



**TECHNICAL UNIVERSITY OF CRETE**

**Dept. Of Electronics and Computer Engineering**

**Methodologies and Algorithms for Energy and  
Thermal Comfort Benchmarking, Rating and  
Classification of Office Buildings**

By

**Triantafyllia G. Nikolaou**

**Physicist, M.Sc.**

A thesis submitted in Technical University of Crete

for the degree of

Doctor of Philosophy (Ph.D)

**Chania, January 2010**

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*To my husband Yiannis*

*and*

*my daughter Maira*

## ABSTRACT

The aim of this PhD thesis is to develop and propose an integrated classification method for office building sector in Greece. The proposed method includes the building energy performance evaluation method, the building stock database creation, the benchmarking process, the energy boundaries definition and building efficiency improvement methods recommendations. The final scope of this classification scheme is the determination of office buildings' performance rating boundaries and the establishment of energy and thermal comfort classes at national level.

The proposed approach of buildings' classification includes the following tasks:

- The development of a dynamic simulation model to calculate the energy demand for heating and cooling and the thermal comfort conditions of office buildings at an hourly and yearly base.
- Energy audits conduction to office buildings in Athens with the aim of buildings' characteristics investigation and simulation model validation.
- The installation of a Building Management System (BMS) in BYTE office building in order to conduct a detailed energy and environmental audit and to use the collected measurements for simulation model validation and improving.
- The simulation model generalization and the creation of a virtual building dataset (VBD) for office buildings in Greece. The philosophy of VBD is based on the creation and simulation of random office buildings that could be found or built in Greece, taking in to account the Greek constructional and operational characteristics of office buildings and Greek legislation. The VBD consists of 30,000 buildings (10,000 in each Climatic Zone) with their detailed constructional and operational data and of their simulation outputs: the annual energy demand for heating and cooling, the energy consumption for electric lighting and office equipment and an indoor thermal comfort indicator.
- The use of VBD data for determining benchmarks such as the Stock Building Reference Value ( $R_s$ ) and the Regulation Reference Value ( $R_r$ ) for each climatic zone of Greece, according to the proposed classification by CEN.
- The investigation of the application of available clustering techniques, such as Hierarchical, K-Means, Gaussian Mixture Models, Fuzzy and Neural clustering

algorithms to the simulated office building dataset towards the establishment of benchmarks and classifications for office buildings in Greece.

- The proposal of an integrated classification scheme for Greek office buildings in terms of energy demand and thermal comfort conditions.

- The investigation of common buildings' characteristics (constructional and operational) in each rating class in order to provide with a tool for adopting improvement recommendations for office buildings' energy efficiency in Greece.

- The evaluation of the proposed classification approach through comparisons with methodologies found in literature and mainly with the proposed CEN method, the discussion of the comparative advantages of the proposed scheme and the future work proposals.

The results of the present doctoral thesis show that the adopted methodology is an integrated and dynamic classification and rating system for Greek office buildings with the following characteristics: reliability, time saving, low budget processes, large flexibility and expandability and an easy update to the new building data and/or policy decisions.

## ABBREVIATIONS

<b>ACH -</b>	Air Changes per Hour
<b>BEMS-</b>	Building Energy Management System
<b>BEPR-</b>	Building Energy Performance Regulation
<b>BESTEST-</b>	Building Energy Simulation TEST
<b>CEN-</b>	Comitè Européenne De Normalization
<b>COP-</b>	Coefficient Of Performance
<b>EPBD-</b>	Energy Performance of Building Directive
<b>EPC-</b>	Energy Performance Certificate
<b>EPI-</b>	Energy Performance Indicator
<b>ERS-</b>	Energy Rating System
<b>EU-</b>	European Union
<b>EUI-</b>	Energy Use Intensity
<b>FC-</b>	Fuzzy Clustering
<b>FCM-</b>	Fuzzy C- Means
<b>GMMC-</b>	Gaussian Mixture Models Clustering
<b>HC-</b>	Hierarchical Clustering
<b>HVAC-</b>	Heating, Ventilating and Air- Conditioning
<b>IEA-</b>	International Energy Agency
<b>NC-</b>	Neural Clustering
<b>PMV-</b>	Predicted Mean Vote
<b>PPD-</b>	Predicted Percentage of Dissatisfied persons
<b>PPM-</b>	Parts Per Million
<b>RES -</b>	Renewable Energy Sources
<b>SOFM-</b>	Self Organizing Feature Map
<b>SOM-</b>	Self Organizing Map
<b>TMY-</b>	Typical Meteorological Year
<b>VBD-</b>	Virtual Building Dataset
<b>VRV-</b>	Variable Refrigerant Volume

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# Chapter 1

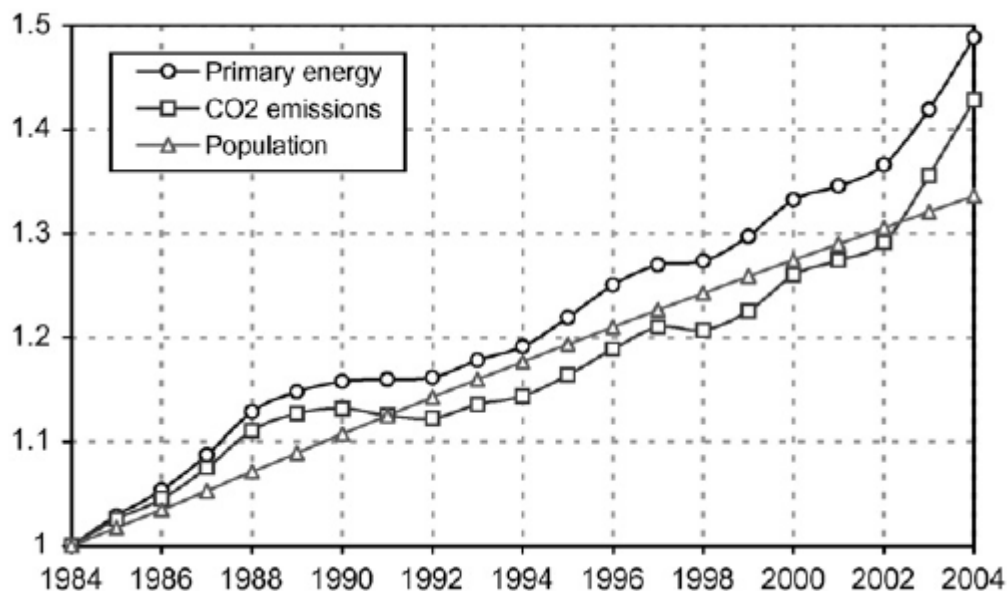
## INTRODUCTION

## CHAPTER 1: INTRODUCTION

### 1.1. The concept of building energy and indoor thermal comfort efficiency

World energy crises, such as the 1979 oil shortage caused by the Iranian revolution or the drastic increase in the price of oil in the early 1990s due to the first Gulf War, raised governmental concerns over the supply of and access to worldwide energy resources. European nations, highly dependent on energy resources from politically unstable areas, were particularly affected.

The rapidly growing world energy use has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). The International Energy Agency (IEA) has gathered frightening data on energy consumption trends. During the twenty years (1984-2004) primary energy has grown by 49% and CO<sub>2</sub> emissions by 43%, with an average annual increase of 2% and 1.8% respectively (Figure 1-1).



**Figure 1-1: Primary energy consumption, CO<sub>2</sub> emissions and world population, Reference year 1984. [Source: International Energy Agency (IEA)]**

Current predictions show that this growing trend will continue. Energy use by nations with emerging economies (Southeast Asia, Middle East, South America and Africa)

will grow at an average annual rate of 3.2% and will exceed by 2020 that for the developed countries (North America, Western Europe, Japan, Australia and New Zealand) at an average growing rate of 1.1%. At the same time, the global contribution from the energy consumption of buildings was steadily increasing, to around 20–40% in developed countries and exceeding the other major sectors, industry and transportation (Lombard et al., 2008).

Today, commercial and residential buildings are some of the largest energy consumers in the world, accounting for 1/4 to 1/3 of the total energy consumption and a similar amount of emissions (Hong et al., 2007).

Energy is used in buildings for various purposes: the most important purposes being for, heating and cooling, ventilation, lighting and the preparation of hot sanitary water. Moreover residential and commercial buildings require additional energy for their installed equipment, appliances and removable devices (IEA, 2008).

According to Eurostat (2008) in The European Union, the building sector shares 40.9% of the final energy consumption. The final energy consumption in EU27 increased during the period 1990-2006 from 1080 Mtoe to 1180 Mtoe. The progression of this trend is shown in Figure 1-2 for each sector separately. As is shown, the final energy consumption of building sector was increased from 440Mtoe to 480 Mtoe.

In order to tap the potential for energy savings and reduction of CO<sub>2</sub> emissions the energy efficiency of buildings has to be improved as soon as possible. The basic principle of building energy efficiency is to use less energy for heating, cooling, and lighting, without affecting the comfort of those who use the building. High-performance buildings not only save on energy costs and natural resources, but also provide a higher quality indoor environment. The benefits of building energy efficiency include (Hong et al., 2007):

- **Reduced Resource Consumption:** Improving building energy efficiency with renewable energy sources significantly reduces demand for new oil supplies and new power plant investment.
- **Minimized Life-cycle Costs:** High levels of building energy efficiency reduce the amount of energy required to operate a building, and reduces costs for the occupants of the building.

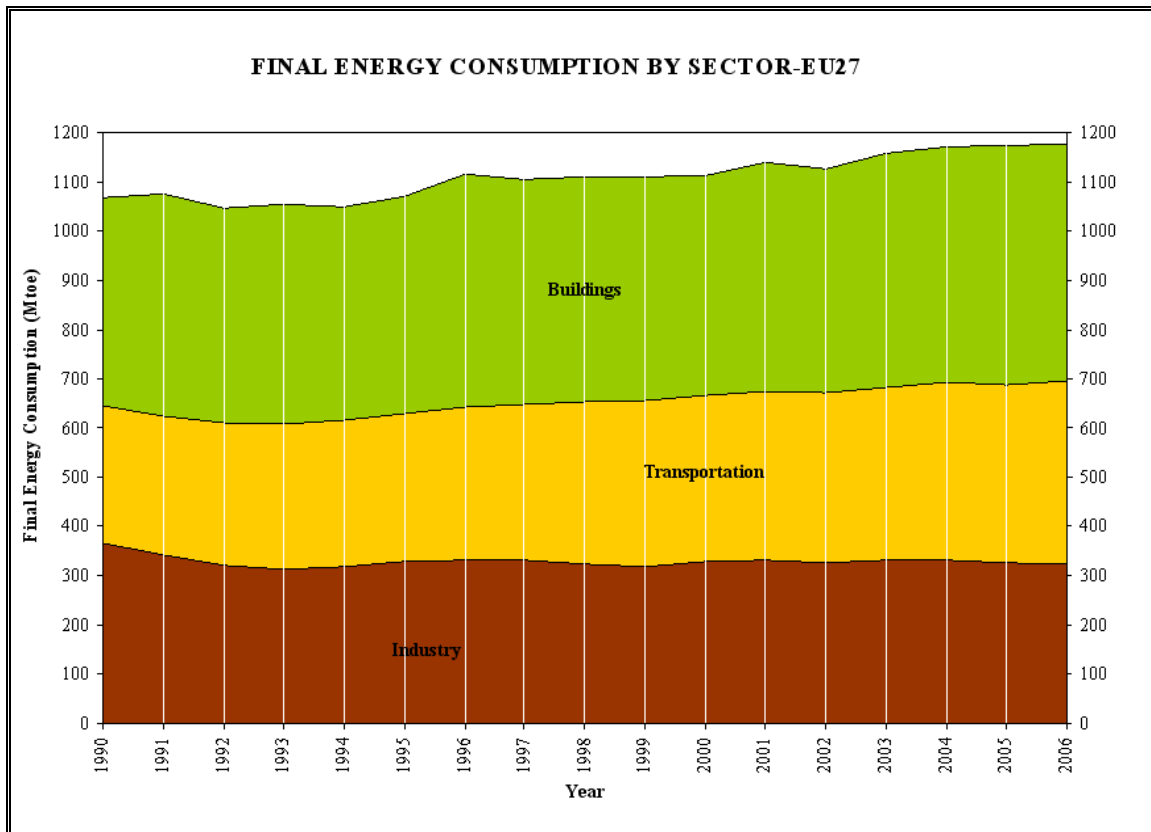


Figure 1-2: Final energy consumption for 1990 – 2006 [Source: Eurostat, 2008]

- **Reduced Environmental Impact:** Buildings contribute to the discharge of four primary pollutants which are mono-nitrogen oxides (NO<sub>x</sub>), sulfur oxide (SO<sub>x</sub>), CO<sub>2</sub>, and particulates. The improvement of building energy efficiency reduces the need for fossil fuels and reduces greenhouse gas emissions.
- **Healthier Indoor Environment:** Efficient buildings also mean a healthier indoor environment for the people who live and work in them. Comfortable temperatures and a quiet work environment are some key features of high-performance buildings.
- **Increased Employee Productivity:** Improved comfort of building occupants contributes to increased employee productivity. Recent studies have shown an increase in employee productivity when buildings have features such as natural light, better control of temperature, and a more intelligent use of space. (Papadimitriou, 2009)

As it is mentioned above, buildings account for close to 40% of the total energy used globally. Given the many possibilities to substantially reduce buildings' energy

requirements, the potential savings of energy efficiency in the building sector would greatly contribute to a society wide reduction of energy consumption. The implications of such potential reduction should not be underestimated, as the scale of energy efficiency in buildings is large enough to influence security policy, climate preservation and public health on a national and global scale (International Energy Agency, 2008).

It was under such circumstances that a new concept relating to energy efficiency in buildings emerged in the early 1990s as an essential method of reducing energy use and CO<sub>2</sub> emissions: energy certification for buildings. An overall objective of energy policy in buildings is to save energy consumption without compromising comfort, health and productivity levels. In other words, consuming less energy while providing equal or improved building services, that is, being more energy efficient. Regulatory bodies (Government, energy agencies, local authorities, etc.) have three basic instruments available for encouraging savings and maximizing energy efficiency in buildings: regulations, auditing and certification.

Building energy regulations, also referred to as building energy codes, establish minimum requirements to achieve energy efficient design in new buildings. The primary aim is saving final energy or any related parameter (primary energy, CO<sub>2</sub> emissions or energy costs) without compromising thermal comfort (Lombard et al., 2009).

ASHRAE Standard 55 (ASHRAE, 1992) describes thermal comfort as “the condition of mind which expresses satisfaction with the thermal environment”. The environmental variables that influence thermal comfort are the air temperature, the mean radiant temperature, the air velocity and the water vapour pressure in ambient air. Two other important variables are the person’s activity level and clothing. The heat balance of the body provides a basis for the development of an equation for the thermal comfort. The equation provides a means of determining all possible acceptable ranges of the environmental variables for given values of activity level and clothing (Kolokotsa, 2001).

While the comfort equation shows how the environmental variables are combined to obtain optimal thermal comfort, it does not indicate the preferred comfort conditions for persons. This is a function of the predicted mean vote (PMV), which provides

information on the degree of discomfort experienced in a thermal environment (Kolokotsa, 2001).

The PMV is a seven-point scale from  $-3$  (cold) to  $+3$  (hot) with  $0$  as the neutral level. A last indicator of the degree of satisfaction with the thermal environment is the percentage of people dissatisfied (PPD). As shown in Figure 1-3, the PPD has a minimum of  $5\%$  for  $PMV=0$ . This implies that it is impossible to satisfy a large group of people under the same conditions (ISO 7730, 2005).

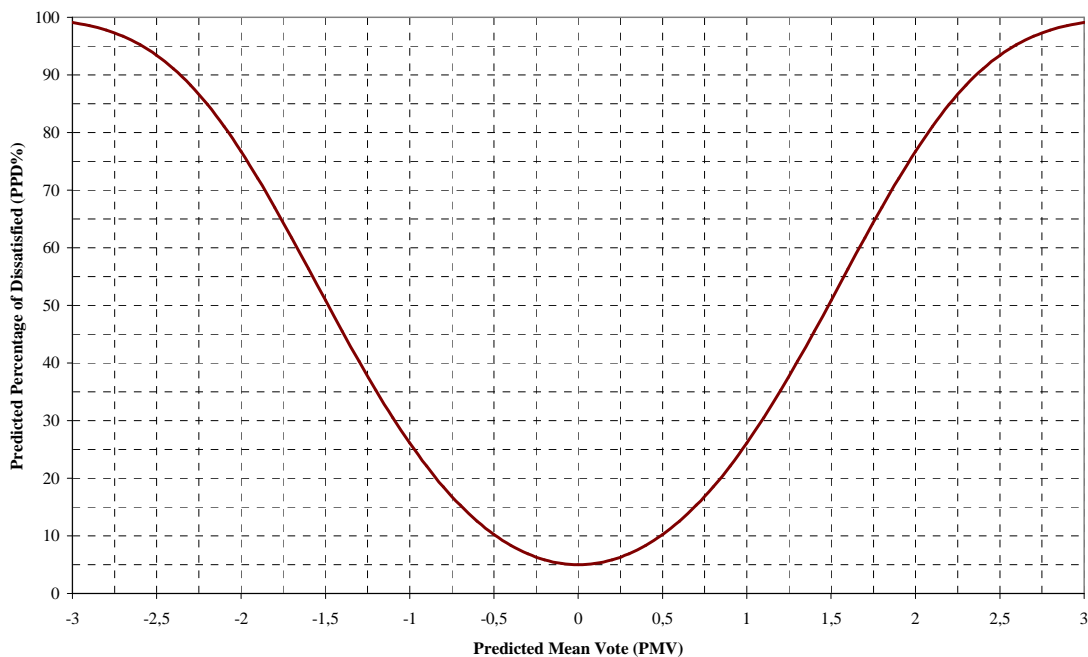


Figure 1-3: The PMV versus PPD diagram

## 1.2. Building Energy Regulation, Certification, Directives and Standards

### 1.2.1. Energy regulation

Energy regulation has a perceptive character, and its objective is to establish and limit the upper bound for the buildings energy consumption. With its normative character, energy regulation establishes the minimum, and often the only, building energy assessment tools that will be introduced in the sector, and has therefore a high responsibility in the internalization of energy assessment.

The success of building energy regulation in effectively controlling the energy consumption in the building sector is associated to the adopted energy performance indicator and to the promoted energy assessment tools.

Nowadays, building energy regulation in the different countries is very inhomogeneous regarding these two elements, as well as regarding the pretended upper bound for building energy requirements, even in the frame of the EU (Casals, 2006).

### **1.2.2. Energy certification**

Energy certification is a mechanism whose main objective is to promote higher energy performance standards than the regulated ones. To reach this objective, energy certification must provide a clear and detailed information about the building's energy performance (energy labeling), allowing for the straight comparison between different buildings. As well as with energy regulation, the indicators implemented in the energy certification will condition its capability to reach the objective. The indicator implemented in the energy regulation should be included among the indicators provided by the energy certification in order to clearly situate the certification on the reference regulated level of energy performance. The energy assessment methods, upon which energy certification is based, are key elements for its success.

A well implemented energy certification scheme must allow for, and promote, a clear quantification of design concepts with potential for building energy consumption reduction, such as bioclimatic architecture, passive solar heating, passive cooling, passive ventilation, integration of renewable energies, always guaranteeing some given comfort levels.

Energy certification may have a compulsory or voluntary character. Compulsory energy certification schemes may introduce some additional burdens on the administration, while voluntary ones do not. However, only through a compulsory energy certification scheme, can this mechanism develop all its potential for energy improvement in the building sector. Voluntary energy certification schemes have a limited scope and not always succeed to send the appropriate signals to the building market. (Casals, 2006)

### 1.2.3. EU Directives and Standards

Already in 1993, the Directive 93/76/CEE clearly pointed to the building sector for its high relevance in the energy consumption and CO<sub>2</sub> emissions within the EU, urging to adopt measures to increase the energy efficiency in this sector. In the European Council Directive 93/76/CEE to limit carbon dioxide emissions by improving energy efficiency, energy certification is presented as one of the cornerstones for achieving energy efficiency in buildings. This certification “*shall consist of a description of their energy characteristics, must provide information for prospective users concerning a building’s energy efficiency*” and additionally, “*may also include options for the improvement of these energy characteristics*”. The directive was non-mandatory and also full of ambiguities (with regards to how to provide information about building energy efficiency) that resulted in low impact implementations of its requirements across Member States.

Almost ten years later, the EU acknowledged the need for a new regulatory instrument and introduced Directive 2002/91/EC (EPBD) on the energy performance of buildings. The aim of the Directive is to “promote the improvement of the energy performance of buildings within the European Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness” (Dahlsveen, 2004). This is to be achieved through the following main actions:

- The creation of a general methodology following a framework provided by the Directive that can be used to calculate the energy performance of buildings. To find the most effective measures for each individual building a multidisciplinary evaluation is needed an energy audit (energy, environmental and economy evaluations and calculations). Member States apply the methodology at national or regional level.
- The application of minimum requirements, as measured by the methodology above, to all new residential and tertiary (generally public and commercial) buildings and to the major refurbishment of existing buildings with floor areas greater than 1,000 m<sup>2</sup>.
- The introduction of an Energy Performance Certificate (EPC) to be available whenever a building is constructed rented out or sold.

- Regular inspection and assessment of boilers, heating systems and air conditioning installations (Elmorth, 2003).

In order to support the implementation of EPBD, CEN created a clear and consistent set of standards as a basis for the national procedures in the Member States. The use of CEN standards for calculating energy performance, including energy performance certification and the inspection of boilers and air conditioning systems reduces costs when compared to developing and maintaining separate standards or guidelines at national level. In addition, Member States with very limited or no experience in the field of the EPBD could benefit from the CEN standards (Buildings Platform, 2006). The groups of CEN Standards that have been developed for the implementation of EPBD are presented in Table 1-1.

**Table 1-1: The Groups CEN Standards [Source: Buildings Platform, 2006]**

<b>Group Name</b>	<b>Content</b>
<b>Group 1</b>	The building physics standards (e.g. describing the calculation of heat transfer by transmission and ventilation, load and summer temperature, solar transmittance and the calculation of the energy need for heating and cooling of the building).
<b>Group 2</b>	Standards on the description and properties (classification) of ventilation systems plus cooling and air conditioning systems.
<b>Group 3</b>	Description of space heating and domestic hot water systems, the generation efficiency, the emission efficiency.
<b>Group 4</b>	Lighting systems for buildings (including the effect of daylight), controls and automation for building services, classification of indoor environment, financial economic evaluation of sustainable energy applications.
<b>Group 5</b>	Inspections of boilers & heating systems, cooling and AC systems and ventilation systems.
<b>Group 6</b>	Energy performance energy certification of buildings, the overall energy use, primary energy and CO <sub>2</sub> emissions, definition of energy performance rating.

The new European standard EN 15217 (EN 15217, 2007) is an attempt to describe methods for expressing energy efficiency and certification of buildings. Energy Performance Certificates are redefined within the development of a certification scheme, which must contain at least:

- An overall Energy Performance Index (EPI) stated in terms of energy consumption, carbon dioxide emissions or energy cost, per unit of conditioned area to allow the comparison between buildings.
- An overall minimum efficiency requirement to be established by the legislation as a limit of the energy performance index ( $EPI_{max}$ ). The standard recommends its

correlation with other parameters (such as climate and building type) or a self reference method.

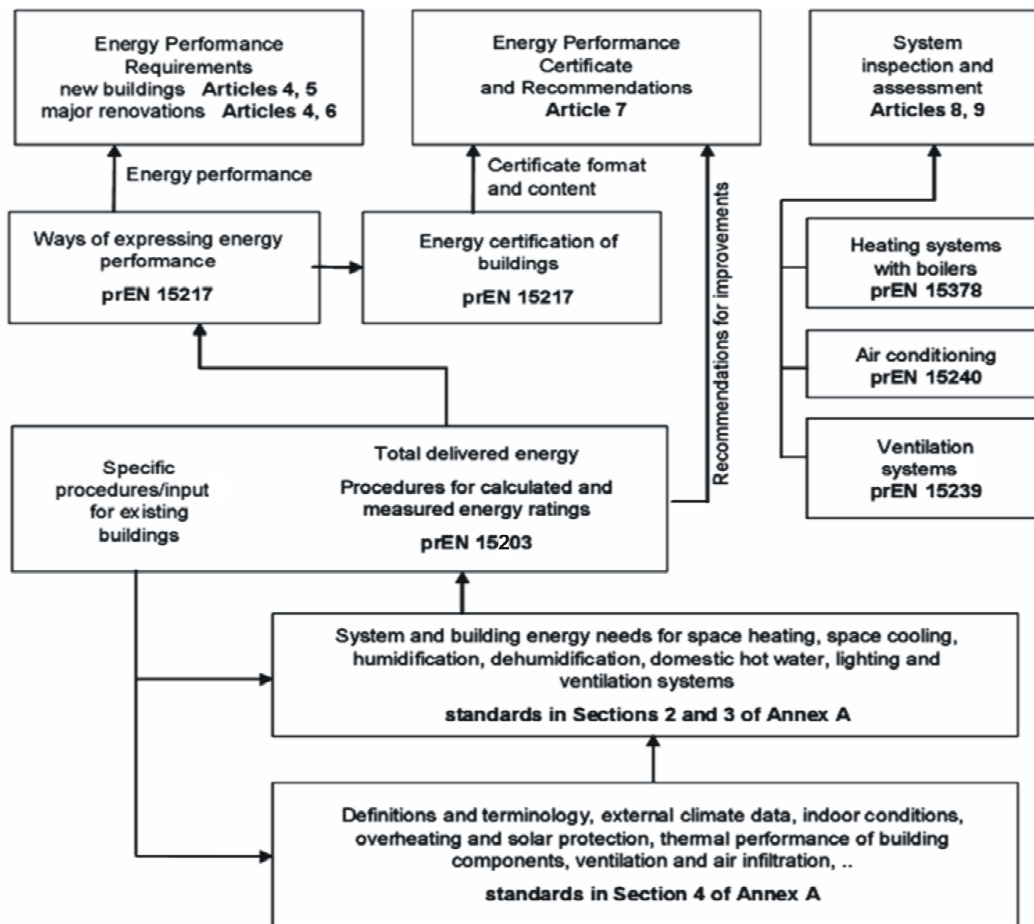


Figure 1-4: Major CEN Standards and their connection with the EPBD [Source: CEN, 2006]

- A label based in the A–G bands to achieve a suitable grading of buildings. A key issue is the definition of the scale that should make reference, at least, to the building energy regulations ( $R_r$ ), the existing building stock ( $R_s$ ) and the zero-energy building ( $R_0$ ).
- Energy consumption by the main building components, such as building envelope and services, together with recommendations of energy efficiency measures for building owners' consideration.

The scope of the certification is therefore extended not only to the energy performance of the building but also to include a minimum requirement and a label or class that allows users to compare and assess prospective buildings. The certificate must

contain, amongst other information, a classification of the building energy efficiency based on an energy label (Lombard et al., 2009).

Also the “End-use Efficiency and Energy Services Directive” (Directive 2006/32/EC, 2006), adopted by the European Council on 14 March and formally entered into force on 17 May 2006, encourages energy efficiency through the development of the energy services market and the delivery of energy efficiency programs and measures to end users.

On May 19th 2008 the Greek Law 3661/2008 “Measures for the building energy consumption reduction” for implementing the Energy Performance Building Directive was published. This Law marries Greek legislation with the Directive 2002/91/EC and provides the measures for the improvement of energy performance of buildings. More specifically this Law (Official Government Gazette, 2008):

- Introduces the evaluation of energy performance of buildings in Greece.
- Promotes the use of new and innovative technologies in the building sector requiring the replacement of conventional fuels with Renewable Energy Sources in order to achieve energy saving.
- Establishes the skill of energy inspecting in Greece.

The energy rating and classification methodologies to be proposed by the Building Energy Performance Regulation (BEPR) are based on the framework set out in the relative CEN Standards.

Nowadays, energy performance demands in the building sector within the EU go from the situation in countries like Denmark and Germany, with rather demanding energy regulations and already established energy certification schemes, to the situation in countries like France and Spain with low regulative demands and without certification processes established at national level.

### **1.3. Structure of the thesis**

The aim of the present thesis is to develop an innovative integrated classification method which will include a building energy performance evaluation method, a building stock database creation methodology, benchmarking processes, classification

and labeling methods and building efficiency improvement recommendations for office building sector in Greece. The present thesis is organized into seven (7) Chapters.

The aim of the 2<sup>nd</sup> Chapter of this thesis is the analysis and evaluation of the relevant research in the field of building energy classification and the identification of the critical gaps the doctoral research should fill. The literature review comprises studies of the last 40 years (post 1970). The review begins with the studies of building energy benchmarking methods and their categories according to the energy performance indicator they use, the statistical analysis and the distribution they are based on, the parameters that have to be taken into account and their final purpose. The review continues with the researches dealing with energy and environmental rating and labeling methods, focusing on the methods proposed by the CEN Standards. In the last part of the literature review some significant researches that investigate the integrated classification methods including the building energy database, the benchmarking method, the building energy performance evaluation and the energy boundaries (classes) definition are presented and analyzed. By summarizing the research work performed so far in the buildings' classification sector, the author reveals the crucial points and analyses the statement of the problem of the PhD research.

In Chapter 3, a simulation model of an office building is created in order to evaluate the energy performance and the indoor thermal comfort at hourly and yearly base of any case study office building. With the aim to collect information about the characteristics of the Greek office building sector and to test the adopted simulation model, simple audits were conducted by the author. The outcomes of these audits are presented in the last part of the chapter.

The aim of Chapter 4 is to present a detailed audit conducted with the aid of an installed BMS in an office building and the adoption of a detailed relevant simulation model. The Chapter begins with an analytical description of the audited building characteristics, the BMS installation details and the collected measured data. In the next part of the chapter, the detailed simulation model and its validation via measurements is proved.

In Chapter 5 a method for a Virtual Building Dataset (VBD) creation for office buildings in Greece and its application to benchmarking and classification procedures

is presented. The Chapter begins with a detailed description of the VBD creation process (thermal model, input data, and selected values). In the next part of the Chapter the validation of the VBD with two energy audits outcomes is presented, while in the last part the benchmarking and classification results based on the CEN procedures using the VBD are presented and discussed.

In Chapter 6 the application of many available clustering techniques, such as the Hierarchical, K-Means, Gaussian Mixture Models, Fuzzy and Neural clustering algorithms to the VBD is investigated towards the establishment of benchmarks and classifications for office buildings in Greece. In the first part of the Chapter the classifications according each method are presented in detail. Then, appropriate indices and criteria are selected in order the best cluster algorithm to be investigated for our theoretical problem and a classification scheme to be proposed in the PhD research framework. In the last part of the Chapter the final results of the selected method are used for the parametric study of buildings' characteristics and the establishment of efficiency improvement methods

In the last Chapter of the thesis, the significant points and the final conclusions are discussed. The innovative parts of the research are outlined and further research activities are proposed.

## **Chapter 2**

# **REVIEW AND STATE -OF -THE -ART ON METHODOLOGIES OF BUILDINGS' CLASSIFICATION**

## **CHAPTER 2: REVIEW AND STATE-OF-THE-ART ON METHODOLOGIES OF BUILDINGS' CLASSIFICATION**

### **2.1. Introduction**

The term building energy classification encompasses any procedure that allows the determination of the quality of a building (in terms of energy use) in comparison with others. In this chapter the previous works in the field of building energy benchmarking, energy rating and labeling in the context of building energy classification are investigated.

### **2.2. Review on building energy efficiency benchmarking methods**

Originally, the word benchmark was used exclusively in topography to precisely define a reference point in terrain or geological analysis. In the 1970s, some companies developed benchmarking tools to allow comparison of key production parameters and thus to check whether improved processes enhanced their performance.

In the 1990s, the term building energy benchmarking started to be used to refer to the comparison of energy use in buildings of similar characteristics. Some authors like Federspiel et al. (Federspiel et al., 2002) distinguish benchmarking from baselining. According to various authors, benchmarking generally includes a comparison of energy performance with other buildings, while baselining generally involves a comparison of past energy performance of a single building with current energy performance.

Benchmarking models developed from energy-efficiency indicators are valuable tools for both governmental and private sector in managing energy consumption. Some governments have used these tools to formulate policies for the efficient use of energy in buildings.

The energy performance metric plays a key role for energy benchmarking of buildings (also known as energy-efficiency indicators). The most common performance metric for whole building energy consumption is Energy Performance Indicator (EPI) or Energy Use Intensity (EUI).

Benchmarking it consists of a comparison of the EPI or EUI of a building with a sample of similar buildings or with the best practice building. A common EPI or EUI used for many building types is annual energy use normalized with floor area but others such as energy per worker or energy per bed may also be used. Energy services companies use the EPI as a starting point in energy audits and assess saving opportunities by comparing with existing references (benchmarks) of average (typical), above average (good) and excellent (best) practice. At the design stage, energy performance indices for different designs are of great use when choosing suitable technologies, particularly if benchmarks for similar buildings are available. Last but not least, governments consider benchmarking in the early conception, development and implementation of energy efficiency policies within the building sector.

The Normalized Performance Indicator (NPI) (Zmeureanu and Fazio, 1998) developed for office buildings in UK, takes into account the heating energy, building size, operating hours, internal temperature and wind exposure.

Typically, energy-efficiency indicators for commercial buildings can be obtained by normalizing the energy use with floor area and/or operational hours. For instance, Filippin (Filippin, 2000) used a sample of energy consumption data and the floor area to calculate the Energy Use Intensity (EUI), i.e., kWh/ft<sup>2</sup> or MJ/m<sup>2</sup>, for school buildings in central Argentina. The calculated EUIs were then ranked as a benchmark table. This simple floor-area-normalized EUI is often used for judging the energy-use performance of a commercial building.

Also, Casals (Casals, 2006) noted that energy intensity was an appropriate indicator for adoption in energy regulations. However, he emphasized that an appropriate indicator should comply with the regulation objectives. He also described energy intensity as a quantitative indicator that should be adopted in many regulation schemes that still use steady-state heat transfer coefficients, such as the Spanish regulation.

On the other hand, Monts and Blissett (Monts and Blissett, 1982) discussed the limitations of using the simple normalized EUI for commercial buildings. It is plausible that other factors (such as an HVAC system) may cause the energy use in specific buildings to be higher (or lower) than that in their peers.

Sharp also made the same argument that such a simple normalized EUI was not good enough for a credible energy consumption performance rating. To account for the effect of other factors that affect energy consumption, benchmarks were developed using a multivariate linear regression approach to correlate other factors representing some important characteristics of buildings with EUI. Moreover, Sharp argued that the mean EUI can be a poor benchmark as distributions of indicators are generally skewed. Hence, Sharp used the standard errors of the resulting regression model to establish the distributional benchmark table, which was considered more reliable as it masked the effect of outliers. The benchmarking process of a specific building makes use of the “best-fitted” regression model to calculate the predicted EUI. With this predicted EUI, a distributional benchmark table (percentile table) is calculated by means of the distribution of standard errors. The actual EUI can be compared with the benchmark table for the benchmark score (Sharp, 1996).

Another common benchmarking method is based on the distribution of residuals of the regression model, in contrast to the approach based on the standard error distribution in Sharp’s method. The residual is the difference between the actual EUI and the predicted EUI. Hence, the residuals are treated as measures of inefficiency. For a given building to be benchmarked, if the actual EUI is less than the predicted EUI (negative residual), it means that the building uses less energy than other similar buildings. Moreover, the distribution of sample residuals from the regression model can be used to construct the corresponding benchmark table. Lovell-Smith and Baldwin (Lovell-Smith and Baldwin, 1988) used this approach where the residuals were not obtained from the regression model. However, they used the mean EUI from the sample as the predicted EUI without considering the normalization of other significant factors. Obviously, this kind of benchmark table does not provide a physical measure. Sharp in his proposed method uses the actual EUI distribution instead.

In the literature energy-efficiency benchmarking methods are also categorized according to the purpose. According to Kinney and Piette (Kinney and Piette, 2002) they are used for two fundamental purposes:

- To identify if a building’s energy performance is good, average or poor with respect to other buildings of its type. This is a robust indicator of whether the

building should be prioritized for action. For this purpose, empirical benchmarks derived from energy statistics for the stock (or analysis of) the stock are applicable.

- To identify if a building's energy performance matches its potential and if not by how much it might be improved cost effectively. For this purpose a realistic model of the building and its systems is theoretically more applicable.

Empirical benchmarks fall into two categories: (a) the conventional type are obtained from bulk statistical data, often corrected for climate, (b) less common but more insightful are parameterized benchmarks which set criterion (good practice) and normative (typical) standards for each energy use of the building.

Model based benchmarking calculates benchmarks based on an idealized model of building performance. Models have the advantage that they can be tweaked to account for a wide range of factors that contribute to variation in energy use. They can also be used to generate targets and compare design alternatives and retrofit scenarios. They offer detailed information and a wide variety of outputs; however it may require a great number of inputs, skilled users and a significant amount of time to gather and input the necessary data, all of which can make the process expensive.

The benchmarking techniques are divided into four categories: Statistical Analysis Benchmarking (also known as Regression Model-Based), Points-Based Rating Systems, Simulation Model-Based Benchmarking, and Hierarchical and End-Use Metrics.

The statistical analysis consists of collecting the survey data and comparing one unit with the others. Chung et al. (Chung et al., 2006) used multiple regression analysis to build a benchmark table by investigating the relationship between EUIs and the explanatory factors. In that study, the most significant factors were found to be the building age, operating hours, floor area, number of consumers and a subjective qualitative description of user behavior and maintenance.

Simulation Model-Based Benchmarking sets up a mathematical model to calculate theoretical energy consumption and makes a comparison between theoretical energy consumption and observed energy consumption in order to evaluate the performance of energy consumption. Federspiel et al. (Federspiel et al., 2002) used numerical software to construct the minimum Energy Usage Intensity (EUI) for laboratories and compared this with observed EUI of the evaluated building.

Carriere et al. (Carriere et al., 1999) implemented DOE-2 simulation software to study the energy-saving potential of large buildings. The simulation method used factors including the properties of building construction material, the energy efficiency of related energy-consuming equipment (such as air conditioners and lights, etc.), and the usage period to calculate the theoretical energy consumption of the building.

Points-Based Rating Systems, including the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System, do not allow comparisons against other buildings, rather they provide standards and guidelines to measure how efficient and environmental friendly a facility is and compare it to best-practice standards. A LEED score is made up for credits assigned for satisfying different criteria including energy efficiency and other environmental factors.

Hierarchical and End-Use Metrics refers to the generation of benchmarks that link energy use to climate and functional requirements. This method is useful for accounting for more of the differences in features affecting energy use.

Many authors have investigated the crucial parameters according to their effect to the energy consumption that have to be taken into account during energy benchmarking methods adoption.

For instance, Lam et al. (Lam et al., 1997) analyzed several characteristics relevant to energy consumption through parametric simulations, developing equations to predict the electricity consumption of commercial buildings in Hong Kong. The statistical analysis indicated shading coefficient (SC) and window to wall ratio (WWR) as significant envelope variables, excluding variables such as floor to floor height and number of storeys.

In Brazil, Signor et al. (Signor et al., 2001) developed multi-variable regression equations for office buildings based on the work of Lam et al. (Lam et al., 1997), but using two building volume indicators: facade area divided by total floor area (to represent shape): and roof area divided by total floor area (to represent number of storeys). The equations focused on the envelope parameters: WWR, SC, projection factor of horizontal solar protection, and thermal transmittance, U-value, and solar absorbtance of the roof. The U-value of the external walls was also analyzed, but it was excluded from the equation due to its nonlinearity, while solar absorbtance of the

external walls was excluded due to its low significance indicated by the simulation results. The final result was annual electricity consumption by area (or annual energy intensity).

Backer and Paciuk (Backer and Paciuk, 2002) reported a study in 2002, which investigated the impact of night ventilation and pre-cooling on peak cooling demand for an office building in coastal region of Israel.

In another research, Olofsson et al. (Olofsson et al., 2009) used PLS method (partial least squares to latent structures) to model different energy performance measures, such as the use of energy for heating, electricity used to operate the building technical system, the building total heat loss coefficient and the use of domestic cold water, in order to enable energy benchmarks. The PLS model was investigated for both the total annual use and the annual use normalized to the available floor area.

Carlo and Lamberts (Carlo and Lamberts, 2008) in their research adopted criteria to evaluate the envelope efficiency level, focusing on the development of a regression equation which provides an electricity consumption indicator. The envelope label is divided into five efficiency levels, from A (more efficient) to E (less efficient), identified according to the electricity consumption indicator. The linear regression equation considers variables such as window to wall ratio (WWR), SHGC, solar protection angles, building volume indicators and the roof U-value. The U-value of the walls was excluded from the equation due to its non-linearity. Its relation with electricity consumption depends on internal gains, exterior temperatures, building size and thermal capacity of the walls and could not be described by a linear regression equation. The envelope efficiency label is obtained by the comparison of the electricity consumption indicator of the proposed building with the electricity consumption indicators of two other building envelopes presented.

It is worth noted that there are significant surveys focusing on this topic in Greece. Papadopoulos et al. (Papadopoulos et al., 2002) after a monitoring survey determined the buildings' energy consumption factors, which are the building size, their surface to heated volume ratio, the thermal insulation and the type and condition of the heating system. In that study the authors also determined the potential and feasibility of energy saving renovation measures.

Daskalaki and Santamouris (Daskalaki and Santamouris, 2002) reported another study in the same year which investigated the energy conservation potential of office buildings in five climatic zones in Europe for different passive retrofit scenarios.

A. Papadopoulos and other authors in a more recent research have investigated the role of HVAC Systems in the energy and environmental efficiency of Greek buildings. Papadopoulos et al. in (Papadopoulos et al., 2008) research investigated the energy, economic and environmental performance of heating systems in Greek buildings. Papakostas and Papadopoulos in (Papakostas and Papadopoulos, 2004) discussed the impact of the relation between indoor and outdoor conditions on the ventilation loads of buildings. Also, Avgelis and Papadopoulos in (Avgelis and Papadopoulos, 2009) developed a method for choosing and managing in the best possible way heating, ventilating and air conditioning (HVAC) systems in new and existing buildings. The method utilises a combination of two analysis' tools, the multicriteria decision-making and the building simulation towards the direction of a holistic assessment of HVAC systems. In order to evaluate the method, a series of HVAC systems are considered for installing in an office building and the multicriteria method Electre III is applied for their selection. The results show that the proposed model allows the classification of alternative technical solutions concerning the HVAC's design, taking into consideration economic, energy and environmental criteria as well as criteria of users' satisfaction.

Karatasou et al. (Karatasou et al., 2006) presented an approach for modeling and predicting hourly building loads using feed forward neural networks where not only the inputs selection, but also the structure of the network is systematically treated. Also in this research the importance of input parameters (energy consumption factors) investigation is outlined. The authors indicated that some of the environmental variables such as the ambient temperature and the solar radiation are important while others such as the wind velocity or humidity can be omitted.

Database information availability is a different crucial issue. The knowledge of building stock energy data of a country is a very significant tool for energy benchmarks establishment. Gathering energy information to populate a database with a representative sample of the building stock is not only expensive but also technically complex. It is not surprising that only a few nations have undertaken this

task to date. Usually, information is collected on site from building owners, tenants, facility managers, etc.

An outstanding example is the US Energy Information Administration (EIA) database and the later surveys for both the residential sector (RECS, EIA, 2001) and commercial buildings (CBECS, EIA, 2003).

Different data collection methods for energy benchmark procedures are found in the literature (Jones et al., 2000), (Hernandez et al., 2008). Santamouris et al. (Santamouris et al., 2007) have collected energy consumption data through energy audits performed in 320 schools in Greece. Argiriou et al. (Argiriou et al., 1994) developed specific questionnaires to perform surveys for office buildings and hospitals' energy use and indoor air quality. DATAMINE project (DATAMINE, 2007) provides the necessary platform to gather building energy data extracted by the energy performance certification procedure.

At European level, the unavailability of building energy use databases has restricted the development of benchmarking tools. Recently, the European projects Euroclass (Santamouris et al., 2005), Europrosper (EUROPROSPER, 2004), ELabel (ELabel, 2007) and ENPER-EXIST (ENPER-EXIST, 2007) have studied the complexity associated with the elaboration of a database of building energy consumptions in Europe and with identifying suitable reference levels as intermediate steps for the development of an energy performance certificate for existing buildings.

Lombard et al. (Lombard et al., 2009) proposes a different approach to database generation based on the application of building energy simulation to a variety of building types for a range of energy parameters (parametric benchmarking). The author claims that careful selection of building types and calculation methods is critical to the validity of the database. Another added constraint is the need to customize building envelopes and HVAC sizing for each climate and system type. An advantage is the possibility of covering a wide range of building energy consumption characteristics with a suitable selection and variation of the energy parameters. Additionally, energy simulation provides a wider range of energy outputs for future comparisons.

The core of benchmarking process is the comparative analysis. A subset of comparable buildings could be obtained by filtering the database against similarity parameters.

This is called the “*comparison scenario*”. Energy intensity frequency distribution curves for that scenario enables determination of a percentile ranking, percentage of buildings with better (or worse) energy performance. Programs such as Energy Star (ENERGY STAR, 1992) score from 1 to 100, based on models and normalization methods of statistical analysis applied to the EIA database. To obtain a certificate (Energy Star Label) the building must achieve a minimum of 75 points, equivalent to belonging to the quartile of better energy efficiency. Other tools such as Cal-Arch (CAL-ARCH, 2003) do not offer any score but represent the energy intensity frequency distribution curve and the relative position of the actual building.

CEN Standard EN ISO 15217 “Energy performance of buildings - Methods for expressing energy performance and for energy certification of buildings” proposes procedures to define reference values and benchmarks. In this standard the global indicator of energy performance for a whole building is measured by an indicator’s value that is expressed (EP) by the weighted sum of a building’s delivered energy:

$$EP_{period} = \sum_{i=1}^n delivered\ Energy_i$$

Where  $i=1,2,\dots,n$  declares the months of a period (heating/cooling).

The energy performance (EP) indicators should be based on two types of ratings according to EN 15203/15315. These types of ratings are ‘standard calculated’ and ‘measured energy’ rating that is described in the following paragraph. EP can represent Primary Energy of a building, Carbon Dioxide Emissions and Net Delivered Energy defined by national policies (e.g. delivered energy).

Referring to EP requirements, there are two ways of expressing them:

(a) Global EP requirement based on an asset rating. This should be an upper limit value of one of the following indicators:

- Delivered energy
- Primary energy
- CO<sub>2</sub> emissions

The requirement can be written:  $EP \leq EP_r$  where EP is the performance indicator and  $EP_r$  is the value which defines the requirement

(b) Specific requirement based on:

- Energy use for one specific purpose (e.g.: heating, cooling, lighting)
- Building's characteristics or of its systems installed considered as a whole
- Building envelope's characteristics or system components

Reference values and benchmarks are used to compare the energy performance of a given building to the energy performance of similar buildings in terms of building use (e.g. apartment blocks, offices, hospitals).

The Standard establishes three types of benchmarks:

- R<sub>r</sub>: Energy performance regulation reference/benchmark.
- R<sub>s</sub>: Building stock reference/benchmark, which represents the energy performance reached by approximately 50% of the national or regional building stock.
- R<sub>0</sub>: Zero energy reference/benchmark, which corresponds to a building that produces as much energy as it uses.

According to standard the use of energy considered when defining the reference values/benchmarks shall be the same as the use of energy considered when establishing the rating. If the rating used is an asset rating, the reference will be obtained with the same assumptions as the asset rating regarding use patterns and internal and external climate.

### **2.3. Review on energy rating methodologies**

“Rating” is perhaps the most confusing term within this framework, as it is indistinctly used to refer to the building energy classification (the rating system), its application (the action of rating) and its final result (the rating figure) (Lombard et al., 2009)

According to literature the most common rating method is to normalize energy use with respect to building size, the annual energy use being divided by the heated floor area or by volume.

In general, the expression energy rating system (ERS) may be used as a synonym of energy classification, that is, a method for assessing energy quality. Examples can be found in both the Home Energy Rating System (HERS) of the Energy Star program

and the US Green Building Council LEED building rating system (LEED-NC, 2005) HERS measure and rate the relative energy efficiency of any house, regardless of its age, location, construction type, or fuel use. The rating evaluates the performance of the thermal envelope, glazing strategies, siting, HVAC systems and other criteria. HERS calculations include estimates of annual energy performance and costs and can provide insight into cost-effective, cost-efficiency improvements (HERS, 2000). According to HERS, dwellings are subject to a standard simulation test for energy rating proposes with standard assumptions including: typical weather for building's location and standard occupant behavior (thermostat set-points, hot water usage, personal appliances usage, etc. The drawback for using this "universal" rating tool is that, for a project where the above factors are different from the standard assumptions, the resulting design is likely to be far from optimum when judged by the normal criteria.

Stein (Stain, 1997) while examining the accuracy of HERS found also that the case studies demonstrated that is more difficult to accurately predict energy use in mild climates than in more severe climates.

Also, Stein and Meier (Stein and Meier, 2000) are more precise in the Energy Rating System definition: "a method for the assessment of predicted energy **use** under standard conditions and its potential for improvement" and usual output (energy use prediction, rating score based on a comparison with a reference building and a list of improvements).

Like HERS, energy rating of commercial buildings operates in several countries. ASHRAE Standard 90.1 (ASHRAE, 1989) which incorporates the Building Energy Cost Budget Method is used as the basis for Commercial Energy Codes in several states in the US. The method involves the use of an energy simulation program to estimate the performance of the proposed building compared to a prototype or reference building. The reference building approach is to be used when a prototype building description is not relevant for the proposed design. The method is intended "only for the purpose of demonstrating design compliance". Input parameters for the prototype or reference buildings are suggested by the Standard, based on the type of the proposed building. The suggested input parameters include the quantity/density and schedules of the occupancy, light, HVAC, and water, HVAC system types, and the thermostat settings. It is also suggested that the prescriptive values for code

compliance be used for the reference building's envelope's thermal properties. The performance of the proposed building is compared to that of the prototype or reference building in terms of the predicted annual energy cost. Although this methodology is more comprehensive than the most energy rating schemes for residential buildings it also, however, poses limitations for the designer. First, since the criteria used are annual energy cost, nothing is known of other possible aims, such as the CO<sub>2</sub> emission and life-cycle costs. Another limitation is that it does not take into account the building location in suggesting the thermostat settings and HVAC systems.

Fels (Fels, 1986) presents the Princeton Scorekeeping Method (PRISM), where he uses the well-known linear relationship called energy signature, between heating energy use and outdoor temperature. Zmeureanu (Zmeureanu, 1992) further developed this normalization method, to analyze utility bills collected in heated or cooled buildings.

Within the framework of Directive 2002/91, energy rating means the evaluation of the building energy performance. In the standard EN 15603 (EN 15603, 2008) CEN proposes two types of ratings: (1) calculated ratings, based on computer calculations to predict energy used by a building for HVAC systems, domestic hot water and lighting and (2) measured (or operational) ratings, based on real metering on-site. Calculated ratings are subdivided into standard (also called asset) and tailored ratings. The asset ratings use the calculation procedure within standard usage patterns and climatic conditions not to depend on occupant behavior, actual weather and indoor conditions, and are designed to rate the building and not the occupant. Asset ratings can be shaped to buildings during the design process (as designed), new buildings (as built) or to existing buildings. For the latter, when calculated under actual conditions (different to standard usage patterns) the rating becomes a tailored rating. In this sense, most of the American ERS are asset ratings for new or existing buildings, while benchmarking tools are normally based on measured ratings applicable only to existing buildings. Definition details for each rating are shown in Table 2-1.

While the schemes described above deal with site energy consumption (or energy costs) as a single rating criterion, some authors propose multi-criteria assessment of building performance. Soebarto and Williamson (Soebarto and Williamson, 2001) developed a building performance assessment methodology and tool based on multi-criteria decision-making approach where the performance of the building is always

compared to a reference building. The criteria include energy use, indoor air quality, thermal comfort, operating plan load, costs, and other environmental degradation, e.g. using nuclear fuel, atmospheric pollution, etc.

**Table 2-1: Definition of energy ratings according to CEN Standard**

Name		Input Data			Utility or purpose
		Use	Climate	Building	
Calculated	Design	Standard	Standard	Design	Building permit, certificate under conditions
	Standard	Standard	Standard	Actual	Energy performance certificate, regulation
	Tailored	Depending on purpose		Actual	Optimization, validation, retrofit planning
Measured	Operational	Actual	Actual	Actual	Energy performance certificate, regulation

In addition, within the framework of the European Joule-Thermie OFFICE project, Roulet et al. (Roulet et al., 2002) developed a multicriteria rating method (ORME) for office buildings. This method is based on a rating method that uses principal component analysis and aims to qualify and sort various retrofitting scenarios based on energy use and thermal comfort condition. The result of the rating method is a single indicator that combines energy and comfort parameters. This score globally characterizes the performance of the building under defined conditions regarding the parameters: energy use for heating, cooling and other appliances, impact on external environment, indoor environment quality and cost. ORME also includes a ranking method that uses partial aggregation techniques and purposes to rank buildings or retrofitting scenarios according to their performance with regard to several aspects. It requires a list of criteria along with an assignment of weight to each of them and allows the user to provide his scale of values.

Several schemes also exist attempting to combine other environmental factors into a single rating score. Examples include the BREEAM technique (Prior, 1993) introduced in the UK in 1990 as a voluntary environmental assessment scheme intended to encourage building owners and operators to adopt “green” practices. The scheme provides a tool and authoritative assessment procedures for quantitative evaluation of the environmental impacts of a building. The evaluation relates to a number of broad issues including, operational energy use and CO<sub>2</sub> emission, sick building syndrome, pollutants released during fire, embodied energy, radon emissions

and the life-cycle use of the building. Credit points are accumulated against the various performance requirements. These are summed to a total score to define Fair, Good, Very Good and Excellent overall performance, with additional requirements of having attained minimum scores in the three performance categories: Global/Resources, Local, and Indoor.

The building energy and environmental assessment method (BE<sub>2</sub>AM,) was developed within the THERMIE programme. The aim is to provide a common and recognized system of assessing, at the design stage, the energy and environmental impact of buildings across Europe. BE<sub>2</sub>AM has three components: (i) Life-cycle analysis of energy in use and embodied energy; (ii) Environmental preference for materials; and (iii) Environmental design opportunities. The rating performance is obtained by comparison with the performance of two reference buildings that comply with local standards. An overall credit rating can be defined as a linear combination of the three credit factors.

Also, LEED™ “Leadership in Energy and Environmental Design” (LEED, 1998) works in a similar way. Applicant buildings must satisfy a number of performance prerequisites and obtain a number of performance credit points to qualify for Bronze, Silver, Gold or Platinum certification.

An international initiative, initially involving the input of teams representing 14 countries, was established to investigate the development of a comprehensive building environmental assessment methodology. The project titled Green Building Challenge'98 was lead by representatives from Canada. The overall goal of GBC'98 was to “develop, test, and demonstrate an improved method of measuring building performance” (Larson and Cole, 1998). The project reconciled the work of many around the world and a so-called “second-generation” framework for assessing energy and environmental performance was developed during the process. The method is embedded in a computer tool GBTool (Anon, 1998). The work has been extended for GBC2000.

## **2.4. Review on energy labeling methods**

It was in the early 1990s when the EU introduced energy labeling with a double objective: to inform consumers about the energy performance of energy consuming

devices and to promote energy savings and energy efficiency. Following the success of its application to domestic appliances (Directive 92/75, 1992), energy labeling was extended to buildings a decade later (Directive 2002/91, 2002).

Building energy labeling, consisting of assigning an energy performance class or label to the building, requires the development of a scale related to a Labeling Index (LI). The choice of the comparison scenario is a key issue for the scale definition.

If there are enough comparable buildings, statistical analysis of the EPI through the cumulative frequency distribution curve allows the use of the percentile as an indicator of the energy position. At this point, labeling is equivalent to assigning percentile intervals (bands) to energy classes. According to Lombard et al. (Lombard et al., 2009), by normalizing the EPI distribution of cumulative frequencies using an average value such as the percentile of 50% (EPI<sub>50</sub>) the labeling index could be defined as:

$$LI = \frac{EPI}{EPI_{50}} \quad (2-1)$$

The scale is defined by fixing the transition values between classes.

As it has been described in Chapter 2.2, standard EN 15217 describes a procedure to define limits between classes based on two references: building regulations and building stock. The first is the overall minimum efficiency requirement set by the regulation as a maximum limit for the energy performance index (EPI < EPI<sub>r</sub>). The second reference corresponds to the energy performance reached by 50% of the building stock (EPI<sub>s</sub>). If the EPI is normalized by the stock reference, the label index for the regulation reference is:

$$LI_r = \frac{EPI_r}{EPI_s} \quad (2-2)$$

According to this methodology CEN scale situates the regulations reference on the boundary between B and C and the stock reference on the boundary between D and E (Table 2-2).

**Table 2-2: Limits between classes for the scale proposed by CEN**

LI <sub>AB</sub>	LI <sub>BC</sub>	LI <sub>CD</sub>	LI <sub>DE</sub>	LI <sub>EF</sub>	LI <sub>FG</sub>
0.5α	α	0.5(α+1)	1	1.25	1.5

Lombard et al. (Lombard et al., 2009) comments that CEN scale suffers from a lack of sensitivity since every new building must comply with the regulation and would be labeled B or A depending on the saving percentage ahead regulations reference.

Another labeling method is the self-reference method that should be used when the comparison with other buildings is not feasible and the only valid reference is set by a Reference Building (RB) generated from the actual building once a set of standard rules are applied. In this case, energy performance comparison must be done on the basis of a labeling index showing the saving percentage in relation to the self-reference:

$$LI = \frac{EPI}{EPI_{RB}}$$

The latter approach does not require a database for the comparison, nor a statistical analysis of the building stock comparison scenario. However, bands must be adjusted for the scale to be sensitive enough to improvement measures.

Criteria to set the scale are subjective and, perhaps, closer to policy decisions than to technical analysis. Thus, there is great disparity between different scales. A key issue is the level of definition or number of classes, with examples such as the 13 bands (A–M) Danish system ELO and the Australian ABGR five stars system.

The CEN's scale reference is set by the regulations, while the BREEAM for office certification and the American LEED-NC propose different self-reference buildings. The latter, rewards with up to 10 points (from a total of 69) if the running costs of the building are below the reference established in Annex G of ASHRAE 90.1.

## **2.5. Review on integrated building energy classification methods**

In the literature there are some significant researches that investigate integrated classification methods including the building energy database, the benchmarking method, the building energy performance evaluation and the energy boundaries (classes) definition.

Hernandez et al. (Hernandez et al., 2008) in their research present a methodology to develop energy benchmarks and rating systems for classifying the Irish Primary

schools. The benchmarking building dataset (46 school buildings) was adopted by detailed in terms of building and energy consumption data questionnaires distribution and collection. Having comparison benchmarks for reference stock buildings and reference regulation buildings and applying the building energy performance classification method proposed in EN 15217 (EN 15217, 2007) the authors rate a sample school building according to asset and operational rating method, in order to compare these two methods that have been proposed by CEN Standard. (EN 15203, 2007) The authors conclude that measured rating represents the actual use of building, while asset rating has the benefit of retrofit scenarios investigation. They also remark that both rating approaches require considerable efforts in data collection and data analysis and they propose, in terms of future prospects of their research, that rating methods should some-how take account of indoor environment issues.

Santamouris et al. (Santamouris et al., 2007) in their research propose an energy classification technique based on intelligent clustering technique. The benchmarking building dataset consists of collected energy data from 320 school buildings from almost all geographic departments of the country. First the energy benchmarks regarding the heating, electricity and total energy consumption based on equal frequency rating procedures are defined (i.e. typical school building-50% of the stock, best practice school building-25% of the stock) leading to a four classes rating. At the next step a five classes rating for heating and total energy consumption is obtained with the application of fuzzy clustering techniques. The proposed method presents important advantages compared to the frequency rating procedures: it offers more robust classes avoiding problems of unbalanced classification, while it considers in a more concise way the common characteristics of the buildings and classify them according to existing similarities.

Lee and Lee (Lee and Lee, 2008) investigate the application of data envelopment analysis (DEA) to classify government office buildings in Taiwan. The benchmarking building dataset consists of collected energy data from 47 office buildings. According to the proposed method the overall building energy efficiency is influenced by scale factors and management factors and then has the effect of scale factors removed to focus on the performance of management factors that may provide an optional indicator to refine the traditional focus on energy consumption per unit floor area. The scale factors for climate-adjusted building energy consumption after regression

analysis are floor area and the number of occupants. The overall energy efficiency is divided into scale efficiency and pure technical efficiency. The pure technical efficiency, calculated by comparing climate-adjusted energy consumption under the same scale, can be expected to represent the effect of management performance. The proposed method leads to a 4 classes rating system where the buildings are classified according to their management performance.

Barelli et al. (Barelli et al., 2009) propose an energy building classification procedure where the corrected energy demand, separately for heating and cooling, is determined independently of buildings location and directly comparable to a standard seasonal performance scale, defined on the entire territory of application. The proposed corrective procedure allows comparing the construction quality of real buildings without taking into account their localization, in order to obtain a homogeneous criterion of evaluation at national level.

By summarizing the research work performed so far in the buildings' classification sector, the following points are revealed:

- The knowledge of building stock energy data of a country is a very significant tool for energy benchmarks establishment, energy rating procedures and energy classes' determination, according to the Directive 2002/91/EC and its implementation in EU member states. The lack of building energy databases in many EU Countries, including Greece, and the difficulties of collecting them through audits lead to the investigation of other potential solutions. A different approach to a database creation is the generation of representative building datasets based on the application of building simulation for a range of energy parameters, such as the building use, building size, constructional characteristics, operational characteristics and climatic conditions. Up to now, the author dealing with building database creation has found no research work that creates large simulated building datasets for energy and thermal comfort benchmarking.
- A detailed building simulation model which provides, with relative accuracy, building performance indicators at hourly and yearly base, such as energy use demand, energy consumption for heating, cooling, ventilation, electric lighting, appliances and hot water, thermal comfort indicators such as indoor

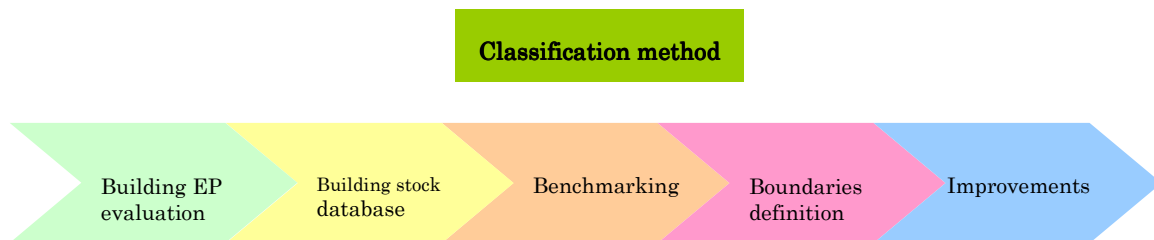
temperature, humidity, PMV, PPD etc, is a core tool for energy and thermal comfort rating, validated building datasets creation, benchmarking and classification.

- Several rating and classification schemes and standards combine indoor environmental performance with building energy performance. These schemes, apart from the building's energy consumption, take into account environmental parameters such as thermal and visual comfort, indoor air quality and noise level (Wong and Mui, 2008) in order to establish environmental benchmarks for buildings. These classifications are based on expensive and time consuming methods and processes such as operational rating results, measurements of environmental parameters, building monitoring, building indoor environment management system application (Kolokotsa et al., 2005) and building audits. The energy performance calculation tools that have incorporated environmental parameters calculation methods has to be generalized in order to create simulated datasets that include not only energy data but also indoor environmental data of buildings, providing thus easier methods for environmental benchmarks establishment and boundaries determination for each building type at national or/and global level.
- Up to now the various techniques been proposed to develop classification schemes (Santamouris, 2001) define energy classes based on the cumulative frequency distribution of the energy consumption of the buildings stock. Such a classification requires that the used sample of building energy data strictly follow a normal distribution, condition which rarely applies given the large variety of the buildings' characteristics. To this direction, Santamouris et al. (Santamouris et al., 2007) in their research propose an energy classification technique based on intelligent clustering technique. The proposed method presents important advantages compared to the frequency rating procedures: it offers more robust classes avoiding problems of unbalanced classification, while it considers the common characteristics of the buildings in a more concise way and classifies them according to existing similarities. The outcomes of this research encourage the investigation of applying various clustering techniques, such as hierarchical, K-Means, Gaussian Mixture Models, Fuzzy and Neural clustering algorithms, to large building datasets for establishing buildings'

performance benchmarks and boundaries towards an integrated classification scheme for Greek office building sector. The establishment of these classifications will permit the comparison of similar buildings in terms of their energy consumption and indoor environment quality.

## 2.6. Problem Statement

In the framework of this PhD thesis, an integrated classification method including the building energy performance evaluation method, the building stock database creation, the benchmarking process, the energy boundaries definition and building efficiency improvement methods recommendations, is developed and proposed for office building sector in Greece (Figure 2-1).



**Figure 2-1: The steps of the integrated building classification method**

The present PhD research targets to acknowledge to two research issues: The creation of a virtual building dataset and the development of a classification method based on clustering techniques.

The steps of the methodology are (Figure 2-2):

- The investigation of the office building characteristics in Greece through small audits. Office buildings located in Athens are audited by the author via detailed questionnaires distribution and many in-situ measurements with the aim of collecting individual details on the construction, activities, energy uses and energy bills.
- The installation of a Building Management System (BMS) in an office building in order to conduct a detailed energy and environmental audit. The measured variables such as the indoor air temperature, the relative humidity, the CO<sub>2</sub> concentration and the energy consumption for heating, cooling and ventilation will be the tool for the (measured) operational rating procedure of the office building.

- The creation of a detailed office building simulation model, validated initially through the small audits and then through the detailed energy audit. The main aims of this simulation model are to approximate reality at a higher degree, since the study is based on the hourly measurements, to provide a reliable tool for calculated (asset) rating of office buildings and to constitute the starting point for a generalised energy rating model for large simulated building datasets creation.
- The creation of large virtual building datasets of office buildings based on the application of building simulation for a range of energy parameters, such as building use, building size, constructional characteristics, operational characteristics and climatic conditions. Therefore, the proposed methodology overcomes the difficulties and time required for collecting building constructional properties and energy bills data by creating them virtually, taking into account all the parameters that may affect the energy performance and indoor thermal comfort. Moreover the proposed method provides flexibility and expandability on building datasets' characteristics, sample size and climatic conditions according to the relevant research scope. The large amount of the output data can be employed for energy and thermal comfort benchmarking, classification, sensitivity analysis, neural network training and eventually for any process that demands a significant number of building data.
- The investigation of the application of available clustering techniques, such as Hierarchical, K-Means, Gaussian Mixture Models, Fuzzy and Neural clustering algorithms to the simulated office building dataset towards the establishment of benchmarks and classifications for office buildings in Greece. Using appropriate indexes and criteria such as validity indexes the present thesis focuses on the selection of the best classification algorithm. The energy and thermal comfort classes that will be produced by the selected method will be compared to the equal frequency distribution methods and the CEN proposed methodology.
- The final classification results will be used for parametric study and detailed investigation of common buildings' characteristics (constructional and operational) in each rating class in order to provide with a tool for adopting improvement recommendations for office buildings' energy efficiency in Greece.

The final target of the present doctoral thesis is to propose an integrated classification dynamic methodology for Greek office building sector with the following characteristics: reliability, time saving and low budget processes, large flexibility and expandability and an easy update to the new building data and/or policy decisions.

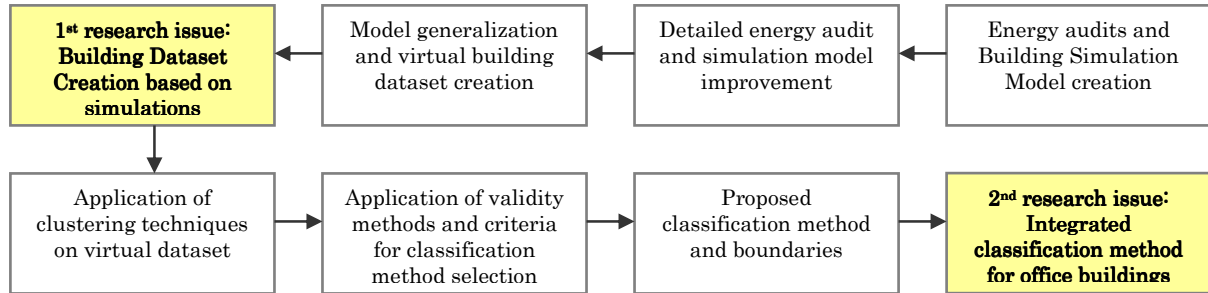


Figure 2-2: The methodology of the research

## Chapter 3

# OFFICE BUILDING SIMULATION MODELS AND SIMPLIFIED AUDITS

## **CHAPTER 3: OFFICE BUILDING SIMULATION MODELS AND SIMPLIFIED AUDITS**

### **3.1. Introduction**

The energy requirements of a building depend on the performance of the envelope components (walls, openings and roof), the lighting and HVAC systems, the local climate, the building orientation, the building surroundings, as well as the behavior of building users. To analyze all these interdependent parameters, especially when large buildings are involved, building simulation is required (Kreider et al., 2002).

Building simulation begun in the 1960s and until 1980s most of the research activities were focused on studies of fundamental theory and algorithms of load and energy estimation. Several methods are available, depending on the complexity of the case and the amount of detail one wants to take into account. A major distinction is between steady-state methods (based on degree-days or temperature bins) and dynamic methods (based on transfer functions) (Stephenson, 1967), (Stephenson and Mitalas, 1967), (Erbs et al., 1983).

During the early 1990s computers were substantially less powerful than they are today; such computers typically allowed only the use of simplified models for calculating ground heat transfer. A common simplified model is ASHRAE's slab-on-grade perimeter heat-loss calculation, which uses perimeter length (m) and an F-factor heat loss coefficient ( $W/m \cdot K$ ) to assimilate a typical steady-state thermal conductance (UA-value ( $W/K$ )) (ASHRAE, 2001), (Wang, 1979). For basement heat loss ASHRAE provides a simplified steady-state calculation method based on heat transfer path lengths that occur at given increments of basement wall depth (Wang, 1979), (ASHRAE, 1993), (Latta and Boileau, 1969). These models can be modified to include one-dimensional (1-D) dynamic conduction modeling of a limited amount of ground, including thermal mass storage, but addressing further detail was typically beyond the capability of most computers (Judkoff and Neymark, 1995).

Because of recent improvements to computers, the state-of-the-art in ground heat transfer modeling has improved. Consequently, a number of mid-level detailed models have been developed and applied to building energy simulation software, including

the following examples of models tested in BESTEST work (Neymark and Judkoff, 2008).

- BASECALC - produces quasi-3-D analysis by combining two dimensional (2-D) finite element simulations with corner correction factors (Beausoleil-Morrison, 1996).
- BASESIMP - correlation method based on more than 100,000 BASECALC simulations (Beausoleil-Morrison and Mitalas, 1997).
- EnergyPlus - monthly 3-D numerical analysis in a preprocessor (Bahnfleth and Pedersen, 1990), (Crawley et al., 2004).
- EN ISO 13370 - European standard below-grade heat transfer calculation methodology applying a 3-D heat loss component varied monthly and a 1-D heat loss component varied hourly; VA114 applies this method; however, the 3-D heat loss component is varied daily (ISO 13370, 1998).

Recent ground heat transfer simulation improvements include the development of stand-alone 3-D detailed numerical models that have also been integrated with whole-building energy simulation programs. Such detailed building and energy systems simulation programs include TRNSYS (TRNSYS, 2004), DOE-2.1E (DOE-2.1E, 2003) and ESP-r (ESP-r, 2005), (Clarke et al., 2007).

In this part of the thesis, a simulation model of an office building has been created in TRNSYS 16 in order to evaluate the energy performance and the indoor thermal comfort at hourly and yearly base of any case study office building (Nikolaou et al, 2008a), (Nikolaou et al., 2008b), (Kolokotsa et al., 2008).

TRNSYS is a transient system simulation program with a modular structure that implements a component-based approach in order to simulate thermal energy systems. Each physical component (referred to as “Types”) in the system is represented by a different FORTRAN subroutine. The subroutines are combined into an executable file controlled by an input file which describes what physical components are involved in the system and how they are interconnected.

The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, while building input data is entered through a dedicated visual interface (TRNBuild). The simulation engine then

solves the system of algebraic and differential equations that represent the whole energy system. In building simulations, all HVAC-system components are solved simultaneously with the building envelope thermal balance and the air network at each time step. In addition to a detailed multizone building model, the TRNSYS library includes components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc.

TRNSYS 16 simulation program has been chosen for the thesis' purpose according to the following criteria:

TRNSYS is included in the new IEA BESTEST cases. Field trials of the new IEA BESTEST cases were conducted with a number of detailed state-of-the-art numerical models and state-of-the art whole-building energy simulation programs, which contained a variety of ground-coupled heat transfer models from around the world (see Table 3-1).

- According to Crawley et al. (Crawley et al., 2008), which in their research describe and contrast the capabilities of twenty energy performance simulation programs TRNSYS has the advantages of providing much more RES and HVAC system components than the other programs, user selectable and/or specified algorithms, all types of economic evaluations, availability of source code and of a large component library.
- Another advantage of TRNSYS is that provides flexibility and modularity in libraries and component adoption by the user. The modular nature of TRNSYS facilitates the addition of new mathematical models to the program. New components can be developed in any programming language and modules implemented using other software (e.g. Matlab/Simulink, Excel/VBA, and EES) can also be directly embedded in a simulation.

In order to investigate the constructional and operational characteristics of office buildings in Greece small audits have been conducted by the author. 10 office buildings located in Athens are audited via detailed questionnaires distribution and many in-situ measurements with the aim of collecting individual details on the construction, activities, energy uses and energy bills.

**Table 3-1: IEA BESTEST - Participating Organizations and Models [Source: Neymark and Judkoff, 2008]**

Analytical Solution, Case GC10a	Authoring Organization	Implemented by
Delsante, Stokes, and Walsh <sup>34</sup>	Commonwealth Scientific and Industrial Research Organisation, Australia	NREL/JNA, <sup>a,b</sup> United States
Verified Numerical Model	Authoring Organization	Implemented by
FLUENT 6.0.20	Fluent, Incorporated, United States	PAAET, <sup>c</sup> Kuwait
MATLAB 7.0.4.365 (R14)	The MathWorks, Inc., United States	Dublin Institute of Technology, Ireland
TRNSYS 16.1	University of Wisconsin/TESS, <sup>d</sup> United States	TESS, <sup>d</sup> United States
Simulation Program	Authoring Organization	Implemented by
BASECALC V1.0e	CETC, <sup>e</sup> Canada	CETC, <sup>e</sup> Canada
EnergyPlus 2.0.0.025	LBNL/UIUC/DOE-BT, <sup>f,g,h</sup> United States	GARD Analytics, Inc., United States
ESP-r/BASESIMP	CETC/ESRU, <sup>e,j</sup> Canada/United Kingdom	CETC, <sup>e</sup> Canada
GHT	NREL, <sup>a</sup> United States	NREL, <sup>a</sup> United States
SUNREL-GC 1.14.01	NREL, <sup>a</sup> United States	NREL, <sup>a</sup> United States
VA114 2.20/ISO-13370	VABI Software BV, The Netherlands; CEN/ISO <sup>j,k</sup>	VABI Software BV, The Netherlands

<sup>a</sup>NREL: National Renewable Energy Laboratory, United States

<sup>b</sup>JNA: J. Neymark & Associates, United States

<sup>c</sup>PAAET: Public Authority for Applied Education and Training, Kuwait

<sup>d</sup>TESS: Thermal Energy Systems Specialists, United States

<sup>e</sup>CETC: CANMET Energy Technology Centre, Natural Resources Canada, Canada

<sup>f</sup>LBNL: Lawrence Berkeley National Laboratory, United States

<sup>g</sup>UIUC: University of Illinois Urbana/Champaign, United States

<sup>h</sup>DOE-BT: U.S. Department of Energy, Office of Building Technologies, Energy Efficiency and Renewable Energy, United States

<sup>i</sup>ESRU: Energy Systems Research Unit, University of Strathclyde, United Kingdom

<sup>j</sup>CEN: European Committee for Standardisation, Belgium

<sup>k</sup>ISO: International Organization for Standardization, Switzerland

Then the 10 audited office buildings have been modeled via the office simulation model according to the information collected by the audits. The calculated by the simulations annual energy consumption of the buildings has been compared to the respective real electricity and fuel consumption (energy and fuel bills). This comparison helps the calibration and validation of the office building model, in order to be used in further office building modeling.

### 3.2. The mathematical description of the model in TRNSYS

In this section the mathematical description and the relative equations of TRNSYS building model are presented in analytical way.

### 3.2.1. Thermal zone

The building model in TYPE 56 is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node (furniture, for example). Thus the node capacity is a separate input in addition to the zone volume.

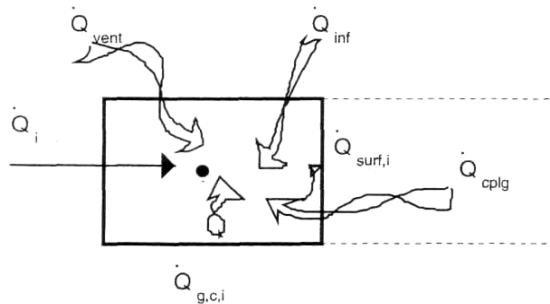


Figure 3-1: Heat balance on the zone air model

### 3.2.2. Convective Heat Flow to the Air Node

The Convective heat flow to the air node is given by the equation:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} \quad (3-1)$$

Where:

$\dot{Q}_{surf,i}$  = convective heat flow from all inside surfaces

$$\dot{Q}_{surf,i} = U_{w,i} \cdot A_{w,i} \cdot (T_{wall,i} - T_{air})$$

$\dot{Q}_{inf,i}$  = infiltration gains (airflow from outside only)

$$\dot{Q}_{inf,i} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{outside} - T_{air})$$

$\dot{Q}_{vent,i}$  = ventilation gains (air flow from a user defined source, like HVAC system)

$$\dot{Q}_{vent,i} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{ventilation,i} - T_{air})$$

$\dot{Q}_{g,c,i}$  = internal convective gains (by people, equipment, illumination, radiators, etc.)

$$\dot{Q}_{g,c,i} = \left[ \frac{kJ}{h} \right]$$

$\dot{Q}_{cp1g,i}$  = gains due to (connective) air flow from zone I to boundary condition

$$\dot{Q}_{cp1g,i} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{zone,i} - T_{air})$$

### 3.2.3. Coupling

The coupling statement allows the definition an air mass flow a zone receives from another zone, considered as a heat flow from or to the air node. The statement does not automatically define the air flow back to the adjacent zone as would occur in an interzonal airchange. To consider this return flow, the corresponding coupling must be defined in the adjacent zone to receive the same air flow in return.

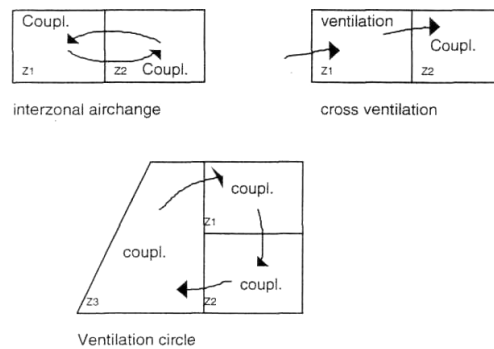


Figure 3-2: The zone coupling

### 3.2.4. Radiative Heat Flows (only) to the Walls and Windows

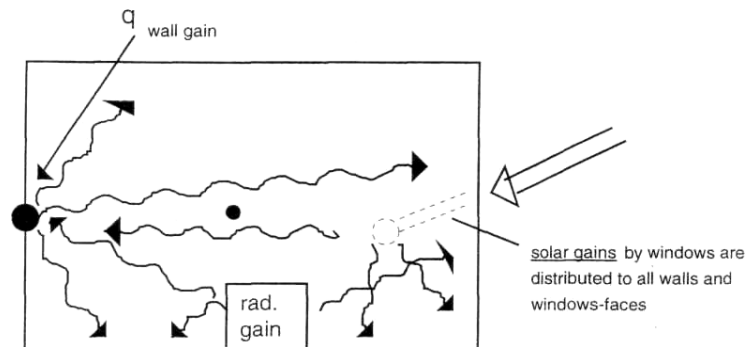


Figure 3-3: Radiative energy flows considering one wall with its surface temperature node

The radiative energy flow considering one wall with its surface temperature node is given by the equation:

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,i,w_i} + \dot{Q}_{sol,w_i} + \dot{Q}_{long,w_i} + \dot{Q}_{wall-gain} \quad (3-2)$$

Where:

$$\dot{Q}_{r,w_i} = \text{radiative gains for the wall surface temperature node} \left[ \frac{kJ}{h} \right]$$

$$\dot{Q}_{g,r,i,w_i} = \text{radiative zone internal gains received by wall} \left[ \frac{kJ}{h} \right]$$

$$\dot{Q}_{sol,w_i} = \text{solar gains through zone windows received by wall} \left[ \frac{kJ}{h} \right]$$

$$\dot{Q}_{long,w_i} = \text{long-wave radiation exchange between this wall and all other walls and windows } (\varepsilon_i = 1) \left[ \frac{kJ}{h} \right]$$

$$\dot{Q}_{wall-gain} = \text{user specified heat flow to the wall or window surface} \left[ \frac{kJ}{h} \right]$$

### 3.2.5. Walls and Windows

Figure 3-4 shows the heat fluxes and temperatures that characterize the thermal behavior of any wall or window. The nomenclature used in Figure 3-4 is defined as follows:

$$S_{s,i} = \text{radiation heat flux absorbed at the inside surface (solar and radiative gains)}$$

$$S_{s,o} = \text{radiation heat flux absorbed at the outside surface}$$

$$\dot{q}_{r,s,i} = \text{net radiative heat transfer with all other surfaces within the zone}$$

$$\dot{q}_{r,s,0} = \text{net radiative heat transfer with all surfaces in view of the outside surface}$$

$$\dot{q}_{w,g,i} = \text{user defined heat flux to the wall or window surface}$$

$\dot{q}_{s,i}$  = conduction heat flux from the wall at the inside surface

$\dot{q}_{s,0}$  = conduction heat flux into the wall at the outside surface

$\dot{q}_{c,s,i}$  = convection heat flux from the inside surface to the zone air

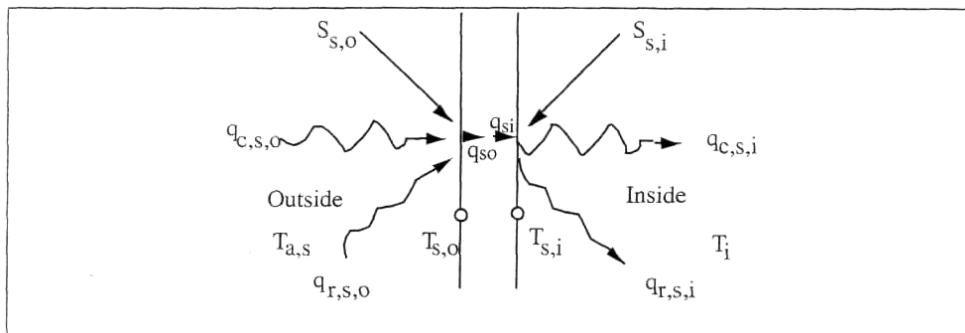
$\dot{q}_{c,s,o}$  = convection heat flux to the outside surface from the boundary / ambient

$T_{s,i}$  = inside surface temperature

$T_{s,o}$  = outside surface temperature

$T_i$  = temperature of zone i (air node)

$T_{a,s}$  = temperature of ambient air at the outer boundary of surface



**Figure 3-4: Surface Heat Flux and Temperatures**

The walls are modeled according to the transfer function relationships of Stephenson and Mitalas (Stephenson and Mitalas, 1971), (Lechner, 1992) defined from surface to surface.

For any wall, the heat conduction at the surfaces is:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \quad (3-3)$$

$$\dot{q}_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^k \quad (3-4)$$

These time series equations in terms of surface temperatures and heat fluxes are evaluated at equal time intervals. The superscript  $k$  refers to the term in the time series. The current time is  $k=0$ , the previous time is for  $k=1$ , etc.

3.2.5.1. *Transfer Function Method by Mitalas*

The method of the transfer function or response factors can be described as the method to tell the "thermal history" of the wall. The wall is considered as a black box. The number of time steps (k) related to the time base (defined by the user) shows whether the wall is a heavy wall with a high thermal mass ( $k < 20$ ) or if only a few time steps have to be considered to describe the thermal behavior of this wall. If the time base of the considered wall is higher than the time- constant, the calculation of the Transfer-function matrix coefficients is stopped. Therefore such a "thin" wall can be replaced by a resistance definition neglecting the thermal mass.

3.2.5.2. *The Long-Wave Radiation*

The long-wave radiation exchange between the surfaces within the zone and the convective heat flux from the inside surfaces to the zone air are approximated using the star network given by Seem (Seem, 1987) and represented in Figure 3-5.

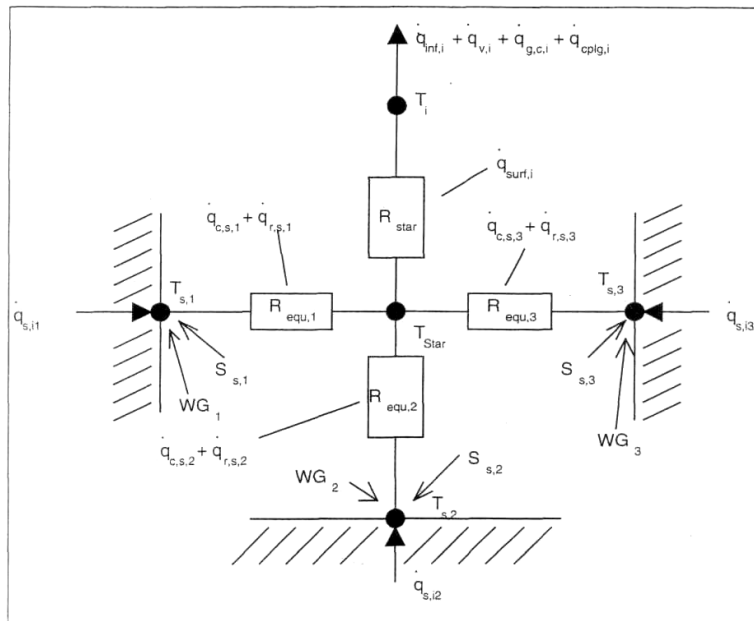


Figure 3-5: Star network for a zone with three surfaces

$$R_{STAR,i} = f(a_i, A_{Surf,i}) = \frac{1}{Q_{surf,i}} (T_{Star} - T_i) \quad (3-5)$$

Methods to calculate the resistances  $R_{equiv,i}$  and  $R_{star,i}$  can be found in (Seem, 1987) Area ratios are used in these calculations to find the absorption factors between all

surfaces. The star temperature can be used to calculate a net radiative and convective heat flux from the inside wall surface:

$$\dot{q}_{comb,s,i} = \dot{q}_{c,s,i} + \dot{q}_{r,s,i}$$

Then:

$$\dot{q}_{comb,s,i} = \frac{1}{R_{equiv,i} A_{s,i}} (T_{s,i} - T_{star}) \quad (3-6)$$

Where:

$\dot{q}_{comb,s,i}$  = combined convective and radiative heat flux

$A_{s,i}$  = inside surface area

For external surfaces the long-wave radiation exchange at the outside surface is considered explicitly using a fictive sky temperature,  $T_{sky}$ , which is an input to the model and a view factor to the sky,  $f_{sky}$ , for each external surface. The total heat transfer  $q_{comb,s,o}$  is given as the sum of convective and radiative heat transfer:

$$\dot{q}_{comb,s,o} = \dot{q}_{c,s,o} + \dot{q}_{r,s,o} \quad (3-7)$$

With:

$$\dot{q}_{c,s,o} = h_{conv,s,o} \cdot (T_{a,s} - T_{s,o})$$

$$\dot{q}_{r,s,o} = \sigma \cdot \varepsilon_{s,o} \cdot (T_{s,o}^4 - T_{fsky}^4)$$

$$T_{fsky} = (1 - f_{sky}) \cdot T_{a,s} + f_{sky} \cdot T_{sky}$$

Where:

$\dot{q}_{comb,s,o}$  = combined convective and radiative heat flux to the surface

$\dot{q}_{c,s,o}$  = convective heat flux to the surface

$\dot{q}_{r,s,o}$  = radiative heat flux to the surface

$h_{conv,s,o}$  = convective heat transfer coefficient at the outside surface

$f_{sky}$  = fraction of the sky seen by the outside surface

$T_{sky}$  = fictive sky temperature used for long-wave radiation exchange

$\varepsilon_{s,o}$  = long-wave emissivity of outside surface (e=1 for walls, value read from window library for windows)

$\sigma$  = Stephan-Boltzmann constant

Energy balances at the surfaces give:

$$\dot{q}_{s,i} = \dot{q}_{comb,s,i} + S_{s,i} + \text{Wall gain} \quad (3-8)$$

$$\dot{q}_{s,o} = \dot{q}_{comb,s,o} + S_{s,o} \quad (3-9)$$

For internal surfaces  $S_s$ , can include both solar radiative and long-wave radiation generated from internal objects such as people or furniture.

Wallgain is a user-defined energy flow to the inside wall or window surfaces. It can describe solar gains changing during the day due to different sun positions or might be used as a simple way to model a floor heating or a ceiling cooling system. For external surfaces,  $S_{s,o}$  consists of solar radiation only.

### 3.2.5.3. External Walls

Equations (3-2) through (3-7) can be combined and manipulated to express the inside surface heat flux for an external wall as a function of the boundary air temperatures:

$$\dot{q}_{s,i} = B_s T_{a,s} - C_s T_{star,i} + D_s \quad (3-10)$$

Where:

$$B_s = \frac{e_s h_{s,o}}{(1-f_s)}$$

$$C_s = \frac{f_s \left( \frac{1}{R_{equiv,i} A_{s,i}} \right)}{(1-f_s)}$$

$$D_s = \frac{f_s S_{s,i} + e_s (S_{s,o} - k_{s,o}) + K_{s,i}}{(1-f_s)}$$

$$e_s = \frac{b_s^o}{a_s^o + h_{s,o}}$$

$$f_s = (b_s^o e_s - c_s^o) R_{equiv,i} A_{s,i}$$

The values for  $K_{s,i}$  and  $K_{s,0}$  are defined by the transfer function equations.

$$K_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k$$

$$K_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^k$$

#### 3.2.5.4. Wall with Boundary Conditions

Equation (3-10) also applies for a wall with a known boundary temperature,  $T_{b,s}$ , with  $T_{b,s}$  substituted for  $T_{a,s}$ .

#### 3.2.5.5. Adjacent, Internal Walls and Walls with Identical Boundary Conditions

For walls adjacent to another zone, internal walls, or walls adjacent zones with identical conditions, equation (3-10) applies, but with:

$$\text{adjacent zone: } T_{a,s} = T_{star,j}$$

$$\text{internal wall: } T_{a,s} = T_{star,i}$$

$$\text{adjacent identical } T_{a,s} = T_{star,i}$$

$$\text{and } B_s = \frac{e_s \frac{1}{R_{equiv,j} A_{s,j}}}{1 - f_s} \quad e_s = \frac{b_s^o}{a_s^o + \frac{1}{R_{equiv,j} A_{a,j}}}$$

Note: For an internal wall, both sides must be considered for the area  $A_s$ .

It is also possible to specify a boundary condition for the outside surface temperature rather than an air temperature by setting  $HBACK < 0.001$ . In this case,  $T_{as} = T_{so} = T_{bs}$ . Equation (3-10) applies, but with:

$$B_s = \frac{b_s^o}{1 + c_s^o R_{equiv,i} A_{s,i}}$$

$$C_s = \frac{c_s^o}{1 + c_s^o R_{equiv,i} A_{s,i}}$$

$$D_s = \frac{K_{s,i} - c_s^o R_{equiv,i} A_{s,i} S_{s,i}}{1 + c_s^o R_{equiv,i} A_{s,i}}$$

### 3.2.5.6. Windows

A window is thermally considered as an external wall with no thermal mass, partially transparent to solar, but opaque to long-wave internal gains. Long-wave absorption is considered to occur only at the surfaces. In the heat balance calculation of the TYPE 56, the window is described as a 2-node model shown in the figure below. The detailed optical and thermal window model is described later. Equations (3 – 10) are valid for a window with:

$$a_s^o = b_s^o = c_s^o = U_{g,s}$$

$$a_s^k = b_s^k = c_s^k = d_s^k = 0 \quad \text{for } k > 0$$

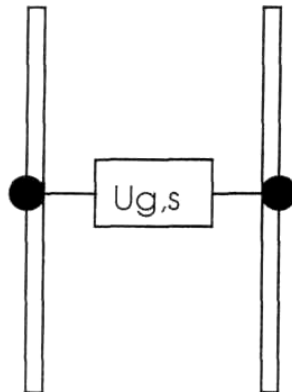


Figure 3-6: Two-node window model used in the TYPE 56 heat balance calculation

### 3.2.5.7. Total Gains from Surfaces in a Zone

The total gain to zone i from all surfaces is the sum of the combined heat transfers or from equations (3-9) and (3-10), is:

$$Q_{surf,i} = \sum A_s \dot{q}_{comb,i} = \sum_{j=1}^{Adj.Zones\ surface\ i\ to\ j} \sum_{i=1} A_s B_s T_{star,j} + \sum_{ext.\ surfaces} A_s B_s T_a + \sum_{int.\ walls} A_s B_s T_{star} + \sum_{known\ bound} A_s B_s T_{b,s} - \sum_{surface\ in\ zone\ i} A_s (C_s T_{star,i} - D_s - S_{s,i}) \quad (3-11)$$

Where:  $A_s$  = the inside area of surface s.

Both sides of an internal wall are considered as inside surfaces and must be included twice in Equation (3-11).

An energy balance on the star node in Figure 3-5 also shows that:

$$\dot{Q}_{surf,i} = \frac{1}{R_{star,i}} (T_{star,i} - T_i) \quad (3-12)$$

### 3.2.6. Infiltration, Ventilation and Convective Coupling

Infiltration and ventilation rates are given in terms of **air changes per hour** for each zone. The mass flow rate is the product of the zone air volume, air density, and air change rate. Infiltration occurs always from outdoor conditions, while ventilation occurs from a specified (possibly variable) temperature. Equal amounts of air are assumed to leave the zone at the zone temperature. The energy gains to any zone i due to infiltration and ventilation are:

$$\dot{Q}_{inf,i} = \dot{m}_{inf,i} C_p (T_a - T_i) \quad (3-13)$$

$$\dot{Q}_{v,i} = \sum_k^{nvent} \dot{m}_{v,k,i} C_p (T_{v,k} - T_i) \quad (3-14)$$

Where:

$\dot{m}_{inf,i}$  = mass flow rate of infiltration air

$\dot{m}_{v,k,i}$  = mass flow rate of ventilation air of ventilation type k

$C_p$  = specific heat of the air

$T_{v,k}$  = temperature of ventilation air of ventilation type k

$T_a$  = ambient air temperature

For each wall or window separating zones of floating temperature or each wall having a known boundary condition, it is possible to specify a convective coupling. This coupling is the mass flow rate that enters the zone across the surface. An equal quantity of air is assumed to leave the zone at the zone temperature. The energy gain due to the convective coupling is the sum of all such gains for all walls or windows in the zone.

$$\dot{Q}_{cp1g,i} = \sum_{adj.zones} \sum_{surfaces\ to\ j} \dot{m}_{cp1g,s} C_p (T_j - T_i) + \dots + \sum_{known\ bound} \dot{m}_{cp1g,s} C_p (T_{b,s} - T_i) \quad (3-15)$$

Where:

$\dot{m}_{cp1g,s}$  = the mass flow rate of air entering zone i across walls or windows

### 3.2.6.1. Floating Zone Temperature (No Heating or Cooling)

The rate of change of internal energy for any free floating zone is equal to the net heat gain or

$$C_i \frac{d}{dt} T_i = \dot{Q}_i \quad (3-16)$$

Where:  $C_j$  is the thermal capacitance of zone i (minimal =  $V_j \rho c_p$  with  $V_j$  = zone volume)

The net heat gain,  $\dot{Q}_j$ , is a function of  $T_j$  and the temperatures of all other zones adjacent to zone i. Note: To simplify the solution of the set of equations,  $\dot{Q}_j$  is considered constant during any time step, evaluated at average values of the zone temperatures. In this case, the solution to the differential equation for final temperature for a given time interval is

$$T_{i,\tau} = T_{i,\tau-\Delta t} + \frac{\bar{\dot{Q}}_{i\Delta t}}{C_i} \quad (3-17)$$

Where:

$\Delta t$  = the simulation time step

$T_{i,\tau-\Delta t}$  = the zone temperature at the beginning of the timestep

The temperature variation is linear, such that the average is

$$T_i = \frac{T_{i,\tau} + T_{i,\tau-\Delta t}}{2} \quad (3-18)$$

If Equation (3-18) is solved for  $T_{i,t}$  and the result substituted into equation (3-17), along with the individual expressions representing the net heat gain, the following is obtained:

$$\begin{aligned} \frac{2C_i(\bar{T}_i - T_{i,\tau-\Delta t})}{\Delta t} = & \sum_{j=1}^{zones} \sum_{surfaces\ i\ to\ j} \dot{m}_{cp\lg,s} C_p \bar{T} + \dot{m}_{inf,i} C_p T_a + \sum_{known\ bound} \frac{d}{dt} m_{icplg,s} C_p T_{b,s} - \\ & \left( \frac{1}{R_{star,i}} - \sum_{known\ boundaries} \sum_{surfaces\ i\ to\ j} \dot{m}_{cp\lg,i} + \sum_{surfaces\ i\ to\ j} \dot{m}_{cp\lg,s} + \dot{m}_{inf,i} \dot{m}_{v,i} \right) \bar{T}_i + \sum \dot{m}_{v,k} C_p T_{v,k} + \dot{Q}_{g,c,i} \end{aligned} \quad (3-19)$$

Equations (3-11) and (3-12) can be equated and regrouped to find:

$$\begin{aligned} \left( \frac{1}{R_{star,i}} - \sum_{int.\ walls} A_s B_s + \sum_{surf.\ in\ i} A_s C_c \right) T_{star,i} - \left( \sum_{adj.\ zone\ walls\ i\ to\ j} \sum A_s B_s \right) T_{star,j} - \frac{1}{R_{star,i}} \bar{T}_i = \\ = \left( \sum_{exterior\ surfaces} A_s B_s \right) T_a + \sum_{known\ boundaries} A_s B_s T_{b,s} + \sum_{surface\ in\ zone\ i} A_s (D_s + S_{s,i}) \end{aligned} \quad (3-20)$$

The set of energy balances given by equations (3-19) and (3-20), written for all zones, results in a linear set of equations in average zone temperatures and average star temperatures. In matrix form,

$$[\mathbf{X}] \cdot [\bar{\mathbf{T}}] = [\mathbf{Z}] \quad (3-21)$$

The matrix can be partitioned such that:

$$[\mathbf{X}] = \begin{bmatrix} \mathbf{X}_{11} & \mathbf{X}_{12} \\ \mathbf{X}_{21} & \mathbf{X}_{22} \end{bmatrix}$$

$$[\mathbf{T}] = \begin{bmatrix} \bar{\mathbf{T}}_1 \\ \bar{\mathbf{T}}_2 \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{T}} \\ \bar{\mathbf{T}}_{star} \end{bmatrix}$$

$$[\mathbf{Z}] = \begin{bmatrix} \mathbf{Z}_1 \\ \mathbf{Z}_2 \end{bmatrix}$$

Where:

$$X_{11,ii} = \left( \sum_{\substack{\text{surfaces} \\ i \text{ to } j}} \dot{m}_{cp1g,s} + \dot{m}_{inf,i} + \dot{m}_{v,i} \right) C_p + \frac{2C_i}{\Delta t} + \frac{1}{R_{star,i}} + \sum_{\substack{\text{known} \\ \text{boundaries}}} \dot{m}_{cp1g,i}$$

$$X_{11,ij} = \sum_{\substack{\text{surfaces} \\ i \text{ to } j}} \dot{m}_{cp1g,s} C_p \text{ for } i \neq j$$

$$X_{12,ij} = \frac{1}{R_{star,i}}$$

$$X_{12,ij} = 0 \text{ for } i \neq j$$

$$X_{21,ii} = -\frac{1}{R_{star,i}}$$

$$X_{21,ij} = 0$$

$$X_{22,ii} = \sum_{\substack{\text{int.} \\ \text{walls}}} A_s B_s + \sum_{\substack{\text{surf.} \\ \text{in zone } i}} A_s C_s$$

$$X_{22,ij} = -\sum_{\substack{\text{adj.} \\ \text{zones}}} \sum_{\substack{\text{walls} \\ i \text{ to } j}} A_s B_s$$

$$Z_{1,i} = \dot{m}_{inf,i} C_p T_a + \sum_{\substack{\text{surfaces} \\ i \text{ to } j}} \dot{m}_{cp1g,s} C_p T_{b,s} + \sum_k \dot{m}_{v,k,i} C_p T_{v,k}$$

$$Z_{2,i} = \left( \sum_{\text{ext.surf}} A_s B_s \right) T_a + \sum_{\substack{\text{known} \\ \text{boundaries}}} A_s B_s T_{b,s} + \sum_{\substack{\text{surf.} \\ \text{in zone } i}} A_s (D_s + S_{s,i})$$

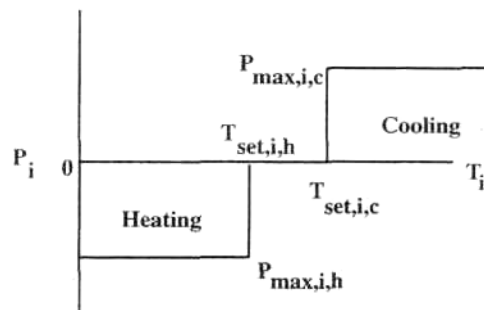
For the case of all zones in floating temperature

$$[\bar{\mathbf{T}}] = [\mathbf{X}]^{-1}[\mathbf{Z}] \quad (3-22)$$

$$T_{i,\tau} = 2\bar{T}_i - T_{i,\tau-\Delta t} \quad (3-23)$$

### 3.2.7. Simplified Heating and Cooling

It is possible to determine the energy requirement for zones controlled in an idealized way. Therefore the heating and cooling energy flow is directly connected to the zone air temperature node. The output of the heating and/or cooling equipment is a function of the zone temperature as shown in Figure 3-7.



**Figure 3-7: Power Output versus Temperature**

Where:

$P_i$  = power output for zone i (- heating, + cooling)

$P_{max,i}$  = absolute value of the maximum power for zone i (+ heating, + cooling)

$T_{set,i}$  = set temperatures for heating or cooling in zone i

For the simulation of heating equipment that produces a partially radiative gain to the zone, the radiative fraction of the supplied heating power may be defined. This fraction of the power is supplied as internal radiative gains and distributed to the walls of the zone. As the set temperature for the heating equipment is related to the air temperature of the zone, the radiative fraction of the heating power cannot be higher than 0.99 in order to have a convective part left to ensure stable control of the heating equipment.

The zone temperature is free floating in the comfort region where the power is zero. If the temperature of a free floating zone is within the heating or cooling regions at the end of a timestep, power is applied throughout the timestep so that the final zone temperature just reaches  $T_{set}$ . If the power required is greater than the maximum specified, then the maximum power is applied throughout the timestep and the zone temperature is again free floating.

The temperature change of the zone air, when power is supplied, is assumed to be linear.

If power is required and enough is available to maintain the final zone temperature at  $T_{set,i}$  then the final and average zone temperatures are known.

$$T_t = T_{set,i}$$

$$T_{reg,i} = \frac{T_{\tau-\Delta t} + T_{set,i}}{2} \quad (3-24)$$

Where:

$T_{reg,i}$  = average zone temperature over the timestep if less than maximum power is required.

It is necessary to consider the general case of zones that are in different control regions. With the inclusion of the control laws, the equations remain linear. For the zones that have floating temperatures, the solution for average zone temperatures and star temperatures is again of the form:

$$[\bar{\mathbf{T}}] = [\mathbf{X}']^{-1}[\mathbf{Z}'] \quad (3-25)$$

The coefficients of the  $X'$  matrix and  $Z'$  vector depend upon the control region. In the comfort zone, with no energy requirement:

$$X'_{ij} = X_{ij} \text{ for all } i \text{ and } j$$

$$Z'_i = Z_i$$

For zones whose temperature falls below the point for maximum heating or above that for maximum cooling

$$X'_{ij} = X_{ij} \text{ for all } i \text{ and } j$$

$$Z'_i = Z_i + P_{\max,i,h} \text{ or } Z'_i = Z_i - P_{\max,i,c}$$

For zones that fall within the heating or cooling regions and require less than maximum power, the final temperature is assumed to be equal to the heating or cooling set temperature and the average room temperature is then  $T_{req,i}$ . Equation (3-16) can be rewritten to include the power requirements.

$$C_i \frac{d}{dt} T = \dot{Q}_i - P_i \quad (3-26)$$

$P_i$  and  $Q_i$  are considered constant over the timestep and  $Q_i$  is evaluated at the average zone temperature. Substituting into Equation (3-26) yields:

$$\begin{aligned} \bar{P}_i - \frac{1}{R_{star,i}} T_{star,i} - \sum_{\substack{adj. \\ zones}} \sum_{i \text{ to } j}^{surfaces} m_{cp1g} C_p \bar{T}_j = \\ - \left[ \frac{1}{R_{star,i}} + \left( \dot{m}_{inf,i} + \dot{m}_{v,i} + \sum_{i \text{ to } j}^{surfaces} \dot{m}_{cp1g} + \sum^{known \ bound} \dot{m}_{cp1g} \right) C_p \right] \bar{T}_{req,i} \quad (3-27) \\ - \frac{C_i}{\Delta t} (T_{set,i} - T_{\tau-\Delta t}) + \dot{m}_{inf} C_p T_a + \sum_k^{nvent} m_{v,k,i} C_p T_{v,k} + \dot{Q}_{g,c,i} + \sum^{known \ bound} \frac{d}{dt} m_{cp} C_p \bar{T}_b \end{aligned}$$

Equation (3-27) is substituted into the set of energy balances on all zones for any zone that is in the less than maximum heating or cooling region. The solution given by equation (3-25) is valid with the following substitutions for zones evaluated with Equation (3-27).

$$X'_{11,ij} = X_{11,ij} \text{ for } i \neq j$$

$$X'_{11,ii} = 1.0$$

$$X'_{12,ij} = X_{12,ij}$$

$$X'_{22,ii} = X_{22,ii}$$

Equation (3-20) is corrected by  $\left( \frac{1}{R_{star,i}} T_{req,i} \right)$  to both sides of the equation, then

$$X'_{21,ii} = 0$$

$$Z'_{2,i} = Z_{2,i} - X_{11,ii} T_{req,i}$$

For any zone  $i$  connected to any zone  $m$  at a fixed *setpoint*, the  $X'$  matrix and the  $Z'$  vector are modified as

$$X'_{11,im} = 0$$

$$Z'_i = Z'_i - X'_{im} T_{req,m}$$

The solution given by Equation (3-25) using the adjusted matrix entries is valid with one further note. The temperature vector actually contains the required power instead of the average zone temperature, for those zones in the less than heating or cooling regions.

### 3.2.8. Optical and Thermal Window Model

A detailed window model has been incorporated into the TYPE 56 component using output data from the WINDOW 4.1 program developed by Lawrence Berkeley Laboratory, USA. This window model calculates transmission, reflection and absorption of solar radiation in detail for windows with up to six panes. External and internal shading devices and an edge correction for different glazing spacer types are considered. More details about mathematical description of glazing, internal and external shading can be found in TRNSYS manual (TRNSYS, 2004).

### 3.2.9. Moisture Balance

In parallel with the sensible energy balance calculation, the model calculates a moisture balance considering free floating humidity ratios or humidification /dehumidification to a certain set-point. In this case it calculates the latent load. There are two models for the calculation of the moisture balance available in TRNSYS. The first model considers sorption effects with an enlarged moisture capacity of the zone air the second, more sophisticated, model offers a surface and a deep moisture buffer in the walls of the zone. More details about the mathematical description of these models can be found in TRNSYS manual (TRNSYS, 2004).

### 3.3. The Simulation Model description

The office building model was adopted using the TRNSYS Simulation Studio visual interface. TRNBuild is the tool used to enter input data for multizone buildings, in order all the building structure details, as well as everything that is needed to simulate the thermal behavior of the building, such as windows optical properties, heating and cooling schedules, etc to be specified (See Figure 3-8).

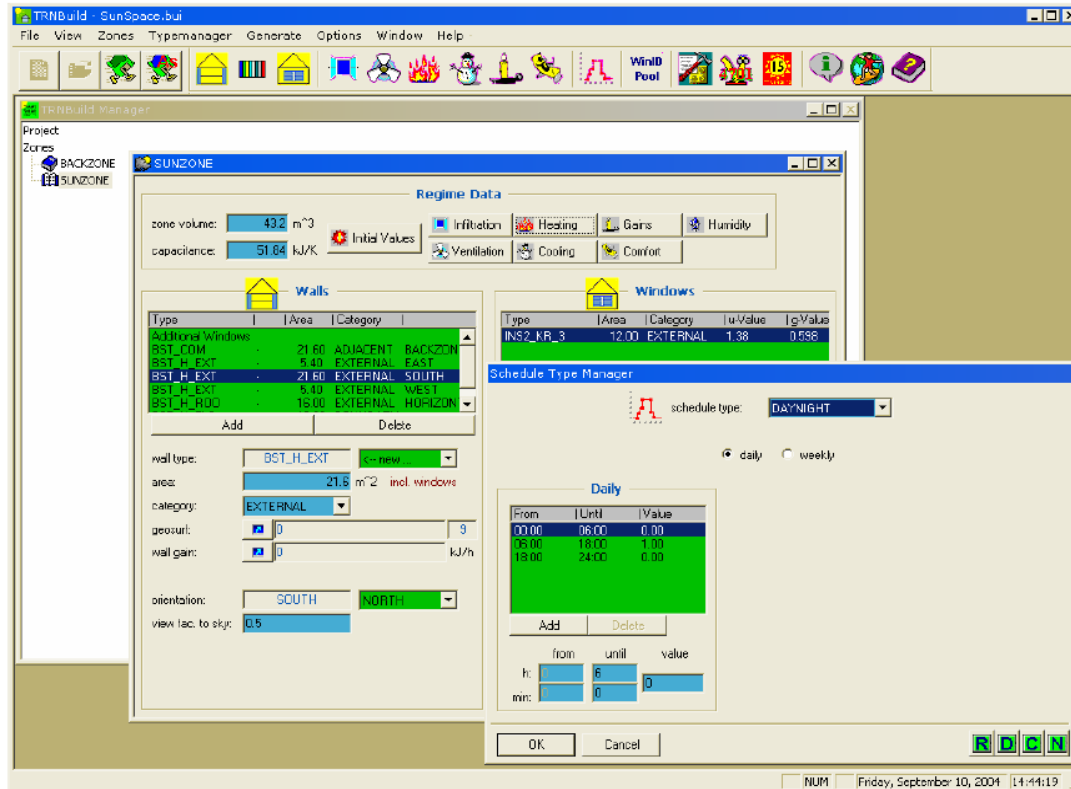


Figure 3-8: TRNBuild interface

#### 3.3.1. TRNBuild Input Data

In the following sections, the program inputs are described for each data group.

##### 3.3.1.1. Building's input data description

The building's envelope data required for the simulation of the building's thermal behavior are listed in Table 3-2.

**Table 3-2: Building’s envelope input data**

	<b>Envelope Data Description</b>
1	Zone volume [m <sup>3</sup> ]
2	Zone Capacitance [kJ/K]
3	External Walls
3.1	Wall Type: The user may select a wall type from TRNSYS wall Library or create a new wall using layers. There is a layer library in TRNSYS but the user may also create new layer type.
3.2	Area of inside surface of wall including windows[m <sup>2</sup> ]
3.3	Wall orientation
3.4	Fraction of the sky in the total hemisphere seen by the wall, used as a weighting factor between Tamb and Tsky [%/100]
3.5	Energy flux to the inside wall surface [kJ/hr]
3.6	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100]
4.	Walls between the zones
4.1	Area of inside surface of wall
4.2	Name of the zone which is adjacent to current zone having this wall in common
4.3	FRONT or BACK - keyword defining whether the front or back of the wall is in the zone.
4.4	Convective flow from adjacent zone to the current zone across this wall [kg/hr]
4.5	Energy flux to the inside wall surface [kJ/hr]
4.6	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100]
5.	Internal Walls: An internal wall is a wall with both surfaces within the same zone. Internal walls are assumed to affect building response only as the result of their mass.
5.1	Total surface area of wall within zone (includes both sides of the wall)
5.2	Energy flow to the wall surface in the current zone [kJ/hr]
5.3	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100].
6.	Walls with known boundary conditions: a wall having a known boundary condition might be a concrete floor resting on ground of a known temperature or a wall adjacent to a zone whose temperature is known. The front of the wall is considered to be at the inside of the zone. Normally, the boundary condition is the temperature of a node connected to the back surface of the wall through a pure resistance.
6.1	Area of inside surface of wall [m <sup>2</sup> ]
6.2	Temperature associated with boundary at side of wall; use the keyword IDENTICAL for a boundary temperature equal to the zone temperature [°C]
6.3	A convective flow from the boundary to the zone across this wall [kg/hr]
6.4	The relative humidity associated to the convective flow from the boundary to the zone across this wall [%]
6.5	Energy flow to the wall surface in the current zone [kJ/hr]
6.6	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100]
7.	External Windows
7.1	Area of inside surface of window opening [m <sup>2</sup> ]
7.2	Orientation for this window
7.3	Fraction of the sky in the total hemisphere seen by the window, used as a weighting factor between Tamb and Tsky [%/100]
7.4	Energy flow to the surface in the current zone [kJ/hr]
7.5	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100]
7.6	Shading factor of the internal shading device (opaque fraction of the device) [%/100]
7.7	Shading factor of the external shading device (opaque fraction of the device) [%/100]
8.	Adjacent Window Data
8.1	Area of inside surface of window opening [m <sup>2</sup> ]
8.2	Name of the zone which is adjacent to current zone having this window in common
8.3	FRONT or BACK - keyword defining whether the front or back of the window is in the zone.
8.4	A convective flow from the adjacent zone to the current zone across this wall [kg/hr]
8.5	Orientation for this window
8.6	Energy flow to the surface in the current zone [kJ/hr]
8.7	Fraction of the total direct solar radiation entering the zone that strikes this surface [%/100]
8.8	Shading factor of the internal shading device [%/100]

**Table 3-3: Building's operational input data**

	<b>Operational Data Description</b>
1.	<b>Schedules</b> Schedules are periodic functions whose output may vary according to the time of day and/or week. Two forms of SCHEDULE TYPEs may be defined. The first requires values of the schedule as a function of the time of day:
1.1	<b>Hourly SCHEDULE TYPE Data</b> The hours of the day at which the output of the schedule will change (starting from 0, ending at 24) [h]. The values of the schedule corresponding to the hours given. The hourly SCHEDULE VALUES change with a step at each of the HOURS given, producing a square-wave.
1.2	<b>Daily SCHEDULE TYPE Data</b> The form for SCHEDULE TYPEs is for specifying the use of different hourly SCHEDULEs as a function of the day of the week. <u>Daily schedule</u> : the days of the week on which the schedule changes [1-7] <u>Hourly schedule</u> : names of previously defined hourly schedules corresponding to the days given. The days of the week are relative to the first day of the simulation. For TRNSYS, the year starts with Monday.
2.	<b>Heating Type</b> The heating power required by a building zone subject to idealized heating control can be determined by specifying a HEATING TYPE for that regime. VENTILATION, AIRCHANGE, TEMPERATURE and HUMIDITY should be defined as INPUTS. A temperature set-point and maximum heating power are required to describe the HEATING TYPE.
2.1	Temperature below which heating begins [°C]
2.2	The maximum heating power [kJ/hr]
2.3	The relative humidity of zone air below which there is humidification of the air (0 for free floating) [%]
2.4	Radiative fraction of the heating power [%/100]
3.	<b>Cooling Type</b> The cooling requirement of any zone subject to idealized cooling control can be determined by specifying a COOLING TYPE for that regime. VENTILATION AIRCHANGE, TEMPERATURE and HUMIDITY should be defined as INPUTS. A temperature setpoint and maximum cooling rate are required to describe the COOLING TYPE.
3.1	Temperature above which cooling begins [°C]
3.2	The maximum cooling power [kJ/hr]
3.3	The relative humidity of zone air above which there is dehumidification of the air (100 for free floating) [%]
4.	<b>Ventilation Type</b> As with infiltration, the ventilation rates are expressed in zone air changes per hour.
4.1	Number of air changes per hour for ventilation flow stream [1/h]
4.2	Temperature of ventilation air flow (ambient temperature if the keyword OUTSIDE is entered) [°C]
4.3	Relative humidity of ventilation air flow [%]
5.	<b>Infiltration Type</b> Infiltration is given in terms of the number of zone air changes per hour. Thus, the infiltration mass flow rate for any zone is the product of the air changes, the zone volume, and the air density. Infiltration air is assumed to be at outside ambient conditions. Air changes per hour from ambient source [1/h]
6.	<b>Gain Types</b> Gains are used within the description of each zone. They are considered to include energy convection, radiation, and humidity. It is possible to scale gains for any zone within the BUILDING description. This scaling may also vary according to a SCHEDULE (Section 1). In this way, generalized gains such as from a single person or single computer terminal may be defined with GAIN TYPEs and subjected to different scales and/or schedule.
6.1	Convective energy gain rate
6.2	Radiative energy gain rate
6.3	Humidity gain (mass per time)

A COMFORT type is used within the description of each zone. The thermal comfort calculation is based on EN ISO 7730. (EN ISO 7730, 2005) A COMFORT type is considered to include clothing factor, metabolic rate, external work and relative air velocity. Note that no influence of direct or diffuse solar radiation onto the occupants is considered for PMV and PPD calculation.

**Table 3-4: Building’s comfort input data**

	Comfort Data Description
1	Clothing Factor [clo]
2	Metabolic Rate [met]
3	External Work [met]
4	Relative Air Velocity [m/s]

EN ISO 7730 provides large variety of clothing factors. Table 3-5 gives a brief summary for common clothing ensembles.

**Table 3-5: Clothing factor of different clothing ensemble**

Clothing Ensemble	Clothing Factor [clo]
Nude	0
Shorts	0.1
Light summer clothing	0.5
Light working ensemble	0.6
Typical business suit	1.0
Typical business suit and cotton coat	1.5
Light outdoor sportswear	0.9
Heavy traditional European business suit	1.5

The metabolic rate represents a heat production depending on the activity level. Table 3-6 gives a brief summary of common values.

**Table 3-6: Metabolic Rate**

Degree of activity	Metabolic rate [met]
Seated, relaxed	1.0
Seated, light work (office, home, school, laboratory)	1.2
Standing, light work (shopping, laboratory)	1.6
Standing moderate work (sale activity, housework)	2.0
Walking, 2 km/h	1.9
Walking, 3 km/h	2.4
Walking, 4 km/h	2.8
Walking, 5 km/h	3.4

### 3.3.2. Model Output Data

Multiple output specifications are possible. Thus it is possible to specify different outputs for different zones. There are optional outputs for zone quantities, for the surfaces within zones or for quantities summed up for a group of zones.

The output types are divided into so called “zone outputs” where a single output is produced for each zone specified and so called “surface outputs” where a single output is produced for specified surfaces of a zone. In addition, outputs for groups of zones can be defined. For this thesis’s purposes the selected outputs are listed in Table 3-7.

**Table 3-7: Simulation model output data**

	<b>Output Description</b>
1	Air temperature of zone [°C]
2	Relative humidity of zone air [%]
3	Absolute humidity of zone air [ $\text{kg}_{\text{water}} / \text{kg}_{\text{dry\_air}}$ ]
4	Sensible heating demand of zone (positive values) [kJ/hr]
5	Sensible cooling demand of zone (positive values) [kJ/hr]
6	Sum of sensible heating demand for specified zones (positive) [kJ/hr]
7	Sum of sensible cooling demand for specified zones (positive) [kJ/hr]
8	Predicted mean vote (PMV) value of zone [-]
9	Predicted percentage of dissatisfied persons (PPD) value of zone [%]

### 3.3.3. TRNSYS Files

TRNBUILD provides data files necessary for using the TRNSYS TYPE 56 Multi-Zone Building component. The user creates a file (\*.BUI), using the interactive interface TRNBUILD describing the building using the BID language. In addition to TRNBUILD, the user may also use any text editor for creating the BUI file.

Apart from the file for the building description (\*.BLD) TRNSYS creates another for the transfer function coefficients (\*.TRN) that characterize the wall constructions. These two files are assigned internally to TYPE and include all information TYPE56 needs about the building.

The information file (\*.INF) contains the processed BUI file followed by the values of wall transfer function coefficients, the overall heat transfer conductance U and the related k-value. Next, the list of inputs required for the Type 56 is printed. These will most commonly be outputs of other components in the TRNSYS simulation. Also, the information file (\*.INF) provides a list of outputs of Type 56 as selected by the user.

These outputs may be inputs to other components. Finally, a brief table with all of the wall types and their k-values is printed to the information file.

### **3.4. Small Audits of office buildings in Athens**

For the purpose of the thesis office buildings located in Athens have been audited by the author for the years 2005 and 2006. In the following sections the data collection procedure and the findings of the audits are presented.

#### **3.4.1. Building data collection**

For the audits purpose questionnaires were conducted in order to collect the required information in terms of building construction characteristics as well as building operational data. Then they have been distributed to a group of office buildings. The building group selection for the auditing was based on the following criteria:

- The research targeted only office buildings, since they were considered to comprise a sector with reasonably homogeneous buildings, occupancy and activity.
- The group should be consist of buildings with various year of construction in order various construction methods to be covered (e.g. with and without thermal insulation, with single and double windows, etc).
- The selected group should cover a variety of building size and occupancy (small to large buildings).

The questionnaires were distributed to 50 office buildings to be filled by each building responsible. Many in-situ measurements were conducted in all office buildings with the aim of collecting details on construction, activities and energy uses in each building and also for thermal zoning determination in each building.

A set of the detailed questionnaires was distributed to the 50 office buildings in Athens. Only 15 (30%) building's responsables were positive to participate in the survey and finally just 10 of the 15 collected questionnaires (20% of the distributed) were valid for the simulation.

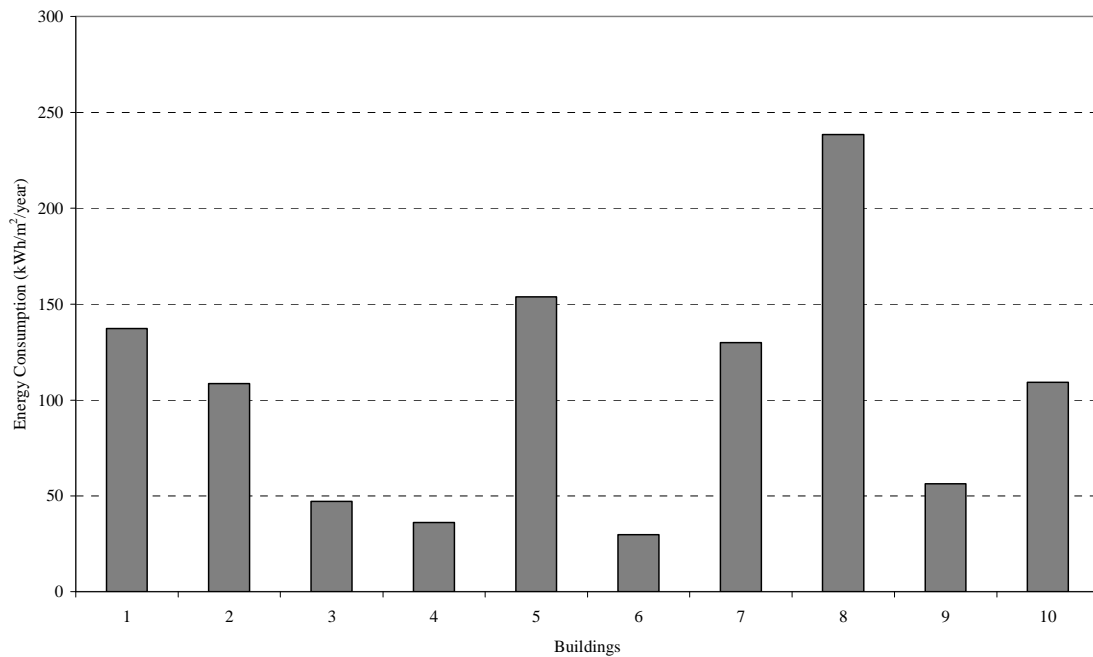
The following information has been collected from each building:

- General information about the building and the occupants (owner, construction year, the heated surface, the daily occupation time schedule).

- Specific information about the building envelope (orientation, walls, ceiling, floors, openings, type of glazing and shading).
- Detailed information about the heating, cooling and lighting systems (power, set points, operation time schedule) and information about the office equipment.
- The annual energy consumption of the building. The consumed electricity and the quantity of fuel were recorded from the building energy bills.

In Table 3-8 the collected data from the audits are presented. As it is observed the sample can not be characterized as representative of Greek office building. The offices that responded to the questionnaires are small (total area < 300 m<sup>2</sup>) and construction year before 1995. The 9 of them have been constructed before 1980. The 30% have walls without insulation, the 80% have single pane windows, while the 60% use glow-lamp lighting system and only 10% use mechanical ventilation system. The annual energy consumption per floor area for each building is presented in Figure 3-9. The minimum energy consumption is 29.85 kWh/m<sup>2</sup>/year, the maximum 238.53 kWh/m<sup>2</sup>/year and the average 104.68 kWh/m<sup>2</sup>/year.

It is observed that building No 8 has high energy consumption compared to the rest. This is explained because of the high energy consumption for lighting 124.58 kWh/m<sup>2</sup>.



**Figure 3-9: The annual energy consumption per floor area of audited office buildings**

Table 3-8: Office building data collected by the audits

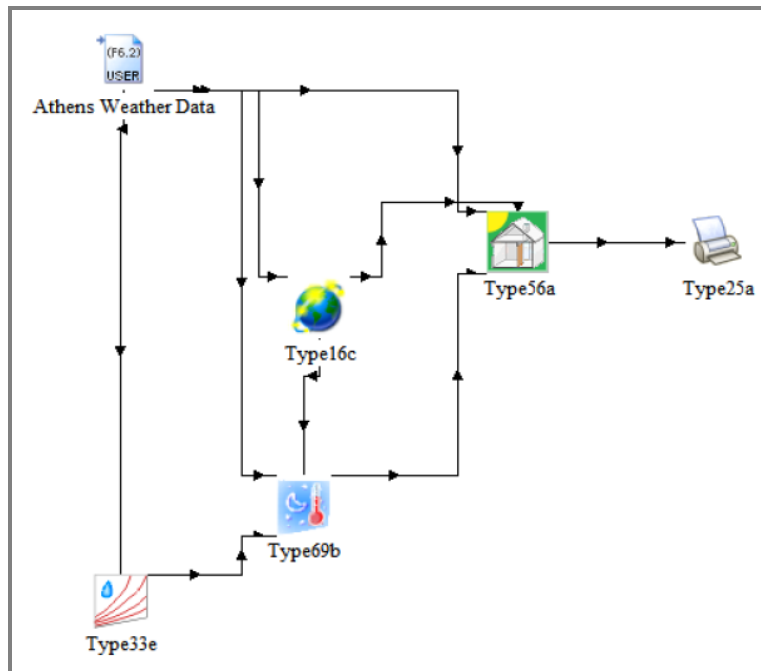
Bld	Constr year	No of floors	Floor area (m <sup>2</sup> )	Wall Type	Window Type	Shading	Electric Lighting System	Heating system	Cooling system	Ventilation system	Office equipment	Occupants	Time schedule
1	1930	1	45	1	2	1	1, 2	2 1x12.000 btu/h 1x 9.000 btu/h	2 1x12.000 btu/h 1x 9.000 btu/h	1	2 PC, 2 Printers, 1 photocoppy machine	3	Monday-Friday 09:00-14:30 18:00-20:30
2	1955	1	135	2	1	0	1, 2	1	2 5x9000btu/h	1	2 PC, 1 Printer, 1 Scanner, 1 photocoppy machine	5	Monday-Friday 11:00-21:30
3	1977	1	53	2	1	0	2	2, 1x12000btu/h	2 1x12000btu/h	1	3 PC, 2 printers, 1 photocoppy machine	2	Monday-Saturday 07:00-20:00
4	1964	1	22	2	1	0	2	1	2 9000btu/h	1	1 PC, 1 Printer, 1 Scanner,	1	Monday-Saturday 09:00-13:00
5	1910	1	26.1	1	1	0	2	1	2 1x9000 btu/h	1	1 PC, 1 Scanner, 1Plotter	2	Monday-Friday 07:30-14:30
6	1960	1	64.6	2	1	1	1,2	1	2 3x9000btu/h	1	2 PC, 2 Printers, 1 photocoppy machine	2	Monday-Friday 08:00-15:00 19:00-22:00
7	1975	1	269.9	1	1	0	2	1	2 10x9000btu/h	1,2	20 PC, 3 Printers, 1 plotter, 2 photocoppy machine, 1 fax	23	Monday-Friday 08:00-16:00
8	1975	1	50	2	1	0	1	1	1 and 2 1x24000btu/h	1	1 PC, 1Printers, 1 photocoppy machine, 1 fax	1	Monday-Friday 08:00-14:00 19:00-21:00 Weekend 08:00-14:00
9	1975	1	86.9	2	1	1	1,2	2, 1x12000btu/h	2 1x12000btu/h	1	2 PC, 2 Printers, 2 scanners, 1 photocoppy machine, 1 plotter	3	Monday-Friday 08:00-15:00 18:00-21:00 Weekend 09:00-14:00
10	1995	1	85	2	2	0	1,2	1	2 3x9000btu/h	1	No	1	Monday-Friday 17:30-21:00
Wall Type: 1=no insulation, 2 =insulation Window Type: 1=single, 2=double Shading: 0=no shading, 1=internal shading, 2=external shading Electric Lighting System: 1= incandescent lamp, 2=fluorescent								Heating System: 1=Central System, 2=Fun Coils Cooling System: 1=Central System, 2=Fun Coils Ventilation System: 1=Natural, 2=Mechanical					

### 3.4.2. The office buildings' simulations in TRNSYS

The thermal behavior of the 10 audited office buildings has been simulated with the aid of the adopted simulation model in TRNSYS. The collected analytical building data (See Table 3-8) are the inputs to the model with the aid of TRNbuild. The simulation parameters (TRNSYS routines-TYPES) are listed in Table 3-9.

**Table 3-9: Parameters of the office building simulation model**

Simulation Parameter	TRNSYS Type	Comments
Climatic Data	Data Reader	National Observatory of Athens –Meteorological Data for the years2005 and 2006
Building Data	56	From the data of the 10 buildings in TRNBuild environment
Psychrometrics	33e	
Effective sky temperature for long-wave radiation exchange	69b	
Overhang and Wingwall Shading	34	
Outputs	QHEAT QCOOL	Heating and Cooling Demand for the building



**Figure 3-10: Office building simulation model realization**

In order to verify the reliability of the model, the actual energy consumption of the 10 buildings is compared to the outputs of the simulation model. The model, though, yields only the Heating and Cooling Demand for the building. Therefore, in order to calculate the total energy consumption that would be comparable to the electricity and fuel bills of the buildings, the annual energy consumption for lighting and equipment was assessed and the total energy consumption was calculated according to the following equation:

$$E \text{ (KWh/m}^2\text{/year)} = (Q_h/n_h + Q_c/n_c + E_{\text{light}} + E_{\text{equip}}) / S \quad (3-28)$$

where:

- $Q_h, Q_c$ : Annual Heating and cooling demand for the building (from the outputs of the model)
- $n_h, n_c$ : Efficiency factor of the heating and cooling system accordingly
- $E_{\text{light}}$ : Annual energy consumption for lighting
- $E_{\text{equip}}$ : Annual energy consumption of electrical appliances and equipment
- $S$ : Floor area ( $\text{m}^2$ )

It is noted that the climatic data that are used for the simulations referred to the respective year that the energy consumption data were collected. (8 buildings with climatic data of 2005 and 2 with climatic data of 2006)

Table 3-10 presents the actual energy consumption of each building and the energy consumption calculated from the simulation model.

**Table 3-10: Actual vs simulated total annual energy consumption for the 10 offices in Athens**

Building	Actual energy consumption (kWh/m <sup>2</sup> /year)	Simulated energy consumption (kWh/m <sup>2</sup> /year)
1	137.40	116.38
2	108.57	103.57
3	47.17	41.00
4	36.00	37.10
5	153.85	166.35
6	29.85	28.25
7	130.00	142.96
8	238.53	224.54
9	56.26	58.08
10	109.20	107.41

The average difference between simulated and actual values is +2.12 kWh/m<sup>2</sup> and it is also systematic, as depicted in Figure 3-11, by the satisfactory linear regression between them (R<sup>2</sup>=0.97).

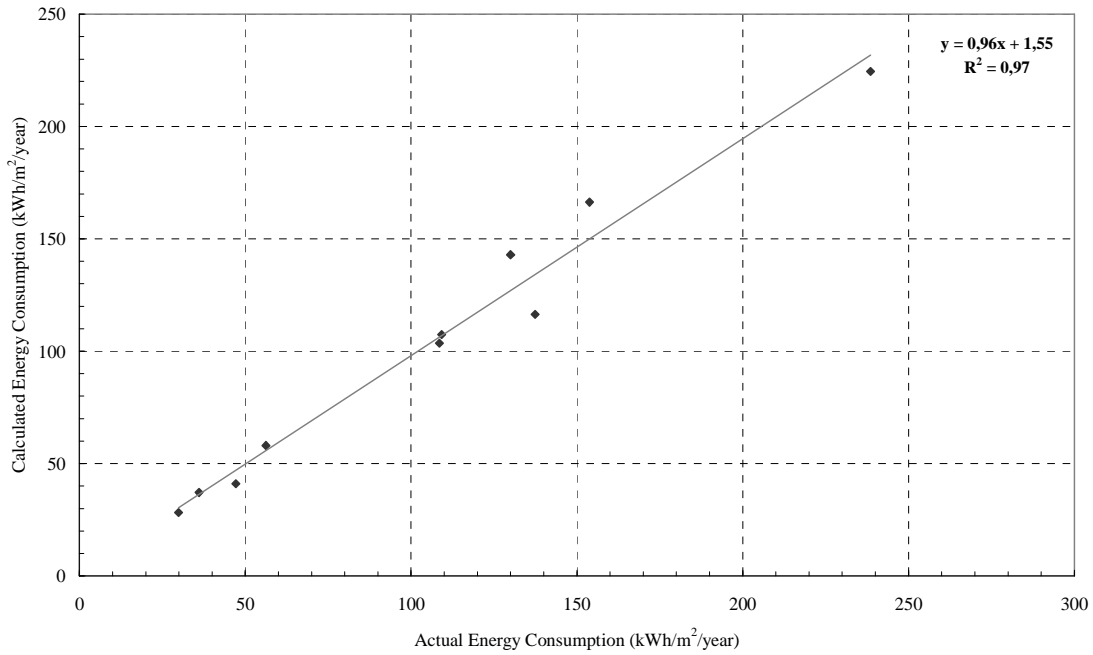


Figure 3-11: Annual Energy Consumption -Experimental values versus TRNSYS calculations

## Conclusions

In this part of the thesis, a simulation model of an office building has been created in TRNSYS 16 in order to evaluate the energy performance at hourly and yearly base of any case study office building.

Small audits have been conducted by the author to 10 office buildings located in Athens in the aim of collecting individual details on the construction, activities, energy uses and energy bills. The audits were conducting for two aims:

- For the investigation of the constructional and operational characteristics of office buildings in Greece.
- For the validation of the adopted simulation model. The 10 audited office buildings have been modeled via the office simulation model according to the information collected by the audits. The calculated by the simulations annual energy consumption of the buildings has been compared to the respective real electricity and fuel consumption (energy and fuel bills). This comparison helps the calibration and validation of the office building model, in order to be used in further office building modeling.

The group of 10 audited office buildings has not be representative for the Greek stock since the majority of the buildings responded to the questionnaires have small floor area and have been constructed before 1980. However, the information gathered from the audits has been a very useful tool for the simulation model accuracy testing and the model improvement. The comparison between the actual and the calculated annual consumption of the buildings has been shown that the model has great accuracy in energy calculations at yearly base.

Given the above conclusions the following points are revealed:

- A detailed audit based on hourly measurements (and not only on energy bills) is necessary in order to investigate parameters such as indoor temperature, humidity, thermal comfort, indoor air quality etc.
- The office building simulation model has to be improved in order to calculate with accuracy the aforementioned parameters apart from energy consumption.

The next step of the research, in the thesis framework, is to conduct a detailed audit to an office building and then a detailed simulation model creation based on measured data.

## Chapter 4

# DETAILED AUDIT AND DETAILED MODEL

# **CHAPTER 4: DETAILED AUDIT AND DETAILED MODEL**

## **4.1. Introduction**

In the Framework of “E-Management for indoor environment and energy savings in buildings” Project of General Secretariat for Research and Technology, a Building Management System (BMS) installed in the office building of BYTE in Athens. The BMS had the purpose to collect and store data at hourly base for energy and environmental rating of the building. Gathering the stored by the BMS data a detailed audit has been conducted for the BYTE office building.

Apart for project’s purposes, these detailed data have been used in order to improve the accuracy of the office building thermal model in TRNSYS. The building is modelled in detail by splitting it into 45 thermal zones. The simulation results are compared with the measured values provided by the BMS for two periods (winter and summer) and the model has been improved based on the monitoring results.

In this chapter the characteristics of the audited office buildings are presented in details. Then the BMS installation of the building is described and the data measurements of the audit are analyzed. In the next step the BYTE building is modeled in TRNSYS and the comparison of measured parameters values with the calculated by the model lead as to significant conclusion regarding the reliability of the model, the accuracy of asset rating compared to operational rating, as well as model application as a general energy audit model for office buildings in Greece.

## **4.2. Building Description**

### **4.2.1. General information**

The BYTE’s building is located on Kallirois street in Athens, Greece and constitutes a self-contained building construction, with extensive reflective glass panels on the majority of the front walls. The building consists of two parts: the existing and the new one (Figure 4-1). The building is mainly used for office accommodation, except

some basement storage spaces and some server rooms. The general information and the design values of BYTE's building are listed on Table 4-1.

**Table 4-1: General information and design values of BYTE's building**

Items	Description
<b>General Information</b>	
Location	Athens, Greece
Building type and stories	Office building, 7 stories above ground.
Operation hours	During weekdays 09:00 – 17:00, although some users still occupy the building spaces afterwards.
<b>Design values</b>	
Space design temperature	20-21 °C during winter period 26 °C during summer period 18-22 °C in the servers' room
Humidity	<60 in the servers' room
Ventilation	For offices where smoking is prohibited, the demand is 30 m <sup>3</sup> /h/person. Where smoking is allowed, the demand is 90 m <sup>3</sup> /h/person.
Lighting	In office spaces the national and international standards are applied, which demand 500 lux on the desktop. In hallways and spaces where permanent user occupation is not required, the demands lower to 200 lux.



**Figure 4-1: The Building of BYTE**

### 4.2.2. Envelope Data

General envelope data are presented in Table 4-2. The layers of walls along with their density, thickness and thermal conductivity coefficient are described on Table 4-3, while the characteristics of the building's openings are described on Table 4-4.

**Table 4-2: General building's envelope data**

Surface Type	Surface area
Outside walls	FW=592.58 m <sup>2</sup>
Openings	FF=326.69 m <sup>2</sup>
Ceiling, roof and ceiling under roof non heat-insulated	FD=182.72 m <sup>2</sup>
Floor	FG=182.72 m <sup>2</sup>
Pilotis Ceiling	FDL=182.72 m <sup>2</sup>
Total Construction Surface	F= 1284.71 m <sup>2</sup>
Construction Volume	V=3800.00 m <sup>3</sup>
Ratio F/V	0.338

**Table 4-3: Walls's constructional characteristics**

Layers (outer to inner)	Density (kg/m <sup>3</sup> )	Layer thickness d (m)	Thermal conductivity coef. K (W/m <sup>2</sup> K)
<b>External Wall</b>			
Lime Cement Mortar	1900	0.020	0.468
Air Brick	1200	0.060	
Insulation	600	0.050	
Air Layer	1204	0.030	
Air Brick	1200	0.060	
Lime Cement Mortar	1900	0.020	
<b>Internal Wall</b>			
Lime Cement Mortar	1900	0.020	0.487
Air Brick	1200	0.090	
Air Layer	1204	0.040	
Insulation	600	0.040	
Air Brick	1200	0.090	
<b>Roof</b>			
Terrace plates	2000	0.020	0.368
Cement Mortar	1900	0.020	
Water-proof material	1050	0.005	
Concrete with tilt 1000	1000	0.100	
Insulation	600	0.070	
Concrete B>160	2400	0.140	
Water vapor barrier	600	0.020	
Lime Cement Mortar	1900	0.020	
<b>Floor/Ceiling</b>			
Marble plates	3000	0.020	0.507
Lime Cement Mortar	1900	0.020	
Concrete B>160	2400	0.150	
Insulation	600	0.050	
Lime Cement Mortar	1900	0.020	

**Table 4-4: Openings**

	Opening Type	Surface F (m <sup>2</sup> )	Thermal conductivity coef. K (kcal/ m <sup>2</sup> h °C)
Ground Floor openings, Sides 1-5	Double Panel 2-4cm	29.12	2.600
Ground Floor openings, Side 6	Double Panel 2-4cm	22.75	2.600
Floor A openings, Side 1	Double Panel 2-4cm	37.38	2.600
Floor A openings, Side 2	Double Panel 2-4cm	9.66	2.600
Floor A openings, Side 3	Double Panel 2-4cm	2.10	2.600

### 4.2.3. Mechanical/Electrical equipment description

The heating/cooling system of the BYTE's building is a VRV (Variable Refrigerant Volume) system. The fundamental characteristic of this system is that it can simultaneously operate in heating and cooling mode at the indoor units (Figure 4-2). It also presents a satisfactory Coefficient of Performance (COP) both in heating and cooling mode. Moreover, the master units (VAM) of the system can connect directly with an automatic control system, such as the one developed by Honeywell (described in following section), which is installed in the building.

**Figure 4-2: Operation of Daikin's VRV**

The local heating/cooling units are of fan coil units and they are shown in Figure 4-3. The outdoor units of the system are shown in Figure 4-4 and the Control Unit in Figure 4-5. Also, the air vents of ventilation system are shown in Figure 4-6.



**Figure 4-3: Local unit of VRV System in BYTE building**



**Figure 4-4: The outdoor units of the VRV system in BYTE building**



Figure 4-5: The control unit of VRV system in BYTE building



Figure 4-6: The air vents of the ventilation system

Regarding the electric lighting system, it consists of lights with fluorescent lamps and aluminum reflector with relatively high performance (Figure 4-7). The electric

lighting system is controlled separately in each zone, allowing for more efficient management.



**Figure 4-7: The electric lighting system of BYTE building.**

### **4.3. The BMS System**

In the BYTE S.A. building the Building Management System (BMS) is installed, in order to serve three main purposes:

- (i) The installation and test of the platform developed for the E-Building project (Kolokotsa et al., 2006)
- (ii) The rational energy use and the eventual reduction of the total energy consumption and
- (iii) The full supervision of all controlled equipment as well as its administration, where applicable, using the main task console (BMS Server).

The main equipment of the BYTE premises consumes electricity:

- (i) VRV air conditioning system
- (ii) Lighting
- (iii) Generators
- (iv) Elevators
- (v) Fire and Access Plants

(vi) Water and sewage pumps.

In addition, with the aid of BMS it is possible to monitor regularly the functional parameters of the building, and store them in appropriate log files.

The measured variables per zone, recorded by the automation system, are the following:

- Indoor air temperature,
- Relative humidity,
- CO<sub>2</sub> concentration,
- Energy consumption per VRV unit (heating, cooling, and ventilation).

All the measurements are stored in ASCII files (history files) in order to have simple and easy access to them.

#### **4.3.1. Honeywell Excel 5000 Open Lon**

The installed BMS is a Lonworks network (Figure 4-10). This network is selected as it provides interoperability and expandability. This means that various components from various manufacturers can be integrated into the network either at the present time or in the future. The application of the above to BYTE building is the incorporation of the followings to the control network (Figure 4-8):

- Honeywell Excel 5000 for the algorithm creation and data collection.
- Daikin Lon Gateway for the VRVs (internal and external units) control and management.
- Tyco Integra multi-meters for electrical values measurements of the substation.
- Echelon iLon100e for data and alarm transfer to the Internet Web Server.

The controllers are connected to the network type TP/FT-10 via transceiver Echelon FTT-10A. The network communication speed is 78 Kbps. The network topology can only be terminated as Bus, Star, Loop, free-form (Free Topology) or double termination. The network supports 64 open communication nodes. With the use of router and repeater it supports up to 32385 nodes. The Figure 4-10 refers to the topology of the network for the new and the existing building.



**Figure 4-8: The Lonworks control network.**

The inspection of the installation is carried out after programming and connecting the Honeywell controller to the LONWORKS network. The controllers are of EXCEL 500 Smart series with external digital and analog input - output control ports modules, direct digital control technology DDC, bear Echelon 3120 or 3150 processor and are certified according to LONMARK 3.2. EXCEL 500 smart controller is the central unit, which manages physical control points and on which the computational algorithms are developed. Data collection from the sensors is performed by external input - output port modules - mounted in special slots - terminal blocks (XSL) and then connected to the central unit and the network. In order to cover the floors in terms of input - output port the following XSL module combinations are employed:

- 12 digital input ports (XFL523B) for dry contact connections.
- 6-port digital output ports (XFL 524B).
- Combination of 2 analogue - 8 digital input and 4 digital output ports (XFC3X).

For the purposes of this project, open programmable controllers are used for controlling the electromechanical applications for which there is no standard control software. They are fully programmable, providing ultimate flexibility in designing control sequences and maintain all necessary commands to control the building equipment (PID, mathematical, logical, time functions and energy management

programs such as optimum start stop, cycling etc). The main application area is that of the central HVAC systems which communicate with one of the terminal unit types (VAV, FCU, etc.). The programming of the controllers is done with the CARE design tool. CARE has been designed by Honeywell to offer a friendly and reliable graphical programming environment.



Figure 4-9: The BMS hardware

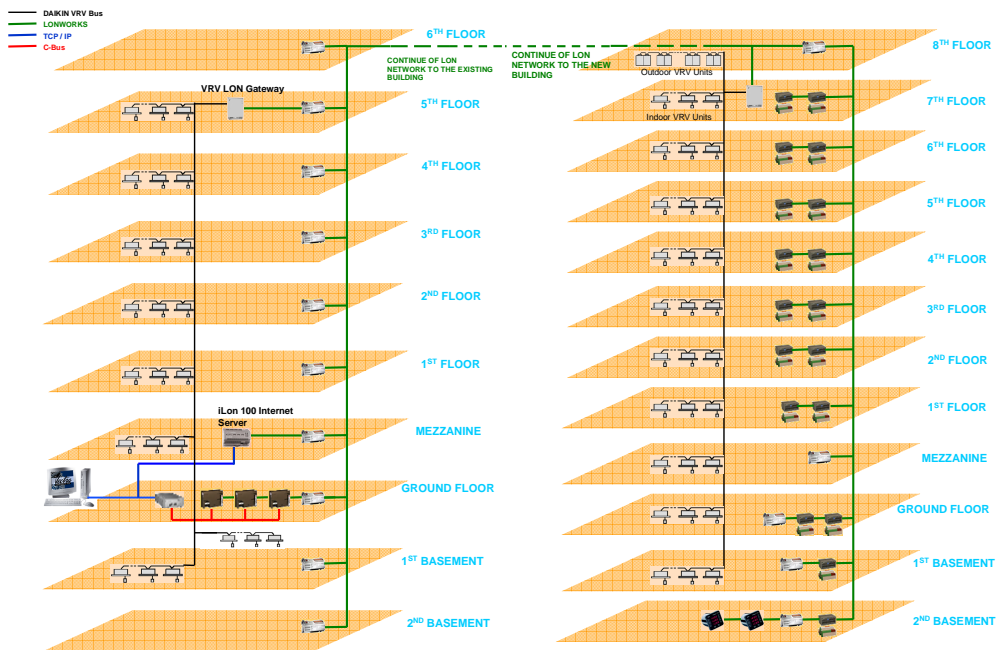


Figure 4-10: The BMS installation using Lonworks

### 4.3.2. Monitoring and management of the installation

In the monitoring station the control and management operating system (Honeywell SYMMETRE R300.2) is installed, which is basically the "interface" between the controlled electromechanical equipment and the user. The user is able to control the installation during the various operation phases, but also to intervene more or less in operation and management, depending on the circumstances and needs that arise. The user could, for example, to change the time schedules, if it was appropriate or even to isolate any part of the installation of the automated mode, by activating and deactivating it.

The main page of the monitoring and management application of the installation is presented in Figure 4-11.

From this front page the user may explore all the building's floors and see the monitored installations. SYMMETRE offers the ability of monitoring all the devices and the hubs of the network.

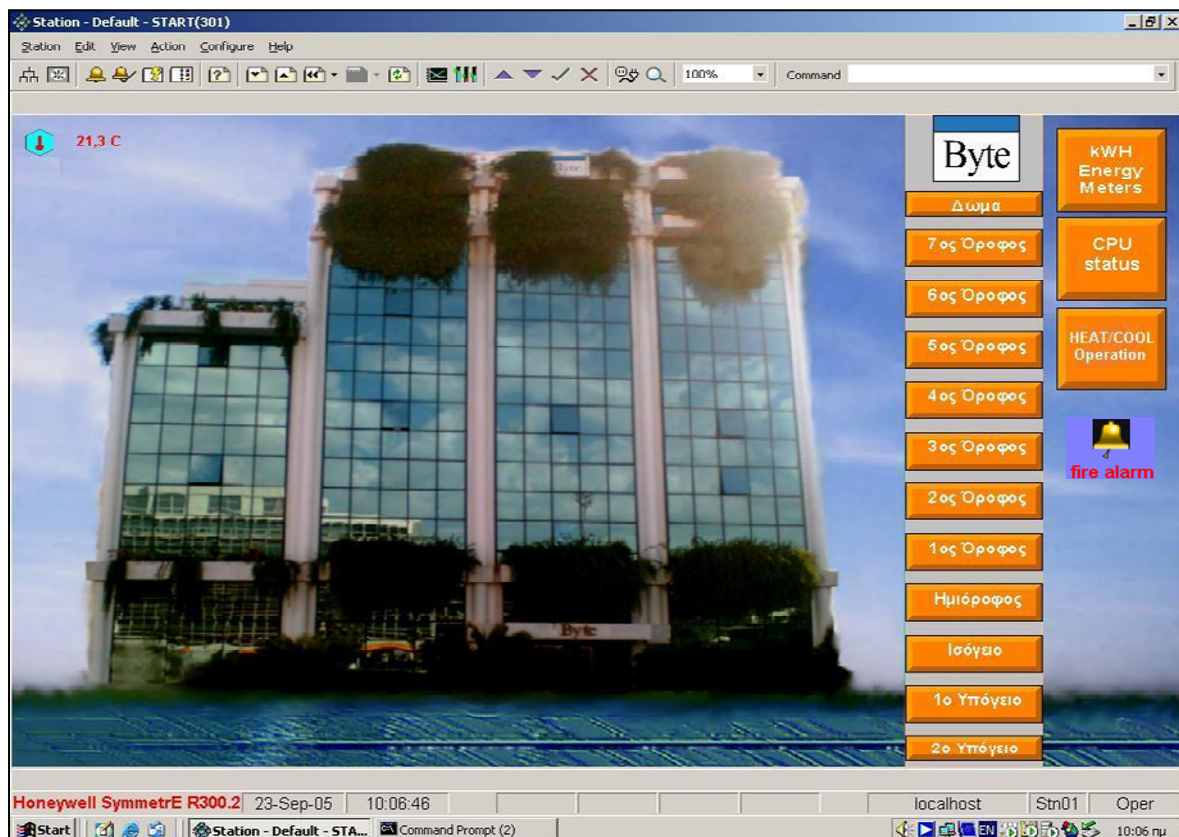


Figure 4-11: The basic interface of the application.

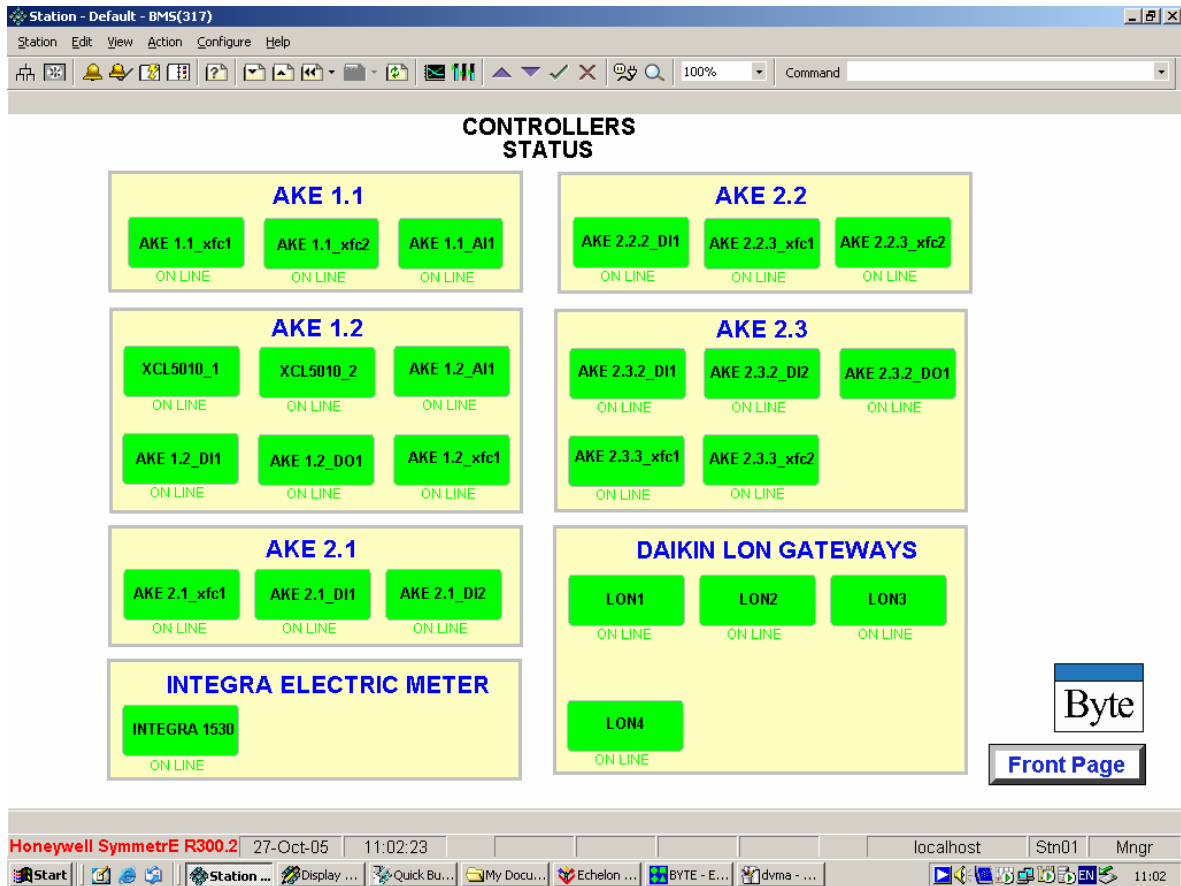


Figure 4-12: The monitoring front page of the installation devices and hubs

In the following paragraphs the detailed description of the systems controlled by the BMS is presented.

### 4.3.3. Heating, Cooling, Ventilation VRV System

The air conditioning loads are covered by a system of VRV central units that serve terminal units in the building zones. For the pre-conditioning purposes roof air exchangers (VAM) have been installed. The installed VRV system of DAIKIN has a socket for LON Gateway which, when connected to the LonWorks network, provides information for monitoring units such as:

- Supervision: indoor temperature, thermostat set points, compressor operation, filters control.
- Control: Remote ON-OFF, set-point control, mode (cool/heat/fan/auto) control

The new and existing building of BYTE has been divided into 45 district thermal zones based on building's geometry. Each zone has 1 to 3 local VRV units and functions individually from the others.

In Figure 4-13, Figure 4-14, Figure 4-15, Figure 4-16, Figure 4-17, Figure 4-18, Figure 4-19 and Figure 4-20, there is an illustration of the floor plans of BYTE building. In these floor plans, the distribution of local VRV units in each building floor is presented in detail.

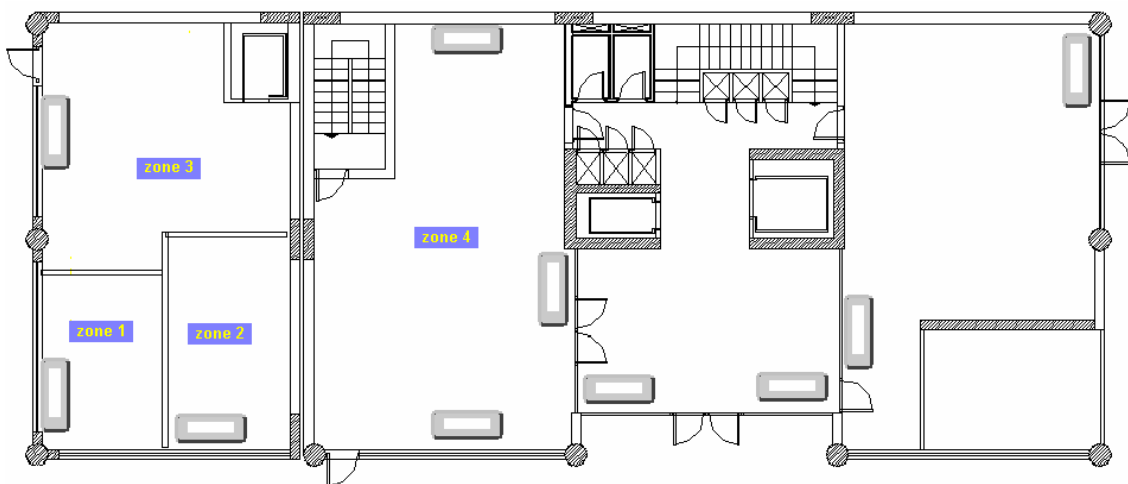


Figure 4-13: Ground Floor and thermal zones plan of BYTE.

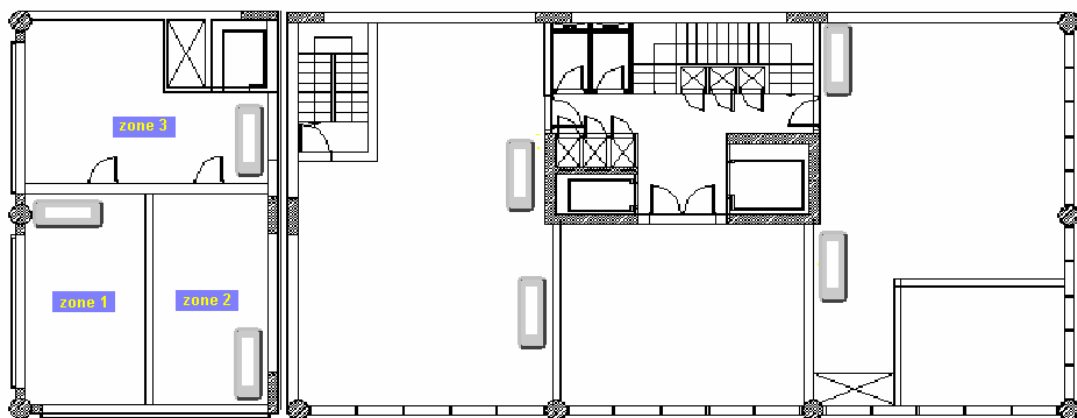


Figure 4-14: Mezzanine and thermal zones plan of BYTE.

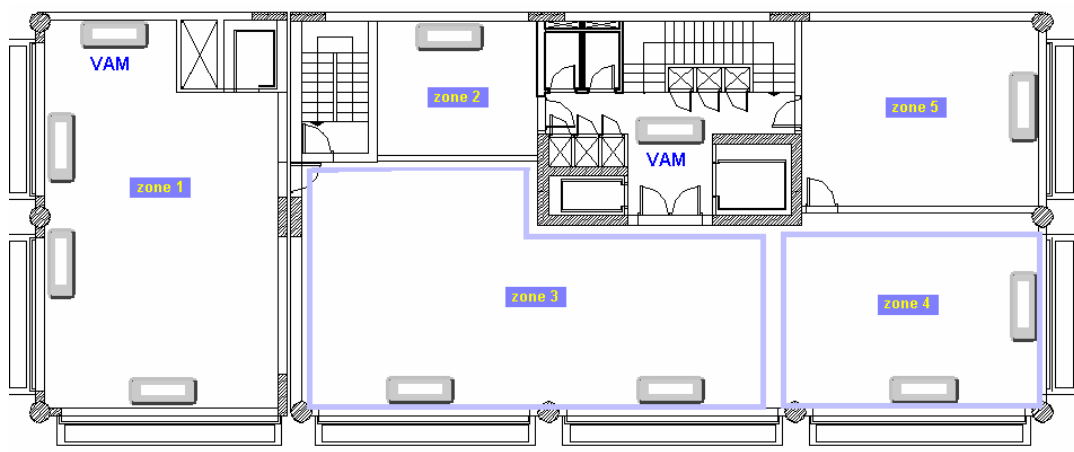


Figure 4-15: 1<sup>st</sup> Floor and thermal zones plan of BYTE

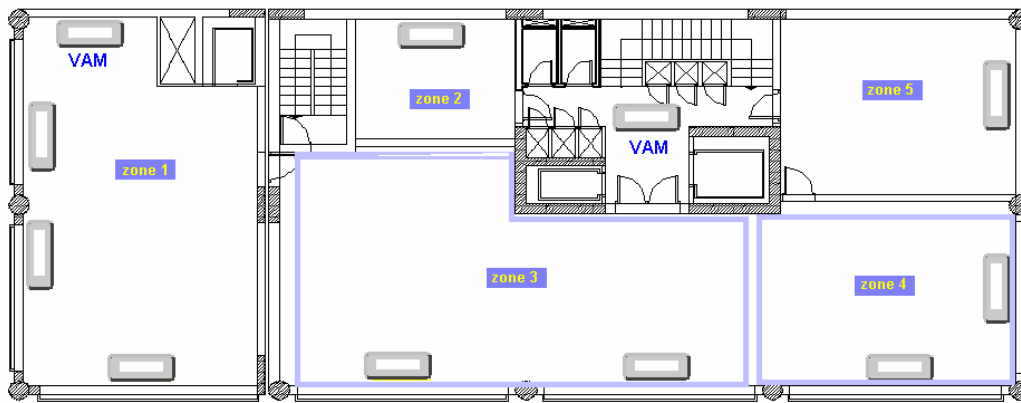


Figure 4-16: 3<sup>rd</sup> Floor and thermal zones plan of BYTE

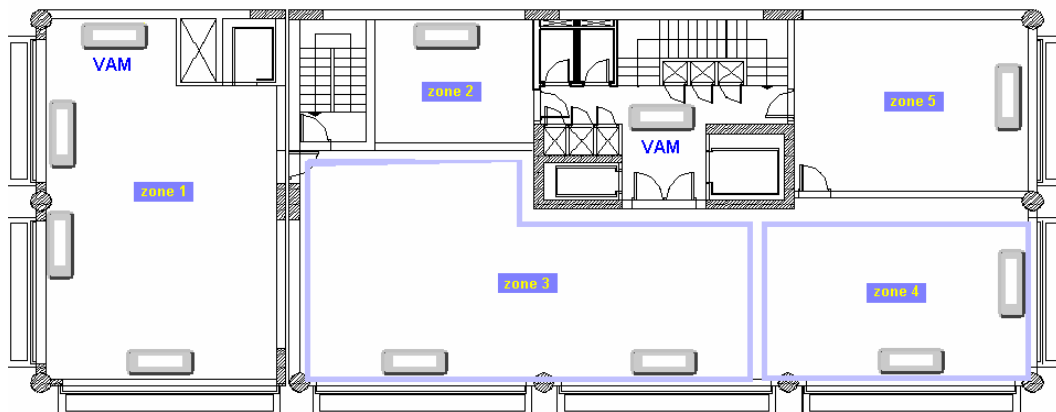


Figure 4-17: 4<sup>th</sup> Floor and thermal zones plan of BYTE

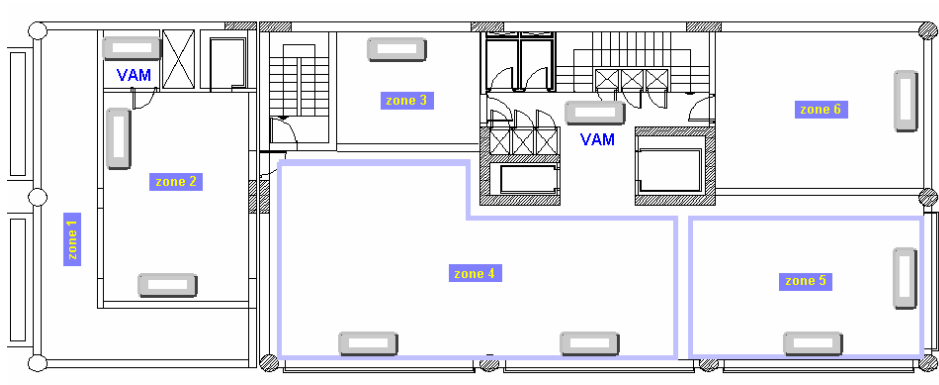


Figure 4-18: 5<sup>th</sup> Floor and thermal zones plan of BYTE

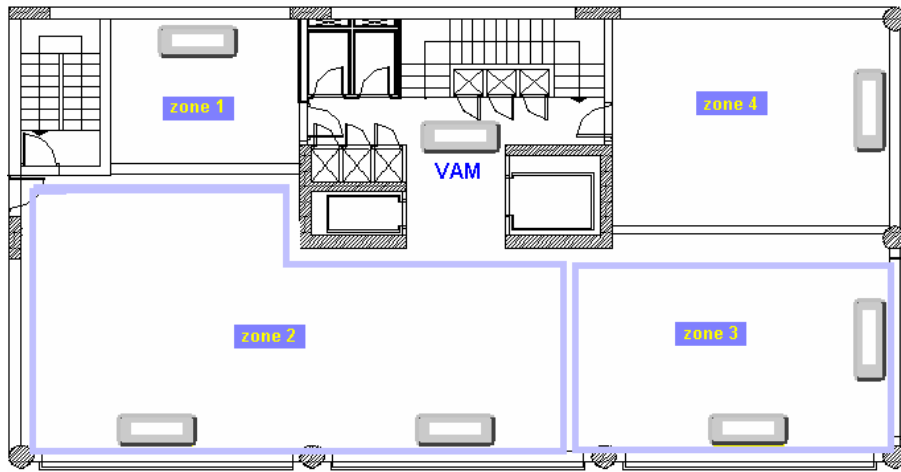


Figure 4-19: 6<sup>th</sup> Floor and thermal zones plan of BYTE

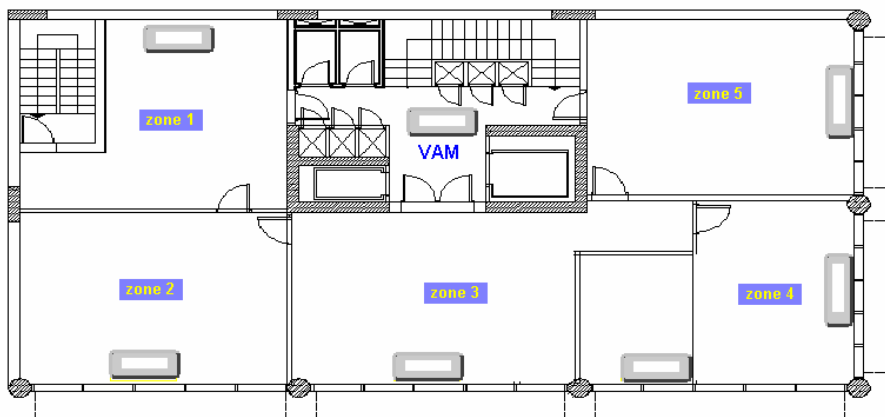
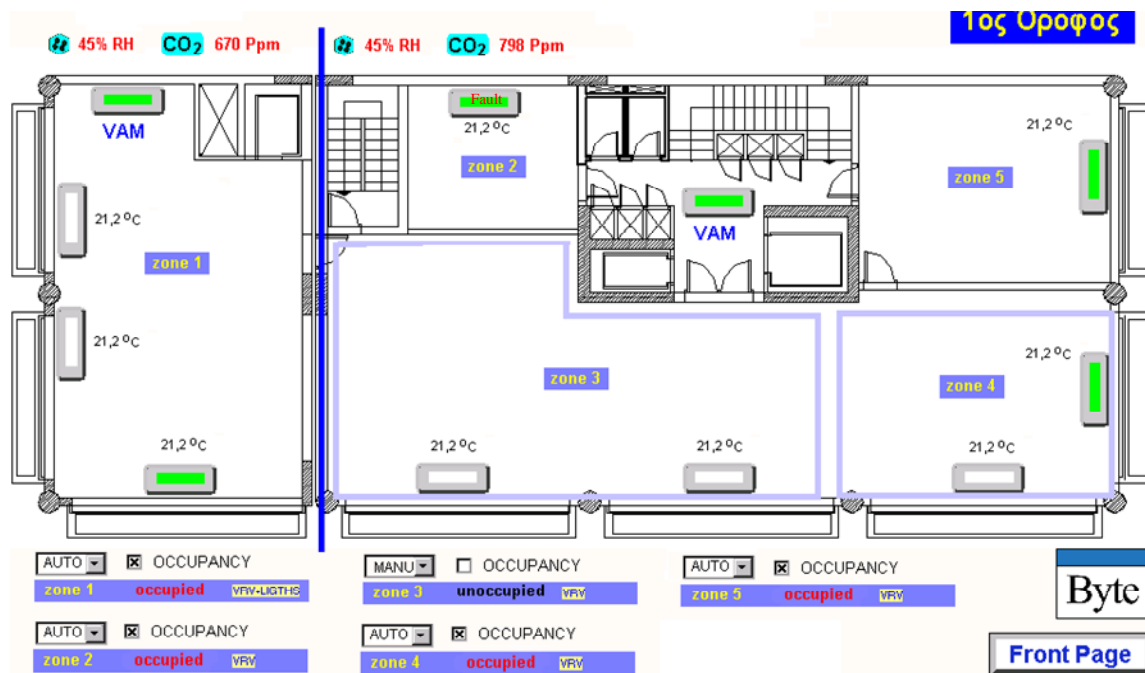


Figure 4-20: 7<sup>th</sup> Floor and thermal zones plan of BYTE

Opening the 1<sup>st</sup> Floor front page, for example, the image illustrated in Figure 4-21 is appeared.



**Figure 4-21: The detailed representation of the instant values of the monitoring parameters in the 1<sup>st</sup> Floor**

In the front page are depicted for the existing and the new building:

- Relative Humidity and CO<sub>2</sub> concentration values.
- The thermal zones, the VRV units with the relative temperature values.
- The VAM units.

The green color indicates that VRV functions, while the indication “fault” indicates a fault existence. The same representation is applied for all the building floors.

#### 4.3.3.1. Control strategy of heating/cooling and ventilation units

There are three control strategy scenarios:

1<sup>st</sup> scenario: Fully automated operation (set/reset). All thermal zones begin and stop automatically heating or cooling at the same time, based on a common time schedule. When the zones are activated the indications on the control are “auto”, “occupancy checked” and “occupied”. There are also the choices the program user to put a zone out of function “occupancy unchecked” or an occupant to put out of function a VRV unit

using the manual control “override”. The VAM unit is activated when one at least VRV unit is activated. From this set/reset function are excluded the following zones (Table 4-5):

**Table 4-5: Zones of BYTE excluded set/reset VRV function**

Zone	Use
Ground Floor -Zone 2	Secretary (local control)
Ground Floor -Zone 3	Seminar Room (local control)
Ground Floor -Zone 4	Conference Room (local control)
Mezzanine -Zone 2	Seminar Room (local control)
Mezzanine -Zone 3	Corridor (local control)
1 <sup>st</sup> Floor * - Zone 2	Meeting Room
3 <sup>rd</sup> Floor* - Zone 2	Meeting Room
4 <sup>th</sup> Floor* - Zone 2	Meeting Room
5 <sup>th</sup> Floor* - Zone 3	Meeting Room
6 <sup>th</sup> Floor*-Zone 1	Meeting Room
7 <sup>th</sup> Floor*- Zone 1	Meeting Room

The zones with (\*) are out of set/reset schedule because are not occupied during the most of the day. The VRVs function is based on presence detectors or manual control.

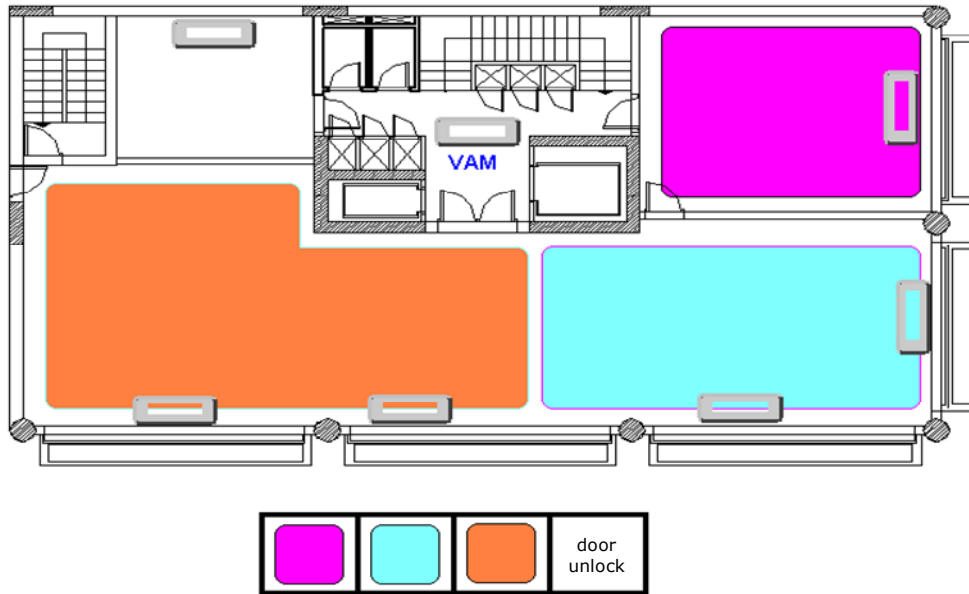
2<sup>nd</sup> Scenario: Extension of the system’s operation. In case of an occupant wishing to stay after the working hours, VRVs operation is extended automatically. For new building the units remain activated with the use of presence detectors, with a time delay of 17 minutes, for system stability. In case of existing building’s zones the VRVs delay is achieved with special extension panel, located in each floor entrance. Each button has an indication led and corresponds to an individual thermal zone (Figure 4-22). When the led is on, means that the zone is activated during the time schedule. In case of some occupants want to extend the VRVs operation they have to press the button until the led is on, and then 2 hours operation extension for the specific zone is achieved. In order to ensure that no VRV will stay activated unintentionally, set/reset procedure is applied twice, once after working time schedule at 17:30 and again at 20:30.

3<sup>rd</sup> scenario: Partially automated operation (set/reset). In this scenario there is the set/reset procedure at 17:30 and 20:30, but the automated beginning of system operation, using a time schedule, is excluded. The operation of the building is as follows:

- In new building VRVs are activated automatically, when occupants’ presence is detected by presence detectors installed in each zone. In existing building the

occupants activate local units (VRV and VAM) every morning using manual control.

- Alternatively a special extension panel could be used, ensuring the automated operation of VAM, but keeping the relative zone activated only for two hours per button press. Manual controls might be use only for turning off a unit in an activated zone.



**Figure 4-22: Control zones of heating/coolong system during operation extension**

#### 4.3.3.2. *VRVs operation recording*

VRVs are operated for heating, cooling or for ventilation only. In both BYTE's buildings there are 19 VRVs groups, the operation of which is controlled by the head VRV of each group (i.e. 19 "master VRVS"). All the local units that belong to the same group have the same external unit. The option "HEAT/COOL OPERATION" in the first front page of SYMMETRE R300.2 leads to Figure 4-23.

In front page of Figure 4-23 the 19 master VRVS, the building area that their group represents and their operation status (heating/cooling/ventilation) are depicted.

7ος Όροφος	LON3 2-01 18 state 3	LON3 2-04 21 state 3	HEATING : 1 COOLING : 3 VENTILATION : 9
6ος Όροφος	LON3 1-13 14 state 3	LON4 1-02 03 state 3	
5ος Όροφος	LON4 1-05 06 state 3	LON4 1-08 09 state 3	
4ος Όροφος	LON3 1-02 03 state 3	LON3 1-07 08 state 3	
3ος Όροφος	LON2 2-02 19 state 3	LON2 2-04 21 state 3	
2ος Όροφος	LON2 1-11 12 state 3	LON2 1-06 07 state 3	
1ος Όροφος	LON1 1-15 16 state 3	LON2 1-02 03 state 3	
Ημιόροφος	LON1 1-07 08 state 3	LON1 1-05 06 state 3	
Ισόγειο	LON4 1-14 15 state 3	LON1 1-09 10 state 3	
Υπόγειο Α	LON1 1-11 12 state 3		




  


Figure 4-23: VRVs operation recording

#### 4.3.4. Energy consumption measurements

The option “KWH ENERGY METERS” in the first front page of SYMMETRE R300.2 leads to front page of Figure 4-24 .

	A' Μετρητής Κατανάλωσης VRV	B' Μετρητής Κατανάλωσης VRV	
7ος Όροφος	9999.99 Kwh	9999.99 Kwh	
6ος Όροφος	9999.99 Kwh	9999.99 Kwh	
5ος Όροφος	9999.99 Kwh	9999.99 Kwh	
4ος Όροφος	9999.99 Kwh	9999.99 Kwh	
3ος Όροφος	9999.99 Kwh	9999.99 Kwh	
2ος Όροφος	9999.99 Kwh	9999.99 Kwh	Μετρητής Κατανάλωσης Φωτισμού
1ος Όροφος	9999.99 Kwh	9999.99 Kwh	
Ημιόροφος	9999.99 Kwh	9999.99 Kwh	
Ισόγειο	9999.99 Kwh	9999.99 Kwh	




  


Figure 4-24: The front page of energy consumption recording per building’s floor

The energy consumption meters deal with the energy consumption of external local units and of the lighting systems of the 1<sup>st</sup> Floor of the new building.

#### 4.3.5. Control of electric lighting system

The electric lighting system has been automated only in the new building. The scenarios are the same to those of VRVs units of new building. The electric lighting in the zones of 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup> and 5<sup>th</sup> floor and of the ground floor and mezzanine is activated and deactivated automatically, since the relative switches on the lighting electric board are in AUTO position. If this doesn't occur the electric lighting is operated only by the wall type button panels.

External lighting system's operation is also automated, based on daily time schedule (20:00-06:00). The front page of control system of electric lighting is depicted in Figure 4-25.

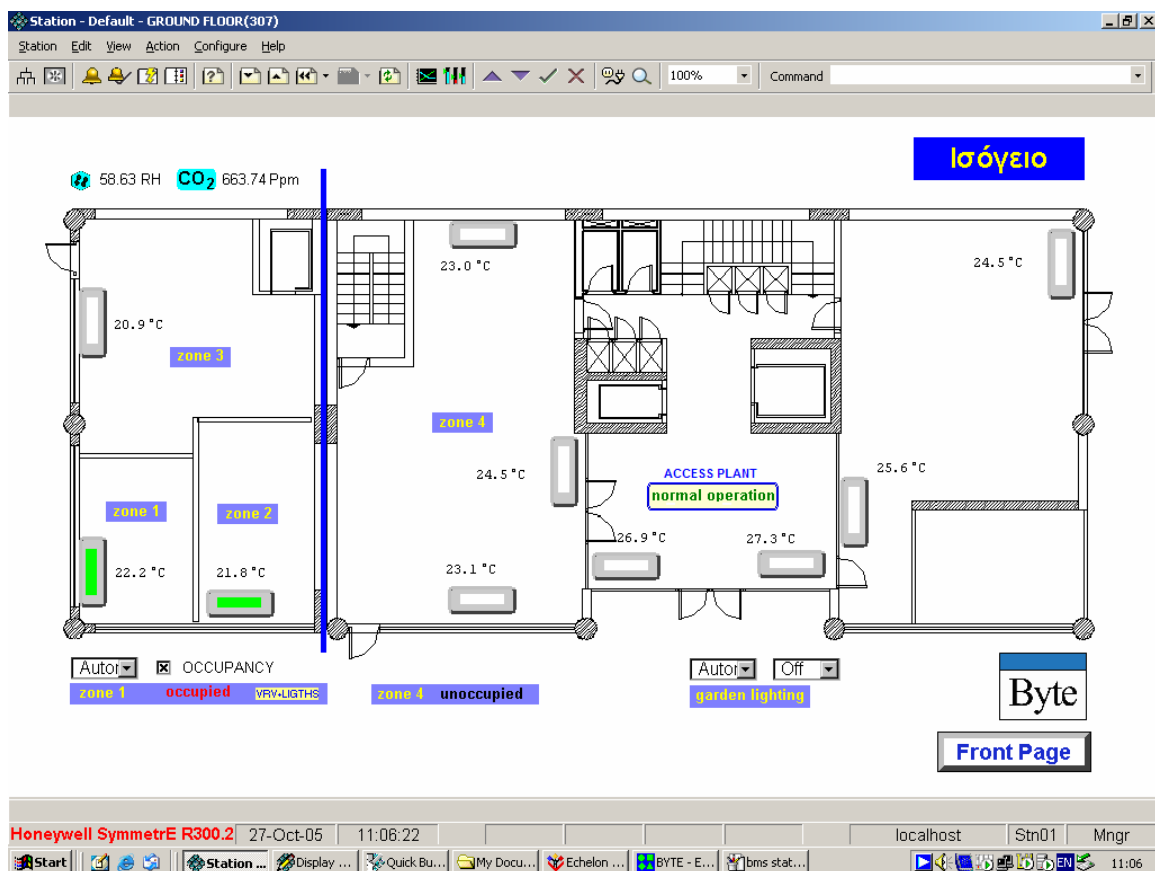


Figure 4-25: The front page of electric lighting control system

From this front page the user has the option to override the time schedule and control the lighting system manually (change the status mode from “auto” to “manual”).

### 4.3.6. Connection of automation system with the substation of electrical supply-Dynamotor

The Substation of electrical supply and the Dynamotor are located in the 2<sup>nd</sup> basement of the existing building. In Figure 4-26 the relative front page is depicted.

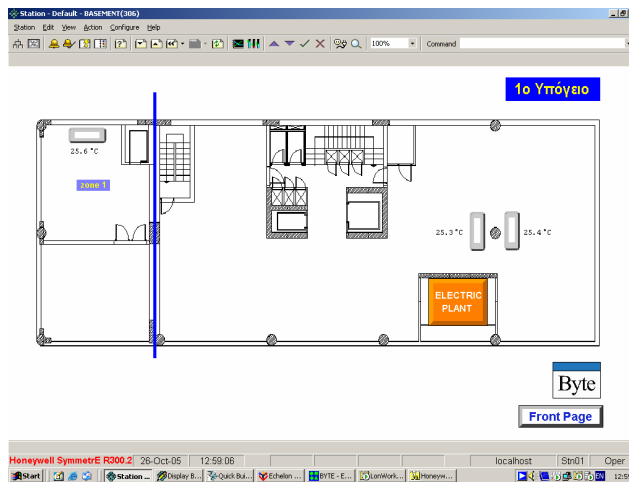


Figure 4-26: The substation of electrical supply representation

By pressing the button “Electric Plant” we go to the front page presented in Figure 4-27. The building is supplied by the transformer (i.e. by P.P.C.) and only if there is power cut off it is supplied automatically by the Dynamotor.

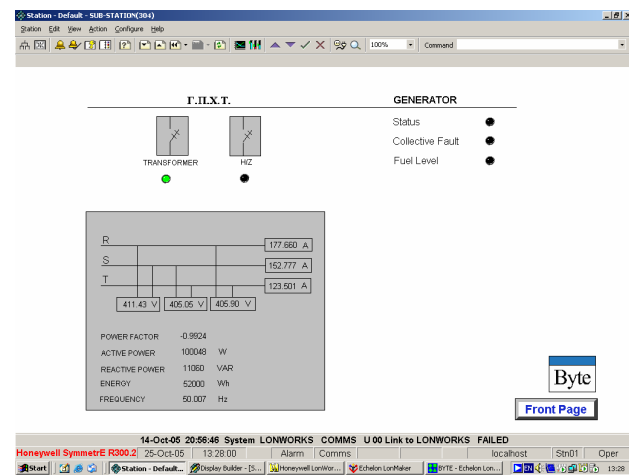
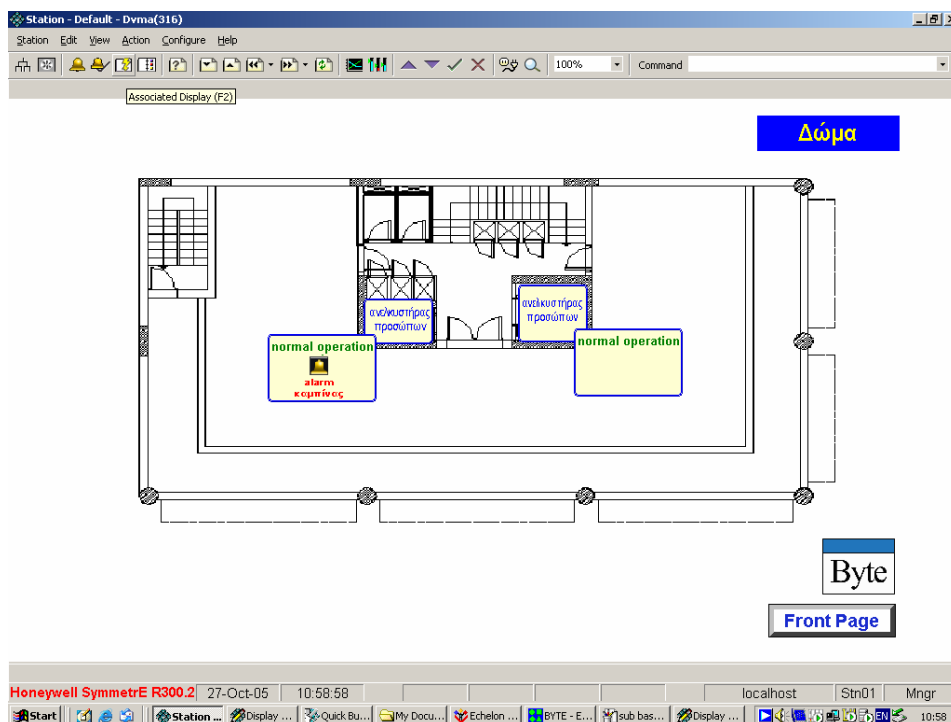


Figure 4-27: Real time representation of the substation status

### 4.3.7. Connection of automation system with the elevators

BYTE buildings have 4 elevators. The new building has an elevator for occupants and the existing building has 2 elevators for occupants and one for cargo. Their connection to the central control system deals with 8 signals in total. Each elevator can trigger a fault signal or a signal to free the passengers from the cabinet. The representation of the aforementioned signals are depicted for the existing building in the front page of 6<sup>th</sup> Floor and for the new building in front pages of 5<sup>th</sup> Floor and the 2<sup>nd</sup> basement.



**Figure 4-28: The representation of status mode of elevators' system**

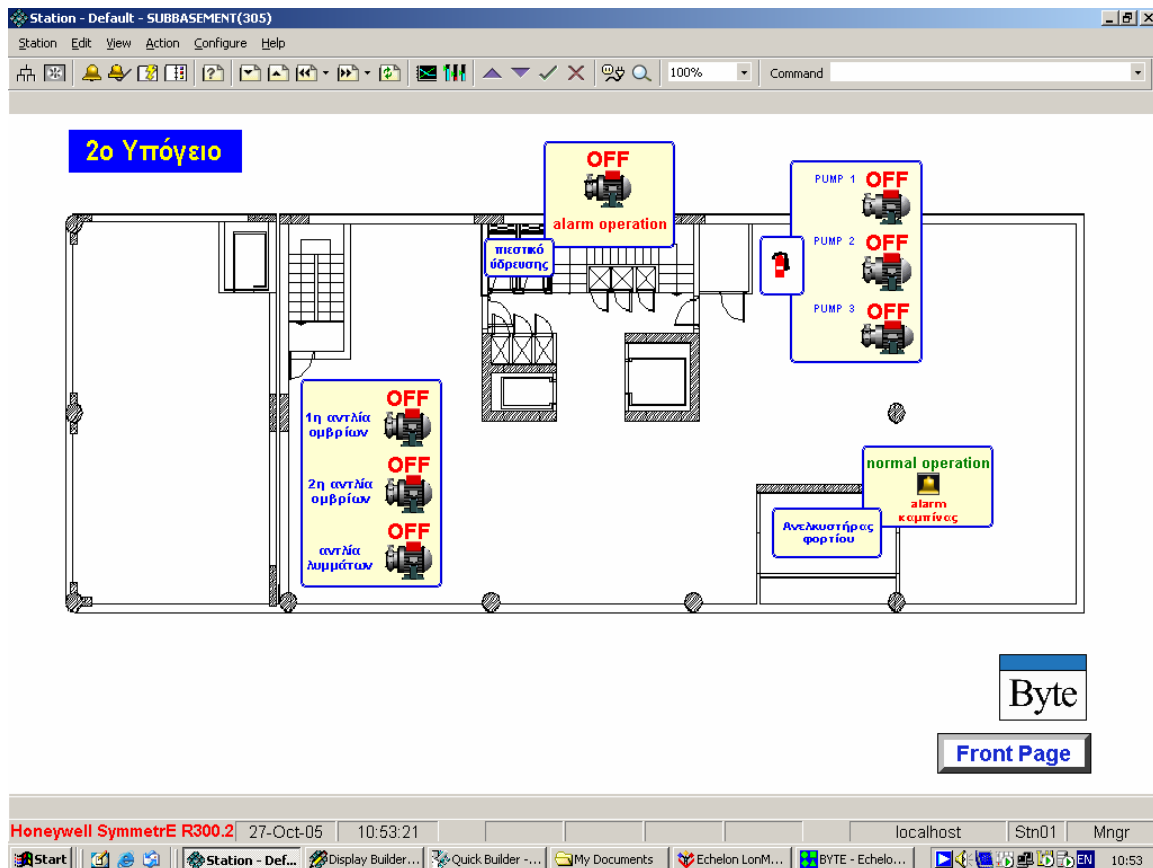
The «normal operation» signal indicates that the elevator is fault free, while the «alarm operation» signal indicates a fault in the system. Finally the “alarm” signal indicates that in the elevator there are people trapped.

### 4.3.8. Fire and Access Plant- Water and sewage pumps

The integration of Fire Plant and Access Plant in the central control and management system regards 2 control signals: The “fire alarm” and the “alarm operation” signal.

In the areas of the 2<sup>nd</sup> basement of the existing building there is the fire extinguish installation, which includes 3 fire pumps, the sewage pump, the rainwater pump and the potable water pump installation.

The signs of the above installations of the 2<sup>nd</sup> basement have supervisory character. When a pump is depicted as “on” is in operation and when the sign is “off” is out of operation. Especially for the water pump system, the fault is depicted in SYMMETRE as «alarm operation».



**Figure 4-29:** The representation of status mode of the fire extinguishes installation, the rainwater pump and the potable water pump installation

#### 4.4. Analysis of the BMS measured data

In this section the collected by the BMS measured data are analyzed in order to investigate the energy and environmental performance of the building in detail and therefore to evaluate the measured (operational) rating of BYTE building. The measurements: indoor air temperature, relative humidity, PMV index and CO<sub>2</sub> concentration are analyzed and presented in each floor for new and existing building in the following paragraphs. The monitoring time period is from 4/12/05 until 22/02/06.

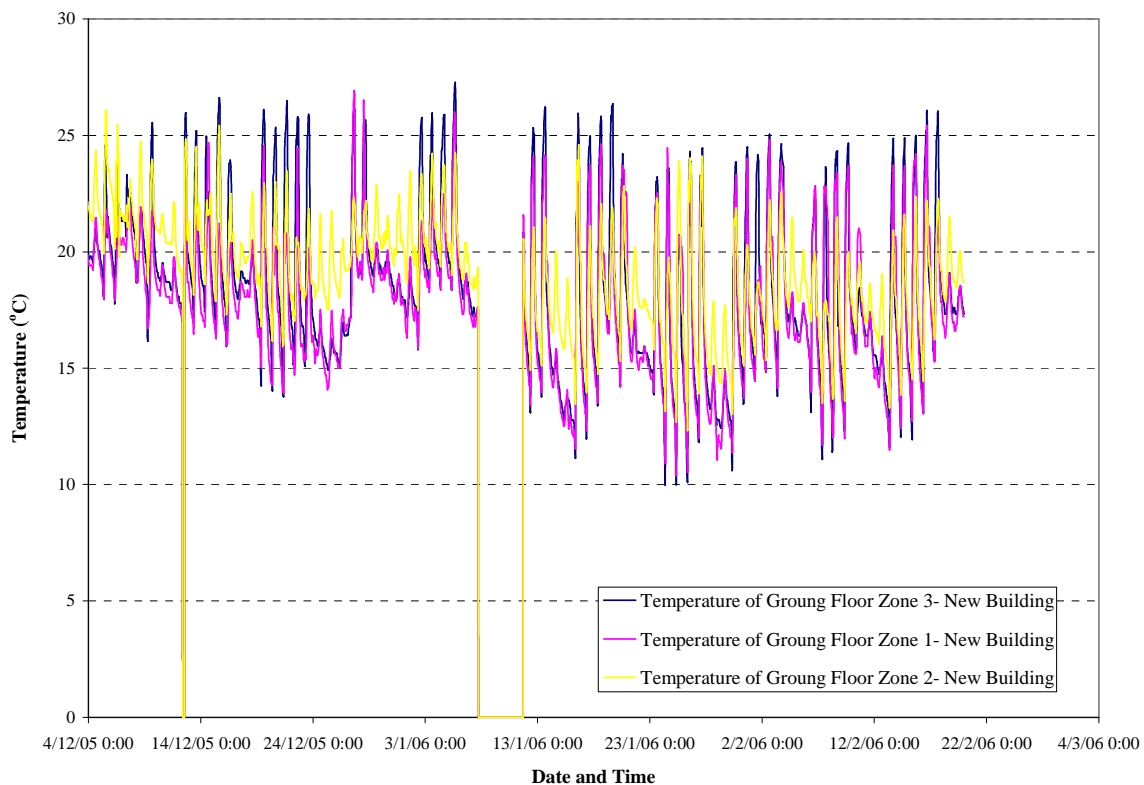
### 4.4.1. Measured data of Ground Floor

#### 4.4.1.1. Thermal performance

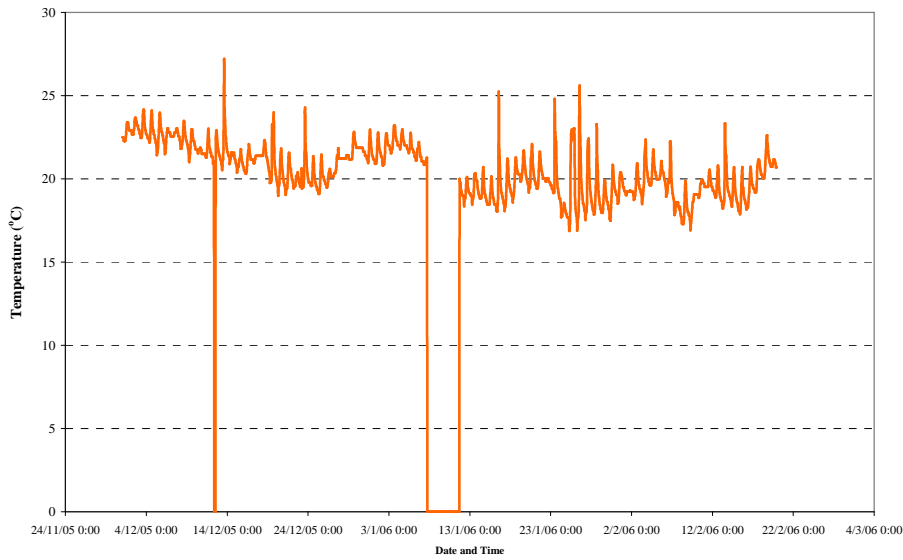
The ground floor has divided into 6 thermal zones in which the temperature values for each zone are measured. Those areas are:

- The reception (existing building),
- The cargo (existing building),
- 3 rooms in the new building, and
- 1 room in the existing building.

The indoor temperature measurements of Ground Floor for new building are presented in Figure 4-30, while for the existing in Figure 4-31.

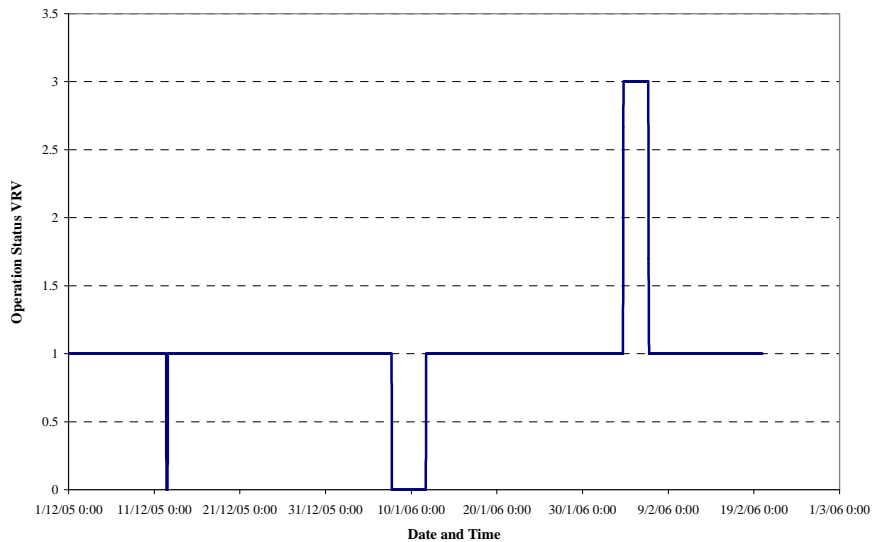


**Figure 4-30: Temperature measurements of Ground Floor-New Building**



**Figure 4-31: Temperature measurements of Ground Floor-Existing Building**

It is observed that in some cases the temperature values of new building are higher than 25°C. This had to be investigated in relation with the VRVs energy consumption during the relative time period. As it is referred in Chapter 4.3 the 19 master VRVs operation status is recorded by BMS, i.e. whether they are in cool mode (status 3), in heat mode (status 1) or in ventilation mode (status 9). After investigating this, it has been observed that VRVs had been operated in heat mode except the time period from 3/2/06 to 6/2/06, when due to system error had been operated in cool mode (Figure 4-32)



**Figure 4-32: VRVs operation status in Ground Floor of new building**

The relative humidity values of the Ground Floor are depicted in Figure 4-33. The environment is characterized rather dry, since the mean relative humidity value varies between 35%-38%. In fact, the relative humidity values are low (30%) during the non-working hours and higher (45%-55%) during the working hours. The PMV index values of Ground floor are depicted in Figure 4-34 and they are in satisfactory levels.

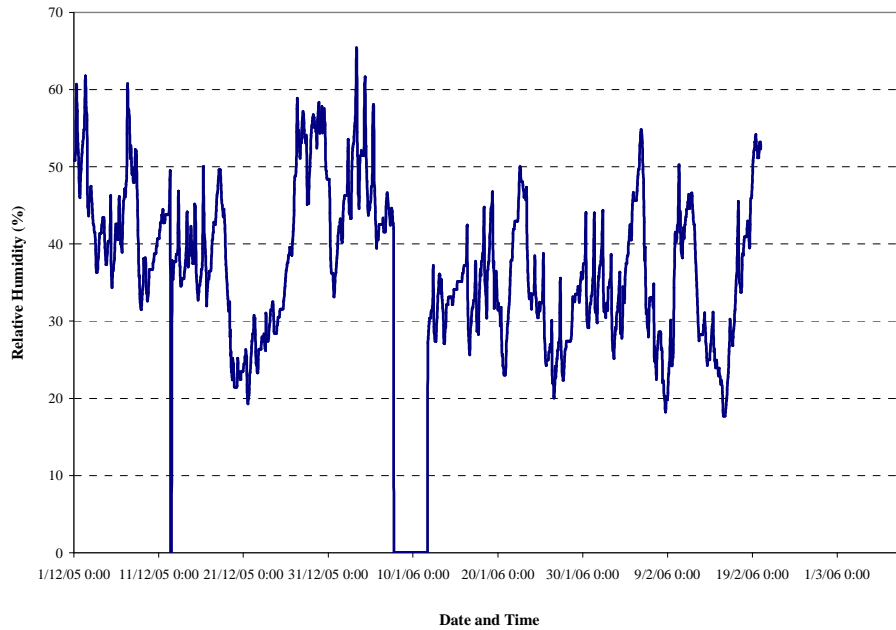


Figure 4-33: Relative humidity measurements of Ground Floor-new building

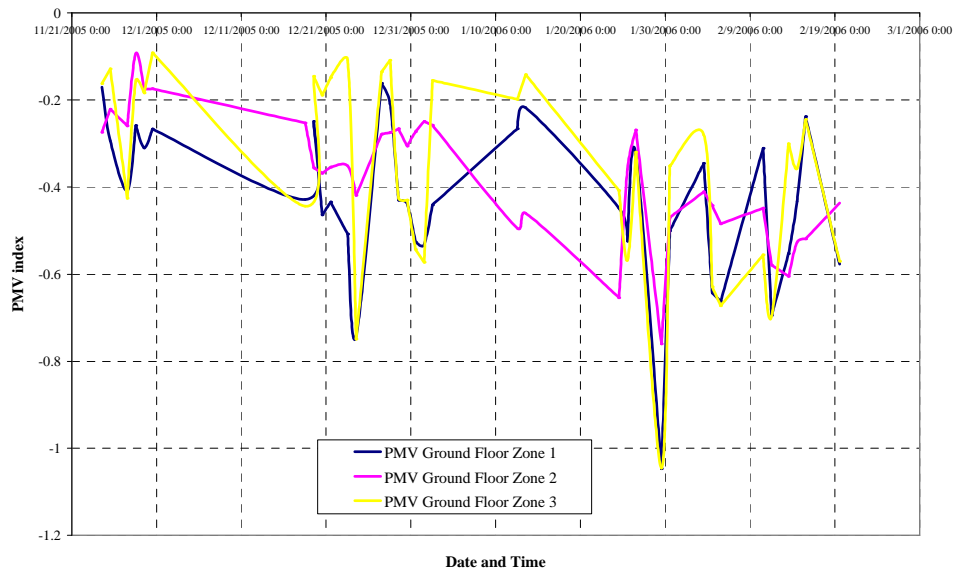


Figure 4-34: PMV index for Ground Floor

#### 4.4.1.2. Indoor air quality performance

The indoor air quality of BYTE building is estimated from the CO<sub>2</sub> concentration measurements, as they are presented in Figure 4-35. The indoor air quality is good, given the fact that the major time interval the CO<sub>2</sub> concentration value is between 400-700 ppm. The concentration increment to unacceptable levels occurs instantly and the management system resets the values to satisfactory levels immediately.

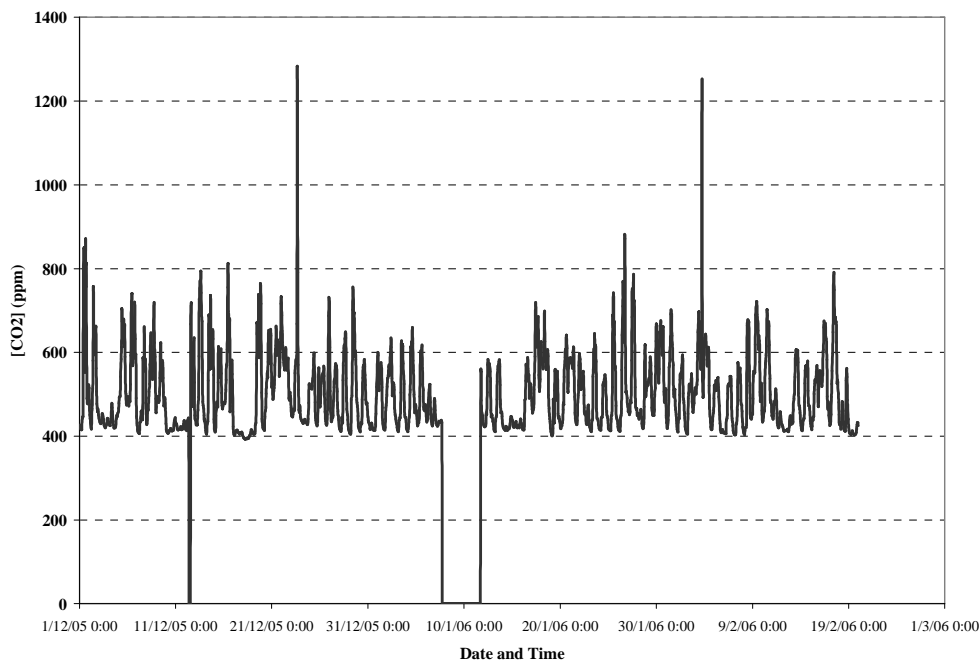


Figure 4-35: CO<sub>2</sub> concentration measurements for Ground Floor

### 4.4.2. Measured data of Mezzanine

#### 4.4.2.1. Thermal performance

The measured temperature values in 3 zones of the mezzanine of new building are rather high (Figure 4-36). The average temperature value of zone 3 for this time period is over the 25°C.

The measured temperature values in zones of the mezzanine of existing building are depicted in Figure 4-37. The temperature values of restaurant are high because of the high heat gains. VRV in restaurant does not function in cool mode (Figure 4-38) and the energy consumption is low.

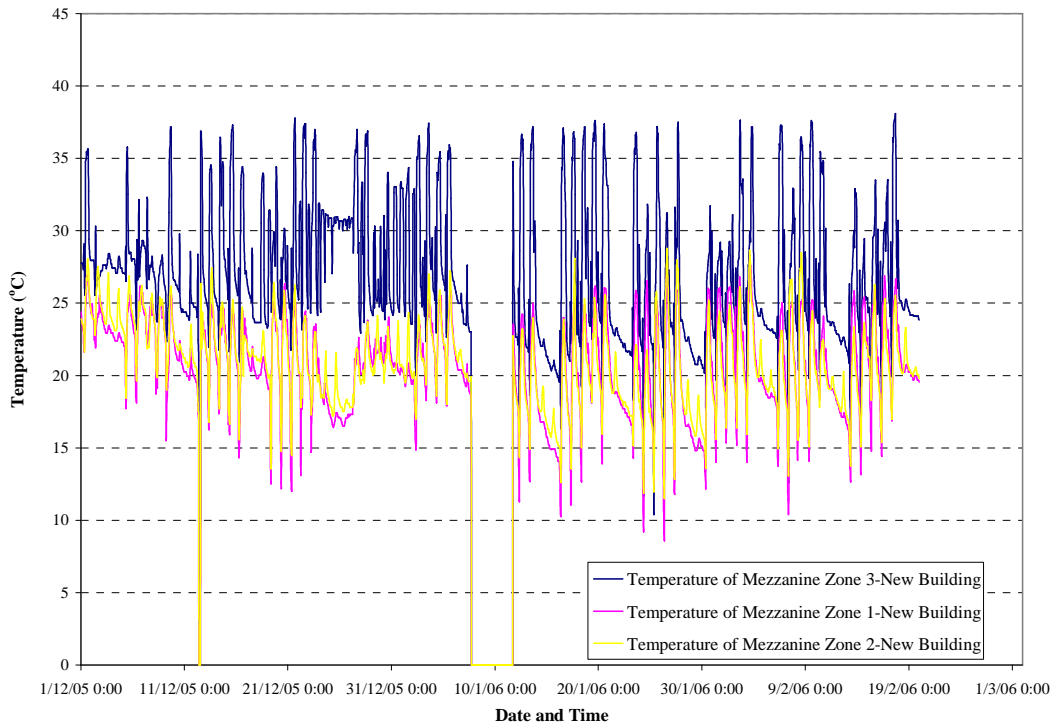


Figure 4-36: Temperature measurements of mezzanine-new building

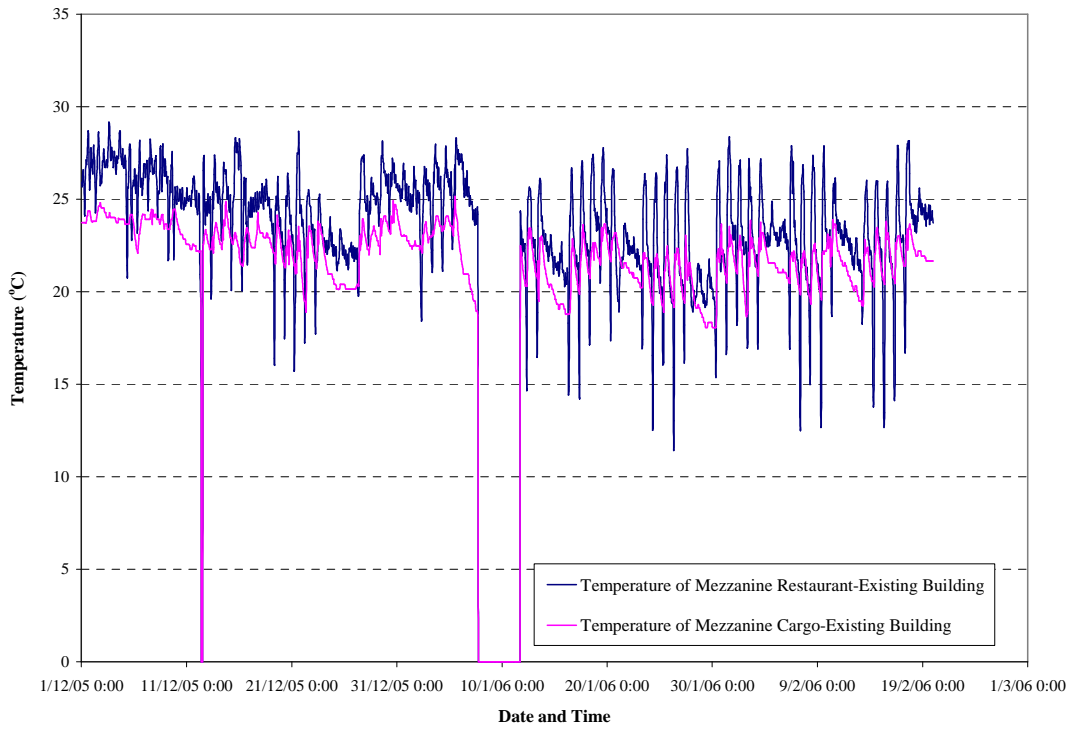
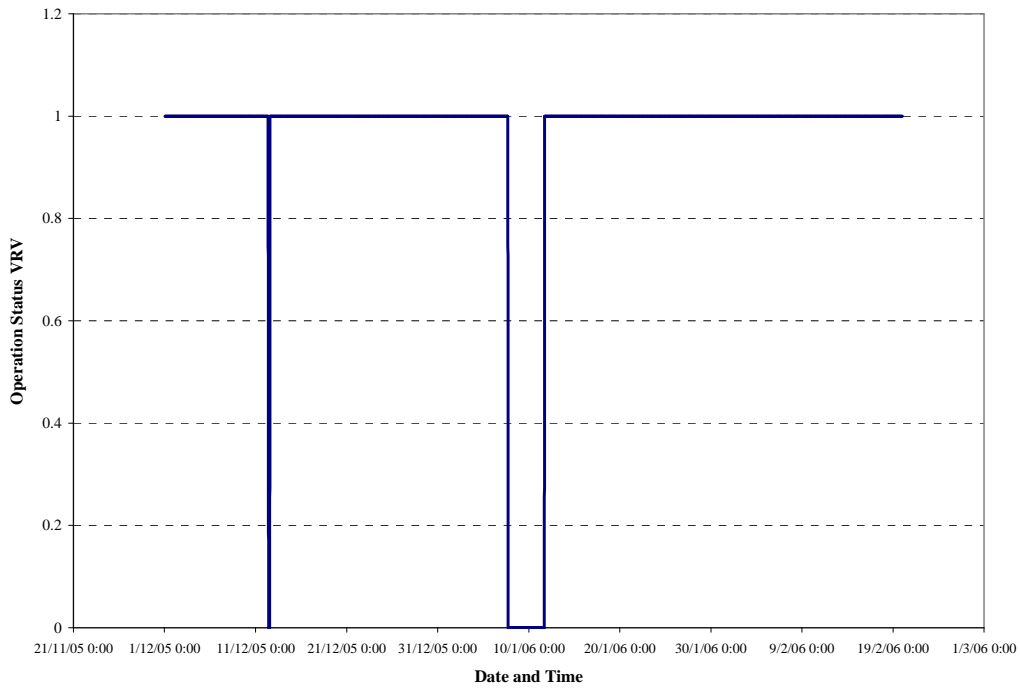
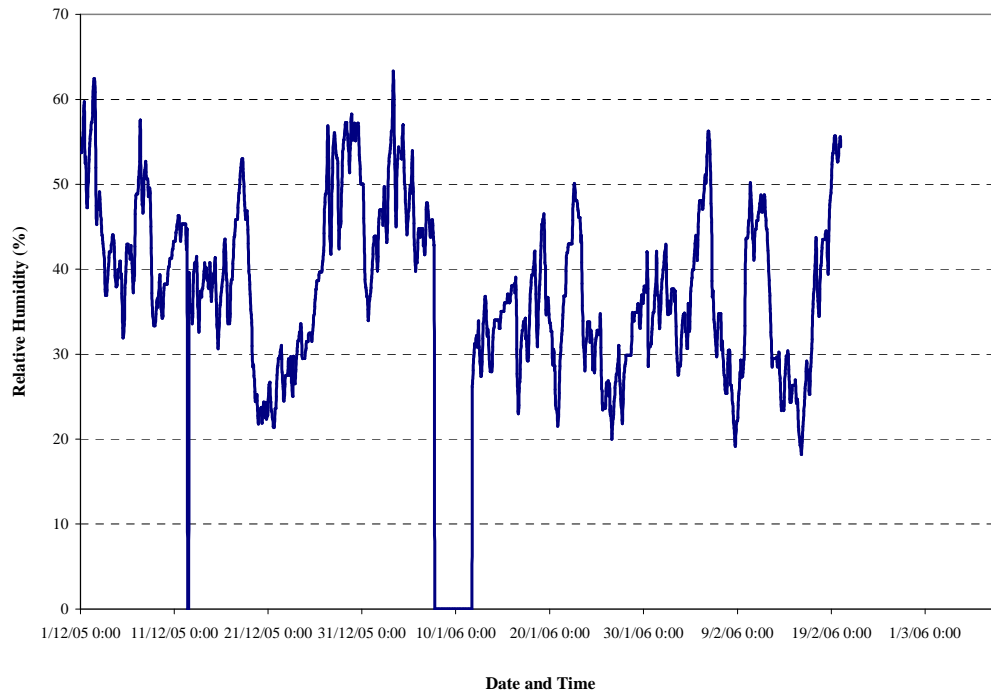


Figure 4-37: Temperature measurements of mezzanine-existing building

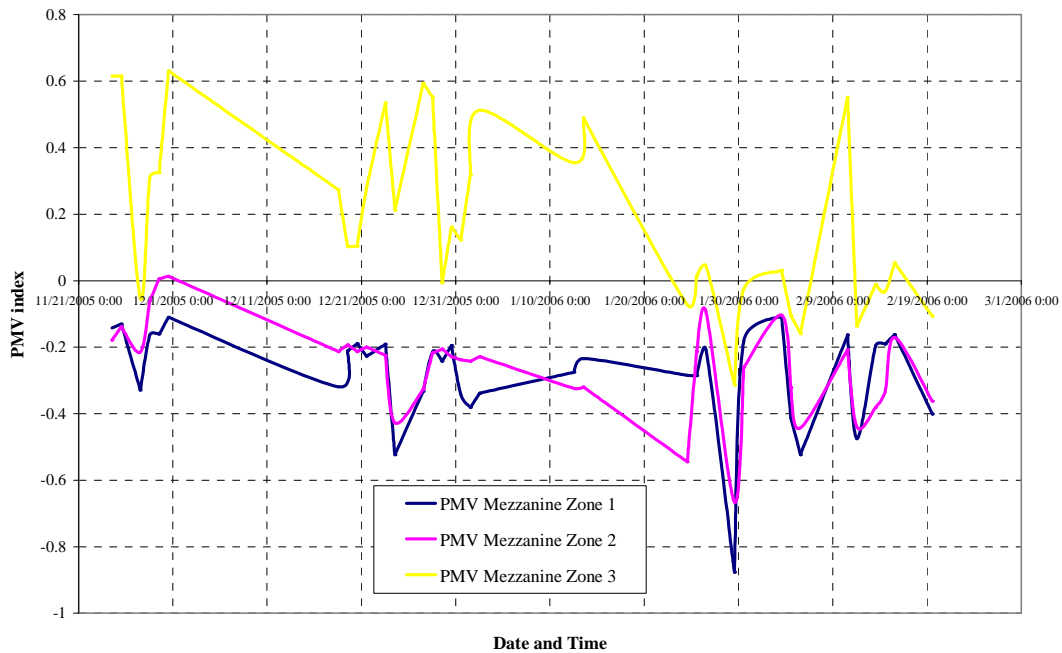


**Figure 4-38: VRVs operation status in Mezzanine (Restaurant) of existing building**

The measured relative humidity values of mezzanine are depicted in Figure 4-39 and PMV index values in Figure 4-40 and are in satisfactory levels.



**Figure 4-39: Relative humidity measurements of Mezzanine**



**Figure 4-40: PMV index for Mezzanine**

### 4.4.3. Measured data of 1<sup>st</sup> Floor

#### 4.4.3.1. Thermal performance

The 1<sup>st</sup> Floor is divided into one thermal zone in new building and into three thermal zones in the existing building. The temperature values in new building are lower in comparison with the mezzanine and ground floor, having average value for the specific time period 16°C (Figure 4-41). The temperature values of the existing building are increased as we move from zone 2 to zone 5 (Figure 4-42). The VRV of zones 4 and 5 measures energy consumption 92 kWh for the specific time period, while the VRV of zones 2 and 3 measures no energy consumption. This fact explains the higher temperature values in zones 4 and 5, given the fact that zones 2 and 3 are meeting rooms (they are not in every day use).

The relative humidity values of 1<sup>st</sup> Floor are in satisfactory levels (Figure 4-43). There is a decrease of relative humidity during the working hours and an increase during night hours (Figure 4-44).

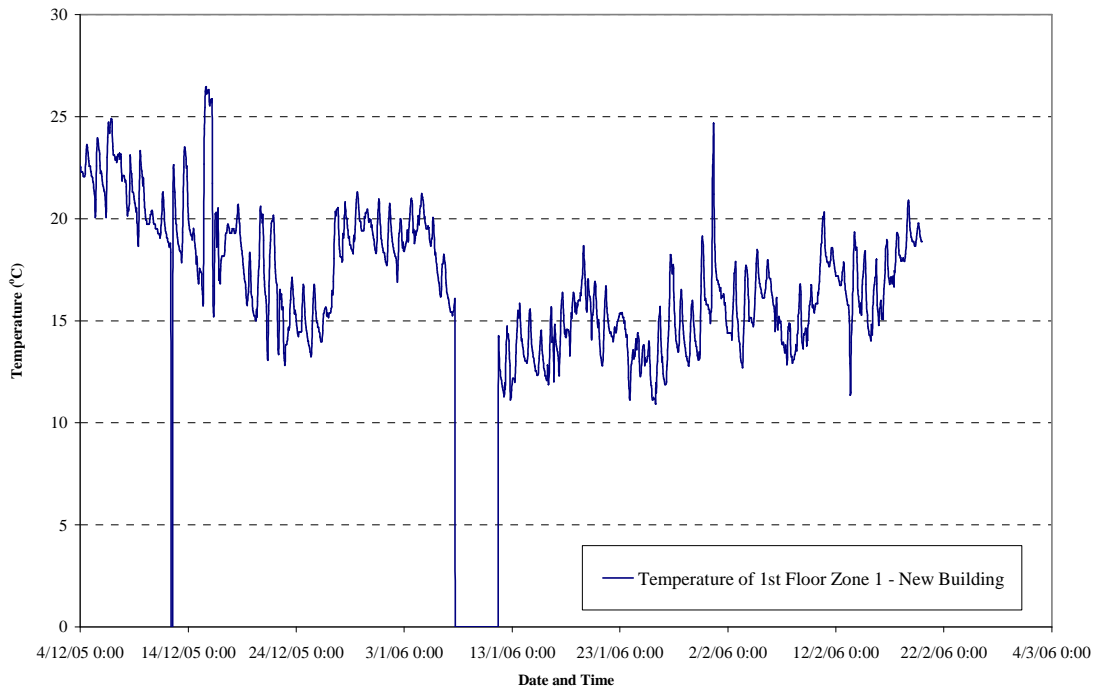


Figure 4-41: Temperature measurements of 1<sup>st</sup> Floor -new building

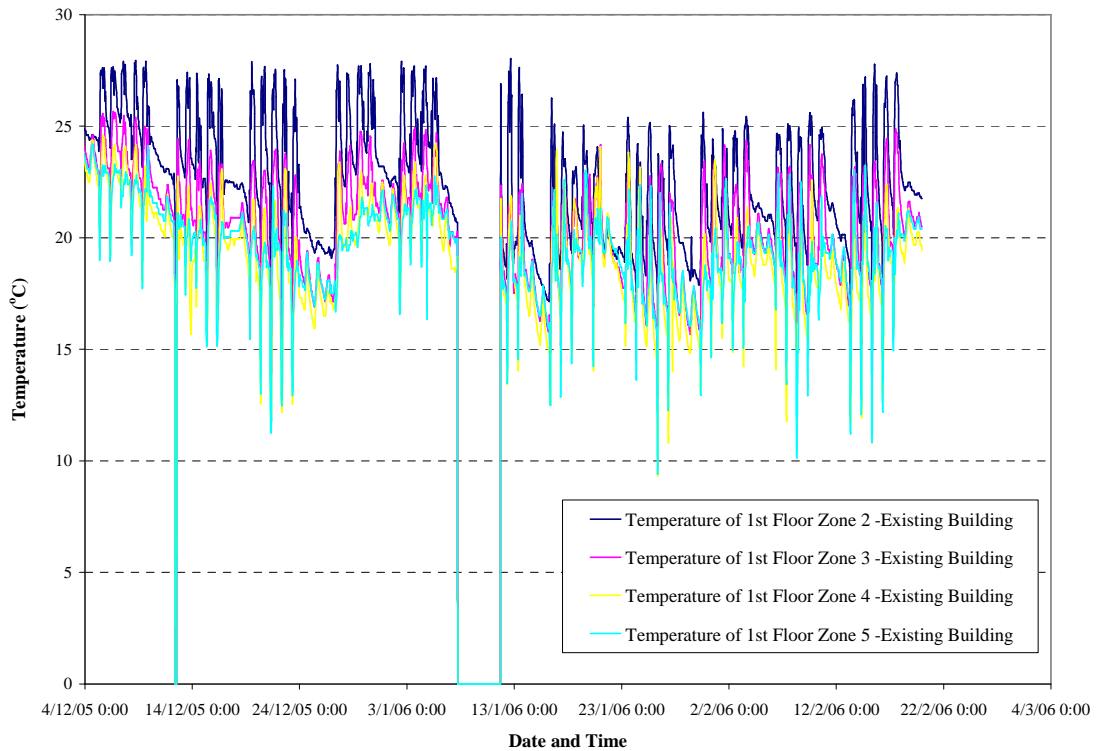


Figure 4-42: Temperature measurements of 1<sup>st</sup> Floor -existing building

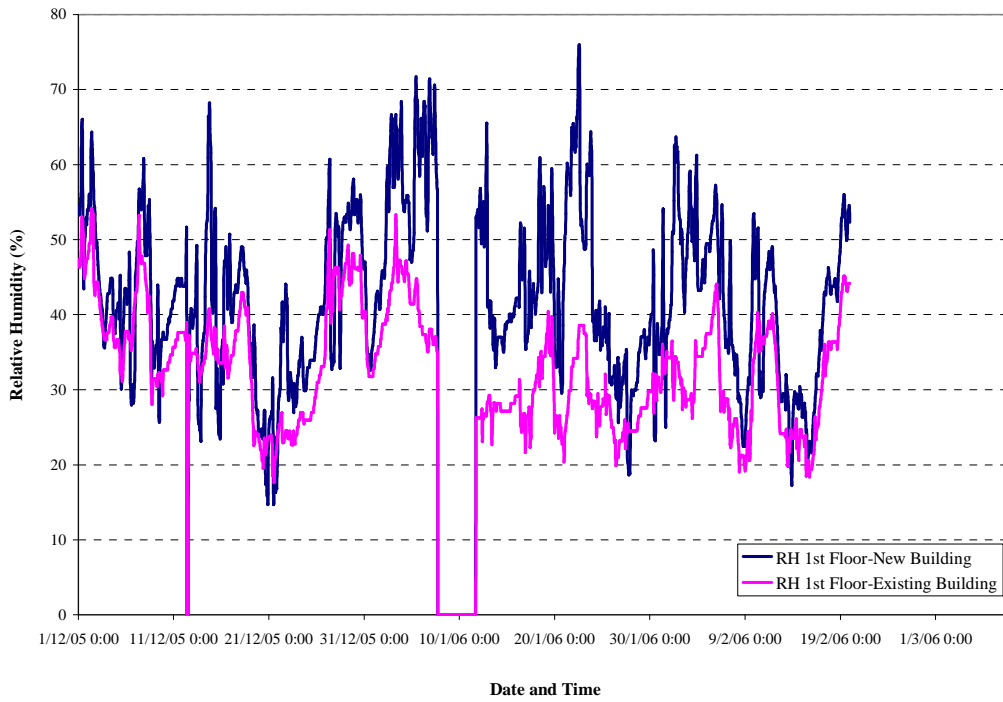


Figure 4-43: Relative humidity measurements of 1<sup>st</sup> Floor

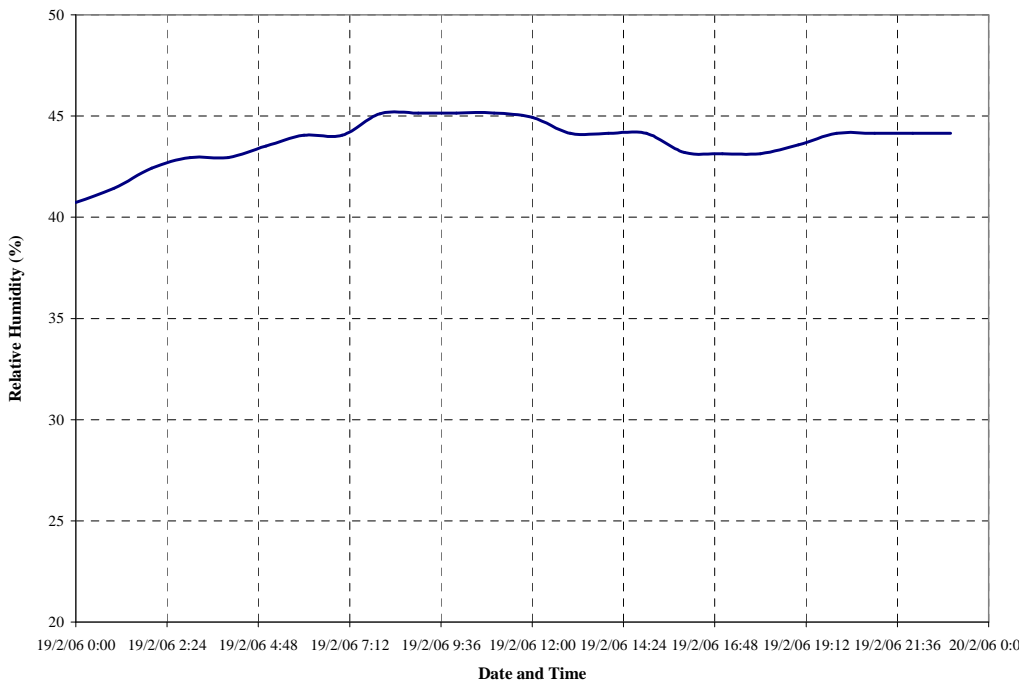


Figure 4-44: Relative humidity measurements of 1<sup>st</sup> Floor-existing building for one day (19/2/2006)

#### 4.4.3.2. Indoor air quality performance

The indoor air quality performance in 1<sup>st</sup> Floor is estimated from the CO<sub>2</sub> concentration measurements presented in Figure 4-45. It is characterized “good”, given the fact that the major time interval the CO<sub>2</sub> concentration values range between 400-700 ppm. The concentration increment to unacceptable levels occurs instantly and the management system resets the values to satisfactory levels immediately.

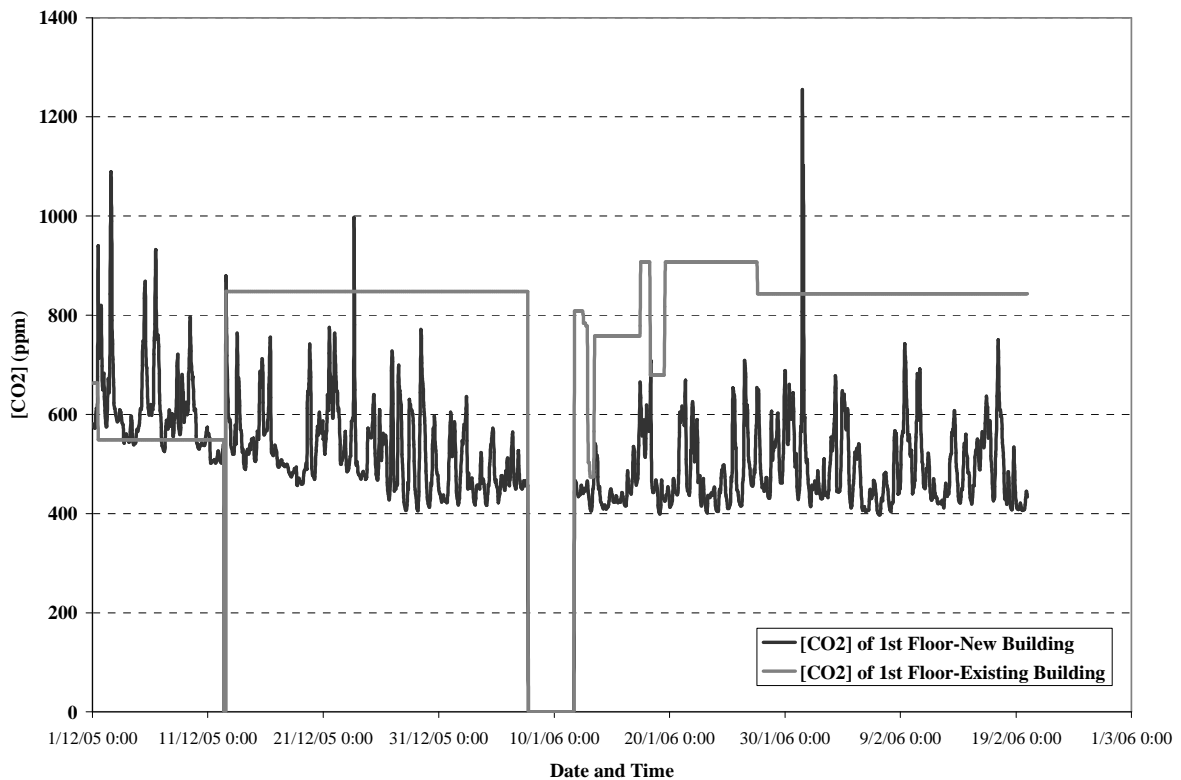


Figure 4-45: CO<sub>2</sub> concentration measurements for 1st Floor

#### 4.4.4. Measured data of 2<sup>nd</sup> Floor

##### 4.4.4.1. Thermal performance

The temperature measurements of 2<sup>nd</sup> Floor in new and existing building are depicted in Figure 4-46 and in Figure 4-47. The recorded values are in normal levels, apart from these of server room which are higher. The relative humidity measured values are in acceptable levels (Figure 4-48) and the PMV index values are in comfort area ( $-0.7 < PMV < 0.7$ ) (Figure 4-49).

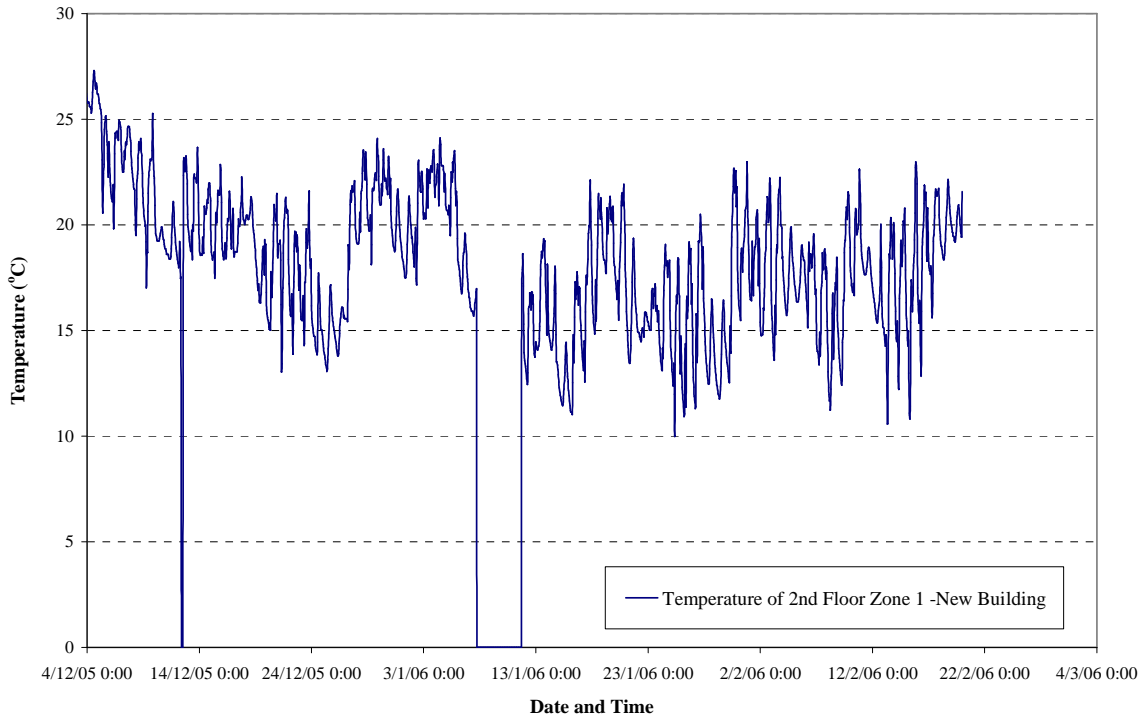


Figure 4-46: Temperature measurements of 2<sup>nd</sup> Floor -new building

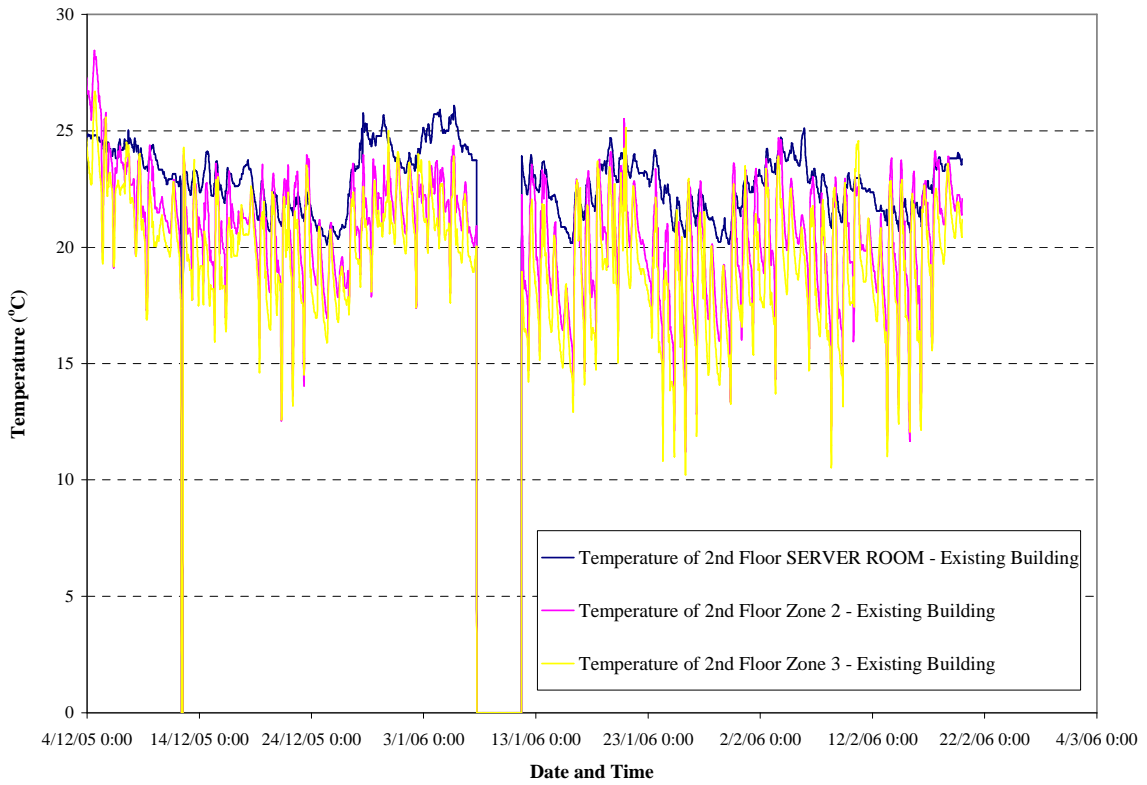


Figure 4-47: Temperature measurements of 2<sup>nd</sup> Floor –existing building

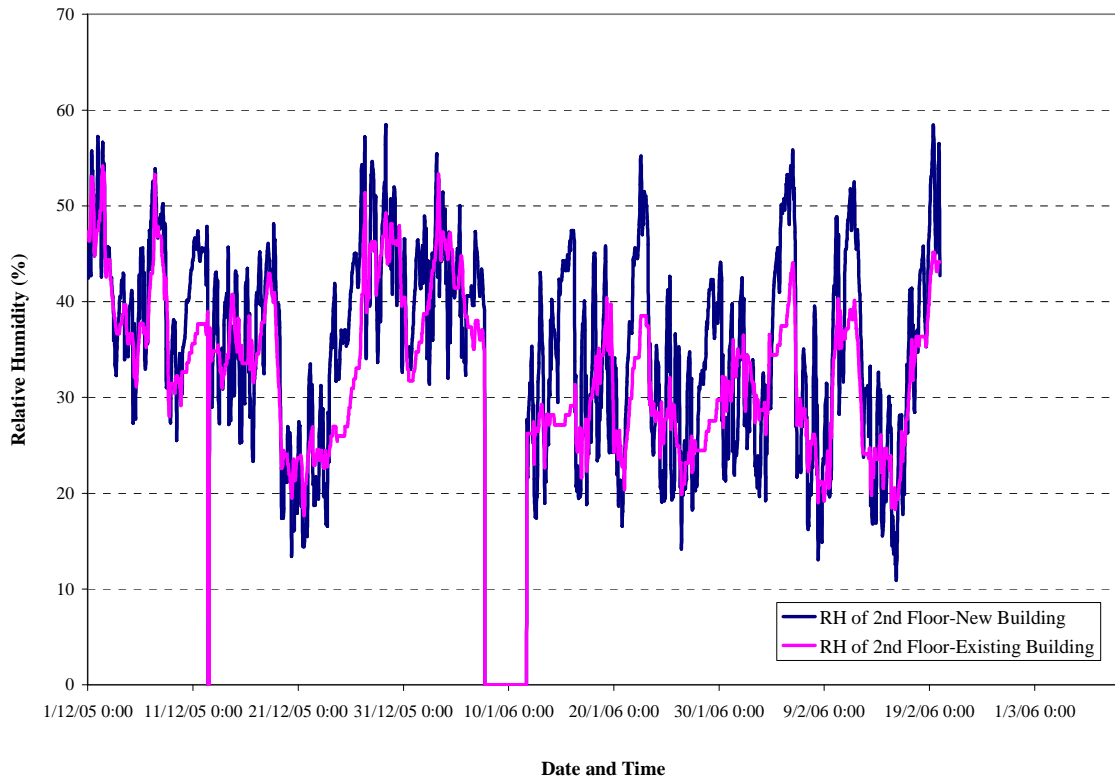


Figure 4-48: Relative Humidity measurements of 2<sup>nd</sup> Floor

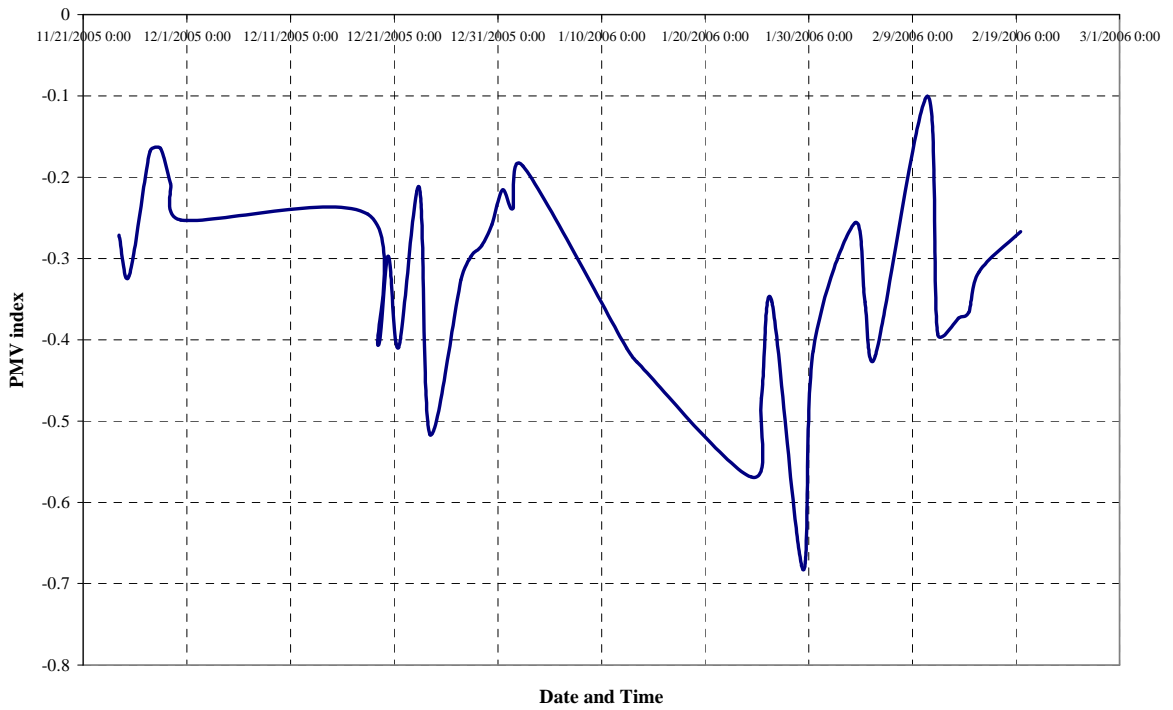


Figure 4-49: PMV index for 2<sup>nd</sup> Floor –Zone 3

#### 4.4.4.2. Indoor air quality performance

The CO<sub>2</sub> concentration measured values are in satisfactory levels (400-800 ppm) (Figure 4-50).

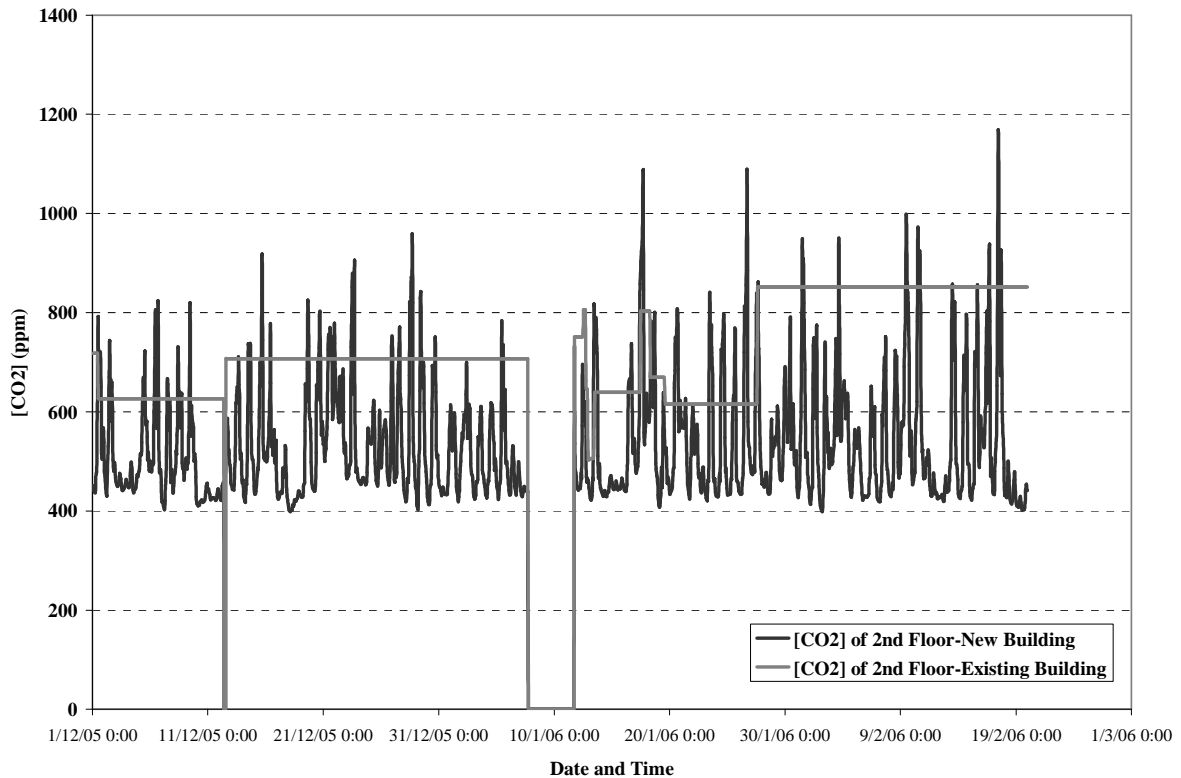


Figure 4-50: CO<sub>2</sub> concentration measurements for 2<sup>nd</sup> Floor

### 4.4.5. Measured data of 3<sup>rd</sup> Floor

#### 4.4.5.1. Thermal performance

The 3<sup>rd</sup> floor is divided into one thermal zone in the new building into three zones in the existing building. The temperature values in the area of the new building are lower than these of the existing building (Figure 4-51 and Figure 4-52). The VRV is in heat mode for the entire time period. In general the recorded temperatures are in satisfactory levels. The relative humidity and the PMV index values of the 3<sup>rd</sup> floor are in comfort area (Figure 4-53 and Figure 4-54).

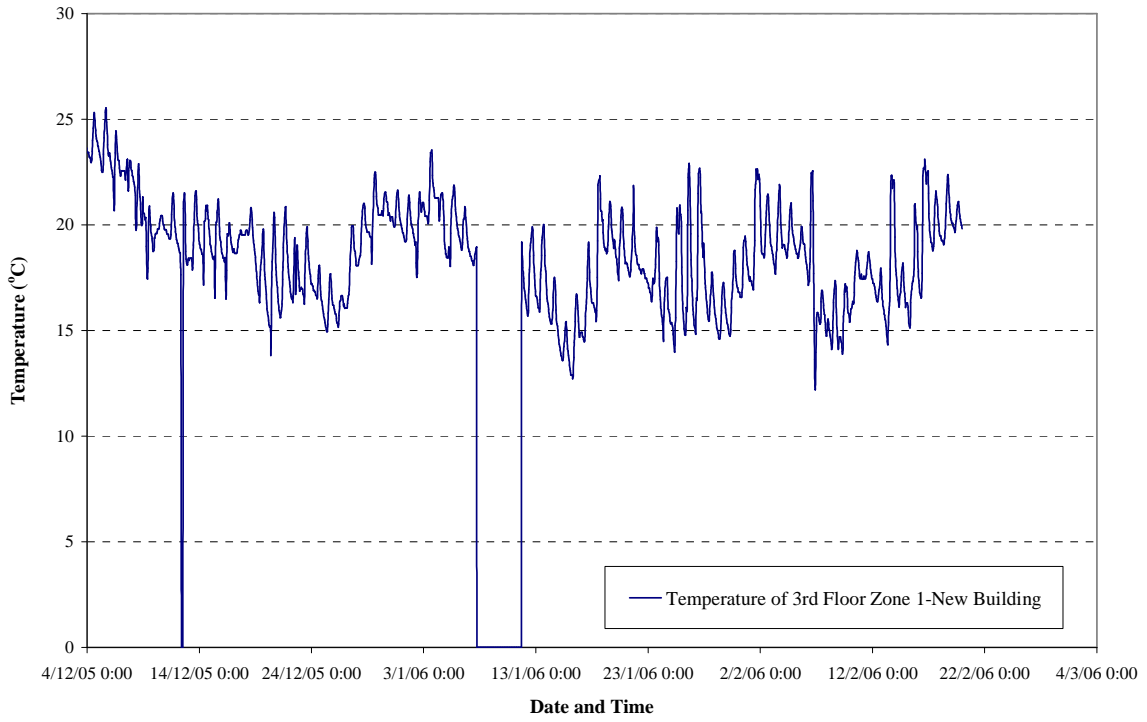


Figure 4-51: Temperature measurements of 3<sup>rd</sup> Floor -new building

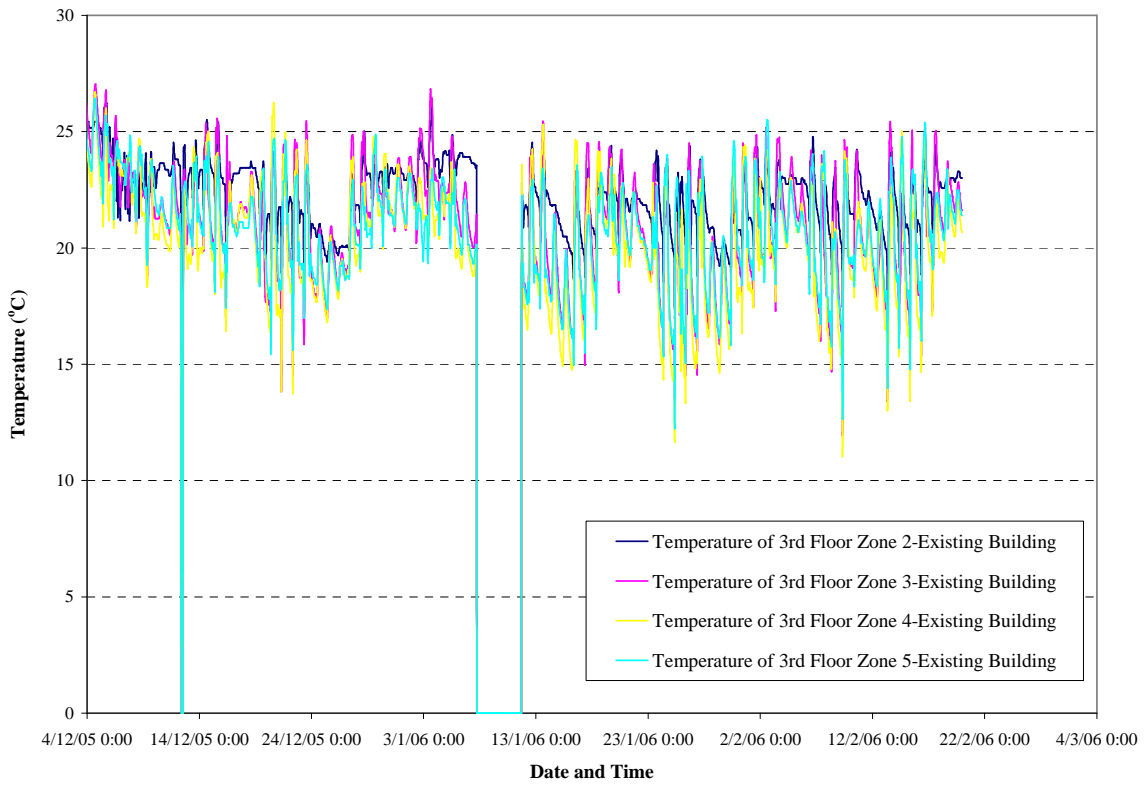


Figure 4-52: Temperature measurements of 3<sup>rd</sup> Floor -existing building

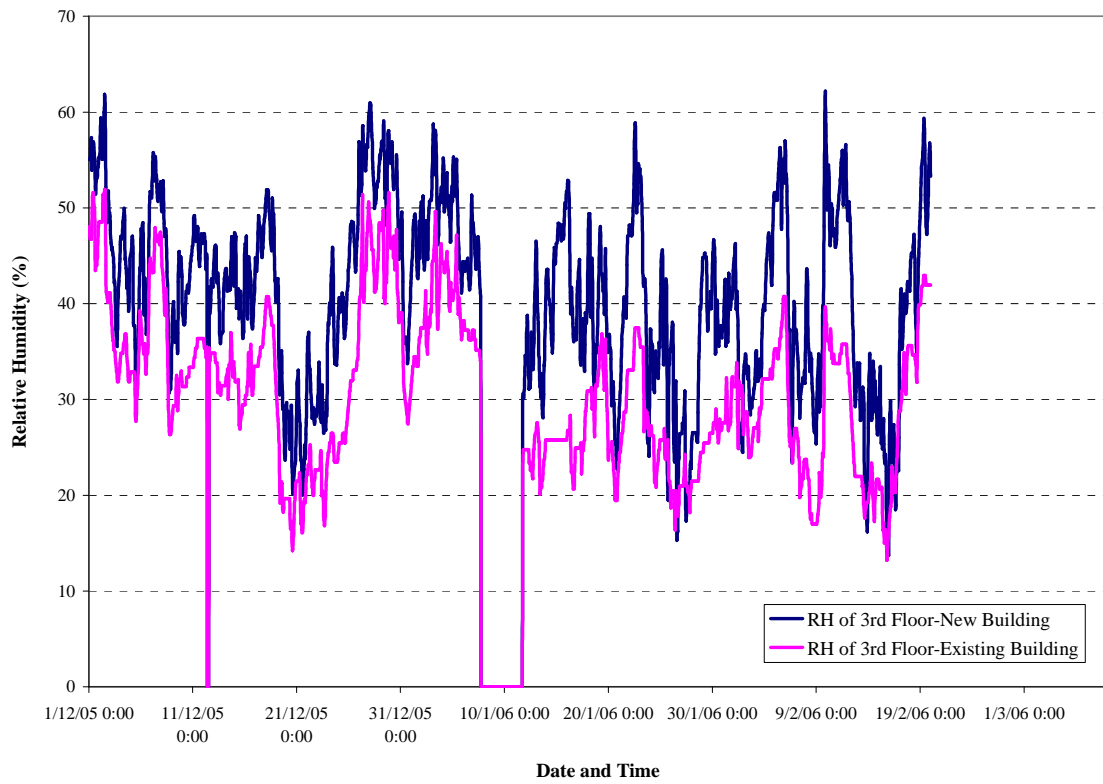


Figure 4-53: Relative Humidity measurements of 3<sup>rd</sup> Floor

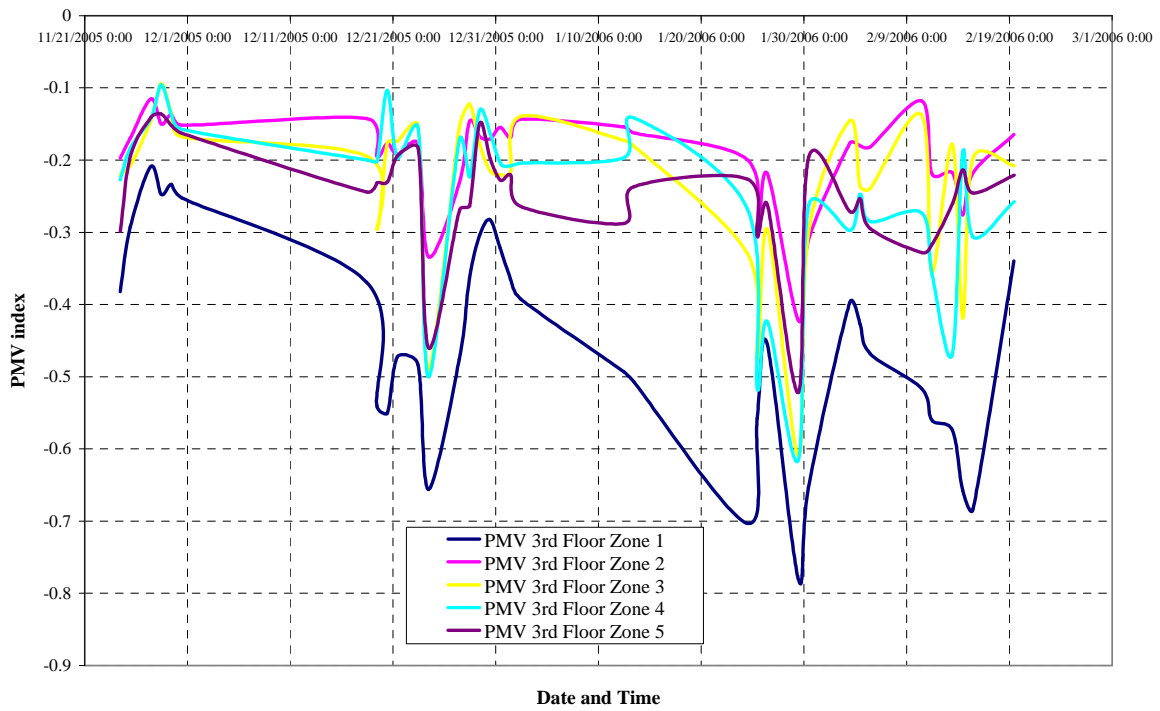


Figure 4-54: PMV index for 3<sup>rd</sup> Floor

#### 4.4.5.2. Indoor air quality performance

The indoor air quality performance in 1<sup>st</sup> Floor is estimated from the CO<sub>2</sub> concentration measurements presented in Figure 4-55. It is characterized “good”, given the fact that the major time interval the CO<sub>2</sub> concentration values range between 600-800 ppm. As it is observed that there is not variation of the concentration values and this occurs because of the low zone use.

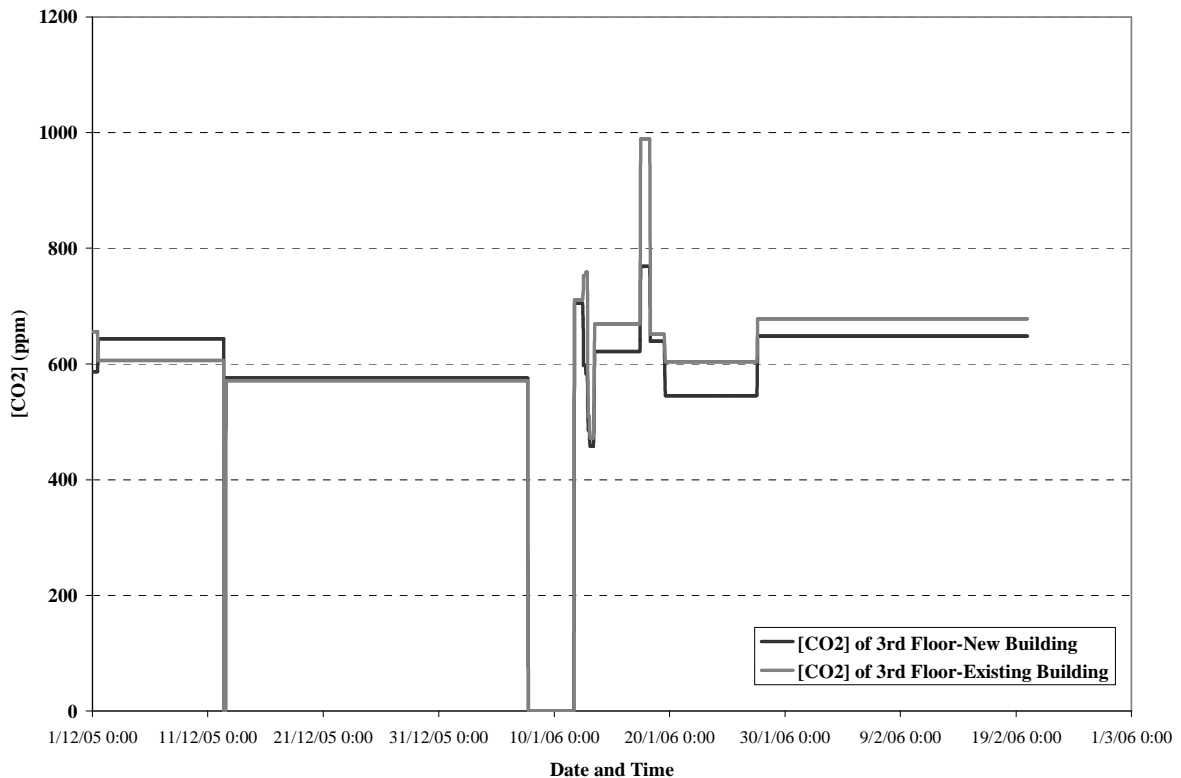


Figure 4-55: CO<sub>2</sub> concentration measurements for 3<sup>rd</sup> Floor

#### 4.4.6. Measured data of 4<sup>th</sup> Floor

##### 4.4.6.1. Thermal performance

The 4<sup>th</sup> floor is also divided into one thermal zone in the new building into three zones in the existing building. The temperature measurements are presented in Figure 4-56 and Figure 4-57. In general the temperatures values are at satisfactory levels (22°C on average). The relative humidity and the PMV index values are in comfort area (Figure 4-58 and Figure 4-59).

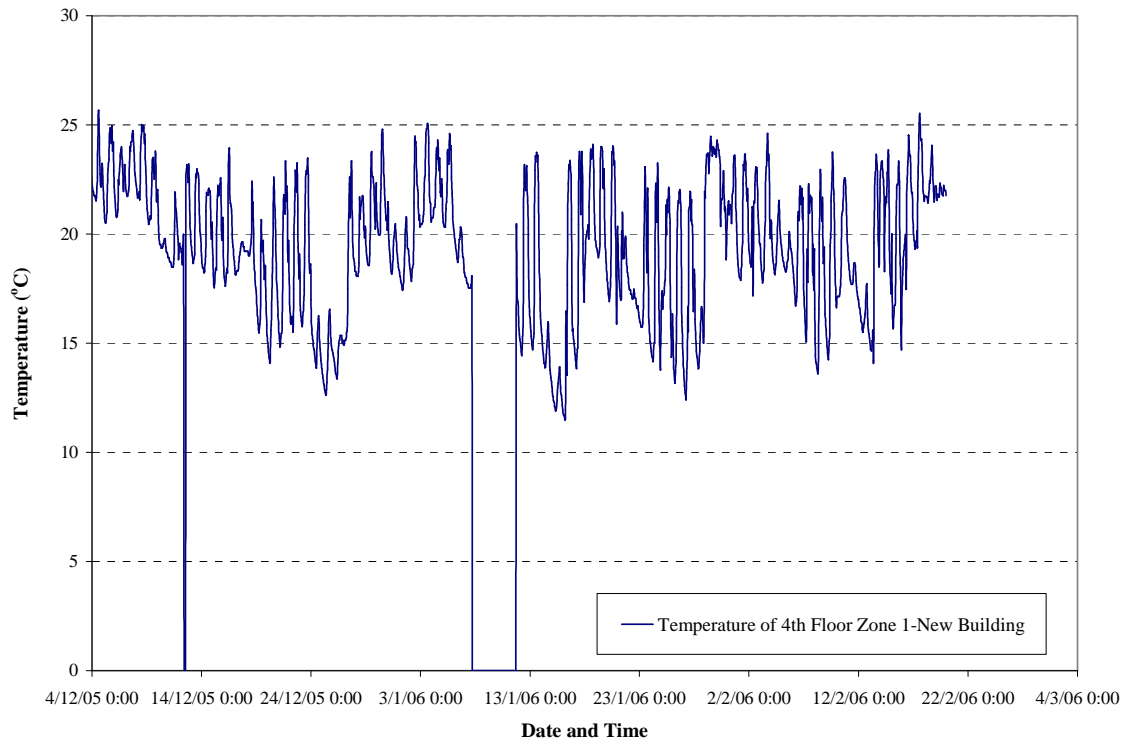


Figure 4-56: Temperature measurements of 4<sup>th</sup> Floor -new building

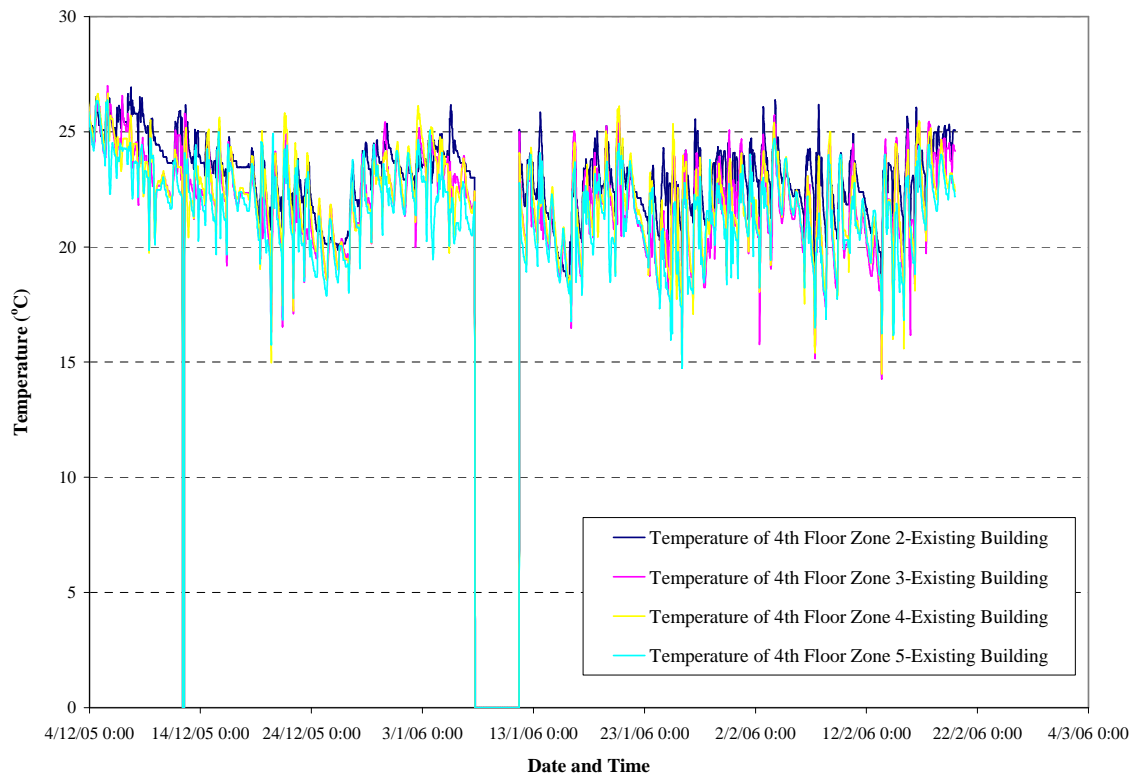


Figure 4-57: Temperature measurements of 4<sup>th</sup> Floor -existing building

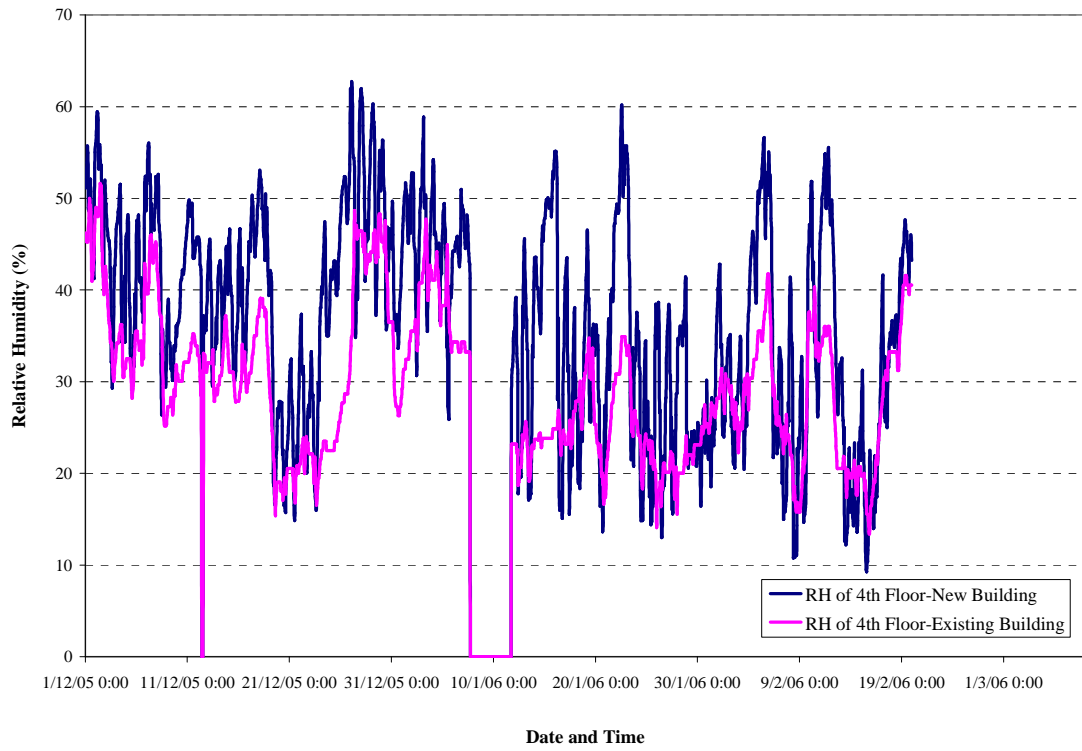


Figure 4-58: Relative Humidity measurements of 4<sup>th</sup> Floor

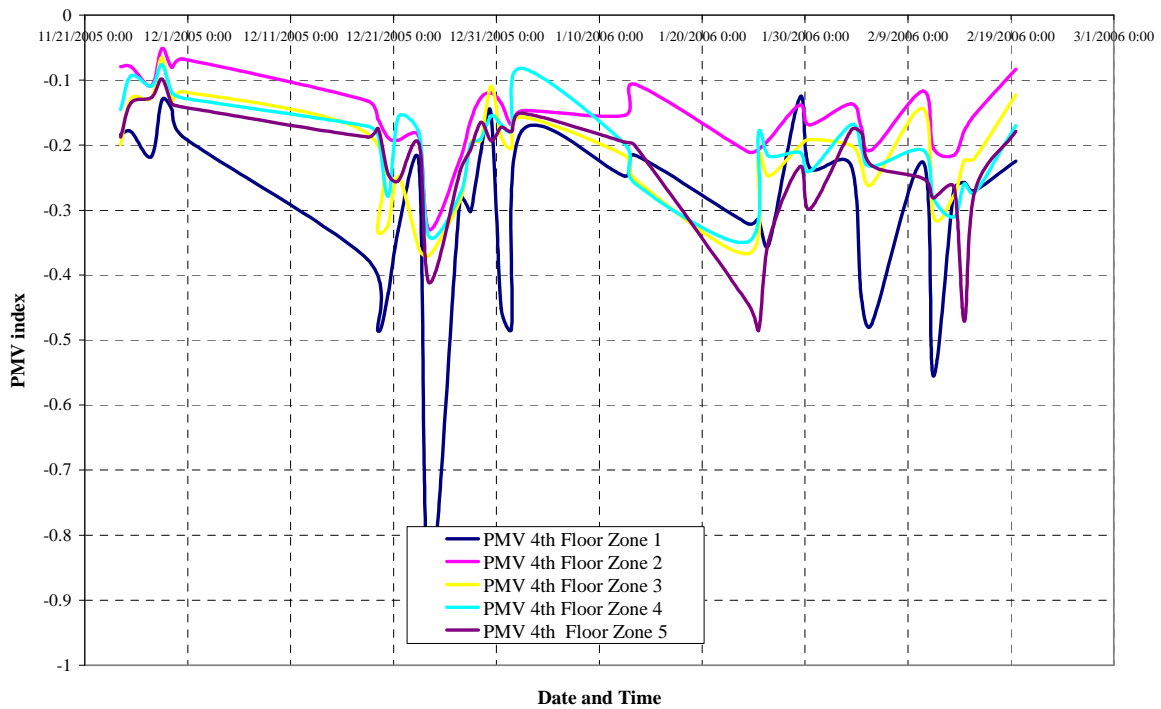


Figure 4-59: PMV index for 4<sup>th</sup> Floor

#### 4.4.6.2. Indoor air quality performance

The indoor air quality is characterized “good”, since the CO<sub>2</sub> concentration varying between 500-750 ppm during the time period of measurements (Figure 4-60).

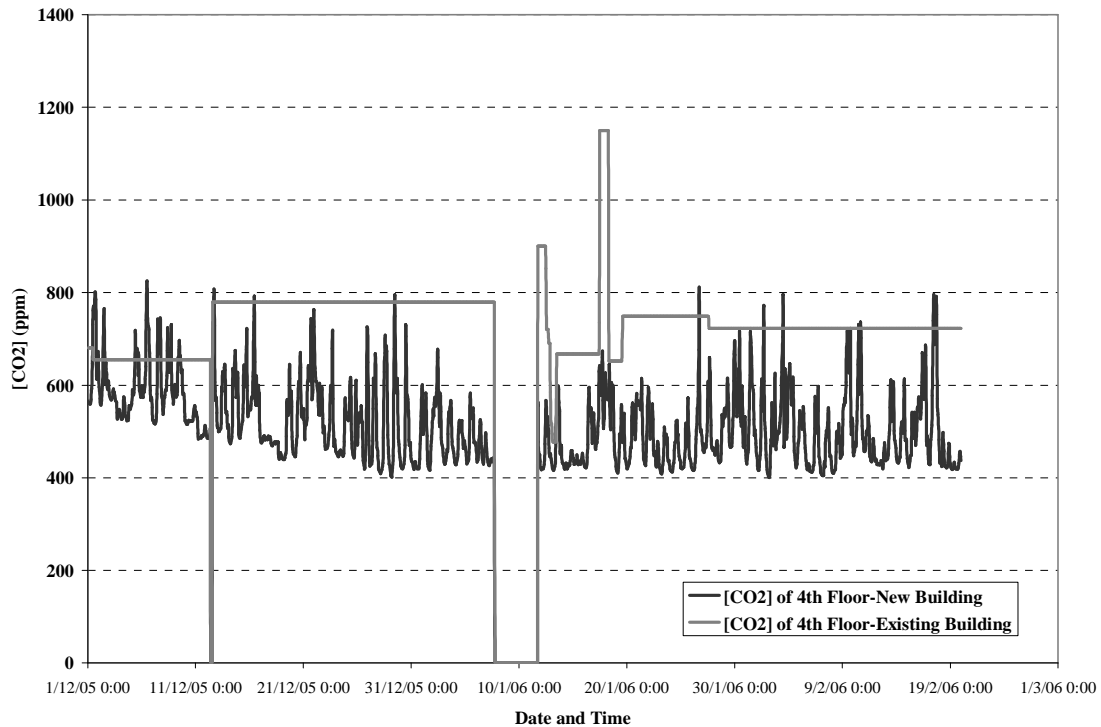


Figure 4-60: CO<sub>2</sub> concentration measurements for 4<sup>th</sup> Floor

#### 4.4.7. Measured data of 5<sup>th</sup> Floor

##### 4.4.7.1. Thermal performance

The 5<sup>th</sup> floor is also divided into one thermal zone in the new building into three zones in the existing building. The temperature measurements are presented in Figure 4-61 and Figure 4-62. In general the temperatures values are at satisfactory levels. The relative humidity of the 5<sup>th</sup> floor ranges between 45-75% and rises the hours the building is not in use (Figure 4-63). The PMV index indicates that the thermal comfort in satisfactory levels (Figure 4-64).

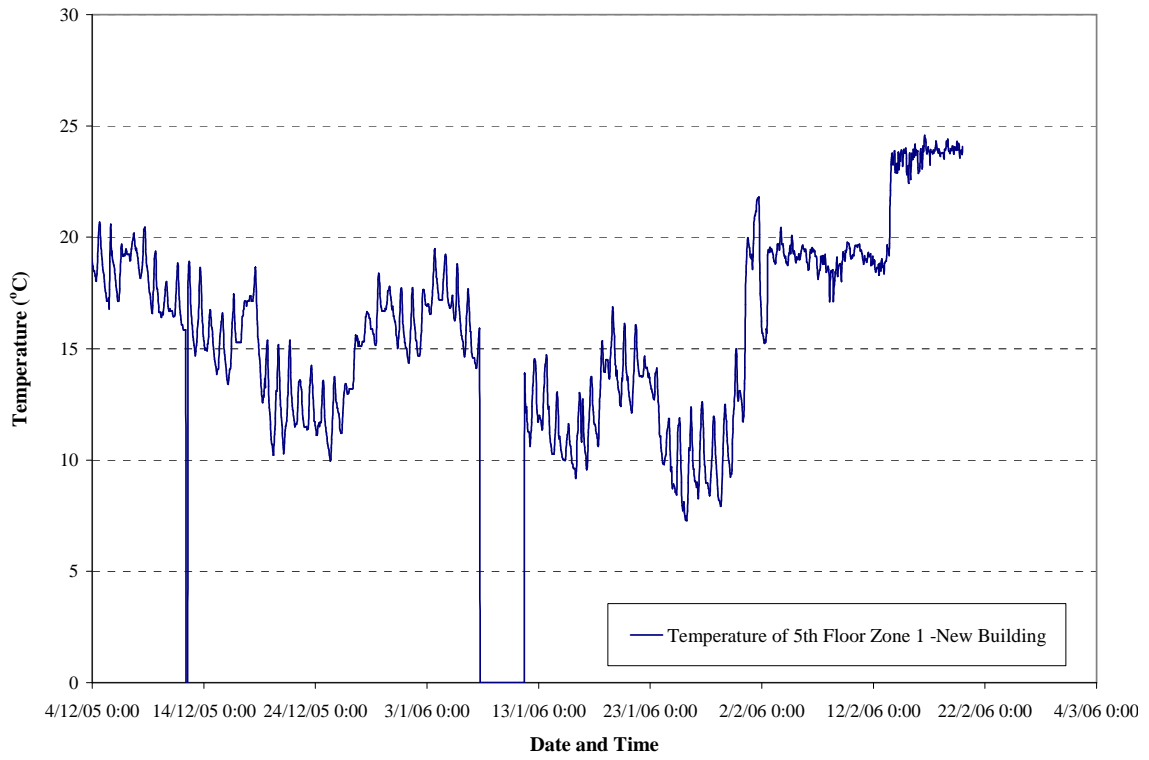


Figure 4-61: Temperature measurements of 5<sup>th</sup> Floor -new building

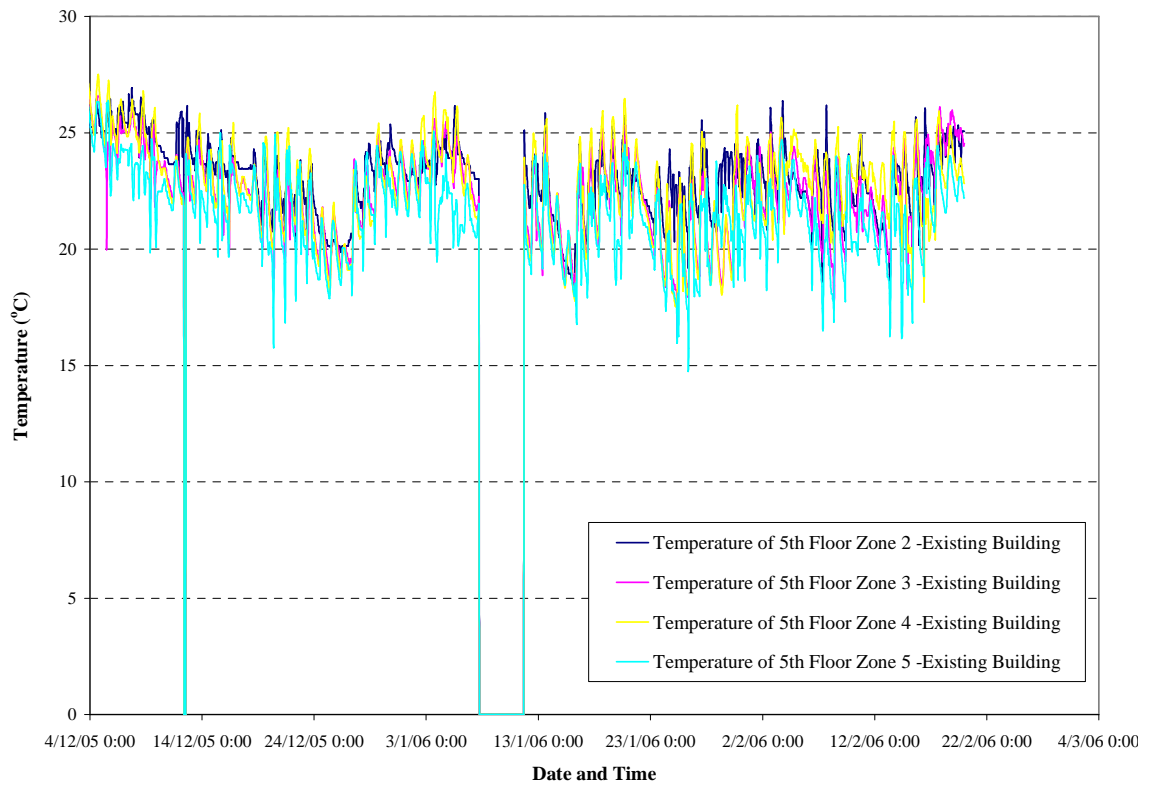


Figure 4-62: Temperature measurements of 5<sup>th</sup> Floor -existing building

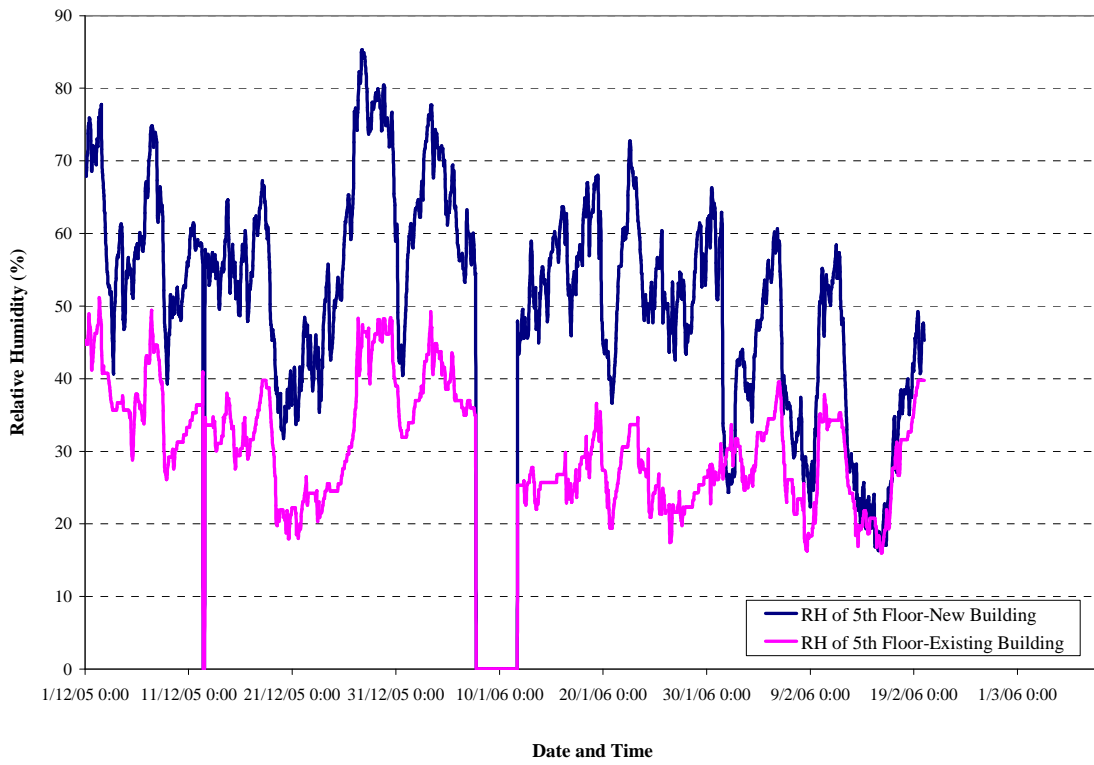


Figure 4-63: Relative Humidity measurements of 5<sup>th</sup> Floor

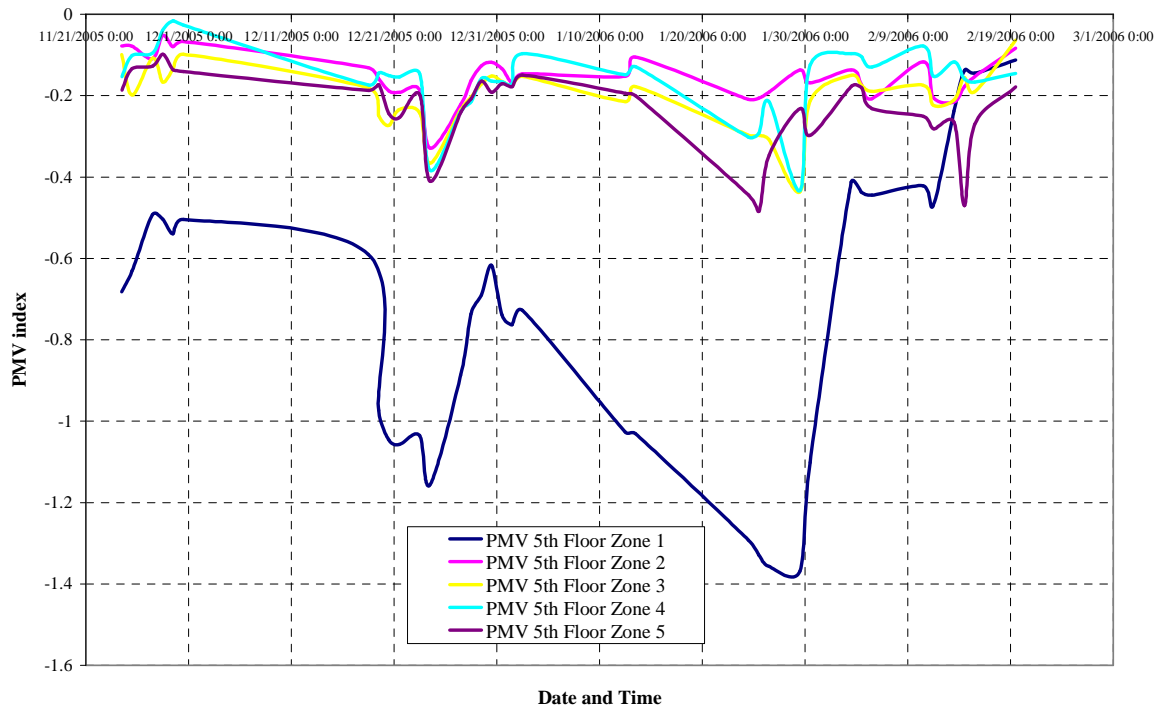


Figure 4-64: PMV index for 5<sup>th</sup> Floor

#### 4.4.7.2. Indoor air quality performance

The indoor air quality in 5<sup>th</sup> Floor is in very good levels, from the CO<sub>2</sub> values presented in Figure 4-65.

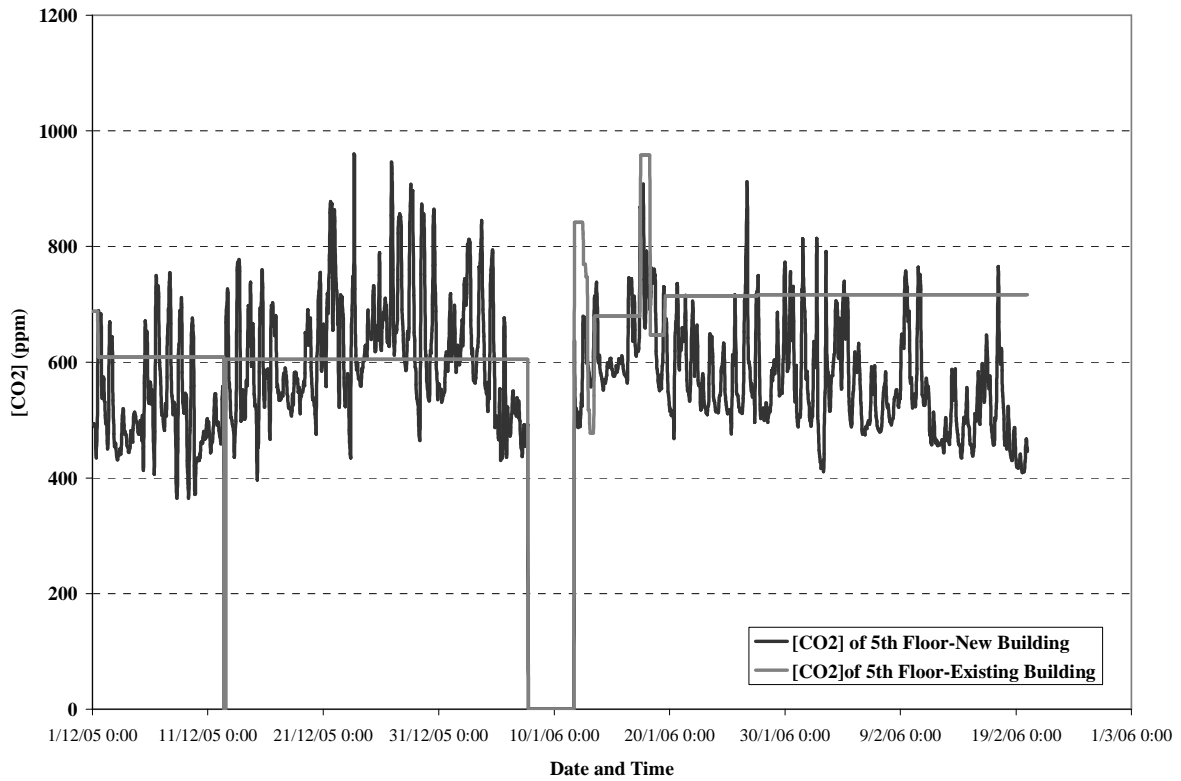


Figure 4-65: CO<sub>2</sub> concentration measurements for 5<sup>th</sup> Floor

### 4.4.8. Measured data of 6<sup>th</sup> Floor

#### 4.4.8.1. Thermal performance

The 6th floor has only zones in the existing building. The temperature measurements are presented in Figure 4-66. The thermal comfort is at a satisfactory level as shown by the relative humidity and PMV index values (Figure 4-67 and Figure 4-68).

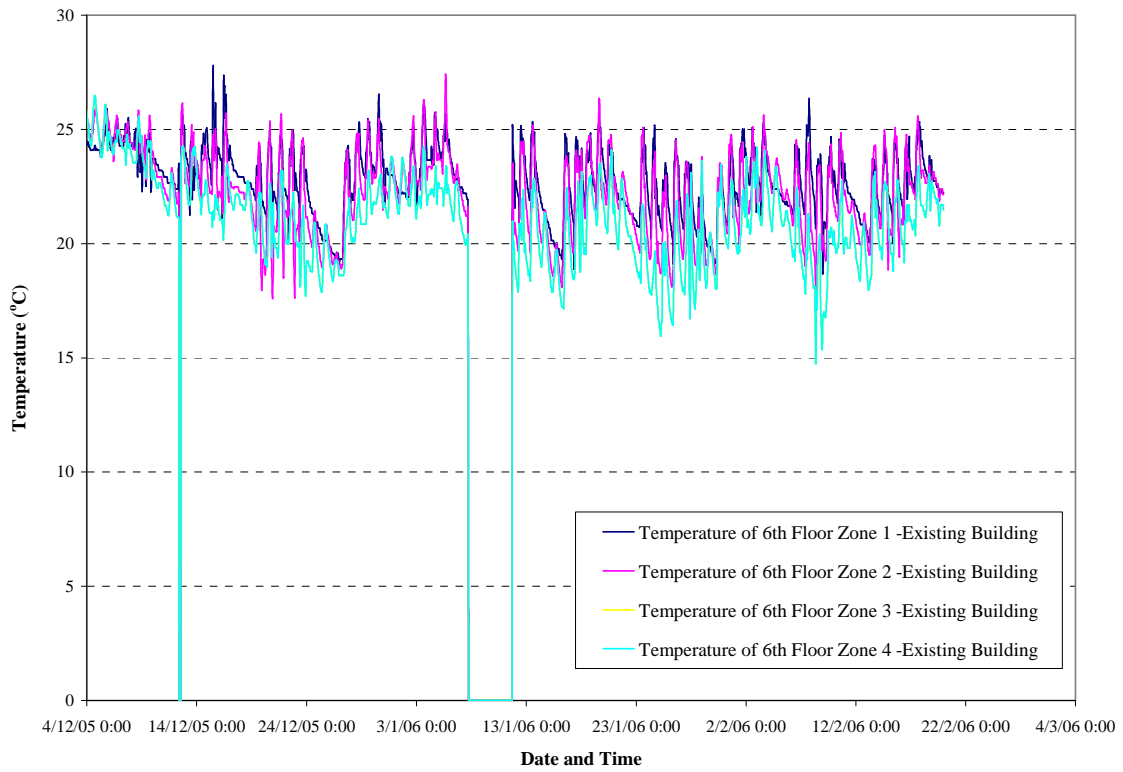


Figure 4-66: Temperature measurements of 6<sup>th</sup> Floor -existing building

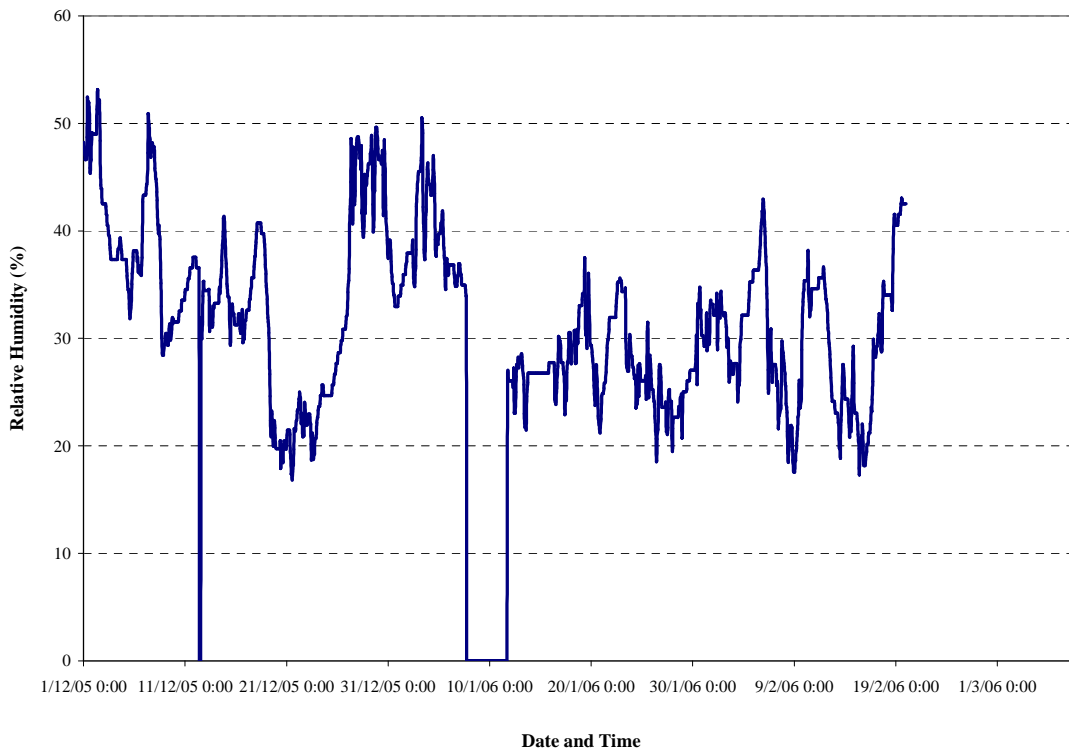


Figure 4-67: Relative Humidity measurements of 6<sup>th</sup> Floor

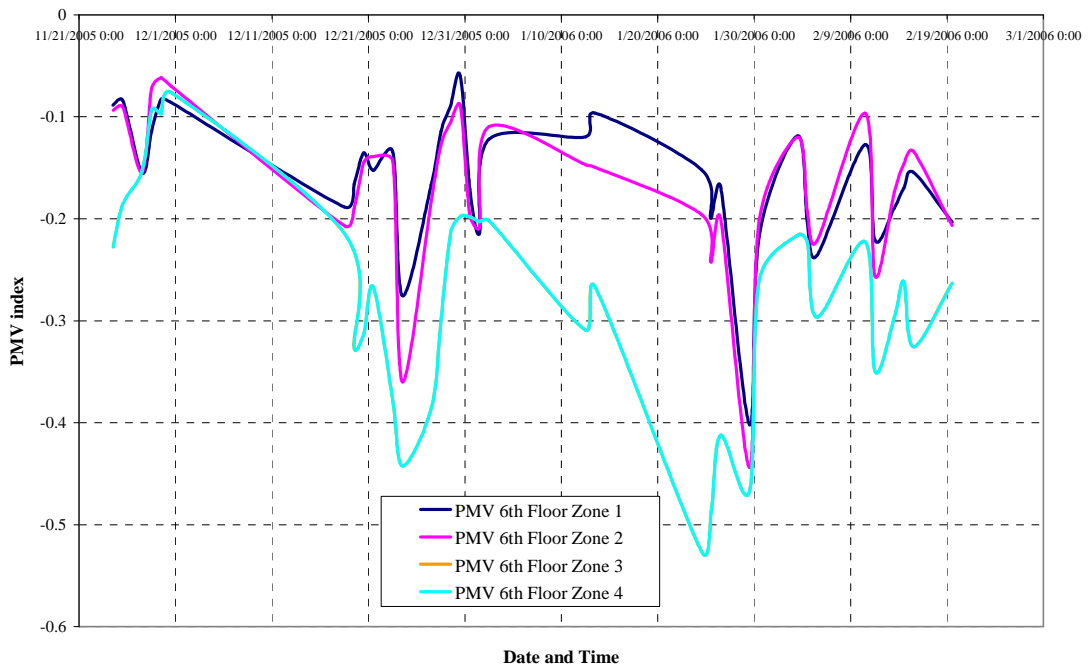


Figure 4-68: PMV index for 6<sup>th</sup> Floor

4.4.8.2. Indoor air quality performance

The zone of the 6th floor where the CO<sub>2</sub> concentration is measured is a meeting room, so the fluctuations of indoor air quality are minimal (Figure 4-69).

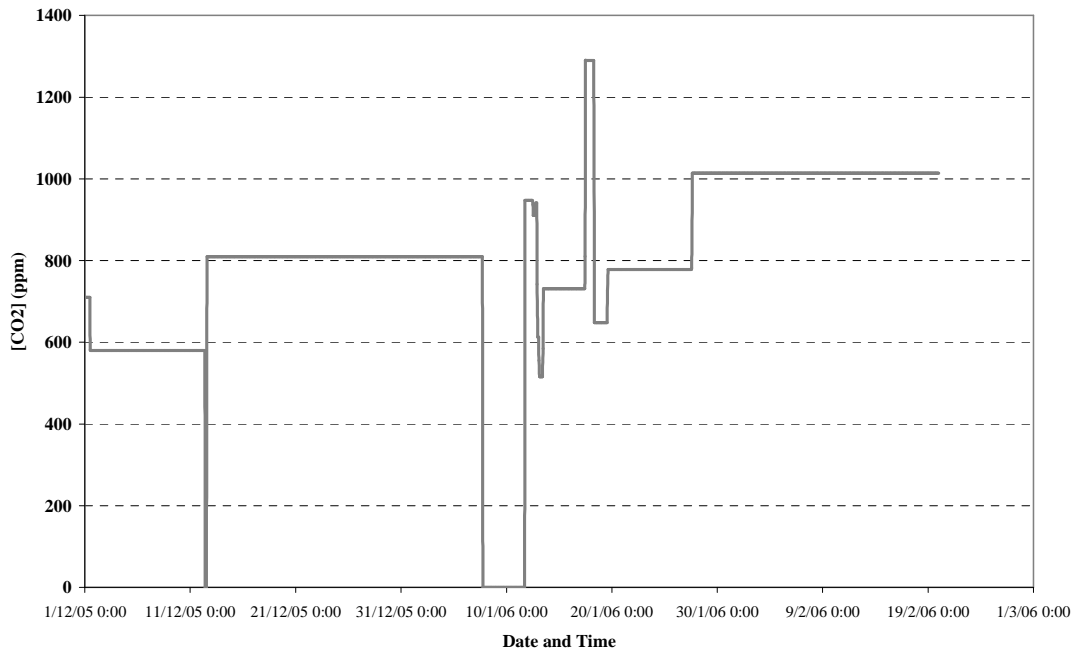
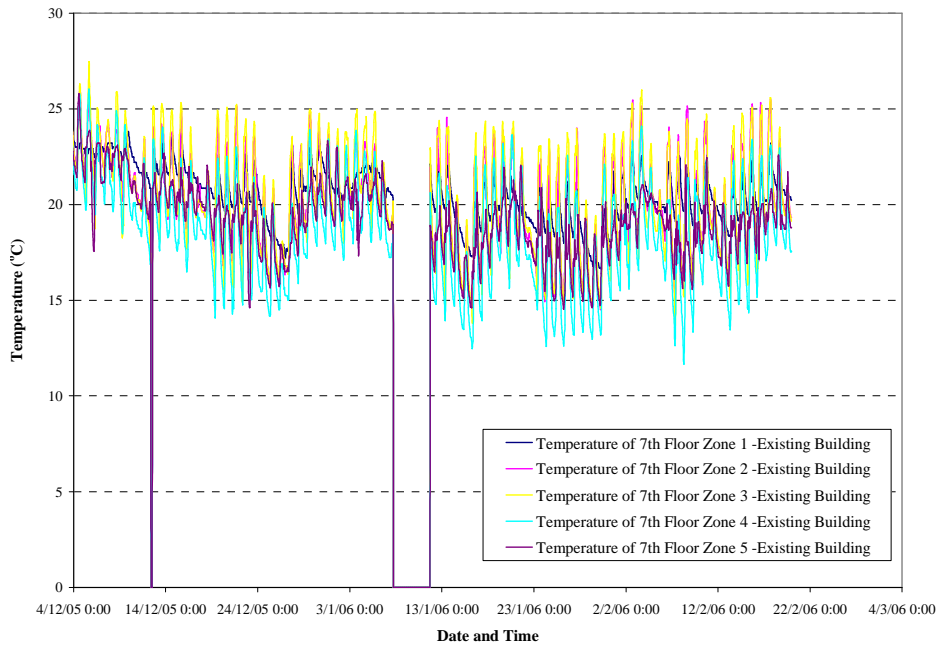


Figure 4-69: CO<sub>2</sub> concentration measurements for 6<sup>th</sup> Floor

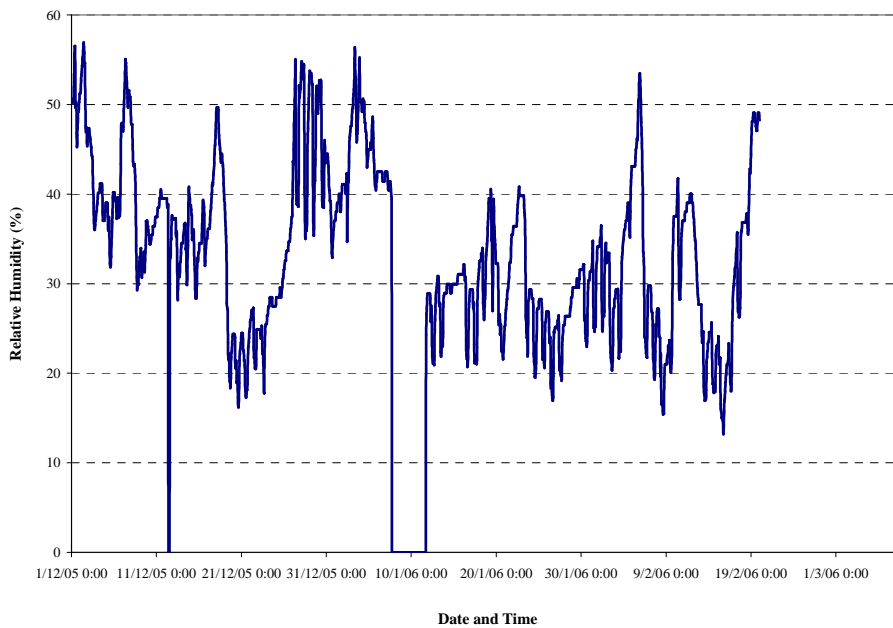
### 4.4.9. Measured data of 7<sup>th</sup> Floor

#### 4.4.9.1. Thermal performance

The temperature levels of the 7<sup>th</sup> floor and the indoor thermal comfort are in satisfactory levels (Figure 4-70 and Figure 4-71 and Figure 4-72).



**Figure 4-70: Temperature measurements of 7<sup>th</sup> Floor -existing building**



**Figure 4-71: Relative Humidity measurements of 7<sup>th</sup> Floor**

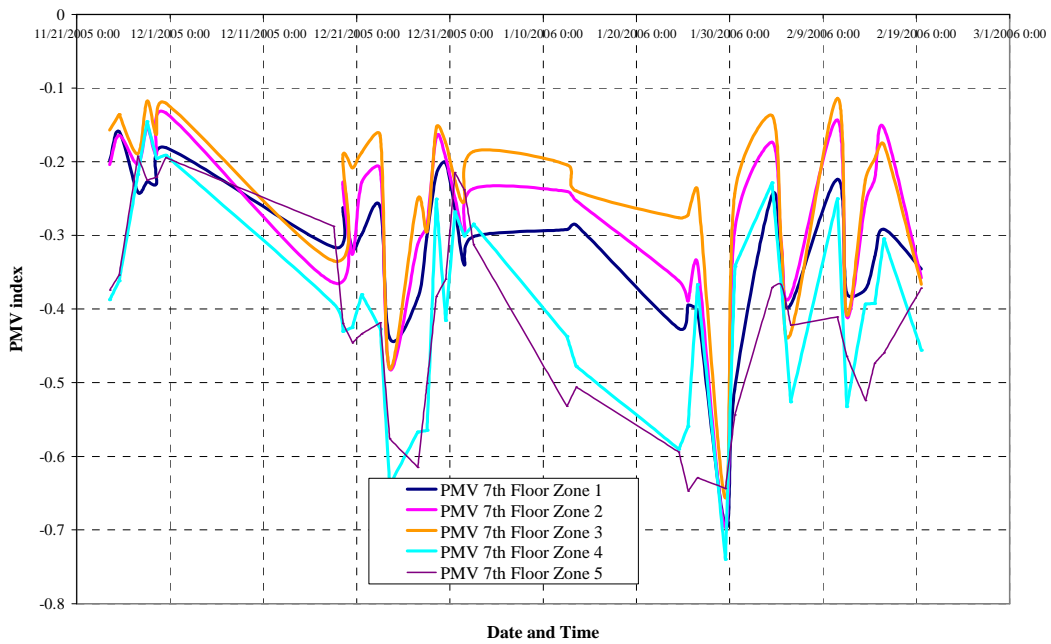


Figure 4-72: PMV index for 7<sup>th</sup> Floor

4.4.9.2. Indoor air quality performance

The zone of the 7<sup>th</sup> floor where the CO<sub>2</sub> concentration is measured is a meeting room, so the fluctuations of indoor air quality are minimal (Figure 4-73).

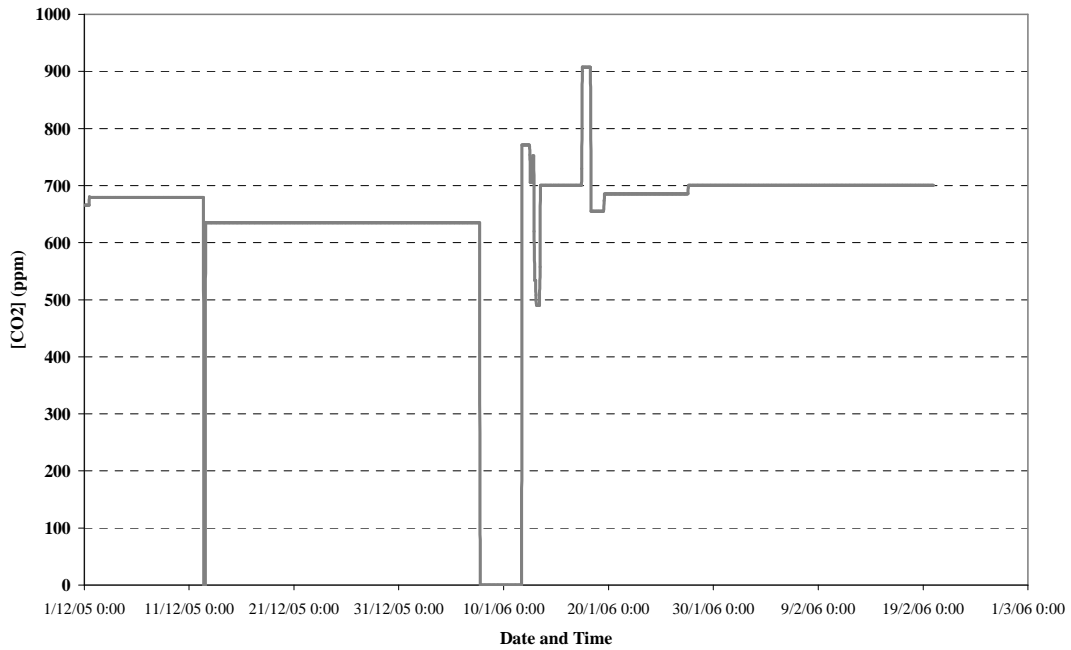
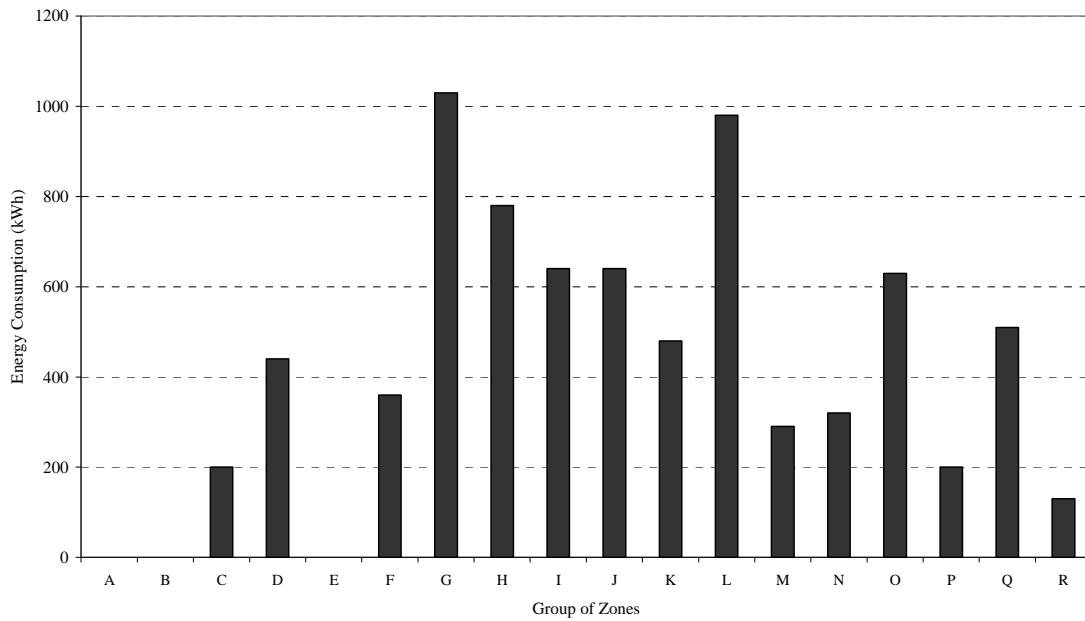


Figure 4-73: CO<sub>2</sub> concentration measurements for 7<sup>th</sup> Floor

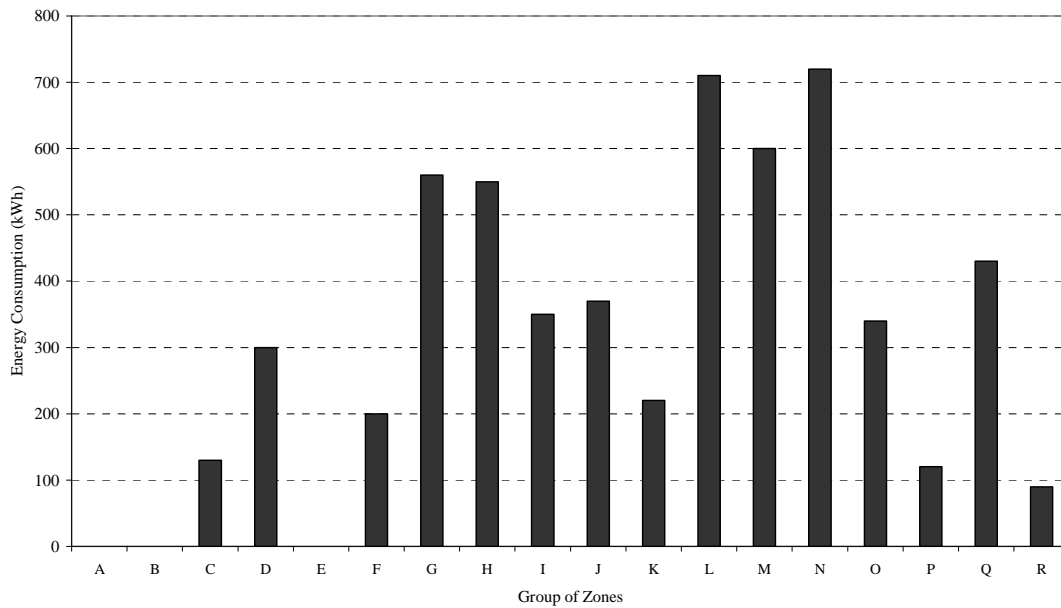
### 4.4.10. The energy consumption of BYTE building

Based on the annual energy consumption, the building of BYTE consumes 135kWh/m<sup>2</sup> annually. The total energy consumption for the months that e-building had been installed in BYTE was about 107600 kWh and consumption for heating was 17130 kWh i.e. the 16% of the total. BYTE therefore consumes for heating about the 15-16% of total consumption while the remaining 85% is the consumption for electric lighting and appliances. The energy consumption per floor area for January and February of 2006 are shown in Figure 4-74 and Figure 4-75 respectively. The highest consumption is recorded at the server rooms where the recorded temperature values are higher than the other zones.



A=Reception-Cargo1	J=Zones 4+5 3rd floor
B=Seminar room	K=Zones 2+3 4th floor
C=Restaurant	L=Zones 4+5 4th floor
D=Cargo 2	M=Zones 3+4 5th floor
E=Zones 1+2 1st floor	N=Zones 5+6 5th floor
F=Zones 4+5 1st floor	O=Zones 1+2 6th floor
G=Server Room+Zone 2 2nd floor	P=Zones 3+4 6th floor
H=Zones 3+4 2nd floor	Q=Zones 1,2,3 7th floor
I=Zones 2+3 3rd floor	R=Zones 4+5 7th floor

**Figure 4-74: The energy consumption for heating, cooling and ventilation of BYTE in January 2006**



**Figure 4-75: The energy consumption for heating, cooling and ventilation of BYTE in February 2006**

## 4.5. The simulation of BYTE building in TRNSYS

### 4.5.1.1. Measured Data

The measured data from the existing ASCII log files were used, as collected from the sensors installed in the building. From this data set, the following measured data were used for the model validation:

- The hourly values of indoor air temperature for each thermal zone of building
- The VRV units' hourly energy consumption values in each building zone.

The measurements period was from 01/01/06 to 20/02/06 and from 23/05 0:00 to 25/07 23:00. Due to a system malfunction no data were available for the period from 07/01/06 to 11/01/06.

### 4.5.1.2. Building thermal zones

As needed by the simulation process, the building (both the existing and the new part) was divided in 45 thermal zones. A first definition of the zones was available from the E-Building project (Kolokotsa et al., 2006). However, the final definition of the zones

was made after taking into consideration the distribution of thermal and cooling loads, the use of each space and its exposure to solar radiation

#### 4.5.1.3. *Simulation parameters*

The main inputs to the simulation program are the following:

a) The hourly climatic data of Athens Greece was obtained by National Observatory of Athens measurements for the year 2006 that correspond to the same days of the BYTE's building measurements (ambient temperature, relative humidity, diffuse and global radiation, wind speed and direction). The meteorological data for the time periods of measurements (winter period 1/1/2006-20/2/2006 and summer period 23/5/2006 – 25/7/2006) are depicted in Figures 4-76 to 4-85.

b) The geometric and construction elements of the building. For each thermal zone, walls, openings, floor and ceiling were modeled according to the architectural diagrams. In addition, the external environment of the building was modeled (building orientation, shading from neighboring buildings).

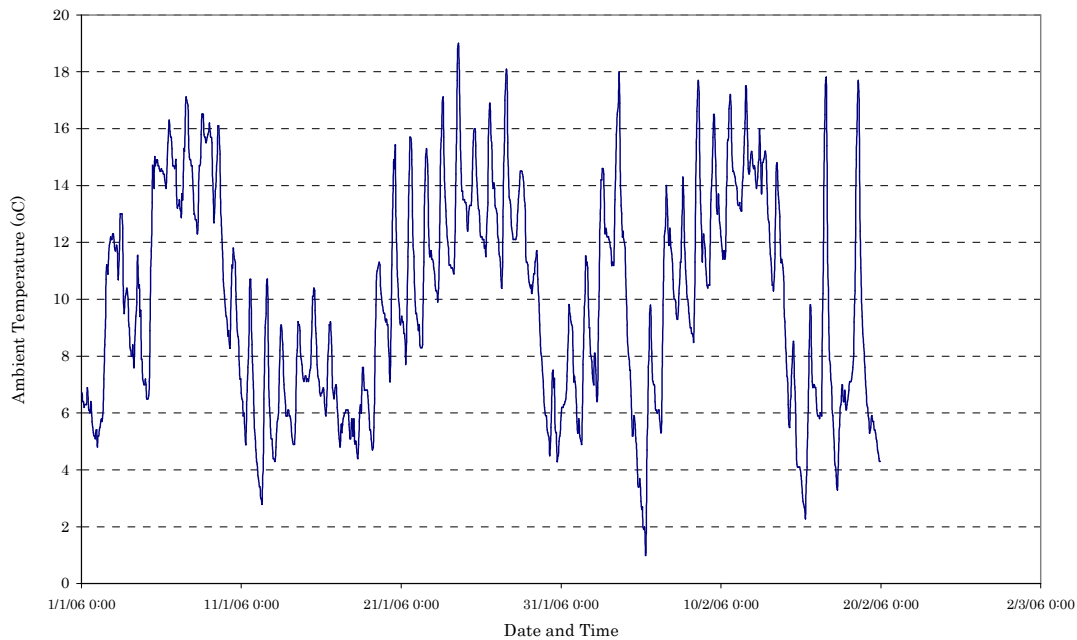
c) The heating/cooling system. VRV local units of varying power (1.3 HP, 1.6 HP and 2 HP) are installed in all thermal zones. Based on the mechanical floor plans and also the in-situ measurements, the heating and cooling power was measured and calculated for each thermal zone.

d) The infiltration and ventilation of the building. There were not available measurements of ventilation rates for BYTE building. The zone infiltration rate was presumed to be equal to 0.3-0.5 ach, while ventilation was considered to be 30 m<sup>3</sup>/h/person in spaces where smoking is prohibited and 90 m<sup>3</sup>/h/person in spaces where smoking is allowed (design values provided by the building designer and the insulation study for the building). In order to correct and verify these values, in situ visits to the building were conducted, during which the difference in ventilation rates between the various zones especially due to occupants' behavior was noticed.

Therefore for the non smoking zones the ventilation rate for the simulation procedure is equal to 30 m<sup>3</sup>/h/person while for the smoking zones is ranging between 4-8 ach, taking into account the TOTEE 1986 standards for offices [Technical Guideline 2425/86, 1986].

e) The internal gains of the building. In order to calculate the internal gains for each zone, the number of workers, computers, the number and power of lights, as well as other devices (printers, scanners, photocopiers, and restaurant ovens) was measured.

The main outputs of TRNSYS are the indoor air temperature at each thermal zone, the heating, cooling and ventilation load. The simulation parameters (TRNSYS routines-TYPES) are listed in Table 4-6.



**Figure 4-76: Ambient Temperature for winter period**

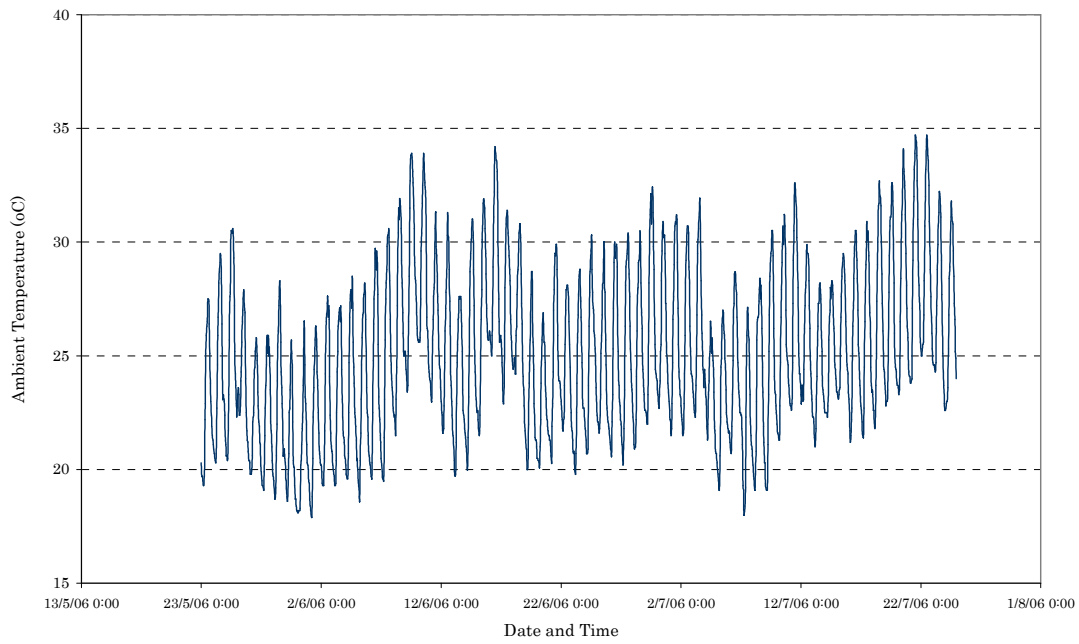


Figure 4-77: Ambient Temperature for summer period

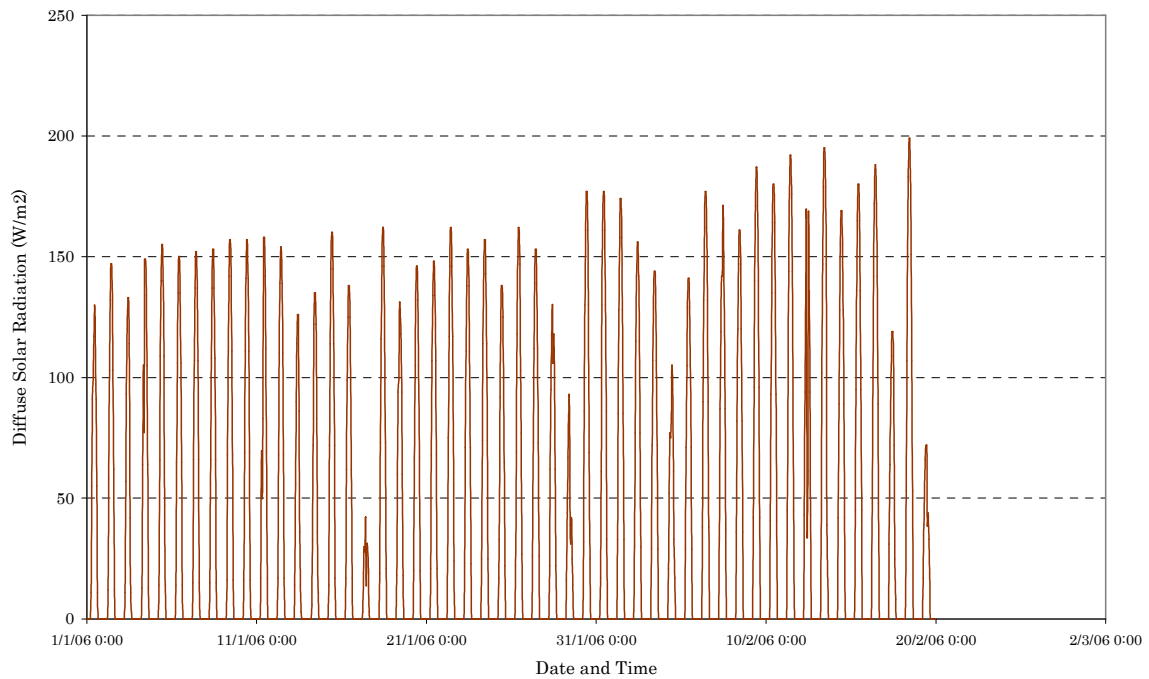


Figure 4-78: Diffuse Solar Radiation for winter period

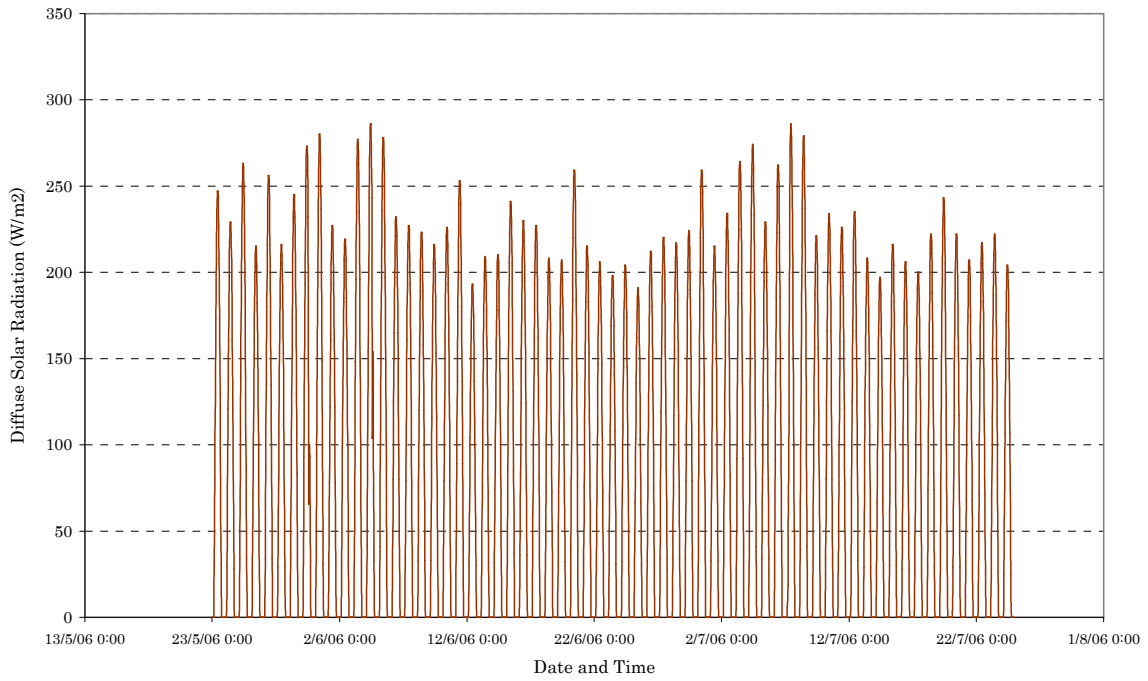


Figure 4-79: Diffuse Solar Radiation for summer period

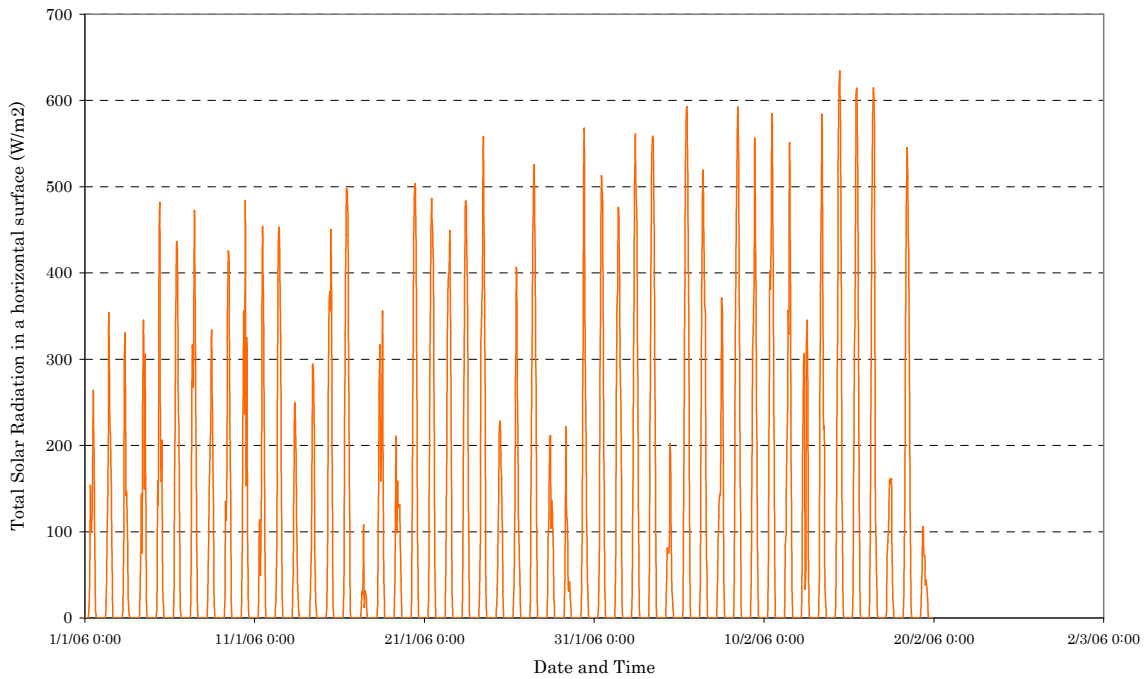


Figure 4-80: Total Solar Radiation in a horizontal surface for winter period

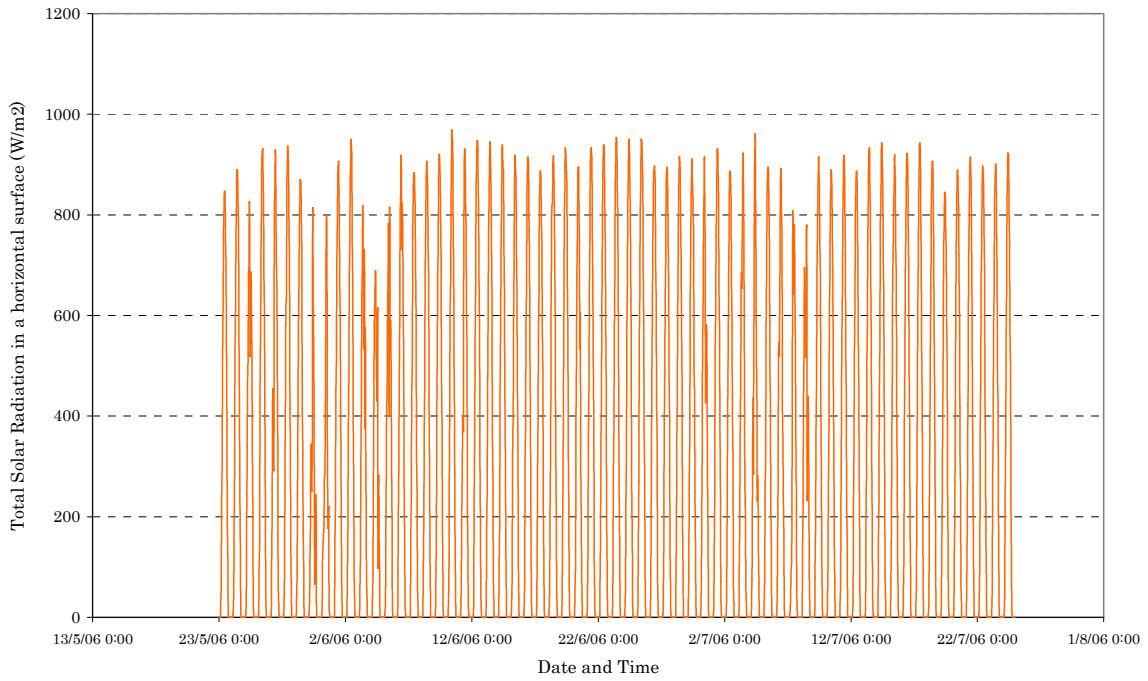


Figure 4-81: Total Solar Radiation in a horizontal surface for summer period

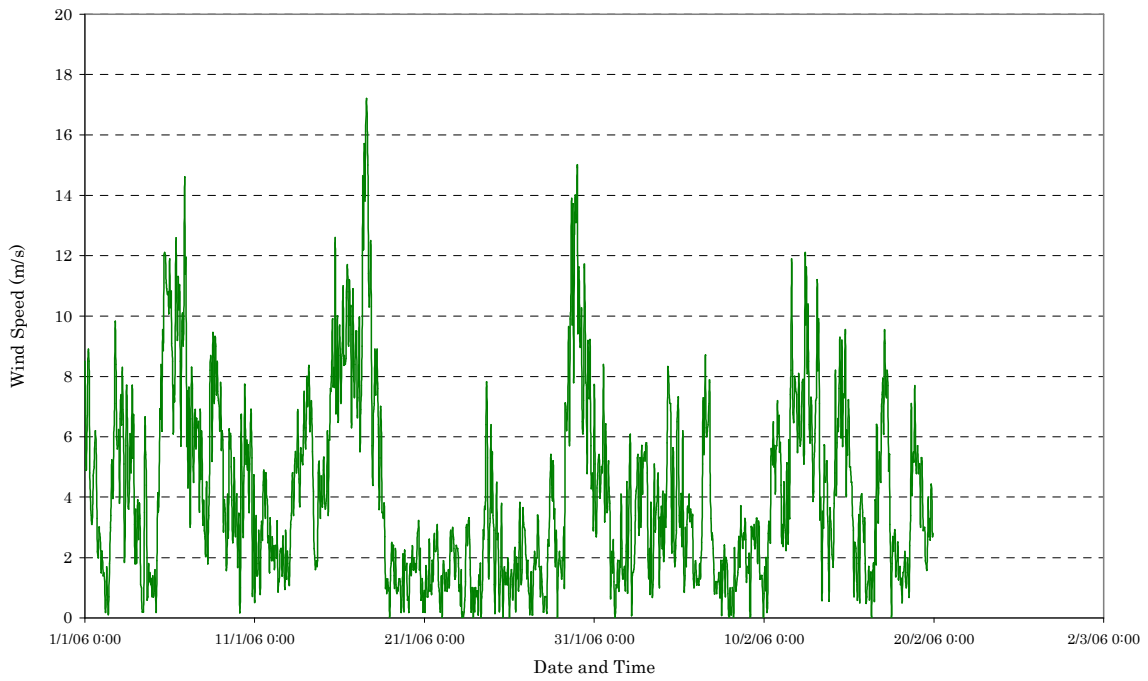


Figure 4-82: Wind speed for winter period

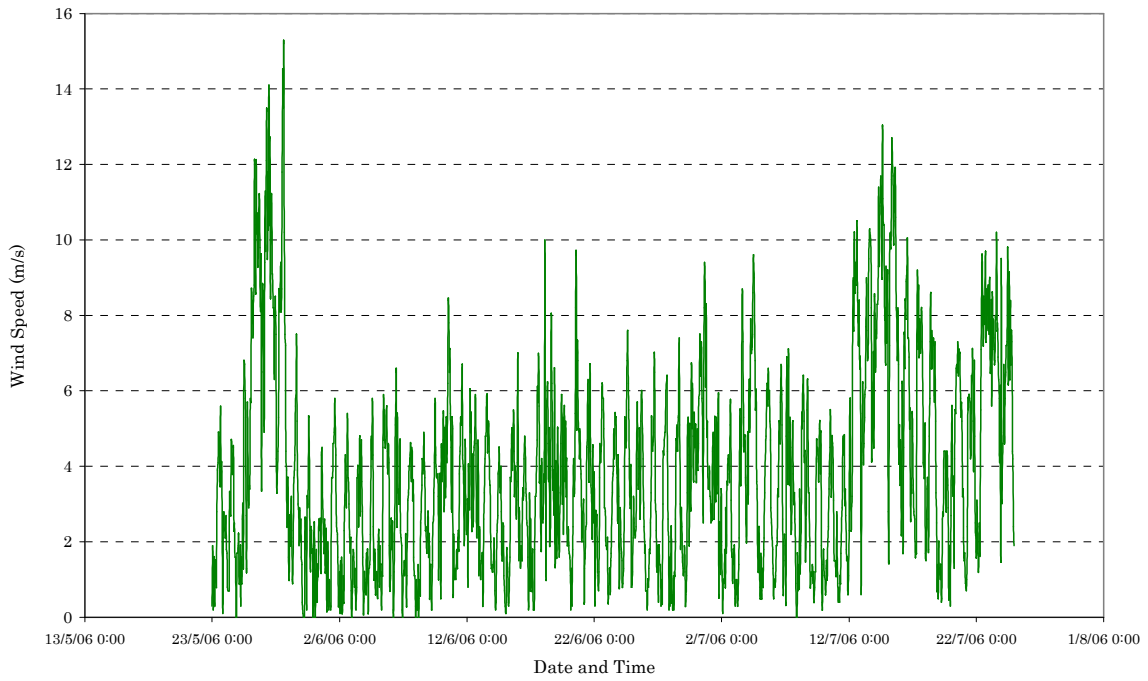


Figure 4-83: Wind speed for summer period

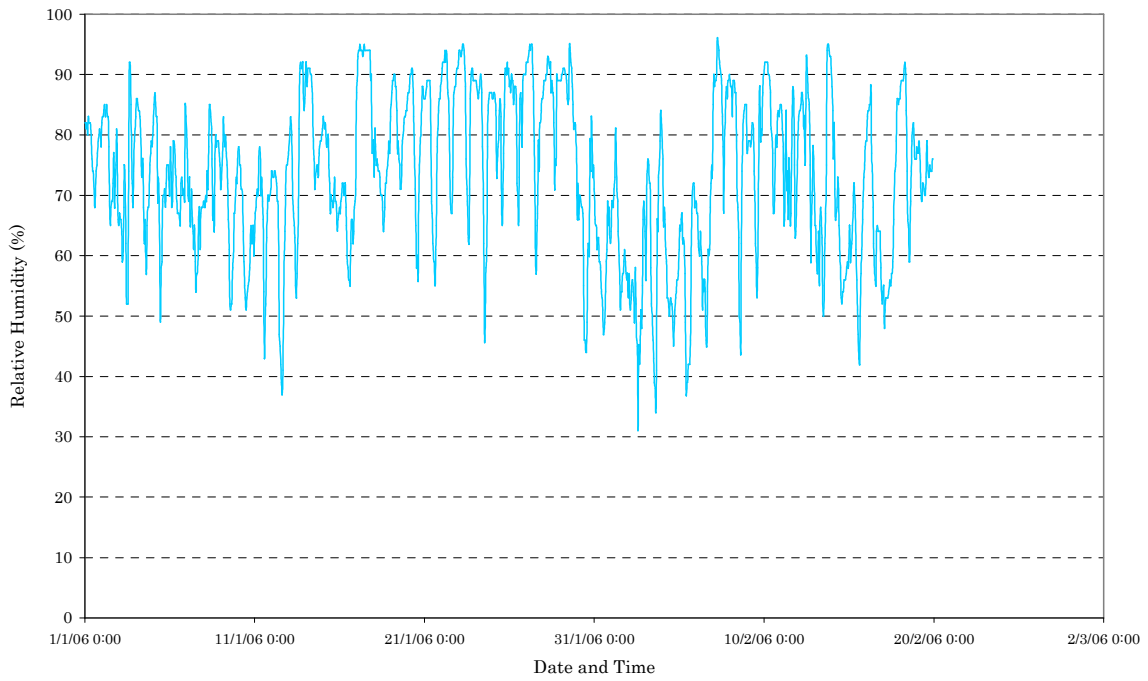
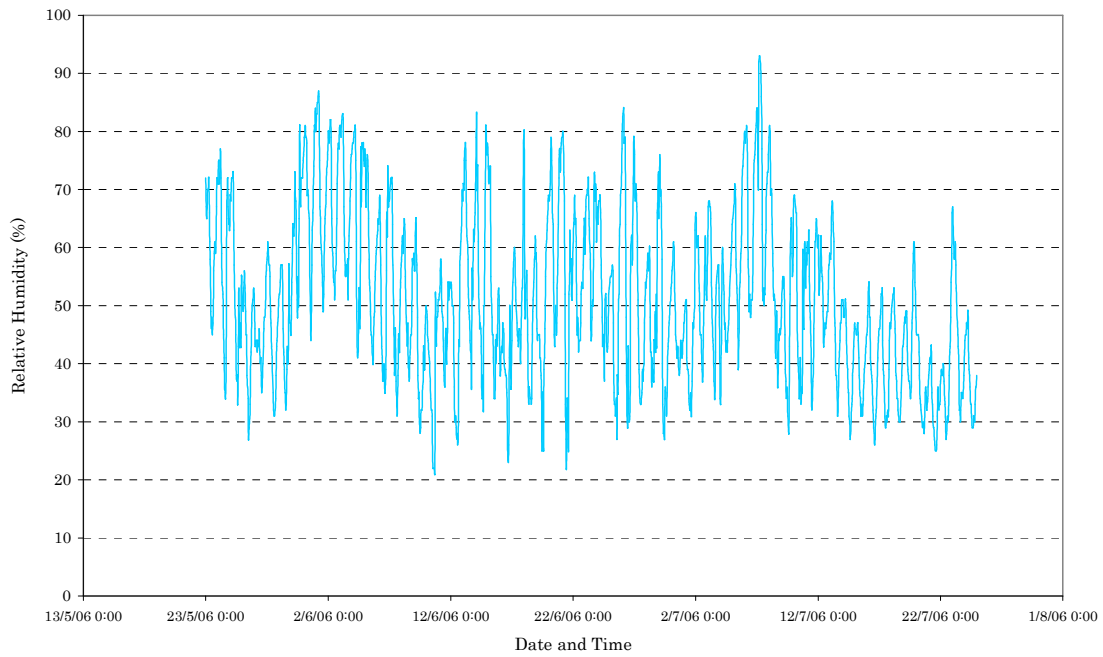


Figure 4-84: Relative Humidity for winter period



**Figure 4-85: Relative Humidity for summer period**

In Figure 4-86 the TRNBuild Input Interface for BYTE building is presented and in Figure 4-87 the Simulation Model of BYTE building is depicted.

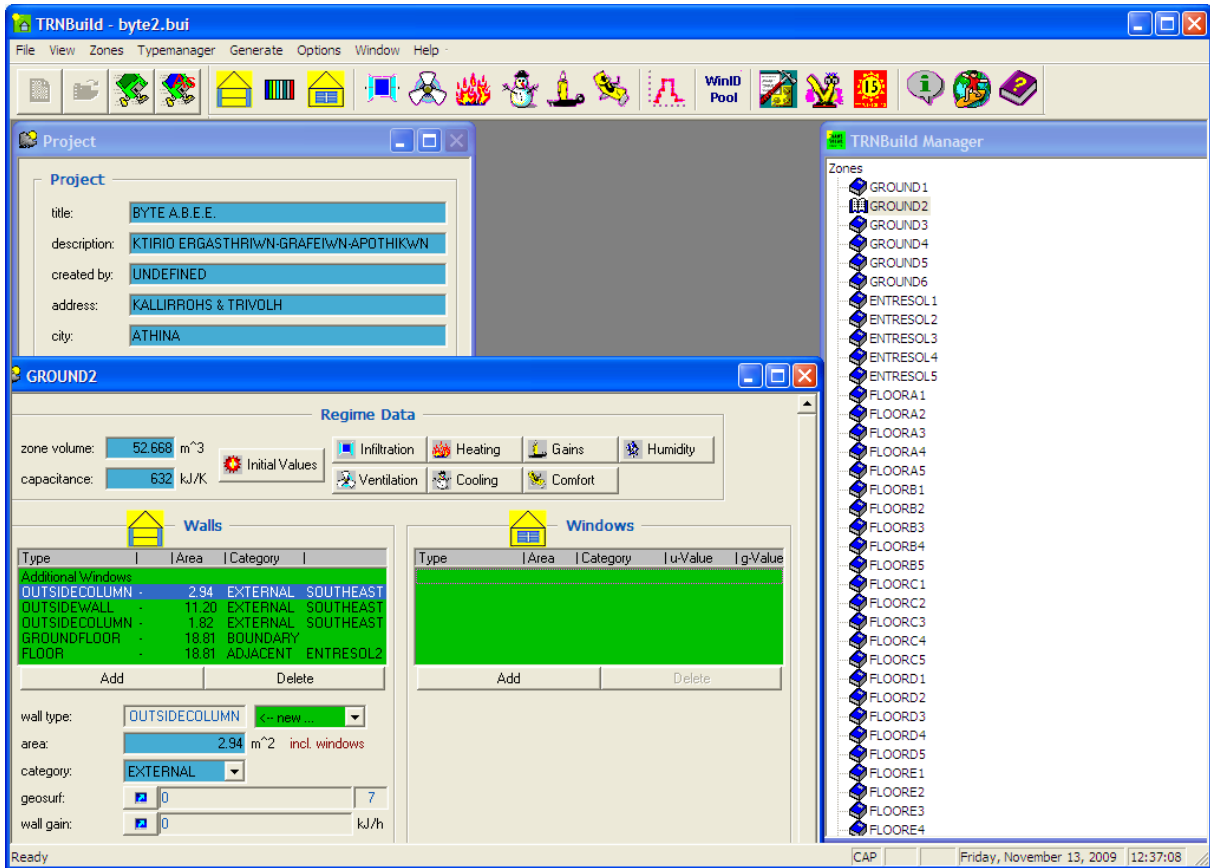


Figure 4-86: TRNBuild Input Data interface for the building of BYTE

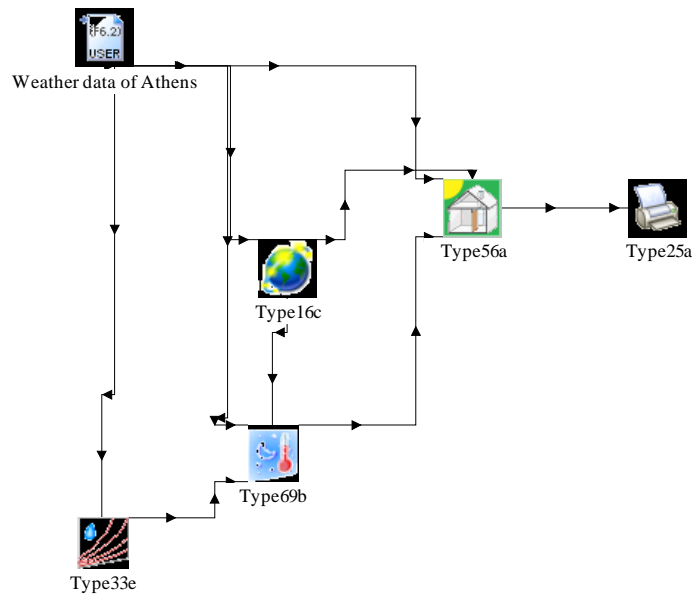


Figure 4-87: The Simulation Model of BYTE building in TRNSYS Simulation Studio

**Table 4-6: The parameters of BYTE's simulation model**

Parameter	TRNSYS Type	Comments
<b><i>INPUTS</i></b>		
Climatic Data	Data reader	Athens (Greece)
Building Data	56	Using TRNBuild
Psychrometrics	33e	
Effective sky temperature for long-wave radiation exchange	69b	
<b><i>OUTPUTS</i></b>		
TIN		Indoor air temperature for each thermal zone
QHEAT QCOOL QVENT		Energy Demand for heating, cooling and ventilation.

The simulation was performed from 01/01 0:00 to 31/12 23:00 with simulation time step equal to 1h. The hourly values of the indoor zone temperature and the heating/cooling/ventilation loads for each zone of the building have been calculated.

## 4.5.2. Simulation results and comparison with measurements

### 4.5.2.1. Indoor air temperature results

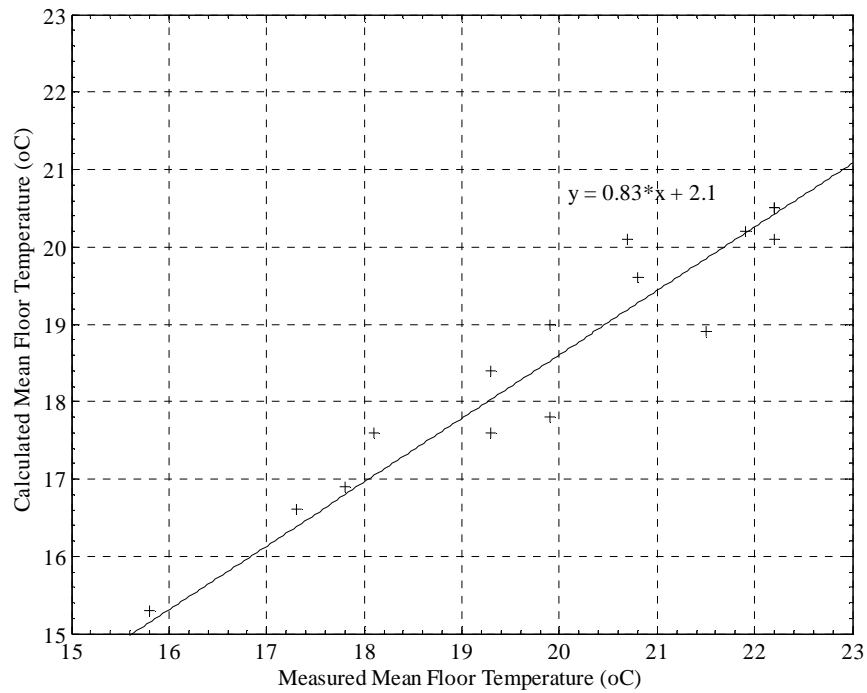
In order to evaluate the validity and reliability of the building model, the hourly measurements of the indoor air temperature for the 45 thermal zones of the building are compared to their equivalents in the model result set. The time period of comparison was between 01/01 0:00 and 20/02 0:00 (winter period) and between 23/05 0:00 and 25/07 23:00 (summer period).

Due to the large volume of the results, the simulated mean temperature for each floor and for each zone for the existing and the new part of the building is compared to the measured values. In Table 4-7, the measured and calculated (through the TRNSYS simulation) values are presented, for each floor for the 2 time periods we have obtained measurements. As illustrated in Figure 4-88 and Figure 4-89, there is a good level of agreement between the two sets of data.

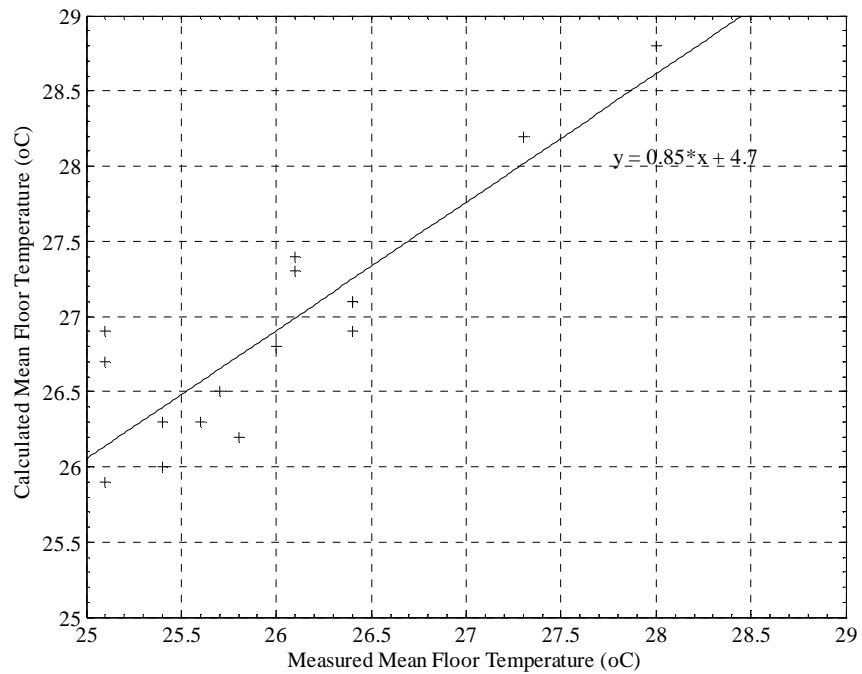
Table 4-7: Measured and calculated mean temperature for each floor of BYTE's building

Group of zones	$\bar{T}_{measured}$ (°C)	$\bar{T}_{TRNSYS}$ (°C)	DIFF	DIFF (%)
Time Period: 01/01/2006 – 20/02/2006				
Basement new	17.8	16.9	-0.91	-5.11
Basement existing	19.9	17.8	-2.08	-10.46
Mezzanine new	22.2	20.5	-1.74	-7.82
Mezzanine existing	22.2	20.1	-2.16	-9.73
1st Floor new	15.8	15.3	-0.54	-3.44
1st Floor existing	19.9	19.0	-0.84	-4.25
2nd Floor new	17.3	16.6	-0.74	-4.27
2nd Floor existing	20.7	20.1	-0.66	-3.16
3rd Floor new	18.1	17.6	-0.48	-2.63
3rd Floor existing	20.8	19.6	-1.15	-5.55
4th Floor new	19.3	17.6	-1.67	-8.66
4th Floor existing	21.9	20.2	-1.75	-7.98
5th Floor new	16.2	14.6	-1.57	-9.71
5th Floor existing	22.2	20.5	-1.71	-7.71
6th Floor existing	21.5	18.9	-2.60	-12.08
7th Floor existing	19.3	18.4	-0.82	-4.26
<b>AVERAGE</b>			<b>-1.34</b>	<b>-6.68</b>
Time Period: 23/05/2006 – 25/07/2006				
Basement new	25.1	25.9	0.78	3.12
Basement existing	26.4	27.1	0.74	2.81
Mezzanine new	28.0	28.8	0.83	2.97
Mezzanine existing	26.4	27.1	0.65	2.47
1st Floor new	27.3	28.2	0.91	3.32
1st Floor existing	25.4	26.0	0.57	2.24
2nd Floor new	26.1	27.3	1.24	4.75
2nd Floor existing	25.4	26.3	0.93	3.66
3rd Floor new	25.1	26.7	1.63	6.49
3rd Floor existing	25.8	26.2	0.43	1.65
4th Floor new	25.1	26.9	1.83	7.31
4th Floor existing	26.1	27.4	1.31	5.02
5th Floor new	25.6	26.3	0.65	2.54
5th Floor existing	26.4	26.9	0.49	1.84
6th Floor existing	26.0	26.8	0.78	3.00
7th Floor existing	25.7	26.5	0.83	3.25
<b>AVERAGE</b>			<b>0.91</b>	<b>3.53</b>

Where:  $\bar{T}_{measured}$  is the measured mean temperature,  $\bar{T}_{TRNSYS}$  is the predicted mean temperature, DIFF is the difference between the measured and the predicted value and D% the difference percentage between the measured and the predicted value.



**Figure 4-88:** Comparison of the calculated mean temperatures of the group of zones using the simulation model in TRNSYS and the measured values for the time period 01/01/2006 – 20/02/2006.



**Figure 4-89:** Comparison of the calculated mean temperatures of the group of zones using the simulation model in TRNSYS and the measured values for the time period 23/05/2006 – 25/07/2006.

Regarding the maximum and minimum temperatures during the two time periods being studied, we can observe the following:

For the time period 01/01/2006 – 20/02/2006: The temperature in all zones ranges from 13.2 °C to 25.1 °C in average, while the corresponding value range produced by the TRNSYS simulation is from 13.7 °C to 25.8 °C.

For each individual thermal zone, the maximum temperature value calculated by TRNSYS differs from the maximum measured one at a percentage ranging from 0.1% (7<sup>th</sup> Floor Zone 2) to 9.2% (Mezzanine Zone 3), while for the minimum values the difference percentage ranges from 0.1% (1<sup>st</sup> Floor Zone 2) to 10.5% (Ground Zone 5).

For the second time period, 23/05/2006 – 25/07/2006: The temperature in all zones ranges from 19.7 °C to 31.4 °C in average, while the corresponding value range produced by the TRNSYS simulation is from 20.5 °C to 32.2 °C.

For each individual thermal zone, the maximum temperature value calculated by TRNSYS differs from the maximum measured one at a percentage ranging from 0.4% (7<sup>th</sup> Floor Zone 2) to 10.2% (Mezzanine Zone 3), while for the minimum values the difference percentage ranges from 0.2% (Mezzanine Zone 3) to 10.1% (2<sup>nd</sup> Floor Zone 2).

Based on the simulation results, we observe that the simulation model calculates, in average, lower values of indoor temperature compared to the corresponding measurements in winter, and higher ones compared to the measurements in summer. This is due to the fact that the simulation model cannot predict the human factor, namely the building users who reported, during interviews, that they increase the set point of the local units during winter and lower the set point during summer in order to achieve a subjective level of thermal comfort. On the contrary, the model considers a fixed set point for all thermal zones (21° C during winter and 26° C during summer).

Moreover, the differences observed can be attributed to the fact that the majority of the workers extend their stay beyond the standard working hours. As a result, the local heating and cooling units operate beyond the time periods taken into account by the model. Consequently, the average winter temperature calculated by TRNSYS is slightly higher than the measured one, while the opposite is true for the average summer temperatures.

The above observations apply to the occupied thermal zones of the building, which also is the majority of the zones. For the thermal zones that are not occupied daily (seminar and meeting rooms) we cannot accurately predict the indoor temperature because the local heating and cooling units are activated only in case these zones become occupied, and during an undefined period. In order to reduce the deviations between simulation and measured values, we assumed that the meeting rooms are occupied once a week and for a 4-hour period, while the seminar rooms are considered to be occupied twice a month for a 6-hour period. The unoccupied zones are located in the new part of BYTE building which explains the fact that in the Table 4-7, the greater difference in calculated and measured mean temperature values are observed in zones located in the new part of the building.

For the validation of the model, a comparison between the real and simulated hourly values of the internal zonal temperatures of the building had to be carried out. Taking into account the real HVAC operation schedule, according to the audit, and the standard operation of BMS schedule, two days (one of winter and one of summer period) have been selected where the operation of the air conditioners followed the given daily schedule in representative zones. In Table 4-8 the  $RMSE_{day}$  between measured and calculated values has been calculated for the representative zones.

$$RMSE_{day} = \sqrt{\frac{\sum_{i=1}^{24} (T_{real,i} - T_{sim,i})^2}{24}} \quad (4-1)$$

Also, the Figure 4-90 to Figure 4-97 contain plots of the measured indoor temperature, the corresponding values calculated by simulation, the difference between measurements and simulation and the ambient temperature for the four thermal zones and for the days of 15/02/06 and 05/07/06.

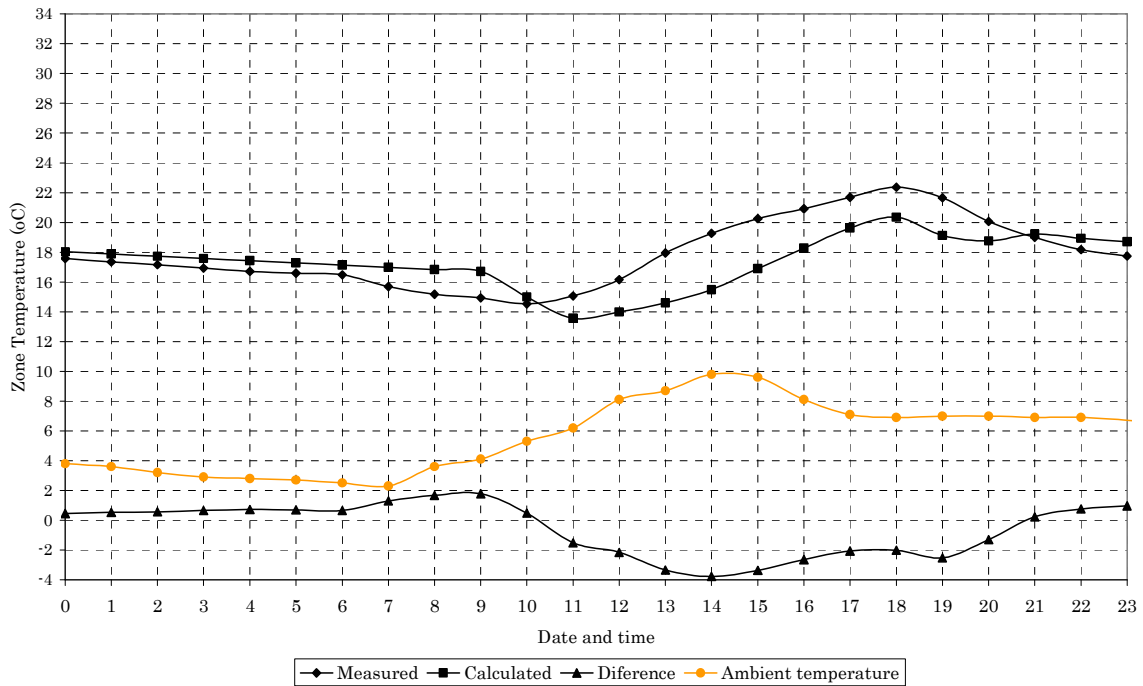


Figure 4-90: Measured and calculated indoor air temperature of Basement Zone 2 (Seminar Room) for the day of 15/02/2006

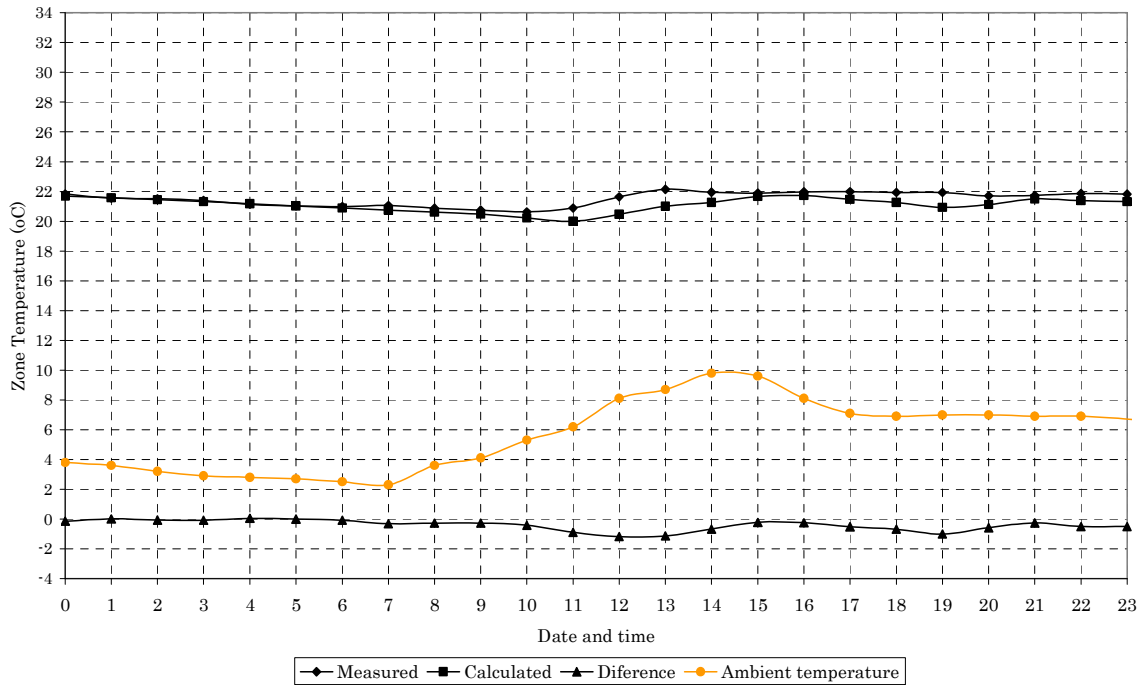


Figure 4-91: Measured and calculated indoor air temperature of 2<sup>nd</sup> Floor Zone 5 (Laboratory) for the day of 15/02/2006

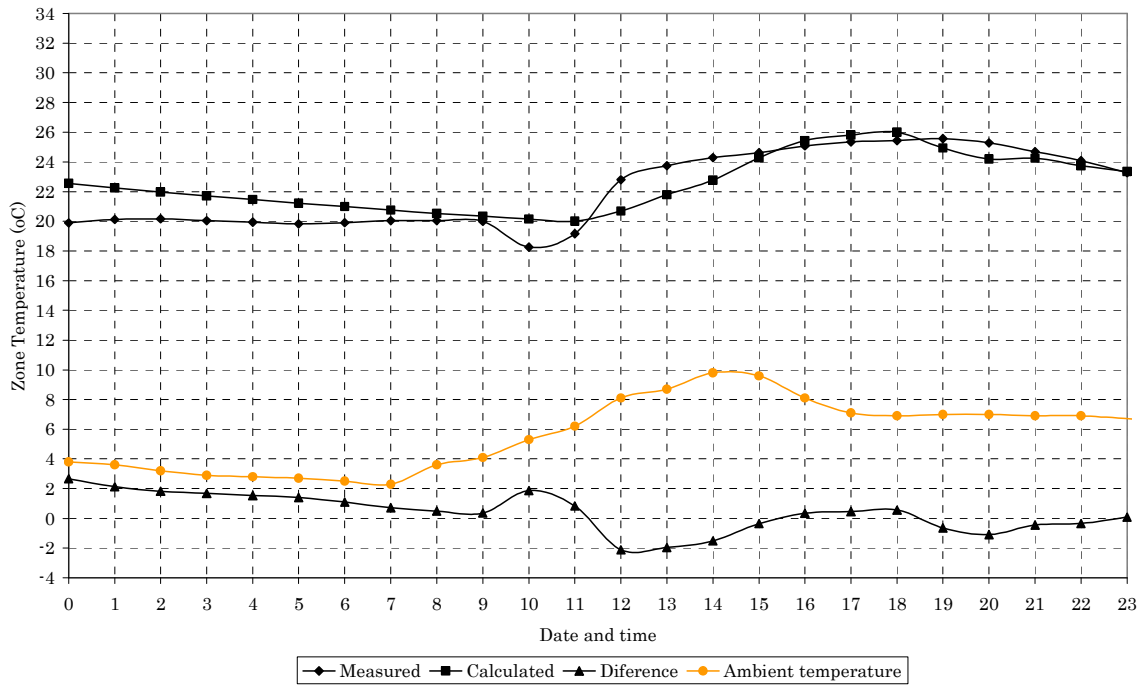


Figure 4-92: Measured and calculated indoor air temperature of 5<sup>th</sup> Floor Zone 4 (Office) for the day of 15/02/2006

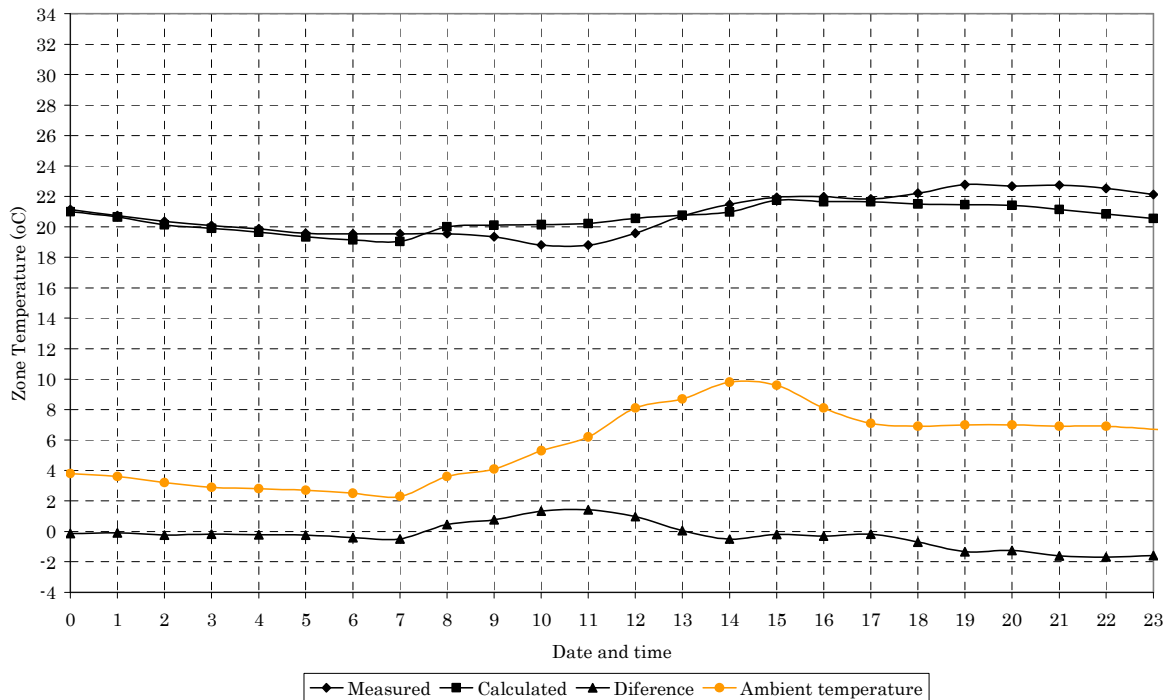


Figure 4-93: Measured and calculated indoor air temperature of 6<sup>th</sup> Floor Zone 3 (Office) for the day of 15/02/2006

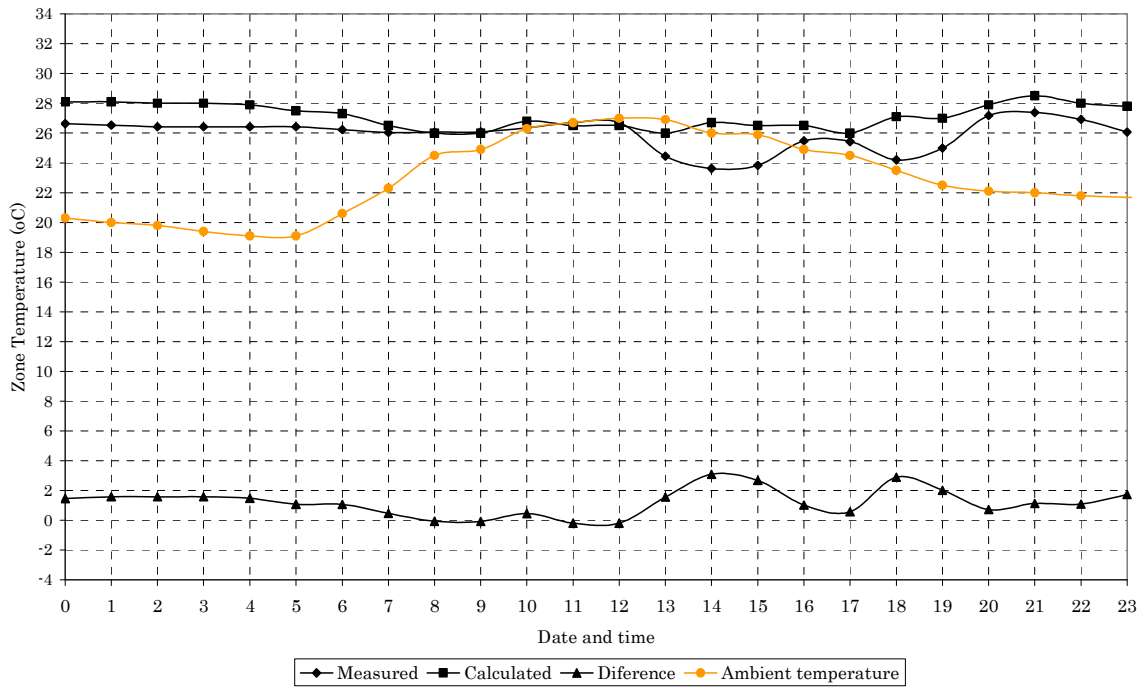


Figure 4-94: Measured and calculated indoor air temperature of Basement Zone 2 (Seminar Room) for the day of 05/07/2006

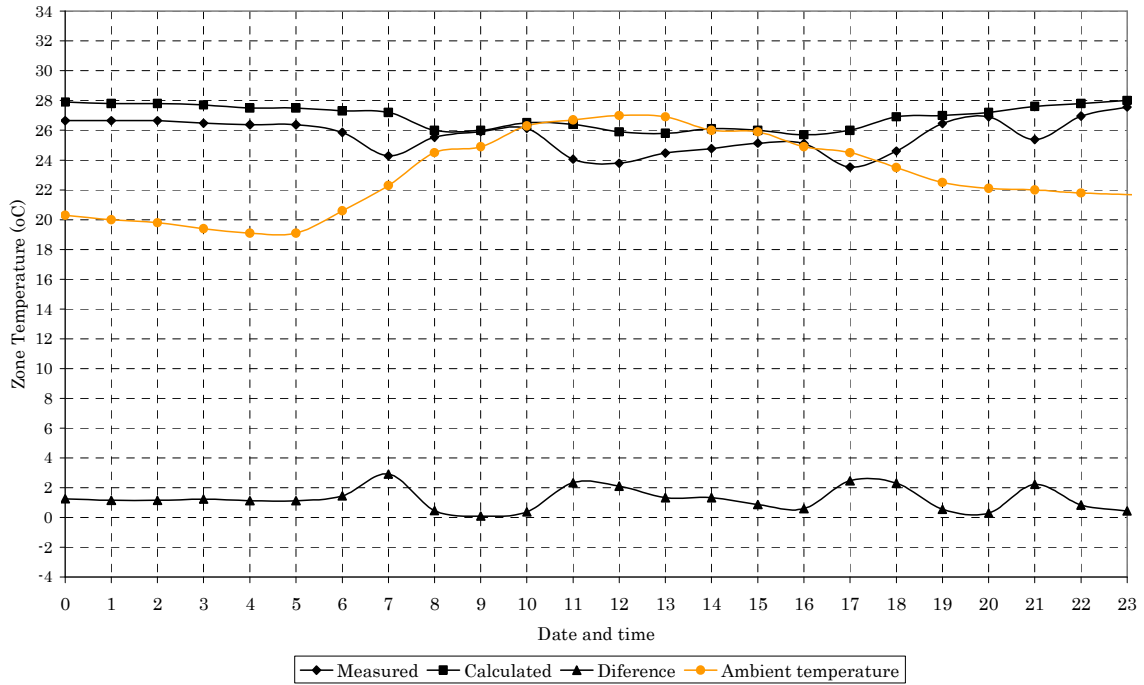


Figure 4-95: Measured and calculated indoor air temperature of 2<sup>nd</sup> Floor Zone 5 (Laboratory) for the day of 05/07/2006

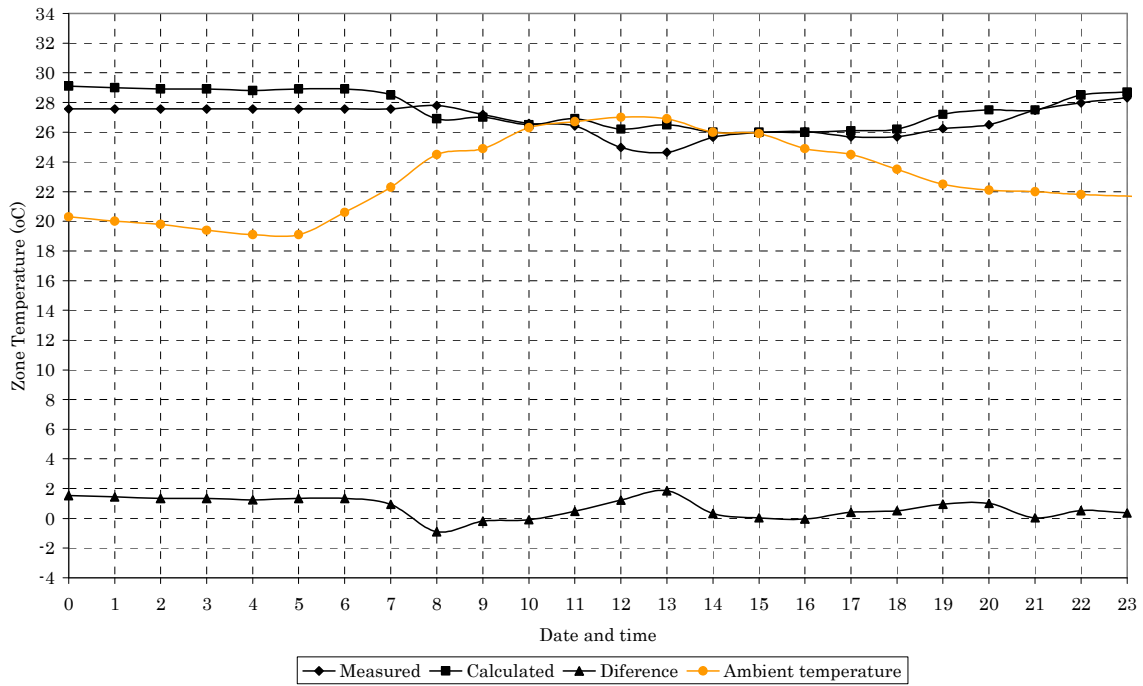


Figure 4-96: Measured and calculated indoor air temperature of 5<sup>th</sup> Floor Zone 4 (Office) for the day of 05/07/2006.

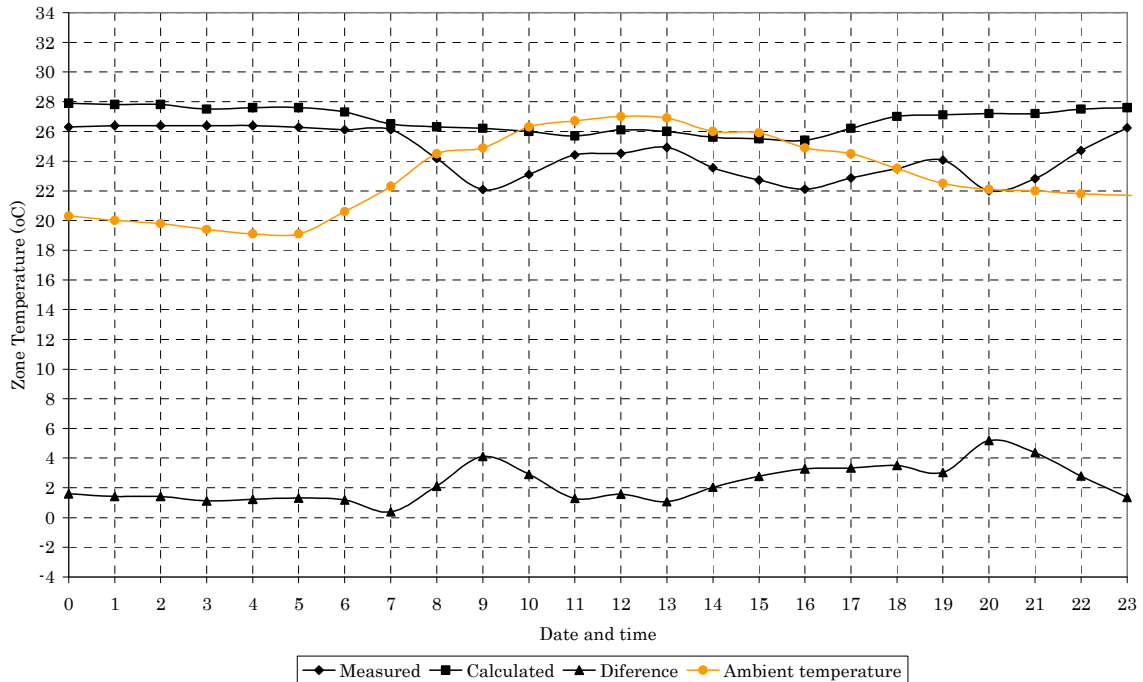


Figure 4-97: Measured and calculated indoor air temperature of 6<sup>th</sup> Floor Zone 3 (Office) for the day of 05/07/2006.

**Table 4-8: RMSE for hourly indoor temperature values of selected zones for 2 selected days**

Thermal Zone	RMSE for hourly indoor temperature values (°C)	
	15/02/2006	05/07/2006
Basement Zone 2 (Seminar Room)	2.7	1.5
2 <sup>nd</sup> Floor Zone 5 (Laboratory)	0.5	1.5
5 <sup>th</sup> Floor Zone 4 (Office)	2.6	1.0
6 <sup>th</sup> Floor Zone 3 (Office)	3.0	1.8

We can observe in the above figures that the measured indoor air temperature is higher than the corresponding calculated one during the operating hours of the building. These differences are obviously caused by the higher thermal gains due to the higher number of people occupying the zone in comparison to the number considered by the model.

In Figure 4-91, the deviations are considerably smaller compared to the Figure 4-90, due to the fact that this zone is a laboratory that operates on predefined conditions and is occupied daily by a fixed number of workers.

In Figure 4-92, we observe a relatively good approximation of the indoor air temperature by the simulation model. During a certain time period, the measured values are slightly higher than the calculated ones.

In Figure 4-93, we note that during the hours that the thermal zone is unoccupied, the measured and calculated values of the indoor air temperature are in total agreement. In simulation, we considered that the office and therefore the thermal unit located inside, operates from 09:00, which leads to elevated indoor air temperature values, while in reality the one worker that occupies this thermal zone activates the unit from 12:00 to 21:00.

In Figure 4-94, it should be noted that there is a variation of the measured temperature during the operating hours of the building, which can be attributed to the occasional use of the seminar room during that day.

Similarly in Figure 4-95, the indoor air temperature is subject to variations during the operation of the laboratory, apparently attributed to the activation/deactivation of the air-conditioning system.

In Figure 4-96 and Figure 4-97, the calculated temperature values are higher than the measured ones and there are great variations in measured values during the day.

This may be caused by a decrease of the local units' set point and by consecutive activations/deactivations of the cooling system.

#### *4.5.2.2. Energy consumption for heating, cooling and ventilation*

During the installation of the BMS in the BYTE's building, energy consumption meters were installed on every VRV unit. These meters record the total hourly energy consumption for heating, cooling and ventilation. Having obtained measurements for the time period from 01/01/06 to 20/02/06, a comparison is performed with the corresponding energy consumption values produced by the simulation of the BYTE's building during the same time period. It should be mentioned that no energy consumption data were available for the summer period. The results are presented in Table 4-9.

From Table 4-9 and Figure 4-98, we note that during the period 01/01/06-20/02/06 the values calculated by the simulation model are lower than the measured ones. This conforms to the observations so far and is justified by the fact that local units operate for a longer time than the one assumed by the model either because of workers staying late at their offices or because of some offices being occupied on weekends when the model considers the heating/cooling system to be deactivated in the whole building. Moreover, in case of rooms that are not permanently occupied (seminar and meeting rooms), it is not possible to predict the energy consumption since we cannot determine the frequency and duration of the operation of the heating/cooling system. In Figure 4-99, we conclude that there is a good agreement between the measured and the calculated energy consumptions for the group of studied zones.

**Table 4-9: Measured and Calculated energy consumption for heating, cooling and ventilation**

Thermal Zones	Energy Consumption of thermal zones (kWh)		
	EXP	TRN	DIFF
Reception-Cargo1	0	0	0
Seminar room	0	36	36
Restaurant	330	316	-14
Cargo 2	740	715	-25
Zones 1 and 2 1st floor	0	70	70
Zones 4 and 5 1st floor	560	544	-16
Server room and zone 2 2nd floor	1590	1513	-77
Zones 3 and 4 2nd floor	1330	1210	-120
Zones 2 and 3 3rd floor	990	938	-52
Zones 4 and 5 3rd floor	1010	986	-24
Zones 2 and 3 4th floor	700	580	-120
Zones 4 and 5 4th floor	1690	1514	-176
Zones 3 and 4 5th floor	890	783	-107
Zones 5 and 6 5th floor	1040	963	-77
Zones 1 and 2 6th floor	970	845	-125
Zones 3 and 4 6th floor	320	297	-23
Zones 1,2,and 3 7th floor	940	872	-68
Zones 4 and 5 7th floor	220	200	-20
<b>TOTAL</b>	<b>13320</b>	<b>12382</b>	<b>-938</b>

EXP: experimental values, TRN: TRNSYS results, DIFF: Difference between TRNSYS results and experimental values

According to the above results, the measured energy consumption in the case study building was 13,320 kWh for cooling, heating and ventilation during the time period 01/01/06-20/02/06, while according to the simulation results, the consumption for the same time period is 12,382 kWh, 7% lower. In the seminar room and zones 1 and 2 on the first floor, there was no recorded energy consumption, apparently because these zones were not occupied during this period. However, the model assumes that they were occupied twice a month for a 6-hour period each time.

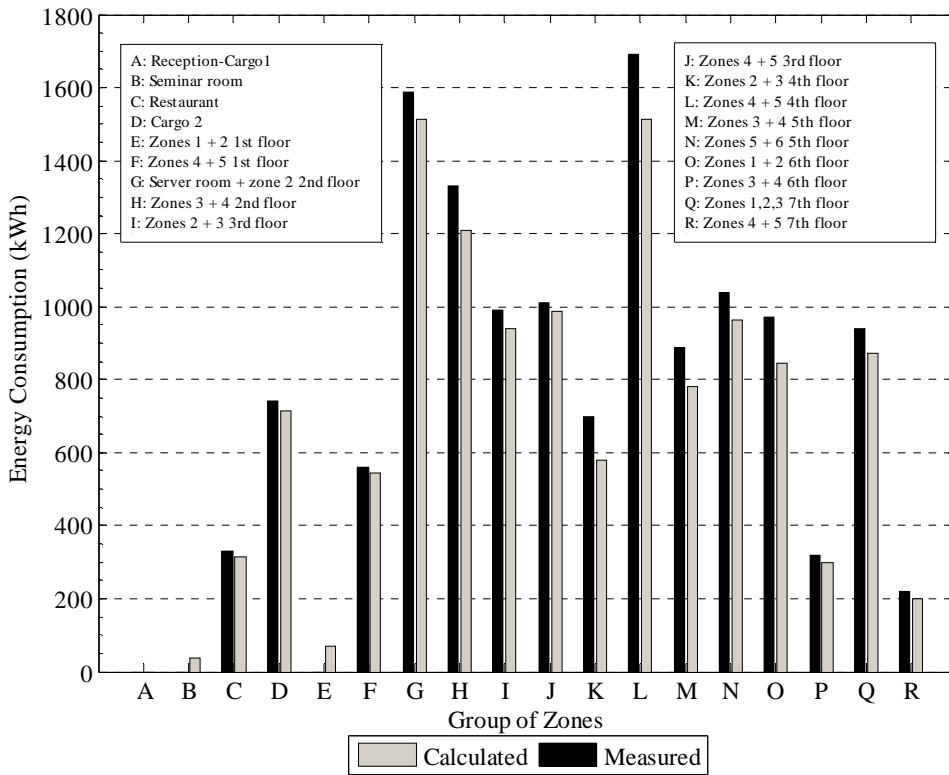


Figure 4-98: Measured and calculated energy consumption for heating, cooling and ventilation.

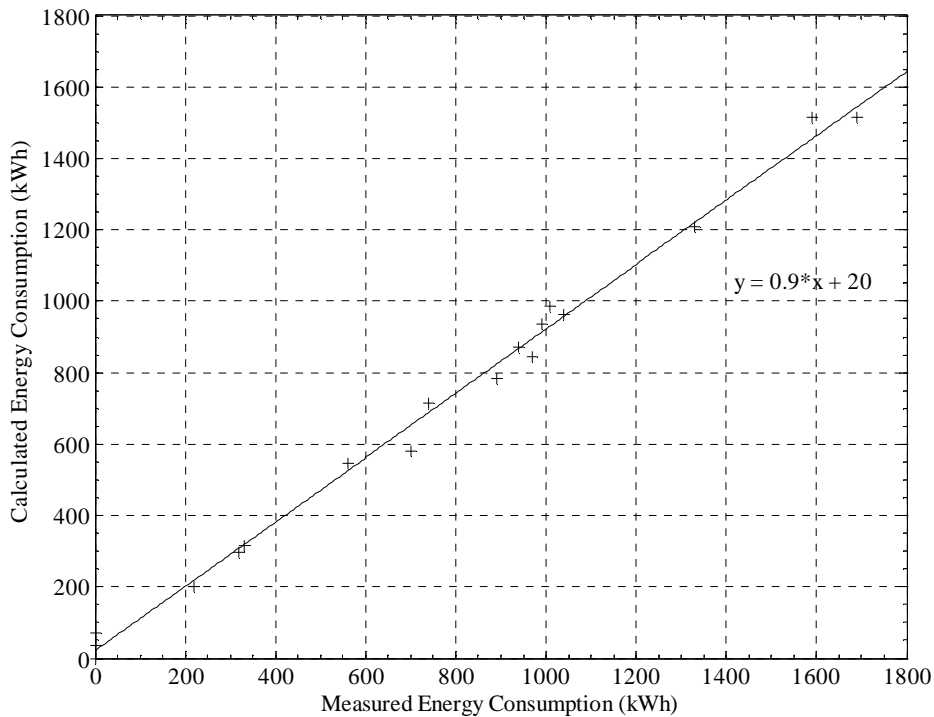


Figure 4-99: Energy consumption of thermal zones- Experimental values vs TRNSYS calculations.

## 4.6. Conclusions

In this Chapter of the thesis the detailed audit to BYTE office building and the simulation model improvement based on the findings of the audit have been presented and analyzed. In the Framework of “E-Management for indoor environment and energy savings in buildings” Project, a BMS had been installed in the premises of BYTE in Athens, with the aid to provide hourly measurements of energy and environmental building parameters.

The monitored detailed data have been used in order to improve the accuracy of the office building thermal model in TRNSYS. The BYTE building simulation results are compared with the measured values for two periods (winter and summer) and the model has been improved based on the monitoring results. The improvements of detailed model compared to the simple simulation model are the followings:

- The model approximates reality at a higher degree, since the study is based on hourly measurements and not on energy bills.
- Apart from energy consumption data the model takes in to account and calculates environmental parameters such as indoor temperature, humidity and PMV indicator in each thermal zone of the building at hourly base.
- In the improved model there is the ability to compare separately the real values of energy consumption for heating, cooling, ventilation, lighting and equipment with the respective simulated values, which is not possible with the energy bills.

However there are difficulties to the whole process such as:

- The hardness of collecting the building data with accuracy (the occupancy of each thermal zone, the equipment, the operating hours per zone etc). Many in-situ measurements are needed as well.
- It was challenging to model some parameters, such as the behavior of the building users. Many users did not use the indoor sunshades (louvers), kept windows open and activated/deactivated the local heating/cooling units at their will. This unpredictable behavior however, contains semantics for the parameters studied by the model (indoor temperature, energy consumption of heating-cooling-ventilation units).

The comparison of the measured data with those produced by simulation showed that the model is reliable enough in predicting the thermal behaviour of the building.

However, apart from accuracy of the model, the comparison between measured and calculated values leads as to conclusions related on asset and operational rating of buildings. It is showed that the calculated (asset) energy rating, based on a mathematical validated model of the building can give a rough estimate of the indoor air temperature and the heating/cooling energy consumption of the building. However, a 7% difference between the actual and the calculated energy consumption found in our research is important for the energy rating of the building as it could lead to a higher energy category. Consequently, the calculated energy rating method could be used as a preliminary energy consumption estimation method while the measured method could be used for the final energy classification of the building.

The development of the BYTE building model constitutes the starting ground for a generalized energy rating model for office buildings which, through a series of simulations of a considerable number of buildings, with exhaustive search on the building constructive parameters variations, will provide very useful results for the definition of the energy rating categories of office buildings in Greece and the EU countries in general.

## Chapter 5

# VIRTUAL BUILDING DATASET (VBD) FOR BENCHMARKING AND CLASSIFICATION OF OFFICE BUILDINGS

# CHAPTER 5: VIRTUAL BUILDING DATASET (VBD) FOR BENCHMARKING AND CLASSIFICATION OF OFFICE BUILDINGS

## 5.1. Introduction

The knowledge of building stock energy data of a country is a very significant tool for energy benchmarks establishment, energy rating procedures and building classification boundaries determination, according to the Directive 2002/91/EC and its implementation in EU member states. The lack of building energy databases in many EU Countries, including Greece, and the difficulties of collecting them lead to the investigation of other potential solutions.

Different data collection methods for energy benchmark procedures are found in the literature (Jones et al., 2000), (Hernandez et al., 2008) Santamouris et al. (Santamouris, 2007) have collected energy consumption data through energy audits performed in 320 schools in Greece. Argiriou et al. (Argiriou et al., 1994) developed specific questionnaires to perform surveys for office buildings and hospitals' energy use and indoor air quality. DATAMINE project (DATAMINE, 2007) provides the necessary platform to gather building energy data extracted by the energy performance certification procedure. Lack of energy data still remains a significant drawback. This leads to the investigation of other approaches in order to define the necessary boundaries based on local characteristics.

Lombard et al. in their survey (Lombard et al., 2009) claim that “*building database information availability is a crucial issue. Gathering energy information to populate a database with a representative sample of the building stock is not only expensive but also technically complex. It is not surprising that only a few nations have undertaken this task to date*”. Usually, information is collected on site from building owners, tenants, facility managers, etc. An outstanding example is the US Energy Information Administration (EIA) database and the later surveys for both the residential sector (RECS, EIA 2001) and commercial buildings (CBECS, EIA 2003). According to the authors “*A different approach to database generation is the application of building energy simulation to a variety of building types for a range of energy parameters*

*(parametric benchmarking). Careful selection of building types and calculation methods is critical to the validity of the database. Another added constraint is the need to customize building envelopes and HVAC sizing for each climate and system type. An advantage is the possibility of covering a wide range of building energy consumption characteristics with a suitable selection and variation of the energy parameters. Additionally, energy simulation provides a wider range of energy outputs for future comparisons”.*

The aim of this part of the thesis is to create a Virtual Building Dataset (VBD) of office buildings in Greece, as a benchmarking and classification tool. The philosophy of the VBD is based on the creation and simulation of random office buildings that could be found or built in Greece, taking in to account the Greek constructional and operational characteristics of office buildings and Greek legislation. The VBD consists of 30,000 buildings (10,000 in each Climatic Zone) with their detailed constructional and operational data and of their simulation outputs: the annual specific energy consumption for heating, cooling, electric lighting, office equipment and an indoor thermal comfort indicator (Nikolaou et al., 2009).

Therefore, the proposed methodology overcomes the difficulties and time required for collecting building constructional and energy bills data by creating them virtually, taking into account all parameters that may affect the energy performance and indoor thermal comfort of office buildings.

The VBD results will be used, in the next steps of the thesis for:

- (a) Assessing energy and thermal comfort benchmarks and classes, based on CEN proposed method.
- (b) Applying clustering algorithms in order to investigate the appropriate method for office building classification and labeling.
- (c) Buildings’ characteristics investigation (U-value of walls and roofs, glazing type, shading, ventilation etc) in order to understand common features of buildings rated in the same class.

The proposed VBD provides flexibility and expandability on building datasets’ characteristics, sample size and climatic conditions according to the relevant research scope. The large number of the developed data can also be used for sensitivity

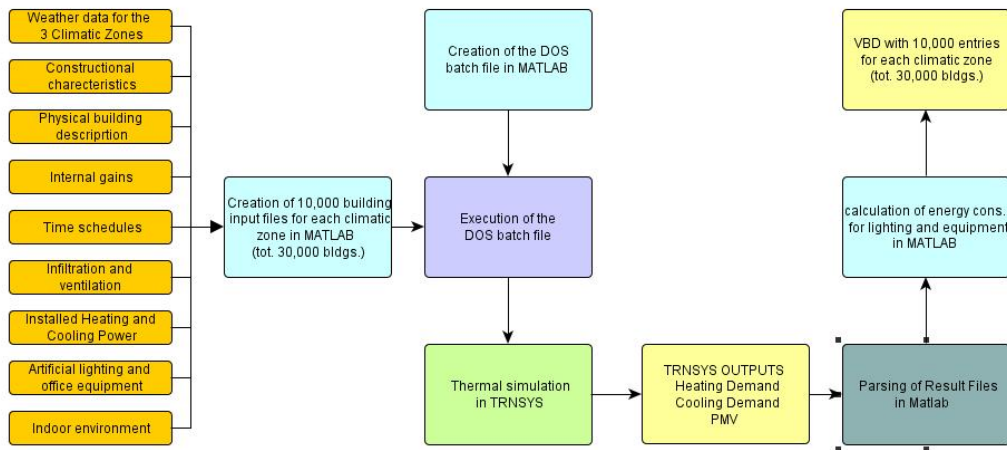
analysis, neural network training as well as to any process that demands a significant number of building data.

## **5.2. Description of the VDB creation process**

The virtual dataset philosophy is based on the creation and modeling of random buildings. These random buildings rely on the constructional and operational characteristics of office buildings in Greece (NHSS, 2000) and on the related Greek legislation. The term “random” refers to the random selection of all the parameters that determine the energy performance of the building. Based on this concept, a sample of 30,000 office buildings (10,000 buildings per climatic zone) in Greece was modeled and simulated using the validated office building model in TRNSYS (See Chapter 4).

The overall procedure is developed by coupling TRNSYS with Matlab™. TRNSYS is the core of the process, employed for the simulation of each building while MatLab was used for all the peripheral tasks (building input file creation, result file parsing, etc.).

Each virtual building’s parameter (i.e. weather data, constructional characteristics, physical building description, internal gains, time schedules, infiltration and ventilation, installed heating and cooling capacity, electric lighting, office equipment and indoor environment, see Figure 5-1) is selected randomly from its prescribed range following a uniform stochastic distribution. A suitable batch file is created to convert these MatLab input files to TRNSYS building model files (Described in detail in Chapter 4) and allow the virtual building’s simulation. The values of heating and cooling demand as well as the PMV for each virtual building are then stored along with the values of its parameters creating thus a fully exploitable input/output data entry. For calculating the energy consumption for heating and cooling the heating load has to be divided with heating efficiency factor (i.e.0.75, 0.8 etc) and the cooling demand with COP values (i.e. 2,3,4, 5 etc). The procedure is executed automatically for the 30,000 buildings using the suitable batch file. Figure 5-1 illustrates the overall VDB creation process.



**Figure 5-1: Schematic of VBD creation proces**

### 5.3. The TRNSYS office building thermal model

The building thermal model used by TRNSYS for the VBD creation is based on the validated office building thermal model (Chapter 4). For 30,000 simulations of random buildings and VBD creation this model has been generalized in terms of:

- Creating templates input files, where each parameter will be written automatically.
- Automating the creation of the building input files for each climate zone.
- Random selection of input values.
- Automatically execution of 30,000 simulation runs
- Automatically storage of simulation outputs.

Section 5.6.1 includes a detailed description of the VBD creation process (thermal model, input data, and selected values).

## 5.4. The input data

### 5.4.1. Weather data

Three climatic zones, as determined in Technical Guideline 2425/86 of Technical Chamber of Greece, (Technical Guideline 2425/86, 1986) are considered for the virtual dataset creation procedure.

**Climatic Zone A:** South region of Greece including the prefectures of: Crete, Cyclades, Dodecanese, Samos, Messinia, Lakonia, Argolida, Zakynthos, Kefalonia, and Ithaki.

**Climatic Zone B:** Central region of Greece including the prefectures of: Korinthos, Iliia, Achaia, Aitolokarnania, Fthiotida, Fokida, Viotia, Attica, Evoia, Magnisia, Sporades, Lesvos, Chios, Kerkyra, Lefkada, Thesprotia, Preveza and Arta.

**Climatic Zone C:** North region of Greece including the prefectures of: Arcadia, Evritania, Ioannina, Larissa, Karditsa, Trikala, Pieria, Imathia, Pella, Thessaloniki, Kilkis, Halkidiki, Serres, Kavala, Drama, Thasos, Samothraki, Xanthi, Rodopi, Evros, Grevena, Kozani, Kastoria, Florina.

For each climatic zone a city has been selected for the simulations:

- Heraklion, Crete hourly data (Climatic Zone A)
- Athens, hourly data (Climatic Zone B)
- Thessaloniki, hourly data (Climatic Zone C).

The criterion for selecting these cities is not the climate but the office building stock size of the cities. For example, the climatic data of Thessaloniki are not typical for zone C because the high humidity of the city leads to cooling loads similar to those of Athens (Papakostas and Papadopoulos, 2004). However, the office building stock of Thessaloniki accounts for more than 70% of the total number of buildings in zone C.

For the buildings' simulation Meteonorm hourly Weather Datasets have been used for the three aforementioned cities.

#### **5.4.2. Material and element library creation**

Based on databases of materials and structural elements dominating the Greek building sector (Papadopoulos et al., 2008), (Papamanolis, 2005), a new material and element library is created in TRNSYS for the purpose of VBD creation. This library formulates the constructional characteristics of the Greek building stock and is used for the development of each virtual building following the common buildings' manufacturing practice for different periods. (Thermal Insulation Code for Buildings, 1979), (Karekos, 2001), (Papadopoulos, 1987).

The breakdown of the Greek building stock for different periods of construction is illustrated in Figure 5-2. The buildings constructed before 1980 (pre-1980) correspond

to 74.6% of the total building stock. These buildings are not thermally insulated since they constructed before the implementation of the national Thermal Insulation Regulation (TIR) (Thermal Insulation Code for Buildings, 1979), and exhibit a poor energy performance, while for the vast majority of them they are equipped with old electromechanical installations (NHSS, 2000). The percent of buildings that have been constructed during 1990s is estimated based on the building construction activity for this period (NHSS, 1997).

The main categories of the Greek building stock according to end use of the buildings are: dwellings, hospitals, hotels, schools and offices/commercial buildings (Figure 5-3). There are also other uses including industrial buildings, churches, athletic facilities, storage areas, closed parking spaces, etc., which account for 21.9% of the total stock, the majority of which have periodic use and a limited overall contribution to the total energy consumption.

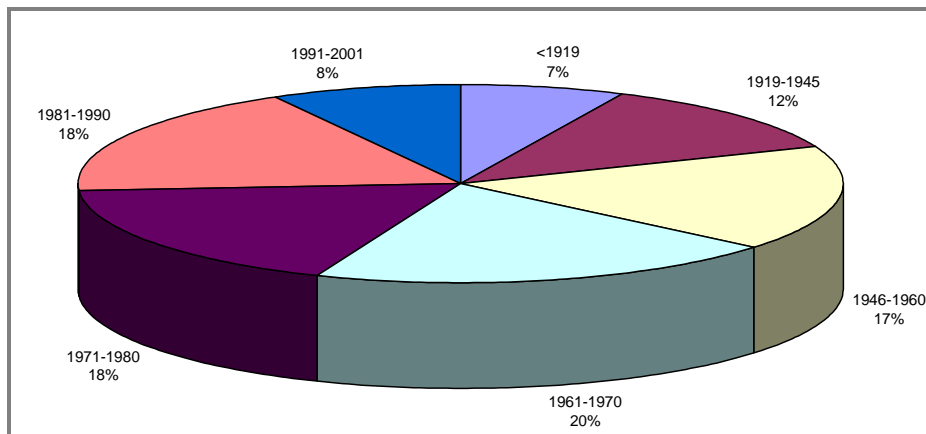


Figure 5-2: Breakdown of Greek building stock for different periods of construction

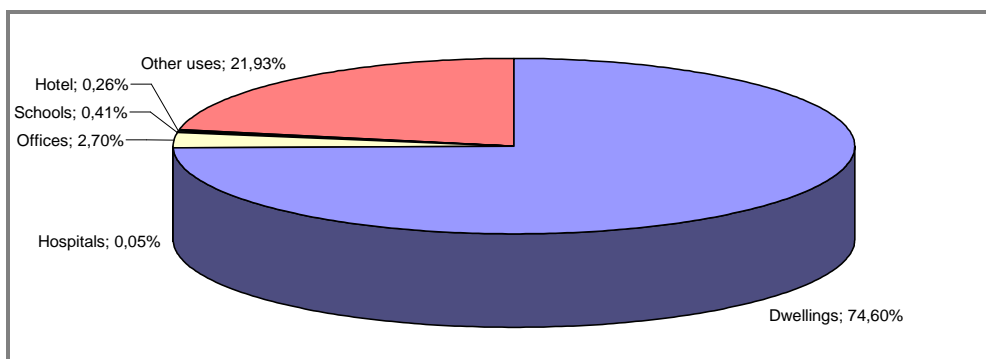


Figure 5-3: Building categories of the Greek building stock

According to EPA-NR Survey (EPA-NR, 2005), office and commercial buildings accounts 150,317 in Greece with total floor area 81,123,291 m<sup>2</sup>. Referring to typical construction 35% have insulated walls ( $U=0.7 \text{ W/m}^2\text{K}$ ), 45% have insulated roof ( $U=0.5 \text{ W/m}^2\text{K}$ ), 45% have single glazing and 55% double glazing.

Referring to typical HVAC and electromechanical installations office and commercial buildings use according to the survey:

- For Heat Production: 80% use central heat production (oil fired boilers), 5% use central heat production (gas fired boilers) and 15% use electricity.
- For Cold Production: 25% use central cold production (electric compressor chillers) 15% use central heat pumps, and 45% use local heat pumps.
- For Air Conditioning: 15% use central air-handling units, 60% use local air-conditioning units (i.e. split units, compact wall units), 20% use natural ventilation and 5% use fans.
- For Lighting: 20% use incandescent, 75% use fluorescent and 5% use high vapor.
- For Controls: 80% use simple time controls, 10% space thermostats, 15% central system temperature regulation and 2% BMS.

For this library construction the particularities of Greek office building sector, as they have been described by Papadopoulos et al. in (Papadopoulos et al., 2008), have been taken into account. It is noted that in case that the dataset referred to buildings other than office buildings (i.e. dwellings, hotels, schools, hospitals, etc) different construction elements should have been taken into account.

### 5.4.3. Physical description of the buildings

Since the building's shape, fraction of openings and orientation influence significantly its energy consumption (Depecker et al., 2001) all possible combinations of the above are included in the dataset development process taking into consideration the Greek building stock characteristics (Balaras et al., 2007).

Therefore the number of stories for the virtual buildings varies from 1 to 8, the floor dimensions from 16 to 80m, the floor area per story from 256 to 6400 m<sup>2</sup> the fraction of openings is between 40 and 80% and all possible orientations (NSEW, SEW, NEW,

NSW, NSE, NS, EW, NE, NW, SW, SE) are considered. The height of each floor is supposed to remain constant for all buildings and equal to 2.8m.

The shading coefficients range (internal and external shading factors) is selected based on a research of thesis' author related to the contribution of shading in improving the energy performance of office buildings (Nikolaou et al., 2007). According to this survey the shading factor of internal and the external shading devices ranges from 0-0.8.

#### **5.4.4. Internal gains**

Every office building is supposed to accommodate 6-14 persons per 100m<sup>2</sup>. The heat gains from occupants are calculated by TRNSYS based on ISO 7730 (EN ISO 7730, 2005). The selected degree of activity is seated, light work, typing (typical application for offices) with total heat adjusted 150W, sensible heat 75W and latent 75W.

Every person is supposed to operate a PC with a color monitor, while the heat gains from electric lighting are almost 55W/m<sup>2</sup> (halogenstrahler).

#### **5.4.5. Energy consumption for electric lighting and office equipment**

The electric lighting energy consumption for each office building produced by the VBD is evaluated by considering a luminance level of 500 lm/m<sup>2</sup> for each thermal zone, according to the CEN related standard (EN 15251, 2006) and a lighting efficacy equal to 50 lm/W according to the related literature (Kreider et al., 2002). Depending on the randomly chosen zone dimensions, the lighting efficacy and the operating hours, the annual electric lighting energy consumption is calculated by a specific subroutine in MatLab. The energy consumption of office appliances (computers, printers, faxes etc.) is calculated by considering a constant value of 0.2217 kWh per occupant according to the literature (Krarti, 2000).

#### **5.4.6. Time Schedules**

The typical operating schedules for office buildings are considered, according in-situ measurements for the survey performed by the author in BYTE office building.

Monday to Friday 08:00-22:00 with occupancy schedule:

08:00-09:30 with 70% occupancy.

09:30-17:30 with 100% occupancy.

17:30-22:00 with 30% occupancy.

Saturday 08:00 -14:00 with 20%occupancy.

#### **5.4.7. Infiltration and ventilation**

The infiltration and ventilation rates of the building's zones are strongly related to the energy consumption for heating and cooling. The infiltration rate for the dataset development ranges between 0.2 to 2 ach (Kreider et al., 2002), (Krarti, 2000), (Kolokotsa and Nikolaou, 2007) and the ventilation rate between 0.5 to 10 ach (Technical Guideline 2425/86, 1986), (Kreider et al., 2002), (ASHRAE Standard 62-99, 1999).

#### **5.4.8. The installed Heating and Cooling power**

The building thermal model requires the installed heating and cooling capacity for each thermal zone. In real buildings, these capacities are determined based on the heating and cooling loads assessed during the design phase. In real buildings these values are determined from the thermal and cooling loads study during the design phase of the building.

For the specific application the steady-state method for peak heating loads (Kreider et al., 2002) and the ASHRAE CLF-CLTD method (ASHRAE, 2009) for cooling load calculation are modeled and incorporated in the overall procedure. According to the randomly selected parameters for each virtual building (climatic zone, building size, orientation of openings, type of wall, window, occupants, infiltration and ventilation rates etc.) the installed heating and cooling power at zone level is calculated and forwarded to the TRNSYS model as input.

Because in quite many office buildings in Greece there is a combination of natural ventilation with central HVAC systems (Avgelis and Papadopoulos, 2009) the simulated buildings are considered to be fully air-conditioned, in combination with natural ventilation. For each building an average natural ventilation rate is selected randomly (see Section 5.4.7).

All parameters that are randomly selected together with their selected range are tabulated in Table 5-1.

**Table 5-1: The simulation parameters and their range of values**

Parameter	Range of Values	Comments-References
Climatic Zones	A, B, C	Determined in (Technical Guideline 2425, 1986 )
No of storeys	1-8	
Floor area	256-6400 m <sup>2</sup>	
Wall unit conductance	U=0.452-1.743 W/m <sup>2</sup> K	
Roof unit conductance	U=0.335-3.18 W/m <sup>2</sup> K	
U values of used glass according to window type	U=5.68 W/m <sup>2</sup> K	Single
	U=2.83 W/m <sup>2</sup> K	Double
	U=1.4 W/m <sup>2</sup> K	Low-e
Fraction of Openings	40-80%	Percentage of opening area on a wall of a specific orientation.
Orientation of openings	NSEW, SEW, NEW, NSW, NSE, NS, EW, NE, NW, SW, SE	Facades with openings, with all the possible combinations.
Infiltration rate	0.2-2 ach	(EN 1525, 2006), (Kreider et al., 2002)
Ventilation rate	0.5-10 ach	(Technical Guideline 2425, 1986), (EN 1525, 2006), (Kreider et al., 2002)
Internal shading factor	0-0.8	(EN 1525, 2006)
External shading factor	0-0.8	(Nikolaou et al., 2007) ,(EN 1525, 2006)
Set Point for Heating	20-26 °C	(Technical Guideline 2425, 1986)
Set Point for Cooling	22-26 °C	(Technical Guideline 2425, 1986),
Power of the heating and cooling system	Calculated in MatLab	(Kreider et al., 2002), (ASHRAE, 2009)
Occupancy (occupants/ 100 m <sup>2</sup> )	6-14	
Electric lighting	50 lumen/W	(Krarti, 2000)
Office equipment consumption	0.2217 kW/h/occupant	(Krarti, 2000)
Operating time schedule	Monday-Friday 08:00-22:00 Saturday 08:00-14:00	Monday-Friday 08:00-09:30 – 70% occupancy 09:30-17:30- 100%occupancy 17:30-22:00-30%occupancy Saturday 20%occupancy

## 5.5. Indoor Environment

Apart from the energy consumption, the thermal simulation model evaluates the indoor thermal comfort by calculating the Predicted Mean Vote (PMV) of a representative thermal zone on hourly basis. The annual indoor environmental performance of each building is evaluated by calculating the percentage of time of the occupied hours that PMV lies between the acceptable range  $-0.7 < PMV < +0.7$ , according to the recommended values of the relevant CEN Standard (EN 1525, 2006),

According to Standard, assuming different criteria for the PPD-PMV (EN ISO 7730) different categories of the indoor environment are established. Recommended PMV and PPD ranges are given in the Table 5-2. The PMV-PPD index takes in to account the influence of all 6 thermal parameters (clothing, activity, air- and mean radiant temperature, air velocity and humidity) and can be directly used as criteria. By an assumed combination of activity and clothing, an assumed 50% relative humidity and low air velocities it is possible to establish a corresponding range of operative temperatures and express the criteria as a temperature range. For the design and dimensioning further criteria for the thermal environment (draught, vertical air temperature differences, floor temperature, and radiant temperature asymmetry) should be taken into account (see EN ISO 7730).

**Table 5-2: Recommended PMV and PPD ranges according EN 15251 Standard**

Building Category	Explanation	Thermal State of the body as a whole	
		PPD (%)	PMV
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	<6	-0.2<PMV<+0.2
II	Normal level of expectation and should be used for new buildings and renovations	<10	-0.5<PMV<+0.5
III	An acceptable, moderate level of expectation and may be used for existing buildings	<15	-0.7<PMV<+0.7
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	<15	PMV<-0.7 or PMV>+0.7

## 5.6. The simulation process

Like every model in TRNSYS, the building thermal model referred herein is defined by a computer input file, named with the extension \*.dck, while the parameter values are defined in another input file with the extension \*.bui. These two files are both in ASCII format and they are user editable. This is the feature that was properly exploited for the creation of the VBD. Particularly, the simulation process of 30,000 buildings comprises three distinct stages; construction of input files, batch execution of simulations and result data unification.

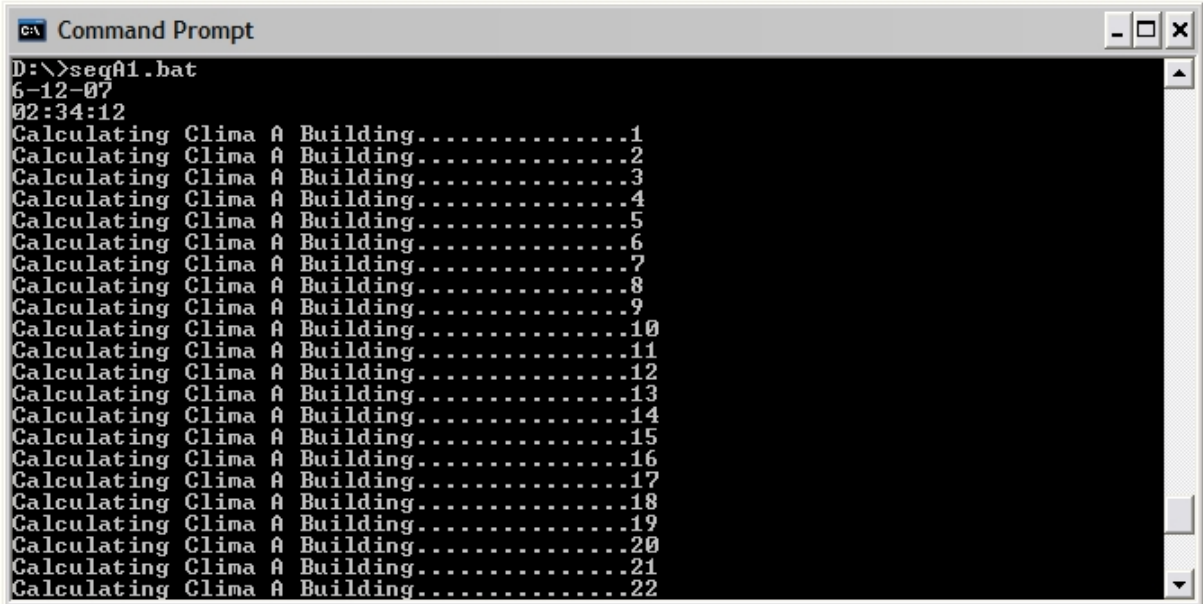
### 5.6.1. Construction of Input Files

The creation of each virtual building was materialized by the proper construction of its BUI and DCK input files. At first, a template BUI and a template DCK file were

created, where the values of each parameter to be defined were replaced by a machine distinguishable verbal variable (e.g. @@VENTILATIONVALUE@@). A script in MatLab was then written to automate the creation of the building input files for each climate zone (Figure 5-4). After prescribing the number of virtual buildings to produce as well as the range of each parameter, the script starts to prepare the input files for each virtual building.

First, it randomly selects the values of each definition parameter (number of stories, orientation, etc.) supposing a uniform distribution scheme for each variable range. As soon as the parameters are set, the script ensures that the virtual building defined in this iteration is unique and no identical building has already been defined in a previous iteration.

If the building is unique, its parameter values are written into an index file along with the index number of the building. Afterwards, the script creates a directory named after the index number of the building and starts reading, line-by-line, the template input files. If there is a verbal variable present in the ASCII line read, it replaces it with its numerical value already defined and appends it to the building's bui or dck file. Otherwise, it copies the line unchanged. As soon as the construction of the input files of a building is completed, the script starts a new iteration for the definition of the next virtual building.



```
Command Prompt
D:\>seq01.bat
6-12-07
02:34:12
Calculating Clima A Building.....1
Calculating Clima A Building.....2
Calculating Clima A Building.....3
Calculating Clima A Building.....4
Calculating Clima A Building.....5
Calculating Clima A Building.....6
Calculating Clima A Building.....7
Calculating Clima A Building.....8
Calculating Clima A Building.....9
Calculating Clima A Building.....10
Calculating Clima A Building.....11
Calculating Clima A Building.....12
Calculating Clima A Building.....13
Calculating Clima A Building.....14
Calculating Clima A Building.....15
Calculating Clima A Building.....16
Calculating Clima A Building.....17
Calculating Clima A Building.....18
Calculating Clima A Building.....19
Calculating Clima A Building.....20
Calculating Clima A Building.....21
Calculating Clima A Building.....22
```

Figure 5-4: The automated creation of the building input files for each climate zone

### **5.6.2. Batch Execution of Simulations**

One feature of TRNSYS is that it can be used in batch mode where its simulation engine can be executed directly from DOS command prompt. Thus, a specific building simulation can be run solely with a single command, in a proper syntax form, eliminating the need to open TRNSYS and run a simulation by hand. The use of the DOS switch "/h" after the command suppresses the loading of TRNSYS graphical interface, reducing dramatically the total simulation time. Exploiting this feature, a script was written in MatLab that produces DOS batch files with the respective DOS commands for each simulation. After each DOS simulation command, another six DOS commands are added in the batch file in order to delete the TRNSYS intermediate log files after the simulation is completed; a step necessary to minimize waste of hard disk space and retain only the results output file.

Additionally, as the execution time required for the 30,000 virtual building simulations on one computer was calculated to be in the order of magnitude of weeks, the script is written in a way that permits the user to define how many building simulation commands to include in each batch file. Thus, a number of batch files can be created which allows for the parallel execution of TRNSYS on many computers, minimizing the total execution time required.

### **5.6.3. Result Data Unification**

As soon as the simulations are completed, the directories of the 30,000 virtual buildings containing the necessary input and output files were gathered from all the computers on one hard disk. Another script in MatLab takes care for the reading and unification of the results of all the buildings in each climate zone in a single file. The outcome is a tabulated ASCII file where each line contains the index number of the building, the values of its definition parameters and the values of the Heating Energy Consumption, Cooling Energy Consumption, Lighting Energy Consumption, Total Energy Consumption and Percentage of time the PMV lies between the specified ranges. (Figure 5-5 and Figure 5-6)

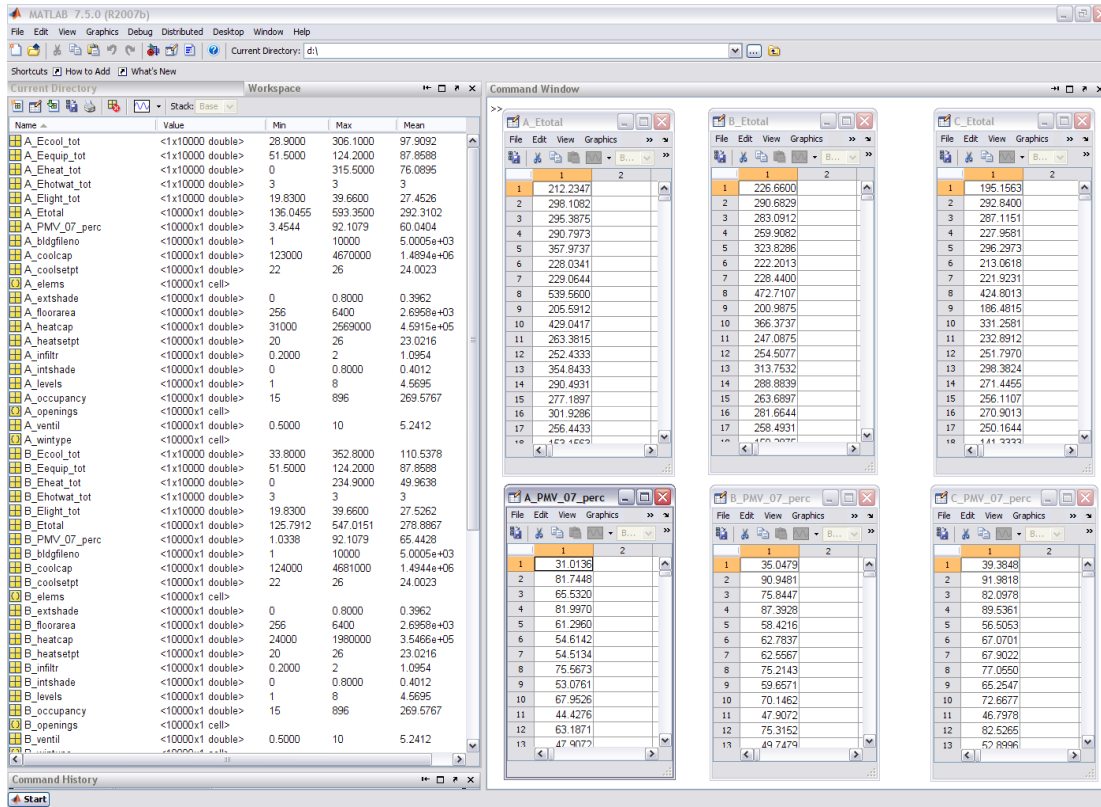


Figure 5-5: VBD in MatLab

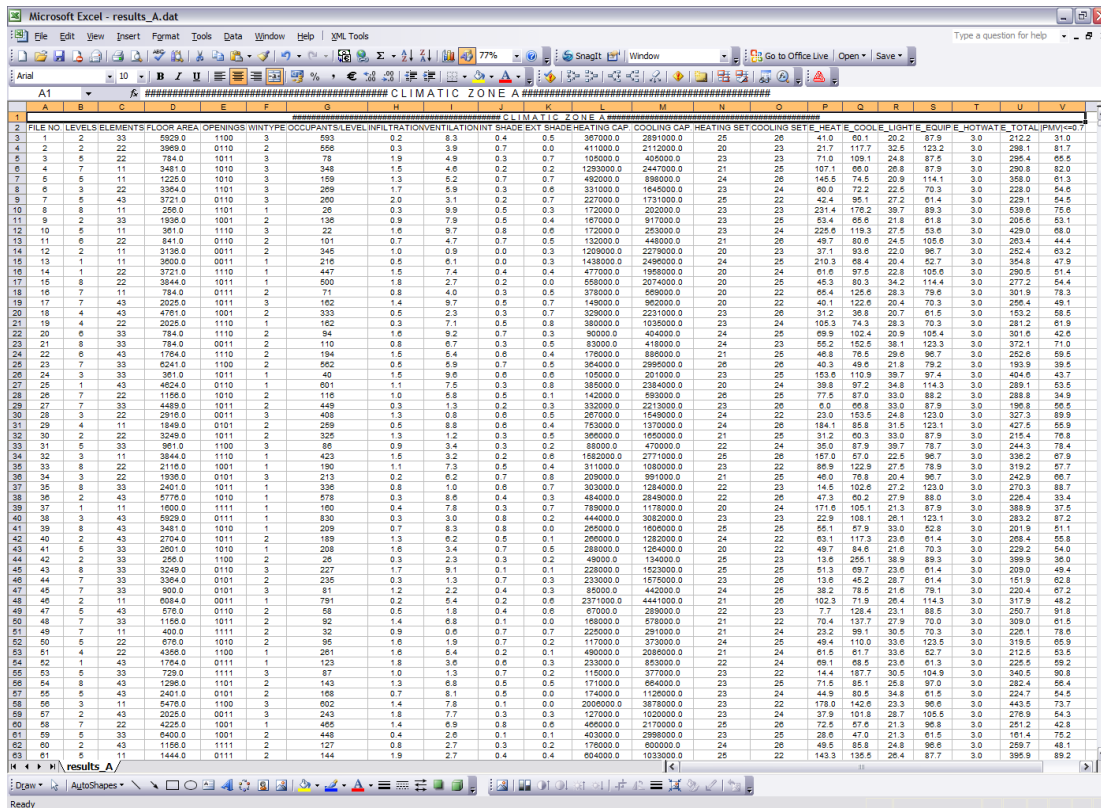


Figure 5-6: VBD in Excel

## 5.7. VBD Results

### 5.7.1. Energy Demand Benchmarks

The energy demand benchmarks of the VBD are presented for each climatic zone. The outcomes of the 30,000 simulations for office buildings in Greece are presented in the following figures for each climatic zone. The simulation outputs for each building are: the energy consumption for heating and cooling demand. In the following figures (Figures 5-7 and 5-8) the cumulative frequency distribution of the energy demand for heating and cooling are illustrated for the three climatic zones.

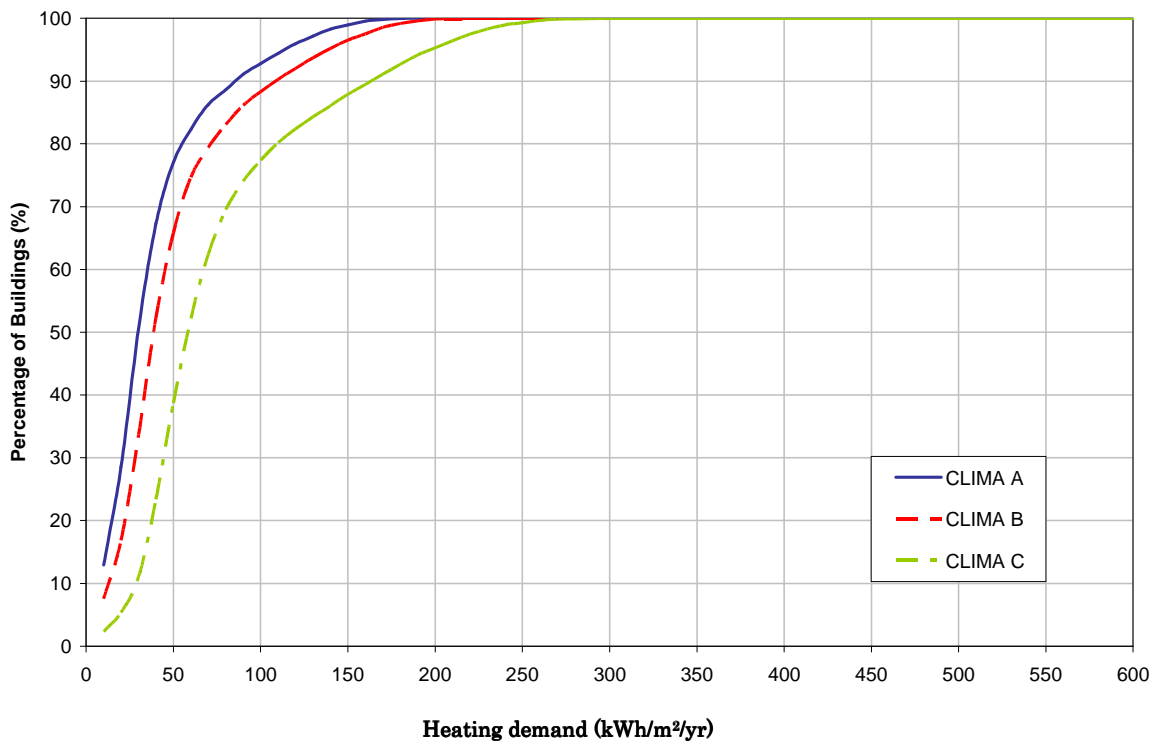
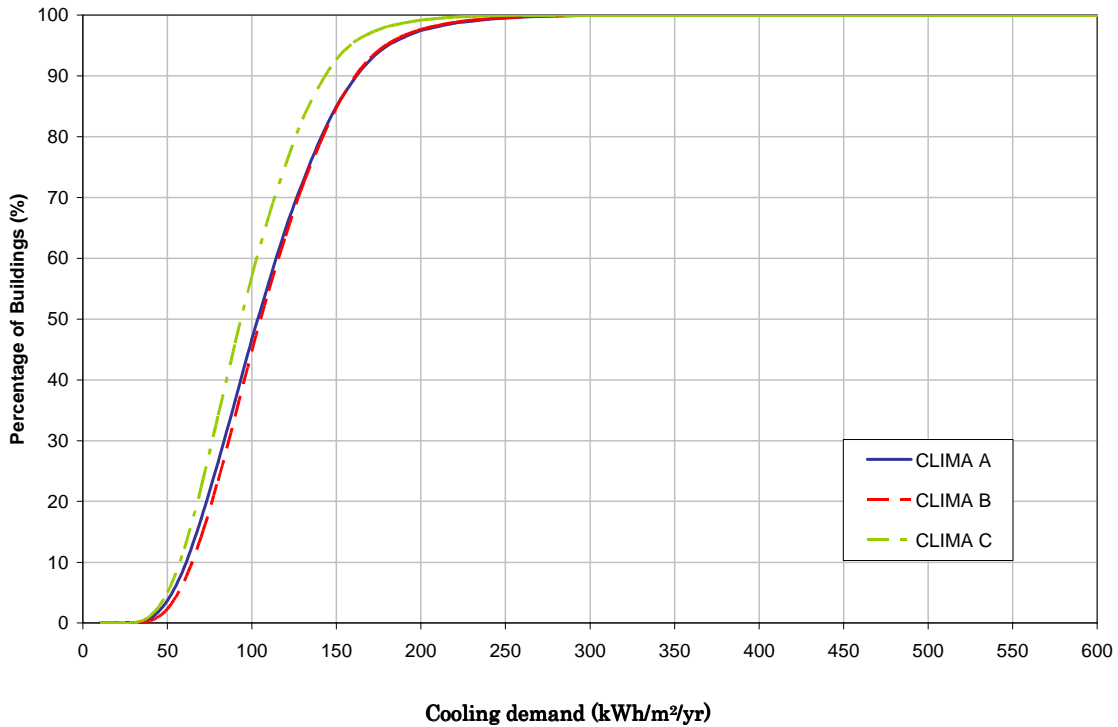


Figure 5-7: Cumulative frequency distribution of heating demand in three climatic zones



**Figure 5-8: Cumulative frequency distribution of cooling demand in three climatic zones**

The large amount of energy data produced by the VBD is used for office buildings energy benchmarking in Greece. The outcomes of the statistical analysis of the 30,000 energy building datasets are presented in Table 5-3.

**Table 5-3: The VBD energy demand benchmarks for office buildings in Greece**

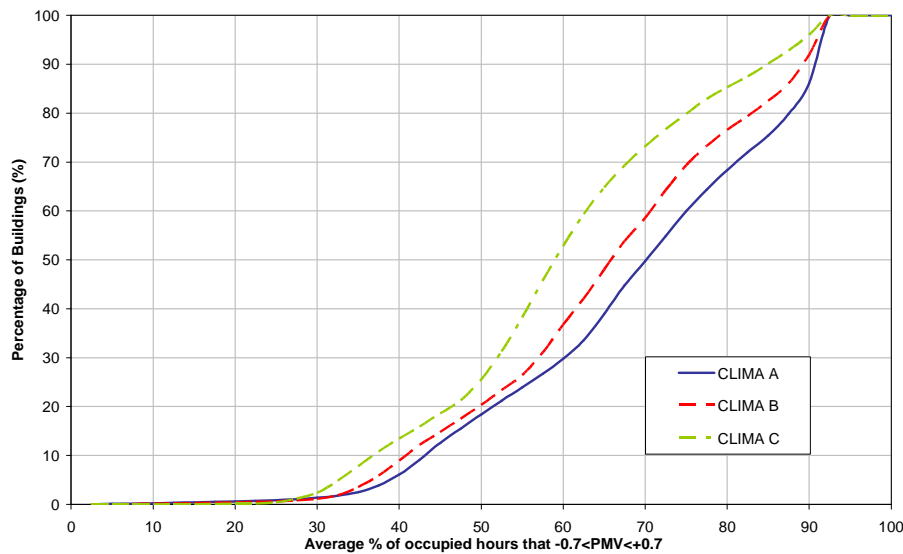
Type of Energy Consumption	Energy demand (kWh/m <sup>2</sup> /year)		
	Climatic Zone		
	A	B	C
Mean energy demand for heating	38.7	50.0	76.1
Typical office building (50% of the stock)-heating	29.7	38.8	58.0
Best practice office building (top 25% of the stock)- heating	18.0	25.2	41.1
Mean energy demand for cooling	108.8	110.5	97.9
Typical office building (50% of the stock)-cooling	103.7	105.3	93.5
Best practice office building (top 25% of the stock)- cooling	78.7	81.5	72.2

As it is observed from the Table 5-3 the mean energy demand for heating has large deviation from the typical energy demand (i.e. the demand that corresponds to the 50% of the cumulative frequency distribution of the stock), which means that VBD contains many buildings with high heating energy demand and their statistical distribution is not normal (Figure 6-5). This occurs because VBD contains many old buildings without insulation, which has important impact to heating demand (see Chapter 6.6.1). On the

contrary, the mean and typical values for cooling demand are very close (i.e. the distribution is very close to normal) because the cooling demand of buildings is not so strongly related with insulation and depends on other building parameters (i.e. ventilation schemes, shading methods, infiltration, etc). (see Chapter 6.6.1).

### 5.7.2. Thermal Comfort Benchmarks

The quality of the indoor environment, apart from which also affects health, productivity and comfort of the occupants, the indoor thermal comfort benchmarking for office building in Greece is also assessed. The chosen indicator (PMV Indicator) according to the CEN Standard is the number of % of occupied hours when the PMV is in the range between  $-0.7$  and  $+0.7$ . In Figure 5-9 the cumulative frequency distributions of the average % of occupied hours that  $-0.7 < \text{PMV} < +0.7$  in climatic zones A, B and C are presented.



**Figure 5-9: Cumulative frequency distribution of the average % of occupied hours that  $-0.7 < \text{PMV} < +0.7$  in three climatic zones**

The indoor thermal comfort benchmarks according to the VBD simulation results for office buildings in Greece are presented in Table 5-4.

**Table 5-4: Indoor thermal comfort benchmarks for office buildings in Greece**

PMV benchmarks	Average % of occupied hours that $-0.7 < PMV < +0.7$		
	Climatic Zone		
	A	B	C
Mean PMV indicator	68.6	65.4	60.0
Typical office building (50% of the stock)-PMV indicator	70.1	65.9	59.0
Best practice office building (top 75% of the stock)- PMV indicator	84.6	78.8	71.3

As it is observed from Table 5-4 the mean and typical values are very close, which means that the distribution is almost normal. The stochastic combination of several of the random variables (see Table 5-1) of equal probability (i.e. uniform distribution) occurring simultaneously for the PMV estimation, results in an approximate normal distribution of PMV index of the dataset considered as a whole.

It is noted that buildings in Climatic Zone A (Southern Greece) have better indoor thermal conditions in comparison to the other two climatic zones. Considering the increased outdoor temperatures and solar radiation during the winter in Southern Greece, a building may have acceptable indoor thermal environment even with a poorly maintained or undersized heating system.

Additionally in the summer period the high values of the wind velocity in Climatic Zone A (especially in the islands) provide an acceptable indoor thermal environment.

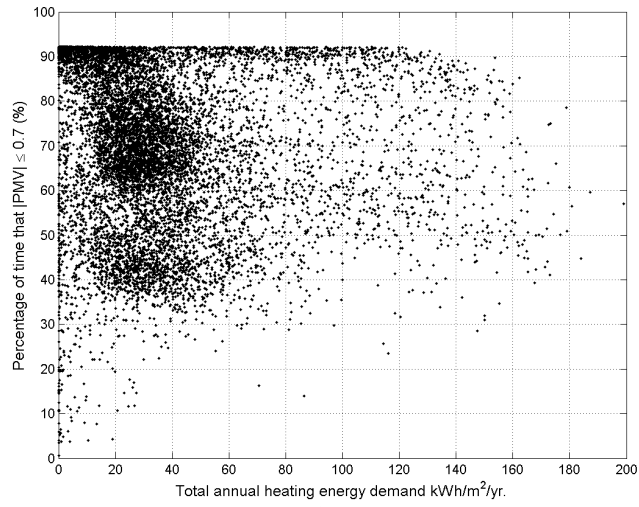
### 5.7.3. Thermal Comfort vs. Energy Consumption

The next step is the investigation of the thermal comfort in relation to the energy consumption of the buildings. In Figures 5-10 and 5-11, the normalized annual energy demand in relation to PMV indicator is depicted for the sample of 30,000 office buildings and for the three climatic zones.

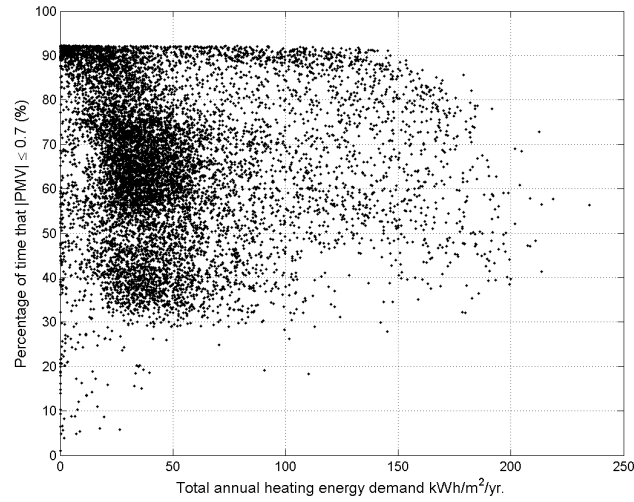
A close examination of the above mentioned figures leads to the following observations:

- In terms of energy and PMV footprints, there is a wide data scattering which depicts the potential of the VBD to generate both normal and marginal office buildings, leading to a reliable distribution.

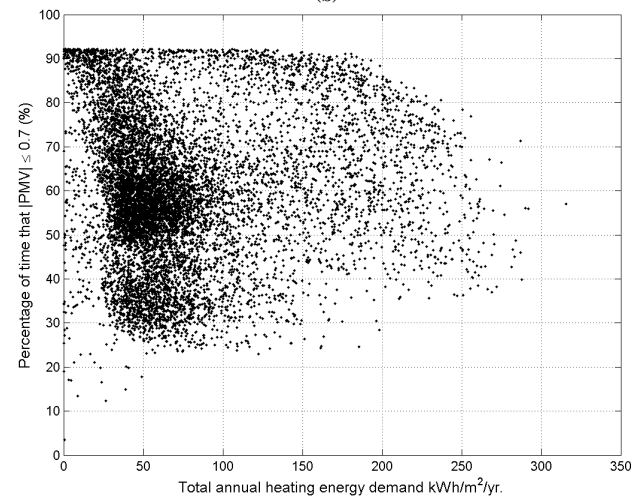
- An absolute maximum of PMV value is found at 91-92%, creating a sharp-like edge at the top. This is both anticipated and explainable for the best practice buildings as far as the PMV indicator is concerned. On some working days, during the morning when the heating-cooling system is activated, there is a small time lag for the system to reach the set point that provides the desirable thermal comfort conditions. This lag counts for the remaining 8-9% of the time that the absolute PMV is greater than the value of 0.7.
- There are buildings demonstrating excellent indoor thermal comfort demanding small amounts of energy. These buildings are found in the upper left corner of each Energy-PMV figures, which constitute the best practice buildings in each climate zone. Given that the VBD features all the characteristics of each building, it is relatively easy to identify all the best practice buildings, classify their characteristics and establish guidelines for the most efficient retrofit scenarios for each individual climatic zone.



(a)

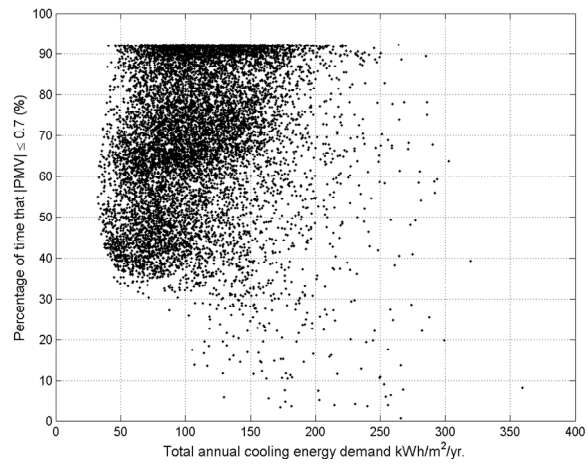


(b)

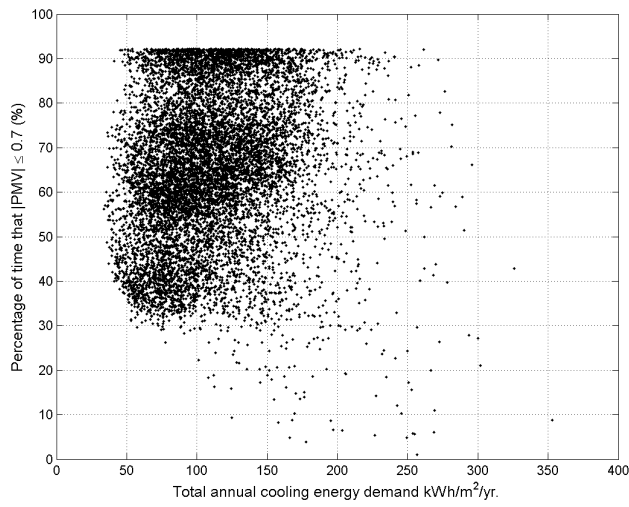


(c)

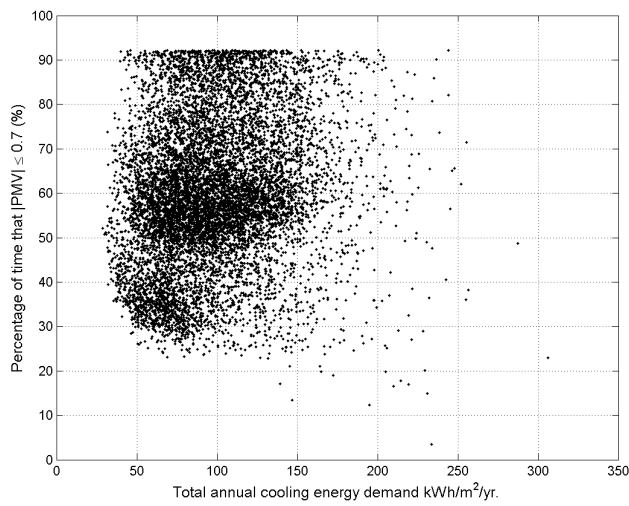
**Figure 5-10: Heating demand in relation to PMV indicator for Climatic Zones A (a), B (b) and C(c)**



(a)



(b)



(c)

Figure 5-11: Cooling demand in relation to PMV indicator for Climatic Zones A (a), B (b) and C(c)

## 5.8. Classification according to CEN Standard using VBD

### 5.8.1. The CEN Standards benchmarks

The relevant standards of CEN are found in the EN ISO 15217 “Energy performance of buildings – Methods for expressing energy performance and for energy certification of buildings” and this clarifies the different possible approaches for certification.

Reference values and benchmarks are used to compare the energy performance of a given building with the energy performance of similar buildings. Different reference values shall be defined for classes of buildings having different building functions (e.g. apartment blocks, offices, hospitals). The following references can be used:

- $R_r$  : Energy performance regulation reference/benchmark.
- $R_s$ : Building stock reference/benchmark. It represents the energy performance reached by approximately 50% of the national or regional building stock.
- $R_0$ : Zero energy reference/benchmark. This corresponds to a building that produces as much energy as it uses.

The use of energy considered when defining the reference values/benchmarks shall be the same as the use of energy considered when establishing the rating. If the rating used is an asset rating, the reference will be obtained with the same assumptions as the asset rating regarding use patterns and internal and external climate (EN 15217, 2007).

The energy performance certificate is expected to classify buildings on a banded scale from A (best) to G (worst). The A-G bands will provide a broad indicator of energy performance of the building and they will be complemented by a numeric indicator that provides more scrutiny. An important aspect of the energy performance certificate is that it is to be accompanied by recommendations for cost-effective improvements to the building (Anderson, 2006).

Annex B of EN ISO 15217 provides a simple procedure to define the limits of the classifications of energy performance (EP). The steps of this procedure are the following:

- Define the type of the building (e.g. office building).

- Select the references  $R_r$  and  $R_s$  corresponding to this building type.
- Define the value of the energy performance of the building EP: Calculate  $\frac{EP}{R_r}$  and

$$\frac{EP}{R_s}$$

- Determine the classification indicator C with the following rules:

If  $\frac{EP}{R_r} \leq 1$  take  $C = \frac{EP}{R_r}$  (EP is better than  $EP_r$ )

If  $1 \leq \frac{EP}{R_s}$  take  $C = 1 + \frac{EP}{R_s}$  (EP is poorer than  $EP_s$ )

In other case  $C = 1 + \frac{EP - R_r}{R_s - R_r}$  (EP is between the  $EP_r$  and  $EP_s$ )

- Determine the performance class with the following rules:

Class A if  $C < 0.5$

Class B if  $0.5 \leq C < 1$

Class C if  $1 \leq C < 1.5$

Class D if  $1.5 \leq C < 2$

Class E if  $2 \leq C < 2.5$

Class F if  $2.5 \leq C < 3$

Class G if  $3 \leq C$

In addition Annex B of EN ISO 15217 provides two examples of the energy certificate format. These examples are presented in Figure 5-12 and refer to one single rating and to two ratings shown together.

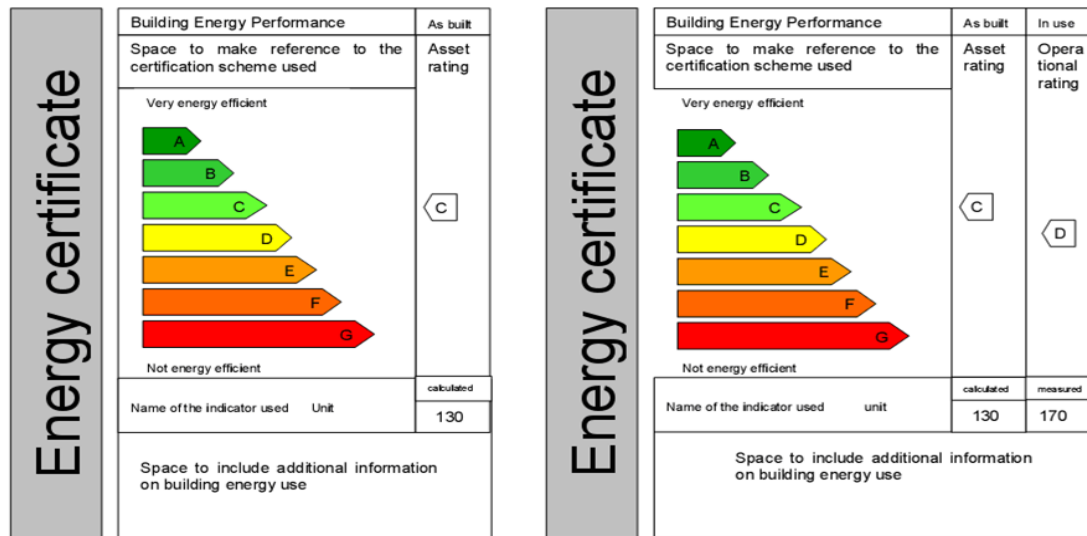


Figure 5-12: Examples of energy certificates' format [Source: EN 15257, 2007]

The establishment of energy benchmarks ( $R_0$ ,  $R_s$ ,  $R_r$ ) is essential in order to rate and certify a building. Benchmarking requires uniformly collected key usage indicators and identification of the property’s specific characteristics (drivers) that must be taken into consideration for grouping the key indicators.

### 5.8.2. Energy classification according to CEN method

Taking into account the VBD benchmarks and applying the proposed CEN method for energy boundaries determination the following classifications for office buildings in Greece are proposed. In the framework of the present thesis, the method has been applied to heating and cooling demand for the three climatic zones. In the case of applying this method to the total energy consumption using VBD the heating efficiency and the COP values has to be taken in to account.

#### 5.8.2.1. Heating Demand classification according to CEN method

According to VBD energy benchmarks (Table 5-3) Building Stock Reference ( $R_{s-h}$ ) and Building Regulation Reference ( $R_{r-h}$ ) for heating energy demand and for each climatic zone are presented in Table 5-7. The Building Regulation Reference has been evaluated as the 75% of Building Stock reference according the draft of Greek Energy Performance Building regulation.

**Table 5-5: Building Stock and Regulation Reference for heating**

	Climatic Zones		
	A	B	C
Building Stock Reference-heating ( $R_{s-h}$ in kWh/m <sup>2</sup> /y)	30	39	58
Building Regulation Reference -heating ( $R_{r-h}$ in kWh/m <sup>2</sup> /y)	22	29	44

**Table 5-6: Heating Energy Classification for office buildings according to CEN method**

Energy Classes	Energy Demand for Heating (DH) kWh/m <sup>2</sup> /year		
	Climatic Zone A	Climatic Zone B	Climatic Zone C
	A	DH<11	DH<15
B	11 ≤ DH < 22	15 ≤ DH < 29	22 ≤ DH < 44
C	22 ≤ DH < 26	29 ≤ DH < 34	44 ≤ DH < 51
D	26 ≤ DH < 30	34 ≤ DH < 39	51 ≤ DH < 58
E	30 ≤ DH < 45	39 ≤ DH < 58	58 ≤ DH < 87
F	45 ≤ DH < 59	58 ≤ DH < 78	87 ≤ DH < 116
G	59 ≤ DH	78 ≤ DH	116 ≤ DH

#### 5.8.2.2. Cooling Demand classification according to CEN method

According to VBD energy benchmarks (Table 5-3) Building Stock Reference ( $R_{s-c}$ ) and Building Regulation Reference ( $R_{r-c}$ ) for cooling energy consumption and for each climatic zone are presented in Table 5-9. The Building Regulation Reference has been evaluated as the 75% of Building Stock reference according the draft of Greek Energy Performance Building regulation.

**Table 5-7: Building Stock and Regulation Reference for cooling**

	Climatic Zones		
	A	B	C
Building Stock Reference-cooling ( $R_{s-c}$ in kWh/m <sup>2</sup> /y)	104	105	94
Building Regulation Reference-cooling ( $R_{r-c}$ in kWh/m <sup>2</sup> /y)	78	79	70

**Table 5-8: Cooling Demand Classifications for office buildings according to CEN method**

Energy Classes	Energy Demand for Cooling (EC) kWh/m <sup>2</sup> /year		
	Climatic Zone A	Climatic Zone B	Climatic Zone C
A	DC<39	DC<39	DC<35
B	39 ≤ DC < 78	39 ≤ DC < 79	35 ≤ DC < 70
C	78 ≤ DC < 91	79 ≤ DC < 92	70 ≤ DC < 82
D	91 ≤ DC < 104	92 ≤ DC < 105	82 ≤ DC < 94
E	104 ≤ DC < 156	105 ≤ DC < 158	94 ≤ DC < 140
F	156 ≤ DC < 207	158 ≤ DC < 211	140 ≤ DC < 187
G	207 ≤ DC	211 ≤ DC	187 ≤ DC

## **5.9. Adaptability of VBD**

One of the advantages of the VBD proposed method is the flexibility to many parameters. The adopted VBD method is adaptable according to the following parameters:

- The required dataset size of VBD
- The climatic conditions
- The country of which the building stock VBD represents
- The building category
- Heating and cooling system efficiency

VBD is a useful tool to any process requires large number of building datasets. Depending on the research purpose (e.g. rating, clustering, classification, neural network training, retrofit scenarios investigation etc.) each time, VBD method can create the required dataset size, depending on the available hard disc space.

The method can also be applied for any climatic conditions, since climatic data are available in the specific form of TRNSYS input file. Moreover the method can be generalized globally for creating a VBD in any country by changing the weather input data according to the country's climatic zones division and the material and construction databases according to the constructional characteristics of materials and structural elements dominating the country's building sector and the

Following the same concept, VBD is adaptable to any building category by changing the values ranges of all the simulation parameters according the building category (offices, residential buildings, hospitals, schools, etc.) that is investigated and the national codes for indoor environment parameters.

In the same concept, VBD is adaptable to time. After desirable time, e.g. 2, 5, 10 etc. years VBD for office buildings in Greece can be updated by adding new materials and structural elements in VBD libraries, by changing the shading methods, the heating-cooling system, the time schedules and any other parameter.

VBD is a dataset that contains the heating and cooling demand of the buildings. By taking into account the heating and cooling efficiency of the heating-cooling installed

system the total energy consumption may be investigated since the energy consumption for lighting and equipment has been taken into account.

In general, since the core of the VBD method is available, the user may create any kind of building dataset. The accuracy of the adopted dataset depends on the parameter and assumptions selection.

## **5.10. Conclusions**

In this chapter, an innovative approach for producing a Virtual Building Dataset (VBD) is demonstrated in order to investigate the energy and indoor thermal comfort efficiency of a user-defined number of virtual office buildings. The method is applied to 10,000 office buildings for each of the three major climatic zones in Greece. Besides the constructional and operational characteristics of each building, the VBD contains the calculated energy demands for heating, cooling, energy consumption for lighting and appliances as well as the indoor thermal comfort requirements.

The method is easily adapted to any country's building constructional and operational ranges and climatic zone data for producing a respective localized VBD. Such an approach could constitute a reliable and time-saving substitute to the real building data collection required prior to the definition of energy classes.

Moreover, it is important that this virtual building dataset can be used for the definition of the limits of the energy classes (cluster analysis) for each building category. The optimum, though, use of the VBD is in combination with smaller in size but real datasets for each building category, in order to ensure reliable and safe results.

Additionally, the VBD can be used as the basis for a parametric study of one or more building characteristics with respect to the energy and thermal comfort efficiency attained. In order to proceed with an integrated building efficiency approach, correlating the energy consumption to the thermal comfort of the building, VBD proves to be a valuable tool for the definition of respective guidelines.

Moreover, VBD is a useful tool for building energy clustering, energy rating procedures, determination of energy and indoor thermal environment building classification boundaries, neural networks training and validation, multi-criteria

decision making data for building retrofit scenarios, sensitivity analysis and to any process requires large number of building data, in general.

The advantages of the VBD compared to a real dataset is the capability of simulating a large amount of buildings, the flexibility to isolate and study the interaction of various parameters and their effect in the energy performance of the buildings, the possibility to mass study different scenarios for improving the energy efficiency of a large number of buildings and not only on individual case-study buildings.

## Chapter 6

# OFFICE BUILDINGS' CLASSIFICATION USING CLUSTERING TECHNIQUES

## CHAPTER 6: OFFICE BUILDINGS' CLASSIFICATION USING CLUSTERING TECHNIQUES

### 6.1. Introduction

Clustering is one of the most useful tasks in data mining process for discovering groups and identifying interesting distributions and patterns in the underlying data. Clustering problem is about partitioning a given data set into groups (clusters) such that the data points in a cluster are more similar to each other than points in different clusters (Guha et al., 1998).

The main concern in the clustering process is to reveal the organization of patterns into “sensible” groups, which allow us to discover similarities and differences, as well as to derive useful conclusions about them. This idea is applicable in many fields, such as life sciences, medical sciences and engineering. Clustering may be found under different names in different contexts, such as unsupervised learning (in pattern recognition), numerical taxonomy (in biology, ecology), typology (in social sciences) and partition (in graph theory) (Theodoridis and Koutroubas, 1999).

In the clustering process, there are no predefined classes and no examples that would show what kind of desirable relations should be valid among the data that is why it is perceived as an unsupervised process. On the other hand, classification is a procedure of assigning a data item to a predefined set of categories (Fayyad et al., 1996). Clustering produces initial categories in which values of a data set are classified during the classification process.

Cluster analysis is a major tool in a number of applications in many fields of business and science. Hereby, we summarize the basic directions in which clustering are used (Theodoridis and Koutroubas, 1999):

- **Data reduction.** Cluster analysis can contribute in compression of the information included in data. In several cases, the amount of available data is very large and its processing becomes very demanding. Clustering can be used to partition data set into a number of “interesting” clusters.

- **Hypothesis generation.** Cluster analysis is used here in order to infer some hypotheses concerning the data.
- **Hypothesis testing.** In this case, the cluster analysis is used for the verification of the validity of a specific hypothesis.
- **Prediction based on groups.** Cluster analysis is applied to the data set and the resulting clusters are characterized by the features of the patterns that belong to these clusters. Then, unknown patterns can be classified into specified clusters based on their similarity to the clusters' features. Useful knowledge related to our data can be extracted.

A clustering technique has been used in one research for building classification. Santamouris et al (Santamouris et al., 2007) proposed an energy rating and certification method for Greek school buildings based on intelligent clustering techniques. Five energy classes for schools buildings for both total and heating energy consumption have been calculated. The results showed mean energy consumption for heating 68kWh/m<sup>2</sup>/year and for electricity 27kWh/m<sup>2</sup>/year. The energy benchmarks that applied for schools in Greece were for a typical school building (50% of the stock): Heating 57kWh/m<sup>2</sup>/year, Electricity 20 kWh/m<sup>2</sup>/year and for best practice building (top 25% of the stock): Heating 32kWh/m<sup>2</sup>/year, Electricity 10 kWh/m<sup>2</sup>/year. In addition to energy consumption, the comfort and indoor air quality of Greek schools buildings was examined. This proposed energy classification method can be applied in order to classify the energy performance of a school or other types of buildings.

In this doctoral research, five clustering techniques are tested in order to investigate the appropriate method for establishing energy and thermal comfort classifications for the Greek office building sector. The clustering algorithms that have been applied to VBD for this purpose are:

- Hierarchical Clustering (HC)
- K-Means Clustering (KMC)
- Gaussian Mixture Models Clustering (GMM)
- Fuzzy C-Means Clustering (FC)
- Neural Network Based Clustering (NNC)

Each method has been applied to energy demand for heating, energy demand for cooling and PMV index for each climatic zone and for 2 to 9 classes.

Then, in order to evaluate the clustering results of our problem, three internal validity indices have been selected for testing the investigated methods in order to select the appropriate number of clusters (k) and the more efficient algorithm for each case.

The aim of this chapter is to propose a methodology for classifying office buildings in Greece, in terms of energy demand and indoor thermal comfort and then to investigate the common buildings' characteristics in each class. It is noted that the classification does not refer to the final energy consumption of the buildings, i.e. the efficiency coefficients of heating ( $\eta$ ) and cooling (COP) have not been taken into account.

## **6.2. Mathematical description of the clustering algorithms**

### **6.2.1. Hierarchical Clustering**

Hierarchical clustering (HC) is one of the most known unsupervised methods because of its simple concept. HC algorithms organize data into a hierarchical structure according to the proximity matrix. The results of HC are usually represented in a tree structure called dendrogram (Figure 6-1). The root node of the dendrogram reflects the whole dataset (single cluster containing all data objects) and each leaf node corresponds to an individual data object. The intermediate nodes describe the proximity among the objects. The height of the dendrogram expresses the distance between each pair of objects or clusters, or an object and a cluster. The ultimate clustering results can be obtained by cutting the dendrogram at different levels. This representation provides very informative descriptions and visualization for the potential data clustering structures, especially when real hierarchical relations exist in the data, like the data from evolutionary research on different species of organisms.

HC algorithms are mainly divided in two basic categories: agglomerative methods and divisive methods. Agglomerative clustering starts with N clusters and each of them includes exactly one data object. A series of merge operations are then followed out that finally lead all objects to the same group. Divisive clustering proceeds in an opposite way. In the beginning, the entire dataset belongs to one cluster and a procedure successively divides it, until all clusters are singleton clusters. For a cluster

with  $N$  objects, there are  $2^{N-1} - 1$  possible two-subset divisions, which is very expensive in computation. Therefore, divisive clustering is not commonly used in practice (Xu and Wunsch, 2005).

The general agglomerative HC can be summarized by the following procedure:

1. Start with  $N$  singleton clusters. Calculate the proximity matrix for the  $N$  clusters.
2. Search the minimal distance

$$D(C_i, C_j) = \min_{\substack{1 \leq m, l \leq N \\ m \neq l}} D(C_m, C_l) \quad (6-1)$$

Where  $D(*, *)$  is the distance function in the proximity matrix, and combine cluster  $C_i$  and  $C_j$  to form a new cluster.

3. Update the proximity matrix by computing the distances between the new cluster and the other clusters.
4. Repeat steps 2, 3 until all the objects are in the same cluster.

There are many variations of HC algorithms based on different definitions for distance between two clusters. Among the most used variations are:

- Single Linkage clustering (Minimum or Nearest-Neighbor method): The distance between two clusters is determined by the two closest objects in different clusters.
- Complete Linkage clustering (Maximum or Furthest-Neighbor method): The distance between two clusters is equal to the greatest distance between an object of cluster  $i$  and an object of cluster  $j$ .
- Average Linkage clustering: The distance between two clusters is calculated using average values. The average distance is calculated from the distance between each point in a cluster and all other points in another cluster. The two clusters with the lowest average distance are joined together to form the new cluster .
- Centroid Linkage clustering: This variation uses the group centroid as the average. The centroid is defined as the center of the cloud of points.

The major disadvantage for classical HC algorithms is that they lack robustness and are, hence, sensitive to noise and outliers. Once an object is assigned to a cluster, it

will not be considered again, which means that HC algorithms are not capable of correcting possible previous misclassification. The computational complexity for most of HC algorithms is at least  $O(N^2)$  and this limits their ability to handle large datasets within a reasonable time and memory resources (Xu & Wunsch, 2005).

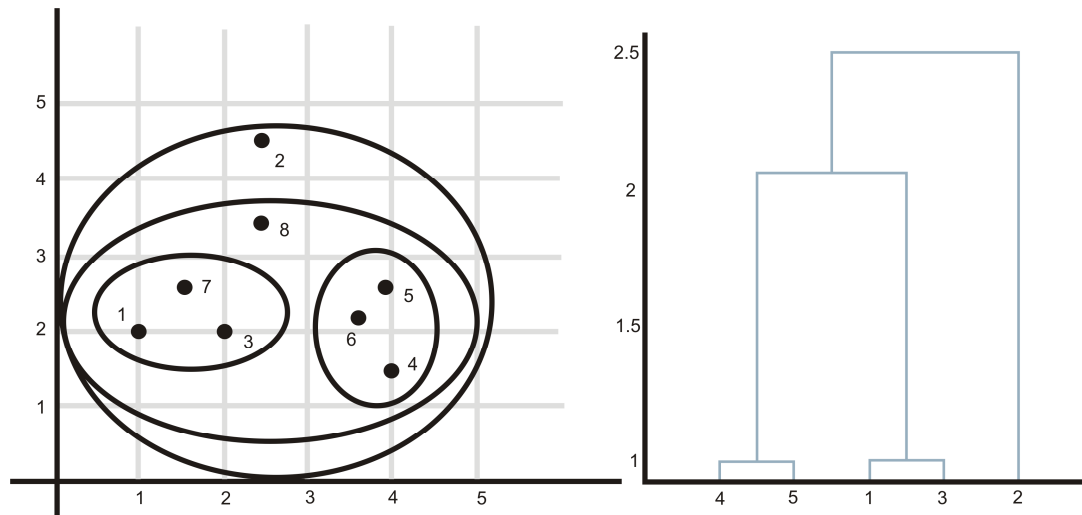


Figure 6-1: Objects into a hierarchy of clusters and the dendrogram

### 6.2.2. K-Means Clustering

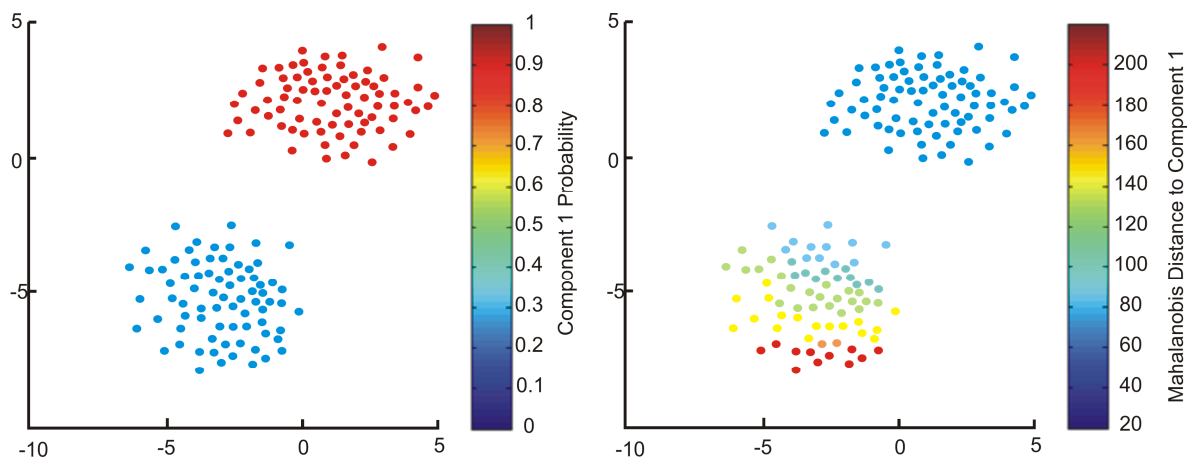
K-means is a partitional clustering technique that assigns a set of objects into K clusters with no hierarchical structure. In principle, the optimal partition, based on some specific criterion, can be found by enumerating all possibilities. The K-means algorithm is very simple and can be easily implemented to solve many practical problems. It can work very well for compact and hyperspherical clusters and can be used to cluster large data sets (Xu & Wunsch, 2005). The algorithm consists of a simple re-estimation procedure as follows. Initially, the data points are assigned at random to the K sets. For step 1, the centroid is computed for each set. In step 2, every point is assigned to the cluster whose centroid is closest to that point. These two steps are alternated until a stopping criterion is met, i.e., when there is no further change in the assignment of the data points (Bishop, 1995).

### 6.2.3. GMM Clustering

Mixture models are a semi-parametric alternative to non-parametric histograms (which can also be used as densities) and provide greater flexibility and precision in modelling the underlying statistics of sample data. (Bishop, 1995).

In the probabilistic view, data objects are assumed to be generated according to several probability distributions. Data points in different clusters were generated by different probability distributions that can be derived from different types of density functions (e.g., multivariate Gaussian). If the distributions are known, finding the clusters of a given data set is equivalent to estimating the parameters of several underlying models (Xu and Wunsch, 2005). Gaussian Mixture clustering involves the model selection, i.e., to determine the number of components in a mixture (also called model order interchangeably) and the estimation of the parameters of each component in a mixture, through the observed data each represented as a vector of features (also referred to as attributes or variables) (Zeng & Cheung, 2008). Gaussian classifiers are strongly dependent on the posterior probability method and the underlying distance method, namely the Mahalanobis distance. The latter is also used for the detection of outliers (Woifel & Ekenel, n.d.). In

Figure 6-2, these two methods are illustrated referring to data from a mixture of two bivariate Gaussian distributions.



**Figure 6-2: The Posterior method and the Mahalanobis method**

### 6.2.4. Fuzzy C-Means Clustering

The Fuzzy C-means clustering algorithm is based on the minimization of an objective function called C-means functional. It is defined by Dunn (Dunn, 1974) as:

$$J(X;U,V) = \sum_{i=1}^c \sum_{k=1}^N (\mu_{ik})^m \|x_k - v_i\|_A^2 \quad (6-2)$$

Where:

$$V = [v_1, v_2, \dots, v_c], v_i \in R^n \quad (6-3)$$

is a vector of cluster prototypes (centers), which have to be determined, and

$$D_{ikA}^2 = \|x_k - v_i\|_A^2 = (x_k - v_i)^T A (x_k - v_i) \quad (6-4)$$

is a squared inner product distance norm.

Statistically, equation (6-2) can be seen as a measure of the total variance of  $x_k$  from  $v_i$ . The minimization of the c-means functional (6-2) represents a nonlinear optimization problem that can be solved by using a variety of available methods, ranging from grouped coordinate minimization, over simulated annealing to genetic algorithms. The most popular method, however, is a simple Picard iteration through the first-order conditions for stationary points of equation (6-2), known as the fuzzy c-means (FCM) algorithm.

### 6.2.5. Neural Clustering (Self Organized Maps-SOM)

A self-organizing map (SOM) or self organizing feature map (SOFM) is a neural - network-based divisive clustering approach. The objective of SOM is to represent high-dimensional input patterns with prototype vectors that can be visualized in a usually two-dimensional lattice structure. Each unit in the lattice is called a neuron, and adjacent neurons are connected to each other, which gives the clear topology of how the network fits itself to the input space. Input patterns are fully connected to all neurons via adaptable weights, and during the training process, neighboring input patterns are projected into the lattice, corresponding to adjacent neurons.

Basic SOM training goes through the following steps (Xu and Wunsch, 2005):

1. Define the topology of the SOM; Initialize the prototype  $Wv_i(0)$ ,  $i = 1, \dots, K$  vectors randomly.

2. Present an input pattern  $\mathbf{x}$  to the network; Choose the winning node  $J$  that is closest to  $\mathbf{x}$ , i.e.,  $J = \arg_i \min \{\|\mathbf{x} - m_i\|\}$
3. Update prototype vectors  $m_i(t+1) = m_i(t) + h_{ci}(t)[\mathbf{x} - m_i(t)]$ , where  $h_{ci}(t)$  is the neighbourhood function that is often defined as:  $h_{ci}(t) = a(t) \exp\left(\frac{-\|r_c - r_i\|^2}{2\sigma^2(t)}\right)$ , where  $a(t)$  is the monotonically decreasing learning rate,  $r$  represents the position of the corresponding neuron, and  $\sigma(t)$  is the monotonically decreasing kernel width function.
4. Repeat steps 2 and 3 until no change of neuron position that is more than a appositive number is observed.

While SOFM enjoy the merits of input space density approximation and independence of the order of input patterns, a number of user-dependent parameters cause problems when applied in real practice. SOM need to predefine the size of the lattice, i.e., the number of clusters, which is unknown for most circumstances. Additionally, trained SOM may be suffering from input space density misrepresentation, where areas of low pattern density may be over-represented and areas of high density under-represented.

### 6.3. Analysis and Results

The five aforementioned clustering algorithms have been applied to VBD. In order to create clusters of each kind energy demand (heating, cooling) for each climatic zone (A, B and C), three different 10,000×1 matrices (A\_E, B\_E and C\_E) have been used from VBD for each case, which contains the energy demand results for the three climatic zones. The quality of indoor environment is expressed with the percentage of time of the occupied hours during which PMV is between the acceptable range - 0.7 < PMV < +0.7, according to the recommended values of European CEN Standard. In order to cluster PMV index for each climatic zone, three different 10,000×1 matrices (A\_PMV, B\_PMV and C\_PMV) have been used.

We have to note that classification based on the input variables has no natural meaning since all the variables are mutually independent and were randomly selected using uniform distribution.

In this section the results of cluster algorithms application to VBD are presented in the following tables.

### 6.3.1. Hierarchical Clustering Results

Table 6-1: Hierarchical classification for heating demand

HEATING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-68.40	0.00-68.40	0.00-68.40	0.00-36.10	0.00-36.10	0.00-36.10	0.00-10.50	0.00 – 10.50
B	68.50-199.00	68.50-116.80	68.50-116.80	36.20-68.40	36.20-68.40	36.20-68.40	10.60-36.10	10.60-36.10
C		117.00-199.00	117.00-153.20	68.50-116.80	68.50-91.80	68.50-91.80	36.20-68.40	36.20-53.90
D			153.70-199.00	117.00-153.20	92.00-116.80	92.00-116.80	68.50-91.80	54.00-68.40
E				153.70-199.00	117.00-153.20	117.00-153.20	92.00-116.80	68.50-91.80
F					153.70-199.00	153.70-176.60	117.00-153.20	92.00-116.80
G						178.80-199.00	153.70-176.60	117.00-153.20
H							178.80-199.00	153.70-176.60
I								178.80-199.00
HEATING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-69.80	0.00-69.80	0.00-69.80	0.00-69.80	0.00-69.80	0.00-41.80	0.00-41.80	0.00-21.40
B	69.90-234.90	69.90-133.50	69.90-133.50	69.90-100.50	69.90-100.50	41.90-69.80	41.90-69.80	21.50-41.80
C		133.70-234.90	133.70-204.80	101.00-133.50	101.00-133.50	69.90-100.50	69.90-100.50	41.90-69.80
D			207.50-234.90	133.70-204.80	133.70-157.90	101.00-133.50	101.00-133.50	69.90-100.50
E				207.50-234.90	158.40-204.80	133.70-157.90	133.70-157.90	101.00-133.50
F					207.50-234.90	158.40-204.80	158,40-204.80	133.70-157.90
G						207.50-234.90	207.50-218.60	158.40-204.80
H							234.90-234.90	207.50-218.60
I								234.90-234.90
HEATING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-111.80	0.00-111.80	0.00-111.80	0.00-68.40	0.00-68.40	0.00-68.40	0.00-10.70	0.00-10.70
B	111.90-15.50	111.90-192.20	111.90-192.20	68.50-111.80	68.50-111.80	68.50-111.80	10.80-68.40	10.8-68.40
C		192.40-315.50	192.40-262.10	111.90-192.20	111.90-150.90	111.90-150.90	68.50-111.80	68.50-111.80
D			263.90-315.50	192.40-262.10	151.00-192.20	151.00-192.20	111.90-150.90	111.90-150.90
E				263.90-315.50	192.40-262.10	192.40-262.10	151.00-192.20	151.00-192.20
F					263.90-315.50	263.90-292.00	192.40-262.10	192.40-222.30
G						315.50-315.50	263.90-292.00	222,90 - 262,10
H							315.50-315.50	263.90-292.00
I								315.50-315.50

Table 6-2: Hierarchical classification for cooling demand

COOLING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	32.50-228.40	32.50-228.40	32.50-138.80	32.50-138.80	32.50-82.90	32.50-82.90	32.50-82.90	32.50-82.90
B	229.90-359.40	229.90-302.50	138.90-228.40	138.90-184.10	83.00-138.80	83.00-138.80	83.00-138.80	83.00-113.60
C		319.40-359.40	229.90-302.50	184.40-228.40	138.90-184.10	138.90-184.10	138.90-184.10	113.70-138.80
D			319.40-359.40	229.90-302.50	184.40-228.40	184.40-228.40	184.40-228.40	138.90-184.10
E				319.40-359.40	229.90-302.50	229.90-302.50	229.90-260.80	184.40-228.40
F					319.40-359.40	319.40-319.40	264.10-302.50	229.90-260.80
G						359.40-359.40	319.40-319.40	264.10-302.50
H							359.40-359.40	319.40-319.40
I								359.40-359.40
COOLING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	33.80-236.70	33.80-236.70	33.80-149.40	33.80-149.40	33.80-93.10	33.80-93.10	33.80-93.10	33.80-93.10
B	238.80-352.80	238.80-301.70	149.50-236.70	149.50-195.50	93.20-149.40	93.20-149.40	93.20-116.60	93.20-116.60
C		325.90-352.80	238.80-301.70	195.90-236.70	149.50-195.50	149.50-195.50	116.70-149.40	116.70-149.40
D			325.90-352.80	238.80-301.70	195.90-236.70	195.90-236.70	149.50-195.50	149.50-195.50
E				325.90-352.80	238.80-301.70	238.80-262.00	195.90-236.70	195.90-236.70
F					325.90-352.80	266.40-301.70	238.80-262.00	238.80-262.00
G						325.90-352.80	266.40-301.70	266.40-301.70
H							325.90-352.80	325.90-325.90
I								352.80-352.80
COOLING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	28.90-180.40	28.90-180.40	28.90-95.50	28.90-95.50	28.90-95.50	28.90-58.30	28.90-58.30	28.90-58.30
B	180.90-306.10	180.90-256.50	95.60-180.40	95.60-142.40	95.60-142.40	58.40-95.50	58.40-95.50	58.40-95.50
C		287.50-306.10	180.90-256.50	142.60-180.40	142.60-180.40	95.60-142.40	95.60-142.40	95.60-119.90
D			287.50-306.10	180.90-256.50	180.90-214.60	142.60-180.40	142.60-180.40	120.00-142.40
E				287.50-306.10	216.30-256.50	180.90-214.60	180.90-214.60	142.60-180.40
F					287.50-306.10	216.30-256.50	216.30-238.70	180.90-214.60
G						287.50-306.10	242.70-256.50	216.30-238.70
H							287.50-306.10	242.70-256.50
I								287.50-306.10

**Table 6-3: Hierarchical classification for quality of indoor environment**

AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE A (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11-29.53	92.11-69.34	92.11-69.34	92.11-69.34	92.11-82.93	92.11-82.93	92.11-82.93	92.11-82.93
B	29.10-0.66	69.31-29.53	69.31-50.56	69.31-50.56	82.91-69.34	82.91-69.34	82.91-69.34	82.91-69.34
C		29.10-0.66	50.53-29.53	50.53-29.53	69.31-50.56	69.31-61.62	69.31-61.62	69.31-61.62
D			29.10-0.66	29.10-19.47	50.53-29.53	61.60-50.56	61.60-50.56	61.60-50.56
E				18.63-0.66	29.10-19.47	50.53-29.53	50.53-29.53	50.53-41.91
F					18.63-0.66	29.10-19.47	29.10-19.47	41.88-29.53
G						18.63-0.66	18.63-7.64	29.10-19.47
H							6.51-0.66	18.63-7.64
I								6.51-0.66
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE B (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11-28.85	92.11-67.88	92.11-67.88	92.11-67.88	92.11-83.31	92.11-83.31	92.11-83.31	92.11-83.31
B	28.27-1.03	67.85-28.85	67.85-46.07	67.85-46.07	83.26-67.88	83.26-67.88	83.26-75.85	83.26-75.85
C		28.27-1.03	46.04-28.85	46.04-28.85	67.85-46.07	67.85-58.95	75.82-67.88	75.82-67.88
D			28.27-1.03	28.27-13.36	46.04-28.85	58.93-46.07	67.85-58.95	67.85-58.95
E				12.08-1.03	28.27-13.36	46.04-28.85	58.93-46.07	58.93-46.07
F					12.08-1.03	28.27-13.36	46.04-28.85	46.04-28.85
G						12.08-1.03	28.27-13.36	28.27-23.53
H							12.08-1.03	22.64-13.36
I								12.08-1.03
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE C (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11-82.30	92.11-82.30	92.11-82.30	92.11-82.30	92.11-82.30	92.11-82.30	92.11-82.30	92.11-82.30
B	82.25-3.45	82.25-46.95	82.25-46.95	82.25-63.87	82.25-63.87	82.25-63.87	82.25-74.31	82.25-74.31
C		46.90-3.45	46.90-22.79	63.84-46.95	63.84-46.95	63.84-46.95	74.26-63.87	74.26-63.87
D			21.08-3.45	46.90-22.79	46.90-22.79	46.90-40.34	63.84-46.95	63.84-56.86
E				21.08-3.45	21.08-12.38	40.32-22.79	46.90-40.34	56.83-46.95
F					3.45-3.45	21.08-12.38	40.32-22.79	46.90-40.34
G						3.45-3.45	21.08-12.38	40.32-22.79
H							3.45-3.45	21.08-12.38
I								3.45-3.45

### 6.3.2. K-Means Clustering Analysis Results

Table 6-4: K-means classification for heating demand

HEATING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-63.30	0.00-34.20	0.00-24.80	0.00-20.00	0.00-16.30	0.00-15.00	0.00-11.90	0.00-11.30
B	63.40-199.00	34.30-82.00	24.90-54.00	20.10-41.50	16.40-32.70	15.10-30.30	12.00-24.70	11.40-23.50
C		82.10-199.00	54.10-99.00	41.60-72.40	32.80-52.50	30.40-47.40	24.80-37.10	23.60-35.40
D			99.30-199.00	72.50-113.80	52.60-81.00	47.50-68.80	37.20-53.20	35.50-50.40
E				114.00-199.00	81.10-118.20	69.90-97.00	53.30-74.90	50.50-69.50
F					118.40-199.00	97.40-129.20	75.10-100.90	69.70-91.50
G						129.60-199.00	101.10-131.30	91.60-114.90
H							131.80-199.00	115.10-140.80
I								141.40-199.00
HEATING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-77.00	0.00-45.20	0.00-32.80	0.00-26.90	0.00-22.00	0.00-19.10	0.00-16.50	0.00-14.60
B	77.10-234.90	45.30-100.50	32.90-67.60	27.00-52.20	22.10-42.00	19.20-36.70	16.60-31.70	14.70-28.10
C		101.00-234.90	67.70-119.50	52.30-87.80	42.10-66.70	36.80-55.80	31.80-46.60	28.20-40.20
D			119.70-234.90	87.90-134.50	66.80-100.50	55.90-81.60	46.70-66.50	40.30-54.10
E				134.70-234.90	101.00-142.20	81.70-114.30	66.70-92.30	54.20-72.70
F					142.30-234.90	114.70-151.70	92.50-121.60	72.80-97.20
G						151.80-234.90	121.70-155.00	97.30-125.60
H							155.20-234.90	125.80-157.80
I								157.90-234.90
HEATING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 -111.50	0.00 -71.90	0.00- 54.20	0.00 -46.80	0.00-38.40	0.00-31.70	0.00-27.00	0.00-25.60
B	111.60-315.50	72.00 -145.50	54.30-102.20	46.90-81.60	38.50-64.20	31.80-54.10	27.10-46.60	25.70-44.40
C		145.60- 315.50	102.30-169.40	81.70-130.40	64.30-99.20	54.20-79.20	46.70-65.50	44.50-61.40
D			169.50-315.50	130.50-189.30	99.30-145.70	79.30-113.60	65.60-90.40	61.50-81.90
E				189.40-315.50	145.80-198.10	113.70-156.40	90.50-123.40	82.00-108.00
F					198.30-315.50	156.50-204.30	123.50-162.30	108.10-139.00
G						204.50-315.50	162.40-207.10	139.10-173.40
H							207.30-315.50	173.80-214.00
I								214.20-315.50

Table 6-5: K-means classification for cooling demand

COOLING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	32.50-117.10	32.50-97.10	32.50-85.10	32.50-76.80	32.50-71.90	32.50-66.20	32.50-63.80	32.50-59.70
B	117.20-359.40	97.20-149.20	85.20-123.50	76.90-107.80	72.00-98.00	66.30-88.20	63.90-84.00	59.80-77.50
C		149.30-359.40	123.60-172.10	107.90-141.30	92.10-124.60	88.30-110.00	84.10-103.60	77.60-94.80
D			172.30-359.40	141.40-188.20	124.70-155.10	110.10-133.60	103.70-124.70	94.90-112.80
E				188.30-359.40	155.20-201.20	133.70-161.60	124.80-148.30	112.90-132.10
F					201.60-359.40	161.70-203.90	148.40-177.50	132.20-154.30
G						205.50-359.40	177.70-221.70	154.40-183.00
H							222.30-359.40	183.10-225.20
I								226.00-359.40
COOLING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	33.80-118.30	33.80-97.90	33.80-88.30	33.80-78.80	33.80-74.60	33.80-69.10	33.80-67.00	33.80-64.40
B	118.40-352.80	98.00-147.00	88.40-125.80	78.90-108.00	74.70-100.10	69.20-90.50	67.10-87.00	64.50-82.20
C		147.10-352.80	125.90-173.10	108.10-140.20	100.20-126.00	90.60-111.60	87.10-106.20	82.30-98.80
D			173.30-352.80	140.30-185.90	126.10-155.10	111.70-134.60	106.30-126.00	98.90-115.90
E				186.10-352.80	155.20-198.40	134.70-161.80	126.10-147.80	116.00-134.50
F					198.80-352.80	161.90-202.70	147.90-175.20	134.60-155.70
G						204.70-352.80	175.50-218.70	155.90-183.20
H							219.00-352.80	183.30-225.50
I								225.80-352.80
COOLING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	28.90-104.40	28.90-56.40	28.90-77.10	28.90-70.40	28.90-64.90	28.90-61.20	28.90-59.00	28.90-56.50
B	104.50-306.10	86.50-129.20	77.20-108.90	70.50-96.70	65.00-86.80	61.30-80.40	59.10-76.50	56.60-72.10
C		129.30-306.10	109.00-147.40	96.80-125.10	86.90-109.30	80.50-99.40	76.60-93.20	72.20-86.50
D			147.50-306.10	125.20-163.40	109.40-134.40	99.50-119.80	93.30-110.90	56.60-101.60
E				163.60-306.10	134.50-170.50	119.90-143.70	111.00-130.70	101.70-117.90
F					170.70-306.10	143.80-179.60	130.80-154.50	118.00-135.90
G						180.10-306.10	154.60-189.40	136.00-158.20
H							189.70-306.10	158.40-191.40
I								192.00-306.10

Table 6-6: K-means classification for quality of indoor environment

AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE A (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10-66.10	92.10-77.00	92.10-81.10	92.10-82.45	92.10-83.00	92.10-85.00	92.10-85.80	92.10-86.60
B	66.00-0.65	76.90-55.50	81.00-66.85	82.40-70.10	82.90-71.35	84.90-75.80	85.70-77.50	86.50-79.00
C		55.40-0.65	66.80-50.80	70-00-57.20	71.30-60.10	75.70-67.10	77.40-69.50	78.90-71.50
D			50.70-0.65	57.15-43.30	60.00-48.10	67.00-57.30	69.40-61.60	71.40-64.70
E				43.20-0.65	48.00-32.25	57.20-46.20	61.50-52.80	64.60-57.25
F					32.15-0.65	46.10-30.50	52.70-43.80	57.10-48.90
G						30.35-0.65	43.70-29.50	18.80-40.70
H							29.10-0.65	40.60-26.80
I								26.60-0.65
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE B (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10-64.70	92.10-74.70	92.10-79.50	92.10-81.10	92.10-81.70	92.10-84.85	92.10-85.10	92.10-85.25
B	64.60-1.00	74.65-53.10	79.40-64.70	81.00-68.35	81.65-70.25	84.80-76.05	85.05-76.65	85.20-76.95
C		53.00-1.00	64.65-48.80	68.30-56.85	70.20-60.85	76.00-67.70	76.60-68.65	76.90-69.25
D			48.75-1.00	56.80-44.10	60.80-50.55	67.65-59.40	68.60-61.10	69.20-62.10
E				44.00-1.00	50.50-39.25	59.35-49.65	61.00-52.60	62.00-55.00
F					39.20-1.00	49.60-38.75	52.50-42.75	54.50-47.10
G						38.70-1.00	42.70-28.25	47.00-39.20
H							28.05-1.00	39.10-25.90
I								25.70-1.00
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE C (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10-62.90	92.10-69.95	92.10-76.50	92.10-79.50	92.10-81.00	92.10-82.40	92.10-83.65	92.10-83.75
B	62.80-3.45	69.90-48.23	76.00-61.00	79.00-66.30	80.50-69.20	82.35-72.20	83.60-74.50	83.70-74.70
C		48.20-3.45	60.50-45.50	66.00-55.30	69.10-59.60	72.15-63.50	74.45-66.50	74.65-66.75
D			45.00-3.45	55.20-42.60	59.50-50.50	63.40-55.70	66.45-59.55	66.70-59.95
E				42.00-3.45	50.40-39.55	55.65-47.10	59.50-53.30	59.90-54.00
F					39.50-3.45	47.00-37.20	53.25-45.60	53.95-47.50
G						37.10-3.45	45.55-36.45	47.45-40.10
H							36.35-3.45	40.05-32.80
I								32.75-3.45

### 6.3.3. Gaussian Mixture Models Results

Table 6-7: Gaussian classification for heating demand

HEATING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00-57.10	0.00-41.50	0.00-3.70	0.00-3.70	0.00-3.70	0.00-3.70	0.00-0.20	0.00-0.20
B	57.20-199.00	41.60-74.90	3.80-42.00	3.80-38.40	3.80-28.90	3.80-29.30	0.30-5.20	0.30-5.20
C		75.10-199.00	42.10-74.50	38.50-65.70	29.00-49.80	29.40-49.50	5.30-30.90	5.30-30.30
D			74.60-199.00	65.80-107.60	49.90-71.90	49.60-73.10	31.00-51.70	30.40 -51.40
E				107.70-199.00	72.00-110.60	73.20-97.50	51.80-76.40	51.50-79.80
F					110.70-199.00	97.60-128.40	76.50-92.10	80.00-91.00
G						128.60-199.00	92.20-125.00	91.10-114.30
H							125.20-199.00	114.40-139.10
I								139.40-199.00
HEATING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 68.80	0.00 - 57.00	0.00 - 6.40	0.00 - 6.50	0.00- 6.90	0.00 - 6.80	0.00 - 6.10	0 - 1.50
B	68.90 - 234.90	57.10 - 96.60	6.50 - 54.20	6.60 - 50.90	7.00 - 42.10	6.90 - 37.30	6.20 - 29.40	1.60 - 9.10
C		96.70 - 234.90	54.30 - 93.30	51.00 - 82.70	42.20 - 64.60	37.40 - 60.10	29.50 - 45.60	9.20 - 37.80
D			93.40 - 234.90	82.80 - 131.10	64.70 - 95.00	60.20 - 83.60	45.70 - 65.00	37.90 - 52.70
E				131.20 - 234.90	95.10 - 136.10	83.70 - 112.90	65.10 - 93.50	52.80 - 68.20
F					136.20 - 234.90	113.00 - 147.00	93.70 - 120.10	68.30 - 91.40
G						147.20 - 234.90	120.20 - 149.90	91.50 - 119.10
H							150.10 - 234.90	119.20 - 146.80
I								146.90 - 234.90
HEATING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 93.30	0.00 - 83.70	0.00 - 68.90	0.00 - 47.30	0.00 - 14.70	0.00 - 15.50	0.00 - 16.30	0.00 - 17.20
B	93.40 - 315.50	83.80 - 139.40	69.00 - 101.00	47.40 - 83.10	14.90 - 57.00	15.60 - 54.90	16.40 - 46.50	17.30 - 44.70
C		139.50 - 315.50	101.10-161.40	83.20 - 126.40	57.10 - 86.50	55.00 - 81.80	46.60 - 64.40	44.80 - 61.70
D			161.50-315.50	126.60 - 188.20	86.60 - 135.50	81.90 - 111.30	64.50 - 86.80	61.80 - 83.10
E				188.60 - 315.50	135.60 - 191.30	111.40 - 152.70	86.90 - 117.10	83.20 - 108.60
F					191.40 - 315.50	152.80 - 196.00	117.20 - 154.90	108.70 - 140.00
G						196.30 - 315.50	155.10 - 195.10	140.10 - 172.10
H							195.20 - 315.50	172.30 - 207.30
I								207.60 - 315.50

Table 6-8: Gaussian classification for cooling demand

COOLING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	32.50 - 120.80	32.50 - 94.40	32.50 - 80.90	32.50 - 74.50	32.50 - 70.50	32.50 - 65.30	32.50 - 62.90	32.50 - 57.60
B	120.90-359.40	94.50 - 180.60	81.00 - 122.30	74.60 - 108.30	70.60 - 98.20	65.40 - 88.80	63.00 - 84.30	57.70 - 76.10
C		180.70 - 359.40	122.40-188.20	108.40 - 143.50	98.30 - 124.40	88.90 - 110.20	84.40 - 103.30	76.20 - 94.70
D			188.30-359.40	143.60 - 193.20	124.50 - 155.20	110.30 - 133.40	103.40 - 124.50	94.80 - 112.90
E				193.30 - 359.40	155.30 - 196.30	133.50 - 162.80	124.60 - 148.90	113.00 - 131.00
F					196.40 - 359.40	162.90 - 198.20	149.00 - 181.50	131.10 - 153.60
G						198.70 - 359.40	181.60 - 222.50	153.70 - 185.20
H							223.40 - 359.40	185.40 - 224.20
I								224.70 - 359.40
COOLING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	33.80 - 121.40	33.80 - 97.90	33.80 - 88.60	33.80 - 77.60	33.80 - 72.80	33.80 - 68.20	33.80 - 66.40	33.80 - 64.30
B	121.50-352.80	98.00 -182.10	88.70 - 127.20	77.70 - 108.40	72.90 - 100.70	68.30 - 90.50	66.50 - 87.80	64.40 - 82.40
C		182.20 - 352.80	127.30-187.50	108.50 - 140.30	100.80 -127.40	90.60 - 111.70	87.90 - 106.80	82.50 - 99.10
D			187.60-352.80	140.40 - 190.50	127.50 - 159.00	111.80 - 134.70	106.90 - 126.90	99.20 - 115.90
E				190.80 - 352.80	159.10 - 198.40	134.80 - 164.70	127.00 - 148.70	116.00 - 134.30
F					198.80 - 352.80	134.80 - 164.70	148.80 - 179.30	134.40 - 156.10
G						202.50 - 352.80	179.40 - 219.70	156.20 - 184.60
H							220.10 - 352.80	184.70 - 223.40
I								224.20 - 352.80
COOLING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	28.90 - 100.00	28.90 - 86.80	28.90 - 77.50	28.90 - 69.40	28.90 - 63.20	28.90 - 60.20	28.90 - 58.80	28.90 - 56.70
B	100.10-306.10	86.90 - 159.40	77.60 - 110.40	69.50 - 97.10	63.30 - 87.00	60.30 - 80.30	58.900 - 77.30	56.80 - 72.40
C		159.50 - 306.10	110.50-164.00	97.20 - 125.80	87.10 - 109.80	80.40 - 99.50	77.40 - 93.70	72.50 - 86.40
D			164.10-306.10	125.90 - 168.60	109.90 - 134.70	99.60 - 120.20	93.80 - 111.20	86.50 - 101.40
E				168.80 - 306.10	134.80 - 170.10	120.30 - 147.40	111.30 - 131.60	101.50 - 118.00
F					170.50 - 306.10	147.50 - 180.40	131.70 - 159.20	118.10 - 135.70
G						180.90 - 306.10	159.30 - 191.40	135.80 - 160.40
H							192.90 - 306.10	160.50 - 191.40
I								192.90 - 306.10

Table 6-9: Gaussian classification for quality of indoor environment

AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE A (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10 - 88.50	92.10 - 88.50	92.10 - 91.70	92.10 - 91.70	92.10 - 91.80	92.10 - 91.80	92.10 - 91.80	92.10 - 91.80
B	88.40 - 0.65	88.40 - 63.70	91.60 - 87.30	91.60 - 87.20	91.75 - 89.20	91.70 - 89.30	91.980 - 89.45	91.70 - 89.50
C		63.60 - 0.65	87.20 - 63.70	87.10 - 53.20	89.20 - 83.40	89.20 - 83.70	89.35 - 84.75	89.40 - 84.60
D			63.60 - 0.65	53.10 - 28.40	83.30 - 54.50	83.60 - 59.40	84.70 - 70.80	84.50 - 70.20
E				28.30 - 0.65	54.40 - 26.30	59.30 - 50.20	70.75 - 58.85	70.10 - 59.30
F					26.20 - 0.65	50.10 - 30.20	58.80 - 48.10	59.20 - 48.20
G						30.00 - 0.65	48.00 - 31.70	48.10 - 34.15
H							31.55 - 0.65	34.05 - 18.45
I								17.60 - 0.65
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE B (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10 - 86.90	92.10 - 86.50	92.10 - 86.90	92.10 - 91.00	92.10 - 91.80	92.10 - 91.80	92.10 - 91.85	92.10 - 91.90
B	86.80 - 1.00	86.40 - 53.75	86.80 - 67.75	91.10 - 85.80	91.70 - 88.80	91.70 - 89.10	91.80 - 88.90	91.80 - 89.00
C		53.70 - 1.00	67.70 - 55.00	85.70 - 46.25	88.70 - 83.25	89.00 - 83.80	89.00 - 83.40	88.90 - 83.40
D			54.90 - 1.00	46.15 - 27.25	83.25 - 47.10	83.70 - 65.10	83.30 - 64.70	83.30 - 64.50
E				27.10 - 1.00	47.00 - 25.30	65.00 - 49.00	64.60 - 52.85	64.50 - 52.60
F					24.90 - 1.00	48.90 - 24.70	52.75 - 44.65	52.50 - 45.90
G						24.50 - 1.00	44.55 - 26.70	45.80 - 40.65
H							26.40 - 1.00	40.60 - 27.30
I								27.20 - 1.00
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE C (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.10 - 84.30	92.10 - 83.30	92.10 - 86.50	92.10 - 89.85	92.10 - 89.85	92.10 - 89.80	92.10 - 89.85	92.10 - 89.80
B	84.25 - 3.45	37.80 - 22.97	86.40 - 69.70	89.80 - 83.45	89.80 - 83.40	89.70 - 83.30	83.45 - 89.80	89.70 - 83.25
C		83.20 - 3.45	69.60 - 43.20	83.40 - 66.90	83.30 - 66.45	83.20 - 67.00	83.40 - 68.00	83.20 - 67.65
D			43.10 - 3.45	66.80 - 44.10	66.40 - 48.10	66.90 - 56.40	67.90 - 59.95	67.60 - 59.80
E				44.00 - 3.45	48.05 - 45.30	56.30 - 47.50	59.90 - 53.55	59.80 - 53.65
F					45.25 - 3.45	47.40 - 43.25	53.50 - 47.90	53.60 - 46.70
G						43.20 - 3.45	47.80 - 42.65	46.60 - 40.60
H							42.60 - 3.45	40.60 - 22.80
I								21.10 - 3.50

### 6.3.4. Fuzzy Clustering Results

Table 6-10: Fuzzy classification for heating demand

HEATING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 63.00	0.00 - 32.10	0.00 - 23.50	0.00 - 18.40	0.00 - 15.40	0.00 - 13.70	0.00 - 11.50	0.00 - 9.80
B	63.20 - 199.00	32.20 - 81.70	23.60 - 52.70	18.50 - 38.80	15.50 - 32.10	13.80 - 28.60	11.60 - 24.30	9.90 - 21.00
C		81.80 - 199.00	52.80 - 99.00	38.90 - 68.90	32.20 - 52.50	28.70 - 44.80	24.40 - 36.80	21.10 - 31.20
D			99.30 - 199.00	69.00 - 111.70	52.60 - 82.50	44.90 - 67.20	36.90 - 53.10	31.30 - 42.50
E				111.90 - 199.00	82.70 - 120.60	67.30 - 95.80	53.20 - 75.20	42.60 - 57.70
F					120.80 - 199.00	96.00 - 128.80	75.30 - 102.00	57.80 - 78.70
G						128.90 - 199.00	102.10 - 132.60	78.80 - 104.50
H							132.70 - 199.00	104.80 - 134.30
I								134.40 - 199.00
HEATING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 77.10	0.00 - 42.00	0.00 - 31.60	0.00 - 24.50	0.00 - 20.90	0.00 - 17.10	0.00 - 16.00	0.00 - 14.20
B	77.20 - 234.90	42.10 - 98.90	31.70 - 66.50	24.60 - 48.00	21.00 - 40.90	17.20 - 33.60	16.10 - 31.60	14.30 - 28.20
C		99.00 - 234.90	66.70 - 119.80	48.10 - 82.90	41.00 - 65.90	33.70 - 50.20	31.70 - 46.60	28.30 - 40.50
D			120.00-234.90	83.00 - 132.00	66.00 - 101.00	50.30 - 74.00	46.70 - 66.70	40.60 - 54.40
E				132.10 - 234.90	101.10 - 143.40	74.10 - 107.40	66.80 - 92.90	54.50 - 73.20
F					143.50 - 234.90	107.50 - 147.30	93.10 - 122.80	73.30 - 97.80
G						147.40 - 234.90	122.90 - 155.90	98.00 - 126.40
H							156.20 - 234.90	126.50 - 158.40
I								158.60 - 234.90
HEATING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 111.30	0.00 - 66.00	0.00 - 52.40	0.00 - 44.30	0.00 - 37.30	0.00 - 31.70	0.00 - 26.90	0.00 - 25.70
B	111.40 - 315.50	66.10 - 140.50	52.50 - 100.70	44.40 - 76.40	37.40 - 62.30	31.80 - 54.00	27.00 - 46.80	25.80 - 44.90
C		140.60 - 315.50	100.80 - 169.90	76.50 - 124.90	62.40 - 97.20	54.10 - 79.40	46.90 - 65.90	45.00 - 62.30
D			170.00 - 315.50	125.00 - 186.40	97.30 - 144.90	79.50 - 114.60	66.00 - 91.60	62.40 - 84.10
E				186.50 - 315.50	145.00 - 198.40	114.70 - 157.90	91.70 - 126.00	84.20 - 112.90
F					198.50 - 315.50	158.10 - 205.20	126.10 - 165.40	113.00 - 146.60
G						205.30 - 315.50	165.50 - 209.20	146.70 - 181.50
H							209.40 - 315.50	181.60 - 219.30
I								219.50 - 315.50

Table 6-11: Fuzzy classification for cooling demand

COOLING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	32.50 - 115.50	32.50 - 93.70	32.50 - 82.50	32.50 - 75.20	32.50 - 70.20	32.50 - 65.90	32.50 - 63.30	32.50 - 59.40
B	115.60-359.40	93.80 - 144.10	82.60 - 119.90	75.30 - 105.70	70.30 - 96.00	66.00 - 88.00	63.40 - 83.50	59.50 - 77.30
C		144.20 - 359.40	120.00-165.50	105.80 - 138.60	96.10 - 122.40	88.10 - 109.60	83.60 - 102.90	77.40 - 94.50
D			165.60-359.40	138.70 - 183.80	122.50 - 152.00	109.70 - 132.80	103.00 - 123.40	94.60 - 112.00
E				183.90 - 359.40	152.10 - 195.60	132.90 - 160.20	123.50 - 145.60	112.10 - 130.60
F					195.90 - 359.40	160.30 - 202.30	145.70 - 172.00	130.70 - 151.80
G						202.60 - 359.40	172.10 - 213.30	151.90 - 178.50
H							213.40 - 359.40	178.60 - 219.40
I								220.10 - 359.40
COOLING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	33.80 - 117.00	33.80 - 95.80	33.80 - 85.30	33.80 - 78.00	33.80 - 72.60	33.80 - 68.80	33.80 - 66.30	33.80 - 64.00
B	117.10-352.80	95.90 - 143.80	85.40 - 121.30	78.10 - 107.20	72.70 - 97.20	68.90 - 90.40	66.40 - 85.90	64.10 - 81.90
C		143.90 - 352.80	121.40-165.00	107.30 - 138.70	97.30 - 122.50	90.50 - 111.70	86.00 - 104.60	82.00 - 98.70
D			165.10-352.80	138.80 - 181.60	122.60 - 150.90	111.80 - 134.60	104.70 - 123.90	98.80 - 115.90
E				181.70 - 352.80	151.00 - 192.30	134.70 - 160.90	124.00 - 145.10	116.00 - 134.40
F					192.50 - 352.80	161.00 - 201.10	145.20 - 170.80	134.50 - 154.90
G						201.40 - 352.80	170.90 - 211.00	155.00 - 181.00
H							211.10 - 352.80	181.10 - 221.40
I								222.00 - 352.80
COOLING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	28.90 - 103.30	28.90 - 84.50	28.90 - 74.60	28.90 - 68.80	28.90 - 63.70	28.90 - 60.50	28.90 - 58.50	28.90 - 56.40
B	103.40-306.10	84.60 - 126.50	74.70 - 105.80	68.90 - 94.50	63.80 - 85.20	60.60 - 79.40	58.60 - 75.80	56.50 - 72.10
C		126.60 - 306.10	105.90-142.40	94.60 - 122.20	85.30 - 107.30	79.50 - 98.00	75.90 - 92.20	72.20 - 86.70
D			142.60-306.10	122.30 - 158.10	107.40 - 132.00	98.10 - 117.80	92.30 - 109.10	86.80 - 101.80
E				158.20 - 306.10	132.10 - 166.40	117.90 - 140.10	109.20 - 127.60	101.90 - 117.90
F					166.60 - 306.10	140.20 - 173.30	127.70 - 149.10	118.00 - 135.70
G						173.60 - 306.10	149.20 - 181.90	135.80 - 157.70
H							182.20 - 306.10	157.80 - 190.60
I								191.00 - 306.10

Table 6-12: Fuzzy classification for quality of indoor environment

AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE A (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 66.29	92.11 - 77.31	92.11 - 81.11	92.11 - 82.83	92.11 - 83.43	92.11 - 85.40	92.11 - 86.16	92.11 - 87.34
B	66.26 - 0.66	77.28 - 55.35	81.09 - 66.52	82.80 - 70.42	83.41 - 71.76	85.38 - 76.05	86.13 - 77.64	87.32 - 80.11
C		55.32 - 0.66	66.49 - 50.68	70.40 - 57.77	71.74 - 60.62	76.02 - 67.35	76.61 - 69.47	80.08 - 72.90
D			50.66 - 0.66	57.74 - 44.66	60.59 - 48.74	67.32 - 57.36	69.44 - 61.37	72.87 - 66.24
E				44.63 - 0.66	48.71 - 34.57	57.34 - 46.29	61.35 - 52.40	66.21 - 58.70
F					34.54 - 0.66	46.27 - 31.19	52.37 - 43.34	58.67 - 49.95
G						31.14 - 0.66	43.32 - 28.52	49.92 - 41.68
H							28.47 - 0.66	41.65 - 27.31
I								26.85 - 0.66
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE B (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 64.73	92.11 - 75.11	92.11 - 79.80	92.11 - 81.29	92.11 - 82.58	92.11 - 85.17	92.11 - 85.53	92.11 - 86.13
B	64.70 - 1.03	75.09 - 52.98	79.78 - 64.73	81.27 - 68.28	82.55 - 71.33	85.15 - 76.30	85.50 - 76.95	86.11 - 78.19
C		52.95 - 1.03	64.70 - 48.69	68.26 - 56.81	71.31 - 62.10	76.27 - 67.95	76.93 - 68.94	78.16 - 70.88
D			48.66 - 1.03	56.78 - 44.23	62.08 - 51.97	67.93 - 59.91	68.91 - 61.55	70.85 - 64.62
E				44.18 - 1.03	51.92 - 41.10	59.88 - 50.40	61.52 - 53.68	64.60 - 58.62
F					41.07 - 1.03	50.38 - 40.14	53.63 - 44.98	58.60 - 51.49
G						40.12 - 1.03	44.96 - 36.64	51.46 - 43.47
H							36.61 - 1.03	43.44 - 35.80
I								35.78 - 1.03
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE C (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 62.53	92.11 - 70.60	92.11 - 76.70	92.11 - 79.98	92.11 - 81.24	92.11 - 82.75	92.11 - 84.32	92.11 - 85.00
B	62.51 - 3.45	70.58 - 48.13	76.65 - 60.77	79.93 - 66.36	81.22 - 68.96	82.73 - 72.14	84.27 - 75.14	84.97 - 76.35
C		48.11 - 3.45	60.74 - 44.86	66.34 - 55.35	68.94 - 59.05	72.11 - 63.19	75.11 - 66.77	76.32 - 68.10
D			44.83 - 3.45	55.32 - 42.46	59.03 - 49.80	63.16 - 55.47	66.74 - 59.58	68.08 - 61.04
E				42.41 - 3.45	49.77 - 38.93	55.45 - 46.82	59.56 - 53.13	61.02 - 54.97
F					38.91 - 3.45	46.80 - 36.94	53.10 - 45.03	54.94 - 48.39
G						36.91 - 3.45	45.01 - 35.83	48.36 - 40.70
H							35.80 - 3.45	40.67 - 33.31
I								33.26 - 3.45

### 6.3.5. Neural Network Based Clustering Results

Table 6-13: Neural classification for heating demand

HEATING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 63.40	0.00 - 34.20	0.00 - 24.80	0.00 - 19.90	0.00 - 16.10	0.00 - 13.30	0.00 - 12.00	0.00 - 10.10
B	63.50 - 199.00	34.30 - 82.10	24.90 - 54.10	20.00 - 41.40	16.20 - 32.50	13.40 - 27.20	12.10 - 24.70	10.20 - 20.90
C		82.20 - 199.00	54.20 - 99.00	41.50 - 72.10	32.60 - 52.50	27.30 - 42.10	24.80 - 37.20	21.00 - 30.90
D			99.30 - 199.00	72.20 - 113.50	52.60 - 81.20	42.20 - 63.00	37.30 - 53.30	31.00 - 42.30
E				113.60 - 199.00	81.30 - 118.80	63.20 - 91.80	53.40 - 74.90	42.40 - 57.20
F					118.90 - 199.00	92.00 - 126.30	75.10 - 100.90	57.30 - 77.90
G						126.40 - 199.00	101.10 - 131.30	78.00 - 103.20
H							131.80 - 199.00	103.40 - 132.70
I								132.90 - 199.00
HEATING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 77.10	0.00 - 45.10	0.00 - 32.90	0.00 - 25.60	0.00 - 21.80	0.00 - 17.70	0.00 - 16.80	0.00 - 15.10
B	77.20 - 234.90	45.20 - 100.50	33.00 - 67.60	25.70 - 49.20	21.90 - 41.80	17.80 - 34.10	16.90 - 32.10	15.20 - 28.90
C		101.00 - 234.90	67.70 - 119.50	49.30 - 82.80	41.90 - 66.50	34.20 - 51.10	32.20 - 47.10	29.00 - 41.20
D			119.70-234.90	82.90 - 130.10	66.70 - 100.40	51.20 - 74.80	47.20 - 66.90	41.30 - 55.10
E				130.20 - 234.90	100.50 - 141.80	74.90 - 107.10	67.00 - 92.60	55.20 - 73.40
F					141.90 - 234.90	107.20 - 146.00	92.70 - 121.60	73.50 - 97.60
G						146.20 - 234.90	121.70 - 155.00	97.70 - 125.80
H							155.20 - 234.90	125.90 - 157.70
I								157.80 - 234.90
HEATING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	0.00 - 111.30	0.00 - 71.40	0.00 - 54.20	0.00 - 45.60	0.00 - 38.60	0.00 - 32.00	0.00 - 27.10	0.00 - 25.80
B	111.40-315.50	71.50 - 144.70	54.30 - 102.30	45.70 - 78.90	38.70 - 64.50	32.10 - 54.30	27.20 - 46.70	25.90 - 44.50
C		144.80 - 315.50	102.50-169.60	79.00 - 126.70	64.60 - 99.60	54.40 - 79.60	46.80 - 65.60	44.60 - 61.60
D			169.90-315.50	126.80 - 186.60	99.70 - 145.90	79.70 - 114.20	65.70 - 90.80	61.70 - 82.20
E				186.70 - 315.50	146.10 - 198.30	114.30 - 156.50	90.90 - 124.10	82.30 - 108.30
F					198.40 - 315.50	156.60 - 204.30	124.20 - 163.00	108.40 - 139.40
G						204.50 - 315.50	163.20 - 207.30	139.50 - 174.10
H							207.60 - 315.50	174.50 - 214.70
I								215.10 - 315.50

Table 6-14: Neural classification for cooling demand

COOLING DEMAND FOR CLIMATIC ZONE A (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	32.50-117.10	32.50 · 97.20	32.50 · 85.30	32.50 · 76.80	32.50 · 72.10	32.50 · 66.90	32.50 · 63.40	32.50 · 59.70
B	117.20-359.40	97.30 · 149.40	85.40 · 123.60	76.90 · 107.90	72.20 · 98.20	67.00 · 89.00	63.50 · 83.40	59.80 · 77.60
C		149.50-359.40	123.70-171.80	108.00 · 141.40	98.30 · 124.90	89.10 · 110.50	83.50 · 102.80	77.70 · 94.90
D			171.90-359.40	141.50 · 187.90	125.00 · 155.40	110.60 · 134.00	102.90 · 123.40	95.00 · 112.90
E				188.00 · 359.40	155.50 · 201.00	134.10 · 161.90	123.50 · 146.50	113.00 · 132.30
F					201.20 · 359.40	162.00 · 203.90	146.60 · 174.50	132.40 · 154.50
G						205.50 · 359.40	174.60 · 217.80	154.60 · 183.40
H							218.20 · 359.40	183.70 · 226.00
I								226.50 · 359.40
COOLING DEMAND FOR CLIMATIC ZONE B (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	33.80 · 118.30	33.80 · 97.90	33.80 · 88.40	33.80 · 78.90	33.80 · 73.90	33.80 · 69.40	33.80 · 66.90	33.80 · 64.50
B	118.40-352.80	98.00 · 147.10	88.50 · 125.80	79.00 · 108.20	74.00 · 98.80	69.50 · 90.80	67.00 · 86.80	64.60 · 82.40
C		147.20 · 352.80	125.90-173.30	108.30 · 140.40	98.90 · 124.20	90.90 · 112.00	86.90 · 105.90	82.50 · 99.00
D			173.40-352.80	140.50 · 186.10	124.30 · 153.00	112.10 · 134.90	106.00 · 125.60	99.10 · 116.00
E				186.20 · 352.80	153.10 · 197.00	135.00 · 162.00	125.70 · 147.40	116.10 · 134.60
F					197.10 · 352.80	162.10 · 203.70	147.50 · 174.90	134.70 · 155.70
G						204.70 · 352.80	175.00 · 217.70	155.90 · 183.50
H							218.20 · 352.80	183.60 · 225.50
I								225.80 · 352.80
COOLING DEMAND FOR CLIMATIC ZONE C (kWh/m <sup>2</sup> /year)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	28.90 · 104.40	28.90 · 86.30	28.90 · 77.00	28.90 · 70.40	28.90 · 64.80	28.90 · 61.10	28.90 · 59.00	28.90 · 56.50
B	104.50 · 306.10	86.40 · 129.10	77.10 · 108.70	70.50 · 96.60	64.90 · 86.60	61.20 · 80.30	59.10 · 76.60	56.60 · 72.20
C		129.20 · 306.10	108.80 · 147.70	96.70 · 125.00	86.70 · 108.90	80.40 · 99.30	76.70 · 93.40	72.30 · 86.80
D			147.80 · 306.10	125.10 · 163.40	109.00 · 134.00	99.40 · 119.90	93.50 · 111.00	86.90 · 101.90
E				163.60 · 306.10	134.10 · 170.10	120.00 · 143.80	111.10 · 130.70	102.00 · 118.20
F					170.50 · 306.10	143.90 · 179.60	130.80 · 154.60	118.30 · 136.10
G						180.10 · 306.10	154.80 · 189.90	136.20 · 158.40
H							190.20 · 306.10	158.50 · 191.40
I								192.90 · 306.10

Table 6-15: Neural classification for quality of indoor environment

AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE A (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 66.09	92.11 - 77.00	92.11 - 81.04	92.11 - 82.55	92.11 - 82.96	92.11 - 85.02	92.11 - 85.83	92.11 - 87.39
B	66.06 - 0.66	76.98 - 55.55	81.01 - 66.87	82.53 - 70.27	82.93 - 71.31	85.00 - 75.87	85.80 - 77.43	87.37 - 80.58
C		55.52 - 0.66	66.84 - 50.86	70.25 - 57.51	71.28 - 60.01	75.84 - 67.30	77.41 - 69.54	80.56 - 73.63
D			50.83 - 0.66	57.49 - 43.72	59.98 - 48.01	67.27 - 57.51	69.52 - 61.62	73.60 - 66.89
E				43.70 - 0.66	47.98 - 31.90	57.49 - 46.44	61.60 - 52.85	66.87 - 59.20
F					31.87 - 0.66	46.42 - 30.74	52.82 - 43.72	59.18 - 50.50
G						30.51 - 0.66	43.70 - 29.70	50.48 - 41.91
H							29.53 - 0.66	41.88 - 27.76
I								27.69 - 0.66
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE B (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 64.62	92.11 - 74.76	92.11 - 79.48	92.11 - 81.04	92.11 - 82.22	92.11 - 84.90	92.11 - 85.17	92.11 - 85.58
B	64.60 - 1.03	74.74 - 53.18	79.43 - 64.65	81.01 - 68.31	82.20 - 71.31	84.87 - 76.22	85.15 - 76.65	85.55 - 77.38
C		53.13 - 1.03	64.62 - 48.79	68.28 - 56.83	71.28 - 62.15	76.20 - 67.95	76.63 - 68.63	77.36 - 69.79
D			48.76 - 1.03	56.81 - 44.05	62.13 - 51.97	67.93 - 59.78	68.61 - 61.07	69.77 - 63.09
E				44.02 - 1.03	51.92 - 40.54	59.76 - 50.00	61.04 - 52.57	63.06 - 56.51
F					40.49 - 1.03	49.97 - 39.01	52.55 - 42.74	56.48 - 48.94
G						38.98 - 1.03	42.71 - 28.27	48.89 - 40.54
H							28.04 - 1.03	40.49 - 27.36
I								27.23 - 1.03
AVERAGE OF OCCUPIED HOURS THAT $-0.7 < PMV < +0.7$ FOR CLIMATIC ZONE C (%)								
Class	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9
A	92.11 - 62.81	92.11 - 69.94	92.11 - 76.48	92.11 - 79.48	92.11 - 80.94	92.11 - 82.43	92.11 - 83.61	92.11 - 85.55
B	62.78 - 3.45	69.92 - 48.21	76.45 - 60.97	79.45 - 66.19	80.91 - 69.19	82.40 - 72.21	83.59 - 74.48	85.50 - 77.81
C		48.18 - 3.45	60.94 - 45.26	66.16 - 55.24	69.16 - 59.51	72.19 - 63.49	74.46 - 66.49	77.76 - 70.30
D			45.21 - 3.45	55.22 - 42.61	59.48 - 50.40	63.46 - 55.70	66.46 - 59.58	70.27 - 63.64
E				42.59 - 3.45	50.38 - 39.54	55.67 - 47.05	59.56 - 53.25	63.62 - 57.59
F					39.51 - 3.45	47.02 - 37.17	53.23 - 45.51	57.56 - 51.49
G						37.12 - 3.45	45.49 - 36.43	51.46 - 43.82
H							36.38 - 3.45	43.80 - 35.17
I								35.15 - 3.45

## 6.4. Evaluation and comparison of clustering results

Clustering is an unsupervised process in the data mining and pattern recognition and the clustering algorithms are very sensitive to their input parameters. Therefore it is very important to evaluate the result of the clustering algorithms. In the case this research the cluster analysis is applied to VBD in order to classify office buildings according to energy demand and thermal comfort index. The obtained results of the aforementioned clustering algorithms have to be evaluated in order to:

- Define when a clustering result is acceptable or not.
- Decide the optimal number of clusters that fits our data set (VBD).
- Select the most efficient clustering method for our problem i.e. office building classification.

The criteria for clustering algorithms evaluation are subjective to:

- **Technical analysis.** For this reason we need quantitative measures to evaluate the results of a clustering algorithm. This task is named Cluster Validity. In this part of the research most commonly used validity indices are applied to the classification results.
- **Energy policy.** The selected method and the number of classes should be applicable to national policy for defining the appropriate performances scales for energy rating, labeling and certification procedures.

### 6.4.1. External criteria measures

External criteria are used either (a) for a comparison of a clustering structure  $C$ , produced by a clustering algorithm, with a partition  $P$  of  $X$  drawn independently from  $C$  or (b) for measuring the degree of agreement between a predetermined partition  $P$  and the proximity matrix,  $PM$ , of  $X$ .

#### 6.4.1.1. Comparison of $P$ with a Clustering $C$

In this case we need a clustering structure  $C$  and a defined partition,  $P$ , before we can apply the cluster validation technique. We consider a clustering,  $C$ , that result from a specific clustering algorithm, and compare it with a independently drawn partition  $P$  of  $X$ . Suppose that  $C = \{C_1, \dots, C_m\}$  and  $P = \{P_1, \dots, P_s\}$ . The number of clusters in  $C$  and

the partition in P do not need to be the same. Consider the following pair of vectors (xu,xv). Then we refer to it depending whether or not this pair of vectors belong to the same cluster or partition (Batistakis et al., 2002). Let us define the following notation:

- SS if both vectors belong to the same cluster in C and to the same group in P.
- SD if both vectors belong to the same cluster in C and to different groups in P.
- DS if both vectors belong to different clusters in C and to the same group in P.
- DD if both vectors belong to different clusters in C and to different groups in P.

Lets define a = SS, the number of pairs of vectors in X that belong to the same cluster in C and to the same group in P; b = SD, the number of pairs of vectors in X that belong to the same cluster in C and to different groups in P; c = DS, the number of pairs of vectors that belong to different clusters in C and to the same group in P; and d = DD the number of pairs of vectors that belong to different clusters in C and to different groups in P. Then  $a + b + c + d = M$ , where M is the total number of possible pairs in X,  $M = N(N - 1)/2$ . Let  $m_1 = a + b$  be the number of pairs of vectors that belong to the same cluster in C, and  $m_2 = a + c$  be the number of pairs of vectors that belong to the same group in P. Using these definitions, we can define statistical indices that help us to measure how similar C and P are.

#### 6.4.1.2. Rand Index

The Rand Index measures the fraction of the total number of pairs that are either in the same cluster and in the same partition, or in different clusters and in different partitions. The Rand index is defined as:

$$R = \frac{(a + d)}{M} \quad (6-5)$$

Where (a + d) is the sum of SS pairs of vector plus the DD pairs. The values of this index lie between 0 and 1, and values close to 1 indicate good agreement between C and P.

6.4.1.3. *Jaccard Coefficient*

The Jaccard Coefficient measures the proportion of pairs that are in the same cluster and in the same partition from those that are either in the same cluster or in the same partition (Batistakis et al., 2002). The Jaccard Coefficient is defined as:

$$J = \frac{a}{a+b+c} \quad (6-6)$$

where  $a+b+c = SS+SD+DS$ . As in the Rand Index, the values of this coefficient lie between 0 and 1, and values close to 1 indicate good agreement between C and P.

6.4.1.4. *Fowlkes-Mallows Index*

The Fowlkes-Mallows (FM) Index is the geometrical mean of two probabilities: the probability that two random objects are in the same cluster given they are in the same group, and the probability that two random objects are in the same group given they are in the same cluster (Batistakis et al., 2002). The FM Index is defined as:

$$FM = \sqrt{\frac{a}{a+b} \frac{a}{a+c}} = \frac{a}{\sqrt{m_1 m_2}} \quad (6-7)$$

As in the Rand Index and Jaccard Coefficient, values close to 1 indicate good agreement between C and P.

**6.4.2. Internal criteria measures**

Using Internal Criteria, we aim to verify whether the clustering structure produced by a clustering algorithm fit the VBD, but using only information including to the dataset.

6.4.2.1. *Silhouette Index*

The Silhouette Index is useful when it is seeking compact and clearly separated clusters (Rousseuw, 1987). In order to construct silhouettes we need a partition obtained by the application of some clustering algorithm, and the proximity matrix containing all the proximities between objects. For a given cluster, this method assign

to each object of the cluster a quantitative measure  $s(i)$ , known as the silhouette width (Bolshakova and Azuaje, 2003).

The silhouette width indicates the membership of object  $i$  in the cluster it has been assigned. Let  $i$  any object in the data set, and denote by  $C_j$  the cluster to which object  $i$  has been assigned. Let  $a(i)$  the average dissimilarity between  $i$  and all the other object in cluster  $C_j$ . Consider any cluster  $C_k$  different to cluster  $C_j$ , and compute  $b(i) = \min_{C_k \neq C_j} d(i, C_k)$ ,  $k = 1, 2, \dots, c$  and  $k \neq j$ .

Then, the silhouette width is defined as:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \quad (6-8)$$

A neighbor of object  $i$  is the cluster  $C_k$  for which the minimum is obtained, that is,  $d(i, C_k) = b(i)$  Cluster  $C_k$  represent the second best choice for object  $i$ .

From the definition we can see that  $-1 \leq s(i) \leq 1$ . A value of  $s(i)$  close to 1 is obtained when the within dissimilarity  $a(i)$  is much smaller than the smallest between dissimilarity  $b(i)$ . Therefore we can say that object  $i$  is well clustered. On the other hand, if  $s(i)$  take values close to  $-1$  implies that  $a(i)$  is much larger than  $b(i)$ . In this case we can say that object  $i$  has been misclassified, so object  $i$  may be reassigned. If  $a(i)$  and  $b(i)$  have similar values then  $s(i)$  is about zero. In this situation object  $i$  lies equally far away from both cluster  $C_j$  and  $C_k$ .

If the data consist of similarities and  $a'(i)$  and  $d'(i, C)$  represent the corresponding average similarities, then  $b'(i) = \max_{C \neq A} d'(i, C)$  (Rousseuw, 1987). The interpretation is in the same way as before. Now, the silhouette width is defined as,

$$s(i) = \frac{a'(i) - b'(i)}{\max\{a'(i), b'(i)\}} \quad (6-9)$$

There is possible to calculate a cluster silhouette  $S_j$ , called average silhouette width, that represents the heterogeneity of cluster  $C_j$  (Rousseuw, 1987). This quantitative measure can be obtained using:

$$S_j = \frac{1}{m} \sum_{i=1}^m s(i) \quad (6-10)$$

We can also consider an overall or global silhouette width denoted by  $GS_u$ , and define as:

$$GS_u = \frac{1}{c} \sum_{j=1}^c S_j \quad (6-11)$$

Where  $U$  is any partition,  $U \leftrightarrow C : C_1 \cup C_2 \cup \dots \cup C_c$ . This global silhouette value is used as a validity index for  $U$ . In order to choose the optimal number of clusters for a data set using this index, choose the partition  $U$  with the maximum  $GS_u$ .

When hierarchical methods are used to divide a data set in groups, there exists a graphical display, called dendrograms that give a visual interpretation of the results obtained by the clustering algorithm. On the other hand, when partitioning technique is used the result of the clustering is a list of clusters with their objects, and it is not possible to construct a dendrogram to obtain some visual help in the interpretation. In 1987, Rousseeuw proposed a graphical display for the partitioning methods in his paper *Silhouettes: a graphical aid to the interpretation and validation of cluster analysis* (Rousseeuw, 1987). This graphical display is called a Silhouette Plot, and is used to obtain a visual interpretation of the result.

#### 6.4.2.2. The Davies-Bouldin Index

Let  $s_i$  be a measure of dispersion of cluster  $C_i$  and  $d(C_i, C_j) \equiv d_{ij}$  the dissimilarity between two clusters. A similarity index  $R_{ij}$  between  $C_i$  and  $C_j$  satisfies the following (Davies and Bouldin, 1967):

- $R_{ij} \geq 0$
- $R_{ij} = R_{ji}$
- If  $s_i = 0$  and  $s_j = 0$  then  $R_{ij} = 0$
- If  $s_j > s_k$  and  $d_{ij} = d_{ik}$  then  $R_{ij} > R_{ik}$
- If  $s_j = s_k$  and  $d_{ij} < d_{ik}$  then  $R_{ij} > R_{ik}$

These conditions state that  $R_{ij}$  is nonnegative and symmetric. A choice for an  $R_{ij}$  that satisfies these conditions is (Kaufman and Rousseeuw, 1990):

$$R_{ij} = \frac{s_i + s_j}{d_{ij}} \quad (6-12)$$

Then the Davies-Bouldin Index is defined as:

$$DB_m = \frac{1}{m} \sum_{i=1}^m R_i \quad (6-13)$$

Where:  $R_i = \max_{\substack{j=1, \dots, m \\ j \neq i}} R_{ij}$  and  $i = 1, \dots, m$

The dissimilarity between cluster  $C_i$  and cluster  $C_j$ , in a  $l$ -dimensional space is defined as:

$$d_{ij} = \|\bar{x}_i - \bar{x}_j\| = \sqrt{\sum_{k=1}^l |\bar{x}_{ik} - \bar{x}_{jk}|^2} \quad (6-14)$$

And the dispersion of a cluster  $C_i$  is defined as:

$$s_i = \sqrt{\frac{1}{n_i} \sum_{x \in C_i} \|x - \bar{x}_i\|^2} \quad (6-15)$$

The  $DB_m$  is the average similarity between each cluster and its most similar one. Small values of  $DB$  are indicative of the presence of compact and well-separated clusters.

#### 6.4.2.3. The Dunn Index

The Dunn Index is defined as:

$$D_m = \min_{i=1, \dots, m} \left\{ \min_{j=i+1, \dots, m} \left( \frac{d(C_i, C_j)}{\max_{k=1, \dots, m} \text{diam}(C_k)} \right) \right\} \quad (6-16)$$

where the dissimilarity function between two clusters  $C_i$  and  $C_j$  is:

$$d(C_i, C_j) = \min_{x \in C_i, y \in C_j} d(x, y) \quad (6-17)$$

and the diameter of a cluster  $C$  is defined as:

$$\text{diam}(C) = \max_{x,y \in C} d(x,y) \quad (6-18)$$

If  $x$  contains compact and well-separated clusters, Dunn's Index will be large, since the distance between clusters is expected to be large and the diameter of the cluster is expected to be small.

### 6.4.3. Cluster validity results and discussion

In order to evaluate the clustering results of our problem, three internal validity indices, described in previous paragraph, have been selected:

- The Silhouette Index,
- The Davies Bouldin Index, and
- The Dunn Index

Specifically, all the cases that clustering algorithms have been applied to (described in paragraph 6.3 of this Chapter) have been tested with these internal validation algorithms in order to investigate the number of clusters ( $k$ ) which best fits our dataset and then investigate, where possible, the more efficient algorithm for each case. External criteria were not applicable, since it was not known in advance the structure of our dataset.

The results of the application of the above validity indices to VBD for each applied cluster algorithm and for each classification parameter are presented in the following tables (Table 6-16-Table 6-18).

The proposed classification should represent the European and national energy policy, should be applicable to a real building rating or labeling system and comparable to the existing rating and classification schemes. Before analyzing the validity results, the following restrictions have to be taken into account in order the obtained results to satisfy the policy criteria, apart from analytical ones.

- For the case of energy classification number of clusters  $k \geq 5$  will be investigated.
- For the thermal comfort classification number of clusters  $k \geq 3$  will be investigated.

**Table 6-16: Validity Indices for heating demand classifications**

<b>Hierarchical Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette Index	<b>0.72061</b>	0.66557	0.65577	0.52751	<b>0.5339</b>	0.53319	0.46083	0.46258
Davies - Bouldin Index	0.44411	0.46208	0.44611	0.48901	0.4871	<b>0.40834</b>	0.42312	0.44037
Dunn Index	3.4915	<b>3.5762</b>	2.8843	2.0597	<b>2.6473</b>	<b>2.6473</b>	0.34695	0.4828
<b>K-means Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.72046</b>	0.59428	0.54056	0.5243	0.51883	0.52401	<b>0.52845</b>	0.52747
Davies - Bouldin	<b>0.44474</b>	0.52484	0.527	0.53045	0.52602	0.51783	<b>0.50863</b>	0.51074
Dunn	<b>3.4828</b>	2.1002	1.5947	<b>1.6008</b>	1.4697	1.4011	1.1465	1.1368
<b>Gaussian Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.69146</b>	0.58844	0.51156	<b>0.52288</b>	0.49263	0.49519	0.50782	0.51253
Davies - Bouldin	0.51134	0.49928	0.51536	0.52808	<b>0.48794</b>	0.48796	0.49484	0.49961
Dunn	<b>2.7775</b>	2.1471	1.644	1.609	<b>1.6111</b>	1.589	1.1284	1.2044
<b>Fuzzy Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.72037</b>	0.57718	0.53701	0.51988	0.51854	0.52374	0.5268	<b>0.52782</b>
Davies - Bouldin	<b>0.44512</b>	0.53209	0.52885	0.5349	0.52626	0.51819	<b>0.51017</b>	0.51152
Dunn	<b>3.4776</b>	1.8182	1.5669	<b>1.4719</b>	1.4486	1.4136	1.1803	1.2157
<b>Neural Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.72055</b>	0.59341	0.54057	0.52213	0.51882	0.52387	<b>0.52802</b>	0.52777
Davies - Bouldin	<b>0.44436</b>	0.52528	0.52697	0.53327	0.52605	0.51804	<b>0.50903</b>	0.5113
Dunn	<b>3.488</b>	2.0839	1.5955	<b>1.5099</b>	1.4677	1.3989	1.1509	1.156

**Table 6-17: Validity Indices for cooling demand classifications**

<i>Hierarchical Clustering</i>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette Index	<b>0.61778</b>	0.6124	0.55074	<b>0.53038</b>	0.527	0.46528	0.46457	0.47065
Davies - Bouldin Index	0.38625	<b>0.31819</b>	0.40592	0.44804	0.44981	0.45722	<b>0.44637</b>	0.45738
Dunn Index	<b>4.1911</b>	3.677	3.1146	2.7072	<b>2.9214</b>	2.5232	2.1339	2.4835
<i>K-means Clustering</i>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.58287</b>	0.54339	0.53168	<b>0.52949</b>	0.52541	0.52662	0.52414	0.52406
Davies - Bouldin	0.57645	0.56113	0.55167	0.53087	0.52475	0.51852	0.51747	<b>0.51493</b>
Dunn	<b>3.0919</b>	2.3563	1.8198	<b>1.5472</b>	1.3078	1.1626	1.0823	0.95473
<i>Gaussian Clustering</i>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.57796</b>	0.51819	0.53073	<b>0.52867</b>	0.52415	0.52327	0.52368	0.52341
Davies - Bouldin	0.58075	0.52434	0.52887	0.52542	0.52352	0.51944	0.51459	<b>0.51382</b>
Dunn	<b>2.9476</b>	2.8371	1.8738	<b>1.5835</b>	1.365	1.1968	1.1049	0.94643
<i>Fuzzy Clustering</i>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.58203</b>	0.54133	0.52841	<b>0.52777</b>	0.52586	0.52488	0.52068	0.52381
Davies - Bouldin	0.57782	0.5618	0.55334	0.5361	0.52663	0.52011	0.52202	<b>0.51573</b>
Dunn	<b>3.0476</b>	2.2809	1.7675	<b>1.4963</b>	1.2667	1.1062	1.0326	0.95541
<i>Neural Clustering</i>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	<b>0.58302</b>	0.54331	0.53163	<b>0.52946</b>	0.5253	0.52664	0.52438	0.52404
Davies - Bouldin	0.57618	0.56114	0.55173	0.53096	0.52484	0.51853	0.51713	<b>0.51474</b>
Dunn	<b>3.0995</b>	2.354	1.8204	<b>1.5465</b>	1.2856	1.1605	1.0955	0.95865

**Table 6-18: Validity Indices for indoor thermal comfort classifications**

<b>Hierarchical Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette Index	0.48929	0.4934	0.45988	0.5449	0.3879	0.37788	0.35319	0.39549
Davies - Bouldin Index	0.41731	0.44438	0.44351	0.46542	0.38222	0.39438	0.40939	0.42668
Dunn Index	2.9627	3.2926	2.442	3.2764	3.2764	2.1718	2.4613	2.3254
<b>K-means Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	0.55696	0.58991	0.57201	0.5589	0.55022	0.54138	0.54161	0.53891
Davies - Bouldin	0.60801	0.48706	0.48303	0.48595	0.49817	0.50059	0.50103	0.5021
Dunn	3.2244	3.3211	2.9925	2.5608	2.6832	2.6151	2.281	2.4934
<b>Gaussian Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	0.46779	0.39816	0.52133	0.51716	0.35191	0.44382	0.46593	0.47408
Davies - Bouldin	0.40878	0.26381	0.46045	0.47241	0.48192	0.49236	0.4968	0.48536
Dunn	2.8995	3.0164	2.2413	0.8993	0.9687	1.1002	1.1169	1.1524
<b>Fuzzy Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	0.55491	0.58984	0.57142	0.55851	0.54945	0.54044	0.53737	0.53051
Davies - Bouldin	0.61227	0.48403	0.4821	0.48584	0.4981	0.5017	0.50409	0.50925
Dunn	3.2256	3.4444	3.0919	2.6406	2.7935	2.6161	2.4378	2.5174
<b>Neural Clustering</b>								
	Number of Clusters (k)							
	2	3	4	5	6	7	8	9
Silhouette	0.55708	0.59	0.57187	0.55873	0.55022	0.54128	0.54158	0.52867
Davies - Bouldin	0.60775	0.48673	0.48322	0.48613	0.49817	0.50064	0.50109	0.50906
Dunn	3.2243	3.3271	2.9883	2.5972	2.6832	2.6094	2.2856	2.2674

In the above Tables, for each index application on each cluster algorithm the best value, which indicates the best number of classes (k), has been underlined with yellow color. It is noted that in Silhouette and Dunn indices high values indicate the optimal number of clusters, while in Davies-Bouldin index values should be as small as possible.

Taking into account the restriction that the selected number of clusters have to be  $k \geq 5$  for energy demand (heating and cooling) and  $k \geq 3$  for thermal comfort (PMV index) classifications, the best index values are indicated with blue color on the tables.

The next step is to investigate the best value of each index for each cluster method. These values are depicted with bold characters in border in the above tables and they are summarized in Table 6-19.

**Table 6-19: The cluster algorithms and number of clusters with the best validity values**

Index	Cluster Algorithm with best index value	Number of Classes (k)
<b>Heating demand classifications</b>		
Silhouette	Hierarchical Clustering	6
Davies - Bouldin	Hierarchical Clustering	7
Dunn	Hierarchical Clustering	6 or 7
<b>Cooling demand classifications</b>		
Silhouette	Hierarchical Clustering	5
Davies - Bouldin	Hierarchical Clustering	8
Dunn	Hierarchical Clustering	6
<b>Thermal Comfort Classifications</b>		
Silhouette	Neural Clustering	3
Davies - Bouldin	Gaussian Clustering	3
Dunn	Fuzzy Clustering	3

For the final selection of the number of classes and the cluster method for each classification case, energy policy criteria such as EU standards and directives, national energy policy and the certification procedures have to be taken into account, as well.

Table 6-20: The limits of heating demand for the case of 6 and 7 classes

<b>6 -Class Classification (HC)</b>			
<b>Energy Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
A	0.00-36.10	0.00-69.80	0.00-68.40
B	36.20-68.40	69.90-100.50	68.50-111.80
C	68.50-91.80	101.00-133.50	111.90-150.90
D	92.00-116.80	133.70-157.90	151.00-192.20
E	117.00-153.20	158.40-204.80	192.40-262.10
F	153.70-199.00	207.50-234.90	263.90-315.50
<b>7 -Class Classification (HC)</b>			
<b>Energy Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
A	0.00-36.10	0.00-41.80	0.00-68.40
B	36.20-68.40	41.90-69.80	68.50-111.80
C	68.50-91.80	69.90-100.50	111.90-150.90
D	92.00-116.80	101.00-133.50	151.00-192.20
E	117.00-153.20	133.70-157.90	192.40-262.10
F	153.70-176.60	158.40-204.80	263.90-292.00
G	178.80-199.00	207.50-234.90	315.50-315.50

Table 6-21: The limits of cooling demand for the case of 5, 6 and 8 classes

<b>5 -Class Classification (HC)</b>			
<b>Energy Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
A	32.50-138.80	33.80-149.40	28.90-95.50
B	138.90-184.10	149.50-195.50	95.60-142.40
C	184.40-228.40	195.90- 236.70	142.60-180.40
D	229.90-302.50	238.80-301.70	180.90-256.50
E	319.40-359.40	325.90-352.80	287.50-306.10
<b>6 -Class Classification (HC)</b>			
<b>Energy Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
A	32.50-82.90	33.80-93.10	28.90-95.50
B	83.00-138.80	93.20-149.40	95.60-142.40
C	138.90-184.10	149.50-195.50	142.60 -180.40
D	184.40-228.40	195.90-236.70	180.90-214.60
E	229.90-302.50	238.80-301.70	216.30-256.50
F	319.40-359.40	325.90-352.80	287.50-306.10
<b>8 -Class Classification (HC)</b>			
<b>Energy Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
A	32.50-82.90	33.80-93.10	28.90-58.30
B	83.00-138.80	93.20 -116.60	58.40-95.50
C	138.90-184.10	116.70-149.40	95.60-142.40
D	184.40-228.40	149.50-195.50	142.60-180.40
E	229.90-260.80	195.90-236.70	180.90-214.60
F	264.10-302.50	238.80-262.00	216.30-238.70
G	319.40-319.40	266.40-301.70	242.70-256.50
H	359.40-359.40	325.90-352.80	287.50-306.10

As it is observed in Table 6-20, for both 6 and 7-class method and for the three climatic zones Building Regulation Reference values (See Table 5-7) are included in Energy Class A. This also occurs with the selected cooling classifications, according to

Table 6-21. For this reason, these methods are rejected, although they have the best validity indices.

The methods where the Regulation Reference Values for heating are included in Class B or C are K-means and Neural with k=8 classes. Between them the K-means is selected because gives better validity values (See Table 6-6 and Table 6-22).

The methods where the Regulation Reference Values for cooling are in Class B are K-means, Gaussian, Fuzzy and Neural with k=7 and 8 classes. For all the methods k=8 classes gives better validity values and among the methods the Neural Clustering is selected because gives better validity values compared to others. (See Table 6-19 and Table 6-23).

The best classifications of thermal comfort are presented in Table 6-29. All the validity indices propose 3 classes. The fuzzy method is selected because of the less computation time that is required and because it gives most robust clusters.

**Table 6-22: The limits of thermal comfort classifications for the case of 3 classes**

<b>3 -Class Classification (GMM)</b>			
<b>Comfort Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
1	92.10 - 88.50	92.10 - 86.50	92.10 - 83.30
2	88.40 - 63.70	86.40 - 53.75	37.80 - 22.97
3	63.60 - 0.65	53.70 - 1.00	83.20 - 3.45
<b>3 -Class Classification (FC)</b>			
<b>Comfort Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
1	92.11 - 77.31	92.11 - 75.11	92.11 - 70.60
2	77.28 - 55.35	75.09 - 52.98	70.58 - 48.13
3	55.32 - 0.66	52.95 - 1.03	48.11 - 3.45
<b>3 -Class Classification (NC)</b>			
<b>Comfort Classes</b>	<b>Climatic Zone A</b>	<b>Climatic Zone B</b>	<b>Climatic Zone C</b>
1	92.11 - 77.00	92.11 - 74.76	92.11 - 69.94
2	76.98 - 55.55	74.74 - 53.18	69.92 - 48.21
3	55.52 - 0.66	53.13 - 1.03	48.18 - 3.45

### 6.5. The proposed classifications

Regarding the analysis presented in previous paragraph, we have concluded to an 8-cluster heating and cooling energy demand system and a 3-cluster thermal comfort classification system for office buildings in Greece.

For the final proposed energy classes, the boundaries values are rounded to integer numbers. In the case of heating and cooling classification 1 extra class (heating 1 class including VBD upper values, cooling 1 class including VBD lower values) has been

added. The final proposed energy classifications are presented in Table 6-23 and Table 6-24.

**Table 6-23: The proposed heating demand classifications for office buildings in Greece**

Energy Classes	Heating Energy Demand (DH) kWh/m <sup>2</sup> /year		
	Climatic Zone A	Climatic Zone B	Climatic Zone C
A+	DH<12	DH <17	DH <27
A	12 ≤ DH <25	17 ≤ DH <32	27 ≤ DH <47
B	25 ≤ DH <37	32 ≤ DH <47	47 ≤ DH <66
C	37 ≤ DH <53	47 ≤ DH <67	67 ≤ DH <91
D	53 ≤ DH <75	67 ≤ DH <92	91 ≤ DH <124
E	75 ≤ DH <101	92 ≤ DH <122	124 ≤ DH <162
F	101 ≤ DH <132	122 ≤ DH <155	162 ≤ DH <207
G	132 ≤ DH <199	155 ≤ DH <235	207 ≤ DH <316
H	199 ≤ DH	235 ≤ DH	316 ≤ DH

**Table 6-24: The proposed cooling demand classifications for office buildings in Greece**

Energy Classes	Cooling Energy Demand (DC) kWh/m <sup>2</sup> /year		
	Climatic Zone A	Climatic Zone B	Climatic Zone C
A+	DC<33	DC<34	DC<29
A	33 ≤ DC<63	34 ≤ DC<66	29 ≤ DC<59
B	63 ≤ DC<84	66 ≤ DC<86	59 ≤ DC<76
C	84 ≤ DC<103	86 ≤ DC<105	76 ≤ DC<92
D	103 ≤ DC<123	105 ≤ DC<124	92 ≤ DC<109
E	123 ≤ DC<146	124 ≤ DC<145	109 ≤ DC<128
F	146 ≤ DC<172	145 ≤ DC<171	128 ≤ DC<149
G	172 ≤ DC<213	171 ≤ DC<211	149 ≤ DC<182
H	213 ≤ DC	211 ≤ DC	182 ≤ DC

The final proposed classifications for thermal comfort are presented in Table 6-25.

**Table 6-25: The proposed thermal comfort classifications for office buildings in Greece**

Comfort Classes	Percentage of time that $ PMV  \leq 0.7$ (PMV <sub>IND</sub> %)		
	Climatic Zone A	Climatic Zone B	Climatic Zone C
1	77 < PMV <sub>IND</sub>	75 < PMV <sub>IND</sub>	71 < PMV <sub>IND</sub>
2	55 < PMV <sub>IND</sub> ≤ 77	53 < PMV <sub>IND</sub> ≤ 75	48 < PMV <sub>IND</sub> ≤ 71
3	PMV <sub>IND</sub> ≤ 55	PMV <sub>IND</sub> ≤ 53	PMV <sub>IND</sub> ≤ 48

In Figures 6-3 and 6-4 the limits of the proposed classifications are depicted on VBD building sample.

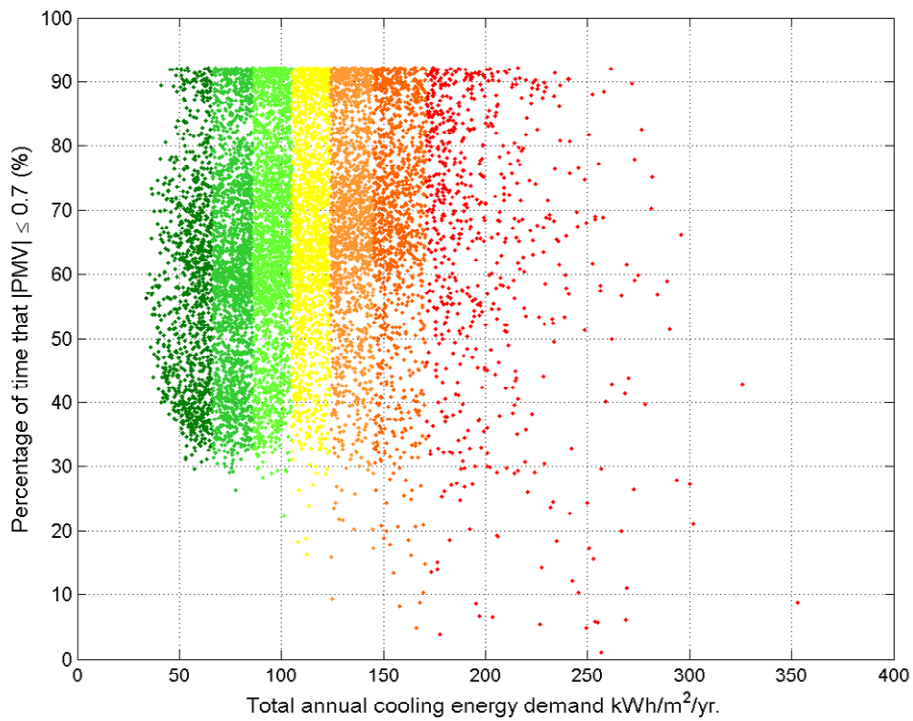
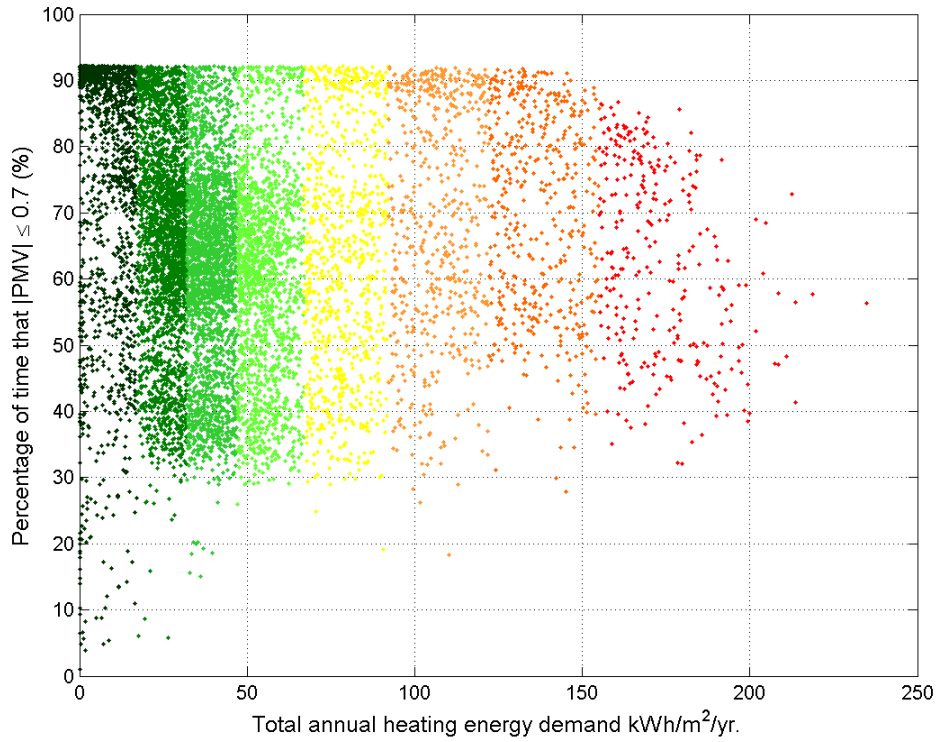


Figure 6-3: The representation of energy classifications on VBD

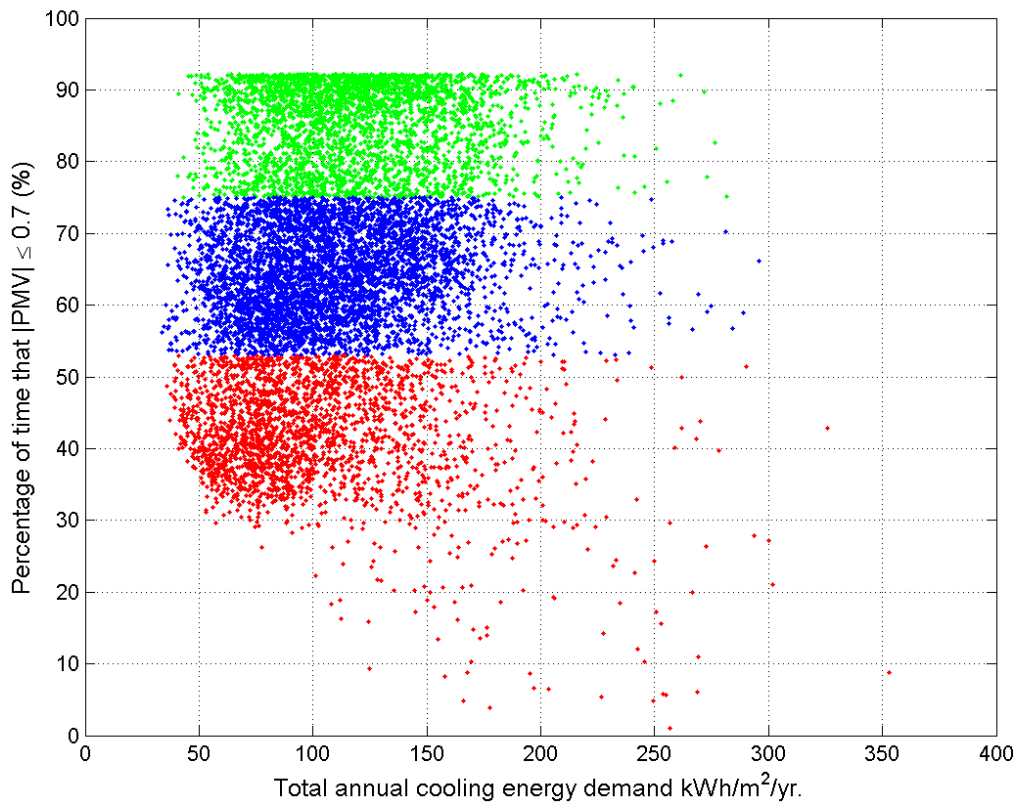
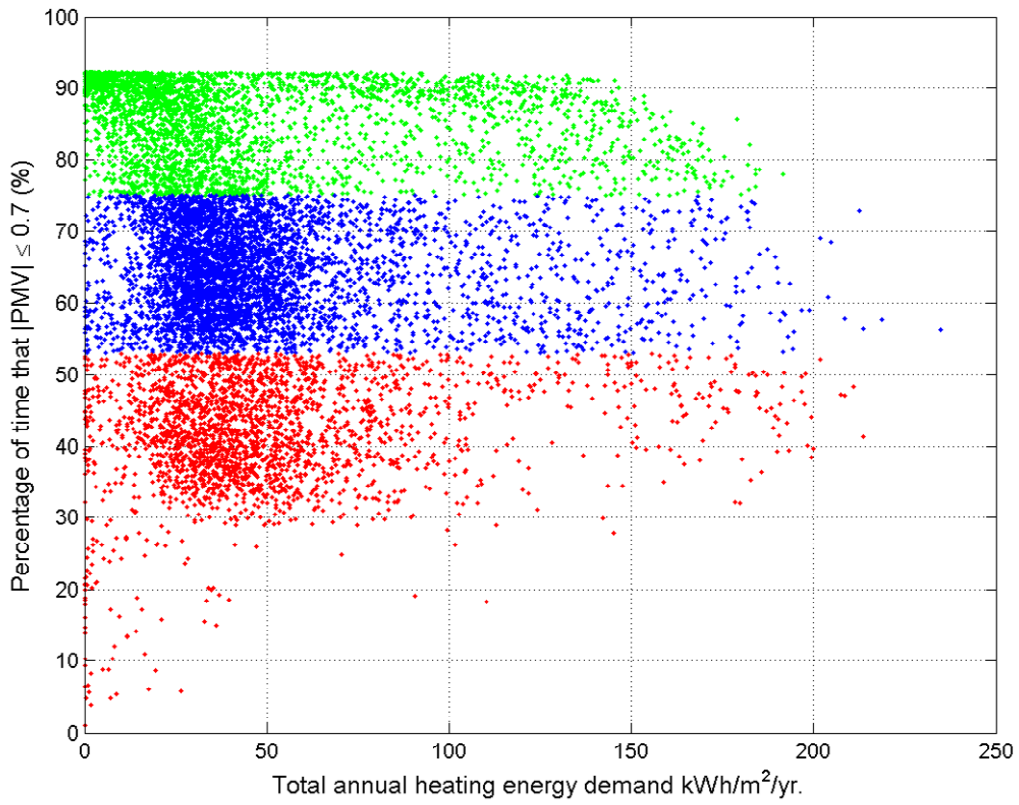


Figure 6-4: The representation of comfort classification on VBD

According to the proposed classifications the efficiency of each office building deals with two parameters: the energy that the building demands for heating and cooling and the thermal comfort of the indoor environment that is achieved by this amount of energy consumption. A building that demands a small amount of energy having an unacceptable indoor environment for occupants can not be characterized as “efficient”. The classification system for office buildings that is proposed in this research combines these two aspects of the term “efficient”.

The proposed classification boundaries are compared to CEN classification limits. We have to note that both methods use VBD data as building sample and that the methods have different number of classes: cluster method proposes 9 classes, while CEN proposes 7 classes. In Table 6-26 the two classifications for climatic zone B are presented. A first examination of the limits in the above table, leads us to change the name of classes having the classifications of Table 6-27.

A closer examination of the boundaries presented in the above table, lead us to the following comments:

- For the case of “best practice class”, represented by the 1<sup>st</sup> class each time we have to note that: “A Class” of cluster analysis refers to office buildings with the heating energy demand lower than 15 kWh/m<sup>2</sup> /yr. while the corresponding amount stood at 17 kWh/m<sup>2</sup> /yr. according to CEN method. CEN proposes more strict criteria for best practice class, while cluster is more encouraging for buildings belonging to Class A.
- For the case of “minimum requirements class” i.e. the class with the limit of building regulation reference the boundary values of two methods are very close: 32 kWh/m<sup>2</sup> /yr for cluster method and 29 kWh/m<sup>2</sup> /yr for CEN method.
- The Building Stock Reference value for Climatic Zone B (39 kWh/m<sup>2</sup> /yr) is included in Energy Class C for the case of cluster analysis method, complying with the EU energy policy.
- Cluster method has larger range for D and E class, while this class is split to D and E class and F and G respectively to the CEN method. This encourages Greek office building with high energy demand for heating to reach easier class B by improving their energy efficiency after retrofits.

- The proposed method has larger range (17-235 kWh/m<sup>2</sup>/yr) comparing to CEN range (15-78 kWh/m<sup>2</sup>/yr). This occurs because the proposed method is based on the whole dataset (30,000 data) while the CEN method is based only on the building stock reference value (1 data). The proposed classification takes into account the energy characteristics of all the buildings of the sample and not only the value that corresponds to the 50% of the stock.

**Table 6-26: Comparison of proposed classes against CEN 1**

Heating Energy Demand (DH) kWh/m <sup>2</sup> /year		
CLIMATIC ZONE B		
Energy Classes	Cluster	CEN
A+	DH <17	
A	17 ≤ DH <32	DH <15
B	32 ≤ DH <47	15 ≤ DH <29
C	47 ≤ DH <67	29 ≤ DH <34
D	67 ≤ DH <92	34 ≤ DH <39
E	92 ≤ DH <122	39 ≤ DH <58
F	122 ≤ DH <155	58 ≤ DH <78
G	155 ≤ DH <235	78 ≤ DH
H	235 ≤ DH	

**Table 6-27: Comparison of proposed classes against CEN 2**

Heating Energy Demand (DH) kWh/m <sup>2</sup> /year (CL. ZONE B)			
Energy Classes	Cluster	Energy Classes	CEN
A	DH <17	A	DH <15
B	17 ≤ DH <32	B	15 ≤ DH <29
C	32 ≤ DH <47	C	29 ≤ DH <34
D	47 ≤ DH <67	D	34 ≤ DH <39
		E	39 ≤ DH <58
E	67 ≤ DH <92	F	58 ≤ DH <78
		G	78 ≤ DH
F	92 ≤ DH <122		
G	122 ≤ DH <155		
H	155 ≤ DH <235		
I	235 ≤ DH		

Summarizing the above comments, we underline that the proposed method complies with the EU proposed energy policy, is more encouraging and gives more “fair” classes, as this method considers the characteristics of all the building stock and classifies them according to existing similarities.

## 6.6. Classification and buildings' characteristics investigation

Taking into consideration the proposed classifications, some of the buildings' characteristics are investigated in order to understand common features of buildings rated in the same class.

Before investigating the characteristics, it is very useful to investigate the distribution of buildings in each class. In Tables 6-28 and 6-29 the percentages of buildings that are classified in each class (according to energy demand classifications) are presented for the climatic zone B (central region of Greece including Athens), while in Table 6-30 the percentages of buildings according to thermal comfort classes are presented.

**Table 6-28: Buildings' distribution according to heating demand classification**

Energy Classes	Boundaries	Percentage of buildings (%)
A+	DH <17	13.5
A	$17 \leq \text{DH} < 32$	24.1
B	$32 \leq \text{DH} < 47$	24.7
C	$47 \leq \text{DH} < 67$	16.0
D	$67 \leq \text{DH} < 92$	8.4
E	$92 \leq \text{DH} < 122$	5.7
F	$122 \leq \text{DH} < 155$	4.7
G	$155 \leq \text{DH} < 235$	3.0
H	$235 \leq \text{DH}$	0.0

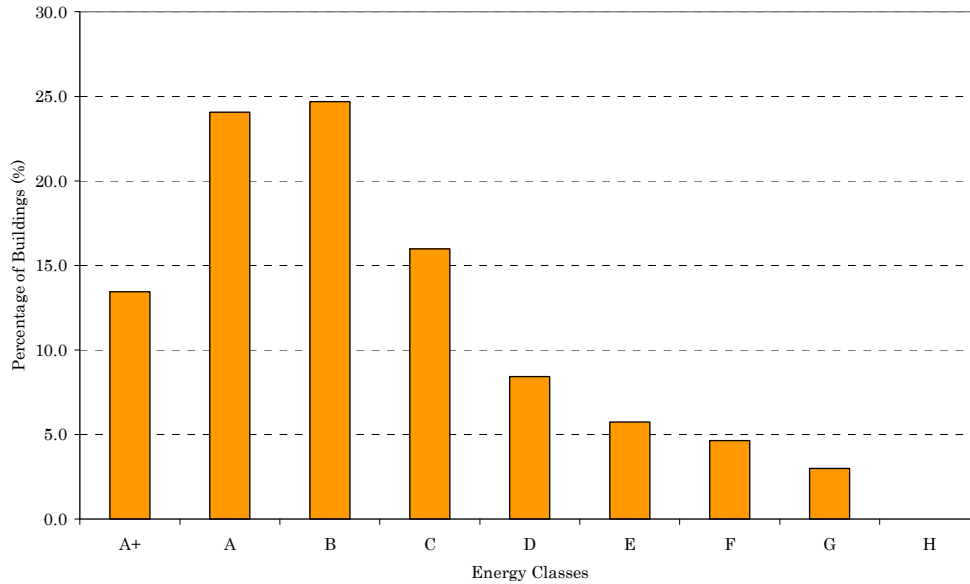
**Table 6-29: Buildings' distribution according to cooling demand classification**

Energy Classes	Boundaries	Percentage of buildings (%)
A+	DC <34	0.0
A	$34 \leq \text{DC} < 66$	10.8
B	$66 \leq \text{DC} < 86$	19.1
C	$86 \leq \text{DC} < 105$	19.9
D	$105 \leq \text{DC} < 124$	17.3
E	$124 \leq \text{DC} < 145$	14.9
F	$145 \leq \text{DC} < 171$	11.3
G	$171 \leq \text{DC} < 211$	6.8
H	$211 \leq \text{DC}$	0.0

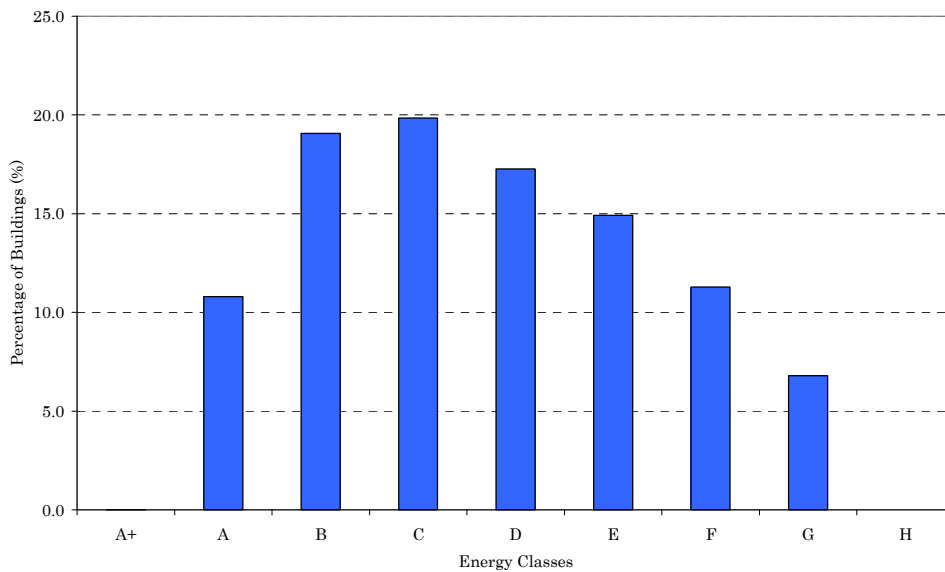
**Table 6-30: Buildings' distribution according to thermal comfort classification**

Comfort Classes	Percentage of buildings (%)
1	30.66
2	45.51
3	23.83

The above percentages are illustrated in the following Figures (Figure 6-5, 6-6 and 6-8).



**Figure 6-5: The buildings' distribution into energy classes (heating demand classification)**



**Figure 6-6: The buildings' distribution into energy classes (cooling demand classification)**

The difference between the above distributions occurs because of the different selected classification method for heating and cooling based on validity indices. The heating classification is based on K-means clustering algorithms, while the cooling on Neural SOM clustering technique. In Figure 6-7 the buildings' distribution into cooling

energy classes based on K-Means clustering technique is depicted. As it is observed, the distributions of heating and cooling classifications are very similar if the same clustering method is applied.

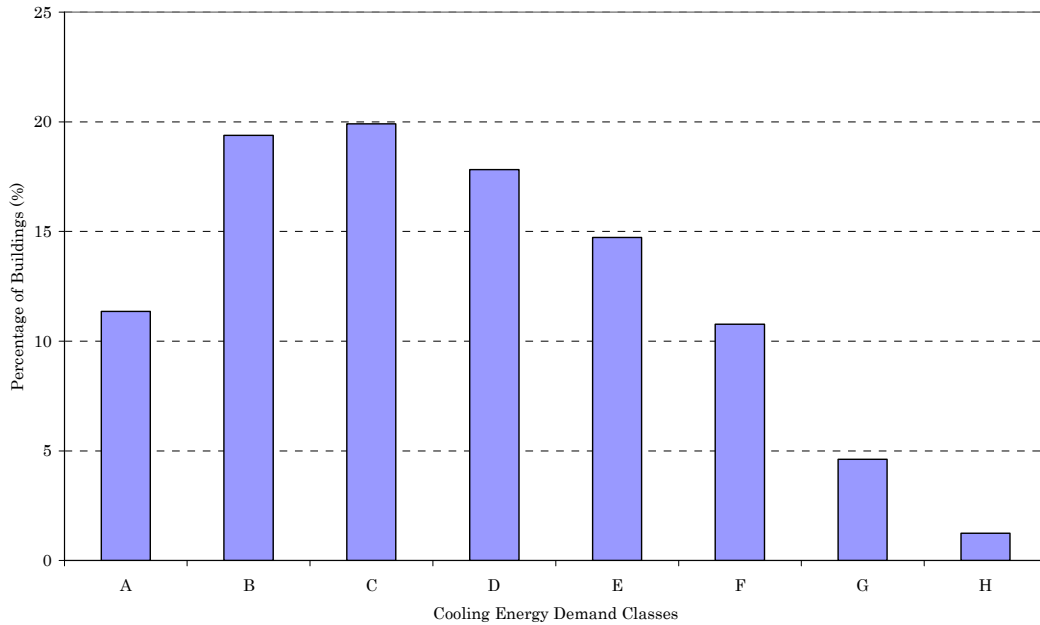


Figure 6-7: Cooling demand classification according to the K-Means clustering technique

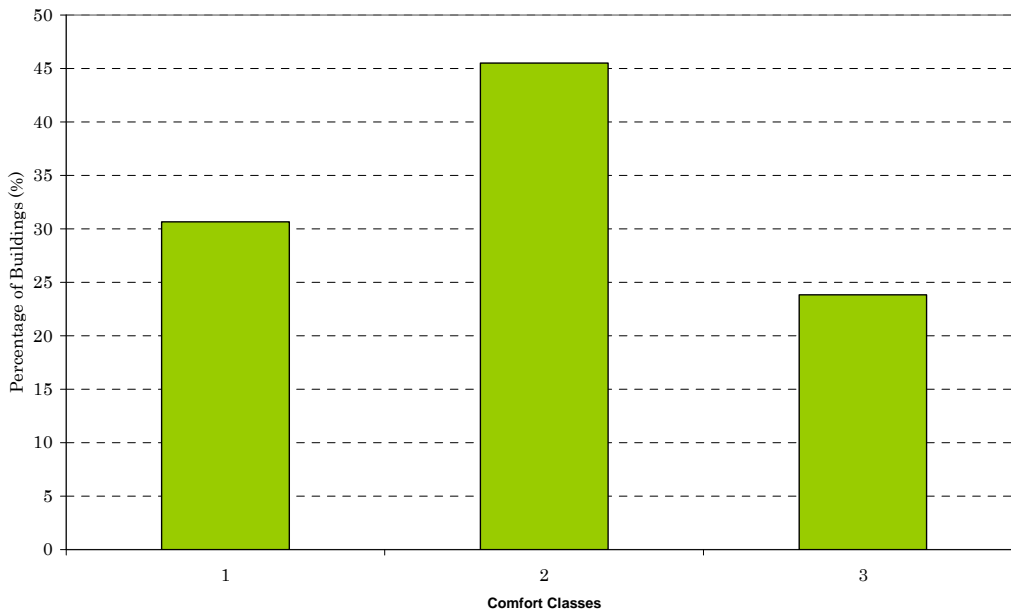


Figure 6-8: The buildings' distribution into thermal comfort classes

As it is observed, the majority of buildings are classified in energy class B for the case of heating demand classification and in class C for the cooling demand classification. This validates the accuracy of the selected classification method, since according to various proposed classification methods (see the CEN proposed method) the typical building belongs in third or fourth class. Referring to the thermal comfort classes, the majority of buildings belong to class 2. Since there is not any comfort classification in the literature up to now, we can propose that the reference building belongs to class 2 and the regulation reference to class 1.

The characteristics under investigation include U-value of walls and roofs, type of glazing, external shading and ventilation rates. This detailed analysis refers only to climatic zone B in order to examine buildings with medium heating and cooling energy consumption needs. The percentages of buildings according to the constructional and operational characteristics are presented in Table 6-31.

**Table 6-31: Energy classification and building characteristics**

Heating Demand Classification								
Classes	Window Type			Wall and Roof Type				Average ventilation rate (ach)
	W1	W2	W3	WR1	WR2	WR3	WR4	
% of the building stock								
A+	20.7	34.9	44.4	11.4	21.7	32.5	34.4	2.0
A	21.4	36.3	42.2	6.7	19.0	36.5	37.9	4.6
B	33.3	32.5	34.1	8.3	33.7	29.5	28.5	5.9
C	48.2	30.9	20.9	18.5	40.8	22.1	18.5	6.1
D	50.8	27.5	21.7	53.0	24.3	11.4	11.3	6.0
E	44.6	27.0	28.4	83.4	10.3	3.8	2.4	6.4
F	31.8	36.3	31.8	97.2	1.7	0.9	0.2	7.1
G	48.8	25.8	25.4	99.0	0.3	0.3	0.3	8.1
H	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
Cooling Demand Classification								
Classes	Window Type			Wall and Roof Type				Average ventilation rate (ach)
	W1	W2	W3	WR1	WR2	WR3	WR4	
% of the building stock								
A+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
A	36.1	32.4	31.5	18.3	28.3	26.5	26.9	4.2
B	35.7	32.7	31.6	23.5	26.9	24.8	24.8	5.0
C	35.2	32.5	32.2	26.2	25.4	24.0	24.3	5.3
D	34.0	32.4	33.6	26.6	21.9	26.4	25.1	5.5
E	33.9	31.4	34.7	27.2	25.3	25.3	22.3	5.7
F	30.6	34.3	35.2	25.2	25.4	23.8	25.6	5.8
G	23.4	35.3	41.2	25.6	20.6	26.7	27.1	5.0
H	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
Window Types: W1: Single U=5.58 W/m <sup>2</sup> /K, W2: Double U=2.38 W/m <sup>2</sup> /K, W3: Low-e U=1.4 W/m <sup>2</sup> /K								
Wall and Roof Types:								
WR1: U <sub>wall</sub> =1.743W/m <sup>2</sup> /K, U <sub>roof</sub> =3.18W/m <sup>2</sup> /K WR3: U <sub>wall</sub> =0.643/m <sup>2</sup> /K, U <sub>roof</sub> =0.452W/m <sup>2</sup> /K								
WR2: U <sub>wall</sub> =1.354W/m <sup>2</sup> /K, U <sub>roof</sub> =0.5W/m <sup>2</sup> /K WR4: U <sub>wall</sub> =0.452W/m <sup>2</sup> /K, U <sub>roof</sub> =0.452W/m <sup>2</sup> /K								

### 6.6.1. Energy classification and construction elements

The construction elements (walls and roofs) are correlated strongly with heating energy demand. As shown in Table 6-31, all of buildings in “G Class” (99%) of heating classification consist of buildings with elements of high U-values ( $U_{\text{wall}}=1.743 \text{ W/m}^2/\text{K}$  and  $U_{\text{roof}}=3.18 \text{ W/m}^2/\text{K}$  and no insulation). On the contrary the cooling demand of buildings is not so strong related with insulation and depends on other building parameters. The percentage of elements with the highest U-value (wall without insulation) and the lowest U-values (wall with high insulation) are presented in Figure 6-8 and Figure 6-9.

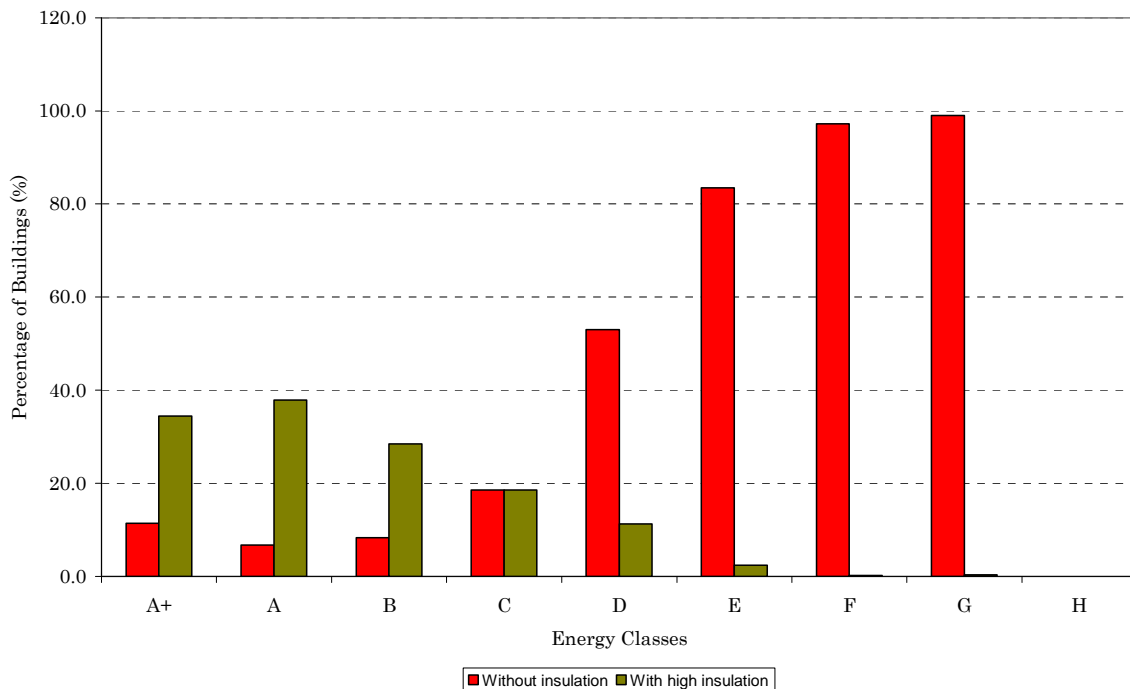
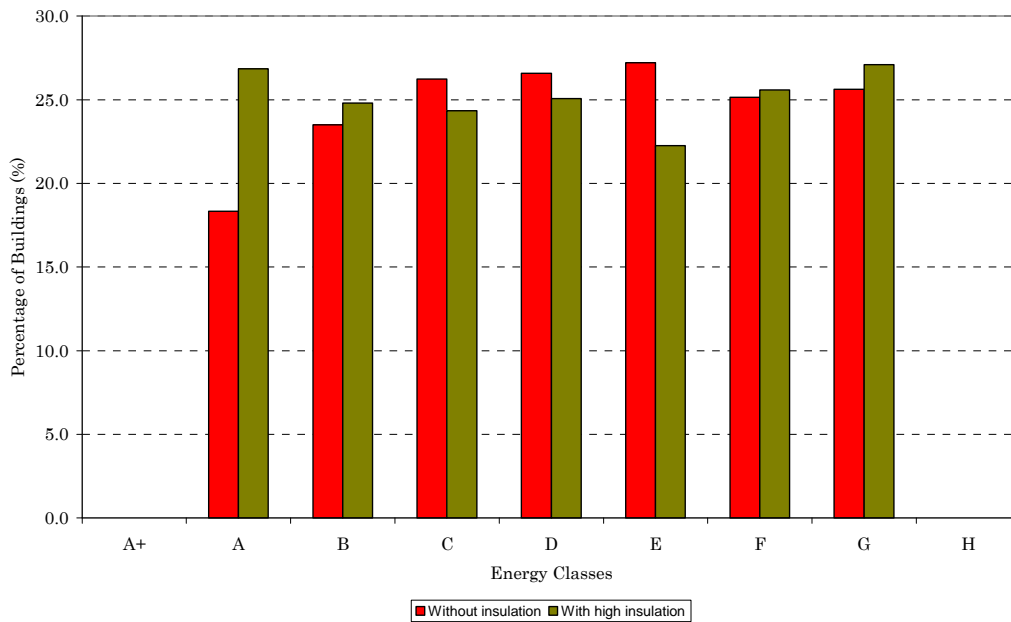


Figure 6-9: Type of elements and heating demand classification



**Figure 6-10: Type of elements and cooling demand classification**

Glazing plays provides view and daylight, but can also increase energy consumption due to its poor insulation value. Considering the obtained results, the type of glazing affect energy demand while the proportion of single glazed windows is increased as the energy demand increases. As a result the percentage of office buildings with double glazed and low-E windows is usually decreased as the heating and cooling demand is increased. The variation of single glazed and low-E windows is illustrated in the figures below.

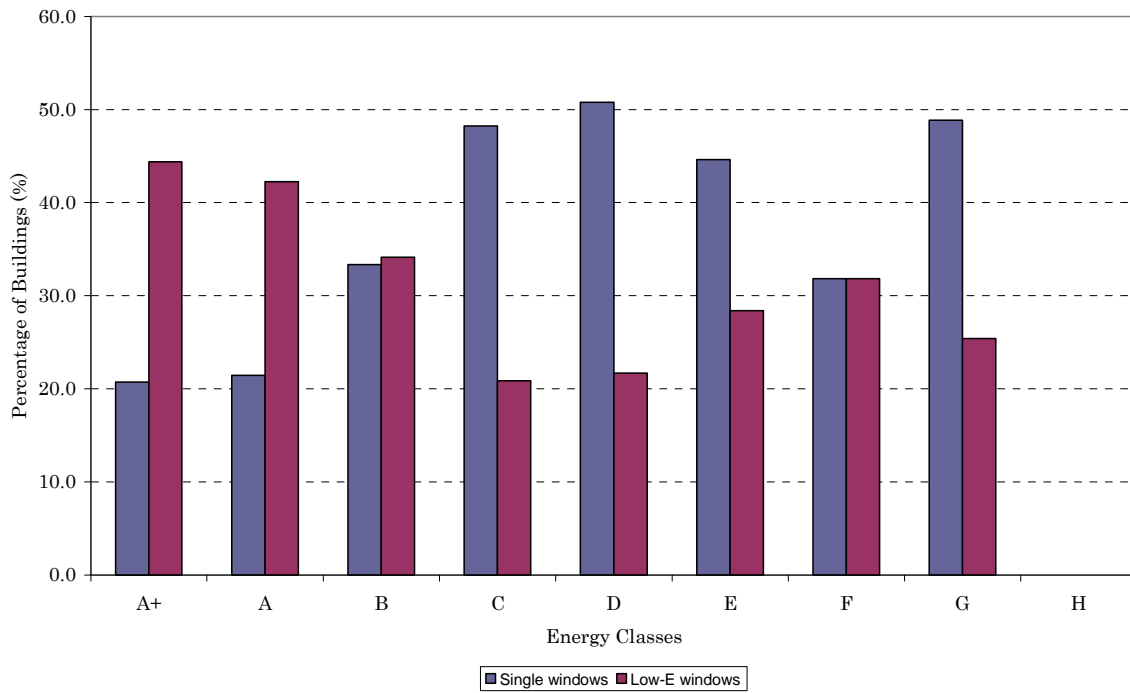


Figure 6-11: Type of windows and heating demand classification

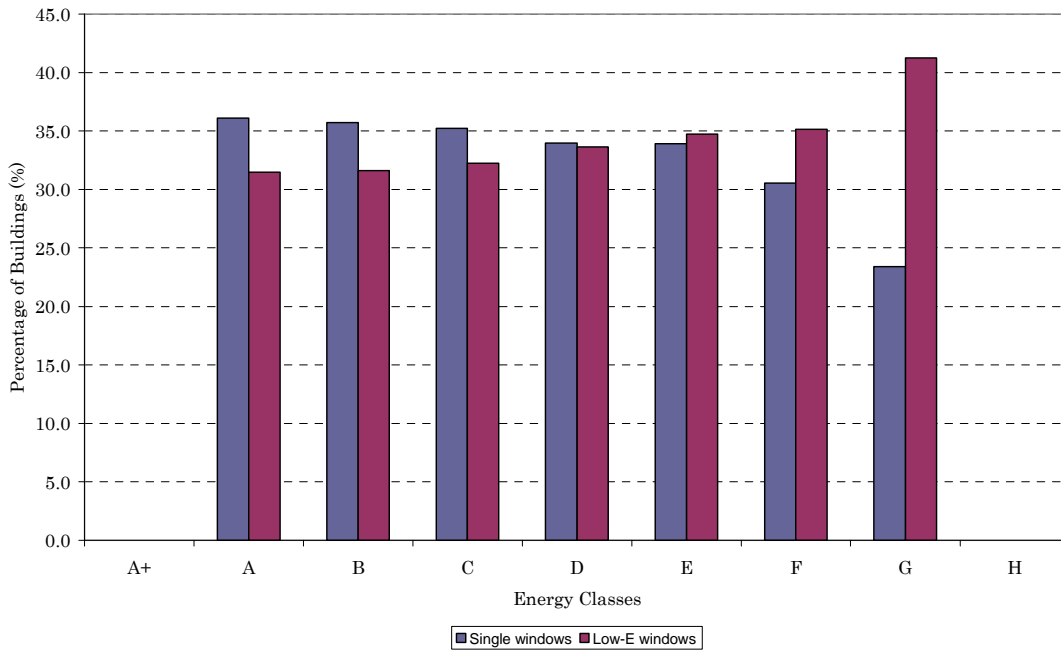


Figure 6-12: Type of windows and cooling demand classification

### 6.6.2. Energy classification and ventilation

Ventilation consumes energy, primarily because the ventilation air is thermally conditioned, i.e., heated, cooled, and dehumidified or humidified. In mechanically ventilated buildings, the operation of ventilation fans also consumes energy. The capacity of heating and cooling equipment must also be increased as the amount of ventilation air provided increases. Thus, ventilation rates have often been minimized, particularly after the energy crisis in the early 1970s, in order to reduce equipment and energy costs. In order to examine the correlation between ventilation rate and total energy consumption, the average values for each class and method were calculated. According to Table 6-31, ventilation rate is increased as energy demand for heating and cooling is increased. The relative values range from and 2 ACH to 8.1 ACH. These variations are illustrated in Figure 6-10.

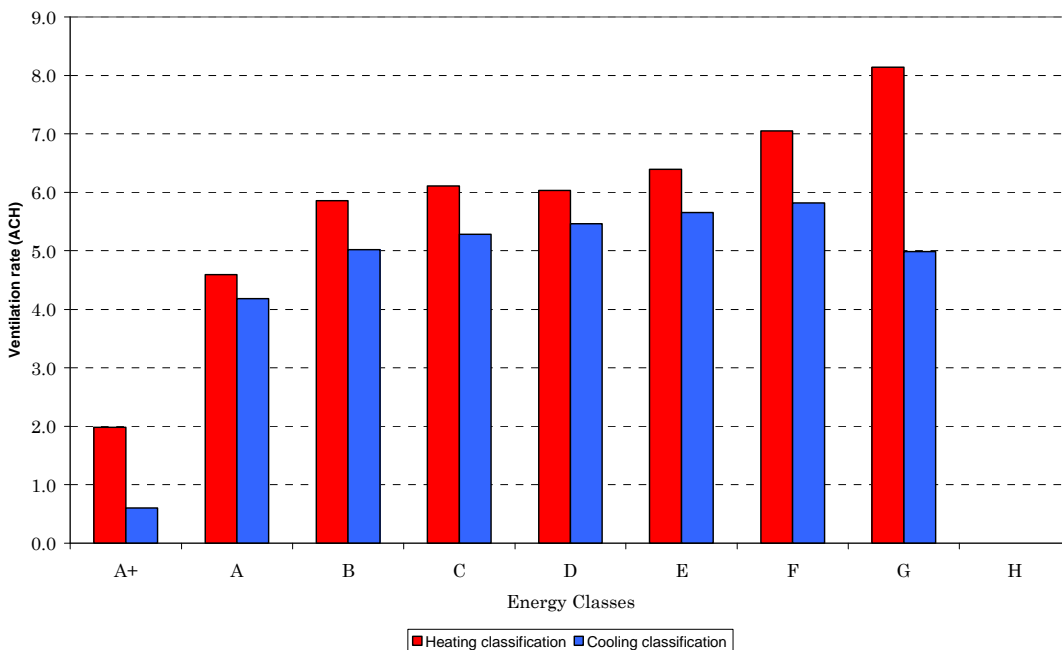


Figure 6-13: Ventilation rates and energy classification

### 6.6.3. Improving the efficiency of office buildings

The analysis of building characteristics on each class, presented in previous paragraph, shows that every energy class has common features (U-values of walls and roofs, type of glazing, etc.). The corresponding features of buildings rated either as either “A Class” or “B Class” must be taken into consideration for the improvement of

office buildings' energy categories. The proposed total energy classification indicates that "A Class" and "B Class" refer mainly to buildings with insulated constructional elements and double or Low-E windows. Similar proportions derive from the corresponding heating energy classification. Additionally, buildings rated in classes with low cooling energy consumption include offices with an adequate external shading factor.

The obtained outputs indicate the selection and maintenance of appropriate ventilation rates as a crucial parameter of energy consumption. The goal is to provide adequate ventilation with respect to the quality of indoor air while considering the corresponding heating and cooling energy consumption needs of buildings. For this reason, relevant standards have been established (CEN, etc.), which determine appropriate levels of ventilated air flows ( $\text{m}^3/\text{h}$ ) according to buildings' energy use, occupancy density of area and other factors. Referring to the clustering results, the variation of ventilation throughout energy classes show that slight relevant increments result in higher amounts of energy consumption.

Maintaining good indoor air quality requires attention to the building's heating, ventilation, and air conditioning (HVAC) system, the design and layout of the space and pollutant source management. HVAC systems include all of the equipment used to ventilate, heat, and cool the building, to move the air around the building (ductwork) and to filter and clean the air. These systems can have a significant impact on how pollutants are distributed and removed. They can even act as sources of pollutants in some cases, such as when ventilation air filters become contaminated with dirt and/or moisture and when microbial growth results from stagnant water in drip pans or from uncontrolled moisture inside of air ducts.

## **6.7. Conclusions**

In this Chapter, five clustering techniques have been tested in order to investigate the appropriate method for establishing energy and thermal comfort classifications for the Greek office building sector. The clustering algorithms that have been applied to VBD for this purpose are: Hierarchical Clustering (HC), K-Means Clustering (KMC), Gaussian Mixture Models (GMM), Fuzzy C-Means Clustering (FC) and Neural Clustering (SOM). Each method has been applied to energy demand for heating,

energy demand for cooling and PMV index for each climatic zone and for 2 to 9 classes.

In order to evaluate the clustering results of our problem, three internal validity indices: The Silhouette Index, the Davies Bouldin Index, and the Dunn Index have been selected for testing the classifications. All the cases that clustering algorithms have been applied, have been tested with these internal validation algorithms in order to investigate the number of clusters ( $k$ ) which best fits our dataset and then investigate the more efficient algorithm for each case. External criteria were not applicable, since it was not known in advance the structure of our dataset.

As the proposed classification should represent the European and national energy policy, the following restrictions have been taken into account in order the obtained results to satisfy the policy criteria, apart from analytical ones.

- For the case of energy classification number of clusters  $k \geq 5$  will be investigated.
- For the thermal comfort classification number of clusters  $k \geq 3$  will be investigated.
- For the final selection of the classification system, the Building Stock and Regulation Reference Values of Greek building stock have to be taken into account for a successful rating and certification scheme.

According the aforementioned restrictions the following classification methods have been proposed for office buildings for each climatic zone in Greece:

- An 8 cluster (9-class) heating energy demand classification based on K-Means Clustering technique.
- An 8 cluster (9-class) cooling energy demand classification based on Neural (SOM) Clustering technique.
- A 3 cluster (3-class) thermal comfort classification based on Fuzzy Clustering technique.

The comparison of the proposed method with the CEN method leads us to the following conclusions:

- The proposed method incorporates the thermal comfort of the indoor environment as a parameter for building's efficiency. According to this rating system, building that demands a small amount of energy having an unacceptable indoor

environment for occupants can not be characterized as “efficient”, which may occur when rating with CEN method.

- The proposed method relies on the EU proposed energy policy, is more encouraging and gives more robust classes, as this method considers the common characteristics of the buildings and classifies them according to existing similarities.

The buildings parameter investigation has shown that U-values of roofs and walls play a significant role in heating energy demand. The common characteristic of buildings rated in “A Class” of total and heating energy classification is that the majority of them were constructed with high insulated elements. The relative U-values stood at 0.643 W/m<sup>2</sup> K or 0.452 W/m<sup>2</sup> K for walls and 0.452 W/m<sup>2</sup> K for roofs. Respectively, “G Class” includes mainly poor insulated buildings with high U-values of 1.743 W/m<sup>2</sup> K for walls and 3.18 W/m<sup>2</sup> K for roofs.

In order to improve office buildings' energy categories the new office buildings must be constructed using elements with lower U-values, while the existing buildings must be renovated appropriately by adding insulation in external wall and roofs. Glazed areas in offices usually share a noticeable proportion of the total external surface of the building. For this reason the replacement of single glazed windows with double or Low-E is proposed in order to reduce relative transmission losses. It should be remembered however that the use of improved glazing may result in decreased daylighting and collection of solar energy. Additionally, the heat gain/loss ratio will, nevertheless, be greatly improved. Considering the orientation of windows and the external climatic conditions, the appropriate use of shading configurations will have as a result the reduction of cooling energy consumption.

## Chapter 7

# FINAL CONCLUSIONS AND FUTURE PROSPECTS

## **CHAPTER 7: FINAL CONCLUSIONS AND FUTURE PROSPECTS**

In this doctoral research an integrated classification method, in terms of energy and thermal comfort efficiency, for office buildings in Greece has been developed. The proposed scheme includes the creation of the detailed simulation model for evaluating the buildings' performance, the creation of the building stock dataset, the definition of the energy and thermal comfort benchmarks, the clustering method for determining the number of classes and their limits and finally recommendations for building efficiency improvement methods. The points that should be discussed in this Chapter are:

### **1. Simple and detailed energy audits**

Two types of energy audits have been conducted by the author in the framework of this thesis: 10 simple audits (preliminary or walk-through audits) to office buildings and a detailed audit based on BMS measurements in BYTE office building. The detailed audit approximates reality at a higher degree, since the study is based on hourly measurements and not only on energy bills. Apart from energy consumption data the model takes into account and calculates environmental parameters such as indoor temperature, humidity and PMV indicator in each thermal zone of the building at an hourly base.

However, there are difficulties and drawbacks to the detailed process such as the high cost of BMS installation and the long time required for data collection and auditing procedure.

### **2. Asset and operational rating**

During simulation model validation, the comparison between measured and calculated values has revealed conclusions related on asset and operational rating of buildings. It is shown that the calculated (asset) energy rating can give a rough estimate of the indoor air temperature and the heating/cooling energy consumption of the building and can be used as a preliminary energy consumption estimation method, while the measured method can be used for the final energy classification of the building.

### **3. Simulated building datasets**

In this PhD research, an innovative approach for producing a Virtual Building Dataset (VBD) has been demonstrated in order to investigate the energy and indoor thermal comfort efficiency of a user-defined number of virtual office buildings. The method has been applied to 10,000 office buildings for each of the three major climatic zones in Greece. Besides the constructional and operational characteristics of each building, the VBD contains the calculated energy demands for heating and cooling, the energy consumption for lighting and appliances as well as the indoor thermal comfort requirements.

It is shown that the VBD produces an extensive spectrum of office building profiles, which renders it a representative virtual sample of the building stock. The method is easily adapted to any country's building constructional and operational ranges and climatic zone data for producing a respective localized VBD.

Such an approach could constitute a time-saving substitute to the real building data collection required prior to the definition of energy classes.

Moreover, it is important that this virtual building dataset can be used for the definition of the limits of the energy classes (cluster analysis) for each building category. The optimum, though, use of the VBD is in combination with smaller in size but real datasets for each building category, in order to ensure reliable and safe results.

Additionally, the VBD can be used as the basis for a parametric study of one or more building characteristics with respect to the energy and thermal comfort efficiency attained. In order to proceed with an integrated building efficiency approach, correlating the energy consumption to the thermal comfort of the building, VBD proves to be a valuable tool for the definition of respective guidelines.

Moreover, VBD is a useful tool for building energy clustering, energy rating procedures, determination of energy and indoor thermal environment building classification boundaries, neural networks training and validation, multi-criteria decision making data for building retrofit scenarios, sensitivity analysis and to any process requires large number of building data, in general.

The advantages of the VBD compared to a real dataset is the capability of simulating a large amount of buildings, the flexibility to isolate and study the interaction of various parameters and their effect in the energy performance of the buildings, the possibility to mass study different scenarios for improving the energy efficiency of a large number of buildings and not only on individual case-study buildings.

#### **4. Application of clustering techniques for energy and thermal comfort classification**

Using VBD as building sample, five clustering techniques have been tested in order to investigate the appropriate method for establishing energy and thermal comfort classifications for the Greek office building sector. The clustering algorithms that have been applied to VBD for this purpose are: Hierarchical Clustering (HC), K-Means Clustering (KMC), Gaussian Mixture Models (GMM), Fuzzy C-Means Clustering (FC) and Neural Clustering (SOM).

For the evaluation of the cluster methods, three internal validity indices: The Silhouette Index, the Davies Bouldin Index, and the Dunn Index have been selected for testing the classifications, in terms of the best number of classes and the method that best fits on VBD.

As the proposed classification should comply with the European and national energy policies, restrictions have been taken into account in order the obtained results to meet the policy criteria.

The innovation of the proposed method, in comparison to the CEN method, is that the thermal comfort of the indoor environment has been incorporated into the classification system. The proposed method complies with the EU proposed energy policy, is more encouraging and gives more robust classes, as it considers the common characteristics of the buildings and classifies them according to the existing similarities.

#### **5. Buildings parameter investigation and efficiency improvement**

The buildings' parameter investigation has shown that U-values of roofs and walls play a significant role in energy consumption. In order to upgrade the energy category of an office building, elements with lower U-values must be employed during construction for the new office buildings, while appropriate renovation to this

direction (e.g. adding insulation in external wall and roofs) must be proposed in case of existing buildings.

Glazed areas in offices usually share a noticeable proportion of the total external surface of the building. Thus, the replacement of single glazed windows with double or Low-E is proposed in order to reduce relative transmission losses. It should be remembered, though, that the use of improved glazing may result in decreased daylighting and collection of solar energy. Additionally, the heat gain/loss ratio will, nevertheless, be greatly improved. Considering the orientation of the windows and the external climatic conditions, the appropriate use of shading configurations will lead to the reduction of cooling energy consumption.

Summarizing all the above, the innovative parts of the present thesis are:

- The adoption of a detailed simulation model validated with hourly measured monitoring data, which has been generalized in order to simulate a large amount of office buildings.
- The adoption of a Virtual Building Dataset that overcomes the barrier of lack of available building data.
- The adaptability of VBD to any country's building constructional and operational ranges and climatic zone data for producing a respective localized VBD.
- The adaptability of VBD to new constructional and operational data.
- The fact that VBD constitutes a useful tool for the training and validation of neural networks, multi-criteria decision making data for building retrofit scenarios, sensitivity analysis, investigation of applications such as cool roofs, external insulation, new construction elements and other methods requiring a large number of building data.
- The proposed limits for energy and thermal comfort classification are based on clustering techniques, optimally identified during a detailed and analytical investigation among various clustering algorithms.
- The thermal comfort of the indoor environment has been incorporated into the classification system, with a 3-class proposed rating system.
- As VBD contains detailed information about buildings' characteristics, the proposed classification method allows for the investigation of parameters that characterize each energy and environmental class, leading to the ability of investigating multiple class upgrading methods.

- The adoption of an integrated classification dynamic methodology for Greek office building sector with the following characteristics: time saving and low budget processes, large flexibility and expandability and an easy update to the new building data and/or policy decisions.

Finally, based on the topics discussed earlier in this Chapter, further research effort should be put in:

**1. Classification based on the final energy consumption of buildings.** Having the results of VBD concerning the heating and cooling demands (loads) of the buildings, the proposed method can be applied to the final energy consumption of buildings by taking into account the heating and cooling efficiency coefficient for each building, since VBD already contains the energy consumption for lighting and equipment. First the values for coefficients have to be selected, for example  $n = 0.7 \div 0.9$ ,  $COP = 2 \div 5$  etc, then the loads have to be transformed into consumptions by dividing the loads with the above efficiency coefficients and finally to add the energy consumption for lighting and equipment.

**2. The generalization of the VBD to other building categories in Greece.** Following the same concept of VBD creation, the dataset can be generalized to any building category (hospitals, schools, dwellings etc.). The method is based on the change of the value ranges of all the simulation parameters according to each building category. The new value ranges must be complying with the national codes and the outcomes of the audits that have been conducted to each building category.

**3. The generalization of the VBD at a global level.** The method can be generalized globally for creating a VBD in any country by changing the weather input data according to the country's climatic zones division and the constructional characteristics of materials and structural elements dominating the country's building sector.

**4. The incorporation of indoor air quality and visual comfort in the proposed classification scheme.** This can be achieved by including indoor air quality (e.g. CO<sub>2</sub> concentration), and visual comfort parameters (e.g. luminance levels) in VBD. In this case, the thermal model (adopted in TRNSYS or other simulation program) has to be in cooperation with an air flow model (TRNFLOW, COMIS, etc) and with a luminance model.

**5. The training and validation of neural networks using the VBD data.** The VBD data, including the proposed classifications, can be used in order to train a neural network for office buildings' rating and classification. The neural network will take into account some basic inputs of building' characteristics (e.g. floor area, fraction of openings, wall type, window type, heating and cooling system) and, without any simulation process, it will estimate the class that a building belongs to.

**6. The use of the VBD for multi-criteria decision making for building retrofit scenarios and sensitivity analysis.** The large amount of data that VBD contains can be used for various kinds of data analysis for investigating the contribution of each parameter to building's energy and environmental efficiency.

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