True Then
                                Select Case SysType
                                    Case "CVTR"
                                        Array_System_ocp = f_CVTR(Loadqes_ocp, Loadqis_ocp, _
                                        Loadqel_ocp, Loadqil_ocp, _
                                                            A_, B_, C_, Ve, Vi, _
                                                            PSF_rated, PRF_rated, OACtrl_n, _
                                                            XOAmin, E_, VOAmax, TOAbin_ocp, _
                                                            wOAbin_ocp, HasEcmz)
                                        LTEQ_Opt = (FracAe * QLTEQe_ocp + FracAi * QLTEQi_ocp) * _
                                        Hrsbin_ocp / 3412 'calculate in main
                                        FANP_Opt = Array_System_ocp(7) * Hrsbin_ocp / 3412
                                        ELE_Opt = LTEQ_Opt + FANP_Opt
                                        CHW_Opt = Array_System_ocp(2) * Hrsbin_ocp / 1000
                                        HHW_Opt = Array_System_ocp(6) * Hrsbin_ocp / 1000
                                        RHstore = Array_System_ocp(28)
                                        YN_ExCap = Array_System_ocp(29)

                                    Case "DDCV"
                                        Array_System_ocp = f_DDCV(Loadqes_ocp, Loadqis_ocp, _
                                        Loadqel_ocp, Loadqil_ocp, _
                                                            A_, B_, C_, D_, Ve, Vi, _
                                                            PSF_rated, PRF_rated, OACtrl_n, _
                                                            XOAmin, E_, VOAmax, TOAbin_ocp, _
                                                            wOAbin_ocp, HasEcmz)
                                        LTEQ_Opt = (FracAe * QLTEQe_ocp + FracAi * QLTEQi_ocp) * _
                                        Hrsbin_ocp / 3412
                                        FANP_Opt = Array_System_ocp(6) * Hrsbin_ocp / 3412
                                        ELE_Opt = LTEQ_Opt + FANP_Opt
                                        CHW_Opt = Array_System_ocp(2) * Hrsbin_ocp / 1000
                                        HHW_Opt = Array_System_ocp(5) * Hrsbin_ocp / 1000
                                        RHstore = Array_System_ocp(40)
                                        YN_ExCap = Array_System_ocp(41)
```

```
            Case "SDVAV"
                Array_System_ocp = f_SDVAV(Loadqes_ocp, Loadqis_ocp, _
                Loadqel_ocp, Loadqil_ocp, _
                                    A_, B_, C_, VTD, Vemin, Vimin, _
                                    PSF_rated, PRF_rated, OACtrl_n, _
                                    XOAmin, E_, VOAmax, TOAbin_ocp, _
                                    wOAbin_ocp, HasEcmz, VAVM_n)
                LTEQ_Opt = (FracAe * QLTEQe_ocp + FracAi * QLTEQi_ocp) * _
                Hrsbin_ocp / 3412
                FANP_Opt = Array_System_ocp(7) * Hrsbin_ocp / 3412
                If ReheatType = "Electric" And PreheatType = "Electric" Then
                    ELE_Opt = LTEQ_Opt + FANP_Opt + (Array_System_ocp(3) + _
                    Array_System_ocp(4) + Array_System_ocp(5)) * Hrsbin_ocp _
                    / 3412
                    HHW_Opt = 0
                ElseIf ReheatType = "Electric" And PreheatType = "Hot Water" _
                Then
                    ELE_Opt = LTEQ_Opt + FANP_Opt + (Array_System_ocp(4) + _
                    Array_System_ocp(5)) * Hrsbin_ocp / 3412
                    HHW_Opt = Array_System_ocp(3) * Hrsbin_ocp / 1000
                ElseIf ReheatType = "Hot Water" And PreheatType = "Electric" _
                Then
                    ELE_Opt = LTEQ_Opt + FANP_Opt + Array_System_ocp(3) * _
                    Hrsbin_ocp / 3412
                    HHW_Opt = (Array_System_ocp(4) + Array_System_ocp(5)) * _
                    Hrsbin_ocp / 1000
                Else
                    ELE_Opt = LTEQ_Opt + FANP_Opt
                    HHW_Opt = Array_System_ocp(6) * Hrsbin_ocp / 1000
                End If
                CHW_Opt = Array_System_ocp(2) * Hrsbin_ocp / 1000
                RHstore = Array_System_ocp(35)
                YN_ExCap = Array_System_ocp(36)

            Case "DDVAV"
                Array_System_ocp = f_DDVAV(Loadqes_ocp, Loadqis_ocp, _
                Loadqel_ocp, Loadqil_ocp, _
                                    A_, B_, C_, D_, VTD, Vemin, Vimin, _
                                    PSF_rated, PRF_rated, OACtrl_n, _
                                    XOAmin, E_, VOAmax, TOAbin_ocp, _
                                    wOAbin_ocp, HasEcmz, VAVM_n)
                LTEQ_Opt = (FracAe * QLTEQe_ocp + FracAi * QLTEQi_ocp) * _
                Hrsbin_ocp / 3412
                FANP_Opt = Array_System_ocp(6) * Hrsbin_ocp / 3412
                ELE_Opt = LTEQ_Opt + FANP_Opt
                CHW_Opt = Array_System_ocp(2) * Hrsbin_ocp / 1000
                HHW_Opt = Array_System_ocp(5) * Hrsbin_ocp / 1000
                RHstore = Array_System_ocp(47)
                YN_ExCap = Array_System_ocp(48)
        End Select
    Else
        Select Case SysType
            Case "CVTR"
                Array_System_unocp = f_CVTR(Loadqes_unocp, Loadqis_unocp, _
                Loadqel_unocp, Loadqil_unocp, _
                                    A_, B_, C_, Ve, Vi, _
                                    PSF_rated, PRF_rated, OACtrl_n, _
                                    XOAmin, E_, VOAmax, TOAbin_unocp, _
                                    wOAbin_unocp, HasEcmz)
                LTEQ_Opt = (FracAe * QLTEQe_unocp + FracAi * QLTEQi_unocp) * _
                Hrsbin_unocp / 3412
                FANP_Opt = Array_System_unocp(7) * Hrsbin_unocp / 3412
                ELE_Opt = LTEQ_Opt + FANP_Opt
                CHW_Opt = Array_System_unocp(2) * Hrsbin_unocp / 1000
                HHW_Opt = Array_System_unocp(6) * Hrsbin_unocp / 1000
                RHstore = Array_System_unocp(28)
                YN_ExCap = Array_System_unocp(29)

            Case "DDCV"
                Array_System_unocp = f_DDCV(Loadqes_unocp, Loadqis_unocp, _
                Loadqel_unocp, Loadqil_unocp, _
                                    A_, B_, C_, D_, Ve, Vi, _
                                    PSF_rated, PRF_rated, OACtrl_n, _
                                    XOAmin, E_, VOAmax, TOAbin_unocp, _
                                    wOAbin_unocp, HasEcmz)
                LTEQ_Opt = (FracAe * QLTEQe_unocp + FracAi * QLTEQi_unocp) * _
                Hrsbin_unocp / 3412
                FANP_Opt = Array_System_unocp(6) * Hrsbin_unocp / 3412
                ELE_Opt = LTEQ_Opt + FANP_Opt
                CHW_Opt = Array_System_unocp(2) * Hrsbin_unocp / 1000
                HHW_Opt = Array_System_unocp(5) * Hrsbin_unocp / 1000
                RHstore = Array_System_unocp(40)
                YN_ExCap = Array_System_unocp(41)
```

```
                            Case "SDVAV"
                                Array_System_unocp = f_SDVAV(Loadqes_unocp, Loadqis_unocp, _
                                Loadqel_unocp, Loadqil_unocp, _
                                                    A_, B_, C_, VTD, Vemin, Vimin, _
                                                    PSF_rated, PRF_rated, OACtrl_n, _
                                                    XOAmin, E_, VOAmax, TOAbin_unocp, _
                                                    wOAbin_unocp, HasEcmz, VAVM_n)
                                LTEQ_Opt = (FracAe * QLTEQe_unocp + FracAi * QLTEQi_unocp) * _
                                Hrsbin_unocp / 3412
                                FANP_Opt = Array_System_unocp(7) * Hrsbin_unocp / 3412
                                If ReheatType = "Electric" And PreheatType = "Electric" Then
                                    ELE_Opt = LTEQ_Opt + FANP_Opt + (Array_System_unocp(3) + _
                                    Array_System_unocp(4) + Array_System_unocp(5)) * _
                                    Hrsbin_unocp / 3412
                                    HHW_Opt = 0
                                ElseIf ReheatType = "Electric" And PreheatType = "Hot Water" _
                                Then
                                    ELE_Opt = LTEQ_Opt + FANP_Opt + (Array_System_unocp(4) + _
                                    Array_System_unocp(5)) * Hrsbin_unocp / 3412
                                    HHW_Opt = Array_System_unocp(3) * Hrsbin_unocp / 1000
                                ElseIf ReheatType = "Hot Water" And PreheatType = "Electric" _
                                Then
                                    ELE_Opt = LTEQ_Opt + FANP_Opt + Array_System_unocp(3) * _
                                    Hrsbin_unocp / 3412
                                    HHW_Opt = (Array_System_unocp(4)+ Array_System_unocp(5)) _
                                    * Hrsbin_unocp / 1000
                                Else
                                    ELE_Opt = LTEQ_Opt + FANP_Opt
                                    HHW_Opt = Array_System_unocp(6) * Hrsbin_unocp / 1000
                                End If
                                CHW_Opt = Array_System_unocp(2) * Hrsbin_unocp / 1000
                                RHstore = Array_System_unocp(35)
                                YN_ExCap = Array_System_unocp(36)

                            Case "DDVAV"
                                Array_System_unocp = f_DDVAV(Loadqes_unocp, Loadqis_unocp, _
                                Loadqel_unocp, Loadqil_unocp, _
                                                    A_, B_, C_, D_, VTD, Vemin, Vimin, _
                                                    PSF_rated, PRF_rated, OACtrl_n, _
                                                    XOAmin, E_, VOAmax, TOAbin_unocp, _
                                                    wOAbin_unocp, HasEcmz, VAVM_n)
                                LTEQ_Opt = (FracAe * QLTEQe_unocp + FracAi * QLTEQi_unocp) * _
                                Hrsbin_unocp / 3412
                                FANP_Opt = Array_System_unocp(6) * Hrsbin_unocp / 3412
                                ELE_Opt = LTEQ_Opt + FANP_Opt
                                CHW_Opt = Array_System_unocp(2) * Hrsbin_unocp / 1000
                                HHW_Opt = Array_System_unocp(5) * Hrsbin_unocp / 1000
                                RHstore = Array_System_unocp(47)
                                YN_ExCap = Array_System_unocp(48)
                        End Select
                    End If
                    'Energy cost calculated at nN, nA, nB, nC, nD, nE
                    EnergyCost_bck = Price_ELE * ELE_Opt + Price_CHW * CHW_Opt / 1000 + _
                    Price_HHW * HHW_Opt / 1000
                    'If newly calculated total energy cost is less while complying with
                    comfort requirement, previously stored value "EnergyCost" will be replaced
                    If YN_ExCap = False And RHstore >= RHz1 And RHstore <= RHz2 And _
                    EnergyCost_bck < EnergyCost Then
                        Flag = True
                        EnergyCost = EnergyCost_bck
                        O_LTEQ_Opt = LTEQ_Opt: O_FANP_Opt = FANP_Opt: O_ELE_Opt = ELE_Opt
                        O_CHW_Opt = CHW_Opt: O_HHW_Opt = HHW_Opt
                        Array_Load_ocp_str = Array_Load_ocp: Array_Load_unocp_str = _
                        Array_Load_unocp
                        Array_System_ocp_str = Array_System_ocp: Array_System_unocp_str = _
                        Array_System_unocp
                    End If
                Next nE
            Next nD
        Next nC
    Next nB
Next nA
'Check if further narrow down searching is necessary
If nN = 1 Then
    EnergyCost_Ntemp = EnergyCost
Else
    If Abs(EnergyCost_Ntemp - EnergyCost) < 0.01 Then
        Exit For
    Else
        EnergyCost_Ntemp = EnergyCost
    End If
End If
dA = b_A2 - b_A1
dB = b_B2 - b_B1
dC = b_C2 - b_C1
dD = b_D2 - b_D1
dE = b_E2 - b_E1
```

```
        If A_ - 0.25 * dA >= b_A1 Then b_A1 = A_ - 0.25 * dA
        If A_ + 0.25 * dA <= b_A2 Then b_A2 = A_ + 0.25 * dA
        If B_ - 0.25 * dB >= b_B1 Then b_B1 = B_ - 0.25 * dB
        If B_ + 0.25 * dB <= b_B2 Then b_B2 = B_ + 0.25 * dB
        If C_ - 0.25 * dC <= b_C1 Then b_C1 = C_ - 0.25 * dC 'b_C1>b_C2
        If C_ + 0.25 * dC >= b_C2 Then b_C2 = C_ + 0.25 * dC 'b_C1>b_C2
        If D_ - 0.25 * dD >= b_D1 Then b_D1 = D_ - 0.25 * dD
        If D_ + 0.25 * dD <= b_D2 Then b_D2 = D_ + 0.25 * dD
        If E_ - 0.25 * dE >= b_E1 Then b_E1 = E_ - 0.25 * dE
        If E_ + 0.25 * dE <= b_E2 Then b_E2 = E_ + 0.25 * dE
    Next nN

    If Flag = True Then
        With ThisWorkbook.Worksheets("BinData")
            If IFOCP = True Then
                'output loads and components of sensible load
                .Cells(BinNum + 5, 30) = Array_Load_ocp_str(0) * FracAe
                .Cells(BinNum + 5, 31) = Array_Load_ocp_str(1) * FracAi
                .Cells(BinNum + 5, 32) = Array_Load_ocp_str(2) * FracAe
                .Cells(BinNum + 5, 33) = Array_Load_ocp_str(3) * FracAi
                .Cells(BinNum + 5, 34) = Array_Load_ocp_str(4) * FracAe
                .Cells(BinNum + 5, 35) = Array_Load_ocp_str(5) * FracAe
                .Cells(BinNum + 5, 36) = Array_Load_ocp_str(6) * FracAe
                .Cells(BinNum + 5, 37) = Array_Load_ocp_str(7) * FracAe
                .Cells(BinNum + 5, 38) = Array_Load_ocp_str(8) * FracAe
                .Cells(BinNum + 5, 39) = Array_Load_ocp_str(9) * FracAi
                .Cells(BinNum + 5, 40) = Array_Load_ocp_str(10) * FracAi
                .Cells(BinNum + 5, 41) = Array_Load_ocp_str(11) * FracAi
                .Cells(BinNum + 5, 42) = Array_Load_ocp_str(12) * FracAi
                .Cells(BinNum + 5, 43) = Array_Load_ocp_str(13) * FracAi
                'output system simulation result
                Select Case SysType
                    Case "CVTR"
                        For j = 0 To 28
                            .Cells(BinNum + 5, j + 44) = Array_System_ocp_str(j)
                        Next j
                    Case "DDCV"
                        For j = 0 To 40
                            .Cells(BinNum + 5, j + 44) = Array_System_ocp_str(j)
                        Next j
                    Case "SDVAV"
                        For j = 0 To 35
                            .Cells(BinNum + 5, j + 44) = Array_System_ocp_str(j)
                        Next j
                    Case "DDVAV"
                        For j = 0 To 47
                            .Cells(BinNum + 5, j + 44) = Array_System_ocp_str(j)
                        Next j
                End Select
            Else
                .Cells(BinNum + 37, 30) = Array_Load_unocp_str(0) * FracAe
                .Cells(BinNum + 37, 31) = Array_Load_unocp_str(1) * FracAi
                .Cells(BinNum + 37, 32) = Array_Load_unocp_str(2) * FracAe
                .Cells(BinNum + 37, 33) = Array_Load_unocp_str(3) * FracAi
                .Cells(BinNum + 37, 34) = Array_Load_unocp_str(4) * FracAe
                .Cells(BinNum + 37, 35) = Array_Load_unocp_str(5) * FracAe
                .Cells(BinNum + 37, 36) = Array_Load_unocp_str(6) * FracAe
                .Cells(BinNum + 37, 37) = Array_Load_unocp_str(7) * FracAe
                .Cells(BinNum + 37, 38) = Array_Load_unocp_str(8) * FracAe
                .Cells(BinNum + 37, 39) = Array_Load_unocp_str(9) * FracAi
                .Cells(BinNum + 37, 40) = Array_Load_unocp_str(10) * FracAi
                .Cells(BinNum + 37, 41) = Array_Load_unocp_str(11) * FracAi
                .Cells(BinNum + 37, 42) = Array_Load_unocp_str(12) * FracAi
                .Cells(BinNum + 37, 43) = Array_Load_unocp_str(13) * FracAi
                Select Case SysType
                    Case "CVTR"
                        For j = 0 To 28
                            .Cells(BinNum + 37, j + 44) = Array_System_unocp_str(j)
                        Next j
                    Case "DDCV"
                        For j = 0 To 40
                            .Cells(BinNum + 37, j + 44) = Array_System_unocp_str(j)
                        Next j
                    Case "SDVAV"
                        For j = 0 To 35
                            .Cells(BinNum + 37, j + 44) = Array_System_unocp_str(j)
                        Next j
                    Case "DDVAV"
                        For j = 0 To 47
                            .Cells(BinNum + 37, j + 44) = Array_System_unocp_str(j)
                        Next j
                End Select
            End If
        End With
    End If
    f_Optimization = Array(EnergyCost, O_LTEQ_Opt, O_FANP_Opt, O_ELE_Opt, O_CHW_Opt, O_HHW_Opt)
End Function
```

```
Public Function f_Load(ByVal TOA As Double, ByVal IFOCP As Boolean, ByVal AHUoff As Boolean, _
    ByVal Te As Double, ByVal Ti As Double)

    'Transmission load conduction
    Awindow1 = Xwindow1 * Height * Length
    Awindow2 = Xwindow2 * Height * Width
    Awindow3 = Xwindow3 * Height * Length
    Awindow4 = Xwindow4 * Height * Width
    Awindow_tot = Awindow1 + Awindow2 + Awindow3 + Awindow4

    Awall1 = Height * Length - Awindow1
    Awall2 = Height * Width - Awindow2
    Awall3 = Height * Length - Awindow3
    Awall4 = Height * Width - Awindow4
    Awall_tot = Awall1 + Awall2 + Awall3 + Awall4

    Aroof = Length * Width
    Aground = Length * Width

    XAe = Ae / (Ae + Ai)
    XAi = 1 - XAe

    UAtote = Uwall * Awall_tot + Uwindow * Awindow_tot + XAe * (Uroof * Aroof + Uground * Aground)
    UAtoti = Uwindow * Awindow5 + Uroof * (XAi * Aroof - Awindow5) + XAi * Uground * Aground

    If IFOCP = False And AHUoff = True Then
        Te = Te - 13 + 0.192 * TOA 'linear regression relationship from measured room temp
        Ti = Ti - 13 + 0.192 * TOA
    End If
    QTe = UAtote * (TOA - Te)
    QTi = UAtoti * (TOA - Ti)


    'Building orientation identification
    Select Case Ort
        Case "N"
            Ort1 = 0
        Case "NNE"
            Ort1 = 1
        Case "NE"
            Ort1 = 2
        Case "ENE"
            Ort1 = 3
        Case "E"
            Ort1 = 4
        Case "ESE"
            Ort1 = 5
        Case "SE"
            Ort1 = 6
        Case "SSE"
            Ort1 = 7
    End Select

    Ort2 = Ort1 + 4
    Ort3 = Ort2 + 4

    If Ort1 <= 3 Then
        Ort4 = Ort3 + 4
    Else
        Ort4 = Ort3 + 4 - 16
    End If

    'maximum solar heat gain factors (ASHRAE Fundamentals 89, Table 34)
    MSHGF_24_Jan = Array(27, 27, 41, 128, 190, 240, 253, 241, 227, 241, 253, 240, 190, 128, 41, 27,214)
    MSHGF_24_Jul = Array(45, 116, 176, 210, 213, 185, 129, 65, 46, 65, 129, 185, 213, 210,176, 116,278)
    MSHGF_32_Jan = Array(24, 24, 29, 105, 175, 229, 249, 250, 246, 250, 249, 229, 175, 105, 29, 24,176)
    MSHGF_32_Jul = Array(40, 111, 167, 204, 215, 194, 150, 96, 72, 96, 150, 194, 215, 204,167, 111,273)
    MSHGF_40_Jan = Array(20, 20, 20, 74, 154, 205, 241, 252, 254, 252, 241, 205, 154, 74, 20, 20, 133)
    MSHGF_40_Jul = Array(38, 102, 163, 198, 216, 203, 170, 129, 109, 129, 170, 203,216,198,163,102,262)
    MSHGF_48_Jan = Array(15, 15, 15, 53, 118, 175, 216, 239, 245, 239, 216, 175, 118, 53, 15, 15, 85)
    MSHGF_48_Jul = Array(37, 96, 156, 196, 214, 209, 187, 158, 146, 158, 187, 209, 214, 196,156,96,244)

    '24 hour average CLTD for walls and roofs + LM correction (ASHRAE Fundamentals 89, Table 29,31,32)
    'CLTDcorr=(CLTD+LM)+(78-Tr)+(To-85) Tr is indoor design T, To is average outdoor T on design day.
    CLTDS_24_Jul = Array(13, 17, 20, 20, 22, 18.5, 18, 14, 11, 14, 18, 18.5, 22, 20, 20, 17, 30)
    CLTDS_32_Jul = Array(13, 16, 19, 20, 22, 20.5, 20, 16, 14, 16, 20, 20.5, 22, 20, 19, 16, 30)
    CLTDS_40_Jul = Array(12, 15, 18, 20, 22, 21.5, 21, 19, 18, 19, 21, 21.5, 22, 20, 18, 15, 30)
    CLTDS_48_Jul = Array(12, 14, 18, 20, 23, 22.5, 24, 22, 21, 22, 24, 22.5, 23, 20, 18, 14, 29)
    CLTDS_24_Jan = Array(8, 9, 10, 11, 16, 18.5, 30, 22, 30, 22, 30, 18.5, 16, 11, 10, 9, 18)
    CLTDS_32_Jan = Array(7, 8, 9, 9, 14, 6.5, 17, 21, 26, 21, 17, 6.5, 14, 9, 9, 8, 41)
    CLTDS_40_Jan = Array(7, 8, 8, 8, 13, 15.5, 22, 27, 28, 27, 22, 15.5, 13, 8, 8, 8, 10)
    CLTDS_48_Jan = Array(6, 7, 7, 7, 11, 13.5, 20, 24, 25, 24, 20, 13.5, 11, 7, 7, 7, 5)

    'CLFtot for glass with interior shading (ASHRAE Fundamentals 89, Table 39)
    CLFtot_glass = Array(11.58, 5.74, 5.13, 5.34, 5.5, 5.86, 6.23, 6.45, 6.44, 6.48, 6.2, 5.83, _
    5.47, 5.33, 5.15, 5.77, 8.21)
```

```
'MSHGF (interpolate between two closest latitudes)
If Lat >= 24 And Lat <= 32 Then
    MSHGF1_Jul = MSHGF_24_Jul(Ort1) + (MSHGF_32_Jul(Ort1) - MSHGF_24_Jul(Ort1)) * (Lat - 24) / 8
    MSHGF1_Jan = MSHGF_24_Jan(Ort1) + (MSHGF_32_Jan(Ort1) - MSHGF_24_Jan(Ort1)) * (Lat - 24) / 8
    MSHGF2_Jul = MSHGF_24_Jul(Ort2) + (MSHGF_32_Jul(Ort2) - MSHGF_24_Jul(Ort2)) * (Lat - 24) / 8
    MSHGF2_Jan = MSHGF_24_Jan(Ort2) + (MSHGF_32_Jan(Ort2) - MSHGF_24_Jan(Ort2)) * (Lat - 24) / 8
    MSHGF3_Jul = MSHGF_24_Jul(Ort3) + (MSHGF_32_Jul(Ort3) - MSHGF_24_Jul(Ort3)) * (Lat - 24) / 8
    MSHGF3_Jan = MSHGF_24_Jan(Ort3) + (MSHGF_32_Jan(Ort3) - MSHGF_24_Jan(Ort3)) * (Lat - 24) / 8
    MSHGF4_Jul = MSHGF_24_Jul(Ort4) + (MSHGF_32_Jul(Ort4) - MSHGF_24_Jul(Ort4)) * (Lat - 24) / 8
    MSHGF4_Jan = MSHGF_24_Jan(Ort4) + (MSHGF_32_Jan(Ort4) - MSHGF_24_Jan(Ort4)) * (Lat - 24) / 8
    MSHGF5_Jul = MSHGF_24_Jul(16) + (MSHGF_32_Jul(16) - MSHGF_24_Jul(16)) * (Lat - 24) / 8
    MSHGF5_Jan = MSHGF_24_Jan(16) + (MSHGF_32_Jan(16) - MSHGF_24_Jan(16)) * (Lat - 24) / 8
End If

If Lat > 32 And Lat <= 40 Then
    MSHGF1_Jul = MSHGF_32_Jul(Ort1) + (MSHGF_40_Jul(Ort1) - MSHGF_32_Jul(Ort1)) * (Lat - 32) / 8
    MSHGF1_Jan = MSHGF_32_Jan(Ort1) + (MSHGF_40_Jan(Ort1) - MSHGF_32_Jan(Ort1)) * (Lat - 32) / 8
    MSHGF2_Jul = MSHGF_32_Jul(Ort2) + (MSHGF_40_Jul(Ort2) - MSHGF_32_Jul(Ort2)) * (Lat - 32) / 8
    MSHGF2_Jan = MSHGF_32_Jan(Ort2) + (MSHGF_40_Jan(Ort2) - MSHGF_32_Jan(Ort2)) * (Lat - 32) / 8
    MSHGF3_Jul = MSHGF_32_Jul(Ort3) + (MSHGF_40_Jul(Ort3) - MSHGF_32_Jul(Ort3)) * (Lat - 32) / 8
    MSHGF3_Jan = MSHGF_32_Jan(Ort3) + (MSHGF_40_Jan(Ort3) - MSHGF_32_Jan(Ort3)) * (Lat - 32) / 8
    MSHGF4_Jul = MSHGF_32_Jul(Ort4) + (MSHGF_40_Jul(Ort4) - MSHGF_32_Jul(Ort4)) * (Lat - 32) / 8
    MSHGF4_Jan = MSHGF_32_Jan(Ort4) + (MSHGF_40_Jan(Ort4) - MSHGF_32_Jan(Ort4)) * (Lat - 32) / 8
    MSHGF5_Jul = MSHGF_32_Jul(16) + (MSHGF_40_Jul(16) - MSHGF_32_Jul(16)) * (Lat - 32) / 8
    MSHGF5_Jan = MSHGF_32_Jan(16) + (MSHGF_40_Jan(16) - MSHGF_32_Jan(16)) * (Lat - 32) / 8
End If

If Lat > 40 And Lat <= 48 Then
    MSHGF1_Jul = MSHGF_40_Jul(Ort1) + (MSHGF_48_Jul(Ort1) - MSHGF_40_Jul(Ort1)) * (Lat - 40) / 8
    MSHGF1_Jan = MSHGF_40_Jan(Ort1) + (MSHGF_48_Jan(Ort1) - MSHGF_40_Jan(Ort1)) * (Lat - 40) / 8
    MSHGF2_Jul = MSHGF_40_Jul(Ort2) + (MSHGF_48_Jul(Ort2) - MSHGF_40_Jul(Ort2)) * (Lat - 40) / 8
    MSHGF2_Jan = MSHGF_40_Jan(Ort2) + (MSHGF_48_Jan(Ort2) - MSHGF_40_Jan(Ort2)) * (Lat - 40) / 8
    MSHGF3_Jul = MSHGF_40_Jul(Ort3) + (MSHGF_48_Jul(Ort3) - MSHGF_40_Jul(Ort3)) * (Lat - 40) / 8
    MSHGF3_Jan = MSHGF_40_Jan(Ort3) + (MSHGF_48_Jan(Ort3) - MSHGF_40_Jan(Ort3)) * (Lat - 40) / 8
    MSHGF4_Jul = MSHGF_40_Jul(Ort4) + (MSHGF_48_Jul(Ort4) - MSHGF_40_Jul(Ort4)) * (Lat - 40) / 8
    MSHGF4_Jan = MSHGF_40_Jan(Ort4) + (MSHGF_48_Jan(Ort4) - MSHGF_40_Jan(Ort4)) * (Lat - 40) / 8
    MSHGF5_Jul = MSHGF_40_Jul(16) + (MSHGF_48_Jul(16) - MSHGF_40_Jul(16)) * (Lat - 40) / 8
    MSHGF5_Jan = MSHGF_40_Jan(16) + (MSHGF_48_Jan(16) - MSHGF_40_Jan(16)) * (Lat - 40) / 8
End If

QSOL1_Jul = MSHGF1_Jul * Awindow1 * SC1 * CLFtot_glass(Ort1) * FPS_Jul / 24
QSOL2_Jul = MSHGF2_Jul * Awindow2 * SC2 * CLFtot_glass(Ort2) * FPS_Jul / 24
QSOL3_Jul = MSHGF3_Jul * Awindow3 * SC3 * CLFtot_glass(Ort3) * FPS_Jul / 24
QSOL4_Jul = MSHGF4_Jul * Awindow4 * SC4 * CLFtot_glass(Ort4) * FPS_Jul / 24
QSOL5_Jul = MSHGF5_Jul * Awindow5 * SC5 * CLFtot_glass(16) * FPS_Jul / 24   'add to interior zone
QSOL_Jul = QSOL1_Jul + QSOL2_Jul + QSOL3_Jul + QSOL4_Jul                    'add to exterior zone

QSOL1_Jan = MSHGF1_Jan * Awindow1 * SC1 * CLFtot_glass(Ort1) * FPS_Jan / 24
QSOL2_Jan = MSHGF2_Jan * Awindow2 * SC2 * CLFtot_glass(Ort2) * FPS_Jan / 24
QSOL3_Jan = MSHGF3_Jan * Awindow3 * SC3 * CLFtot_glass(Ort3) * FPS_Jan / 24
QSOL4_Jan = MSHGF4_Jan * Awindow4 * SC4 * CLFtot_glass(Ort4) * FPS_Jan / 24
QSOL5_Jan = MSHGF5_Jan * Awindow5 * SC5 * CLFtot_glass(16) * FPS_Jan / 24   'add to interior zone
QSOL_Jan = QSOL1_Jan + QSOL2_Jan + QSOL3_Jan + QSOL4_Jan                    'add to exterior zone

M_QSOLe = (QSOL_Jul - QSOL_Jan) / (Tpkc - Tpkh)
M_QSOLi = (QSOL5_Jul - QSOL5_Jan) / (Tpkc - Tpkh)

QSOLe = QSOL_Jan + M_QSOLe * (TOA - Tpkh)
QSOLi = QSOL5_Jan + M_QSOLi * (TOA - Tpkh)


'CLTDS (interpolate between two closest latitudes)
If Lat >= 24 And Lat <= 32 Then
    CLTDS1_Jul = CLTDS_24_Jul(Ort1) + (CLTDS_32_Jul(Ort1) - CLTDS_24_Jul(Ort1)) * (Lat - 24) / 8
    CLTDS1_Jan = CLTDS_24_Jan(Ort1) + (CLTDS_32_Jan(Ort1) - CLTDS_24_Jan(Ort1)) * (Lat - 24) / 8
    CLTDS2_Jul = CLTDS_24_Jul(Ort2) + (CLTDS_32_Jul(Ort2) - CLTDS_24_Jul(Ort2)) * (Lat - 24) / 8
    CLTDS2_Jan = CLTDS_24_Jan(Ort2) + (CLTDS_32_Jan(Ort2) - CLTDS_24_Jan(Ort2)) * (Lat - 24) / 8
    CLTDS3_Jul = CLTDS_24_Jul(Ort3) + (CLTDS_32_Jul(Ort3) - CLTDS_24_Jul(Ort3)) * (Lat - 24) / 8
    CLTDS3_Jan = CLTDS_24_Jan(Ort3) + (CLTDS_32_Jan(Ort3) - CLTDS_24_Jan(Ort3)) * (Lat - 24) / 8
    CLTDS4_Jul = CLTDS_24_Jul(Ort4) + (CLTDS_32_Jul(Ort4) - CLTDS_24_Jul(Ort4)) * (Lat - 24) / 8
    CLTDS4_Jan = CLTDS_24_Jan(Ort4) + (CLTDS_32_Jan(Ort4) - CLTDS_24_Jan(Ort4)) * (Lat - 24) / 8
    CLTDS5_Jul = CLTDS_24_Jul(16) + (CLTDS_32_Jul(16) - CLTDS_24_Jul(16)) * (Lat - 24) / 8
    CLTDS5_Jan = CLTDS_24_Jan(16) + (CLTDS_32_Jan(16) - CLTDS_24_Jan(16)) * (Lat - 24) / 8
End If

If Lat > 32 And Lat <= 40 Then
    CLTDS1_Jul = CLTDS_32_Jul(Ort1) + (CLTDS_40_Jul(Ort1) - CLTDS_32_Jul(Ort1)) * (Lat - 32) / 8
    CLTDS1_Jan = CLTDS_32_Jan(Ort1) + (CLTDS_40_Jan(Ort1) - CLTDS_32_Jan(Ort1)) * (Lat - 32) / 8
    CLTDS2_Jul = CLTDS_32_Jul(Ort2) + (CLTDS_40_Jul(Ort2) - CLTDS_32_Jul(Ort2)) * (Lat - 32) / 8
    CLTDS2_Jan = CLTDS_32_Jan(Ort2) + (CLTDS_40_Jan(Ort2) - CLTDS_32_Jan(Ort2)) * (Lat - 32) / 8
    CLTDS3_Jul = CLTDS_32_Jul(Ort3) + (CLTDS_40_Jul(Ort3) - CLTDS_32_Jul(Ort3)) * (Lat - 32) / 8
    CLTDS3_Jan = CLTDS_32_Jan(Ort3) + (CLTDS_40_Jan(Ort3) - CLTDS_32_Jan(Ort3)) * (Lat - 32) / 8
    CLTDS4_Jul = CLTDS_32_Jul(Ort4) + (CLTDS_40_Jul(Ort4) - CLTDS_32_Jul(Ort4)) * (Lat - 32) / 8
    CLTDS4_Jan = CLTDS_32_Jan(Ort4) + (CLTDS_40_Jan(Ort4) - CLTDS_32_Jan(Ort4)) * (Lat - 32) / 8
    CLTDS5_Jul = CLTDS_32_Jul(16) + (CLTDS_40_Jul(16) - CLTDS_32_Jul(16)) * (Lat - 32) / 8
    CLTDS5_Jan = CLTDS_32_Jan(16) + (CLTDS_40_Jan(16) - CLTDS_32_Jan(16)) * (Lat - 32) / 8
End If
```

```
If Lat > 40 And Lat <= 48 Then
    CLTDS1_Jul = CLTDS_40_Jul(Ort1) + (CLTDS_48_Jul(Ort1) - CLTDS_40_Jul(Ort1)) * (Lat - 40) / 8
    CLTDS1_Jan = CLTDS_40_Jan(Ort1) + (CLTDS_48_Jan(Ort1) - CLTDS_40_Jan(Ort1)) * (Lat - 40) / 8
    CLTDS2_Jul = CLTDS_40_Jul(Ort2) + (CLTDS_48_Jul(Ort2) - CLTDS_40_Jul(Ort2)) * (Lat - 40) / 8
    CLTDS2_Jan = CLTDS_40_Jan(Ort2) + (CLTDS_48_Jan(Ort2) - CLTDS_40_Jan(Ort2)) * (Lat - 40) / 8
    CLTDS3_Jul = CLTDS_40_Jul(Ort3) + (CLTDS_48_Jul(Ort3) - CLTDS_40_Jul(Ort3)) * (Lat - 40) / 8
    CLTDS3_Jan = CLTDS_40_Jan(Ort3) + (CLTDS_48_Jan(Ort3) - CLTDS_40_Jan(Ort3)) * (Lat - 40) / 8
    CLTDS4_Jul = CLTDS_40_Jul(Ort4) + (CLTDS_48_Jul(Ort4) - CLTDS_40_Jul(Ort4)) * (Lat - 40) / 8
    CLTDS4_Jan = CLTDS_40_Jan(Ort4) + (CLTDS_48_Jan(Ort4) - CLTDS_40_Jan(Ort4)) * (Lat - 40) / 8
    CLTDS5_Jul = CLTDS_40_Jul(16) + (CLTDS_48_Jul(16) - CLTDS_40_Jul(16)) * (Lat - 40) / 8
    CLTDS5_Jan = CLTDS_40_Jan(16) + (CLTDS_48_Jan(16) - CLTDS_40_Jan(16)) * (Lat - 40) / 8
End If

If COLORwall = "Dark colored" Then Kwall = 1
If COLORwall = "Medium colored" Then Kwall = 0.83
If COLORwall = "Light colored" Then Kwall = 0.65
If COLORroof = "Dark colored" Then Kroof = 1
If COLORroof = "Light colored" Then Kroof = 0.5

CLTDScorr1_Jul = CLTDS1_Jul * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr2_Jul = CLTDS2_Jul * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr3_Jul = CLTDS3_Jul * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr4_Jul = CLTDS4_Jul * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr5_Jul = CLTDS5_Jul * Kroof + (78 - Te) + (Todes - 85)
CLTDScorr5_Jul_i = CLTDS5_Jul * Kroof + (78 - Ti) + (Todes - 85)

CLTDScorr1_Jan = CLTDS1_Jan * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr2_Jan = CLTDS2_Jan * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr3_Jan = CLTDS3_Jan * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr4_Jan = CLTDS4_Jan * Kwall + (78 - Te) + (Todes - 85)
CLTDScorr5_Jan = CLTDS5_Jan * Kroof + (78 - Te) + (Todes - 85)
CLTDScorr5_Jan_i = CLTDS5_Jan * Kroof + (78 - Ti) + (Todes - 85)

QTS1_Jul = Awall1 * Uwall * CLTDScorr1_Jul * FPS_Jul
QTS2_Jul = Awall2 * Uwall * CLTDScorr2_Jul * FPS_Jul
QTS3_Jul = Awall3 * Uwall * CLTDScorr3_Jul * FPS_Jul
QTS4_Jul = Awall4 * Uwall * CLTDScorr4_Jul * FPS_Jul
QTS5e_Jul = Aroof * XAe * Uroof * CLTDScorr5_Jul * FPS_Jul
QTS5i_Jul = (Aroof * XAi - Awindow5) * Uroof * CLTDScorr5_Jul_i * FPS_Jul   'add to interior zone
QTS_Jul = QTS1_Jul + QTS2_Jul + QTS3_Jul + QTS4_Jul + QTS5e_Jul             'add to exterior zone

QTS1_Jan = Awall1 * Uwall * CLTDScorr1_Jan * FPS_Jan
QTS2_Jan = Awall2 * Uwall * CLTDScorr2_Jan * FPS_Jan
QTS3_Jan = Awall3 * Uwall * CLTDScorr3_Jan * FPS_Jan
QTS4_Jan = Awall4 * Uwall * CLTDScorr4_Jan * FPS_Jan
QTS5e_Jan = Aroof * XAe * Uroof * CLTDScorr5_Jan * FPS_Jan
QTS5i_Jan = (Aroof * XAi - Awindow5) * Uroof * CLTDScorr5_Jan_i * FPS_Jan   'add to interior zone
QTS_Jan = QTS1_Jan + QTS2_Jan + QTS3_Jan + QTS4_Jan + QTS5e_Jan             'add to exterior zone

M_QTSe = (QTS_Jul - QTS_Jan) / (Tpkc - Tpkh)
M_QTSi = (QTS5i_Jul - QTS5i_Jan) / (Tpkc - Tpkh)

If TOA > Te Then
    QTSe = QTS_Jan + M_QTSe * (TOA - Tpkh)
Else
    QTSe = 0
End If

If TOA > Ti Then
    QTSi = QTS5i_Jan + M_QTSi * (TOA - Tpkh)
Else
    QTSi = 0
End If
'Note: transmission load solar component is counted only when Tambient > Troom

'Internal heat gain from occupants
QsOCPe_ocp = 245 * OCPe * AOF_ocp
QsOCPi_ocp = 245 * OCPi * AOF_ocp
QsOCPe_unocp = 245 * OCPe * AOF_unocp
QsOCPi_unocp = 245 * OCPi * AOF_unocp

QlOCPe_ocp = 155 * OCPe * AOF_ocp
QlOCPi_ocp = 155 * OCPi * AOF_ocp
QlOCPe_unocp = 155 * OCPe * AOF_unocp
QlOCPi_unocp = 155 * OCPi * AOF_unocp

QLTEQe_ocp = 3412 * XAe * LTEQ_ocp
QLTEQi_ocp = 3412 * XAi * LTEQ_ocp
QLTEQe_unocp = 3412 * XAe * LTEQ_unocp
QLTEQi_unocp = 3412 * XAi * LTEQ_unocp

If IFOCP = True Then
    qes = QTe + QSOLe + QTSe + QsOCPe_ocp + QLTEQe_ocp
    qis = QTi + QSOLi + QTSi + QsOCPi_ocp + QLTEQi_ocp
    qel = QlOCPe_ocp
    qil = QlOCPi_ocp
```

```
        f_Load = Array(qes, qis, qel, qil, _
                QTe, QSOLe, QTSe, QsOCPe_ocp, QLTEQe_ocp, _
                QTi, QSOLi, QTSi, QsOCPi_ocp, QLTEQi_ocp)
    Else
        qes = QTe + QsOCPe_unocp + QLTEQe_unocp
        qis = QTi + QsOCPi_unocp + QLTEQi_unocp
        qel = QlOCPe_unocp
        qil = QlOCPi_unocp
        f_Load = Array(qes, qis, qel, qil, _
                QTe, 0, 0, QsOCPe_unocp, QLTEQe_unocp, _
                QTi, 0, 0, QsOCPi_unocp, QLTEQi_unocp)
    End If
End Function


Public Function f_CVTR(ByVal qes As Double, ByVal qis As Double, _
    ByVal qel As Double, ByVal qil As Double, _
    ByVal Te As Double, ByVal Ti As Double, ByVal TCL As Double, _
    ByVal Ve As Double, ByVal Vi As Double, _
    ByVal PSF As Double, ByVal PRF As Double, _
    ByVal OACtrl As Integer, ByVal XOAmin As Double, ByVal VOAmin As Double, ByVal VOAmax As Double, _
    ByVal TOA As Double, ByVal wOA As Double, ByVal ECM As Boolean)

    'supply air temperatures and flow rates
    TeS = Te - qes / (1.08 * Ve)
    TiS = Ti - qis / (1.08 * Vi)

    'reheat coil consumption
    qeRH = 1.08 * Ve * (TeS - TCL)
    qiRH = 1.08 * Vi * (TiS - TCL)

    'flow rates and fractions
    VT = Ve + Vi
    Xe = Ve / VT:   Xi = Vi / VT

    'return air temperature
    TR = Xe * Te + Xi * Ti                                     '*

    'outside air
    If OACtrl = 1 Then                                         '*
        If VOAmax > VT Then VOAmax = VT
        XOA = XOA_ECM(ECM, TOA, XOAmin, TCL, TR, VOAmax / VT)        '*
        VOA = XOA * VT                                         '*
    End If                                                     '*
    If OACtrl = 2 Then                                         '*
        VOA = VOA_ECM(ECM, TOA, VOAmin, TCL, TR, VT, VOAmax)      '*
        XOA = VOA / VT                                         '*
    End If                                                     '*
    XR = 1 - XOA                                               '*
    VR = XR * VT                                               '*

    'system cooling capacity varification
    If TeS < TCL Or TiS < TCL Or VOA > VT Then
        ExCap = True
    Else
        ExCap = False
    End If

    'fan power and temperature rise
    dTSF = 0.7457 * 3412 * PSF / (1.08 * VT)                   '*
    dTRF = 0.7457 * 3412 * PRF / (1.08 * VT)                   '*

    'preheat load
    TMA = XOA * TOA + XR * (TR + dTRF)                         '*
    If TMA < TCL - dTSF Then                                   '*
        TPH = TCL - dTSF                                       '*
        qPH = 1.08 * VT * (TPH - TMA)                          '*
    Else                                                       '*
        TPH = TMA                                              '*
        qPH = 0                                                '*
    End If                                                     '*
    TCE = TPH + dTSF                                           '*

    'humidity ratios for latent load calculation
    wCL = w_RH(TCL, 0.9, 14.696)                               '*
    wRw = wCL + (qel + qil) / (4840 * VT)
    wRd = wOA + (qel + qil) / (4840 * XOA * VT)
    wMA = XOA * wOA + XR * wRw

    If wMA < wCL Then                                          '*
        WetCoil = False                                        '*
        wR = wRd                                               '*
    Else                                                       '*
        WetCoil = True                                         '*
        wR = wRw                                               '*
    End If                                                     '*
```

```
    wMA = XOA * wOA + XR * wR                                   '*
    wPH = wMA                                                   '*
    wCE = wPH                                                   '*

    RH = wR / w_sat((Te + Ti) / 2, 14.696) * 100                '*

    'consumptions
    qCs = 1.08 * VT * (TCE - TCL)

    If WetCoil = False Then
        qCl = 0
    Else
        qCl = 4840 * VT * (wCE - wCL)
    End If

    qCT = qCs + qCl                                             '*
    qHT = qPH + qeRH + qiRH
    qFT = 0.7457 * 3412 * (PSF + PRF)                           '*

    f_CVTR = Array(qCs, qCl, qCT, qPH, qeRH, qiRH, qHT, qFT, _
            dTSF, dTRF, TeS, TiS, TR, TMA, TPH, TCE, Te, Ti, TCL, _
            VOA, VR, VT, _
            XOA, XR, _
            wR, wMA, wCL, WetCoil, RH, ExCap)
End Function


Public Function f_DDCV(ByVal qes As Double, ByVal qis As Double, _
    ByVal qel As Double, ByVal qil As Double, _
    ByVal Te As Double, ByVal Ti As Double, _
    ByVal TCL As Double, ByVal THLset As Double, _
    ByVal Ve As Double, ByVal Vi As Double, _
    ByVal PSF As Double, ByVal PRF As Double, _
    ByVal OACtrl As Integer, ByVal XOAmin As Double, ByVal VOAmin As Double, ByVal VOAmax As Double, _
    ByVal TOA As Double, ByVal wOA As Double, ByVal ECM As Boolean)

    VT = Ve + Vi
    Xe = Ve / VT:   Xi = Vi / VT

    'return air temperature
    TR = Xe * Te + Xi * Ti                                      '*

    'outside air
    If OACtrl = 1 Then                                          '*
        If VOAmax > VT Then VOAmax = VT
        XOA = XOA_ECM(ECM, TOA, XOAmin, TCL, TR, VOAmax / VT)        '*
        VOA = XOA * VT                                          '*
    End If                                                      '*
    If OACtrl = 2 Then                                          '*
        VOA = VOA_ECM(ECM, TOA, VOAmin, TCL, TR, VT, VOAmax)     '*
        XOA = VOA / VT                                          '*
    End If                                                      '*
    XR = 1 - XOA                                                '*
    VR = XR * VT                                                '*

    'fan power and temperature rise
    dTSF = 0.7457 * 3412 * PSF / (1.08 * VT)                    '*
    dTRF = 0.7457 * 3412 * PRF / (1.08 * VT)                    '*

    'preheat load
    TMA = XOA * TOA + XR * (TR + dTRF)                          '*
    If TMA < TCL - dTSF Then                                    '*
        TPH = TCL - dTSF                                        '*
        qPH = 1.08 * VT * (TPH - TMA)                           '*
    Else                                                        '*
        TPH = TMA                                               '*
        qPH = 0                                                 '*
    End If                                                      '*

    TCE = TPH + dTSF                                            '*
    THE = TCE

    If THE > THLset Then
        THLact = THE
    Else
        THLact = THLset
    End If

    'supply air temperatures and flow rates
    TeS = Te - qes / (1.08 * Ve)
    TiS = Ti - qis / (1.08 * Vi)

    'system cooling and heating capacity varification
    If TeS < TCL Or TiS < TCL Or TeS > THLset Or TiS > THLset _
        Or VOA > VT Then
        ExCap = True
```

```
    Else
        ExCap = False
    End If

    VeC = Ve * (THLact - TeS) / (THLact - TCL)
    VeH = Ve - VeC
    ViC = Vi * (THLact - TiS) / (THLact - TCL)
    ViH = Vi - ViC

    'flow rates and fractions
    VC = VeC + ViC: VH = VeH + ViH
    If VC > 0 Then
        XeC = VeC / VC
        XiC = ViC / VC
    Else
        XeC = 0
        XiC = 0
    End If
    If VH > 0 Then
        XeH = VeH / VH
        XiH = ViH / VH
    Else
        XeH = 0
        XiH = 0
    End If
    XC = VC / VT:   XH = VH / VT

    'humidity ratios for latent load calculation
    wCL = w_RH(TCL, 0.9, 14.696)                        '*
    wRw = (XC * wCL + XH * XOA * wOA + (qel + qil) / (4840 * VT)) / (1 - XH * XR)
    wRd = wOA + (qel + qil) / (4840 * XOA * VT)
    wMA = XOA * wOA + XR * wRw                          '*

    If wMA < wCL Then                                   '*
        WetCoil = False                                 '*
        wR = wRd                                        '*
    Else                                                '*
        WetCoil = True                                  '*
        wR = wRw                                        '*
    End If                                              '*

    wMA = XOA * wOA + XR * wR                           '*
    wPH = wMA                                           '*
    wCE = wPH                                           '*

    RH = wR / w_sat((Te + Ti) / 2, 14.696) * 100        '*

    'consumptions
    qCs = 1.08 * VC * (TCE - TCL)

    If WetCoil = False Then
        qCl = 0
    Else
        qCl = 4840 * VC * (wCE - wCL)
    End If

    qCT = qCs + qCl                                     '*
    qH = 1.08 * VH * (THLact - THE)
    qHT = qPH + qH
    qFT = 0.7457 * 3412 * (PSF + PRF)                   '*

    f_DDCV = Array(qCs, qCl, qCT, qPH, qH, qHT, qFT, _
            dTSF, dTRF, TeS, TiS, TR, TMA, TPH, TCE, Te, Ti, TCL, THLset, _
            VeC, ViC, VeH, ViH, VC, VH, VOA, VR, VT, _
            XeC, XiC, XeH, XiH, XC, XH, XOA, XR, _
            wR, wMA, wCL, WetCoil, RH, ExCap)
End Function


Public Function f_SDVAV(ByVal qes As Double, ByVal qis As Double, _
    ByVal qel As Double, ByVal qil As Double, _
    ByVal Te As Double, ByVal Ti As Double, ByVal TCL As Double, _
    ByVal VTD As Double, ByVal Vemin As Double, ByVal Vimin As Double, _
    ByVal PSF_rated As Double, ByVal PRF_rated As Double, _
    ByVal OACtrl As Integer, ByVal XOAmin As Double, ByVal VOAmin As Double, ByVal VOAmax As Double, _
    ByVal TOA As Double, ByVal wOA As Double, _
    ByVal ECM As Boolean, ByVal VSM As Integer)

    'supply air temperatures and flow rates
    If qes <= 0 Then
        TeS = Te - qes / (1.08 * Vemin)
        Ve = Vemin
        If TeS > 120 Then
            TeS = 120
            Ve = qes / (1.08 * (Te - TeS))
        End If
    Else
```

```
    If Te <= TCL Then
        ExCap = True
    Else
        If qes / (1.08 * (Te - TCL)) < Vemin Then
            TeS = Te - qes / (1.08 * Vemin)
            Ve = Vemin
        Else
            TeS = TCL
            Ve = qes / (1.08 * (Te - TeS))
        End If
    End If
End If

If qis <= 0 Then
    TiS = Ti - qis / (1.08 * Vimin)
    Vi = Vimin
    If TiS > 120 Then
        TiS = 120
        Vi = qis / (1.08 * (Ti - TiS))
    End If
Else
    If Ti <= TCL Then
        ExCap = True
    Else
        If qis / (1.08 * (Ti - TCL)) < Vimin Then
            TiS = Ti - qis / (1.08 * Vimin)
            Vi = Vimin
        Else
            TiS = TCL
            Vi = qis / (1.08 * (Ti - TiS))
        End If
    End If
End If

'reheat coil consumption
qeRH = 1.08 * Ve * (TeS - TCL)
qiRH = 1.08 * Vi * (TiS - TCL)

'flow rates and fractions
VT = Ve + Vi
If VT = 0 Then VT = 0.01
Xe = Ve / VT:   Xi = Vi / VT

'return air temperature
TR = Xe * Te + Xi * Ti                                    '*

'outside air
If OACtrl = 1 Then                                        '*
    If VOAmax > VT Then VOAmax = VT
    XOA = XOA_ECM(ECM, TOA, XOAmin, TCL, TR, VOAmax / VT)        '*
    VOA = XOA * VT                                        '*
End If                                                    '*
If OACtrl = 2 Then                                        '*
    VOA = VOA_ECM(ECM, TOA, VOAmin, TCL, TR, VT, VOAmax)      '*
    XOA = VOA / VT                                        '*
End If                                                    '*
XR = 1 - XOA                                              '*
VR = XR * VT                                              '*

'system cooling capacity varification
If TeS < TCL Or TiS < TCL Or VT > VTD Or VOA > VT Then
    ExCap = True
Else
    ExCap = False
End If

'fan power and temperature rise
PLR = VT / VTD
PSF = FANP(PSF_rated, PLR, VSM)
PRF = FANP(PRF_rated, PLR, VSM)
dTSF = 0.7457 * 3412 * PSF / (1.08 * VT)                  '*
dTRF = 0.7457 * 3412 * PRF / (1.08 * VT)                  '*

'preheat load
TMA = XOA * TOA + XR * (TR + dTRF)                        '*
If TMA < TCL - dTSF Then                                  '*
    TPH = TCL - dTSF                                      '*
    qPH = 1.08 * VT * (TPH - TMA)                         '*
Else                                                      '*
    TPH = TMA                                             '*
    qPH = 0                                               '*
End If                                                    '*

TCE = TPH + dTSF                                          '*

'humidity ratios for latent load calculation
wCL = w_RH(TCL, 0.9, 14.696)                              '*
```

```
    wRw = wCL + (qel + qil) / (4840 * VT)
    wRd = wOA + (qel + qil) / (4840 * XOA * VT)
    wMA = XOA * wOA + XR * wRw

    If wMA < wCL Then                                        '*
        WetCoil = False                                      '*
        wR = wRd                                             '*
    Else                                                     '*
        WetCoil = True                                       '*
        wR = wRw                                             '*
    End If                                                   '*

    wMA = XOA * wOA + XR * wR                                '*
    wPH = wMA                                                '*
    wCE = wPH                                                '*

    RH = wR / w_sat((Te + Ti) / 2, 14.696) * 100             '*

    'consumptions
    qCs = 1.08 * VT * (TCE - TCL)

    If WetCoil = False Then
        qCl = 0
    Else
        qCl = 4840 * VT * (wCE - wCL)
    End If

    qCT = qCs + qCl                                          '*
    qHT = qPH + qeRH + qiRH
    qFT = 0.7457 * 3412 * (PSF + PRF)                        '*

    f_SDVAV = Array(qCs, qCl, qCT, qPH, qeRH, qiRH, qHT, qFT, _
            dTSF, dTRF, TeS, TiS, TR, TMA, TPH, TCE, Te, Ti, TCL, _
            Ve, Vi, VOA, VR, VT, _
            Xe, Xi, XOA, XR, _
            PLR, PSF, PRF, wR, wMA, wCL, WetCoil, RH, ExCap)
End Function


Public Function f_DDVAV(ByVal qes As Double, ByVal qis As Double, _
    ByVal qel As Double, ByVal qil As Double, _
    ByVal Te As Double, ByVal Ti As Double, _
    ByVal TCL As Double, ByVal THLset As Double, _
    ByVal VTD As Double, ByVal Vemin As Double, ByVal Vimin As Double, _
    ByVal PSF_rated As Double, ByVal PRF_rated As Double, _
    ByVal OACtrl As Integer, ByVal XOAmin As Double, ByVal VOAmin As Double, ByVal VOAmax As Double, _
    ByVal TOA As Double, ByVal wOA As Double, _
    ByVal ECM As Boolean, ByVal VSM As Integer)

    'supply air temperatures and flow rates
    If qis > 0 Then
        TiS = TCL
        ViC = qis / (1.08 * (Ti - TiS))
        ViH = 0
    Else
        TiS = THLset
        ViH = qis / (1.08 * (Ti - TiS))
        ViC = 0
    End If

    If qes > 0 Then
        TeS = TCL
        VeC = qes / (1.08 * (Te - TeS))
        VeH = 0
    Else
        TeS = THLset
        VeH = qes / (1.08 * (Te - TeS))
        VeC = 0
    End If

    'THLact and flow rates
    If VeC + VeH < Vemin Then 'Ve=Vemin
        If ViC + ViH < Vimin Then 'Vi=Vimin
            VT = Vemin + Vimin
            Xe = Vemin / VT: Xi = Vimin / VT
        Else 'Vi>Vimin
            If qis >= 0 Then
                VT = Vemin + ViC
                Xe = Vemin / VT: Xi = ViC / VT
            Else
                VT = Vemin + ViH
                Xe = Vemin / VT: Xi = ViH / VT
            End If
        End If
        TR = Xe * Te + Xi * Ti
        If OACtrl = 1 Then Stop
```

```
    If OACtrl = 2 Then
        VOA = VOAmin
        XOA = VOA / VT
    End If
    XR = 1 - XOA
    VR = XR * VT
    dTSF = 2 'assumed
    dTRF = 0 'assumed
    TMA = XOA * TOA + XR * (TR + dTRF)
    If TMA < TCL - dTSF Then
        TPH = TCL - dTSF
    Else
        TPH = TMA
    End If
    TCE = TPH + dTSF
    THE = TCE
    If THE > THLset Then
        THLact = THE
    Else
        THLact = THLset
    End If
    TeS = Te - qes / (1.08 * Vemin)
    VeC = Vemin * (THLact - TeS) / (THLact - TCL)
    VeH = Vemin - VeC
End If

If ViC + ViH < Vimin Then 'Vi=Vimin
    If THLact = 0 Then 'Ve>Vemin
        If qes >= 0 Then
            VT = Vimin + VeC
            Xe = VeC / VT: Xi = Vimin / VT
        Else
            VT = Vimin + VeH
            Xe = VeH / VT: Xi = Vimin / VT
        End If
        TR = Xe * Te + Xi * Ti
        If OACtrl = 1 Then Stop
        If OACtrl = 2 Then
            VOA = VOAmin
            XOA = VOA / VT
        End If
        XR = 1 - XOA
        VR = XR * VT
        dTSF = 2 'assumed
        dTRF = 0 'assumed
        TMA = XOA * TOA + XR * (TR + dTRF)
        If TMA < TCL - dTSF Then
            TPH = TCL - dTSF
        Else
            TPH = TMA
        End If
        TCE = TPH + dTSF
        THE = TCE
        If THE > THLset Then
            THLact = THE
        Else
            THLact = THLset
        End If
    End If
    TiS = Ti - qis / (1.08 * Vimin)
    ViC = Vimin * (THLact - TiS) / (THLact - TCL)
    ViH = Vimin - ViC
End If

'flow rates and fractions
Ve = VeC + VeH: Vi = ViC + ViH
VT = Ve + Vi
If VT = 0 Then VT = 0.01
Xe = Ve / VT: Xi = Vi / VT
VC = VeC + ViC: VH = VeH + ViH
If VC > 0 Then
    XeC = VeC / VC
    XiC = ViC / VC
Else
    XeC = 0
    XiC = 0
End If
If VH > 0 Then
    XeH = VeH / VH
    XiH = ViH / VH
Else
    XeH = 0
    XiH = 0
End If
XC = VC / VT: XH = VH / VT
```

```
    'return air temperature
    TR = Xe * Te + Xi * Ti                                          '*
    If OACtrl = 1 Then                                              '*
        If VOAmax > VT Then VOAmax = VT
        XOA = XOA_ECM(ECM, TOA, XOAmin, TCL, TR, VOAmax / VT)         '*
        VOA = XOA * VT                                              '*
    End If                                                          '*
    If OACtrl = 2 Then                                              '*
        VOA = VOA_ECM(ECM, TOA, VOAmin, TCL, TR, VT, VOAmax)       '*
        XOA = VOA / VT                                              '*
    End If                                                          '*
    XR = 1 - XOA                                                    '*
    VR = XR * VT                                                    '*

    'system cooling and heating capacity verification
    If TeS < TCL Or TiS < TCL Or TeS > THLset Or TiS > THLset _
        Or VT > VTD Or VOA > VT Then
        ExCap = True
    Else
        ExCap = False
    End If

    'fan power and temperature rise
    PLR = VT / VTD
    PSF = FANP(PSF_rated, PLR, VSM)
    PRF = FANP(PRF_rated, PLR, VSM)
    dTSF = 0.7457 * 3412 * PSF / (1.08 * VT)                        '*
    dTRF = 0.7457 * 3412 * PRF / (1.08 * VT)                        '*

    'preheat load
    TMA = XOA * TOA + XR * (TR + dTRF)                              '*
    If TMA < TCL - dTSF Then                                        '*
        TPH = TCL - dTSF                                            '*
        qPH = 1.08 * VT * (TPH - TMA)                               '*
    Else                                                            '*
        TPH = TMA                                                   '*
        qPH = 0                                                     '*
    End If                                                          '*

    TCE = TPH + dTSF                                                '*
    THE = TCE

    If THE > THLset Then
        THLact = THE
    Else
        THLact = THLset
    End If

    'humidity ratios for latent load calculation
    wCL = w_RH(TCL, 0.9, 14.696)                                    '*
    wRw = (XC * wCL + XH * XOA * wOA + (qel + qil) / (4840 * VT)) / (1 - XH * XR)
    wRd = wOA + (qel + qil) / (4840 * XOA * VT)
    wMA = XOA * wOA + XR * wRw                                      '*

    If wMA < wCL Then                                               '*
        WetCoil = False                                             '*
        wR = wRd                                                    '*
    Else                                                            '*
        WetCoil = True                                              '*
        wR = wRw                                                    '*
    End If                                                          '*

    wMA = XOA * wOA + XR * wR                                       '*
    wPH = wMA                                                       '*
    wCE = wPH                                                       '*
    RH = wR / w_sat((Te + Ti) / 2, 14.696) * 100                    '*

    'consumptions
    qCs = 1.08 * VC * (TCE - TCL)

    If WetCoil = False Then
        qCl = 0
    Else
        qCl = 4840 * VC * (wCE - wCL)
    End If

    qCT = qCs + qCl                                                 '*
    qH = 1.08 * VH * (THLact - THE)
    qHT = qPH + qH
    qFT = 0.7457 * 3412 * (PSF + PRF)                               '*

    f_DDVAV = Array(qCs, qCl, qCT, qPH, qH, qHT, qFT, _
            dTSF, dTRF, TeS, TiS, TR, TMA, TPH, TCE, Te, Ti, TCL, THLset, _
            VeC, ViC, VeH, ViH, VC, VH, Ve, Vi, VOA, VR, VT, _
            XeC, XiC, XeH, XiH, XC, XH, Xe, Xi, XOA, XR, _
            PLR, PSF, PRF, wR, wMA, wCL, WetCoil, RH, ExCap)
End Function
```

```
Public Function FANP(ByVal Pfan_rated As Double, ByVal PLR As Double, ByVal VSM As Integer) As Double
    If VSM = 1 Then FANP = Pfan_rated * (0.00153 + 0.0052 * PLR + 1.1086 * PLR ^ 2 - 0.1164 * PLR ^ 3)
    If VSM = 2 Then FANP = Pfan_rated * (0.351 + 0.308 * PLR - 0.541 * PLR ^ 2 + 0.872 * PLR ^ 3)
    If VSM = 3 Then FANP = Pfan_rated * (0.371 + 0.973 * PLR - 0.342 * PLR ^ 2)
End Function


Public Function XOA_ECM(ByVal ECM As Boolean, ByVal TOA As Double, ByVal XOAmin As Double, _
    ByVal TCL As Double, ByVal TR As Double, ByVal XOAmax As Double) As Double
    If ECM = False Then
        XOA_ECM = XOAmin
    Else
        If TOA > 65 Then
            XOA_ECM = XOAmin
        Else
            If TOA >= TCL Then
                XOA_ECM = XOAmax
            Else
                XOA_ECM = Application.WorksheetFunction.Max(XOAmin, _
                    Application.WorksheetFunction.Min(XOAmax, (TCL - TR) / (TOA - TR))) 'TOA<TCL
            End If
        End If
    End If
End Function


Public Function VOA_ECM(ByVal ECM As Boolean, ByVal TOA As Double, ByVal VOAmin As Double, _
    ByVal TCL As Double, ByVal TR As Double, ByVal VT As Double, ByVal VOAmax As Double) As Double
    If ECM = False Then
        VOA_ECM = VOAmin
    Else
        If TOA > 65 Then
            VOA_ECM = VOAmin
        Else
            If TOA >= TCL Then
                VOA_ECM = Application.WorksheetFunction.Min(VOAmax, VT)
            Else 'TOA<TCL
                VOA_ECM = Application.WorksheetFunction.Max(VOAmin, _
                    Application.WorksheetFunction.Min(VOAmax, (TCL - TR) / (TOA - TR) * VT))
            End If
        End If
    End If
End Function

Public Function w_sat(ByVal TOA As Double, ByVal Pt As Double) As Double
    Dim C(20) As Double, pw As Double, T As Double
    C(1) = -10214.165: C(8) = -10440.39:
    C(2) = -4.8932428: C(9) = -11.29465:
    C(3) = -0.0053765794: C(10) = -0.027022355:
    C(4) = 0.00000019202377: C(11) = 0.00001289036:
    C(5) = 3.5575832E-10: C(12) = -0.000000002478068:
    C(6) = -9.0344688E-14: C(13) = 6.5459673
    C(7) = 4.1635019
    T = TOA + 459.67
    If TOA < 32 Then
        pw = C(1) / T + C(2) + C(3) * T + C(4) * T ^ 2 + C(5) * T ^ 3 _
        + C(6) * T ^ 4 + C(7) * Log(T)
    Else
        pw = C(8) / T + C(9) + C(10) * T + C(11) * T ^ 2 + C(12) * T ^ 3 _
        + C(13) * Log(T)
    End If
    pw = Exp(pw)
    w_sat = 0.62198 * pw / (Pt - pw)
End Function

Public Function w_RH(ByVal TOA As Double, ByVal RH As Double, ByVal Pt As Double) As Double
    Dim C(20), pw, T, Pwh, wsat As Double
    C(1) = -10214.165: C(8) = -10440.39:
    C(2) = -4.8932428: C(9) = -11.29465:
    C(3) = -0.0053765794: C(10) = -0.027022355:
    C(4) = 0.00000019202377: C(11) = 0.00001289036:
    C(5) = 3.5575832E-10: C(12) = -0.000000002478068:
    C(6) = -9.0344688E-14: C(13) = 6.5459673
    C(7) = 4.1635019
    T = TOA + 459.67
    If TOA < 32 Then
        pw = C(1) / T + C(2) + C(3) * T + C(4) * T ^ 2 + C(5) * T ^ 3 _
        + C(6) * T ^ 4 + C(7) * Log(T)
    Else
        pw = C(8) / T + C(9) + C(10) * T + C(11) * T ^ 2 + C(12) * T ^ 3 _
        + C(13) * Log(T)
    End If
    pw = Exp(pw)
    Pwh = RH * pw
    wsat = 0.62198 * pw / (Pt - pw)
    w_RH = 0.62198 * Pwh / (Pt - Pwh)
End Function
```

VITA

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