



**Technical University of Crete  
School of Electrical and Computer Engineering  
Electrical Power Systems Laboratory**

**Diploma Thesis**

**Modeling, Simulation for Energy Control of HVAC System in Building**

**Georgia Venianaki  
A.M. 2011030084**

**Thesis Committee:**

**Professor Georgios Stavrakakis (supervisor)**

**Professor Michail Zervakis**

**Doctor Eleftheria Sergaki**

**Chania, May 2018**



## ABSTRACT

This diploma thesis was carried out within of the obligations of the students of the Department of Electrical and Computer Engineering of the Technical University of Crete, for obtaining their diploma. The title of the thesis is 'Modeling, Simulation for Energy Control of HVAC System in Building'. The subject of this diploma thesis is the air conditioning system's study of a two-storey residence, i.e. the theoretical planning process, to the practical application and the calculations that a study needs from the beginning to the completion. Different types of HVAC systems are studied for each independent home space of area and the final optimal selection of the proposed system is based on techno-economic criteria. The cost of each component is computed according to the prices of 2017

The diploma thesis initially deals with the purpose and necessity of installing a HVAC system resulting in ideal comfort conditions for comfortable and healthy living in enclosed areas. Then are mentioned, the different types of HVAC systems and by which criteria they are chosen to suit their needs. In addition, is given a detailed description of five building energy modeling programs, EnergyPlus, DOE -2, DeST, TRYNSYS and ESP -r. After the final selection of the EnergyPlus program, a complete conditioning study is being done in a double storey house, which consists of nine thermal zones, six of which are conditioned.

The building that is selected is a two-storey house of 128.57 m<sup>2</sup>, with its main axis being developed in the north-south direction. Most and larger openings are located in the South, which are the main entrance of solar radiation and natural lighting of the building. On the north side of the house there are mainly auxiliary and not often used spaces, such as storage and bathrooms, while the openings placed there are fewer and smaller in size. Finally, it is worth noting that the building meets the basic thermal insulation rules, with double glazing windows and insulating material being put only in the building's shell and not interior.

The building is energetically simulated by using EnergyPlus™ software and Google Sketch Up plug-in. In order to investigate better the energy behavior of the building and its passive systems, seven alternative operating scenarios, divided into three study cases, were conducted. In the first, the building is located in three cities in Greece with heterogeneous climatic data, in Athens, Andravida and Thessaloniki, and compares the thermal loads, gains and costs. In the second, a comparison of the energy which is consumed and the operating cost of three different HVAC systems are made when the house is located in Athens. Also, the size that would be sufficient to meet the building's needs, as well as the cost of installing the three different air-conditioning systems was determined. In the third case, the building in study is placed in Thessaloniki and we repeat what we did in the second case. That is, comparison of operation and installation costs of the three different systems.

The study concludes with the final selection, which results from the analysis and comparison of life cycle cost of the three different systems at a depth of 15 years.

**Keywords:** Air conditioning, HVAC systems, building energy modeling programs (BEMPs), thermal loads, refrigerant loads, heat gains, heat losses, EnergyPlus,

Variable Refrigerant Flow (VRF), Variable Refrigerant Volume (VRV), Fan Coil Unit (FCU), Variable Air Volume (VAV)

**Acronyms:**

Designer's Simulation Toolkit (DeST),  
Energy Simulation Software tool (ESP -r),  
Fan Coil Unit (FCU),  
Technical Chamber of Greece (TEE),  
Technical Instructions TEE (TOTEE),  
Transient System Simulation Tool (TRNSYS),  
Variable Air Volume (VAV),  
Variable Refrigerant Flow (VRF),  
Variable Refrigerant Volume (VRV),  
Building Energy Modeling Programs (BEMPs),  
Heating Ventilation and air – conditioned (HVAC)

## ΠΕΡΙΛΗΨΗ

Η παρούσα εργασία εκπονήθηκε στα πλαίσια των υποχρεώσεων των φοιτητών του τμήματος Ηλεκτρολόγων Μηχανικών και Μηχανικών Υπολογιστών της ομότιτλης σχολής του Πολυτεχνείου Κρήτης, για την απόκτηση του διπλώματος τους. Ο τίτλος της εργασίας είναι 'Μοντελοποίηση, Προσομοίωση για Ενεργειακό Έλεγχο Συστήματος Κλιματισμού σε Κτίριο'. Αντικείμενο της παρούσας διπλωματικής εργασίας αποτελεί η μελέτη κλιματισμού μιας διώροφης κατοικίας, δηλαδή η διαδικασία σχεδιασμού σε θεωρητικό επίπεδο μέχρι την πρακτική εφαρμογή και τους υπολογισμούς που χρειάζεται μία μελέτη από την έναρξη μέχρι την ολοκλήρωση της. Πραγματοποιείται η διερεύνηση διαφορετικών συστημάτων κλιματισμού για τον κάθε ανεξάρτητο χώρο της οικίας και η τελική βέλτιστη επιλογή του προτεινόμενου συστήματος βασίζεται σε τεchnοοικονομικά κριτήρια.

Η διπλωματική εργασία αρχικά πραγματεύεται το σκοπό και την αναγκαιότητα της εγκατάστασης ενός συστήματος κλιματισμού με αποτέλεσμα τη διαμόρφωση ιδανικών συνθηκών άνεσης για άνετη και υγιεινή διαβίωση στους κλειστούς χώρους. Στη συνέχεια αναφέρεται στους διάφορους τύπους συστημάτων κλιματισμού και με ποια κριτήρια γίνεται η επιλογή τους σύμφωνα με τις ανάγκες του κάθε χώρου. Ακόμη, γίνεται αναλυτική περιγραφή πέντε προγραμμάτων ενεργειακής προσομοίωσης, EnergyPlus, DOE -2, DeST, TRNSYS και ESP -r. Μετά την τελική επιλογή του προγράμματος EnergyPlus γίνεται εκπόνηση μιας πλήρους μελέτης κλιματισμού σε μια διώροφη κατοικία, η οποία αποτελείται από εννέα θερμικές ζώνες εκ των οποίων οι έξη είναι κλιματιζόμενες.

Το κτήριο που επιλέχθηκε είναι μία διώροφη μονοκατοικία 128,57 τ.μ., με τον κύριο άξονά του να αναπτύσσεται στη διεύθυνση Βορράς - Νότος. Τα περισσότερα και μεγαλύτερα ανοίγματα τοποθετούνται στον Νότο, τα οποία αποτελούν την κύρια είσοδο ηλιακής ακτινοβολίας και φυσικού φωτισμού στο κτήριο. Στη βόρεια όψη της οικίας υπάρχουν κυρίως βοηθητικοί και μη συχνά χρησιμοποιούμενοι χώροι, όπως η αποθήκη και τα μπάνια, ενώ τα ανοίγματα που τοποθετούνται εκεί είναι λιγότερα σε αριθμό και μικρότερα σε έκταση. Τέλος, αξίζει να σημειωθεί ότι το κτήριο πληροί τους βασικούς κανόνες θερμομόνωσης, με διπλούς υαλοπίνακες και μονωτικό υλικό μόνο στο κέλυφος του κτηρίου και όχι στο εσωτερικό του.

Το κτήριο προσομοιώθηκε ενεργειακά με τη χρήση του λογισμικού EnergyPlus™ και τη βοήθεια του Google Sketch Up. Για την καλύτερη διερεύνηση της ενεργειακής συμπεριφοράς του κτηρίου και των παθητικών συστημάτων αυτού, διεξήχθησαν επτά εναλλακτικά σενάρια λειτουργίας, τα οποία χωρίζονται σε τρεις περιπτώσεις. Στην πρώτη, το κτήριο τοποθετείται σε τρεις πόλεις τις Ελλάδας με ετερογενή κλιματικά δεδομένα, στην Αθήνα, στην Ανδραβίδα και στη Θεσσαλονίκη, και συγκρίνονται τα θερμικά φορτία, κέρδη και κόστη. Στην δεύτερη, πραγματοποιείται σύγκριση της καταναλισκόμενης ενέργειας και του κόστους λειτουργίας τριών διαφορετικών συστημάτων κλιματισμού όταν η οικία τοποθετείται στην Αθήνα. Ακόμα, προσδιορίζεται το μέγεθος που θα επαρκούσε για να καλύψει τις ανάγκες του κτηρίου, καθώς και το κόστος εγκατάστασης των τριών διαφορετικού τύπου συστημάτων κλιματισμού. Στην τρίτη περίπτωση, τοποθετούμε το υπό μελέτη κτήριο στη Θεσσαλονίκη και

επαναλαμβάνουμε όσα κάναμε στην δεύτερη περίπτωση. Δηλαδή, σύγκριση κοστών λειτουργίας και εγκατάστασης των τριών διαφορετικών συστημάτων.

Η μελέτη ολοκληρώνεται με την διεξαγωγή της τελικής επιλογής, η οποία προκύπτει από την ανάλυση και σύγκριση του κόστους ζωής των τριών διαφορετικών συστημάτων, σε βάθος 15ετίας.

**Λέξεις κλειδιά:** Κλιματισμός, κλιματιστικά συστήματα, προγράμματα ενεργειακής προσομοίωσης κτηρίων, θερμικά φορτία, ψυκτικά φορτία, θερμικά κέρδη, θερμικές απώλειες, EnergyPlus, Variable Refrigerant Flow (VRF), Variable Refrigerant Volume (VRV), Fan Coil Unit (FCU), Variable Air Volume (VAV)

### **Ακρωνύμια:**

Designer's Simulation Toolkit (DeST),  
Energy Simulation Software tool (ESP –r),  
Fan Coil Unit (FCU),  
Τεχνικό Επιμελητήριο Ελλάδας (TEE),  
Τεχνικές Οδηγίες TEE (TOTEE),  
Transient System Simulation Tool (TRNSYS),  
Variable Air Volume (VAV),  
Variable Refrigerant Flow (VRF),  
Variable Refrigerant Volume (VRV),  
Building Energy Modeling Programs (BEMPs),  
Heating Ventilation and air – conditioned (HVAC)

## **Acknowledgements**

I ought to express my warmly gratitude to Dr. Eleftheria Sergaki, senior teaching personnel at Technical University of Crete, for providing me the opportunity to work on this diploma thesis, as well as, her valuable advices and tools needed throughout my study.

I would, also, like to thank my supervisor, Professor George Stavrakaki, and Professor Michael Zervaki for spending time reading and reviewing this thesis.

Last, but not least, I would like to thank Mrs. Chrysi – Maria Iliaki, Business Director, for her motivation at the beginning of my writing.

## Table of Contents

<b>ABSTRACT.....</b>	<b><i>i</i></b>
<b>Keywords.....</b>	<b><i>i</i></b>
<b>Acronyms.....</b>	<b><i>ii</i></b>
<b>ΠΕΡΙΛΗΨΗ.....</b>	<b><i>iii</i></b>
<b>Λέξεις κλειδιά.....</b>	<b><i>iv</i></b>
<b>Ακρωνύμια.....</b>	<b><i>iv</i></b>
<b>Acknowledgements.....</b>	<b><i>v</i></b>
<b>Chapter 1 Introduction.....</b>	<b><i>1</i></b>
1.1. Thesis objective .....	1
1.2. Thesis importance .....	1
1.3. Thesis outline.....	2
1.4. Comfort Conditions.....	3
1.4.1. Usefulness of HVAC systems .....	3
1.4.2. Conditions of Comfort Temperature .....	3
1.4.3. Factors that affect the climate of a space .....	5
1.4.4. The role of external climate.....	6
1.4.5. Operating Conditions of Buildings .....	6
1.4.6. Energy efficiency of buildings [19].....	7
1.4.7. Climate zones.....	8
1.5. Introduction in HVAC Systems .....	11
1.5.1. Historical Review .....	11
1.5.2. Definitions - Basic Operations of a HVAC System .....	11
1.5.3. Advantages of proper use of the air conditioner .....	12
1.5.4. Disadvantages of using air conditioners .....	12
1.5.5. Ways to deal with .....	13
1.5.6. Air Conditioning Applications .....	13
1.5.7. Noise and vibration .....	14
<b>Chapter 2 Classification of HVAC Systems.....</b>	<b><i>16</i></b>



2.1.	<i>General</i> .....	16
2.2.	<i>Classification of air conditioning systems based on the degree of air treatment</i> .....	16
2.3.	<i>Air conditioning systems based on the heat transfer media</i> .....	17
2.3.1.	All air systems .....	17
2.3.2.	Chilled water systems.....	19
2.3.3.	Air-Water systems .....	21
2.4.	<i>Air conditioning systems based on device location and scope of application</i> .....	23
2.4.1.	Unitary air conditioning systems .....	23
2.4.2.	Central air conditioning systems .....	28
2.4.3.	Components of central air treatment units.....	34
2.5.	<i>Conclusion</i> .....	36
<b>Chapter 3 Available Software Tools for Energy Building Simulation .....</b>		<b>37</b>
3.1.	<i>Introduction</i> .....	37
3.1.1.	Building Energy Modeling Programs (BEMPs) .....	37
3.1.2.	Advantages of Energy Simulation Tools .....	37
3.1.3.	Need of comparison of BEMPs' .....	38
3.2.	<i>Steps to perform in a BEMP</i> .....	38
3.2.1.	Step one of BEMP – Create the building .....	39
3.2.2.	Step two of BEMP – Building Simulation .....	39
3.2.3.	Step three of BEMP – Analysis of results.....	39
3.3.	<i>Presentation of available Energy Simulation Software tools</i> .....	40
3.3.1.	EnergyPlus .....	41
3.3.2.	DOE-2.1E.....	44
3.3.3.	DeST (Designer's Simulation Toolkit).....	46
3.3.4.	ESP –r (Energy Simulation Software Tool) .....	49
3.3.5.	TRNSYS.....	51
3.4.	<i>Comparison of Energy Simulation Software tools</i> .....	52
3.5.	<i>Conclusions</i> .....	55
<b>Chapter 4 Building Modeling in EnergyPlus® .....</b>		<b>56</b>
4.1.	<i>Description of simulation software</i> .....	56
4.1.1.	Google SketchUp design program .....	56
4.1.2.	Create a simulation model using the OpenStudio tool .....	56

4.2.	<i>Simulation in EnergyPlus™</i> .....	57
<b>Chapter 5 Simulation of a Greek two storey detached house</b> .....		<b>60</b>
5.1.	<i>Location and description of the building in study</i> .....	60
5.2.	<i>Definition of thermal zones to simulate the building</i> .....	63
5.3.	<i>Construction elements, materials and layers</i> .....	65
5.4.	<i>Climate data</i> .....	68
5.5.	<i>Shadowing of the building</i> .....	74
5.6.	<i>Use and operation of the building</i> .....	75
5.6.2.	<i>Schedules</i> .....	76
5.6.3.	<i>Internal gains</i> .....	77
5.7.	<i>Thermal study</i> .....	81
5.7.2.	<i>Interior design conditions</i> .....	81
5.7.3.	<i>External environment conditions</i> .....	82
5.7.4.	<i>Calculation of ventilation, heating and thermal loads</i> .....	82
5.8.	<i>HVAC templates</i> .....	83
5.8.1.	<i>VRF HVAC system</i> .....	83
5.8.2.	<i>VAV HVAC system</i> .....	84
5.8.3.	<i>FCU HVAC system</i> .....	86
5.9.	<i>Zone airflow</i> .....	89
5.10.	<i>General assumptions in EnergyPlus</i> .....	90
5.11.	<i>Conclusions on using EnergyPlus®</i> .....	91
<b>Chapter 6 Results of Simulations</b> .....		<b>93</b>
6.1.	<i>Comparative heating/ cooling loads' results between cities</i> .....	93
6.2.	<i>Comparative thermal gains and losses results between cities</i> .....	98
6.3.	<i>Comparative energy consumption and cost results between HVAC systems</i> .....	111
6.4.	<i>Conclusions</i> .....	120
<b>Chapter 7 Sizing and Installation cost of three HVAC systems</b> .....		<b>121</b>
7.1.	<i>HVAC systems sizing</i> .....	121
7.2.	<i>Components</i> .....	122
7.2.1.	<i>VRV system components</i> .....	122
7.2.2.	<i>VAV system components</i> .....	123
7.2.3.	<i>FCU system components</i> .....	124

7.3.	<i>Installation costs analysis</i> .....	125
7.4.	<i>Comparison of installation costs</i> .....	127
<b>Chapter 8 Conclusions</b> .....		<b>129</b>
8.1.	<i>Conclusion</i> .....	129
<b>References</b> .....		<b>131</b>
<b>Appendix A Normalized diagrams</b> .....		<b>133</b>
<b>Appendix B Comparison of HVAC types in Thessaloniki</b> .....		<b>137</b>
a.	<i>Energy consumption comparison</i> .....	137
b.	<i>Operation costs comparison</i> .....	139
c.	<i>Installation costs comparison</i> .....	139
<b>Appendix C Life Cycle Cost Analysis</b> .....		<b>142</b>

# **Chapter 1 Introduction**

## **1.1. Thesis objective**

The objective of this diploma thesis is to use reliable building simulation software (EnergyPlus®) in the implementation of a building, to calculate its heating, cooling and ventilation needs (HVAC). The simulation software that has been selected has many advantages over others tools, due to its ability to provide a full and detailed description of all variables affecting load calculation, its flexibility in its calculation methods and its credibility in the calculation of results. In addition to all of the above, it is an open source software which is continuously evolving in order to include more energy systems.

Another objective of this diploma is to compare the energy performance of HVAC system in three different cities of Greece, Athens (N37°54', E23°43'), Andravida (N37°55', E21°16') and Thessaloniki (N40°31', E22°58'), which have different weather conditions. In order to achieve this goal we placed the same building in each one of the three cities. Then, we calculated and compared the heating and cooling loads that are needed to meet heating and cooling needs, respectively in the each one of the three cities, using EnergyPlus®.

Lastly, we aim to compare the operation and installation cost of three different HVAC systems, Variable Refrigerant Flow (VRF), Fan Coil Unit (FCU) and Variable Air Volume (VRV), which consist of different components and have different technical characteristics, when the building is placed in the city of Athens. This intended to make the decision on which of the three HVAC system is more suitable (functionally and financially) for our case of study. All of the above have a final goal, which is to carry out a complete air conditioning study for a building in order to achieve the ideal comfort temperatures which cover the needs of its residents.

## **1.2. Thesis importance**

Nowadays, due to the rapid weather changes and people's lifestyle, the necessity of installing an air conditioning system resulting in ideal comfort conditions for comfortable and healthy living in enclosed spaces is increasing. These facts make the development of air conditioning more and more important. Preparing an air conditioning study for a space is a complex problem, whose correct conformation is a combination of a variety of techno – economic criteria and factors, such as the climatic conditions of the area, the constructional components of the building, the type and use of each space, as well as the specifics and requirements of each installation. The desired goal is to create comfort conditions in the interior when unfavorable external conditions prevail. At the same time, however, the final installation should be technically and functionally applicable, financially acceptable, safe and reliable and be in accordance with applicable regulations and laws.

### **1.3. Thesis outline**

This diploma thesis includes eight chapters. In more detail, first chapter introduces the objective and importance of the study, with a view to providing a justification for the choice of its subject. In addition, is notified the necessity of installing a HVAC system resulting in the creation of ideal indoor comfort conditions for comfortable and healthy living in enclosed spaces. Comfort conditions for each space are examined and how they vary according to the type, use and requirements of each space. Also, analyzes the parameters that affect comfort conditions and can be adjusted by a HVAC system.

The second chapter analyzes HVAC systems, which are classified by main criterion the way and means by which the final conditioning of the desired indoor climate conditions in the air – conditioned space is achieved. The classification of air conditioning systems is based on three basic criteria: the air treatment level, the heat transfer medium and the location of the appliances together with the application area. Particular weight is given in the third classification, which is the classification based on the location of the devices and the extent of application and is extensively analyzed.

In the third chapter there is a reference, a detailed description and a comparison of five of the most popular building energy modeling programs (BEMPs), EnergyPlus, DeST, DOE – 2, TRNSYS and ESP – r. First are mentioned common features and steps which are followed to use all of the BEMPs. Then, specific mention is made in each of the above tools, while at the end of this chapter an analytical comparison table is presented.

In the next chapter, the basic features of the software used are presented and described. In particular, Google SketchUp to create the geometric model, use of OpenStudio through Google SketchUp to create the building simulation model and EnergyPlus to simulate and calculate loads.

In the fifth chapter, the data collection required for the simulation is described in detail. These are presented in the way they were used as input to the simulation program. It describes the building, the climate of the three different cities in which it is located, the physical properties of the building shell, every interior space, its use, hourly operation, people, and other thermal gains. In addition, the conditions to be applied under regulations for the calculation of loads and a description of the HVAC systems are used as selected.

In the sixth chapter are presented the results of simulations and comparison is made for thermal loads, thermal gains and thermal losses between the three different cities. Also, are presented the results of simulations and comparison is made for electric energy consumptions and operation costs between the three different HVAC systems. All results are commented in order to evaluate whether the resulting values are expected.

In the seventh chapter, sizing of the three different HVAC systems is made, in order to choose the individual components of each one, which cover the needs of the building in study. Then, final installation cost of each one is computed according to the price catalogue of Daikin for 2017, and results are compared.

In the eighth and last chapter of this thesis, the conclusions of the study are presented.

## 1.4. Comfort Conditions

### 1.4.1. Usefulness of HVAC systems

Since the early years of human existence, efforts were being made to protect every living organism from extremes and therefore dangerous temperature changes, which were inseparable, associated with the natural - biological effort for survival. For that reason, man has been trying, since ancient times, to ensure pleasant, or at least tolerable environmental conditions, in the areas of his residence and employment. Climate and conditions that prevailed in it had been important factors for the selection of regions and areas where people were resident.

Nowadays, where many people spend the most part of their daily time in indoor places, air conditioning of buildings is necessary to keep conditions that respond with fullness, safety, reliability and affordability, to requirements of man for comfort and healthy living in indoor places of stay, residence and work.

Technology and financial possibilities of people have formed a multi-faceted matrix of requirements, which can be covered by each conditioning and artificial ventilation system. Condition for full climate comfort, takes as basic parameters the temperature and humidity of the spaces, the purity, mode and speed of air movement and intensity of noise.

In every installation the selection of air conditioner system has to combine a range of needs and desires of users, with feasible technological solutions, economic criteria, the necessary functionality, as well as hygiene and safety of building's users and handlers of the equipment.

### 1.4.2. Conditions of Comfort Temperature

The feeling of thermal comfort or wellness is ensured when the heat produced by the human organism is diffused in the environment with the same speed as it is produced. In this way a steady thermal balance between man and his environment is achieved and there are not phenomena due to lack of comfort conditions such as sweating and shivering. The 'comfort' of people involves many subjective data. We can distinguish them between 'ideal', 'desirable' and 'feasible' comfort conditions.

- **Ideal** comforts are those that satisfy in an excellent way the set of climatic requirements of the space and are adjusted by an ideal way to the wishes and goals of users.
- **Desirable** are those comfort conditions selected for a space and which are satisfactorily approaching ideal comfort conditions, but without neglecting reasonable cost and technological factors possibilities.
- **Feasible** are the environmental conditions which can be achieved from a particular facility, operating with acceptable techno-economic data, specific-actual external conditions.

That is, for each space some 'ideal' conditions of comfort can be identified that will be realistically adapted to the result 'desirable'. The desired comfort

Conditions will be the starting point for all of the technical calculations combined with possible worse average prices of the external circumstances. The final air-conditioning installation at every moment of its actual operation will shape a real - feasible condition of internal conditions.

Below, the ASHRAE 55, Thermal Environmental Conditions for Human Occupancy (Figure 1) is presented, proposing conditions which have been experimentally established and accepted by at least 80% of the occupants in the building.

Type of Space	°F		°C	
	Summer	Winter	Summer	Winter
Residences, apartments, hotel and motel guest rooms, convalescent homes, offices, conference rooms, classrooms, courtrooms, and hospital patient rooms	74–78	68–72	23–26	20–22
Theaters, auditoriums, churches, chapels, synagogues, assembly halls, lobbies, and lounges	76–80	70–72	24–27	21–22
Restaurants, cafeterias, and bars	72–78	68–70	22–26	20–21
School dining and lunch rooms	75–78	65–70	24–26	18–21
Ballrooms and dance halls	70–72	65–70	21–22	18–21
Retail shops and supermarkets	74–80	65–68	23–27	18–20
Medical operating rooms <sup>a</sup>	68–76	68–76	20–24	20–24
Medical delivery rooms <sup>a</sup>	70–76	70–76	21–24	21–24
Medical recovery rooms and nursery units	75	75	24	24
Medical intensive care rooms <sup>a</sup>	72–78	72–78	22–26	22–26
Special medical care nursery units <sup>a</sup>	75–80	75–80	24–27	24–27
Kitchens and laundries	76–80	65–68	24–27	18–20
Toilet rooms, service rooms, and corridors	80	68	27	20
Bathrooms and shower areas	75–80	70–75	24–27	21–24
Steam baths	110	110	43	43
Warm air baths	120	120	49	49
Gymnasiums and exercise rooms	68–72	55–65	20–22	13–18
Swimming pools	75 or above	75	24	24
Locker rooms	75–80	65–68	24–27	18–20
Children's play rooms	75–78	60–65	24–26	16–18
Factories and industrial shops	80–85	65–68	27–29	18–20
Machinery spaces, foundries, boiler shops, and garages	—	50–60	—	10–16
Industrial paint shops	—	75–80	—	24–27

<sup>a</sup> Variable temperature range required with individual room control.

**Figure 1 – Recommended room temperature variations**

The parameters that contribute to the configuration of the thermal comfort conditions and which can be regulated by an air-conditioning system are:

- air temperature of space
- temperature of the surfaces surrounding the space
- humidity of the air in the space
- air movement in space
- renewal of the air
- purity of the air in the space

The above parameters have to do more with air hygiene, they are interdependent and create comfort conditions when they are in balance and have some values.

In addition to the above, the following factors contribute to the creation of a sense of well-being:

- noise and vibrations
- electric radiation
- radioactivity
- lighting

#### **1.4.3. Factors that affect the climate of a space**

The climate of a space is affected by the following factors:

- External environment, with significant changes, both seasonally and during a 24-hour period, in factors such as temperature, humidity, lighting, speed and direction of air flow, radiation (solar, cosmic etc.) etc.
- Construction data
- Content of the space
- Usage of the space
- Orientation of the space is also important
- As well as its position in relation to winds

Consideration should be also given to factors related to positive and negative effects of technology such as poor air quality of cities, increased pollution from factories or from jam traffic etc.

Constructional data of the shell are related to quality and thermo - insulating, thermo - absorbing, thermo-accumulative and sound insulation of walls and window frames, angle of incidence, direct or indirect, of solar radiation, the existence of gaseous flow paths, etc.

Content of space in living organisms as well as materials, appliances and equipment is essential. Presence of people burdens the space with thermal loads, moisture, odors, etc. Similarly, room equipment such as lighting, appliances, machinery and production units are a determining factor in shaping the desired climate of space.

Usage of space is also a determining factor for the selection of the desired climate conditions as well as quantitative assessment of loads has to be covered by installation of air condition.

Finally, it should be mentioned that the need to ensure adequate and given air quality which was achieved earlier (in the usual at least residential and work buildings) with natural ventilation through the carvings and the exposures, does not apply today. Instead, in underground or closed air-conditioned spaces where it is intended incoming air by means of engravings and openings to be reduce, the climate study has to deal with the problem of renewal air (with fresh air from the environment) or its artificial improvement with caution.



#### **1.4.4. The role of external climate**

Term external climate refers to all natural and artificial environmental elements of the area around a building. These factors influence to a greater or less extent the indoor climate. Every building intended for human use, must be in a harmonious relationship with the surrounding area and can be adjusted with flexibility and functionality in any weather's changes or other external influences. Extreme temperature conditions of summer and winter season, humidity, intensity of the winds, sunshine of the area, possible occurrence of periods of heat and frost, are essential elements which researchers has to take seriously into account.

Calculation of an air conditioning installation starts from setting the climatic elements of the area in which the building is located or the space where the air conditioning system will be installed. In case that the building that is being studied is not near to a measuring station, the design values are estimated by the values of the nearest geographic or climatic station.

Constructional configuration of the shell of each building depends on a significant percentage, from the correlation of the desired temperature condition, humidity, air currents inside the building and outdoor climate. Taking into account that the building accepts the effects of natural and artificial environment, it should be able to accept effects such as:

- Heat radiation of the sun (direct and indirect)
- Other solar radiation
- Temperature change during day (night) and during the change of the seasons
- Effects of rain, humidity, frost, wind
- Dust and caustic impurities contained in air and rain, coming from waste or exhaust gases from adjacent residential and industrial installations
- Vibrations and noise from vehicles' circulation or machinery or industrial or craft activity

The uncertainty of climatic conditions requires researchers to rely on statistical data, collected and evaluated appropriately for each region. It is obvious that the necessity of passive protection of the internal climate is more intense, the more adverse the environmental and climatic conditions of the area.

#### **1.4.5. Operating Conditions of Buildings**

The actual operating conditions of a building may vary in case, depending on the use and/or users of the building. So, it is necessary to define and standardize the acceptable, under the standard, building operating conditions of a particular use, in order to, easily and with less influence of the researcher's subjectivity, determine the estimated energy consumption, which will eventually characterize the energy performance of the building, according to and European standards. The estimated energy consumption, which finally will characterize the energy performance of the building, is determined by calculations accepting and using

the set values for operating conditions per building. Operating conditions of the building which affect the energy behavior of the building are as follows:

- period of time and working hours of the building
- desired room's temperature for the summer and winter
- desired humidity of the area for the summer and winter
- required fresh air of the space
- level of general room's lighting
- typical consumption of hot water by building type

Note that in special cases of buildings and/or special areas of buildings and generally in cases which require more detailed treatment, operating conditions are determined by design conditions in case.

Specific operating conditions of individual premises of a building (corridors, warehouses, etc.) are taken into account only when the building is designed or during the design of the thermal zone, while during the energy study for each parameter (temperature, relative humidity, etc.) a single value, which corresponds to the general use of the building, according to the respective tables, is taken into account.

Also, in as many subclasses of buildings there is no a fixed value of parameters (temperature, relative humidity, etc.), the general category's value is taken into account. For example, museum warehouses can get the value given for warehouses in general, unless special conditions are required.

#### **1.4.6. Energy efficiency of buildings [19]**



Buildings are responsible for 40% of energy consumption and 36% of CO<sub>2</sub> emissions in the EU. While new buildings generally need fewer than three to five liters of heating oil per square meter per year, older buildings consume about 25 liters on average. Some buildings even require up to 60 liters.

Currently, about 35% of the EU's buildings are over 50 years old. By improving the energy efficiency of buildings, we could reduce total EU energy consumption by 5-6% and lower CO<sub>2</sub> emissions by about 5%.

## **Key laws**

The 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive are the EU's main legislation covering the reduction of the energy consumption of buildings.

On the 30 November 2016 the Commission proposed an update to the Energy Performance of Buildings Directive to help promote the use of smart technology in buildings and to streamline the existing rules. The Commission also published a new buildings database – the EU Building Stock Observatory – to track the energy performance of buildings across Europe.

Under the existing Energy Performance of Buildings Directive:

- energy performance certificates are to be included in all advertisements for the sale or rental of buildings
- EU countries must establish inspection schemes for heating and air conditioning systems or put in place measures with equivalent effect
- All new buildings must be nearly zero energy buildings by 31 December 2020 (public buildings by 31 December 2018)
- EU countries must set minimum energy performance requirements for new buildings, for the major renovation of buildings, and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls and so on)
- EU countries have to draw up lists of national financial measures to improve the energy efficiency of buildings.

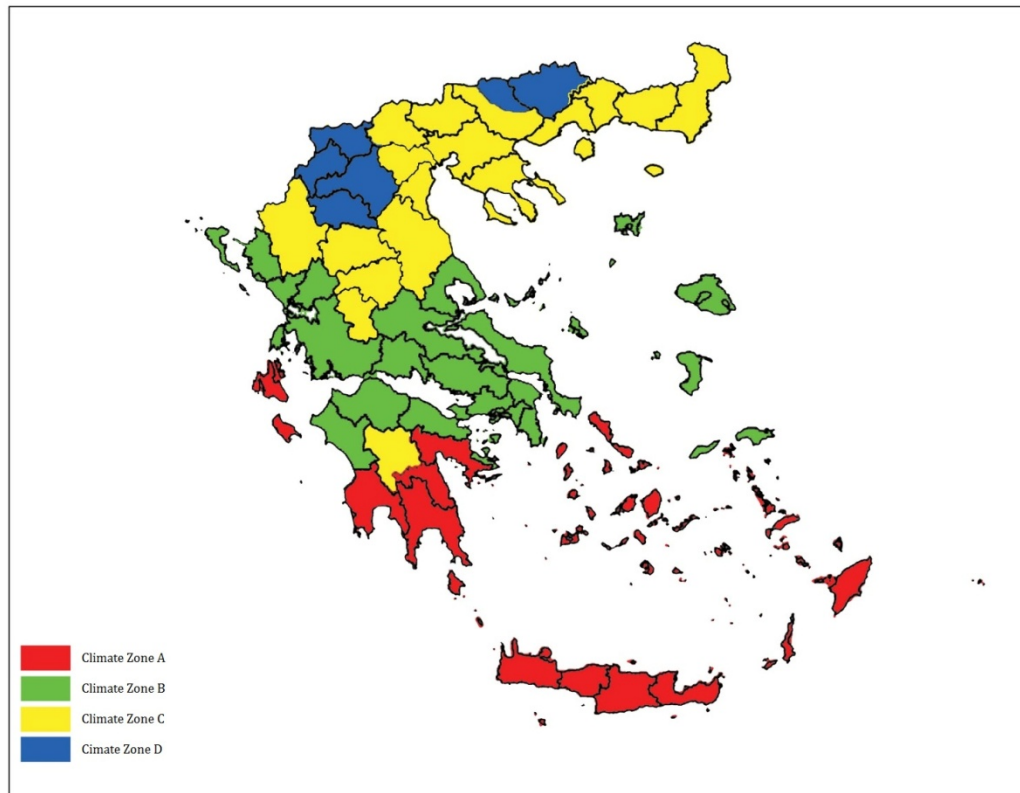
Under the Energy Efficiency Directive:

- EU countries make energy efficient renovations to at least 3% of buildings owned and occupied by central government
- EU governments should only purchase buildings which are highly energy efficient
- EU countries must draw-up long-term national building renovation strategies which can be included in their National Energy Efficiency Action Plans.

## **1.4.7. Climate zones**

### ***1.4.7.1. Climate zones of Greece***

In order to implement the European's Union decision, as referred above, Greek territory is divided into four climatic zones [20]. The boundaries of each climate zone consist of isothermal curves of the annual mean ambient temperature that differ by at least 4 °C. Climate zones are discrete in the following way, as shown in Figure 2.



**Figure 2 – The four climate zones of Greece [18]**

Climate zone	Prefectures
<b>Zone A</b>	Heraklion, Chania, Rethymno, Lassithi, Cyclades, Dodecanese, Samos, Messenia, Laconia, Argolis, Zakynthos, Kefallinia, Ithaca
<b>Zone B</b>	Corinthia, Ilia, Achaia, Aitoloakarnania, Fthiotida, Fokida, Viotia, Attica, Euboea, Magnesia, Sporades, Lesvos, Chios, Corfu, Lefkada, Thesprotia, Preveza, Arta
<b>Zone C</b>	Arcadia, Evritania, Ioannina, Larissa, Karditsa, Trikala, Pieria, Imathia, Pella, Thessaloniki, Kilkis, Khalkidhiki, Serres, Kavala, Drama, Thasos, Samothrace, Xanthus, Rodopi, Evros
<b>Zone D</b>	Grevena, Kozani, Kastoria, Florina

**Table 1 – Prefectures of each zone [17]**

In each prefecture, areas at an altitude of more than 600 meters from the surface of the sea are part of the next coldest climate zone than they belong to according to the above. For zone D, all areas, irrespective of altitude, are included in zone D.

#### 1.4.7.2. *Climate zones of Europe [21]*

The four climate zones of Europe are: the Mediterranean zone, the Maritime zone, the North-East zone and the South-east zone.

- **Mediterranean zone** includes the countries or parts of countries around the Mediterranean Sea, together with Jordan, Macedonia and Portugal.
- **Maritime zone** is the zone north of the line from the coastal zone of south-west France, through Lyon (France), to the south border of Switzerland and Austria, west of the border between Austria and Hungary, west of the border between Czech Republic and Slovakia, west of the river Oder (between Poland and Germany). This zone also includes Ireland, Sweden and the United Kingdom.
- **North-east zone** is the zone in the north-eastern part of Europe: the countries and the regions east of the river Oder (between Poland and Germany), north of the border between Czech Republic and Poland, west of the border between Poland and Ukraine, north of the border between Ukraine and Belarus, Russia north of 50° latitude.
- **South-east zone** includes Bosnia-Herzegovina, Bulgaria, Croatia, Hungary, Moldova, Romania, and south Russia of 50° latitude, Slovakia, Slovenia, Serbia and Montenegro, Turkey, Ukraine, except the Mediterranean coastal zones.

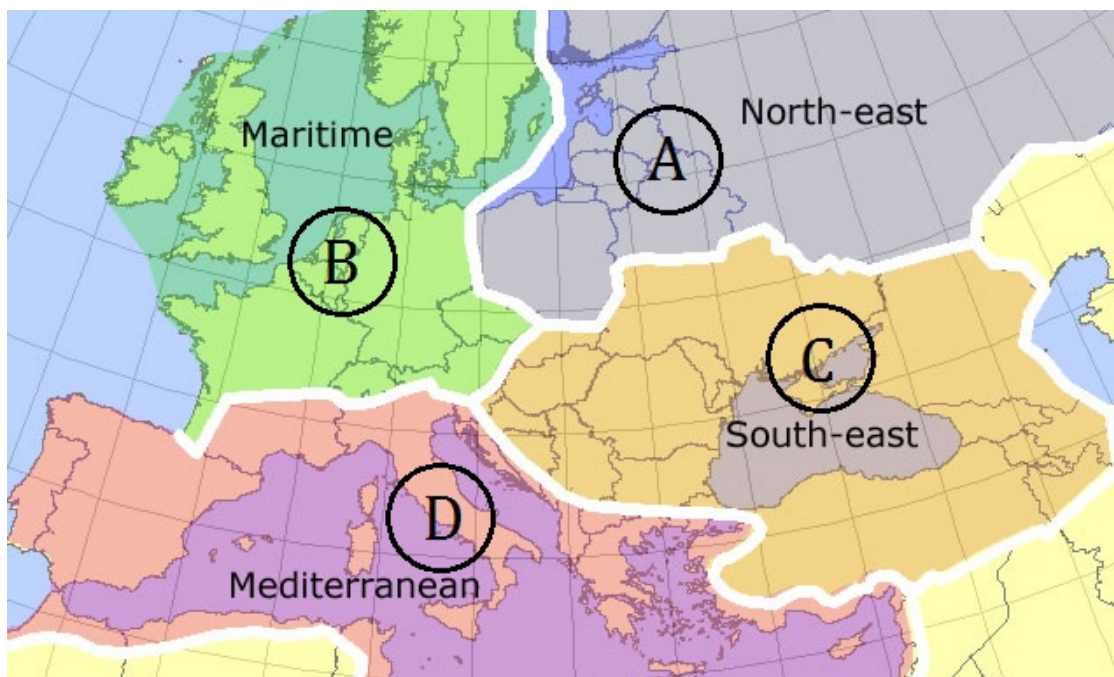


Figure 3 – Climate zones of Europe [21]

These zones are presented above, which also indicates that there is an area of gradual change in climate between the zones proposed. Data from other zones may in any case be considered acceptable if the actual prevailing conditions are comparable.

## 1.5. Introduction in HVAC Systems

### 1.5.1. Historical Review

Early commercial air conditioning applications were built to cool the air more for the growth of the industry than for personal comfort. In 1902, the first modern electric air conditioner was invented by Willis Havilland Carrier in Syracuse, New York. Designed to improve the production control process at a printing plant, this invention not only regulates temperature but also humidity. Later, Carrier's technology was applied to increase productivity in the workplace, and Carrier America's Air Conditioning Company was set up to respond to rising demand. Over time air conditioning has begun to be used to improve comfort in homes and vehicles.

In 1906, Stuart W. Cramer of South Carolina, USA, was investigating methods of adding moisture to his fabric factory's atmosphere. Cramer invented the term "air conditioning" by using it in the patent application he filed that year. He combined humidification with ventilation to "regulate" and change the atmosphere in factories, by controlling the levels of moisture so much needed in fabric factories. This evaporation of water in the air to provide a cooling effect is now known as evaporating cooling.

First air conditioners and refrigerators used toxic or flammable gases such as ammonia, methane chloride, and propane, which if leaked could lead to fatal accidents. In 1928, Thomas Midgley Jr. created Freon, the first chlorofluorocarbon gas. This refrigerant was much safer for man but later proved to be harmful to the atmosphere by destroying ozone in the stratosphere.

Nowadays, dimensions of condensers and evaporators are significantly reduced. New and more reliable automation systems are being implemented. Use of plastic reduces the weight of air conditioners. More and more requirements for central air conditioning are increasing.

### 1.5.2. Definitions - Basic Operations of a HVAC System

In a broader sense, the term **HVAC system** may refer to any form of cooling, heating, ventilation or disinfection that modifies the air's condition. Air conditioning system is a device, system or mechanism that stabilizes air's temperature and humidity of the area used for cooling, as well as heating according to the properties of air at a given point in time, usually by the use of cooling cycle but sometimes with the use of exhaust, most common comfortable for the cooling of buildings and motor vehicles.

**Climate** is characterized a set of environmental elements such as temperature, humidity, speed and direction of air movement, air composition (gas ratio, presence of impurities and vapors, and solid or liquid suspensions).

**Artificial ventilation** is the process of forced air replacement of a closed space. During this process a percentage of the air of the space is continuously removed and replaced by fresh air received from the outside environment.

The difference between the term "Air conditioning" and "Cooling" is that in the air conditioning installations of buildings except the cooling of the spaces we achieve at the same time, we process the air so that we can control its humidity and purity. That is, an air conditioning installation offers control of temperature, humidity and air quality in the building's premises. While in a cooling installation we only achieve room temperature control.

Basic operations performed by an air conditioning system are:

- **Heating:** is the process of adding thermal energy (heat) to the air of the conditioned space in order to raise the temperature or keep the temperature within certain limits (using thermostats).
- **Cooling:** is the process of removing thermal energy (heat) from the air of the conditioned space in order to low the temperature or keep the temperature within certain limits (using thermostats).
- **Humidification:** is the process of adding water (humidity) to the air of the conditioned space in order to raise the relative humidity or keep it within certain limits.
- **Dehumidification:** is the process of removing water (humidity) from the air of the conditioned space in order to reduce the relative humidity or keep it within certain limits.
- **Air refresh:** is the process of receiving outside air and discharge indoors air in order to dilute air impurities and ensure the necessary indoor air quality.
- **Air purification:** is the process of removing particles and organic air contaminants from the air in order to improve and keep indoor air quality.

Air refresh and air purification are together called **ventilation**.

### 1.5.3. Advantages of proper use of the air conditioner

There are two main reasons why the use of air conditioners is particularly attractive and widespread in Europe. The first reason is their excellent energy efficiency and the second is saving of money. Everyone can easily conclude that the two reasons are correlated with each other. Good energy efficiency means low power consumption and therefore the use of air conditioners is an economical solution. In addition, good energy efficiency means that we can achieve the desired room temperature, with accuracy, in a short period of time. One more important advantage of using air conditioners is the autonomy in setting different temperatures in different rooms of the space, at will of users.

### 1.5.4. Disadvantages of using air conditioners

Unfortunately, the use of air conditioners has both health effects and environmental impacts. Air-conditioning systems can promote the growth and spread of microorganisms, such as *Legionella pneumophila*, the infectious agent responsible for Legionnaires' disease, or thermophilic actinomycetes. The most common health effects associated with frequent use of air conditioners are allergies, colds and headaches.

Innovation in air conditioning technologies continues, with much recent emphasis placed on energy efficiency. Production of the electricity used to operate air conditioners has an environmental impact, including the release of greenhouse gases. Therefore, Freon, the refrigerant fluid used in air conditioners is harmful to the atmosphere and is associated with ozone depletion in the stratosphere. Biological effects result from this includes increase of skin cancer cases, plant disasters, and a decline in ocean plankton.

#### **1.5.5. Ways to deal with**

- Frequent maintenance is the most basic and important factor for the proper operation of the air conditioner, so frequent filter changes, depending on use, are necessary.
- Also, correct setting of the temperature at reasonable values, i.e. comfort temperature, is essential, so that there is no heat or cold sensation in the air conditioned space.
- In addition, for proper energy management, the air conditioner must remain closed when no person is in the room.
- Natural ventilation of space and fresh air renewal are important for two main reasons. First, the continuous use of the air conditioner dries the air, especially when the room remains closed. Secondly, enclosure spaces usually collect dust. The air conditioner recycles the dust that exists in the atmosphere, increasing the risk of allergies.
- A common mistake many people make is that they are standing in positions that have direct contact with the air conditioner. Due to that, those people often suffer from neck collapses, headaches and muscle spasms.
- Last but not least, installation the air conditioner should be in the most appropriate position of the place, so that there is the minimum possible energy loss. In general, it is preferable to install air conditioners away from radiators (e.g. electric kitchens) so as not to reduce their efficiency during summer months. Similarly, the outdoor unit should be protected from weather and extreme temperature changes, as well as it should be free from peripheral obstructions within a radius of 35 cm.

#### **1.5.6. Air Conditioning Applications**

Today, in the 21st century, the term HVAC is no more alien to common man. With increasing global warming and degrading outdoor air quality due to pollution, the demand for Air conditioning is escalating everywhere around the world. Therefore, we find HVAC systems at almost all places, be it shopping mall, commercial complex, hotels, hospitals, offices or low/ high rise residential buildings. Two decades ago, HVAC systems were looked upon as 'Luxury items'. But now, things are changing so quickly in a civilized society, that, HVAC systems have become an essential part of building services. A typical person in modern society spends around 90% of day time indoors. So it is not surprising that providing a healthy, comfortable indoor environment has become a vital factor in



current economy. Application wise air conditioning is either for human comfort or process control. It is further classified as residential, commercial, industrial air conditioning [8, 15]. Refer below Table 2.

- A) **Comfort** air conditioning, which usually occupied by engineering engineers, and where center of the interest is man. Comfort applications aim to provide a building indoor environment that remains relatively constant despite changes in external weather conditions or in internal heat loads. These facilities aim to create wellness conditions in every kind of accommodation such as office buildings, residences, meeting rooms, theaters, sales areas, etc.
- B) **Industrial** air-conditioning, which is intended to serve the objectives of the craft industry, industry and generally production or labor space. Industrial air-conditioning plants are targeted at people (worker health protection) or the production process (creating a special environment that favors some chemical or biological evolution or some mechanical processing) or both (improving the productivity of people and machines).
- C) **Commercial** applications air conditioning, which aims to meet the needs and high demands of nursing homes, surgical facilities, laboratory investigations, special treatments, etc. These facilities ensure special conditions of temperature and humidity as well as very high requirements of air purity to ensure the control of airborne particulates, microbes, bacteria and other microorganisms [8].

Residential	Commercial	Industrial
High/low rise buildings	Hotels, restaurants	Textile, paper, printing
Individual villas	Shopping malls, retail stores	Food processing
Dwelling units	Offices, hospitals, clinics	Dairy, milk plant
Hostels, lodging	Theaters, auditoriums	Pharmaceuticals
	Schools, colleges	IT Data centers
	Labs, libraries, medicals	Control rooms
	Gymnasium, museums	Precision Mfg

**Table 2 – Air conditioning applications**

#### **1.5.7. Noise and vibration**

Mechanical equipment and in particular air conditioning systems are one of the building noise sources. Air conditioning and ventilation facilities include numerous devices that make noise and vibration, which are transmitted to the interior, in a greater or lesser extent, and can adversely affect the comfort of people.

Generally in air-conditioning installations noise causes:

- Central machinery, i.e. chillers, boilers, fans, air conditioners, pumps, cooling towers, etc., which may either be installed inside the building or some of them outside the building (e.g. cooling towers, fans, pumps, etc.). These are the main sources of noise in an air conditioning installation.
- Distribution networks, i.e. air ducts, pipes and fittings. Noise from distribution networks can be generated due to the high air velocity in the air ducts, especially in the bulkheads, or due to leakage. Still due to the oscillation of the walls of the ducts and the pipes. Due to turbulent flow in the plenum and the cross-section changeover components and due to the high flow velocity in the piping.
- Silent noises that do not originate from this facility, but are transported to the space with the help of the air ducts and the air ducts pipes.
- Machinery and installation devices operating in spaces such as induction terminals or fan coils, high-speed mixing and distribution boxes, autonomous air-conditioning units, air intakes, etc.

Noise associated with the installation, but also those who are transported in places from other causes, are serious sources of discomfort and must be handled promptly by the designer and installer. Noise produced by the operation of the installation should be considered not only as independent sources of noise, but also in conjunction with the overall burden generated by the interference of internal and external noise.

Noise problems are handled with careful selection and sizing of the installation and an appropriate design for isolation or absorption of noise. Typically, three basic noise control techniques are applied to air conditioning:

- Interventions at the source of noise
- Interventions in noise transmission paths
- Interventions in space

To evaluate the sound sources, from the acoustic point of view, the sound power level is used relative to a given reference sound power level, expressed in dB and measured within the range of acoustic frequencies. Measurement of this size is done in special laboratories and is given by machine manufacturers.

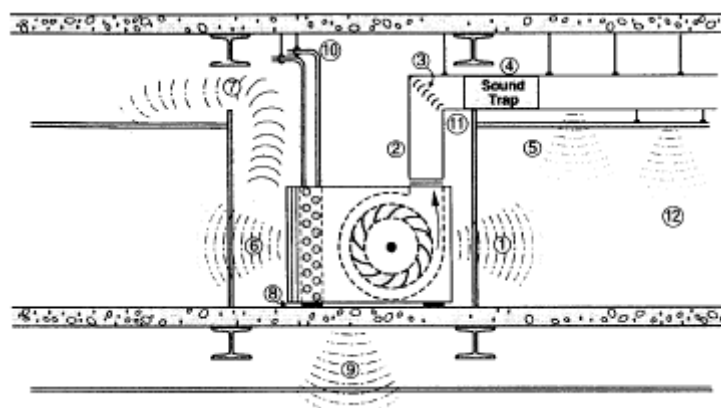


Figure 4 – Transmission of noise through walls and ducts [28]

## Chapter 2 Classification of HVAC Systems

### 2.1. General

There is a wide variety of air conditioning systems available in market. One should have knowledge of all such systems with their merits and demerits as per the requirements. So, the present chapter gives a wide overview and introductory information which will help in HVAC system selection as per the application.

The separation of buildings into thermal zones helps in their choice system to be used for their air conditioning. The basic classification of air-conditioning systems is done with main criterion way and means by which the final configuration of the desired indoor climate conditions in the air-conditioned space is achieved. The air conditioning installation attempts to control at least the temperature or refresh the air of a space.

Air conditioning systems are been classified by three basic criteria: 1) the degree of air treatment, 2) the heat transfer media, and 3) location of devices and scope of application. Particular weight is given to the third class, which is the most important one.

### 2.2. Classification of air conditioning systems based on the degree of air treatment

Air conditioning systems, depending on the degree of treatment they provide in the air, can be distinguished in:

- a) **airing - ventilation systems**, which ensure the renewal of a room's air.
- b) **partial air conditioning systems**, which, in addition to air renewal, also provide a partial treatment which mainly involves cleaning and heating of air. In order to achieve the desired result, adjusting devices are usually provided.
- c) **complete air conditioning systems**, which ensure: maintaining the temperature and humidity of a closed space within predetermined limits and includes devices for:
  - cleaning
  - heating
  - cooling
  - humidification
  - dehumidification
  - and renewal of air

as well as local or central automatic temperature and humidity adjustment devices.

In each air conditioning system we distinguish:

- air supplied to the room (supply air-ventilation)

- air-evacuated (exhaust / return-ventilation air)
- the part of the take-off / return air returned to the enclosure (recirculation)
- the air discharged into the environment
- ambient air (fresh outside air)

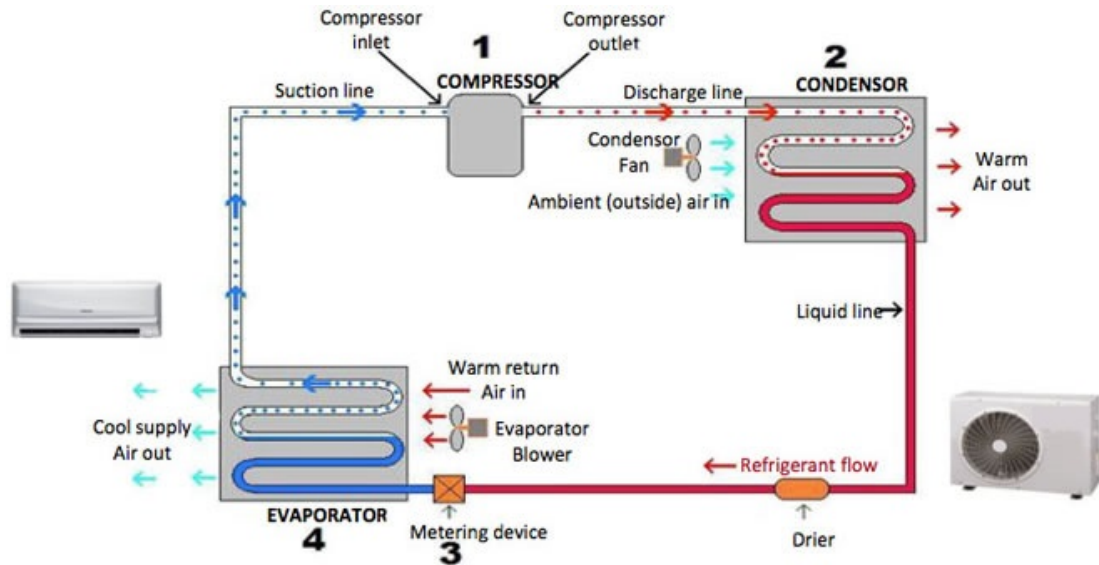


Figure 5 – Air treatment from an air conditioning system [26]

### 2.3. Air conditioning systems based on the heat transfer media

Also, considering the way and the means by which the final configuration of the comfort conditions in the air-conditioned space is achieved, we distinguish the four categories of air conditioning systems [2]:

- all air system
- water system
- air- water system
- unitary refrigerant based system

#### 2.3.1. All air systems

As the name suggests, air is used as the media in an all air system. Air transports thermal energy from the conditioned space to the HVAC plant. As shown in Figure 6, in these systems air is processed in the A/C plant namely AHU (Air Handling Unit). AHU consists of Dampers, Mixing chambers, Filters, Cooling/ Heating coils, Humidifiers, Fans/ Blowers etc. in a packaged cabinet. This processed air is then supplied to the conditioned spaces through Air Distribution system. Air Distribution system consists of Ducts, Dampers and Diffusers. This air extracts (or supplies in case of winter) the required amount of sensible and latent heat from the conditioned space. The duct that supplies the air to spaces is called Supply Air Duct (SAD). The return air from the conditioned space is conveyed back to the plant, where it again undergoes the required processing

thus completing the cycle. The duct that returns the air from spaces to A/C plant is called Return Air Duct (RAD). Adequate Fresh air is always supplied by AHU to maintain Ventilation and Indoor Air Quality (IAQ).ASHRAE 62.1 standards are followed for ventilation, mostly [3] .Outside Fresh air and Return air are balanced in proportion by rule 'Supply Air = Return Air + Fresh Air'. Since fully treated air is supplied by AHU. No further processing of air is required by terminal units in the conditioned space. All air systems can be further classified into [2]:

1. single duct, constant volume, single zone system
2. single duct, constant volume, multi zone system
3. single duct, variable volume (VAV) system
4. dual duct, constant volume system
5. dual duct, variable volume (VAV) system

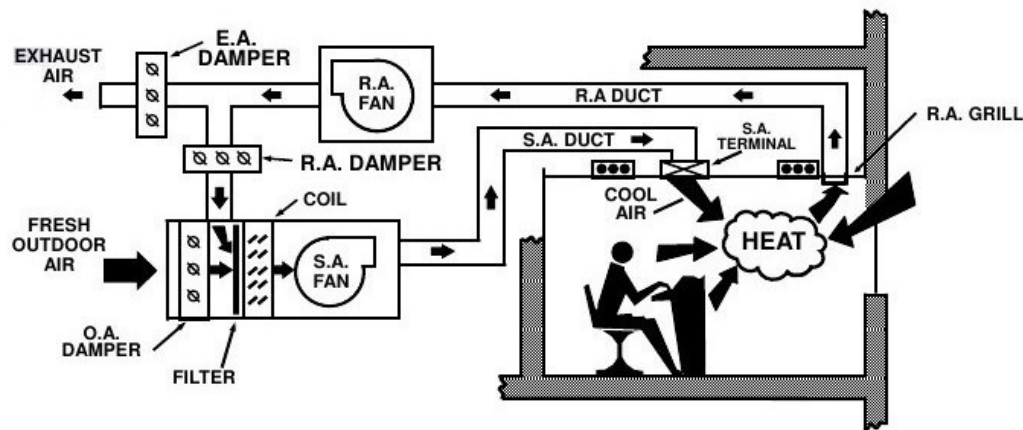


Figure 6 – Schematic of all air system [27]

The single duct systems can provide either cooling or heating using the same duct, but not both heating and cooling simultaneously. While, dual duct systems can provide both cooling and heating simultaneously.

#### **2.3.1.1. Advantages of all air systems:**

1. Effective room air distribution and ventilation is possible under widely varying load conditions
2. All air systems present great opportunities for energy conservation such as heat recovery wheels.
3. Precise control is possible by use of high class controls. Close range of temperature ( $\pm 0.15^{\circ}\text{C}$ ) and humidity ( $\pm 0.5 \%$ ) can be achieved [4].
4. Simultaneous cooling and heating can be provided by dual duct system. Also, switching between summer and winter mode is quite easy in air systems.

5. AHU which is a complete package can be remotely located, well away from conditioned spaces. It helps to reduce noise levels in occupied spaces.
6. Stairwell pressurization, kitchen ventilation etc. can be easily achieved.

#### **2.3.1.2. Disadvantages of all air systems:**

1. Since systems are quite large in size, require separate spaces like AHU room. It reduces use of effective floor space. Particularly in high rise buildings, it is difficult to provide long runs of ducts, as AHUs are located either on roof or basement.
2. Difficult to install in existing buildings, as large space is required in false ceiling to lay the ducts [4].
3. Testing, Adjusting, Balancing (TAB) may be very difficult task in case of VAV systems.

#### **2.3.1.3. Applications of all air systems:**

1. Precision HVAC applications such as data centers, research labs, process industries, clean rooms, operation theatres, hospitals etc. where accurate and precise control of space environment is required[2, 5] .
2. Theatres, auditorium, functional halls, retail stores etc. where loads are uniform with small external loads.
3. Large corporate buildings with varied requirements of heating and cooling which can be served by dual duct systems with simultaneous cooling and heating.
4. Multi zone all air systems are suitable for offices, classrooms, hotels, ships etc. where individual control is required.

### **2.3.2. Chilled water systems**

In this system, water is used as working fluid that transports thermal energy between conditioned space and A/C plant. Chilled water is circulated for cooling while Hot water is circulated through coils for space heating. As only water is supplied by HVAC plant to the space, fresh air has to be supplied by another unit to maintain Indoor air quality and ventilation. These systems are also known as chilled water systems for cooling applications. Based on number of pipes used in system, they are classified as 2-pipe system and 4-pipe system.

A 2-pipe system can provide either cooling or heating only, but not both at a time. As shown in Figure 7, chiller supplies cold water or heater supplies hot water to different spaces. Out of 2 pipes, one is for supply and the other is for return of water to central plant. Chilled water/ hot water circulates through fan coil units (FCU), or convectors or radiators located in the each space. Thermal energy is exchanged between water and air in the conditioned space. Flow control valve controls the water flow rate as per load variation. Flow control valve is driven by zone thermostat which gives signal to adjust flow rate as per

load. Since the same inside air is circulated repeatedly by terminal units, fresh air ventilation must be supplied by external units.

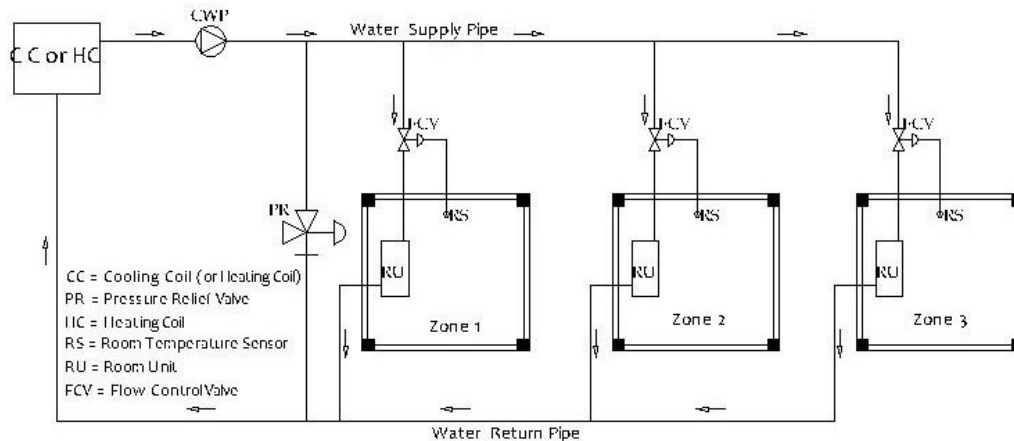


Figure 7 – Multi zone, 2 pipe, all water system [22]

A 4-pipe system consists of two supply pipelines– one for cold water and one for hot water; and two return water pipelines. The cold and hot water are mixed in a certain proportion as per the zone load, and the mixed water is supplied to the terminal units in the conditioned space. The return water is split into two streams, one stream flows to the heating coil while the other flows to the cooling coil.

Terminal units used in all water system are of basically three types namely fan coil units (FCU), convector and radiator [6].

**Convectors** are mainly used for heating applications. Hot water is circulated through heating coil. Space air heating takes place by natural convection.

**Radiators** are also used for space heating applications. Heat transfer occurs majorly by radiation. Recently radiators are also being used for cooling applications by radiant cooling or chilled beam technology [3].

#### 2.3.2.1. Advantages of chilled water systems:

1. All water system needs very less space as compared to all air systems for same capacity. Because, water is used as transport media, which has higher specific heat capacity and density than air. Hence, pipe sizes are very small as compared to large sized ducts. Therefore, system consumes very less space due to absence of big duct works and fans [6].
2. Less expensive central A/C plant solution is offered by all water system [6].
3. It is more suitable for individual room/ zone control.
4. Simultaneous cooling and heating is possible with 4-pipe system[4]
5. It can be easily installed in the old buildings without making many changes in the existing space setting.

#### ***2.3.2.2. Disadvantages of chilled water systems:***

1. Multiplicity of fan coil units means a great deal of maintenance work and cost [6].
2. Control of space humidity is limited, as only cooling and dehumidification occurs and FCUs do not have humidifiers or reheat coils [5].
3. Separate ventilation system must be used to supply fresh air, which adds to cost. Also control of ventilation air is not precise.
4. Condensate may cause problems of dampness in ceiling or walls if condensate drain fails.

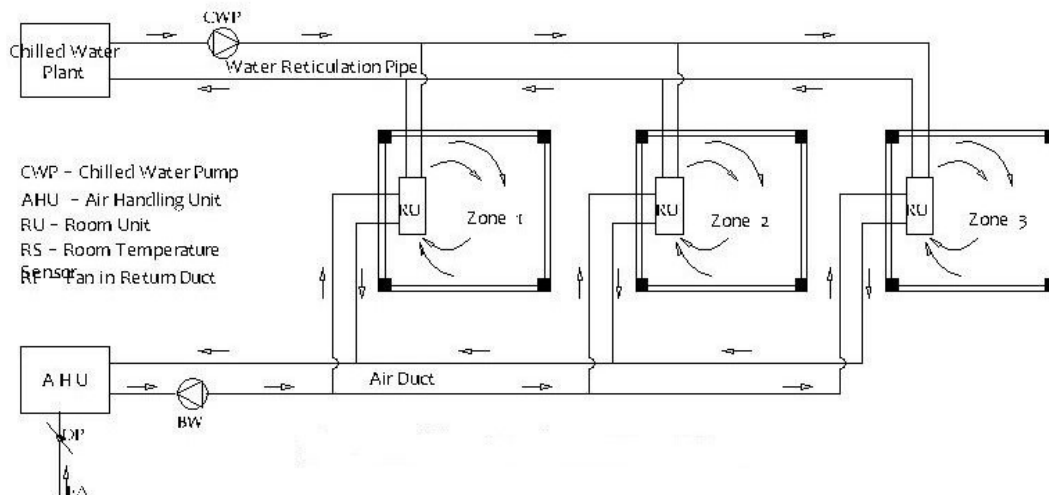
#### ***2.3.2.3. Applications of chilled water systems:***

1. All water systems are suitable for use as low cost central HVAC systems in multi zone high rise commercial applications [6].
2. All water system is best solution to replace all air system in high rise tall buildings, as it is much easier to carry water through small sized pipes than air through very big sized ducts across farther heights [5].
3. It is very effective system in certain applications where space extremely limited, such as narrow ceiling and shafts .i.e. Buildings which were originally not designed for HVAC systems.
4. In case of individual room control as required in hotels, multi storey apartments, offices etc. all water systems are more famous.

#### **2.3.3. Air-Water systems**

Air water system employs best features of all air and all water systems. Combination air-water system distributes both chilled water and /or hot water and conditioned air from a central system to the individual spaces. Terminal units in each zone provide cooling or heating to that zone. One type of air water system uses FCU as terminal units to provide major part of air conditioning and central AHUs are used to supply only ventilation air directly into the space [6]. Another type uses 'Induction units' as terminal units. It receives supply air from central AHU, called as primary air and chilled / hot water from central chiller [6]. Primary air is delivered at high pressure in plenum chamber and discharged into space through high velocity nozzles. This induces room air into induction unit, where it mixes with primary air. Room air is called as secondary air. Supply air is mixture of primary and secondary air. Therefore no fan is required in induction unit. Figure 8 shows schematic of multi zone air- water system.





**Figure 8 – Schematic of multi zone air- water system [26]**

Normally terminal unit like FCU keeps on cooling the room air again and again with the help of cooling coil circulating chilled water. Therefore sensible cooling load is handled by water system. Ventilation air is supplied by central AHU of air system. AHU supplies cooled and dehumidified fresh air which can take care of room latent loads. Because of this, there is no condensation problem with cooling coils. Similarly, in winter system heated and humidified fresh air is supplied by AHU and hot water circulates through heating coil of terminal unit.

#### **2.3.3.1. Advantages of Air-Water systems:**

1. Simultaneous heating and cooling is possible in air-water system.
2. Lot of space is saved, as only ventilation air is supplied through ducts and chilled/ hot water is passed through pipes [4].
3. Economic control of individual zones is possible using room thermostats which can either regulate secondary air or secondary water in FCUs.
4. Since there is no latent load on cooling coil, troubles due to condensation do not occur. It prevents marshy or damp regions in the conditioned space.
5. Servicing, repair, replacement, maintenance works etc. are relatively easier than all water systems.
6. Positive pressures can be maintained in conditioned spaces under all varying loads [2].

#### **2.3.3.2. Disadvantages of Air- Water systems:**

1. There are a lot of complications in system operation and controls as both air and water have to be handled carefully.
2. Mostly air- water systems find limited applications in perimeter zones [4].

3. Constant supply of fresh air has to be supplied to all zones, no matter whether spaces are occupied are not. Because control is only for cooling/ heating coil through room thermostat [5].
4. In case of unusual high latent loads, excessive condensation may cause damp environment and discomfort in the zone.
5. As systems are complicated with greater extent of controls, normally air-water systems are costlier than all water systems.

#### ***2.3.3.3. Applications of Air- Water systems:***

1. It is much suitable for retrofitting of existing buildings, where there is space restriction.
2. It is very good solution for perimeter zone buildings with large sensible loads [4].
3. It can be used where close control of humidity in the space is not necessary.
4. It serves well for large office buildings, hotels, lodges etc.

### **2.4. Air conditioning systems based on device location and scope of application**

The most common classification of air conditioning systems is based on size and extent criteria, which correlate the position of the heat unit (thermal machine) with the air-conditioned area and the scope of application of the air conditioning system. Depending on the location of the air conditioners in relation to the air-conditioned space and the scope of application of the system, the following two main categories of air conditioning systems are distinguished:

- unitary air conditioning systems
- central air conditioning systems

#### **2.4.1. Unitary air conditioning systems**

Air conditioning systems which are designed to condition a space (or part of it) from a direct location are known as unitary systems. The main feature of the unitary air conditioning units is that they can be placed in any room without the need for a central engine room. So, their main application is in places where no central conditioning has been provided during the initial construction. Mostly, most households choose to install unitary air conditioning systems. Their technical name is split type air conditioners, because they consist of an external and an indoor unit. The most common unitary air conditioning systems are:

- window air conditioners
- cooling only split systems
- heat pump
- packaged terminal heat pump

- portable units
- floor mounted units
- wardrobe units

#### **2.4.1.1. Window Air Conditioners**

As the name implies, a window air conditioner is typically installed in a window or custom opening in a wall, so that one side of them (the "back") is outside and the other side (the "inside") is in the room. They are unified, that is they are not composed of an internal and external device, but the whole air conditioner is in a single compact shell.



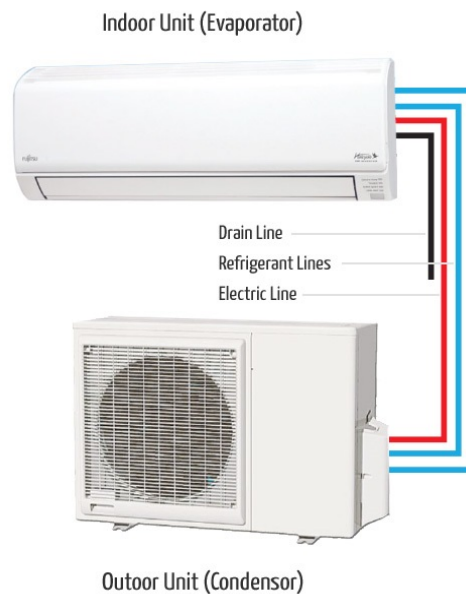
The disadvantage of this type is that its installation requires the opening of a vacuum on a wall large enough to accommodate the air conditioner. The Window AC can only cool small areas and are not intended to provide cooling to multiple rooms or zones. These air conditioners are manufactured as cool only or can provide both cooling and heating. An optional damper in the unit can provide fresh outdoor air if necessary.



Window air conditioners were the first air conditioners built for home use and in the past were very widespread. Today, such air conditioners are still in circulation in some countries (mainly in the Far East), but they are no longer in Europe and America. Thus, in addition to an old "forgotten" of the years air conditioner, it is unlikely that you will meet this type of air conditioner.

#### **2.4.1.2. Wall Mounted Units**

These are the most popular air conditioners. Split-systems are typically found in residential or small commercial buildings. A split system is a combination of an indoor air handling unit, which is placed on the inner wall, and an outdoor condensing unit, placed on the outer wall. The indoor air handling unit contains a supply air fan and an air-to-refrigerant heat exchanger (or cooling coil), and the expansion device. The outdoor condensing unit consists of a compressor and a condenser coil.



Because they are placed somewhere high up on the wall, they have a better cooling performance than hot air accumulates at the highest levels of the interior. These systems is the most common type of air conditioners, their price is the lowest of all the other types (for the same power), while they also have the highest energy efficiency rating (EER) of all the available A/C systems.

#### **2.4.1.3. Heat Pump**

Heat pumps are similar to cooling only systems with one exception. A special valve in the refrigeration piping allows the refrigeration cycle to be operated in reverse. A cooling only system cools the indoor air and rejects heat to the outdoors.



A heat pump can also cool the indoor air, but when the valve is reversed, the indoor air is heated. A supplementary electric resistance heater may also be used to assist the heat pump at lower outdoor temperatures. In colder climates, heat pumps require a de frost period. During defrost times the electric heater is the only means of heating the interior of the building. These units are manufactured as either split or packaged systems.

#### **2.4.1.4.    *Packaged Terminal Heat Pump (PTHP)***

Packaged terminal heat pumps (PTHP) are similar to a window-mounted air conditioner. These units are typically installed in a sleeve passing through the outdoor wall of an apartment, hotel, school classroom, etc. PTHPs are completely self contained and require only an electrical connection in addition to the opening in the building shell.



They use the outdoor air as the heat source in winter and as a heat sink in summer. They also can provide ventilation air. Flexibility and lower installed cost are the primary advantages of the PTHP. Disadvantages include in-room maintenance, higher operating cost, relatively short life, imprecise "on-off" temperature control, and they can be rather noisy.

#### **2.4.1.5.    *Portable Units***

The outdoor and indoor units of portable air conditioners are unified on the same device shell. They have the advantage of being easy to move around the home or office; they do not need installation and have lower purchase costs.



They have low power, making them economical to energy consumption, but at the same time limited cooling and thermal efficiency.

#### **2.4.1.6. Floor Mounted Units**

Floor air conditioners offer the solution in cases where we want to air a space without showing the wall mounted air conditioners.



This option is usually selected for architectural sites. In addition to aesthetics, floor air conditioners have the advantage of taking air from the floor (where the air is colder), making it an ideal choice for air conditioning of large open spaces and high ceilings that wall conditioners would not cool uniformly due to the way they recycle the air, but the higher air layers and the less air near the floor would become hotter.



They can be placed on the floor without taking up much space and can be easily placed under a window. They have very good thermal performance, are relatively silent in operation and easy to maintain. However, in relation to the wall units, they do not achieve such good cooling because the hot air tends to accumulate at the highest levels of the space and have a higher purchase cost.

#### **2.4.1.7. Wardrobe Units**

These are large in size, of high power units designed to air condition spaces, usually professional, over 60 m<sup>2</sup>. Wardrobe air conditioners are the worst air conditioners in terms of energy efficiency and comfort.



As far as energy efficiency rating is concerned, only inverter cabinets are at the best case in category A. As far as comfort is concerned, wardrobe air conditioners do not provide great comfort, because they blow large supply air from a single outlet, which results in people sitting near the air conditioner getting warm (when the air conditioner is running on heat) or cool (when operating under cooling) too much. However, there are few times when our wardrobe air conditioner solves our hands and allows us to cool a space without much installation costs.

#### **2.4.2. Central air conditioning systems**

Air conditioning systems which are designed to condition the various building rooms from a central location and are recognized by the components required to distribute air in rooms are known as central systems.

In central air conditioning systems, the central engine room (boiler room, chiller room, heat exchanger) is relatively far away from the air-conditioned areas. Terminal units are located in each space and they are connected to the central



engine room by the use of suitable ducts (airways, hot or cold water ducts, or refrigerant pipes).

A central air conditioning installation includes:

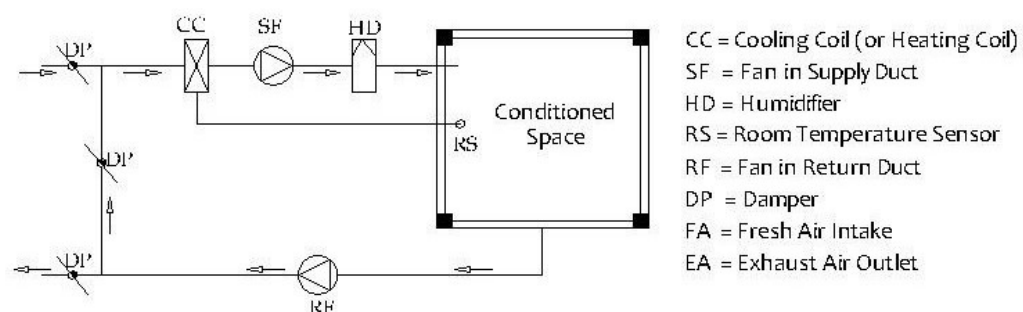
- The central thermal processing unit, which can process air, water or refrigerant fluid.
- The pipeline network, supply and/or abduction of heat duct (pipes or airways).
- Elements of local processing or supply of and diffusion or reception of heat to (or from) the air of the space, as well as elements of reception and removal of 'polluted' air.
- Automata and control systems, which are necessary to adapt the unit to the needs of the space.

The most common central air conditioning systems are:

- single duct, constant volume, single zone systems
- single duct, constant volume, multi zone systems
- single duct, variable volume systems
- Fan Coil Units (FCU)
- dual duct, constant volume systems
- variable refrigerant volume (VRV) systems

#### **2.4.2.1. Single duct, constant volume, single zone system**

In a single duct system, there is only one supply duct, through which either hot air or cold air flows, but not both simultaneously. In a constant volume system, the volumetric flow rate of supply air is always maintained constant. It is a single zone system as the control is based on temperature and Relative humidity (% RH) measured at a single point, as shown in Figure 9.



**Figure 9 – Schematic of single duct, constant volume, single zone system [22]**

Here a zone refers to a space conditions controlled by one thermostat. However, the single zone may consist of a single room or one floor or whole building with several rooms. The cooling/ heating capacity in the single zone, constant volume

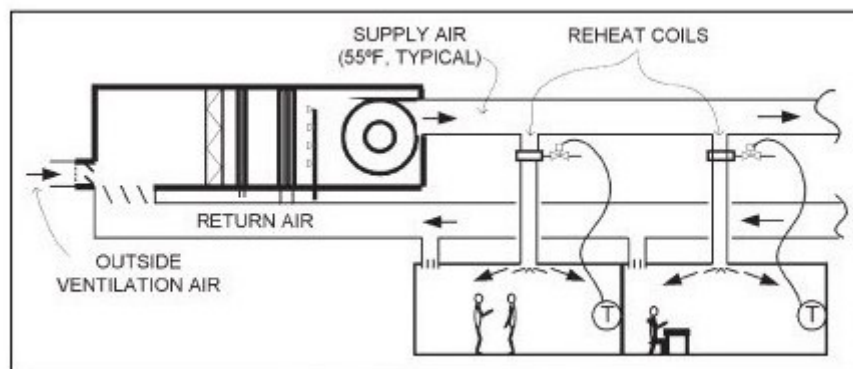


systems is varied by varying the supply air temperature and humidity, while keeping the supply airflow rate constant. Volume control dampers (VCD) are used to balance the Return air and Fresh air flows. Since single zone system is controlled by zone thermostat and humidistat, the location of these sensors in the zone is very crucial for performance of system.

Control is achieved by either coil control or face-and-bypass control. In coil control, flow rate of chilled water and hot water through cooling coil and heating coil is varied to vary supply air temperature and humidity. In face-and-bypass control, some of the supply air is by passed off the cooling/ heating coil to control supply conditions.

#### ***2.4.2.2. Single duct, constant volume, multi zone system***

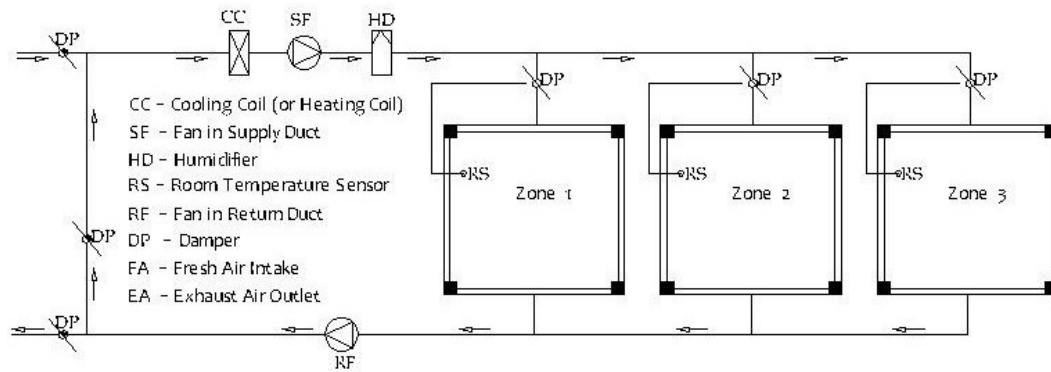
For very large buildings having variety of spaces and zones differing in requirements of cooling or heating, it is not feasible to provide several individual single zone systems for every zone or space. Multi zone system is selected for such application. In Figure 10, multi zone system with reheat terminal units is shown. Constant volume of supply air is supplied to every zone. Reheat coil is controlled by room thermostat as per the zone requirements.



**Figure 10 – Single duct, constant volume, multi zone system [23]**

#### ***2.4.2.3. Single duct, variable volume (VAV) system***

In this system, supply air temperature is kept constant and volume flow rate of supply air is varied as the cooling or heating load varies in the space or zone. Each zone is provided with VAV box consisting of zone damper and thermostat. Thermostat gives signal to zone damper of VAV box, which governs the supply air flow to the zone.



**Figure 11 – Schematic of single duct, variable volume, multi zone system [22]**

#### **Advantages of VAV systems:**

1. Since supply air flow is varied as per the load, low energy is consumed due to low fan power as compared to full capacity running of fan in constant volume system
2. Since air temperature is maintained constant, energy is saved in cooling system as air is not required to cool to very low temperature and reheat again.

#### **Drawbacks of VAV systems:**

1. At low load conditions, VAV supplies less fresh air, causing problems of Indoor air quality, ventilation and room air distribution.
2. Precise Humidity control is quite difficult in VAV systems.

#### **2.4.2.4. Fan Coils Unit**

FCU is a small package comprising a fan/ blower, cooling/ heating coil, air filters, louvers, condensate drain pipe etc. Typical FCU is shown in Figure 12. Chilled water is circulated through finned tube coils. Fan/ blower draws in the warm air from conditioned space. Warm air passes over cooling coils, where it is cooled and dehumidified to supply conditions. Condensate is collected in drain pan after dehumidification and then discharged through condensate drain pipe.

Sometimes duct able FCU is used for relatively large spaces. A short duct runs to 3-4 spaces from FCU which supplies air to supply diffusers. Return diffusers are also provided. This duct system ensures proper air distribution. FCUs are available up to 5-10 TR capacity (Ton of Refrigeration). FCU can supply up to 2000 CFM air. Generally for FCU, by a thumb rule, 1 TR  $\equiv$  400 CFM [5]. Mostly FCUs are ceiling mounted in the false ceiling. Capacity is controlled by varying chilled water flow rate. Room thermostat senses and signals the variation in space temperature to control valves to regulate chilled water flow.

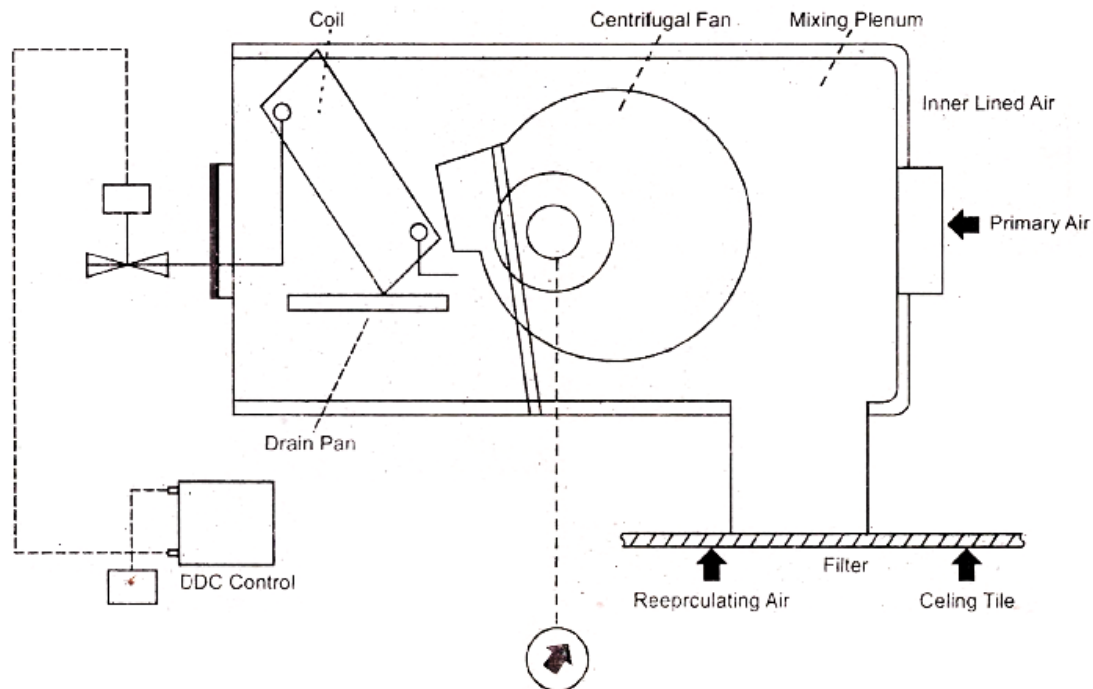


Figure 12 – Components of FCU

#### 2.4.2.5. Dual duct, constant volume system

A dual-duct system employs a different approach for establishing zone control. In a dual-duct system, cooling and heating coils are placed in separate ducts, and the hot and cold air flow streams are mixed, as needed, for temperature control within each zone. In this system, the air from the supply fan is split into two parallel ducts, downstream of the fan. One duct is for heating and the other for cooling. A layout of three zones of a dual-duct system is shown in Figure 13.

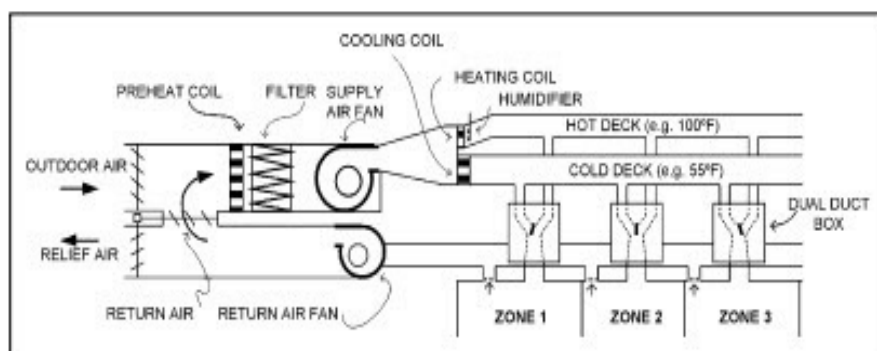


Figure 13 – Dual duct, constant volume system [24]

The duct with the heating coil is known as the hot deck, and the duct with the cooling coil is the cold deck. These constant volume dual-duct systems usually use a single, constant-volume supply fan to supply the two ducts.

Dual-duct systems achieve the zoned temperature control by mixing the hot and cold air streams in a dual-duct box while maintaining a constant airflow. As in

the reheat system described earlier, the heating and cooling effects are fighting against each other when the load is less than peak load. The combined energy use leads to energy inefficiency, which is the biggest disadvantage of dual-duct systems. The energy inefficiency may be reduced by these methods:

Minimizing the temperature of the hot deck using control logic based on zone loads or outside temperature  
 Raising the cold deck temperature when temperature and humidity conditions make it practical  
 Using variable volume dual-duct mixing boxes  
 The system also has a high first cost, since it requires two supply ducts. These two ducts need additional space above the ceiling for the second supply duct and connections.

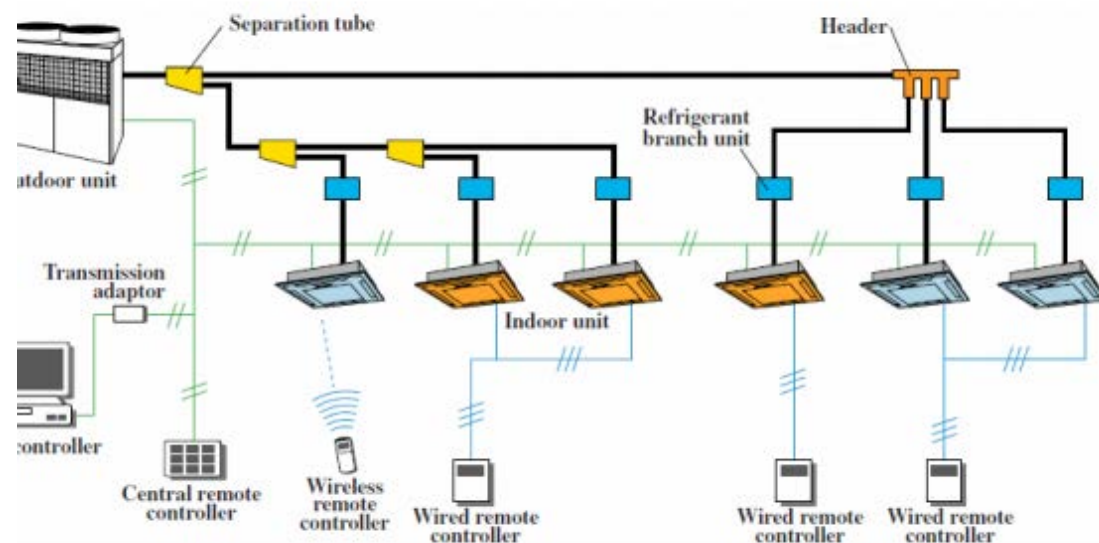


Figure 14 – Variable Refrigerant Volume (VRV) system [25]

#### 2.4.2.6. Variable Refrigerant Volume system (VRV)

VRV system is a multi-split type air conditioner for commercial buildings that uses variable refrigerant flow control developed to provide users with the ability to maintain individual zone control in each room and floor of a building. This technology circulates only the minimum amount of refrigerant needed at any one time and enables individual climate control of air conditioning zones. Precise individual control and inverter technology minimize energy consumption to deliver optimum energy savings. Modular design of outdoor units and wide selection of indoor units ensure system designs that are ideally suited to the environments where they are installed. VRV systems enable individual climate control settings for each zone to provide the utmost in comfort to commercial building settings. In addition to a maximum connection of 64 indoor units to 1 outdoor unit, large allowances for piping length and level difference provide a flexible layout.

### **2.4.3. Components of central air treatment units**

Each central air treatment unit consists of the following parts, in which the various air treatment components are mounted:

- air purification section
- air mixing section
- section of frontal and bypass diaphragms
- thermal treatment section
- air humidifying section
- fan section

#### **Air purification section**

Air purification is achieved by flat or angular filters, defined or discarded type, and appropriate guides for easy place and export. Quality and type of filters, impermeability of unfiltered air passage between filters or between filters and shells, must be determined by the designer, depending on the use of the air condition unit. The most common used filters in the central air conditioning units are colloidal, dry and electrostatic filters.

#### **Air mixing section**

In most cases, a percentage of the return air is reused by mixing with fresh air. This section connects the fresh air and recirculation air intake ducts directly or indirectly. Indirect is the connection when there are pre-sections of treatment, cleansing, or thermal of the air quantities which will be mixed. At the points of delivery there are multilayer diaphragms for adjusting the flow rate. These diaphragms are usually interconnected and moving opposite, so that as the diaphragm of the re-circulating air opens, both the diaphragm of the fresh air closes.

#### **Section of frontal and bypass diaphragms**

This section is usually omitted in small air-conditioning installations. It is used when it is desired that part of the air is not subjected to a heat treatment i.e. to bypass the part of the treatment and be driven straight into the flow fan section. Internally, it consists of two opposite movable diaphragms, one behind the treatment section and one from the top. Using a hand lever or servomotor, the amount of air that passes through the bypass will be adjusted.

#### **Thermal treatment section**

It is the main part of a central air conditioning unit. Here is the transmission of heat from the water (or steam or refrigerant) into the air. Inside the department there are elements, refrigerant and heating or just one common. The satisfactory transfer of heat from the water to the element depends on how the element is

made. Commonly used elements are made of 3/8" or 5/8" copper tubes with aluminum fins, mechanically expanded in the copper tubes and with various blade densities, per unit length of tube. The quality of the detachment and the configuration of the fins determine the performance of the element per unit area, for a given air inlet speed and temperature.

### **Air humidifying section**

This section is usually embedded or in direct contact (and succession) with the heat treatment section. It consists internally of a tube with nozzles (beak). It is located above a basin and ends up outside the unit where it is connected via a solenoid valve with a water network. In the front part of the section are placed the drip collectors, to hold the droplets drawn by the air. When the humidification requirements are increased, a re-circulating water pump (for lower water consumption) and a steam humidifier can also be installed.

### **Fan section**

The central air treatment unit includes a fan or fans that create the necessary vacuum or overpressure for airflow in both the air condition and the air ducts. Proper fan selection is a key factor for unit noise, vibration and economy in operation. Two types of fans are commonly used:

1. forward fans
2. backward fans

For low static network pressures fans with front sloping fins are used due to the advantages of this type of impellers at low pressures to ensure low noise levels.

For higher static pressures fans with reversible blade impellers are preferred because they perform better in these conditions, better performance and less noise.

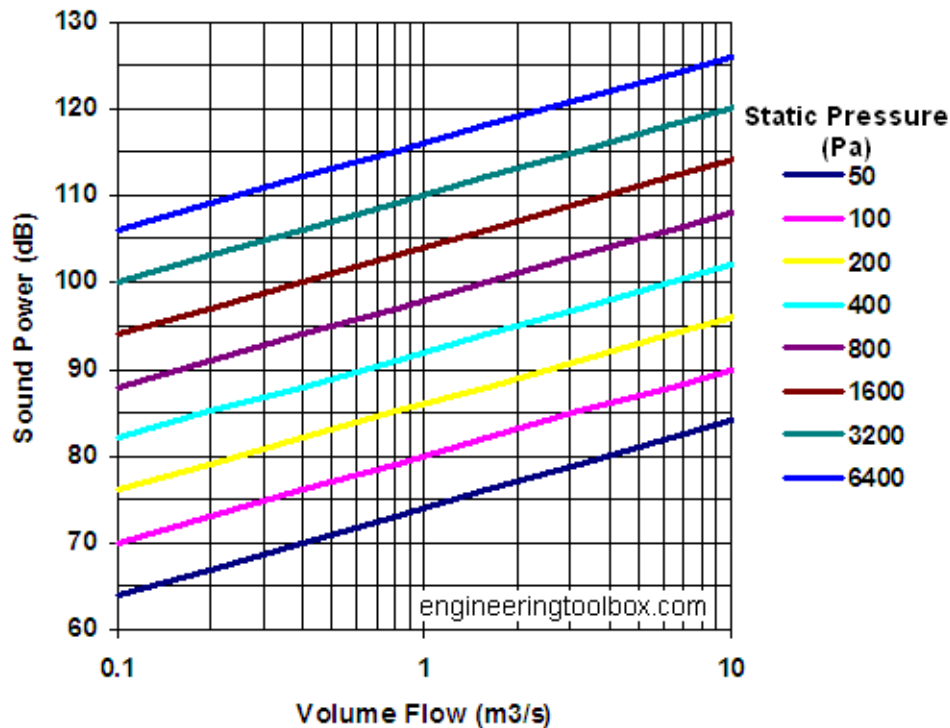


Figure 15 – Noise diffusion diagram for different static pressures of fan section of HVAC system

## 2.5. Conclusion

Broadly there are four large groups under which all categories of HVAC systems fall. All air system, all water system, air-water system are central A/Cs while DX (Direct Expansion) system is unitary, non central A/C. All these HVAC systems with their subtypes have been explained along with their merits and drawbacks.

Typical applications for variety of spaces have also been described. This will help in selecting the right type of HVAC systems to suit particular application. To name a few:

- All air systems are used in IT data center, hospitals, clean-rooms etc. where precise control of space humidity is required.
- All water systems are used for existing buildings with limited space.
- Air-water combination is suitable for buildings with large exposures.
- Unitary systems are best for low cost and very low load intermittent applications.

Such examples help to understand system selection criteria and make the decision making easier for planning engineer, client or engineering students.

## **Chapter 3 Available Software Tools for Energy Building Simulation**

### **3.1. Introduction**

#### **3.1.1. Building Energy Modeling Programs (BEMPs)**

Computer simulation is one of the most effective and economic methods to predict and analyze building energy consumption and performance. The simulation industry has developed rapidly since the 1960s, with hundreds of Building Energy Modeling Programs (BEMPs) developed and used around the world [9].

The energy simulation software tools can be important for reducing the cost of energy in buildings [1]. About one third of the energy consumption in buildings is used to increase thermal conditions of the dwellings and for lighting. Thermal simulation software tools for buildings allow to:

- Determine the appropriate size of HVAC systems;
- Analyze the energy consumption;
- Calculate the cost of the energy used.

#### **3.1.2. Advantages of Energy Simulation Tools**

The rules concerning the requirements on building envelope's thermal behavior have become increasingly restrictive. Nowadays, designers need tools that answer to very specific questions even during the initial design phase. Through the use of energy simulation software designers can consider specific choices, (e.g., heating and cooling). Designers can also predict the thermal behavior of buildings prior to their construction and simulate the costs of energy in existent buildings in their current conditions, establishing the best thermal retrofitting measures to adopt in the buildings under analysis. Besides the energy consumption, simulation software tools can also be used calculate to the following variables:

- Indoor temperatures;
- Needs for heating and cooling;
- Consumption needs of HVAC systems;
- Natural lighting needs of the occupants;
- Interior comfort of the inhabitants;
- Levels of ventilation.

The calculation of energy consumptions spent in dwellings still to build or to retrofit allow a more accurate determination of design charges and help to decide with highest accuracy the possible devices to be used in a room (limited zone) or dwelling.



Energy simulation software tools can also allow considering all the regulations in force and simultaneously provide a sense of comfort to its inhabitants through a correct design of heating and cooling systems. Such software have also available tools to improve constructive solutions through simulating the incorporation of passive solar systems in buildings, such as horizontally and vertically shading systems and a more accurate study of the HVAC system loads to use.

### **3.1.3. Need of comparison of BEMPs'**

As it was mentioned before, energy simulation software tools are an important support used for building designers to reduce the cost of energy in buildings. The energy simulation software allow to determinate with accuracy some variables that can support designers to take decisions about the best measures to apply for any building to built or already existent. There are several BEMPs in the market, which are used in the design stages of new energy efficient buildings, the planning stages of energy retrofits for existing buildings, and the development of building energy codes and standards and energy labeling programs in the building industry.

However, more and more practical applications show that large discrepancies exist in results from different modelers using different BEMPs for the same building. This is a large problem for the simulation industry and the subject of much attention. Some believe that the simulation methodology is flawed and attribute the discrepancies to the different calculation engines of different BEMPs. This may hinder the development and application of BEMPs. Consequently, it is important for the simulation industry to understand the reasons for these discrepancies and define the application scope of each program. To solve the problem and promote the development of BEMPs, the detailed comparison of BEMPs' engines is a fundamental and significant step.

A number of studies have been conducted to compare the advantages and disadvantages of several BEMPs. For comparison purposes, BEMPs can be divided into two parts:

- the load-side calculations and
- the HVAC system-side calculations.

This chapter focuses on the HVAC system-side calculations. Compared to methodologies for testing load-side calculations, the HVAC system comparison process is at an early stage. There exists no widely accepted testing procedure that can be used directly. The inter-program comparison of HVAC system calculations for commonly used BEMPs is of great significance for users to gain a better understanding of each simulation program. This will also lead to a more effective use of building simulation in scientific research and engineering practice.

## **3.2. Steps to perform in a BEMP**

There is an increasingly range of energy simulation software tools available, with the ability to calculate increasingly complex energy requirements, with more

variables and a more rigorous approach. Generally speaking in all energy simulation software tools there are three steps that have to be performed in a building simulation.

### **3.2.1. Step one of BEMP – Create the building**

Creation of the building is the earlier stage of an energy simulation. This process can be done for example by inserting the coordinates in the software tool such as in Energy Plus simulation software or by uploading files from other software, such as AutoCAD or Google Sketch Up. The introduction of coordinates is performed according to a certain reference (which is located in a pre-determined position).

Concerning the structure of the building and its construction, it is essential to specify the dimensions of the organizational structure, geometry and materials used in the components of the building architecture.

### **3.2.2. Step two of BEMP – Building Simulation**

In this step, it is established which variables are to consider in the simulation of the building and make the software tool run.

The thermal performance of the building can vary according to its use. Therefore it is important to specify the type of building (office, housing, etc.), the human activities carried out, the existing equipment (lighting, refrigeration, air conditioning systems, furnaces, etc.), and their daily schedules. The description of these parameters allows establishing the internal heat load and ventilation.

### **3.2.3. Step three of BEMP – Analysis of results**

After running the software tool, it should be checked if there are any error or severe mismatch introduced in the variables set. In some cases the simulation software tool issues its own warnings in a final report containing the results from which should be retained all the relevant conclusions.

Depending upon the simulation software tool of energy it is used, the following aspects should be considered:

- **Physical Phenomena:** Hydrothermal behavior, artificial/natural illumination, acoustics, ventilation and air distribution;
- **Energy Systems:** Modeling energy in a building, heating and cooling, thermal mass, cogeneration and renewable energy;
- **HVAC Systems:** Thermal loads and its forecast for optimizing control of components and modeling systems, dynamic behavior and control systems, environmental quality and energy consumption;
- **Human Factors:** Comfort, visual modeling and indoor air quality;
- **Urban Simulation:** Sunlight and shadow effects.

In each building simulation there are four fundamental aspects that must be taken into account:

1. Structure of the building and its organization;
2. Physical phenomena involved in the simulation;
3. Weather conditions;
4. Use of the building.

In relation to physical phenomena, the model seeks to describe the physical behavior of building materials and their components, and their performance on the transfer of heat by conduction, convection and radiation.

### **3.3. Presentation of available Energy Simulation Software tools**

Below are presented four well known BEMPs:

1. DOE-2 and EnergyPlus from the U.S. Department of Energy,
2. ESP-r from the University of Strathclyde, U.K.,
3. DeST from Tsinghua University, China and
4. TRNSYS from the University of Wisconsin,

aiming to identify some of the most important due to their capacity of calculating a significant number of variables and to compare them in order to establish their differences.

The comparison is based on information provided by the program developers in the following categories:

1. general modeling features;
2. zone loads;
3. building envelope and
4. day – lighting and solar;
5. infiltration, ventilation and multi – zone airflow;
6. renewable energy systems;
7. electrical systems and equipment;
8. HVAC systems;
9. HVAC equipment;
10. environmental emissions; economic evaluation;
11. climate data availability,
12. results reporting;
13. validation; and user interface,
14. links to other programs, and availability.

### 3.3.1. EnergyPlus

#### 3.3.1.1. Overview

The entire integrated program can be represented as a series of functional elements: BUILDING/Zone, SYSTEM, and PLANT subroutines are integrated and controlled by the integrated solution manager [10]. These elements have to be linked in a simultaneous solution scheme. The solution scheme generally relies on successive substitution and iteration to reconcile all of the elements using the Gauss-Seidell philosophy of continuous updating.

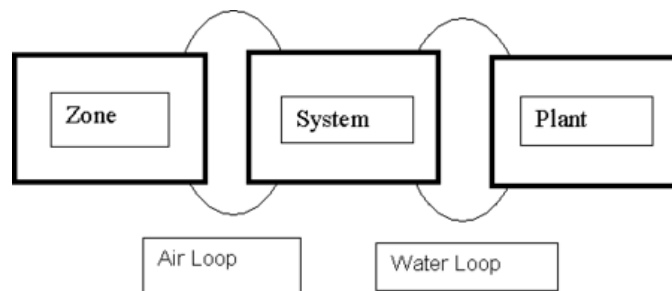


Figure 16 – EnergyPlus. Schematic of simultaneous solution scheme [10]

The elements are connected by fluid loops, and each loop is divided into supply and demand sides [9].

Air loops are divided into two parts as per the following:

1. **Primary air system:** the supply side of the loop, including supply and return fans, central heating and cooling coils, outside-air economizers, and other central conditioning equipment and controls.
2. **Zone equipment:** the demand side of the loop, including air terminals as well as fan coils, baseboards, window air conditioners and so on.

The water loop can be separated into a plant loop and a condenser loop. Similarly, the supply side and demand side can be ruled as following:

1. **Plant demand side:** equipment (coils, baseboards, radioactive systems, etc.) that places a load on the primary equipment (e.g. chillers and boilers).
2. **Plant supply side:** chillers, boilers, etc.
3. **Condenser demand side:** chiller condenser.
4. **Condenser supply side:** cooling tower that cools the condenser water.

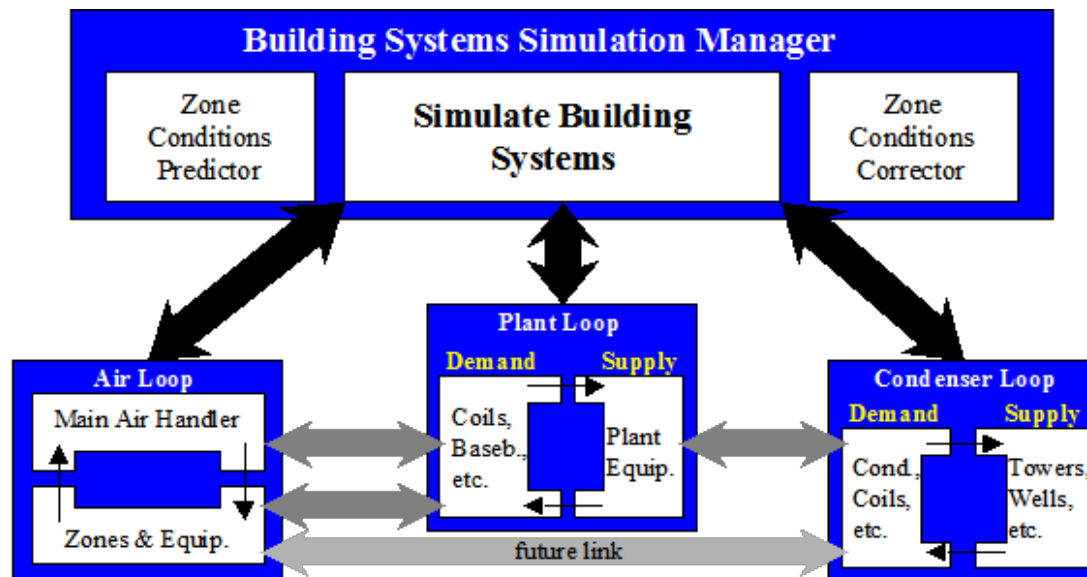


Figure 17 – EnergyPlus. Connections between the main HVAC simulation loops and sub-loops [9]

### 3.3.1.2. Assumptions in EnergyPlus

There are several main assumptions made in EnergyPlus. For reasons of consistency and comprehensibility, it is required that all EnergyPlus models be forward models. That is, the component inputs correspond to the inlet conditions and the outputs correspond to the outlet conditions. For each component several choices of inputs and outputs are possible.

1. AIR SYSTEM CONTROL uses a predictive system energy balance method. It has many characteristics of a predictor-correct method. An assumption was made that if the air system has sufficient capacity (based on the desired zone air temperature) to meet the zone conditioning requirements, those requirements will be met. On the other hand, if the air system cannot provide enough conditioning to the zone, the air system provides its maximum capacity.
2. Simultaneous solution of the system and plant operating parameters requires that the temperature of the water entering the coils must be the same as the temperature leaving the chillers or boilers. Also, the temperature of the return water from the coils must be equal to the chiller or boiler supply water temperature. If the plant has adequate capacity, no iteration is needed (i.e. the supply water temperature equals the set point). But when the plant is overloaded, the plant outlet water temperature is calculated iteratively using the secant method.
3. During each system simulation time step, new zone temperatures and humidity ratios are predicted using previous values. The zone temperatures and humidity ratios are then held constant during the simulation of the air system (and the plant). Then the zone temperatures and humidity ratios are corrected using results from the system simulation. As a result the usual

algebraic loops arising from steady-state air system simulations are eliminated.

4. The properties of the loop (temperature, enthalpy, flow rate, etc.) are stored in the branch nodes. Components on the branch take the conditions of the nodes at their inlet and use that information as well as overall control information to perform calculation for the components. Simulation results are written to the outlet nodes of the component, and also copy to the downstream nodes on the branch.
5. The plant flow resolver is used to adjust the flow rate within the plant and condenser loops. First, the loop manager would simulate all the components on each branch of the loop purely based on the components' own control to satisfy the desired flow rate. Then, the loop manager would resolve the flow and the components are re-simulated with the corrected flows. During this iteration, the flow resolver sets the flow rate. In order not to resort to a pressure-based flow network, a rule-based "flow resolver" was employed. The flow resolver uses a simple predictor-corrector algorithm to enforce mass continuity across the plant splitters.
6. To control the fluid temperature, thermal capacitance is added to the plant loop. This adds stability to the calculations. Once the set point temperature is reached, the storage effects are not included.
7. The loops essentially ignore the node pressures. This is suitable for many applications; however it may cause inaccuracies in the calculation of the pump power. The loop pressure drop is used as the new pump head. If a pump curve is not specified, it is assumed that the pump will always be able to meet the operating point.
8. The loops essentially ignore the node pressures. This is suitable for many applications; however it may cause inaccuracies in the calculation of the pump power. The loop pressure drop is used as the new pump head. If a pump curve is not specified, it is assumed that the pump will always be able to meet the operating point.
9. EnergyPlus can also perform a "loop level" pump-system flow resolution to calculate the loop pressure drop. The flow resolver reads the non-dimensional pump curve, loop pressure constant and rated mass flow rate (or mass flow rate from the last iteration) to calculate the pump operating point.

### **3.3.1.3. Summary**

In conclusion, EnergyPlus is a powerful simulation program. The main idea is successive iteration and analogue simulation. This calculation method leads to a high requirement on convergence and stability, so a series of measures has been taken to improve the performance of the solver. However, EnergyPlus allows users to overwrite internal algorithms or add new calculations via the Energy Management System feature, which improves the flexibility of HVAC simulations.

To eliminate the necessity of solving the interactions between pressures and flow rates, EnergyPlus currently has no duct system model, so the flow rates of different ducts are determined by a ruled flow resolver. The flow resolver

distributes the flow rate according to the characteristics of each branch. This assumption is an effective way to reduce the complexity of the model and improve the speed of convergence. But it does not accurately address the interactions between branches that affect the balance of the flow. Such limitations lead to several un-resolved operating problems, e.g. flow rate adjustments and coil dynamic characteristics.

EnergyPlus calculates the pressure drop based on the flow rate. However, the change of pressure does not affect the branch flow rate. Additionally, the flow rate of each branch has nothing to do with the branch's resistance characteristics. Therefore, the resultant pressure has no practical meaning, and can only be regarded as a reference.

The majority of inputs for EnergyPlus are determined by the user. This requires a high level of expert knowledge in buildings and HVAC systems. The amount of input data is large, which is one of the main reasons for long execution times.

### **3.3.2. DOE-2.1E**

#### **3.3.2.1. Overview**

DOE-2 is a program that uses sequential simulation modules. It has one subprogram for the translation of user inputs (the Building Description Language (BDL) processor), and four simulation subprograms (LOADS, SYSTEMS, PLANT, and ECON). The SYSTEM and PLANT subprograms constitute the HVAC subroutines. LOADS, SYSTEMS, and PLANT are executed in sequence. Outputs from the SYSTEMS and PLANT modules become inputs to the ECON module. Then the ECON subprogram calculates utility cost as part of the economic reports.

The SYSTEMS subprogram uses the output information from the LOADS program and a list of user-defined system characteristics to handle secondary systems. The PLANT subprogram uses hourly results from the LOADS and SYSTEMS programs, combined with user instructions, to handle primary systems. SYSTEM calculates the performance of air-side equipment (fans, coils, and ducts). It corrects the constant temperature loads from the LOADS subprogram by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and the thermostat set points. The outputs of SYSTEMS are airflow rates and coil loads. PLANT calculates the behavior of boilers, chillers, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. It takes into account the part-load characteristics of the primary equipment in order to calculate the fuel and electrical demands of the building [9, 13, and 14].

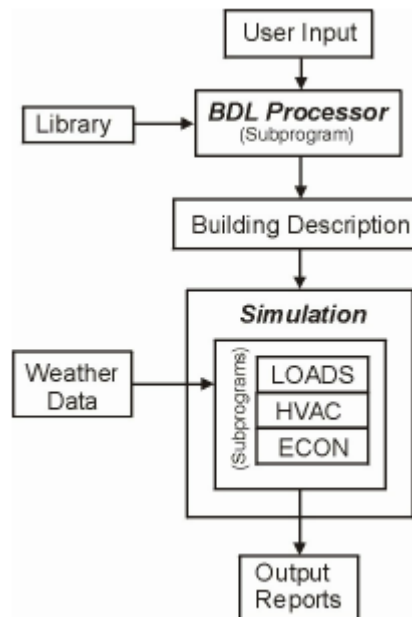


Figure 18 – DOE –2 calculation flow chart [9]

### 3.3.2.2. Assumptions in DOE –2.1E

Several assumptions are made in DOE –2.1E, including:

1. The dynamics of the interactions between the HVAC equipment and the building are calculated by the simultaneous solution of the room air temperature weighting factors with the action of equipment controller. To eliminate the necessity of solving the interactions of all the zones simultaneously, the zone temperatures from the previous hour are used to approximate the heat flow across internal walls. Likewise, to eliminate the need to iterate until all of the temperatures in the equipment loop converge, temperature histories are used in the calculation of equipment capacities. This is a good approximation if the derivative of the zone temperature is roughly constant.
2. The moisture content of the air is calculated by assuming a steady state solution of the system moisture balance. The moisture condensation on cooling coils is simulated by characterizing the coils by their bypass factors and then solving the bypass relation simultaneously with the system moisture balance.
3. A linear relationship is assumed to describe the interaction of the thermostat, space temperature, and equipment output. First, the capacity is estimated by using the dry – and wet – bulb temperatures from the end of the previous time step (hour). Then according to the estimated equipment capacity, the corresponding relationship with zone temperature is used to decide the equipment's capacity.
4. The equipment capacity and energy input are expressed as the product of a "rated" value and modifier functions. It is assumed that it can be well approximated by the product of multiple modifier functions.



5. As all of the information is communicated in one direction only, a subprogram “upstream” cannot make use of any information “downstream”, like the overload cases. In the PLANT subroutine, if the coil load is not met, it will pass the overload to successive time steps until it is finally met, or the heating or cooling is scheduled to be switched off. The one – way flow of information also does not allow several building control strategies to be simulated, such as adjusting the lighting loads according to the electrical loads.
6. If multiple sizes of given equipment type are operating simultaneously, the program models them as if all the equipment was lumped together into one large unit. It assumes that the same type of equipment will have identical performance curves regardless of their sizes. Also, it is assumed that all equipment of the same type will be operating at the same fraction of their design capacities.
7. Electricity needed to operate a boiler or a storage tank pump is not accounted for in the total energy of PLANT.
8. The PLANT subprogram does not make checks to see if the type of equipment and fuel types the user inputs are compatible.

### **3.3.2.3. Summary**

DOE –2.1E is a simulation program with a long history and a comprehensive set of functions. However, due to the lack of further development since the early 1990s, there are several weaknesses in the software. The main problem is the structure of the software. It has no feedback process, and the one direction calculation flow contains a lot of simplifications compared to real HVAC systems. Facing the increasingly complex system schemes and control methods which are currently emerging, DOE –2 cannot adequately satisfy some user requirements, particularly those with feedback situations.

To simplify the calculation process and avoid iterative calculations, in DOE –2 the zone temperatures from the previous hour are used to approximate the heat flow across internal walls and temperature balances. This method will introduce inaccuracies when the zone temperatures fluctuate significantly.

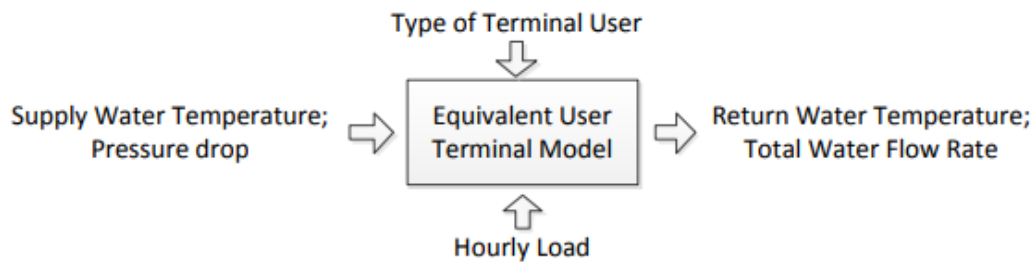
Meanwhile, the SYSTEMS subroutine corrects the constant-temperature loads by the LOADS subprogram using room air temperature weighting factors. It does not perform a true zonal heat balance and will also lead to inaccuracies.

### **3.3.3. DeST (Designer’s Simulation Toolkit)**

#### **3.3.3.1. Overview**

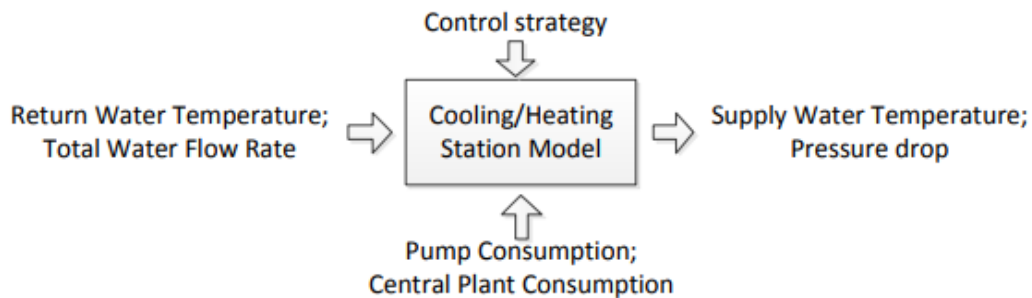
DeST separates the heating/cooling station (central plant) from the supply side, dividing them into two modules (equivalent user terminal and heating/cooling station). The equivalent terminal model is a simplified model to reflect the main properties of air terminals. The two modules iterate to obtain the results. DeST performs detailed modeling of ducts, chillers, and pumps in the heating/cooling station side. Exact and strict physical equations based on first principles are

used, but in the user terminal side, a curve is used to reflect the changes of whole flow rate, pressure drop, and heat transfer [11].



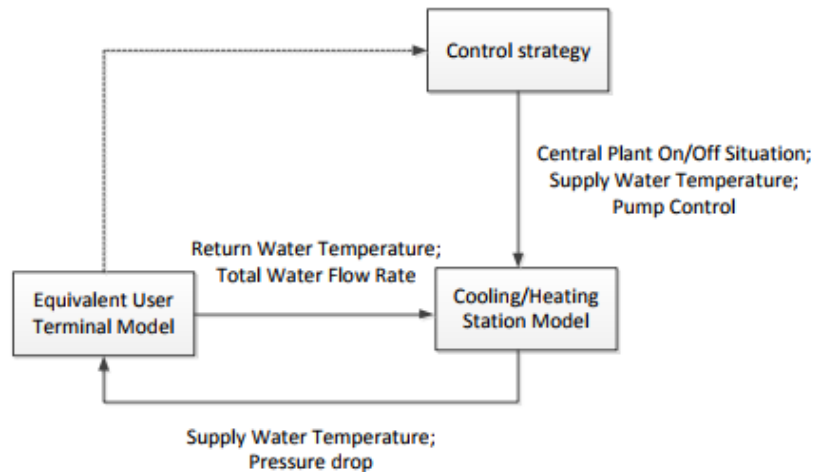
**Figure 19 – DeST. Equivalent user terminal model [9]**

DeST builds equivalent user terminal models for different end types. As Figure 19 shows, in the terminal model, when the terminal user type and hourly load have been input, and the user side supply water temperature  $t_{w,in}$  and the pressure drop  $\Delta P$  have been calculated, then through the equivalent user terminal model, the chiller water flow rate in user side and the return water temperature  $t_{w,out}$  are calculated. The equivalent user terminal model can reflect the overall performance and the time average situation. In this way, the terminal system is separated from the complex dynamic control. In the heating/cooling station model, as Figure 20 shows, when the control strategy of heating and cooling station has been determined, and the return water temperature and flow rate have been input, the supply water temperature and pressure drop can be calculated [9].



**Figure 20 – DeST. Heating/ cooling station model [9]**

After the modeling of equivalent user terminal and heating/cooling station, based on the inside coupling relationship, iterative calculations are performed to obtain the actual flow rate, pressure drop, and water temperature, thus maintaining the consistency of water flow rate, pressure drop, and heating/cooling load on both the user side and supply side. The combined iteration method is illustrated in Figure 21.



**Figure 21 – DeST. Iterations between equivalent user terminal model and the heating/cooling station model [9]**

### **3.3.3.2. Assumptions in DeST**

DeST makes several important assumptions:

1. For the lower level closed-loop controls, DeST only checks to see whether a set point can be met by regulating equipment. If the set point can be met, DeST calculates the regulated variables, such as the cooling outputs, pump rotation speed, and valve pressure drops. Otherwise, the control apparatus will be opened to the maximum position.
2. For the overall upper level control strategies for the cooling and heating plants, DeST uses detailed simulations, e.g., when determining the operating status of each chiller and pump. Because control strategies can vary significantly, DeST cannot cover all possibilities, but it does provide a few simple control strategies for users to choose. Users can enter code for control strategies based on their needs using a list of parameters and variables provided by DeST.

### **3.3.3.3. Summary**

With the concept of an equivalent user terminal, the iterative calculations between demand side and supply side has been simplified, which also decreases the complexity of the iterative calculations and improves the chance of convergence. DeST's whole simulation structure is simpler and clearer compared to other programs. So far the equivalent user terminal has covered several typical HVAC systems. This needs to be expanded for new HVAC systems.

### 3.3.4. ESP –r (Energy Simulation Software Tool)

#### 3.3.4.1. Overview

ESP –r allows an in-depth appraisal of the factors which influence the energy and environmental performance of buildings. The ESP –r system has been the subject of sustained developments since 1974 with the objective of simulating building performance in a manner that:

- a) is realistic and adheres closely to actual physical systems,
- b) supports early –through –detailed design stage appraisals, and
- c) enables integrated performance assessments in which no single issue is unduly prominent.

ESP –r attempts to simulate the real world as rigorously as possible and to a level which is consistent with current best practice. By addressing all aspects simultaneously, ESP –r allows the designer to explore the complex relationships between a building's form, fabric, air flow, plant and control. ESP –r is based on a finite volume, conservation approach in which a problem (specified in terms of geometry, construction, operation, leakage distribution, etc.) is transformed into a set of conservation equations (for energy, mass, momentum, etc.) which are then integrated at successive time-steps in response to climate, occupant and control system influences. ESP-r comprises a central Project Manager around which are arranged support databases, a simulator, various performance assessment tools and a variety of third party applications for CAD, visualization and report generation [12, 26].

**Keywords:** energy simulation, environmental performance, commercial buildings, residential buildings, visualization, complex buildings and systems.

**Expertise Required:** Understanding of thermo-physical processes in buildings, environmental systems and controls as well as domain expertise for electrical, micro-toxin and CFD assessment domains (if used).

**Users:** Primarily in Europe but with users and developers worldwide.

**Audience:** Engineers, researchers, energy consultants, multi-disciplinary design firms.

**Input:** Building geometry can be defined via CAD tools, in-built CAD facilities or click-on-grid or image. ESP-r supports a building representation of arbitrary complexity (but most users work with models of 10 – 50 thermal zones. Models can be exported to other assessments tools such as EnergyPlus, Radiance (visual simulations) or VRML worlds. Constructional and operational attribution is achieved by selecting entities from support databases and associating these with the surfaces and spaces comprising the model. Models can be further attributed to account for temporal shading and isolation patterns, explicit radiation view factors, facade-integrated photovoltaic modules, temperature dependent thermo- physical properties and CFD domains. As required, component networks can be defined to represent, for example, HVAC systems, distributed fluid flow (for the building-side air or plant-side working fluids) and electrical distribution

systems. Alternatively, users can use idealized environmental controls for early design-stage explorations.

**Simulations:** With ESP -r, functionality follows description – simple models and operating regimes composed in a few minutes can be extended, in steps, to encompass the simultaneous solution of fabric (1/2/3D), air flow (network and/or coupled, transient CFD), electrical power, embedded renewable, plant system components, indoor air quality and lighting assessments via Radiance. Building and flow simulations can be undertaken at frequencies of one minute to one hour and system simulations can be from fractions of a second to an hour.

**Output:** An interactive results analysis module is used to provide many different views of simulation results undertake a variety of performance appraisals and explore the interactions between assessment domains. Tools are provided to enable the construction of an Integrated Performance View which summarizes performance over a range of relevant criteria. Range of analyses is essentially unrestricted and data can be exported to other analysis and graphing tools (but many users find they rarely need to access spreadsheets).

**Strengths:** In addition to state of the art standard simulation features, ESP -r has powerful capability to simulate many innovative or leading edge technologies including daylight utilization, natural ventilation, contaminant distribution, combined heat and electrical power generation and photovoltaic facades, adaptive 3D transient CFD, multi-gridding (2D and 3D conduction), and control systems.

**Weaknesses:** Specialist features require knowledge of the particular subject. Although robust and increasingly used for consulting, ESP -r retains much of the look and feel of a research tool and lacks the extensive databases associated with commercial tools. The current Windows implementation does not conform to the standard look and feel of most Windows applications and lacks a few features available on other platforms. ESP -r does yet provide a built-in undo function. ESP -r dialogs and contextual help messages are a bit heavy on jargon. ESP -r is much better learned via interactions with a mentor than by self-instruction [29].

#### **3.3.4.2. Summary**

The software tool ESP -r (Energy Simulation Software tool) is intended to support the construction project with regard to energy and environmental performance, in a realistic and accurate way. The software tool is mathematical software for a project manager that coordinates the data, simulation, CAD applications, different tools for evaluating performance, display and report generators, etc. The ESP -r uses several complex equations to deal with all aspects at the same time (geometry, construction, operation, distribution, heat dissipation, etc.). These equations are integrated in successive time steps in response to the influences of the occupants, and climate control systems. The geometry of the building can be set in CAD software tools or other similar tools to allow the specification of the geometry of buildings. The models created in this software can be exported to Energy Plus.

The operating conditions are determined through database support. Shading, insulation, HVAC systems, areas of computational fluid dynamics (CFD),

electricity, renewable energy embedded systems, lighting, natural ventilation, combined heat and power generation, facades photovoltaic systems for control of indoor air quality can also be included in the models pre-determined. The time simulation of the building with ESP-r simulation tool can vary in a range from one minute to one hour. The outputs of the simulations can be viewed by the interactions between the domains of assessment or exported to other graphics software. The ESP-r is extremely useful and is a powerful tool to simulate many innovative technologies. However, the program requires a great knowledge and expertise from its users, and requires a long learning process.

### 3.3.5. TRNSYS

#### 3.3.5.1. *Overview*

TRNSYS is a complete and extensible simulation environment for the transient simulation of thermal systems including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts, from simple solar domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc. Throughout its thirty year history TRNSYS has been under continual enhancement by an international group [30].

**Engine and Interface:** At its heart, TRNSYS is a robust algebraic and differential equation solver that is able to read and process a text based input file. On top of this solution engine is stacked an impressive library of components that model everything from simple pumps to detailed multi-zone building; in short a component is anything whose outputs can be represented as a mathematical function of inputs (time-dependent values) and parameters (time independent values). TRNSYS is also endowed with a powerful graphical front end that makes the user's job of assembling a detailed system simulation from component parts a simple endeavor – similar in nature to hooking up the pipes and wires in a real system.

**Online results:** In addition to its flexibility, TRNSYS is also a very transparent tool. Users can watch the value of ANY system variable on an online plot as the simulation progresses (any temperature, flow rate, heat transfer etc.). Output devices also allow the user great flexibility in integrating, printing, and reporting all component variables as well.

**Components:** Because the structure of all components is the same, and because TRNSYS is distributed with its source code, users can and often do develop their own models, expanding the capabilities of the program to suit their needs. We have made heavy use of this feature in our consulting efforts and have written well over 500 components, many of which are cleaned up, fully documented, and are distributed in a series of 13 component libraries for TRNSYS.

**TRNSED:** TRNSYS, while a very complex and vast simulation tool, is equipped with a feature that allows users to develop customized graphical interfaces for specific applications. Using this TRNSED feature, the TRNSYS user can create a

web-page like interface that allows non-TRNSYS users to change system parameters, run simulations, and process output without having to learn the intricacies of the TRNSYS program [31].

### 3.3.5.2. Summary

TRNSYS is a transient system simulation software tool with a modular structure that has been specially designed to develop complex systems related to energy, outlining the problem in a number of smaller components. The components ("Types") may range from simple heat pump to a multi-zone of a building complex. The components are configured through the graphical user interface known as TRNSYS Simulation Studio. In the simulation software tool energy TRNSYS the construction of the building can be achieved by the introduction of data on dedicated visual interface, known for TRNBuild [12].

The software tool sets the time intervals which may vary from 15 minutes to an hour, but may be able to perform simulations in the time interval of 0.1 seconds. The library software tool in addition to a multi zone, allows the use of many commonly used components, including: solar panels, photovoltaic systems, HVAC systems, cogeneration systems, hydrogen, among others. It also allows the creation of routines to manipulate weather data and other data by changing the simulation results. The modular nature of this software tool facilitates the addition of mathematical models to the software tool. The components can be shared among multiple users without having to recompile the software tool due to the use of DLL technology. In addition, this energy simulation software tool allows the user to incorporate other components developed in software tools such as Matlab®, Excel®, VBA, etc. Moreover, the software tool includes the possibility of adding HTML views through a software tool called TRNSED, which enable non-users to view and do parametric studies of TRNSYS files, in a simplified representation of a web page.

## 3.4. Comparison of Energy Simulation Software tools

Each software tool of the mentioned energy simulation software tools has certain characteristics, and specific applications. In order to better understand specific features of each one, Table 3 presents a summary table of the features of each of the software tools mentioned above, in particular: Solution of Simulation; Duration Calculus; Geometric Description; Renewable Energy Systems; Electrical Systems and Equipment; HVAC systems.

	Energy Plus	DOE-2	DeST	ESP-r	TRNSYS
<b>Simulation Solution</b>					
Simulation of loads, systems and solutions	X		X	X	X
Iterative solution of nonlinear systems	X			X	X
<b>Duration of Time Calculation</b>					

	Energy Plus	DOE-2	DeST	ESP-r	TRNSYS
Variable time intervals per zone for interaction of the HVAC system	X			X	
Simultaneous selection of building systems and user				X	X
Dynamic variables based on transient solutions	X			X	
<b>Complete Geometric Description</b>					
Walls, roofs and floors	X	X	X	X	X
Windows, skylights, doors and external coatings	X	X	X	X	X
Polygons with many faces	X	X	X	X	
Imports of buildings from CAD programs	X		X	X	X
Export geometry of buildings for CAD software	X			X	
Import/Export of simulation model of programs	X			X	
Calculation of thermal balance	X	X	X	X	X
Absorption/ release of moisture from building's materials	X				X
Internal thermal mass	X	X	X	X	X
Human thermal comfort	X		X	X	X
Solar analysis	X	X	X		X
Analysis of isolation	X	X	X	X	X
Advanced fenestration	X	X	X	X	X
Calculations of the building in general		X	X	X	X
Surface temperature of zone	X	X	X	X	X
Airflow through the windows	X			X	X
Driving surfaces	X	X	X	X	X
Heat transfer from the soil	X	X	X	X	X
Thermo-physical variable	X				
Day-lighting and lighting controls		X	X	X	
Infiltration of a zone	X	X	X	X	X
Automatic calculation of coefficients of wind pressure	X		X		



	Energy Plus	DOE-2	DeST	ESP-r	TRNSYS
Natural ventilation			X	X	X
Natural and mechanical ventilation	X		X		X
Control open of windows for natural ventilation	X		X	X	X
Air leaks in multiple zones	X		X	X	X
<b>Renewable energy systems</b>					
Solar energy	X		X	X	X
Trope wall	X		X	X	X
Photovoltaic panels	X			X	X
Hydrogen systems				X	X
Wind energy				X	X
<b>Electrical systems and equipment</b>					
Energy production through R.E.	X			X	X
Distribution and management of electrical power loads	X	X		X	X
Electricity generators	X				X
Network connection	X			X	X
<b>HVAC systems</b>					
HVAC idealized	X		X	X	X
Possible configuration of HVAC systems	X		X	X	X
Repetitions cycle air	X		X	X	X
Distribution systems	X			X	X
Modeling CO <sub>2</sub>					X
Each distribution of air per area	X	X	X	X	X
Forced air unit per zone	X	X	X	X	X
Equipment unit	X	X	X	X	X

**Table 3 – Comparison of features of five simulation software tools [12]**

### 3.5. Conclusions

Along with materials and construction techniques also energy simulation software tools of buildings have had developments over the years. Currently there are several energy simulation software tools with different levels of complexity and response to different variables. Among the most complete simulation software tools are the Energy Plus, the DOE-2, the DeST, the ESP-r (Energy Simulation Software tool), and TRNSYS. Being the most complete software tools, these are also the most complex and therefore require greater expertise.

EnergyPlus is a powerful simulation program with the most complete component models and the most adjustable parameters among the five simulation programs. Its main limitations exist in the pressure calculation, flow rate distribution, and calculation convergence.

The calculation speed of DOE -2 is the fastest, and DOE -2 is the simulation program with a long history and complete functions. However, the lack of integrated solutions between loads and systems makes it difficult for DOE -2 to simulate several new HVAC system types and control strategies.

The SCHEME sub - program and the simple and clear HVAC simulation structure make DeST different from the other programs. However, the simulation concept, the overuse of hard-wired parameters, and limited types of component models causes differences versus the other programs.

TRNSYS is the most complete, but depending on the user perspective and final purpose the other software tools could be more appropriated. The major limitation of TRNSYS is to not being able to connect with AutoCAD Software tool for importation and exportation of files. In this aspect Energy Plus and ESP -r are more appropriate.

Amongst the comparable component models, the detailed analysis shows that the assumptions, simplifications and algorithms for the HVAC components are very similar. However, the control strategies in the three programs are quite different, which definitely impacts on the energy calculation results. In conclusion, all five programs fundamentally have the capability for HVAC system simulation and the differences in the simulation results are within a small range.

It should be noted that further research is needed to compare more HVAC system types and control strategies, especially how low energy systems, e.g. natural ventilation, radiant systems, displacement ventilation, to understand the differences and limitations of the BEMPs.

## Chapter 4 Building Modeling in EnergyPlus®

### 4.1. Description of simulation software

#### 4.1.1. Google SketchUp design program

Google SketchUp is basically a three dimensional drawing design program. It is an application which is free for users, while there is a professional publishing which is sold. In SketchUp, you can easily design in two dimensions and at the touch of a button to create a three-dimensional object. It has a wealth of design tools but more. It can receive plug-in extensions that provide tools for modeling or even simulation of processes. Figure 22 shows the workspace of SketchUp. For the present thesis version SketchUp Make 2017 is used.

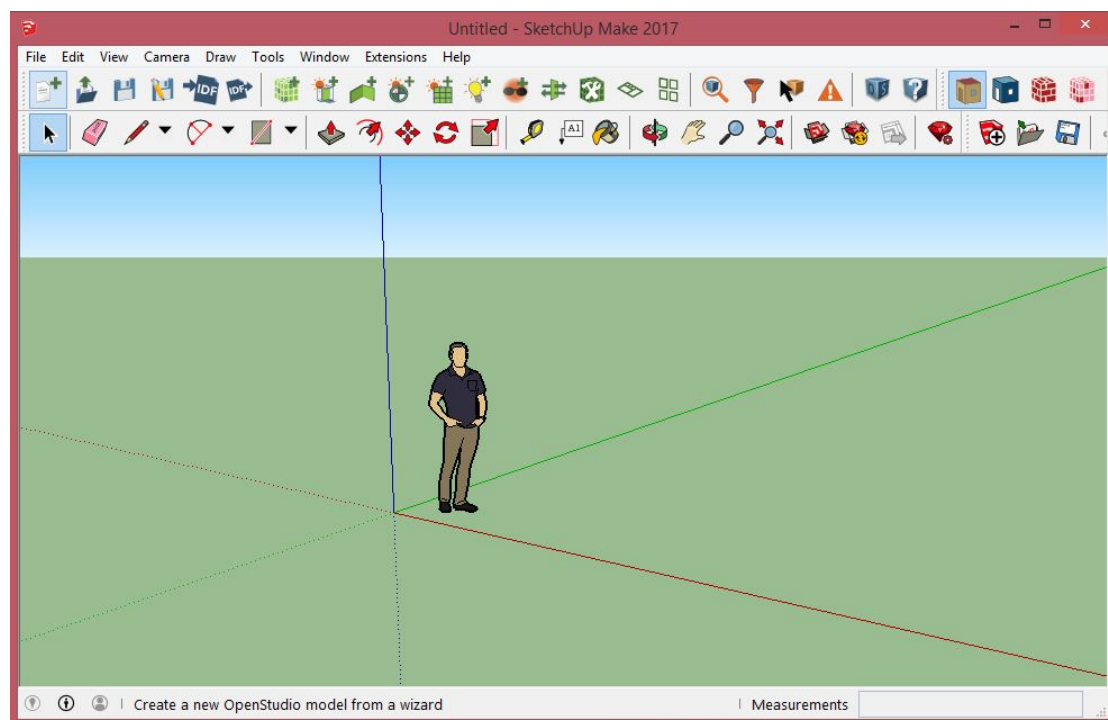
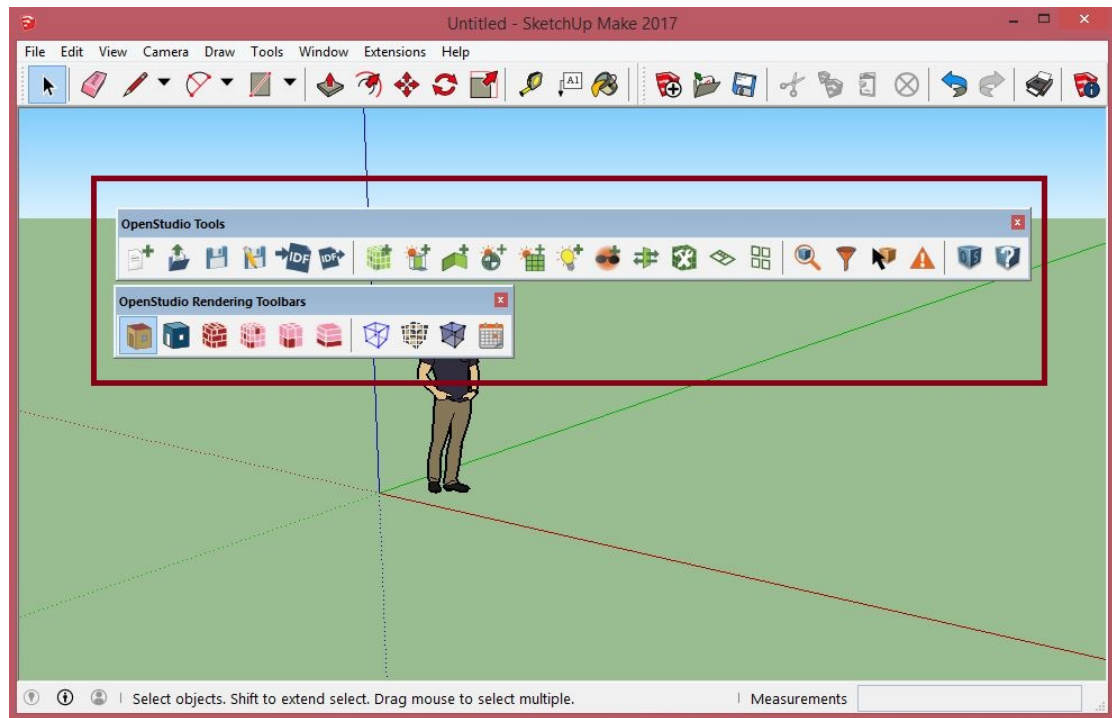


Figure 22 – SketchUp workspace

#### 4.1.2. Create a simulation model using the OpenStudio tool

The Plugin OpenStudio version 2.3.0 is used to create the geometric model of the building as well as the physical description of its shell. OpenStudio is a free application that when designing geometry into SketchUp translates data into input variables for EnergyPlus™. There is the possibility of creating a complete model with electromechanical equipment, lighting and determining the use of spaces. Also, some simple air-conditioning systems can be simulated. Figure 23 shows the OpenStudio Plug-in toolbars.

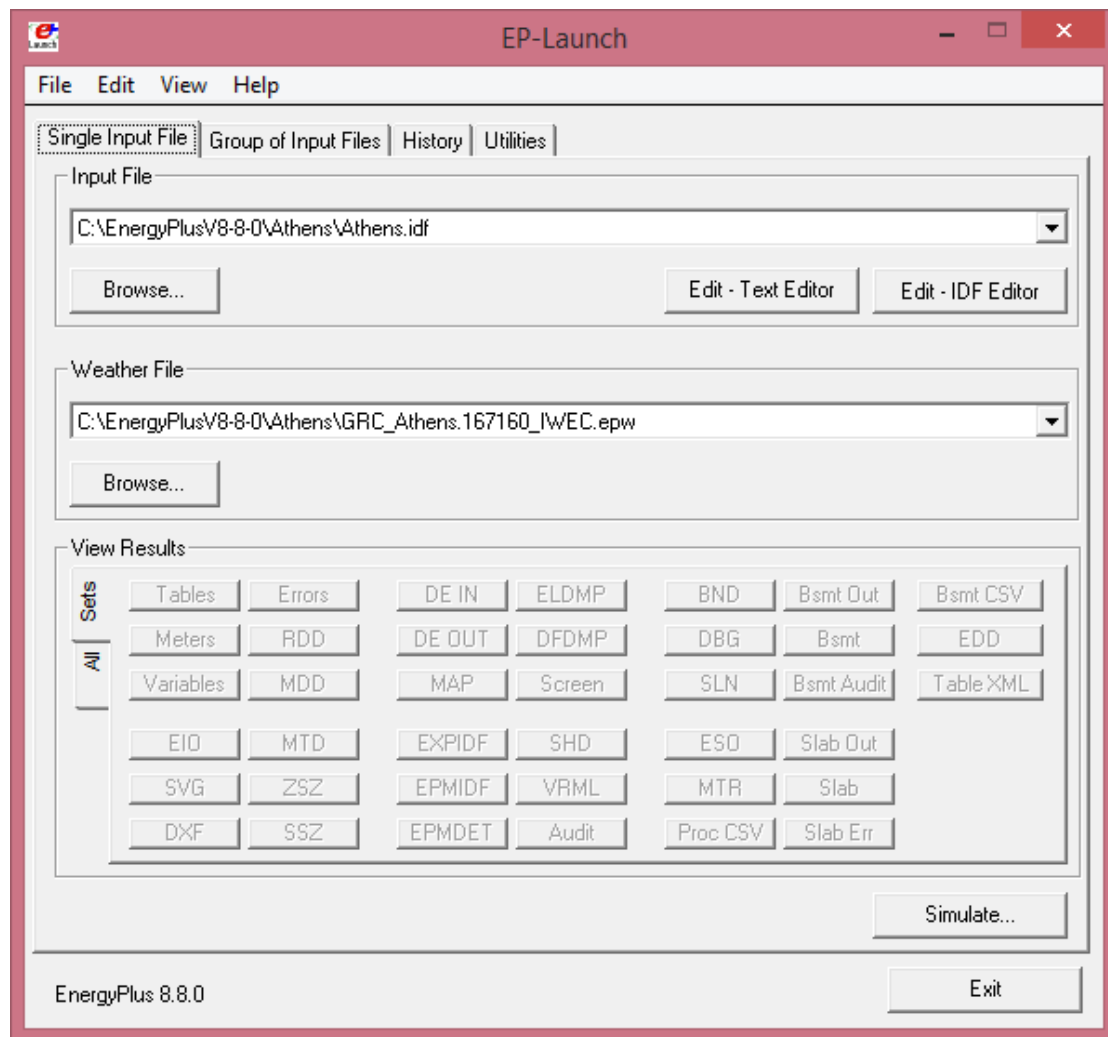


**Figure 23 – OpenStudio Plug-in toolbars**

## 4.2. Simulation in EnergyPlus™

In this study version 8.8.0 of the program is used. The simulation process in EnergyPlus includes the following steps:

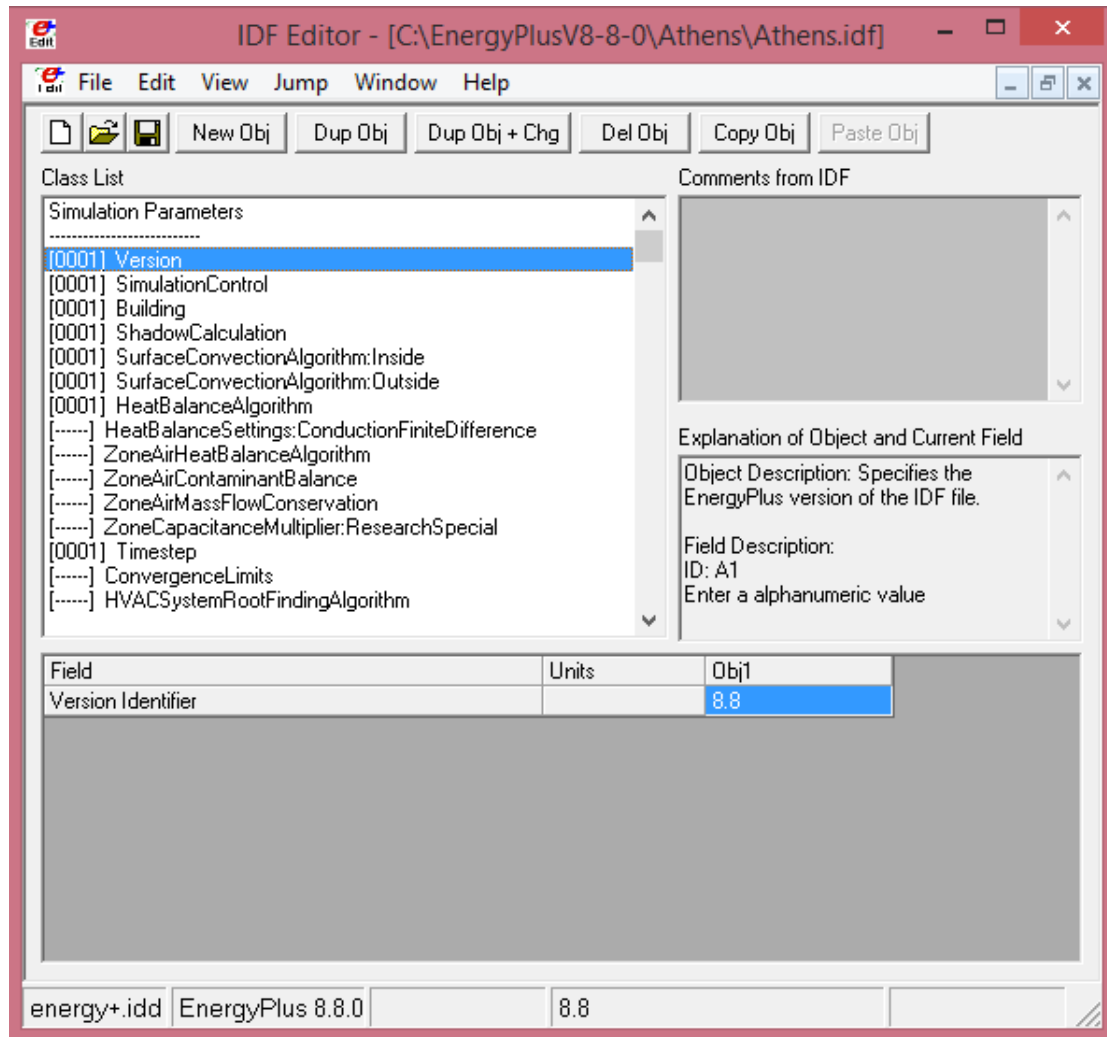
- Importing a climatic file into EP-Launch, the program that collects the independent external files to perform a simulation, Figure 24.



**Figure 24 – EnergyPlus, EP Launch – Main Window**

- Data input to IDF-Editor, the EnergyPlus data input form, Figure 25. In detail, the inputs are:
  - 1) Layout of the model and definition of external factors of the location and location of the building, such as orientation, description of the relief of the surrounding area.
  - 2) Enter data that fully describes the building model geometrically and physically. Full dimensioning of all surfaces, their orientation, thermo-physical properties of building materials of building elements and assembly of each building element on each surface.
  - 3) Separation of thermal zones of the building.
  - 4) Description of functions and use of each thermal zone by setting the operating hours and description of internal loads.
  - 5) Introduction of design conditions, such as thermostatic settings, ventilation conditions, etc.
  - 6) Determination and application of air conditioning systems models that serve the building.

- 7) Selection of simulation models for various calculations.
- 8) Selection of desired data and output files.



**Figure 25 – EnergyPlus, IDF Editor – Design Platform**

- Select in EP-Launch any other file involved in the simulation, e.g. temperature data file for underground spaces.
- Start Simulation

Simulation results are outputted into a series of files, among them .html, .csv, .txt files, as well as design and display files of the building or its components, the choice of type and number is left to the user. Further processing and extraction of conclusions from the output files takes place in other programs, such as EP-Compare for instant display of the results in a chart or spreadsheet type for drawing graphs etc.

## Chapter 5 Simulation of a Greek two storey detached house

### 5.1. Location and description of the building in study

The building that is chosen for the simulation study of its heating and cooling loads is a Greek two storey detached house of total area 128.57 m<sup>2</sup>, which does not truly exist and it is not autonomous, but simulates a typical building that can be used for tourist purposes. On the website of EnergyPlus™, are stored records of climate measurements from various regions of the world, there are no climatic data for all the cities of Greece, except Athens (N37°54', E23°43'), Thessaloniki (N40°31', E22°58') and Andravida (N37°55', E21°16'). Andravida is a town and a former municipality in Elis, in the northwest of the Peloponnese peninsula of Greece, at about 7 km from the Ionian Sea coast. Athens is the capital and largest city of Greece. Athens sprawls across the central plain of Attica that is often referred to as the Athens or Attica Basin. The basin is bounded by four large mountains: Mount Aigaleo to the west, Mount Parnitha to the north, Mount Pentelicus to the northeast and Mount Hymettus to the east. Thessaloniki is the second largest city in Greece, which lies on the northern fringe of the Thermaic Gulf on its eastern coast and is bound by Mount Chortiatis on its southeast. So, because the creation of a climate data record is time-consuming and requires knowledge that is not subject of my studies, it was decided to design a non-existing building which, in theory, could be located in any of the three Greek cities for which there are already climate records.

The shape chosen for the building is generally rectangular, with its main axis being developed in the North-South direction, while the distribution of the main use spaces is made on two floors. This building consists of a ground and a first floor. On the ground floor of the building, there is single space of total area 38.89 m<sup>2</sup>, which is used as living room and a staircase leading to the upper floor, a kitchen room 20.01 m<sup>2</sup> and a storage area of 4.87 m<sup>2</sup>. On the first floor there are three bedrooms of area space 16.38 m<sup>2</sup>, 16.51 m<sup>2</sup> and 12.51 m<sup>2</sup>, respectively. There, also, are a bathroom of 5.6 m<sup>2</sup> and a WC of 3.8 m<sup>2</sup>. All rooms are connected with each other by a corridor of total area 10 m<sup>2</sup>. The total space area of the house is 128.57 m<sup>2</sup> without balconies and outdoors areas. Table 4 presents the geometric data (altitude, surface, etc.) of the floors.

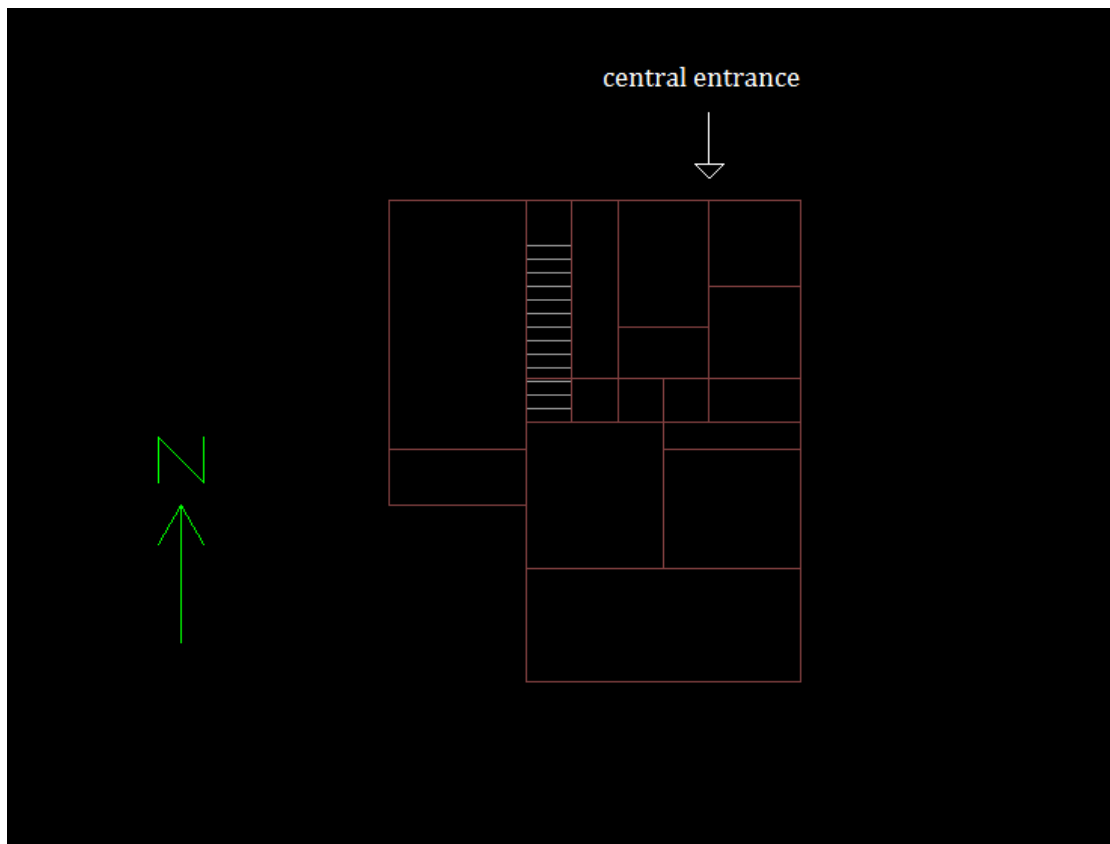
Floor	Altitude (m)	Surface (m <sup>2</sup> )	Mass (m <sup>3</sup> )	Balconies (m <sup>2</sup> )
Ground	3	63.77	191.31	41.26
First	3	64.8	194.4	40.23

Table 4 – Geometric data of floors

As far as the horizontal distribution of spaces is concerned, it develops into functional zones, with kitchen, living room and bedrooms - i.e. areas with higher heating needs - occupying the south side of the building, while utility rooms, such as bathrooms, corridor and storage, were placed on the north side, so as to act as a diaphragm between the main use areas and the cold northern side of the building.

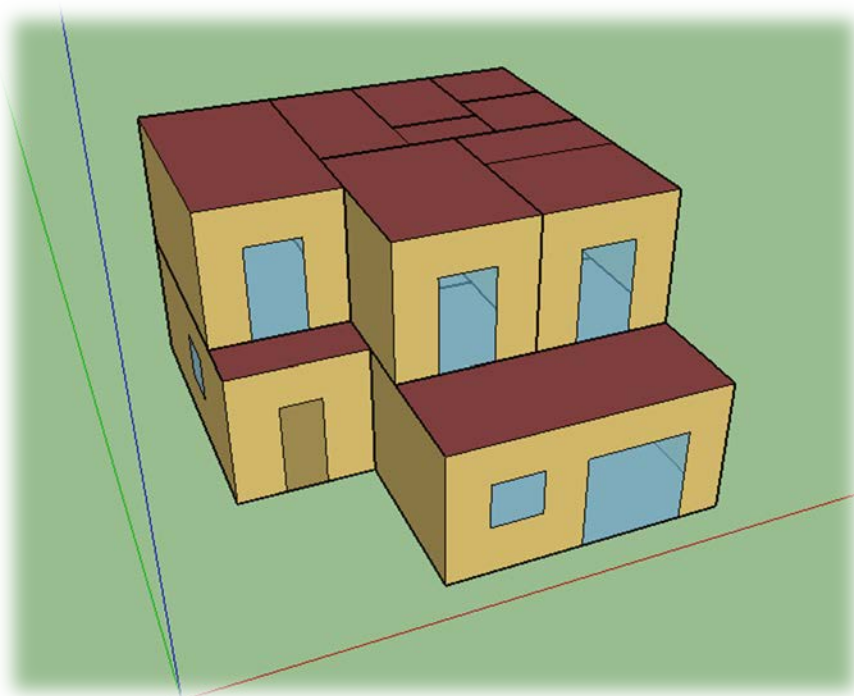
In order to exploit better the solar radiation, openings were selected to meet the requirements of direct profit systems. Specifically, the most and largest openings were placed in the South, in the West and in the East, openings were used to a very limited extent, while in the North were placed small openings in the shell of the stairway, and bathrooms.

Using the Google Sketch Up extension on Energy Plus, the building's simulation was simulated. Thus, the nine thermal zones were created in three-dimensional imaging. For each element of the zone, both the type (wall, floor, roof, door, or window) and its construction (external, intermediate masonry, flooring or masonry on natural ground, roof, etc.) were declared. The central entrance of the building is looking at the north as shown in Figure 26. Its views are shown in Figure 27 and Figure 28.

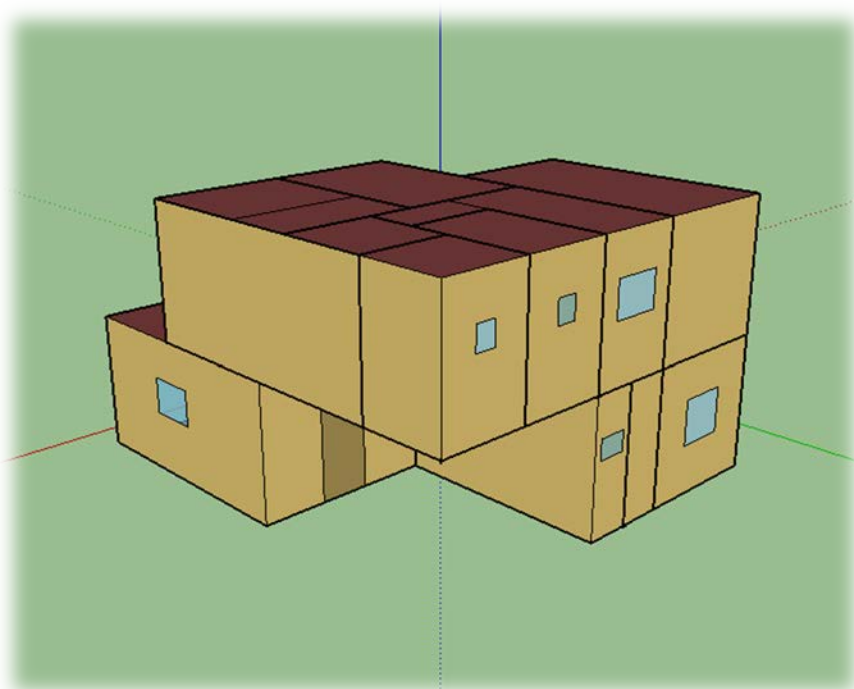


**Figure 26 – Building's top view and orientation using DeepView**





**Figure 27 – Three – dimensional representation of the thermal zones of the building – Southwest view**



**Figure 28 – Three – dimensional representation of the thermal zones of the building – Northeast view**

## 5.2. Definition of thermal zones to simulate the building

Separating buildings in thermal zones is an important part of their energy design and reasonable use of energy, which involves two levels: architectural design based on energy criteria (e.g. bioclimatic design) and design and operation of mechanical heating/ cooling systems.

In the present study the separation of building into thermal zones was determined according to rules and criteria of TEE (Technical Chamber of Greece).

A thermal zone is defined as a space with similar use, same operational profile and common electromechanical systems. In the process of separating a building in thermal zones, the number of separate zones is as low as possible due to input and computational time economy. In addition, a general rule to be followed is that parts of the building with a volume of less than 10% of its total volume should not be considered as autonomous thermal zones but be included in other thermal zones even if their operating conditions justify their consideration as independent zones [16].

Additionally, there are some additional criteria according to which some study section is good to be taken as a separate thermal zone in a building. In particular, a separate thermal zone must be obtained:

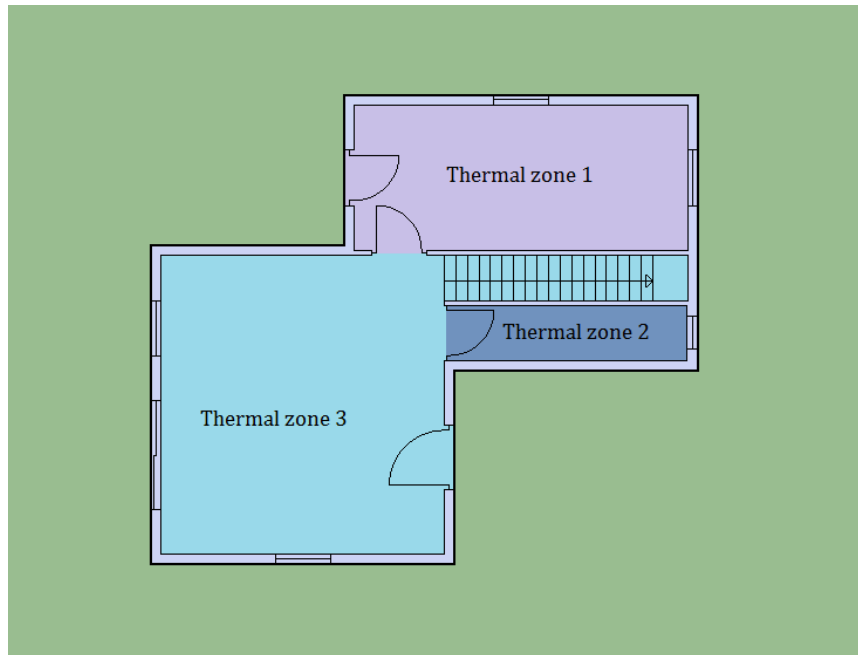
- When the indoor temperature is higher by 4 ° C than the temperature in other parts of the building during both summer and winter periods.
- When there are spaces with different uses, because the use in different parts changes, the internal design conditions, such as temperature, relative humidity and fresh air, change.
- When there are different heating and cooling systems if different internal conditions arise.
- When there are segments that show large differences in energy losses or gains (e.g. solar, thermal) compared to the rest of the building.
- Where there are spaces where the ventilation system (air conditioning or air-conditioning) covers less than 80% of the surface area [16].

Due to the relatively small size of the building, each space where different heat and usage transfer elements were simulated as a different zone. Although the same comfort conditions throughout the building is willing, it can be easily observed that because of the construction, as well as, the morphology of the ground that there are parts of the building that are bordered to the ground (e.g. ground floor's floor) or have many free surfaces.

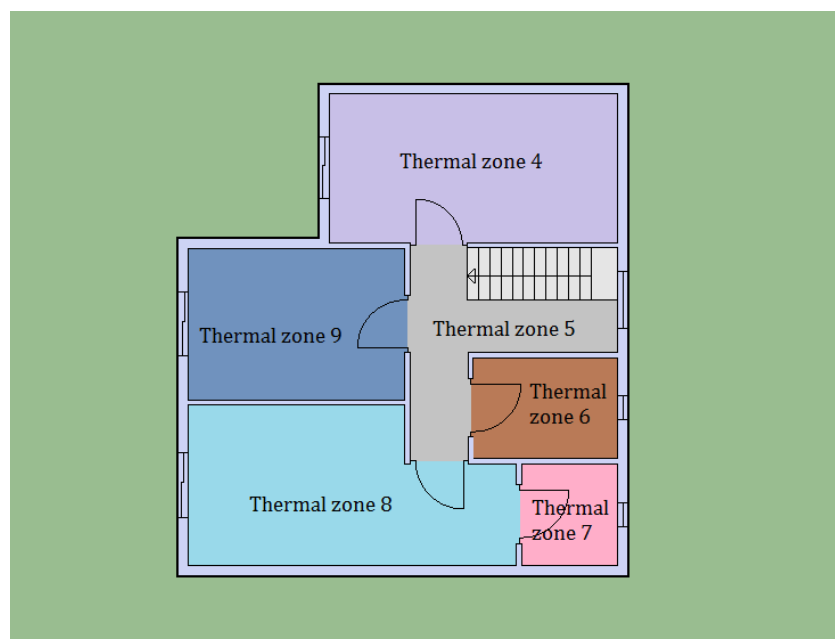
According to these data, the building is divided into nine autonomous thermal zones. According to the above criteria, each floor is divided into a different number of thermal zones according to the profile of solar gains, the orientation, the use of the space and the surface to which they are bound (air, ground etc.). More specifically, the ground floor is divided into three thermal zones, which include a thermal zone for the living room, a thermal zone for the kitchen and a thermal zone for the storage area. While, the first floor is divided in five thermal zones, which include a thermal zone for each one of the three bedrooms, a

thermal zone for the bathroom, a thermal zone for the WC and, lastly, a thermal zone for the corridor.

The aim was to clarify the results of the simulation and the ability to control the internal loads or operating conditions in each space independently of the rest. All thermal zones are considered to be heated or cooled except the storage area and the WC, which are the least used and therefore they have very small requirements. Following, are floor plans of the building showing the separation of spaces in thermal zones, Figure 29 and Figure 30.



**Figure 29 – Top view of the ground floor showing the different thermal zones**



**Figure 30 – Top view of first floor showing the different thermal zones**

### 5.3. Construction elements, materials and layers

The building under study can be considered as whole made of reinforced concrete, while the filling elements consist of double utility perforated bricks of masonry. The building is insulated, the insulation being inside the filling elements, while covering the bearing structure externally. In this study was made the convention that outer shell of the building was entirely made of the filling wall. The roof of the first floor is assumed to be fully insulated, as well as ground floor. Intermediate bearing elements, ground-floor's roof and first-floor's floor are considered to be completely non-insulated. Both on ground and first floor, masonry between rooms is single brickwork without insulation.

Composition of the exterior and interior surfaces of the building is fully defined i.e. the materials with which the walls, floors, ceilings, doors and windows are made of are described in detail. As outer layer we define the layer furthest from the zone in which the structure is located, while the last layer of material defined is also the adjacent to the zone. A full description each structural element and material layers used in the house is given on Table 5 – Table 11, below.

Properties of the materials were taken from T.O.T.E.E. 20701- 2/2017 tables, while calculations for the coefficient of thermal conductivity of construction elements and limits of the permitted coefficient refer to the use of Building Thermal Insulation Regulation (Government Gazette 2367B/ 12-7-2017), if the building is to meet the conditions of this regulation.

Construction element: Outdoor double utility masonry					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
Inside -> outside	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	d (m)	$\lambda$ (W/mK)	$R_i = d / \lambda$ (m <sup>2</sup> K/W)
Plastic paint		1050	0	0.200	0
Plaster	1000	1800	0.015	0.870	0.017
Perforated brickwork	1000	1200	0.090	0.450	0.200
Extruded polystyrene	1450	30	0.040	0.031	1.290
Perforated brickwork	1000	1200	0.090	0.450	0.200
Plaster	1000	1800	0.015	0.870	0.017
Plastic paint		1050	0	0.200	0
Density $\Sigma d$ (m)			0.250		
Thermal Resistance Evaporation				R (m <sup>2</sup> K/W)	1.724
Periodicity coefficient of construction element				U (W/m <sup>2</sup> K)	0.580
Maximum allowed periodicity coefficient (Zone B)				U <sub>max</sub> (W/m <sup>2</sup> K)	0.900

Table 5 – Characteristic properties of exterior masonry of the building materials

Construction element: Indoor single utility masonry					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
Inside -> outside	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	d (m)	$\lambda$ (W/mK)	$R_i$ (m <sup>2</sup> K/W)
Plaster	1000	1800	0.015	0.870	0.017
Perforated brickwork	1000	1200	0.09	0.450	0.200
Plaster	1000	1800	0.015	0.870	0.017
Density $\Sigma_d$ (m)			0.251		
Thermal resistance evaporation *				R (m <sup>2</sup> K/W)	0.234

**Table 6 – Characteristic properties of interior masonry materials with brickwork**

\* The coefficient of thermal conductivity of structural element is not calculated if it is between thermal zones of the same or similar temperature.

Construction element: Floor on natural soil					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
Inside -> outside	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	d (m)	$\lambda$ (W/mK)	$R_i$ (m <sup>2</sup> K/W)
Ceramic tile flooring	840	2000	0.015	1.840	0.008
Cement mortar	1100	2000	0.010	1.400	0.007
Adhesive bonding	1000	1200	0.070	0.460	0.152
Extruded polystyrene	1450	30	0.040	0.031	1.290
Reinforced concrete	1000	2400	0.150	2.000	0.075
Density $\Sigma_d$ (m)			0.285		
Thermal Resistance Evaporation				R (m <sup>2</sup> K/W)	1.532
Periodicity coefficient of construction element				U (W/m <sup>2</sup> K)	0.652
Maximum allowed periodicity coefficient (Zone B)				$U_{max}$ (W/m <sup>2</sup> K)	0.900

**Table 7 – Characteristic properties of flooring on the natural soil**

Construction element: Intermediate floor					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	d (m)	$\lambda$ (W/mK)	$R_i$ (m <sup>2</sup> K/W)
Ceramic tile flooring	840	2000	0.015	1.840	0.008
Cement mortar	1100	2000	0.030	1.400	0.021
Reinforced concrete	1000	2400	0.150	2.000	0.075
Plaster	1000	1800	0.015	0.870	0.017
Density $\Sigma_d$ (m)			0.210		
Thermal resistance evaporation *				R (m <sup>2</sup> K/W)	0.121

**Table 8 – Characteristic properties of intermediate flooring materials**

\* The coefficient of thermal conductivity of structural element is not calculated if it is between thermal zones of the same or similar temperature.

Construction element: Roof					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
Inside -> outside	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	d (m)	$\lambda$ (W/mK)	$R_i$ (m <sup>2</sup> K/W)
Plaster	1000	1800	0.015	0.870	0.017
Reinforced concrete	1000	2400	0.150	2.000	0.075
Extruded polystyrene	1450	30	0.060	0.031	1.935
Cement mortar	1100	2000	0.030	1.400	0.021
Density $\Sigma_d$ (m)			0.255		
Thermal Resistance Evaporation				R (m <sup>2</sup> K/W)	2.048
Periodicity coefficient of construction element				U (W/m <sup>2</sup> K)	0.488
Maximum allowed periodicity coefficient (Zone B)				$U_{max}$ (W/m <sup>2</sup> K)	0.800

**Table 9 – Characteristic properties of roof materials**

The building in study has eight double-glazed exterior windows, including air. Also, it has two wooden front doors and five balcony doors. Finally, all interior doors are considered wooden.

Construction element: Transparent exterior openings		
Construction material	Thermo periodicity $U$ (W/m <sup>2</sup> K)	Solar radiation crossing
Double glazed pane 12mm with metal frame	3.200	0.530

**Table 10 – Characteristic properties of transparent exterior aperture materials**

Construction element: Opaque openings					
Construction material	Heat capacity	Density	Thickness	Thermal conductivity	Thermal resistance
Inside -> outside	$C_p$ (J/kgK)	$\rho$ (kg/m <sup>3</sup> )	$d$ (m)	$\lambda$ (W/mK)	$R_i$ (m <sup>2</sup> K/W)
Wooden door	1630	608	0.025	0.150	0.167
Density $\Sigma_d$ (m)			0.025		
Thermal Resistance Evaporation				$R$ (m <sup>2</sup> K/W)	0.167
Periodicity coefficient of construction element				$U$ (W/m <sup>2</sup> K)	5.988

**Table 11 – Characteristic properties of opaque openings**

#### 5.4. Climate data

The external environment of the building is represented in the simulation using the area's climate record. Climate data records cover both a typical climatic year and specific standard design days (extreme climatic data) to calculate the maximum loads (design loads) which are used in the design of the various HVAC systems (boilers, burners, heat pumps) as well as secondary equipment (pumps, fans). They, also, contain information on various parameters of the area under consideration, such as hourly temperature, hourly humidity, hourly wind speed and direction, hourly atmospheric pressure and hourly solar radiation.

The climate records are IWECC (International Weather for Energy Calculation) and is the result of the ASHRAE Research Project 1015 executed by the ASHRAE Technical Committee 4.2. The creation of the IWECC files took place in two stages. First, 18-year climatic data was collected from the National Climatic Data Center, Asheville, NC. Then these data were processed and twelve typical meteorological months emerged through which the IWECC climatic records were created.

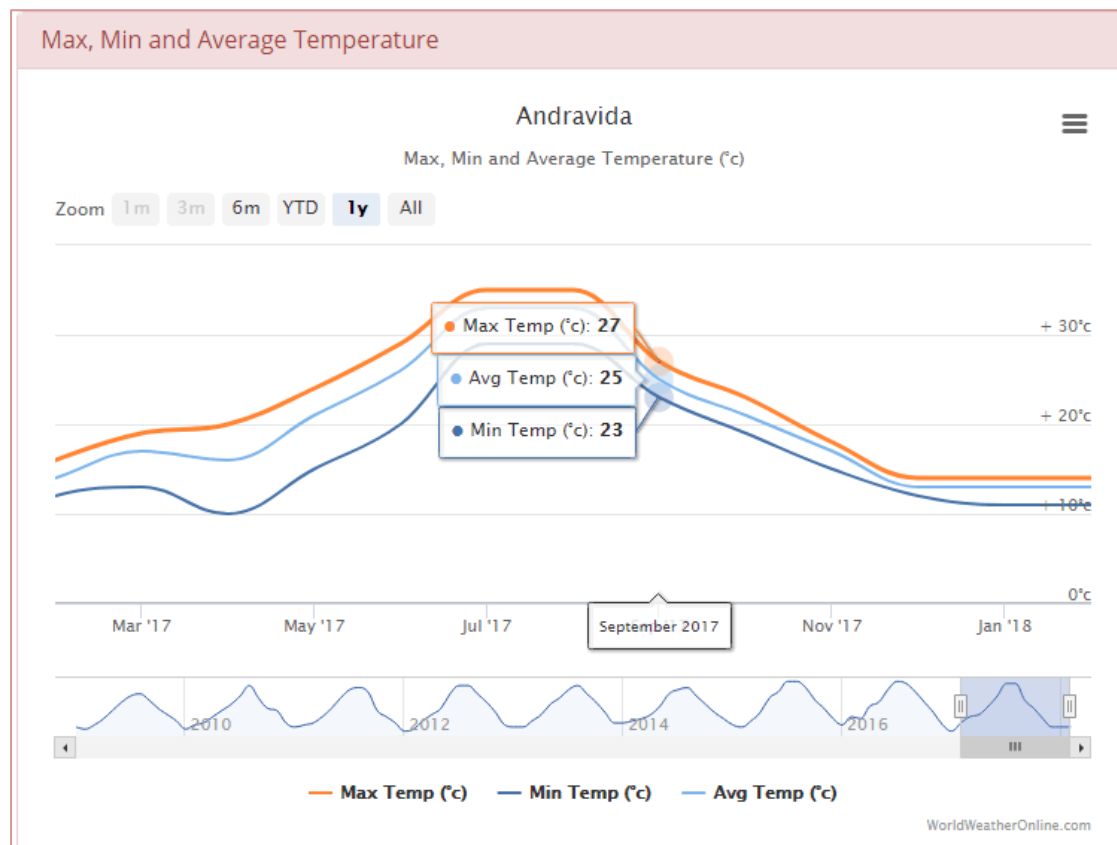
As has already been mentioned, Energy Plus has climate records of many cities at a global level, which have resulted from measurements of meteorological stations in different areas. For Greece, there are stored records of climate measurements in the areas of Athens, Thessaloniki and Andravida. For this study, the building was placed in all three cities.

### Case 1: Andravida

The file data recorded in Andravida's meteorological station, Table 12, while the characteristic values for the area are shown in Table 13.

Location	Andravida
Latitude	N 37° 55'
Longitude	E 21° 16'
Elevation	12m above sea level
Air pressure	101181Pa

**Table 12 – Characteristics of meteorological station of Andravida [34]**



**Figure 31 – Max, min and average temperatures of Andravida during a whole year [32]**



Month	Dry bulb temp.( °C)	Wet bulb temp.( °C)	Dew point temp.( °C)	Wind speed (m/s)	Win d dir.	Groun d temp. (°C)	Diffuse solar rad. (W/m <sup>2</sup> )	Direct solar rad. (W/m <sup>2</sup> )
January	8.3	5.8	6.4	1	N	12.8	51.87	72.62
February	9.2	6.1	6.3	4	N	10.5	71.25	167.17
March	10.9	6.5	7	3.9	N	9.9	95.5	177.37
April	12.4	6.3	9.6	3	N	10.4	113.20	143.91
May	13.3	5.9	12.5	2.2	N	13.6	117.79	147.45
June	13.4	5.9	15.5	1.9	N	17.1	113.04	139.75
July	13.4	6.0	18.0	3.3	N	20.3	97.20	178.70
August	13.7	5.9	16.8	3.9	N	22.7	89.83	193.20
September	12.5	5.9	15.0	1.8	N	23.4	88.33	127
October	12.0	6.1	12.8	2.7	N	22.3	74.79	132.54
November	9.8	5.9	9.7	3.1	N	19.6	55.83	131.33
December	8.3	5.8	8.0	2.4	N	16.2	40.75	91.29

**Table 13 – Average monthly values of climate variables characteristic of Andravida [34]**

Finally, the climate record with a can provide valuable statistics on the general description of the area to which it relates. The following information has emerged from Adravida's climate record, which gives a stigma for the seasonal change in temperature in the area, Table 14.

<b>Coolest month</b>	January
<b>Hottest month</b>	August
<b>Summer period</b>	July - September
<b>Extreme hot weak</b>	12 – 18 August, $T_{\max} = 36.8^{\circ}\text{C}$
<b>Typical summer week</b>	5 – 11 August, $T_{\text{average}} = 23.85^{\circ}\text{C}$
<b>Autumn period</b>	October - December
<b>Typical autumn week</b>	12 – 18 November, $T_{\text{average}} = 14.21^{\circ}\text{C}$
<b>Winter period</b>	January - March
<b>Extreme cold weak</b>	15 – 21 January, $T_{\min} = -1.8^{\circ}\text{C}$
<b>Typical winter week</b>	12 – 18 March, $T_{\text{average}} = 10.27^{\circ}\text{C}$
<b>Spring period</b>	April - June
<b>Typical spring week</b>	6 – 12 May, $T_{\text{average}} = 18.34^{\circ}\text{C}$

**Table 14 Determination of seasons and extremes periods for Andravida [34]**

## Case 2: Athens

The file data recorded in Athens's meteorological station, Table 15, while the characteristic values for the area are shown in Table 16.

Location	Athens
Latitude	N 37° 54'
Longitude	E 23° 43'
Elevation	15m above sea level
Air pressure	101145Pa

Table 15 – Characteristics of meteorological station of Athens [34]

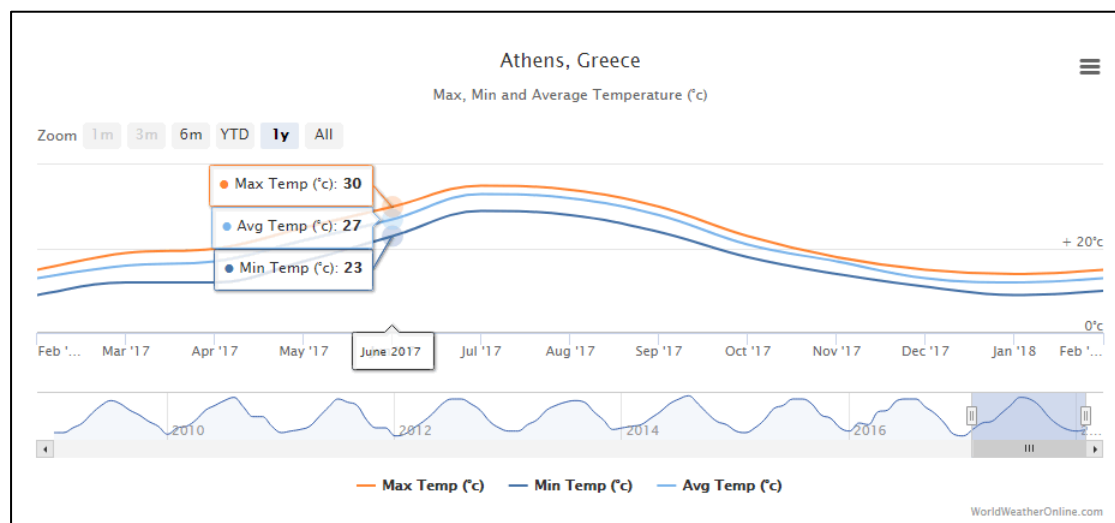


Figure 32 – Max, min and average temperatures of Athens during a whole year [32]

Month	Dry bulb temp.( °C)	Wet bulb temp.( °C)	Dew point temp.( °C)	Wind speed (m/s)	Win d dir.	Groun d temp. (°C)	Diffuse solar rad. (W/m <sup>2</sup> )	Direct solar rad. (W/m <sup>2</sup> )
January	6.8	4.9	4.7	3.3	N	9.7	45.62	86.16
February	7.9	5.4	3.6	3.7	N	11.3	65.7	117.37
March	8.6	5.4	5	3.6	N	14.2	83.75	167.12
April	9	5.1	7.2	2.7	N	17.1	101.91	214.29
May	10.3	5.1	11.9	2.9	N	22.4	111.66	258.95
June	10.3	4.8	12.8	3.7	N	25.2	102.41	311.62
July	10.5	4.9	15.5	3.2	N	26	90.04	313.70
August	10.2	4.8	15.9	3	N	24.6	88.95	276.5
September	9.5	5.4	14.3	3.1	N	21.3	75.75	225.87

Month	Dry bulb temp.( °C)	Wet bulb temp.( °C)	Dew point temp.( °C)	Wind speed (m/s)	Win d dir.	Groun d temp.( °C)	Diffuse solar rad. (W/m <sup>2</sup> )	Direct solar rad. (W/m <sup>2</sup> )
October	8.3	5	12.2	3.2	N	17.2	69.66	146.75
November	7.1	4.7	9.2	3.1	N	13.1	52.62	89.29
December	6.2	4.7	5.1	2.6	N	10.5	43.04	75.37

**Table 16 – Average monthly values of climate variables characteristic of Athens [34]**

Finally, the climate record with a can provide valuable statistics on the general description of the area to which it relates. The following information has emerged from Athens' climate record, which gives a stigma for the seasonal change in temperature in the area, Table 17.

<b>Coolest month</b>	<b>February</b>
<b>Hottest month</b>	<b>August</b>
<b>Summer period</b>	June - August
<b>Extreme hot weak</b>	3 – 9 August, $T_{\max} = 37.2^{\circ}\text{C}$
<b>Typical summer week</b>	29 June – 5 July, $T_{\text{average}} = 26.52^{\circ}\text{C}$
<b>Autumn period</b>	September - November
<b>Typical autumn week</b>	13 – 19 October, $T_{\text{average}} = 19.18^{\circ}\text{C}$
<b>Winter period</b>	December - February
<b>Extreme cold weak</b>	17 – 23 February, $T_{\min} = 2^{\circ}\text{C}$
<b>Typical winter week</b>	13 – 19 January, $T_{\text{average}} = 10.41^{\circ}\text{C}$
<b>Spring period</b>	March – May
<b>Typical spring week</b>	5 – 11 April, $T_{\text{average}} = 15.3^{\circ}\text{C}$

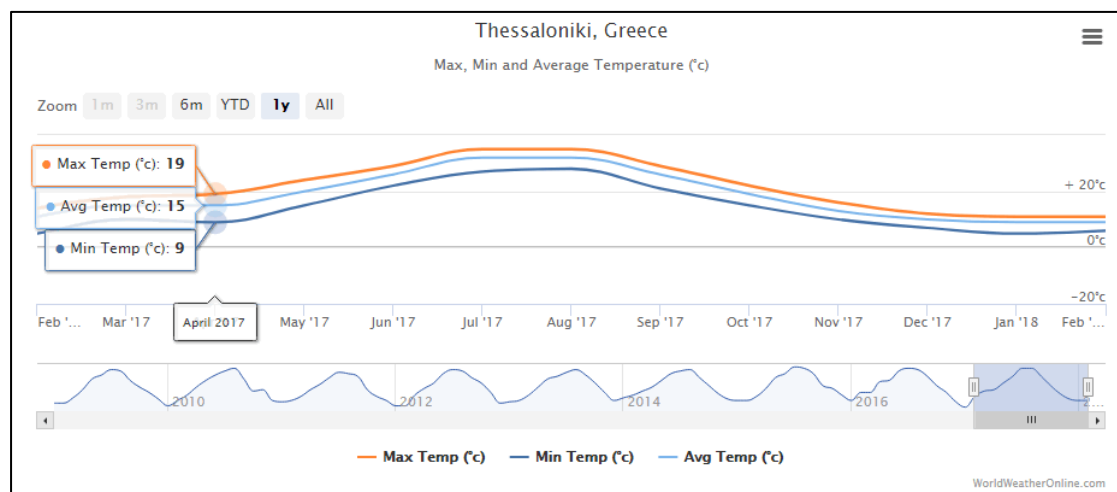
**Table 17 – Determination of seasons and extremes periods for Athens [34]**

### **Case 3: Thessaloniki**

The file data recorded in Thessaloniki's meteorological station, Table 18, while the characteristic values for the area are shown in Table 19.

<b>Location</b>	<b>Thessaloniki</b>
<b>Latitude</b>	N 40° 31'
<b>Longitude</b>	E 22° 58'
<b>Elevation</b>	4m above sea level
<b>Air pressure</b>	101277Pa

**Table 18 – Characteristics of meteorological station of Thessaloniki [34]**



**Figure 33 – Max, min and average temperatures of Athens during a whole year [32]**

Month	Dry bulb temp.( °C)	Wet bulb temp.( °C)	Dew point temp.( °C)	Wind speed (m/s)	Win d dir.	Groun d temp. (°C)	Diffuse solar rad. (W/m <sup>2</sup> )	Direct solar rad. (W/m <sup>2</sup> )
January	9.5	6.8	2.2	2.8	N	10.3	39.54	86.37
February	11.0	7.2	1.1	3.6	N	7.3	49.29	158.83
March	12.6	7.5	1.1	3.4	N	6.5	92.52	125.70
April	13.1	7.1	7.2	2.6	N	7.2	105.73	142.54
May	13.3	6.4	10	3.5	N	11.3	120.43	181
June	13.0	6.0	12.7	3.8	N	15.9	120.73	229.70
July	13.2	6.4	15.3	3.4	N	20.2	101.17	256.29
August	12.6	6.2	15.9	2.8	N	23.3	94.86	230.70
September	12.6	6.6	14.1	2.6	N	24.2	87	179.04
October	11.1	6.4	11.2	2.8	N	22.8	60.45	132.70
November	9	6.1	5.5	2.7	N	19.2	44.54	90.62
December	8.7	6.2	4.3	3.4	N	14.8	38.29	67.70

**Table 19 – Average monthly values of climate variables characteristic of Thessaloniki [34]**

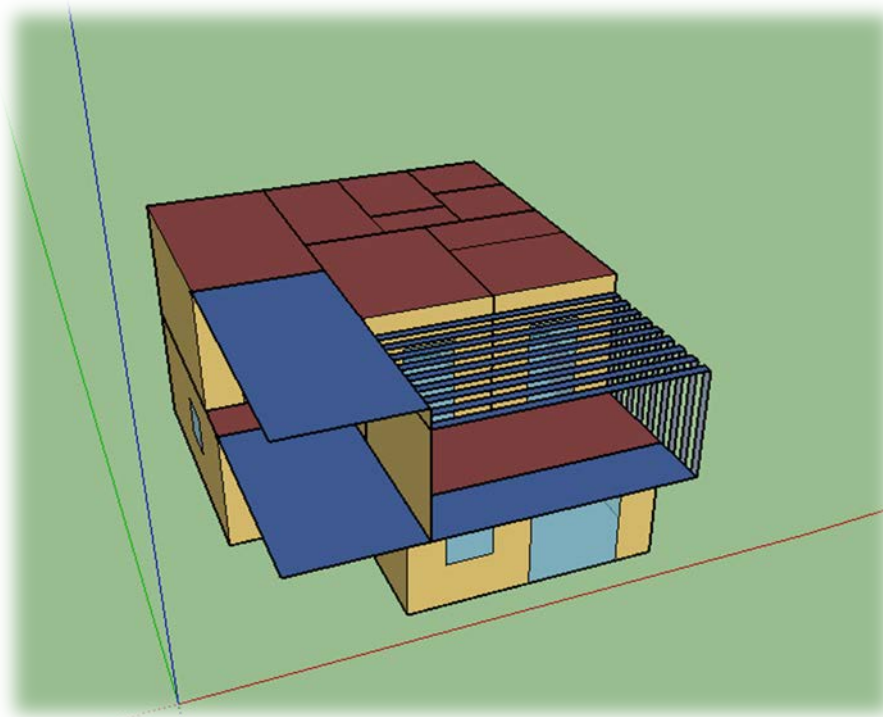
Finally, the climate record with a can provide valuable statistics on the general description of the area to which it relates. The following information has emerged from Thessaloniki's climate record, which gives a stigma for the seasonal change in temperature in the area, Table 20.

<b>Coolest month</b>	January
<b>Hottest month</b>	July
<b>Summer period</b>	May - July
<b>Extreme hot weak</b>	17 – 23 July, $T_{\max} = 34.8^{\circ}\text{C}$
<b>Typical summer week</b>	22 – 28 May, $T_{\text{average}} = 22.51^{\circ}\text{C}$
<b>Autumn period</b>	August - October
<b>Typical autumn week</b>	12 – 18 September, $T_{\text{average}} = 20.89^{\circ}\text{C}$
<b>Winter period</b>	November - January
<b>Extreme cold weak</b>	11 – 17 January, $T_{\min} = -2^{\circ}\text{C}$
<b>Typical winter weak</b>	29 November – 5 December, $T_{\text{average}} = 8.17^{\circ}\text{C}$
<b>Spring period</b>	February - April
<b>Typical spring weak</b>	1 – 7 March, $T_{\text{average}} = 9.84^{\circ}\text{C}$

**Table 20 – Determination of seasons and extremes periods for Thessaloniki [34]**

### **5.5. Shadowing of the building**

The shadowing of the exterior surfaces of the building is accomplished by two type obstacles. The first one is neighboring buildings that are shading some surfaces, mainly on the ground floor, of the building under study at certain times of the day. In addition, shadowing from the upper floors, mainly the ground floor and the first floor, are shaded by the first and second floor terraces respectively. For the first case of neighboring buildings, it was deliberately not taken into account the shadows to the surfaces of the building under study, mainly due to lack of data. Shading from the upper floors is represented in the Google SketchUp model with horizontal projections and calculated by Energy Plus during the year – round simulations. Figure 34, above, shows the Google SketchUp model's shadowing projects for the building in study.



**Figure 34 – Illustration of shadowing on the southwest view**

## **5.6. Use and operation of the building**

The building in study is described as a residential building and we assume that there is a family of four people (two parents and two children). Operating hours of HVAC system and the use by the inhabitants of the building define both the burden of the space with internal loads and the design conditions to be applied in order to calculate the heating and cooling loads.

### **Assumptions:**

- One of the parents has a full-time job (09:00 – 17:00 on Mondays to Fridays) while the other parent works part-time (09:30 – 13:30 on Mondays to Fridays and 11:00 – 15:00 on Saturdays), so he keeps children when they are at home.
- Children go to school 08:00 – 14:00 on Mondays to Fridays.
- Nobody is at home between 09:30 – 14:00.
- Children may have extracurricular activities in the afternoons 17:00 – 19:00 on Mondays to Fridays, while they may hang out with their friends at the weekends 18:00 – 20:00.
- Possible hours of active presence in the house: 06:00 – 09:30 and 14:00 – 24:00 on Mondays – Fridays and 08:00 – 24:00 at the weekends.

### 5.6.2. Schedules

EnergyPlus enables the user to set the time schedules for the time change of various parameters that affect the thermal behavior of the building. This category describes the change of parameters such as lighting, the activity of individuals in the building, the operation of electrical appliances, and the operation of HVAC systems in three stages: daily, weekly and annual description of their changes, as it is mention in detail below. It is mandatory, from the program itself, to include in the schedules all days of the year so that there is no error in the simulation.

In order to simulate the building realistic way, we described different cooling and heating schedules for each one of the conditioned thermal zones, according to time intervals been occupied.

1. **Thermal zone 1: Kitchen:** two different schedules were set. One for the heating operation of HVAC system and one for the cooling operation, as shown in Table 21.

Heating	Monday - Friday	06:30 – 08:50, 13:10 – 14:50 and 18:30 – 20:50
	Saturday - Sunday	07:30 – 09:50, 12:30 – 14:00 and 18:40 – 20:50
Cooling	Monday - Friday	13:10 – 14:50 and 18:30 – 20:40
	Saturday - Sunday	12:30 – 14:00 and 19:30 – 21:40

**Table 21 – System availability schedule – Thermal zone 1**

2. **Thermal zone 3: Living room:** again, two different schedules were set. One for the heating operation of HVAC system and one for the cooling operation, as shown in Table 22.

Heating	Monday - Friday	15:30 – 18:30 and 20:30 – 22:30
	Saturday - Sunday	07:30 – 13:00, 15:00 – 18:00 and 20:00 – 22:30
Cooling	Monday - Friday	11:00 – 13:30, 15:30 – 18:30 and 20:30 – 23:30
	Saturday - Sunday	11:00 – 14:00, 18:00 – 20:00 and 21:30 – 23:30

**Table 22 – System availability schedule – Thermal zone 2**

3. **Thermal zones 4 and 9: Kids' bedroom:** also, two different schedules were set. One for the heating operation of HVAC system and one for the cooling operation, as shown in Table 23.

Heating	Monday - Friday	06:00 – 07:30, 14:00 -16:50 and 20:30 – 23:00
	Saturday - Sunday	07:00 – 08:30, 13:20 – 17:30 and 20:30 – 23:00
Cooling	Monday - Friday	13:20 – 16:30 and 21:00 – 24:00
	Saturday - Sunday	13:20 – 15:30 and 21:00 – 24:00

**Table 23 – System availability schedule – Thermal zones 4 and 9**

4. **Thermal zone 6: Bathroom:** for these thermal zone, only heating operation of HVAC system was set, as shown in Table 24.

Heating	Monday - Friday	08:20 – 09:10, 16:40 – 17:30 and 20:30 – 21:40
	Saturday - Sunday	09:20 – 10:10, 16:40 – 17:30 and 20:30 – 21:40

**Table 24 – System availability schedule – Thermal zone 6**

5. **Thermal zone 8: Master bedroom:** again, two different schedules were set. One for the heating operation of HVAC system and one for the cooling operation, as shown in Table 25.

Heating	Monday - Friday	06:00 – 07:30, 14:00 – 15:30 and 21:30 – 24:00
	Saturday - Sunday	07:00 – 08:30, 15:00 – 16:30 and 21:30 – 24:00
Cooling	Monday - Friday	14:00 – 15:30 and 21:00 – 24:00
	Saturday - Sunday	21:00 – 24:00

**Table 25 – System availability schedule – Thermal zone 8**

All above heating schedules were set to operate during months January – April and November – December, while, cooling schedules were set to operate during months May – October.

In addition, the thermostat schedules were set for heating and cooling mode, human presence at home during the day, the operation of electrical appliances and air penetration due to ventilation, as described in paragraphs below.

### 5.6.3. Internal gains

Except the external environmental conditions and the building materials from which it is constructed, also, other factors such as people living and moving in the place, artificial lighting, electrical appliances, gas equipment, hot water supply, etc. have Impact on the energy behavior and thermal consumption of a building.

In the case of our building, the factors contributing to the internal heat gains are people, lighting and electrical equipment. Internal gains only have a meaning for conditioned zones, as unconditioned spaces are scarcely used and hence their internal heat gains are minimal.

- **People**

Here it is defined the internal heat gains of each conditioned thermal zone of the residence, resulting from human activity. Energy Plus has three different calculation methods for this field, where calculation can be made by simply defining the number of persons of the building, or either by entering a value



corresponding to the persons/ area or area/ persons. So, as shown in Figure 35 below, data have been given to describe the category: thermal zone we have set schedule of human number, and activity level schedule. It should be mentioned that the level of human activity was set at 80 Watt / person, and the fraction radiant was set as 0.5 based on the Technical Instructions of the Technical Chamber of Greece. [16]

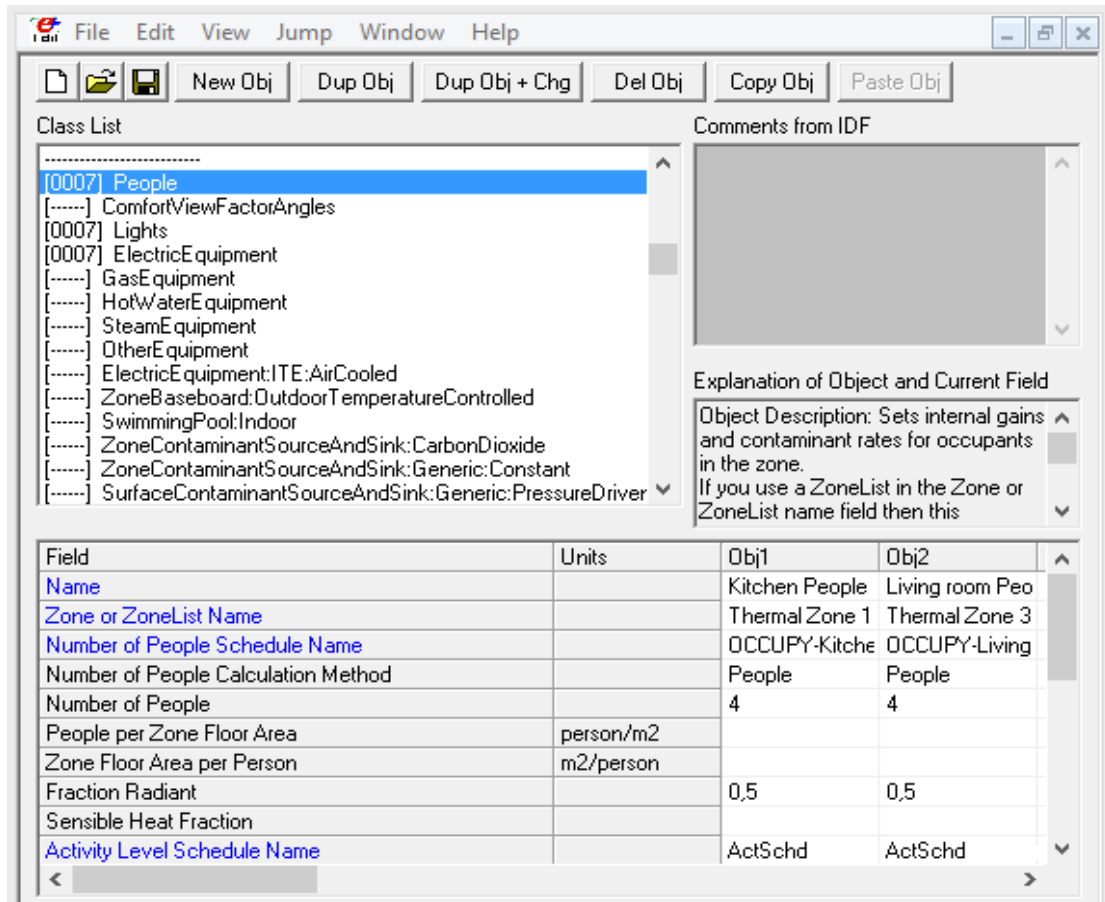


Figure 35 – People insertion in EnergyPlus

Following is a table with the human presence at home during months September – June, when kids have school classes.

Thermal zone	Monday - Friday	Saturday - Sunday
Thermal zone 1	07:30 – 08:50, 14:10 – 14:50 and 19:30 – 20:40	08:30 – 09:50, 13:30 – 14:00, 15:10 – 15:40 and 19:40 – 20:50
Thermal zone 3	15:50 – 16:50, 17:30 – 19:30 and 20:40 – 22:30	08:50 – 13:30, 14:00 – 20:10 and 20:50 – 22:30
Thermal zones 4 and 5	21:30 – 07:30, 14:40 – 16:50 and 19:10 – 20:00	21:30 – 08:30 and 14:00 – 17:50
Thermal zone 6	08:50 – 09:10, 17:10 – 17:30 and 21:00 – 21:40	09:50 – 10:10, 17:10 – 17:30 and 21:00 – 21:40
Thermal zone 8	22:30 – 07:30 and 14:50 – 15:50	22:30 – 08:30 and 15:50 – 16:50

Table 26 – People occupancy in the building for each time interval on weekly basis during months September – October

While, above is a table with the human presence at home during months July – August, when kids have break from school.

Thermal zone	Monday - Friday	Saturday - Sunday
Thermal zone 1	08:30 – 10:50, 13:30 – 14:00 and 20:30 – 21:40	09:30 – 10:50, 13:30 – 14:00, 15:10 – 15:40 and 20:30 – 21:40
Thermal zone 3	09:50 – 13:30, 14:00 – 16:50, 17:30 – 21:00 and 21:30 – 23:30	09:50 – 13:30, 14:00 – 15:50, 18:30 – 21:00 and 21:30 – 23:30
Thermal zones 4 and 5	23:00 – 09:30, 14:00 – 16:50 and 19:40 – 21:00	23:00 – 09:30, 14:00 – 15:50 and 18:40 – 21:00
Thermal zone 6	08:50 – 09:10, 17:10 – 17:30 and 19:10 – 19:50	18:10 – 19:30
Thermal zone 8	23:30 – 08:30 and 14:50 – 15:50	23:30 – 09:30

**Table 27 – People occupancy in the building for each time interval on weekly basis during months July – August**

- **Lighting**

This option defined the contribution of artificial lighting to the domestic heating gains of our residential area. The calculation again concerns only the heated areas of the building, which are also the main use areas of the building. Three different calculation methods are available here, where the gains are calculated either by directly setting the lighting level (in Watts), either by entering a value for the ratio of Watts/ area of the building, or either by entering the ratio of Watts / person of the building. The second method was selected, the schedule for lighting was given, and the power of lighting per square meter was defined at 6.4 W / m<sup>2</sup> according to TEE standards. [16] Also, values for Return Air Fraction, Fraction Radiant, Fraction Visible, and Fraction Replaceable were based on the values in Table 14 of the Energy Plus® User Manual for suspended luminaries. [15] The values are shown in the following Figure 36, aggregated with the remaining input data of that field. Finally, the fraction replaceable is the value of 1, based on and again the user manual, a value that suggests that the artificial lighting of the building does not operate on a continuous basis, only when the levels of natural lighting in the interior of the building are insufficient. [15]

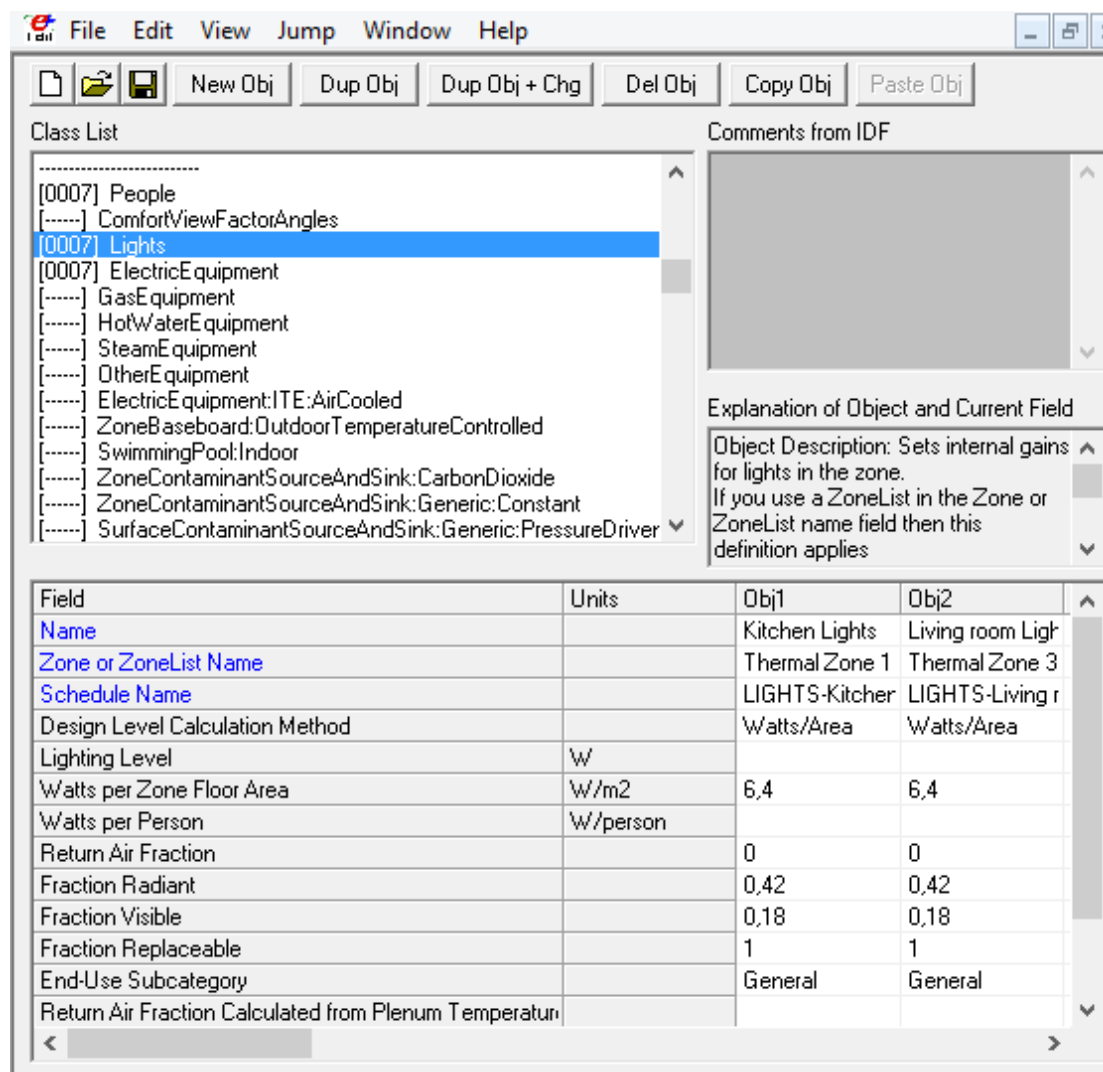


Figure 36 – Lighting insertion in EnergyPlus

Lights schedules for each thermal zone were set to be active according to people occupancy schedules described above, see Table 26 and Table 27. The following table shows the possible hours of lighting use per periods.

November - March	07:00 – 08:00 and 17:00 – 23:00
April - May	07:00 – 08:00 and 18:00 – 23:00
June – August	20:00 – 24:00
September – October	07:00 – 08:00 and 19:00 – 23:00

Table 28 – Activity of lighting for each period

- **Electrical equipment**

Finally, the thermal gains of the zone were determined due to the operation of electrical equipment, used in the building, where again the calculation concerns only the heated zones. There is a choice of three different methods:

the first one directly determines the power of all electrical equipment in the building, in the next one is determined the value of the fraction of the power of the electrical equipment per area of the building, and the last one defines the fraction of the power of the electrical equipment per person of the building. The second method is selected, while the value given in the fraction is equal to  $4\text{W}/\text{m}^2$ , and for each day and hour, an average operating coefficient equal to 0.75, as shown in Table 2.8 of TOTE-1 for residential buildings. [16]

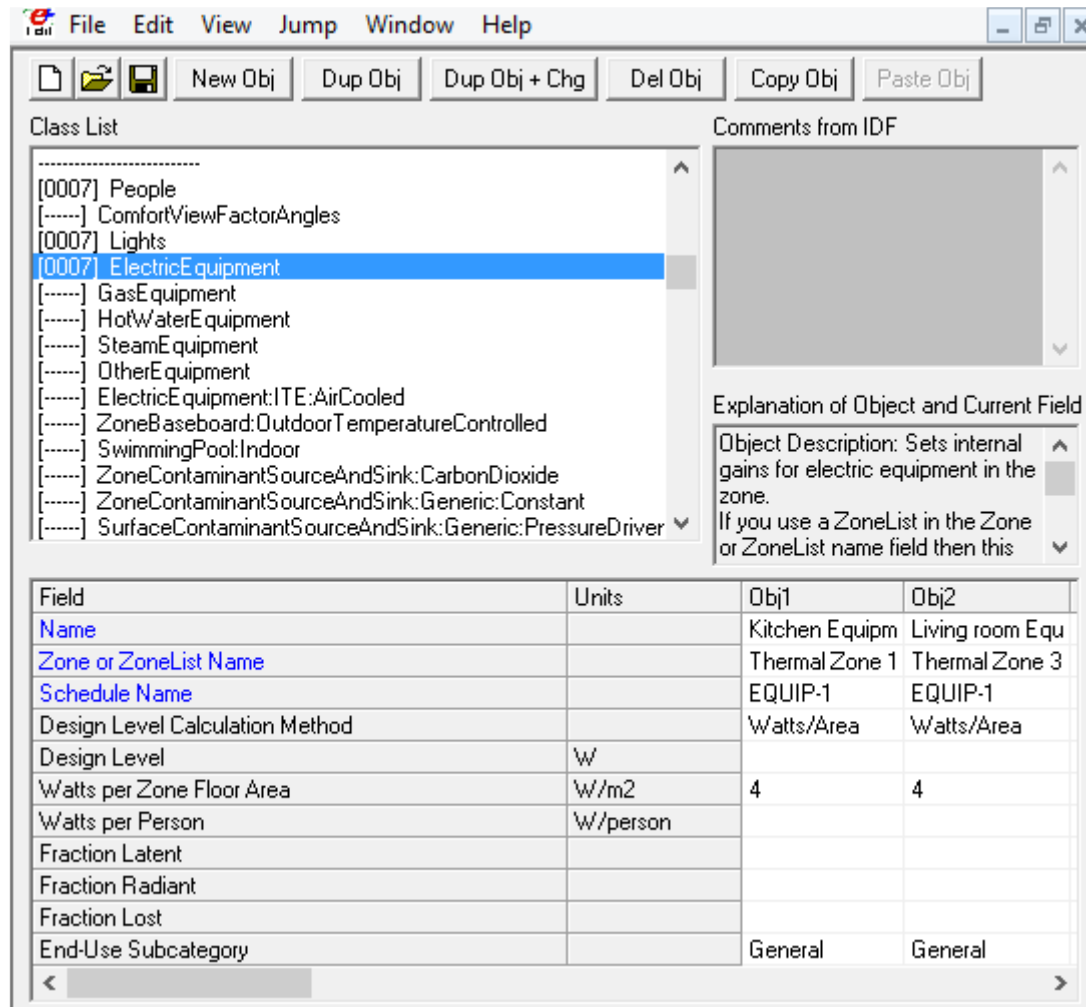


Figure 37 – Electrical equipment insertion in EnergyPlus

## 5.7. Thermal study

### 5.7.2. Interior design conditions

After collecting all the data describing the building shell, the use and operation of the building's premises as well as the external environment, all these information were inserted into the geometric model of the building and the result is the complete simulation model of the building.

The purpose of this simulation is to calculate heating and cooling loads of the building in study during a year. Thermal study, carried out, took into account all

the input data described so far, and additionally, design data of the building on the basis of which the values of the heating and cooling loads will be derived, were defined. The design conditions for the calculations are derived from the data of TEE and are presented in Table 29:

Use of thermal zone	Temperature		Relative humidity		Required fresh air m <sup>3</sup> /h/m <sup>2</sup>
	Winter period	Summer period	Winter period	Summer period	
Bathroom	22°C	26°C	40%	45%	0.75
Bedroom	20°C	26°C	40%	45%	0.75
Corridor	18°C	26°C	40%	45%	0.75
Kitchen	20°C	26°C	40%	45%	0.75
Living room	20°C	26°C	40%	45%	0.75

**Table 29 – Interior design conditions**

When simulating the calculation of the heating and cooling loads it was assumed that the temperature in the building's premises remains constant for cooling or heating throughout the year and coincides with the above values. The same assumption was done to provide fresh air in the rooms. The interrupted operation of the building was taken into account only in the appearance of internal heat gains.

### **5.7.3. External environment conditions**

For the description of external environment conditions, more than one day periods were used for design period. In particular, an annual calculation was made to provide the space heating and cooling loads per month of the year. Data were used, as they were derived from statistical processing of three cities' climate records and were described in Table 13, Table 16 and Table 19.

### **5.7.4. Calculation of ventilation, heating and thermal loads**

The simulation took place in Energy Plus, using the Ideal Loads Air System model. This model performs the calculation of the necessary energy needs to cover the heating and cooling loads of the building without being limited by the application of a particular air-conditioning system. It considers that there is an unlimited possibility of providing air to the desired design conditions of the building, which will cover the needs. The airflow system, which was assumed, is natural ventilation to the point of meeting the required needs.

The input variables of the model set the values in Table 29 for design conditions, temperatures and ventilation conditions, and the load calculations for the design time periods of Table 13 were performed. The heating conditions were used in

February and cooling was used in June and an annual calculation for results per month. The results are presented in the next chapter.

## **5.8. HVAC templates**

The following section describes a first dimension of one or more air-conditioning and ventilation systems that will meet the building's thermal, refrigerant and ventilation needs as studied and calculated in the simulation of loads. The final choice among the available or appropriate systems, for a building such as the one under study, should then come from a thorough study of various factors, such as system autonomy, energy saving potential, initial purchase and installation costs, installation size, installation due to geometric characteristics of the building and others.

For this study, three different types of HVAC systems were examined. First, the VRF system was placed and tested for the three cities, Andravida, Athens and Thessaloniki. Then, the three HVAC systems, VRF, VAV and FCU, were placed and examined for the city of Athens. The results are presented in the next chapter. Below are the parameters according to which the three HVAC systems were defined.

### **5.8.1. VRF HVAC system**

Parts of the system specified in the program are listed below:

- **HVAC template: thermostat**

In this tab, the temperature limits, which, if overcome, put the cooling and heating systems in operation have been set. The timelines specified in the schedules tab were used to determine them. Thus, heating set point and cooling set point were set according to Table 29 for each zone.

- **HVAC template: zone: VRF**

In this tab it was simply defined that the cooling-heating system we used is VRF. It was specified which system will operate to each zone. The only data defined beyond the default program are the names of the zones, systems and thermostats that will be used.

- **HVAC template: system: VRF**

This model simulates a variable-refrigerant-flow (or variable-refrigerant-volume) air-conditioning system. This system type models direct-expansion cooling and/or heating coils configured in a zone terminal unit. Here is a detailed description of the cooling – heating system that will be used by specifying its characteristics. First of all, it was defined that the system is running on electricity. Secondly, we determined that both cooling and heating are done using air. The remaining data is defined based on program default.

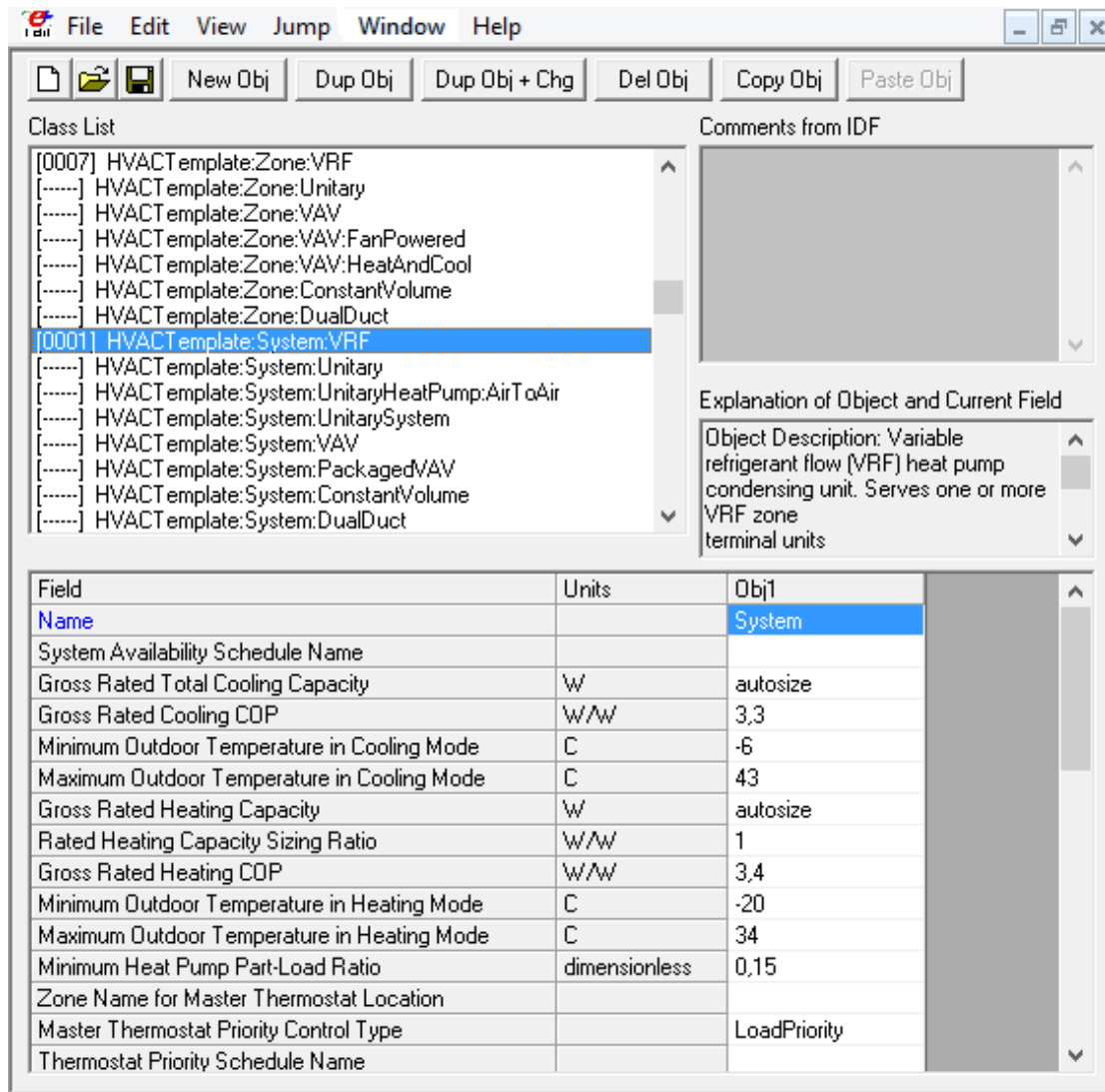


Figure 38 – Introduction of VRF HVAC in EnergyPlus

### 5.8.2. VAV HVAC system

Parts of the system specified in the program are listed below:

- **HVAC template: thermostat**

Again, heating set point and cooling set point were set according to Table 29 for each zone.

- **HVAC template: zone: VAV**

In this tab, it was specified which system will operate to each zone. The only data defined beyond the default program are the names of the zones, systems and thermostats that will be used.

- **HVAC template: system: VAV**

This object simulates the system portion of a variable air volume HVAC configuration with chilled water cooling and several different heating options. For this study five VAV HVAC systems were define. For each object, first, it was defined its name. Secondly, we determined that heating system is

running on electricity. It was, also, defined availability schedules for cooling – heating systems and set point schedules. The remaining data is defined based on program defaults.

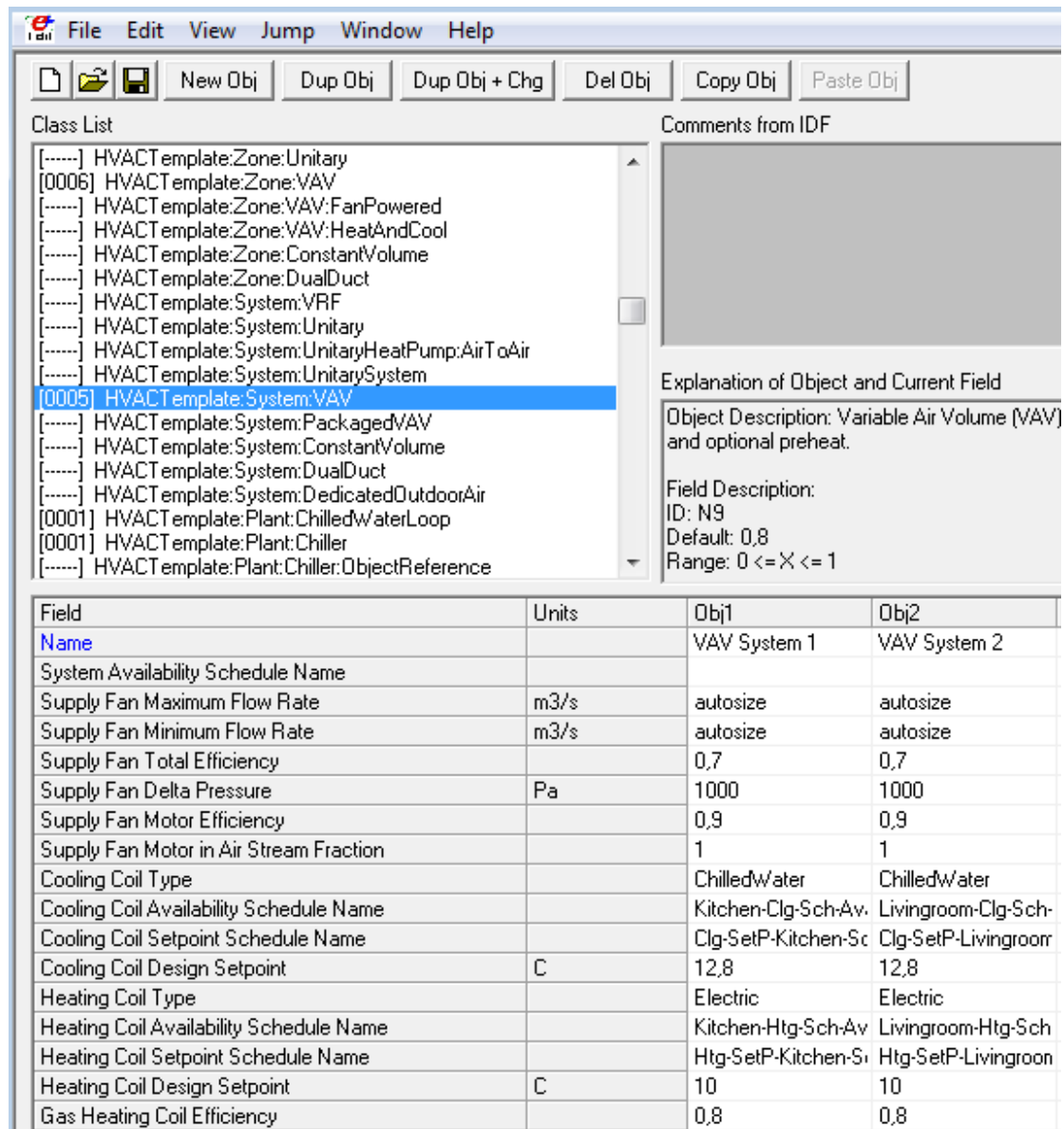


Figure 39 – Introduction of VAV HVAC in EnergyPlus

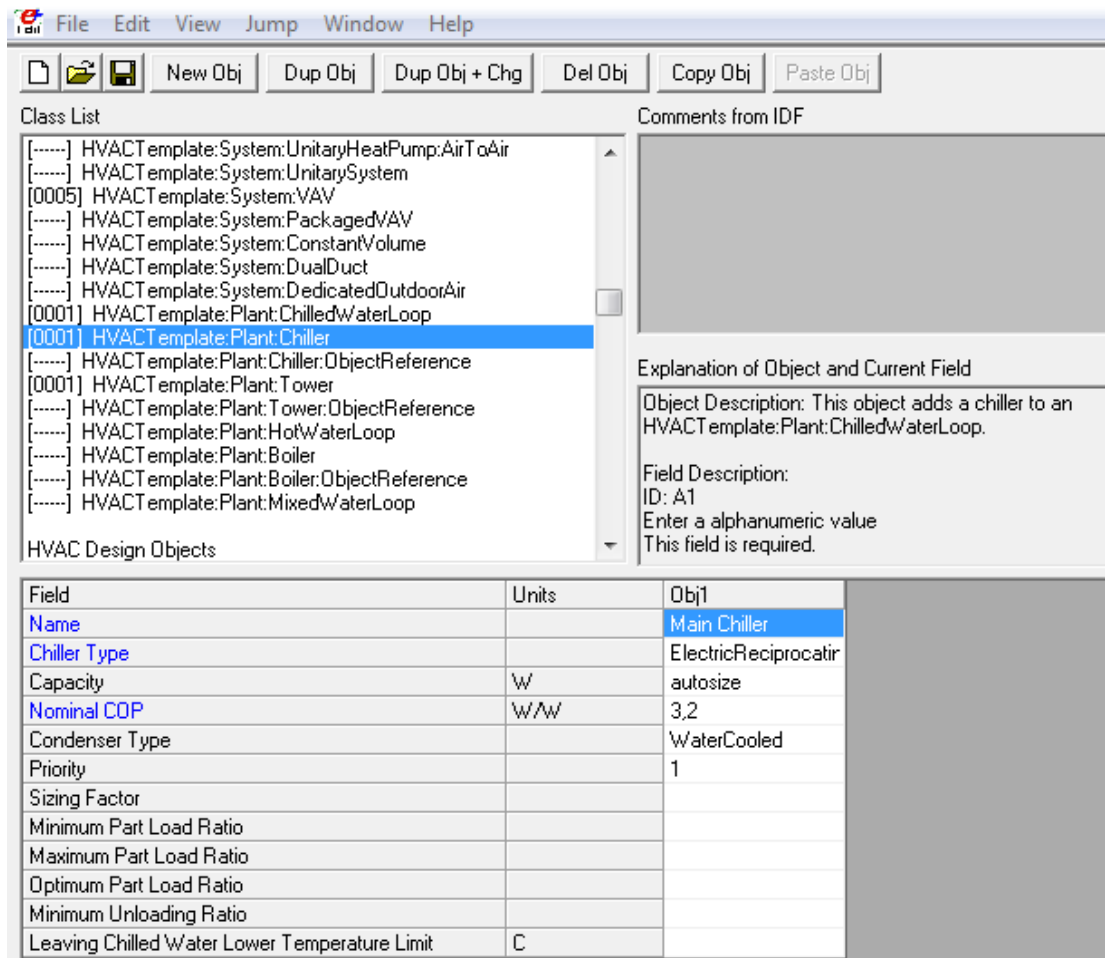
- **HVAC template: Plant: Chilled Water Loop**

The piping systems that connect the chilled water coils in the HVAC template objects with the chillers and the cooling towers are described with this object. The piping systems are called loops and this object describes the controls and pumps on the loops. Only one of these objects may be defined in an input file and all chilled water coils from HVAC template objects are served with this object. All data were defined by default values of the program.



- **HVAC template: Plant: Chiller**

A chiller or purchased cooling source is described with this object. Firstly, it was defined that the chiller runs with electricity. Then, COP was set at 3.2 W/W and as condenser type was set water cooled.



**Figure 40 – Introduction of chiller in EnergyPlus**

- **HVAC template: Plant: Tower**

A cooling tower is described with this object. The only data defined beyond the default program is the type of tower, set as one speed.

### 5.8.3. FCU HVAC system

Parts of the system specified in the program are listed below:

- **HVAC template: thermostat**

Once again, heating set point and cooling set point were set according to Table 29 for each zone.

- **HVAC template: zone: Fan Coil**

This object simulates a 4 pipe fan coil unit with hot water heating coil, chilled water cooling coil, and an outdoor air mixer. There were specified six objects,

one for each conditioned zone. For each object, it was defined its name. It was, also, defined availability schedules for cooling – heating systems and set point schedules. The remaining data is defined based on program defaults.

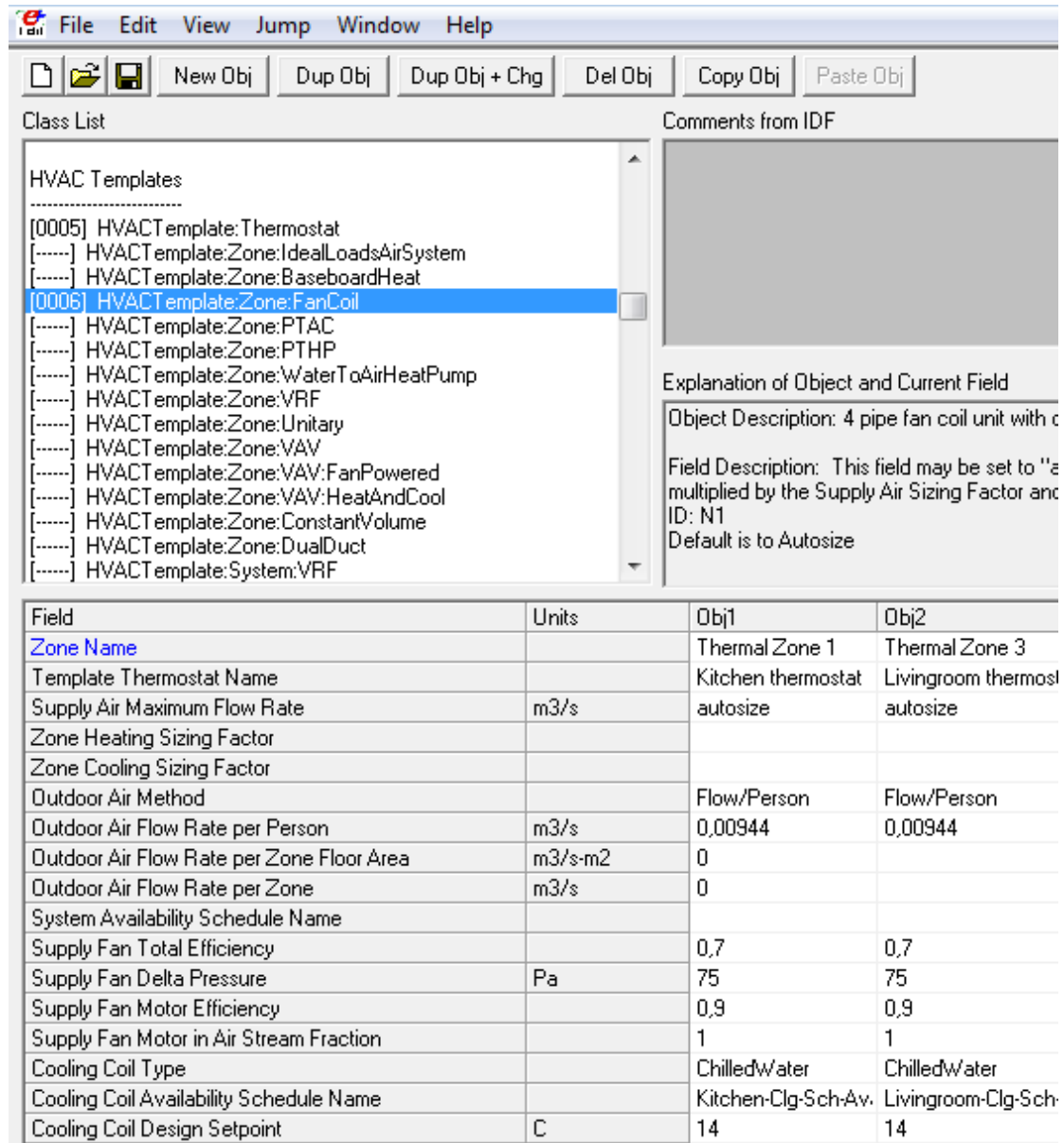


Figure 41 – Introduction of FCU HVAC in EnergyPlus

- **HVAC template: Plant: Chilled Water Loop**

Again, a chilled water loop was defined by default values of the program.

- **HVAC template: Plant: Chiller**

In this tab, a water cooled chiller running on electricity was defined. Also, COP was set at 3.2 W/W.

- **HVAC template: Plant: Tower**

A one speed tower was defined by default values of the program.

- **HVAC template: Plant: Hot Water Loop**

The piping systems that connect the hot water coils in the HVAC template objects with the boilers are described with this object. The piping systems are called loops and this object describes the controls and pumps on the loops. Only one of these objects should be defined in an input file and all hot water coils from HVAC template objects are served with this object. All data were defined by default values of the program.

- **HVAC template: Plant: Boiler**

A boiler or purchased heating source is described with this object. A hot water boiler, running on electricity was specified here.

**Class List**

- [.....] HVAC template: System: Unitary
- [.....] HVAC template: System: UnitaryHeatPump: AirToAir
- [.....] HVAC template: System: UnitarySystem
- [.....] HVAC template: System: VAV
- [.....] HVAC template: System: PackagedVAV
- [.....] HVAC template: System: ConstantVolume
- [.....] HVAC template: System: DualDuct
- [.....] HVAC template: System: DedicatedOutdoorAir
- [0001] HVAC template: Plant: ChilledWaterLoop
- [0001] HVAC template: Plant: Chiller
- [.....] HVAC template: Plant: Chiller: ObjectReference
- [0001] HVAC template: Plant: Tower
- [.....] HVAC template: Plant: Tower: ObjectReference
- [0001] HVAC template: Plant: HotWaterLoop
- [0001] HVAC template: Plant: Boiler**
- [.....] HVAC template: Plant: Boiler: ObjectReference
- [.....] HVAC template: Plant: MixedWaterLoop

**Comments from IDF**

Explanation of Object and Current Fields

Object Description: This object adds a boiler to a Plant or MixedWaterLoop.

Field Description:  
ID: A1  
Enter a alphanumeric value  
This field is required.

Field	Units	Obj1
Name		Main Boiler
Boiler Type		HotWaterBoiler
Capacity	W	autosize
Efficiency		0.8
Fuel Type		Electricity
Priority		1
Sizing Factor		
Minimum Part Load Ratio		
Maximum Part Load Ratio		
Optimum Part Load Ratio		
Water Outlet Upper Temperature Limit	C	
Template Plant Loop Type		

Figure 42 – Introduction of boiler in EnergyPlus

## 5.9. Zone airflow

A very important regulator factor of energy consumption in buildings is the flow of air between the thermal zones and/ or between the indoor and outdoor environment, whether it is caused inadvertently or induced deliberately.

- **Infiltration**

Infiltration is the unintentional airflow caused by the opening and closing of the exterior doors, by cracks or slits around the frames, and in very small quantities even through the structural elements of the building. The software offers a choice of different calculation methods, and the one used in this study determines the value of volume of air flow/ area of the building. This value for conditioned zones is given in paragraph 3.4.1 of TOTE-1 equals to  $5.5 \text{ m}^3/\text{h m}^2 = 0.001527 \text{ m}^3/\text{s m}^2$ , a value corresponding to the reference building that is considered to have sufficiently airtight frames. [16] For the non-conditioned zones a value of  $0.55 \text{ m}^3/\text{h m}^2 = 0.000414 \text{ m}^3/\text{s m}^2$  (for an average floor height of 3m) was given, according to Table 3.27 of TOTE-1, which refers to unconditioned spaces with external window frames and adequate air-tightness. [16]

Class List

- Zone Airflow
- [00091] ZoneInfiltration:DesignFlowRate
- [.....] ZoneInfiltration:EffectiveLeakageArea
- [.....] ZoneInfiltration:FlowCoefficient
- [.....] ZoneVentilation:DesignFlowRate
- [.....] ZoneVentilation:WindandStackOpenArea
- [.....] ZoneAirBalance:OutdoorAir
- [.....] ZoneMixing
- [.....] ZoneCrossMixing
- [.....] ZoneRefrigerationDoorMixing
- [.....] ZoneEarthtube
- [.....] ZoneCoolTower:Shower
- [.....] ZoneThermalChimney

Comments from IDF

Explanation of Object and Current Field

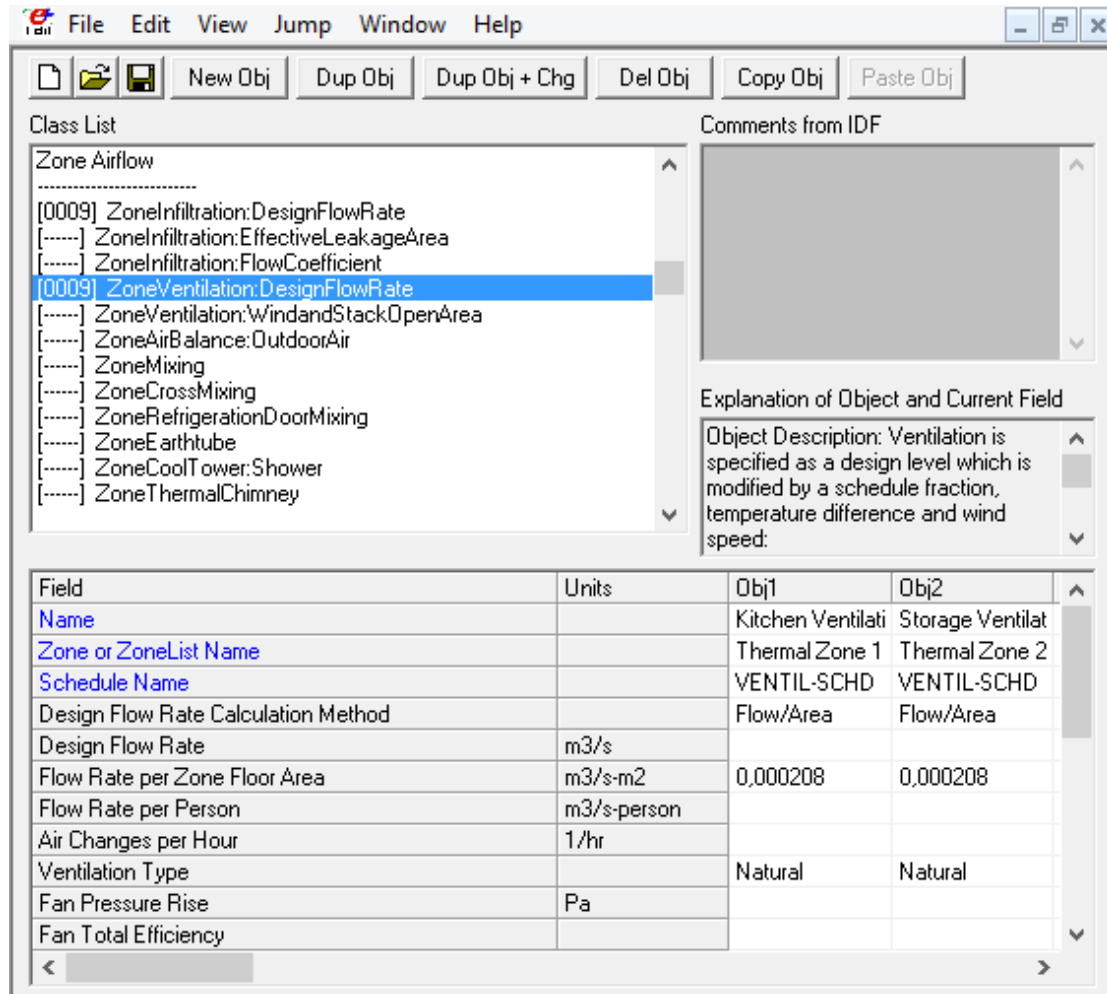
Object Description: Infiltration is specified as a design level which is modified by a Schedule fraction, temperature difference and wind speed:

Field	Units	Obj1	Obj2
Name		Kitchen Infiltratic	Storage Infiltratic
Zone or ZoneList Name		Thermal Zone 1	Thermal Zone 2
Schedule Name		INFIL-SCHD	INFIL-SCHD
Design Flow Rate Calculation Method		Flow/Area	Flow/Area
Design Flow Rate	m3/s		
Flow per Zone Floor Area	m3/s-m2	0.001527	0.000414
Flow per Exterior Surface Area	m3/s-m2		
Air Changes per Hour	1/hr		
Constant Term Coefficient		1	1
Temperature Term Coefficient			
Velocity Term Coefficient			

Figure 43 – Infiltration Design Flow Rate in EnergyPlus

- **Ventilation**

Ventilation is defined as the deliberate flow of air from the outside environment of a building on the inside. Ventilation is divided into a natural (e.g. window opening) and mechanical (e.g. fan ventilation). As it has been mentioned before, for this study, only natural ventilation was taken into account. The calculation method is based on the volume of air flow/ area of the building. For both, conditioned and unconditioned spaces, the value of  $0.75 \text{ m}^3/\text{h m}^2 = 0.000208 \text{ m}^3/\text{s m}^2$ , is given, according to Table 2.3 of TOTE-1, which sets the minimum required fresh air for residential buildings. [16]



**Figure 44 – Ventilation Design Flow Rate in EnergyPlus**

### 5.10. General assumptions in EnergyPlus

Energy requirements of a building can be calculated in two different ways:

- simplifying calculation methods
- simulation calculation methods

In first case, given the simplicity of calculations, accuracy of the results is limited. So, this to be compensated, they are based on a series of assumptions to ensure that the energy effect is not less than the real needs of the building. In simulation methods, there is the possibility of analyzing in detail the actual energy

requirement of the building per hour. The role of simulation is to approach as much as possible the real function of the building and in order to achieve this, a series of algorithms with less or more demanding mathematical background is used, which is able to describe the phenomena in changing conditions near reality.

Simulation of this building in EnergyPlus was carried out with use the following calculation models and algorithms:

- The distribution of solar radiation in the shell of the building is described by FullExterior algorithm. The algorithm calculates the shading from the horizontal headlights of the building as well as the radiation entering the transparent elements inside the building, while the reflectivity of the soil is not taken into account. The total radiation incident to the floor of each thermal zone is absorbed by it according to the absorption coefficient of the material, and the reflected radiation is counted on the diffuse radiation from the surrounding walls [10].
- Building's shadowing resulting from changing the sun's location is re-calculated every 20 days.
- Calculation algorithm for convection heat transfer is TARP. The algorithm correlates the heat transfer coefficient with the temperature difference for different orientations [10].
- The calculation algorithm for convection heat transfer on the exterior surfaces of the building shell is DOE-2. This algorithm has emerged from field studies and uses a correlation from the Klems and Yazdanian measurements for surfaces with some roughness [10].
- The method of total solution simulation is based on the Heat Balance Algorithm [10].
- Conduction Transfer Function algorithm is used to calculate the conduction heat transfer on the building's surfaces. Resulting solutions have been based on sensible heat only, not taking into account the concentration or diffusion of moisture into the building blocks [10].
- Simulation time step was set to 6, i.e. a new heat transfer calculation is performed every 10 minutes.

### **5.11. Conclusions on using EnergyPlus®**

EnergyPlus™ is a very useful and reliable building energy model program which can provide a complete energy study of a building of any size. After having using EnergyPlus™ for our study we can conclude that despite all the useful options and tools it provides, it is not an easy program to use, especially when it comes to the description of buildings' construction. That is, also, the reason why we chose to use another geometry editor, such as Google SketchUp, instead, in order to make the construction of the building in study.

Finally, it is worth noting that, at a time when architecture and science are advancing in the production of new and innovative materials and systems, respectively flexible and enriched must also be the operation of various software,

so as not to force the user to make compromises in order to describe the building he designed, compromises that ultimately result in disputed results.

## Chapter 6 Results of Simulations

This chapter summarizes the results obtained from the three alternative scenarios made in Energy Plus. The way of presentation is particularly supervisory, through tables and diagrams, always aiming at a comparative analysis of results between cities either of heating/ cooling loads or thermal gains/ losses.

### 6.1. Comparative heating/ cooling loads' results between cities

First, it is shown a table which describes the surfaces of the thermal zones, whether air-conditioned or not, the volume and the total of the loads applied.

Thermal zone	Area (m <sup>2</sup> )	Conditioned (Y/ N)	Volume (m <sup>3</sup> )	Above ground gross wall area (m <sup>2</sup> )	Window glass area (m <sup>2</sup> )	Lights (W/ m <sup>2</sup> )	People (m <sup>2</sup> per people)	Plug and process (W/ m <sup>2</sup> )
Thermal zone 1	20.01	Y	60.03	38.61	2.2	6.4	5	4
Thermal zone 2	4.87	N	14.61	17.61	0.3	0	-	0
Thermal zone 3	38.89	Y	116.67	61.62	6.6	6.4	9.72	4
Thermal zone 4	16.38	Y	49.14	34.38	2.52	6.4	16.38	4
Thermal zone 5	10	N	30	6	0.88	0	-	0
Thermal zone 6	5.6	Y	16.8	6	0.22	6.4	5.6	4
Thermal zone 7	3.8	N	11.4	11.7	0.22	0	-	0
Thermal zone 8	16.51	Y	49.53	27.51	2.52	6.4	8.25	4
Thermal zone 9	12.51	Y	37.53	16.83	2.52	6.4	12.51	4

**Table 30 – Conditioned and unconditioned building area**

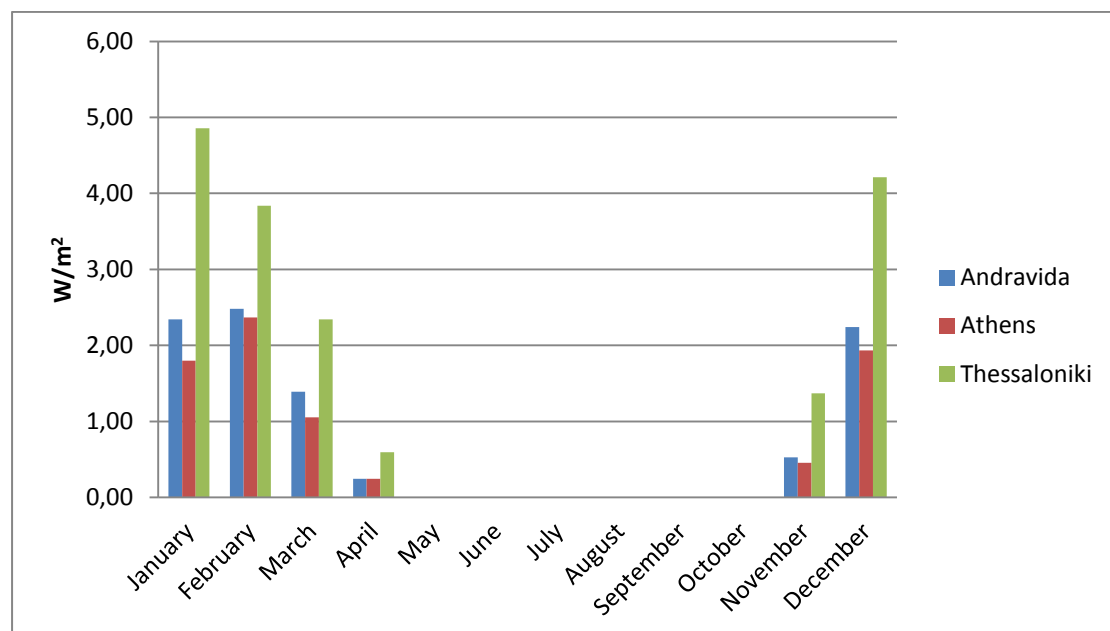
The following tables show the total energy required for the heating and cooling of the building in study, as it was described and presented earlier, to the three different cities of Greece selected. The results relate to heating/ cooling loads consumed by the building as a whole area, either for cooling or for heating or for the combination of the two, are expressed at surface-bound values, i.e. the energy is measured in W/ m<sup>2</sup>, and are presented collectively in tables quoting prices for all cities. At this point, the values were chosen as they are the ones most used in the various energy demanding building standards, and therefore the reader - engineer is more familiar with them.



Table 31 shows the total monthly and annual consumption of heating loads in the three cities bounded to the surface of the building:

Month	Heating loads (W/ m <sup>2</sup> )		
	Andravidia	Athens	Thessaloniki
January	2.34	1.80	4.86
February	2.48	2.37	3.84
March	1.39	1.05	2.34
April	0.25	0.25	0.60
May	0	0	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	0
October	0	0	0
November	0.53	0.46	1.37
December	2.24	1.94	4.21
Annual	9.23	7.87	17.22

**Table 31 – Heating loads in the three cities bounded to the surface of the building**



**Figure 45 – Heating loads in the three cities bounded to the surface of the building**

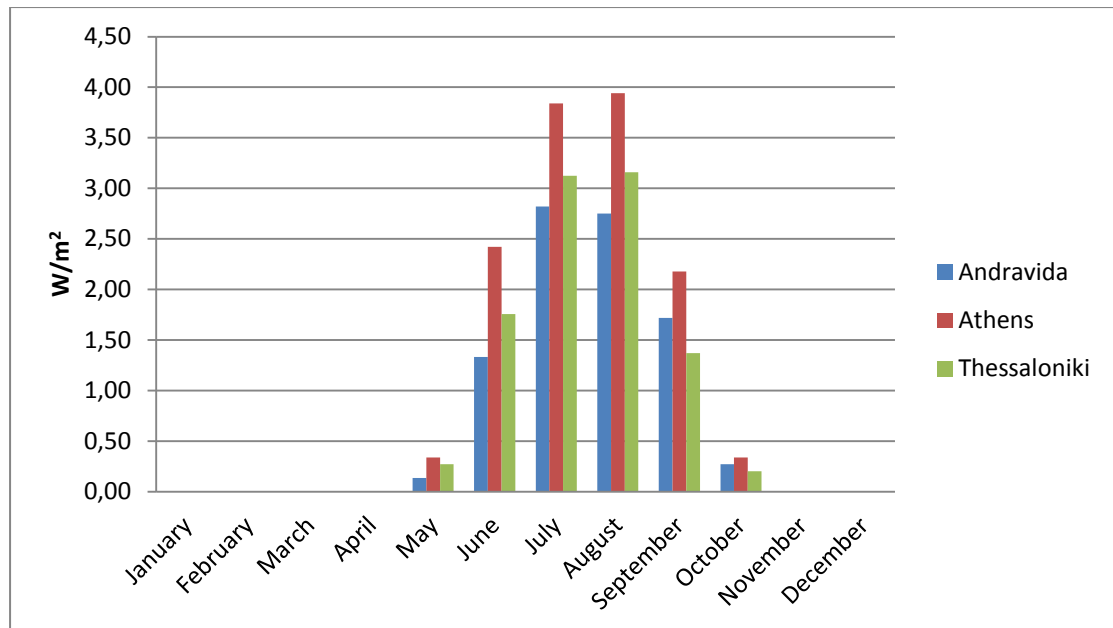
It is noticed that Thessaloniki has the largest annual heating load consumption, with 17.22 W/ m<sup>2</sup>, and Athens has the smallest, with 7.87 W/ m<sup>2</sup>. It seems that Thessaloniki has almost double the consumption of heating load, from the other

cities, with the biggest differences occurring in January, April and November. In all cities, heating loads are zero in May – October, due to the heating system's program as defined in the EnergyPlus Schedules field. Positive impression is attributed to the very small consumptions of April. Finally, questioning is the price of Andravida annual heating load consumption with 9.23 W/ m<sup>2</sup>, for which one would expect to require less heating load from Athens, due to its latitude. All of the above are also illustrated in Figure 45, which makes much more clearly visible that Thessaloniki has the largest heating load consumption in all months.

Table 32 shows the total monthly and annual consumption of cooling loads in the three cities bounded to the surface of the building:

Month	Cooling loads (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0.14	0.34	0.27
June	1.33	2.42	1.76
July	2.82	3.84	3.13
August	2.75	3.94	3.16
September	1.72	2.18	1.37
October	0.27	0.34	0.20
November	0	0	0
December	0	0	0
Annual	9.03	13.06	9.88

**Table 32 – Cooling loads in the three cities bounded to the surface of the building**



**Figure 46 – Cooling loads in the three cities bounded to the surface of the building**

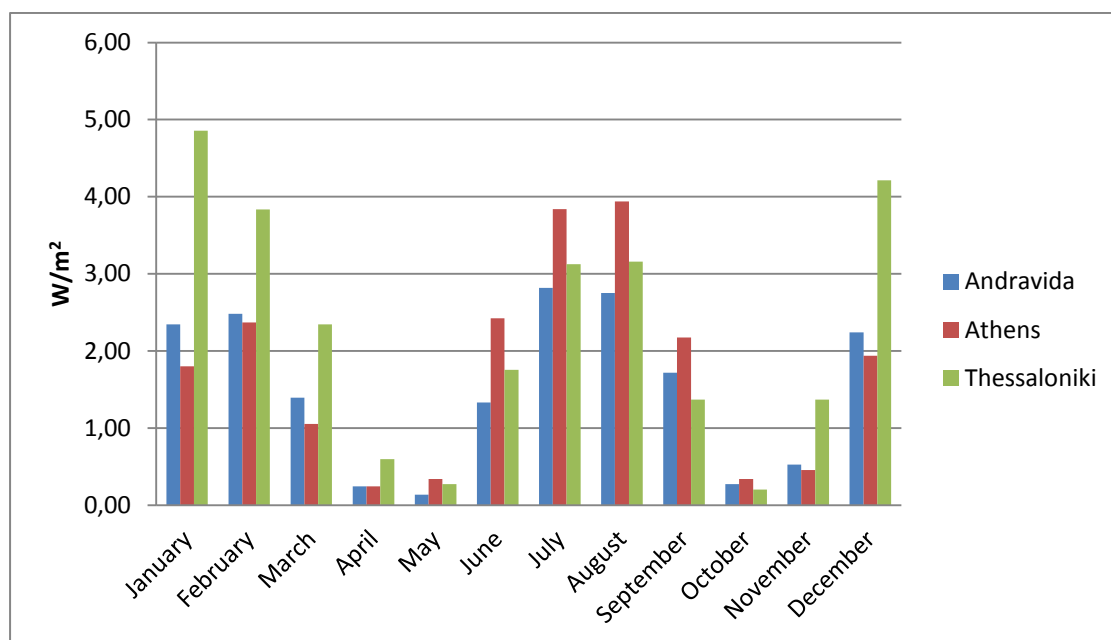
It is noticed that, for months January – April and November-December, cooling loads consumption is zero according to the operating schedule set for the cooling system. While, May and October, the transitional months, show very small energy consumption. Looking at the total annual cooling loads consumption, we see that Athens has the largest consumption of 13.06 W/ m<sup>2</sup> and Andravida has the smallest consumption of 9.03 W/ m<sup>2</sup>. Thessaloniki has cooling load consumption of 9.88 W/ m<sup>2</sup>. However, in contrast to heating loads consumption, cooling loads' prices do not show so great variations in the different cities, as a matter of fact which is also shown by the smoothness of the diagram in Figure 46.

Table 33 shows the total annual consumption of both heating and cooling loads in the three cities bounded to the surface of the building:

Month	Heating and Cooling loads (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
January	2.34	1.80	4.86
February	2.48	2.37	3.84
March	1.39	1.05	2.34
April	0.25	0.25	0.60
May	0.14	0.34	0.27
June	1.33	2.42	1.76
July	2.82	3.84	3.13
August	2.75	3.94	3.16
September	1.72	2.18	1.37

Month	Heating and Cooling loads (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
October	0.27	0.34	0.20
November	0.53	0.46	1.37
December	2.24	1.94	4.21
Annual	18.27	20.92	27.10

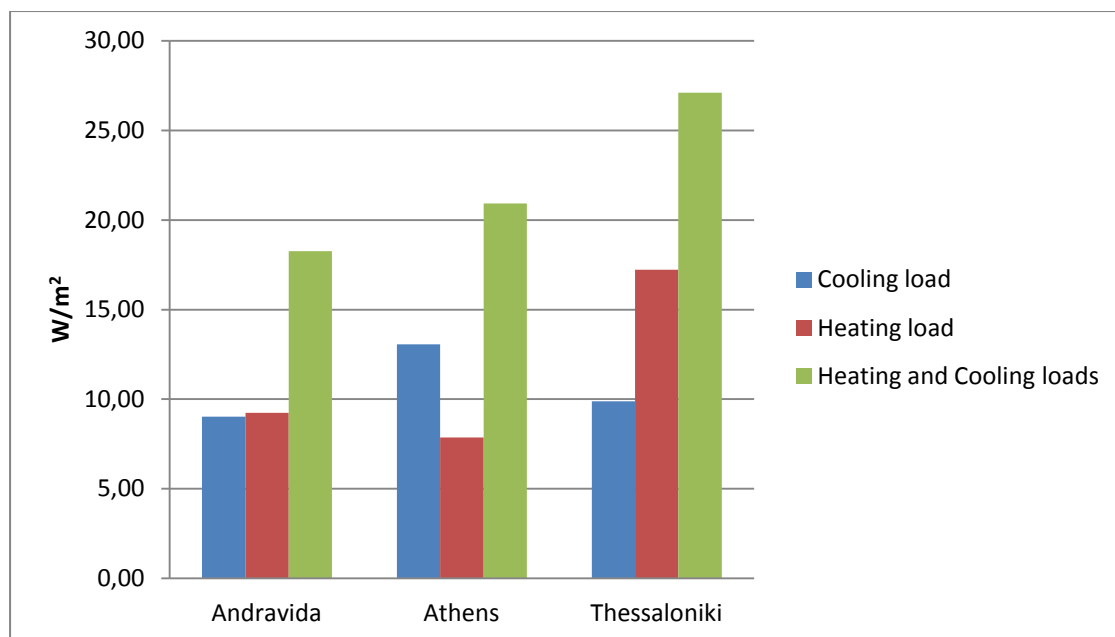
**Table 33 – Heating and cooling loads in the three cities bounded to the surface of the building**



**Figure 47 – Heating and cooling in the three cities bounded to the surface of the building**

It is noticed that, differences in annual load consumption have been normalized. In particular, Andravida requires the smallest amounts of load, with 18.27 W/ m<sup>2</sup>, and Thessaloniki the largest, with 27.10 W/ m<sup>2</sup>. At monthly analysis of results, lowest prices are shown generally in April, May and October, and largest prices in January, February, July, August and December.

Figure 48 shows the annual consumption of heating, cooling and the combination of these loads in each alternative scenario:



**Figure 48 – Heating, cooling and total loads' consumption in the three cities bounded to the surface of the building**

It is noticed, that the loads consumption for cooling and heating in Andravida is almost equal. While for Athens, twice as much as load is needed for cooling than for heating. On the contrary, Thessaloniki requires twice as much as load for heating than for cooling. Also, as it has been mentioned before, Thessaloniki has the largest consumption of total load, while Andravida the lowest.

## 6.2. Comparative thermal gains and losses results between cities

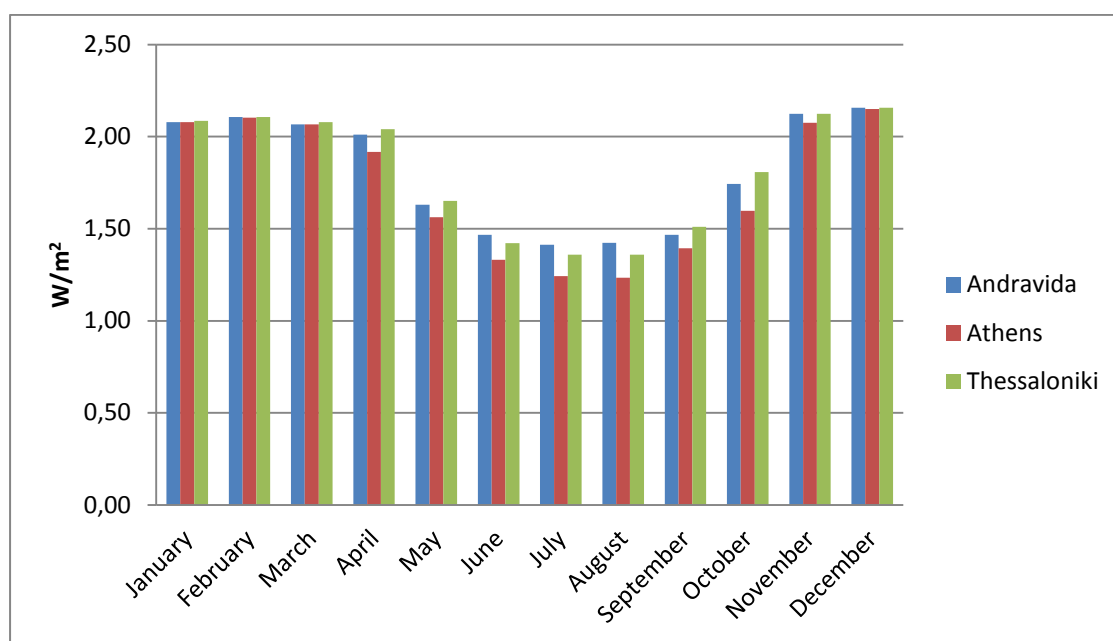
Below, the simulation results of internal heat gains and losses due to equipment, lighting, people, fenestration surfaces and infiltration are presented.

Table 34 shows the monthly heat gains flow due to peoples' occupancy in the building, for each one of three cities in study:

Month	Heat gains due to people (W/ m²)		
	Andravida	Athens	Thessaloniki
January	2.08	2.08	2.09
February	2.11	2.10	2.11
March	2.07	2.07	2.08
April	2.01	1.92	2.04
May	1.63	1.56	1.65
June	1.47	1.33	1.42
July	1.41	1.24	1.36
August	1.42	1.23	1.36

Month	Heat gains due to people (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
September	1.47	1.39	1.51
October	1.74	1.60	1.81
November	2.12	2.07	2.12
December	2.16	2.15	2.16
Annual	21.69	20.75	21.70

**Table 34 – Monthly heat gains flow due to people in the three cities**



**Figure 49 – Monthly heat gains flow due to people in the three cities**

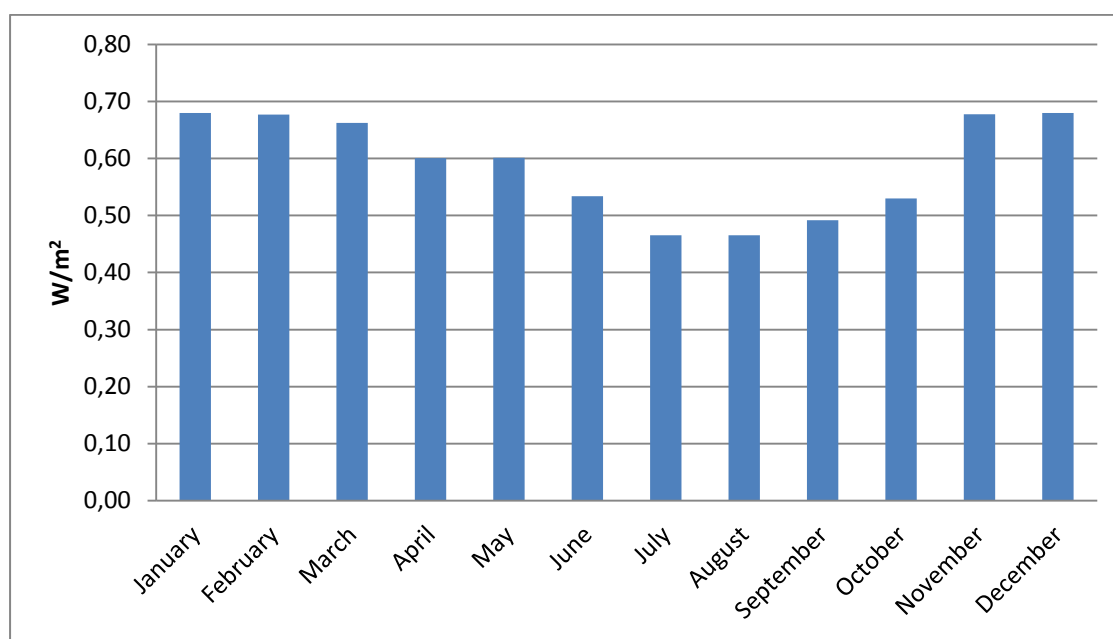
Observing Figure 49, it appears that the prices for heat gains due to the person's occupancy of the building have very few deviations. The greatest variations are observed through months April, May, June, July, August, September, October and November. But, there is not any reasonable explanation, since the same occupancy schedules have been used for all three cities.

Table 35 shows the monthly heat gains flow due to lights in the building, for each one of three cities in study:

Month	Heat gains due to lights (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
January	0.68	0.68	0.68
February	0.68	0.68	0.68
March	0.66	0.66	0.66
April	0.60	0.60	0.60

Month	Heat gains due to lights (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
May	0.60	0.60	0.60
June	0.53	0.53	0.53
July	0.47	0.47	0.47
August	0.47	0.47	0.47
September	0.49	0.49	0.49
October	0.53	0.53	0.53
November	0.68	0.68	0.68
December	0.68	0.68	0.68
Annual	7.06	7.06	7.06

**Table 35 – Monthly heat gains flow due to lights in the three cities**



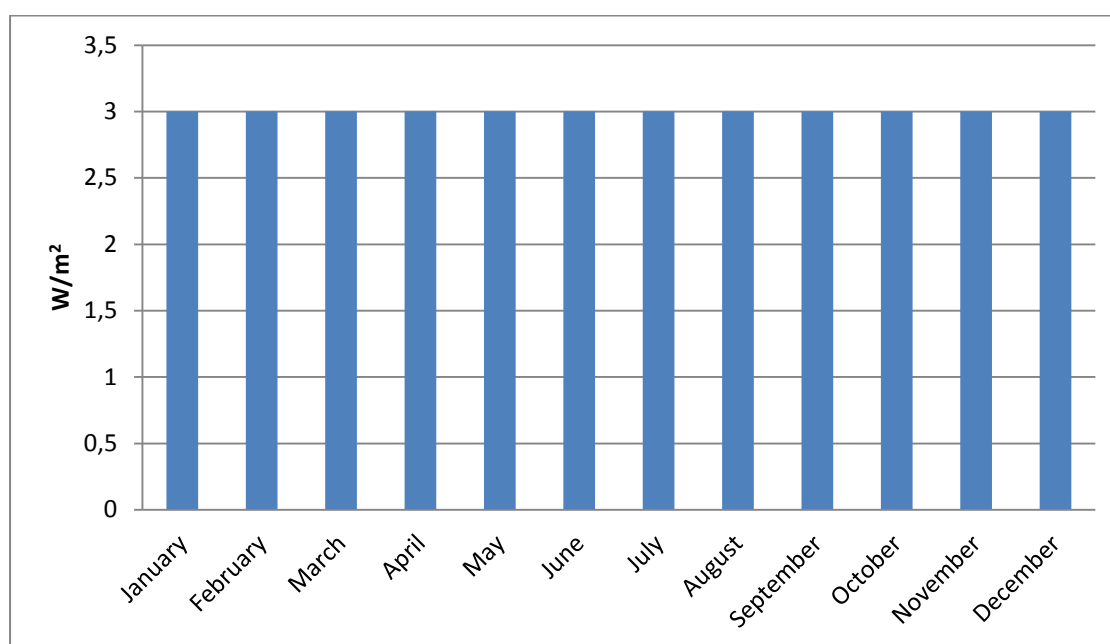
**Figure 50 – Monthly heat gains flow due to lights in the three cities**

It is noticed that, in all three cities, the heat gains due to the lights have the same values. Price matching is expected and is explained by the fact that the same schedules have been used. Reasonable is, also, the fact that there is a small fall in prices during months April, May, June, July, August, and September, when the lights are used fewer hours, shown in Figure 50 .

Table 36 shows the monthly heat gains flow due to equipment in the building, for each one of three cities in study:

Month	Heat gains due to equipment (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
January	3	3	3
February	3	3	3
March	3	3	3
April	3	3	3
May	3	3	3
June	3	3	3
July	3	3	3
August	3	3	3
September	3	3	3
October	3	3	3
November	3	3	3
December	3	3	3
Annual	36	36	36

**Table 36 – Monthly heat gains flow due to equipment in the three cities**



**Figure 51 – Monthly heat gains flow due to equipment in the three cities**

Same as before, it is noticed that, the heat gains due to the electric equipment have the same values in all three cities. This is because of the fact that the same schedules have been used, again, for all cities. Figure 51 shows that prices are same for all months. This happens because the same equipment operation schedule is running during all the months.



Table 37 shows the monthly heat gains flow due to windows of the building, for each one of three cities in study:

Month	Heat gains due to windows (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
January	5.58	7.73	6.74
February	6.36	7.46	9.44
March	6.11	7.10	7.83
April	5.96	6.50	6.45
May	6.37	6.33	6.58
June	6.71	7.19	7.26
July	7.23	7.33	7.27
August	7.37	7.57	7.56
September	8.12	8.94	8.45
October	6.41	8.74	8.17
November	5.64	6.96	7.14
December	4.35	6.91	5.75
Annual	76.21	88.76	88.65

Table 37 – Monthly heat gains flow due to windows in the three cities

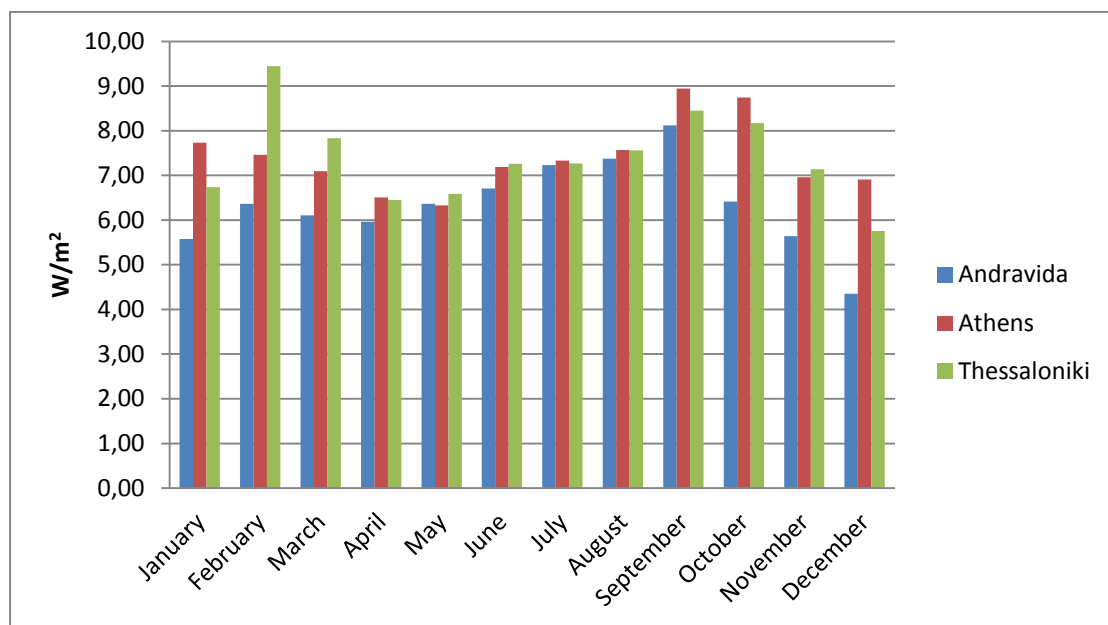


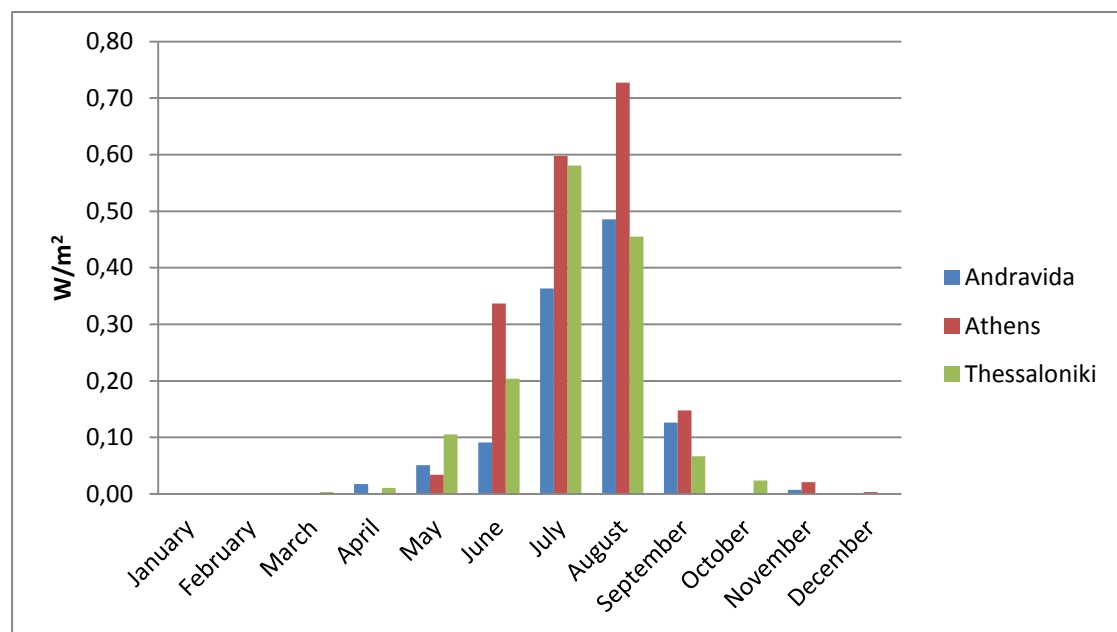
Figure 52 – Monthly heat gains flow due to windows in the three cities

Observing Figure 52, it appears that the prices for heat gains due to the fenestration surfaces of the building have very few deviations. The greatest variations are observed through months January, February, March, September, October, November and December.

Table 38 shows the monthly heat gains flow due to infiltration of the building, for each one of three cities in study:

Month	Heat gains due to infiltration (W/ m <sup>2</sup> )		
	Andravidia	Athens	Thessaloniki
January	0	0	0
February	0	0	0
March	0	0	0
April	0.02	0	0.01
May	0.05	0.03	0.11
June	0.09	0.34	0.20
July	0.36	0.60	0.58
August	0.49	0.73	0.46
September	0.13	0.15	0.07
October	0.00	0	0.02
November	0.01	0.02	0
December	0	0	0
Annual	1.14	1.87	1.45

**Table 38 – Monthly heat gains flow due to infiltration in the three cities**



**Figure 53 – Monthly heat gains flow due to infiltration in the three cities**

Observing Figure 53, it is noticed that, Athens is the city with the largest heat gains ( $1.87 \text{ W/ m}^2$ ) due to infiltration of the building. Next is Thessaloniki with  $1.45 \text{ W/ m}^2$  of thermal gains due to infiltration, while, Andravida is third with  $1.14 \text{ W/ m}^2$ .

Table 39 shows the monthly heat gains flow of the building due to other factors, for each one of three cities in study:

Month	Heat gains due to other factors ( $\text{W/ m}^2$ )		
	Andravida	Athens	Thessaloniki
January	0.31	0.27	0.46
February	0.22	0.25	0.43
March	0.17	0.15	0.18
April	0.01	0	0.01
May	0.04	0.01	0.04
June	0.30	0.85	0.42
July	1.07	2.74	1.26
August	0.78	2.42	1.25
September	0.27	0.34	0.21
October	0.22	0.23	0.33
November	0.16	0.15	0.35
December	0.23	0.30	0.41
Annual	3.79	7.73	5.37

Table 39 – Monthly heat gains flow due to other factors in the three cities

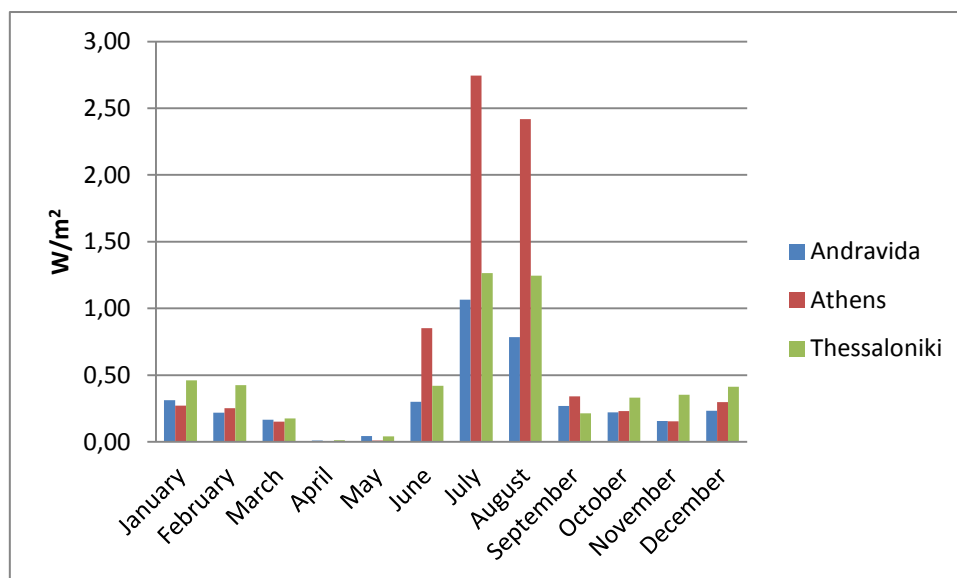


Figure 54 – Monthly heat gains flow due to other factors in the three cities

Observing Figure 54 it is noticed that, Athens is the city with the largest heat gains ( $7.73 \text{ W/ m}^2$ ) due to other factors. Next is Thessaloniki with  $5.37 \text{ W/ m}^2$  of thermal gains due to infiltration, while, Andravida is third with  $3.79 \text{ W/ m}^2$ .

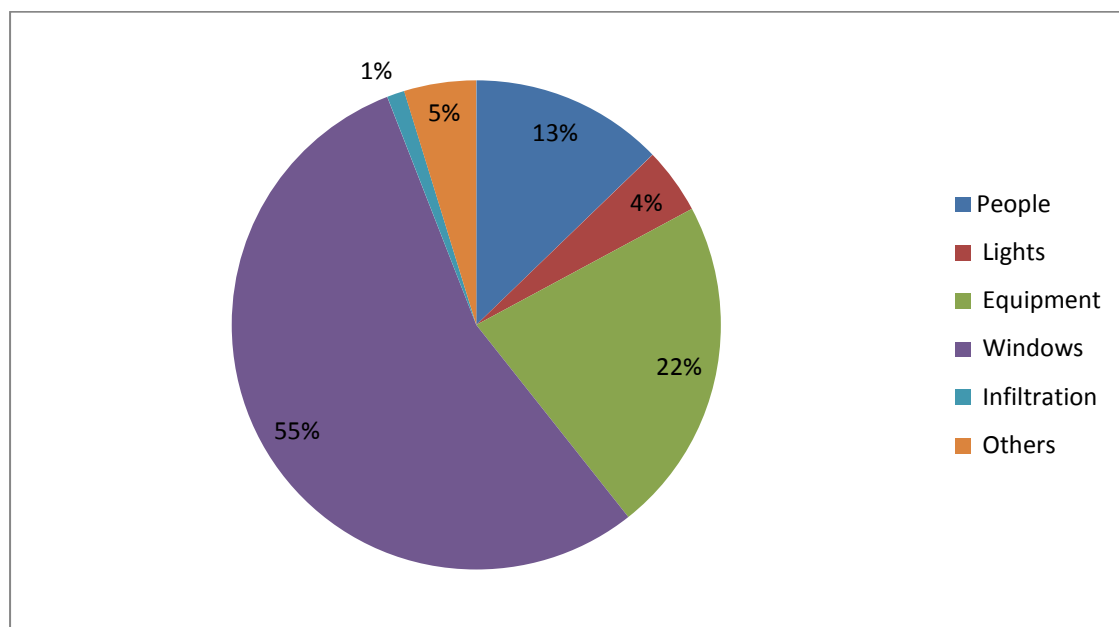
Table 40 shows the total annual heat gains due to different factors for all three cities:

	Total annual heat gains ( $\text{W/ m}^2$ )		
	Andravida	Athens	Thessaloniki
People	21.69	20.73	21.70
Lights	7.06	7.06	7.06
Equipment	36	36	36
Windows	76.21	88.76	88.65
Infiltration	1.14	1.87	1.45
Others	3.79	7.73	5.37
Total	145.89	162.15	160.23

**Table 40 – Total annual heat gains for the three cities**

It is noticed that, differences in total annual heat gains for all the cities have been normalized. However, there were large differences for individual factor, e.g. fenestration surfaces and infiltration of the building.

Figure 55 shows the distribution of annual heating gains due to different load factors:



**Figure 55 – Distribution of annual heat gains due to different load factors**

It is observed that almost half of the gains come from the fenestration surfaces of the building. Great factors are, also, the electric equipment and the human

occupancy. While, less affect have lighting, infiltration of the building and other factors.

Table 41 shows the monthly heat losses flow due to windows of the building, for each one of three cities in study:

Month	Heat losses due to windows (W/ m <sup>2</sup> )		
	Andravidia	Athens	Thessaloniki
January	2.26	2.11	2.75
February	2.24	2.27	2.72
March	2.11	2.02	2.13
April	1.70	1.65	1.64
May	1.63	1.50	1.53
June	1.43	1.27	1.34
July	1.37	1.03	1.16
August	1.49	1.10	1.27
September	1.77	1.53	1.81
October	2.01	2.06	2.15
November	1.83	1.84	2.31
December	2.02	2.15	2.55
Annual	19.85	18.49	20.93

Table 41 – Monthly heat losses flow due to windows in the three cities

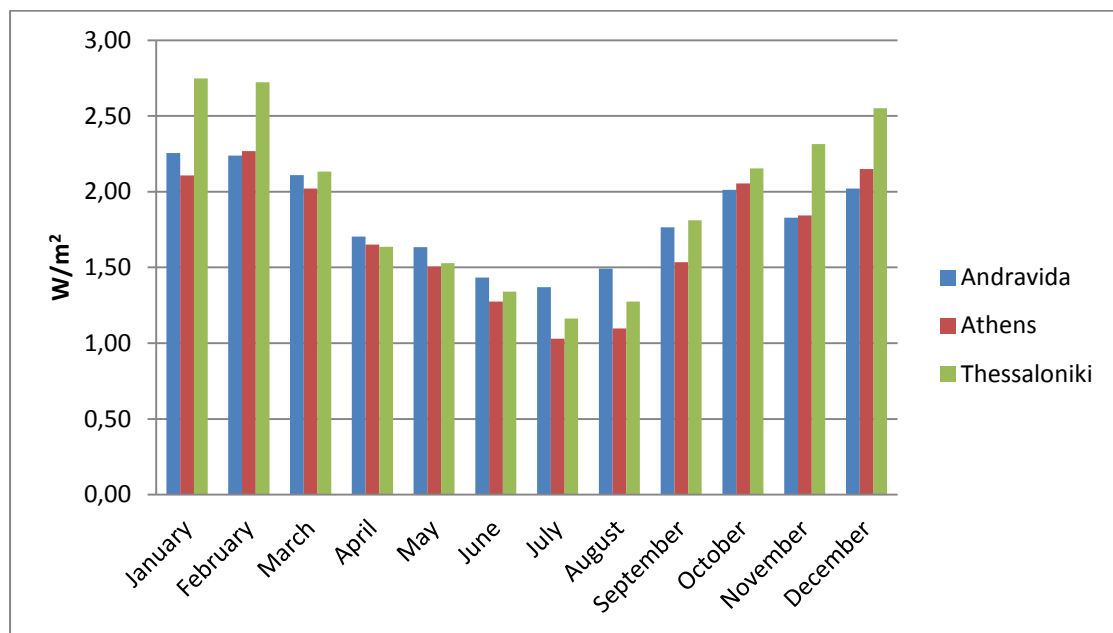


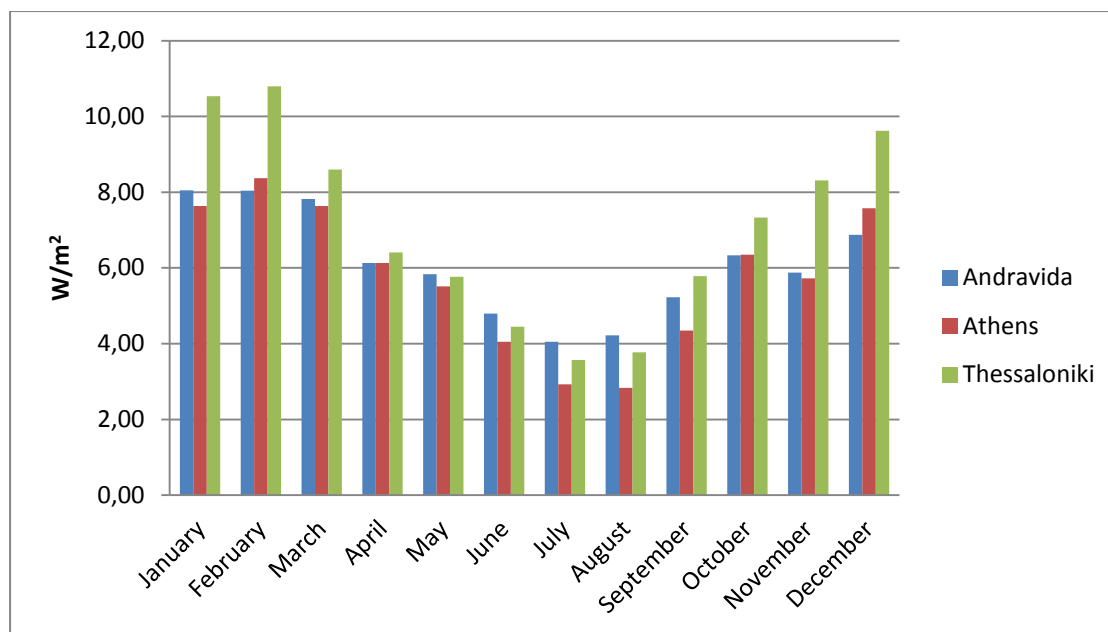
Figure 56 – Monthly heat losses flow due to windows in the three cities

Observing Figure 56, it is noticed that, Thessaloniki is the city with the largest heat losses ( $20.93 \text{ W/ m}^2$ ) due to fenestration surfaces of the building. This is can be explained by the reason that Thessaloniki has the most cold climate of all three cities. Remarkable is, the fact that Andravida has greater heat losses due to fenestration surfaces ( $19.85 \text{ W/ m}^2$ ) compare to Athens ( $18.49 \text{ W/ m}^2$ ) considering its geographical thesis.

Table 42 shows the monthly heat losses flow due to infiltration of the building, for each one of three cities in study:

Month	Heat losses due to infiltration ( $\text{W/ m}^2$ )		
	Andravida	Athens	Thessaloniki
January	8.05	7.64	10.53
February	8.04	8.37	10.79
March	7.82	7.63	8.60
April	6.13	6.13	6.41
May	5.84	5.51	5.77
June	4.80	4.05	4.44
July	4.05	2.93	3.57
August	4.22	2.83	3.77
September	5.22	4.35	5.78
October	6.34	6.35	7.33
November	5.88	5.72	8.31
December	6.88	7.57	9.62
Annual	73.26	69.08	84.92

**Table 42 – Monthly heat losses flow due to infiltration in the three cities**



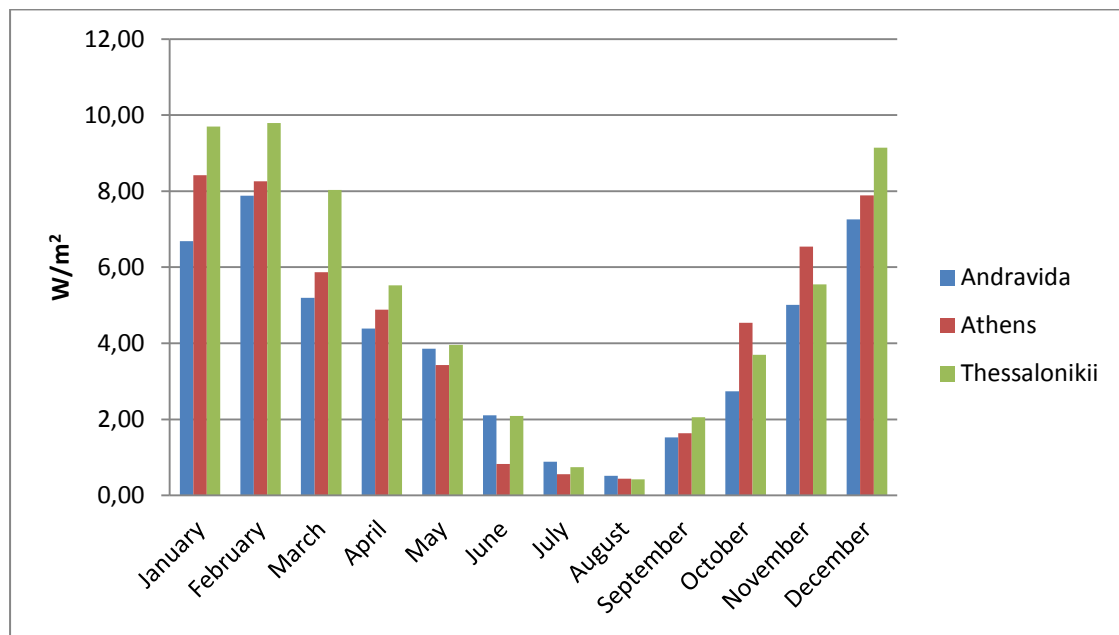
**Figure 57 – Monthly heat losses flow due to infiltration in the three cities**

Same as before, by observing Figure 57, it is noticed that, Thessaloniki is the city with the largest heat losses ( $84.92 \text{ W/ m}^2$ ) due to infiltration of the building. This is can be explained by the reason that Thessaloniki has the most cold climate of all three cities. Remarkable, again, is the fact that Andravida has greater heat losses due to infiltration ( $73.26 \text{ W/ m}^2$ ) compare to Athens ( $69.08 \text{ W/ m}^2$ ).

Table 43 shows the monthly heat losses flow of the building due to other factors, for each one of three cities in study:

Month	Heat losses due to other factors ( $\text{W/ m}^2$ )		
	Andravida	Athens	Thessaloniki
January	6.69	8.42	9.70
February	7.88	8.26	9.79
March	5.19	5.87	8.03
April	4.39	4.88	5.53
May	3.86	3.42	3.96
June	2.11	0.83	2.09
July	0.89	0.56	0.75
August	0.52	0.44	0.42
September	1.53	1.64	2.06
October	2.73	4.54	3.70
November	5.01	6.54	5.55
December	7.26	7.89	9.14
Annual	48.05	53.29	60.71

**Table 43 – Monthly heat losses flow due to other factors in the three cities**



**Figure 58 – Monthly heat losses flow due to other factors in the three cities**

Thessaloniki has the largest heat losses of 60.71 W/ m<sup>2</sup> due to other factors. Looking at Figure 58 , it is observed that Athens has the greatest amount of heat losses only for two months, October and November. Andravida has the least total heat losses of 48.05 W/ m<sup>2</sup> due to other factors.

Table 44 shows the total annual heat losses due to different factor in all three cities of study:

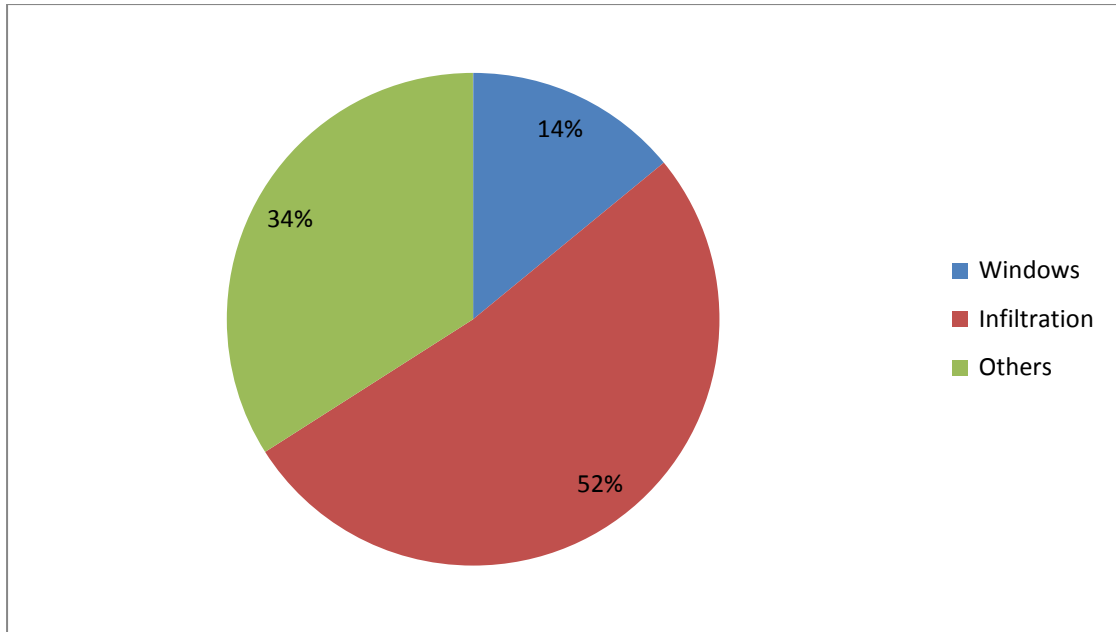
	Total annual heat losses (W/ m <sup>2</sup> )		
	Andravida	Athens	Thessaloniki
<b>Windows</b>	19.85	18.49	20.93
<b>Infiltration</b>	73.26	69.08	84.92
<b>Others</b>	48.05	53.29	60.71
<b>Total</b>	141.16	140.86	166.56

**Table 44 – Total annual heat losses for the three cities**

It is noticed that, differences in total annual heat losses for all the cities have been normalized. However, there were large differences for individual factor, e.g. fenestration surfaces and infiltration of the building.

Figure 59 shows the distribution of annual heating losses due to different load factors:

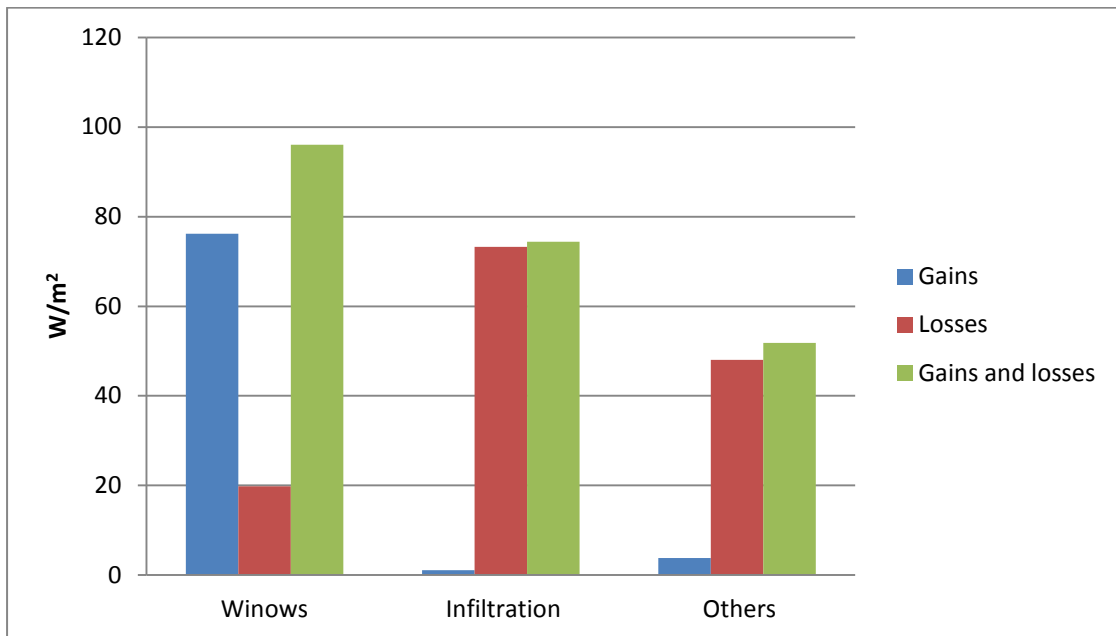




**Figure 59 – Distribution of total annual heat losses due to different load factors**

It is observed that almost half of the losses come from the infiltration of the building. Great factor is, also, some other factors. While, less affect have the fenestration surfaces of the building.

Last, Figure 60 shows total annual heat gains, losses and the combination of them due to different factors:



**Figure 60 – Heat gains and losses due to fenestration surfaces, infiltration of the building and other load factors**

It is noticed, that heat gains due to fenestration surfaces are greater than the losses. On the other hand, losses are greater than gains due to infiltration of the

building. Also, losses are greater than gains due to other factors. Also, it is observed that fenestration surfaces have the greatest thermal effect compare to the other factors.

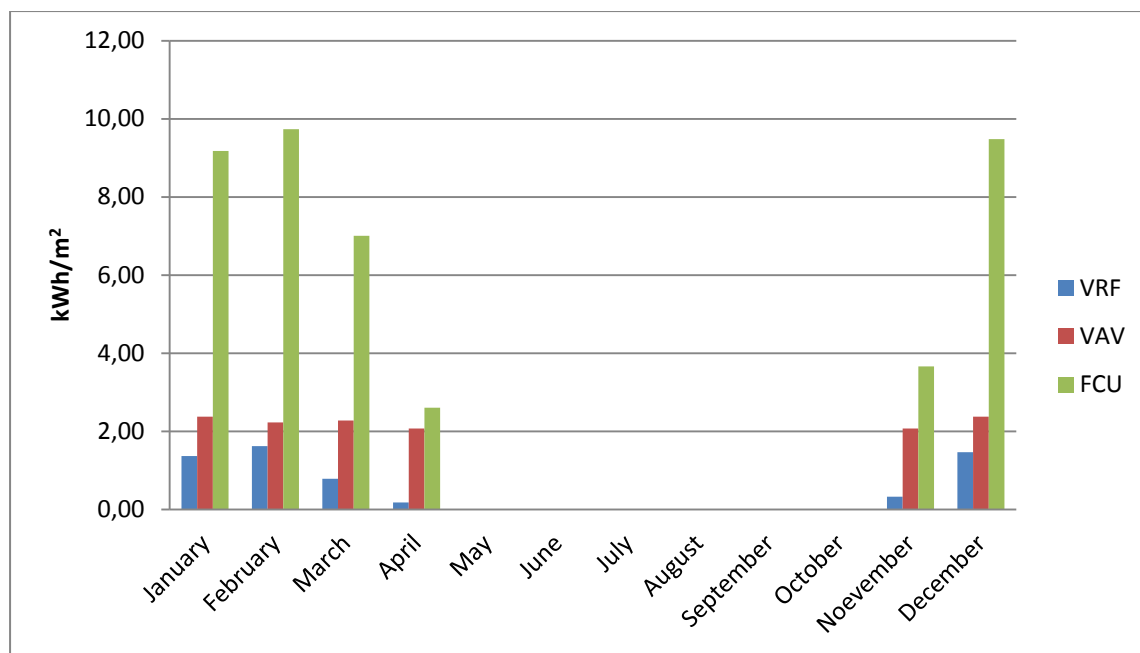
### 6.3. Comparative energy consumption and cost results between HVAC systems

The following tables show the total energy required for the heating and cooling of the building in study, using three different types of HVAC systems, in the city of Athens. For this, have been taken into consider, not only the amount of energy needed to heat or cool the building but also the amount of energy needed for the total operation of systems, i.e. fans and pumps. The results relate to the energy consumed by the building as a whole area, either for cooling or for heating or for the combination of the two, are expressed at surface-bound values, i.e. the energy is measured in kWh/ m<sup>2</sup>, and are presented collectively in tables quoting prices for all different HVAC systems.

Table 45, shows the total monthly and annual energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Heating (kWh/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	1.36	2.38	9.18
February	1.62	2.22	9.73
March	0.78	2.27	7
April	0.18	2.07	2.60
May	0	0	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	0
October	0	0	0
November	0.33	2.07	3.66
December	1.47	2.38	9.48
Annual	5.74	13.40	41.65

**Table 45 – Total energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**



**Figure 61 – Total energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

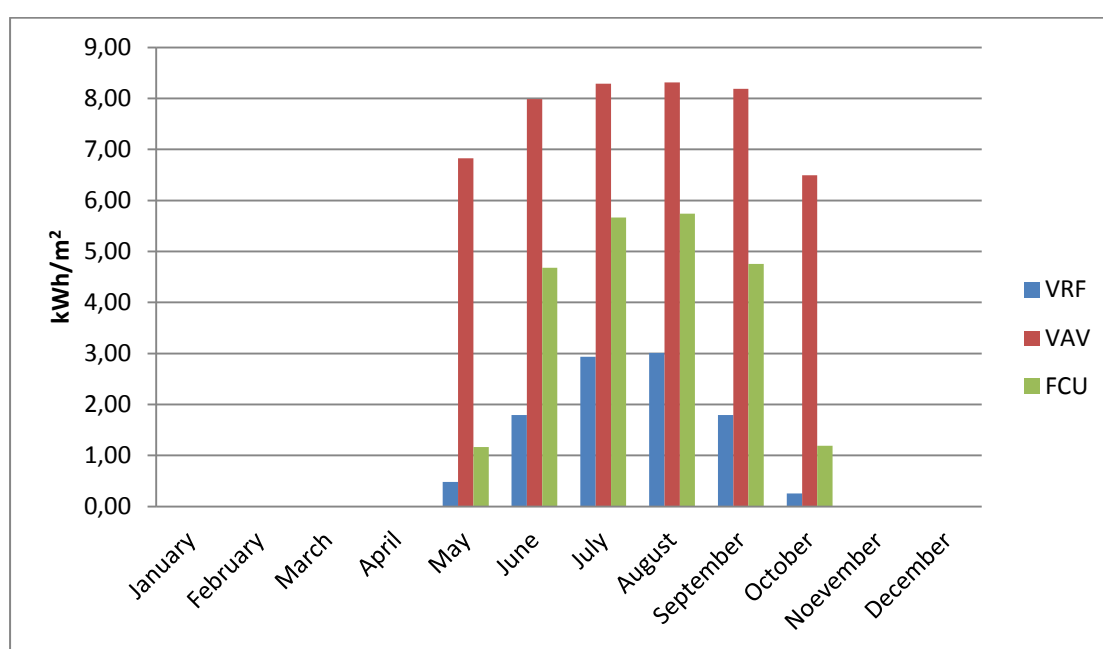
It is noticed that FCU has the largest annual energy consumption for heating, with 41.65 kWh/ m<sup>2</sup>, and VRF has the smallest, with 5.74 kWh/ m<sup>2</sup>, which is less almost seven times. It, also, seems that FCU needs almost triple consumption of heating energy, from the second most energy consuming system, VAV, which needs 13.40 kWh/ m<sup>2</sup>, with the biggest differences occurring in January, February, March and December. Looking, Figure 61, it is clear that the consumption of VAV system is almost the same during all the months, which is remarkable. For all systems, energy consumption is zero in May – October, due to the heating system's program as defined in the EnergyPlus Schedules field.

Table 46, shows the total monthly and annual energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Cooling (kWh/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0.48	6.82	1.16
June	1.79	7.99	4.68
July	2.93	8.29	5.66
August	3.01	8.32	5.74

Month	Cooling (kWh/ m <sup>2</sup> )		
	VRF	VAV	FCU
September	1.79	8.19	4.75
October	0.25	6.50	1.19
November	0	0	0
December	0	0	0
Annual	10.26	46.10	23.18

**Table 46 – Total energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**



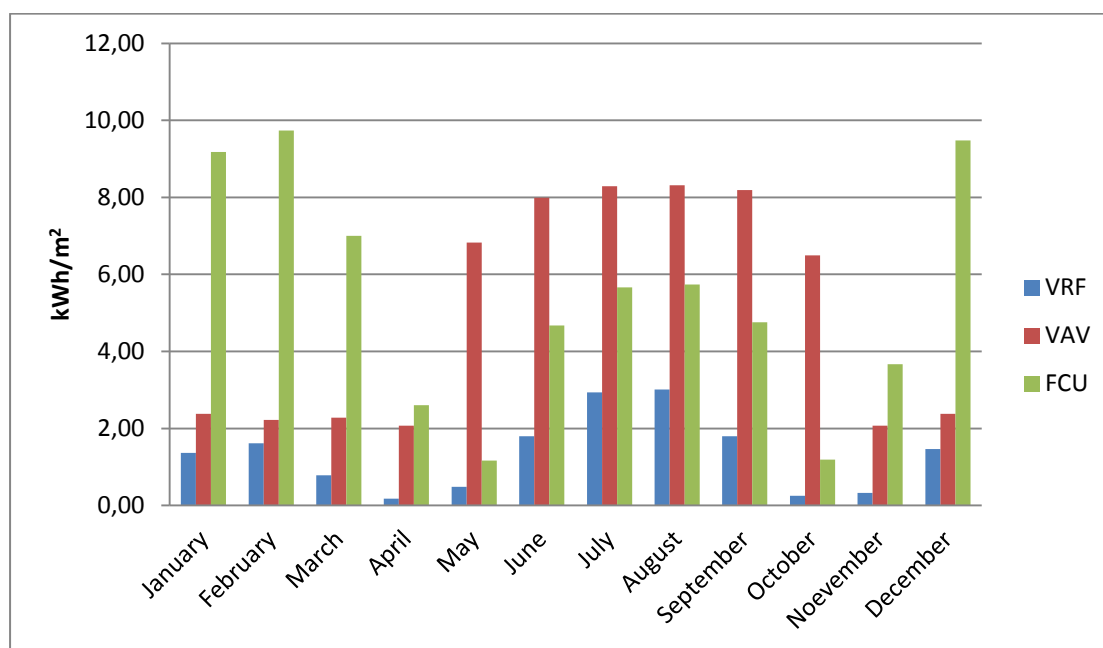
**Figure 62 – Total energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

It is noticed that VAV has the largest annual energy consumption for cooling, with 46.10 kWh/ m<sup>2</sup>, and VRF has the smallest, with 10.26 kWh/ m<sup>2</sup>, which is less almost four times. It, also, seems that VAV needs almost double consumption of cooling energy, from the second most energy consuming system, FCU, which needs 23.18 kWh/ m<sup>2</sup>, with the biggest differences occurring in May and October. Looking, Figure 62, it is clear that the consumption of VAV system needs large amount of energy even for months May and October, which is remarkable. For all systems, energy consumption is zero in January – April and November – December, due to the cooling system's program as defined in the EnergyPlus Schedules field.

Table 47, shows the total annual energy consumption for both heating and cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Heating and Cooling (kWh/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	1.36	2.38	9.18
February	1.62	2.22	9.73
March	0.78	2.27	7
April	0.18	2.07	2.60
May	0.48	6.82	1.16
June	1.79	7.99	4.68
July	2.93	8.29	5.66
August	3.01	8.32	5.74
September	1.79	8.19	4.75
October	0.25	6.50	1.19
November	0.33	2.07	3.66
December	1.47	2.38	9.48
Annual	16.00	59.50	64.83

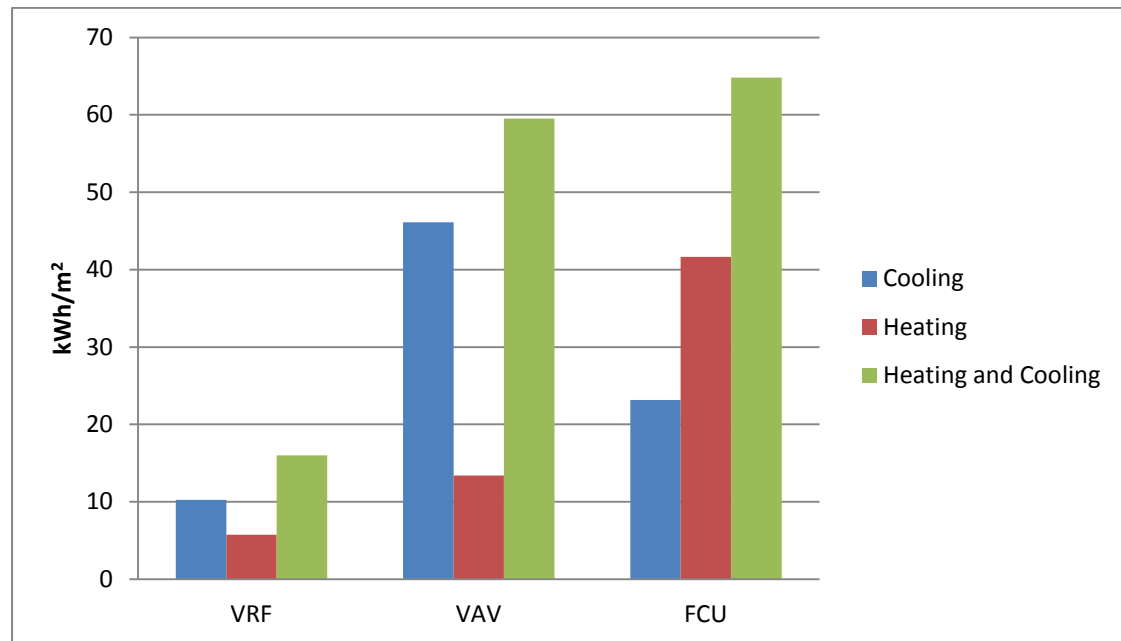
**Table 47 – Total energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU system**



**Figure 63 – Total energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

It is noticed that, differences in annual energy consumption between VAV, needs 59.50 kWh/ m<sup>2</sup>, and FCU, needs 64.83 kWh/ m<sup>2</sup>, have been normalized. Although, VAV requires larger amounts of energy for cooling, while, FCU requires larger amounts of energy for heating. Looking, Figure 63, it is clear that VRF needs the smallest amount of energy, with 16.00 kWh/ m<sup>2</sup>, which is less almost four times from the first most energy consuming system, FCU, with the biggest differences occurring in January, February, March and December.

Figure 64, shows the annual energy consumption for heating, cooling and the combination of these in each alternative scenario:



**Figure 64 – Heating, cooling and total energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU**

It is noticed that, using the VAV system the energy consumption for cooling is almost triple than the energy needed for heating. While VRF system, needs twice as much as energy for cooling than for heating. On the contrary, FCU system requires twice as much as energy for heating than for cooling. Also, as it has been mentioned before, FCU system has the largest consumption of total energy, while VRF the lowest.

After having calculate the energy consumption of all three systems using Energy Plus, is time to calculate, also, the cost. All three of the systems were ordered to run with electricity. So, the cost was calculated by multiply the energy consumption, been calculated and presented above, with the cost in € of a kWh, which is  $0.08990 \text{ €/ kWh} + 13\% \cdot 0.08990 \text{ €/ kWh} = 0.10158$ . It is computed for monthly period and has no any limit of energy consumption amount. [33]

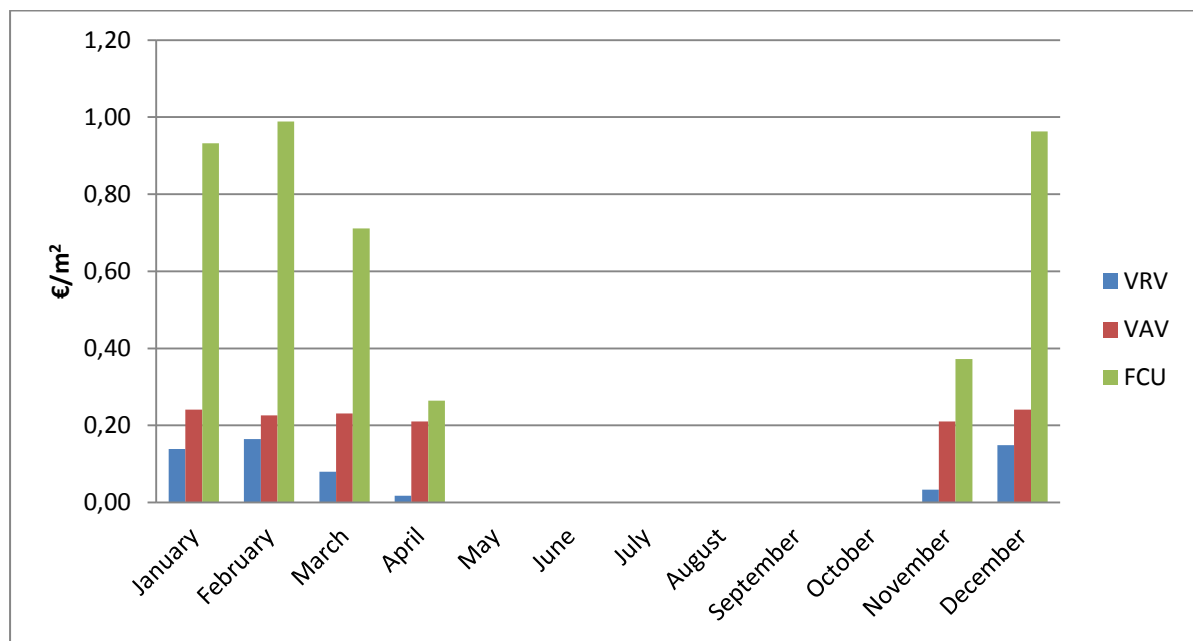
The following tables show the total cost of energy required for the heating and cooling of the building in study, using three different types of HVAC systems, in the city of Athens. The results relate to the cost of energy consumed by the building as a whole area, either for cooling or for heating or for the combination of the two, are expressed at surface-bound values, i.e. the cost is measured in €/

m<sup>2</sup>, and is presented collectively in tables quoting prices for all different HVAC systems.

Table 48, shows the total cost of energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Heating (€/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	0.14	0.24	0.93
February	0.16	0.23	0.99
March	0.08	0.23	0.71
April	0.02	0.21	0.26
May	0	0	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	0
October	0	0	0
November	0.03	0.21	0.37
December	0.15	0.24	0.96
Annual	0.58	1.36	4.23

**Table 48 – Total cost of energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**



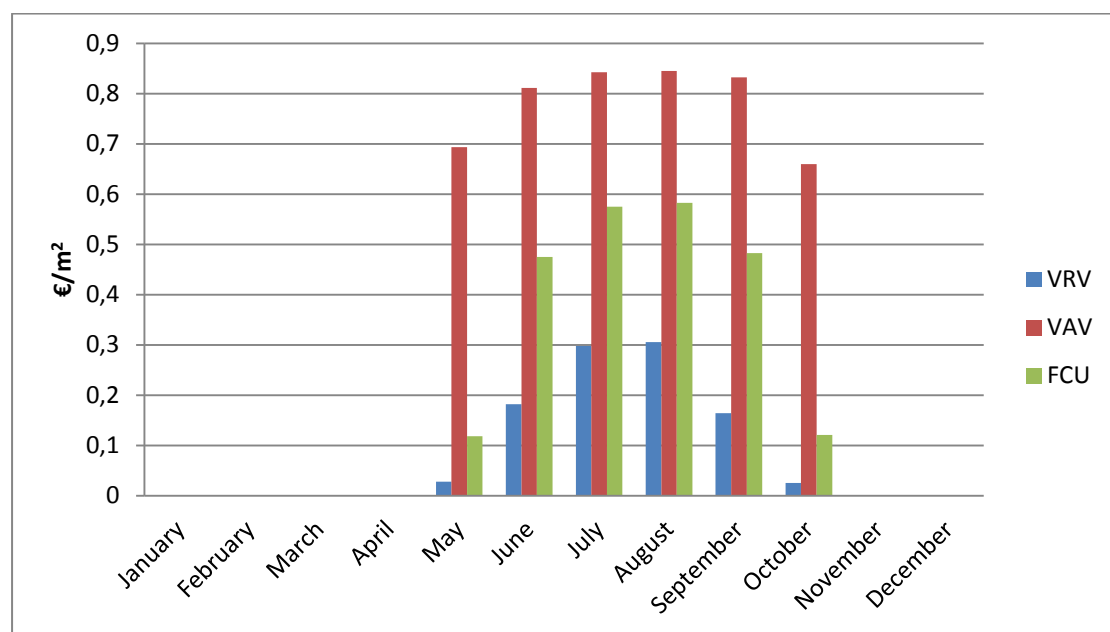
**Figure 65 – Total cost of energy consumption for heating in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

Figure 65, shows total cost of energy consumption for heating as expected. FCU system has the greatest operation cost of 4.23 €/ m<sup>2</sup>, which is sensible since it has the greatest energy consumption. Then, VAV has operation cost of 1.36 €/ m<sup>2</sup> and VRV has the lowest cost of 0.58 €/ m<sup>2</sup>.

Table 49, shows total cost of energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Cooling (€/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0.03	0.69	0.12
June	0.18	0.81	0.48
July	0.30	0.84	0.58
August	0.31	0.84	0.58
September	0.16	0.83	0.48
October	0.03	0.66	0.12
November	0	0	0
December	0	0	0
Annual	1	4.68	2.35

**Table 49 – Total cost of energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**





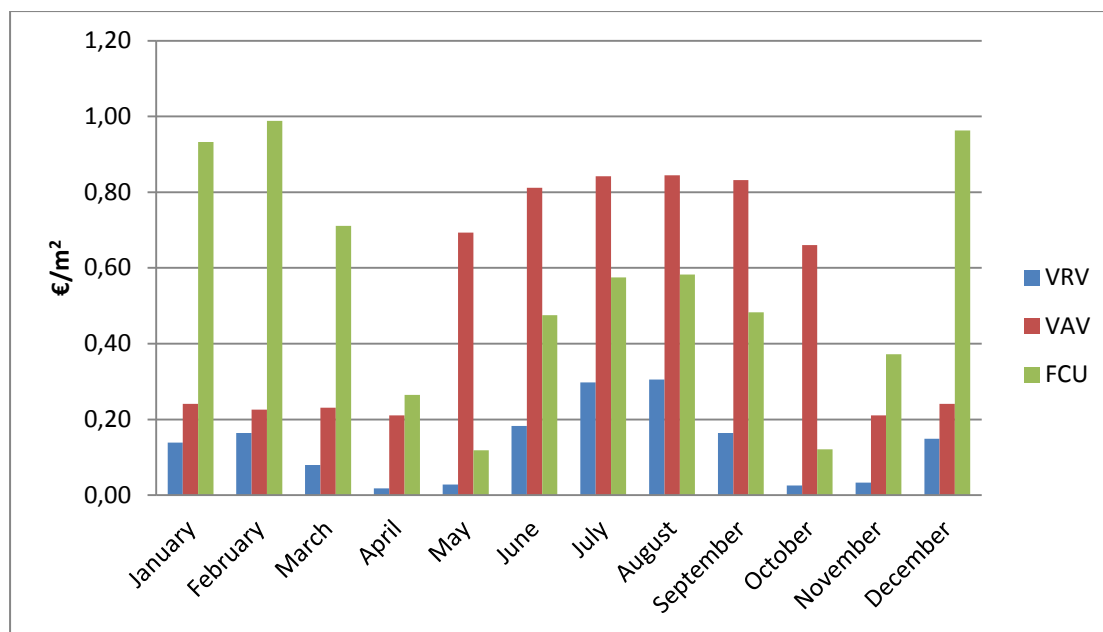
**Figure 66 – Total cost of energy consumption for cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

Figure 66, shows total cost of energy consumption for cooling as expected. VAV system has the greatest operation cost of 4.68 €/ m<sup>2</sup>, which is sensible since it has the greatest energy consumption. Then, FCU has operation cost of 2.35 €/ m<sup>2</sup> and VRF has the lowest cost of 1 €/ m<sup>2</sup>.

Table 50 shows the total annual cost of energy consumption for both heating and cooling in the city of Athens, bounded to the surface of the building, using VRF, VAV and FCU system:

Month	Heating and Cooling (€/ m <sup>2</sup> )		
	VRF	VAV	FCU
January	0.14	0.24	0.93
February	0.16	0.23	0.99
March	0.08	0.23	0.71
April	0.02	0.21	0.26
May	0.03	0.69	0.12
June	0.18	0.81	0.48
July	0.30	0.84	0.58
August	0.31	0.84	0.58
September	0.16	0.83	0.48
October	0.03	0.66	0.12
November	0.03	0.21	0.37
December	0.15	0.24	0.96
Annual	1.59	6.04	6.59

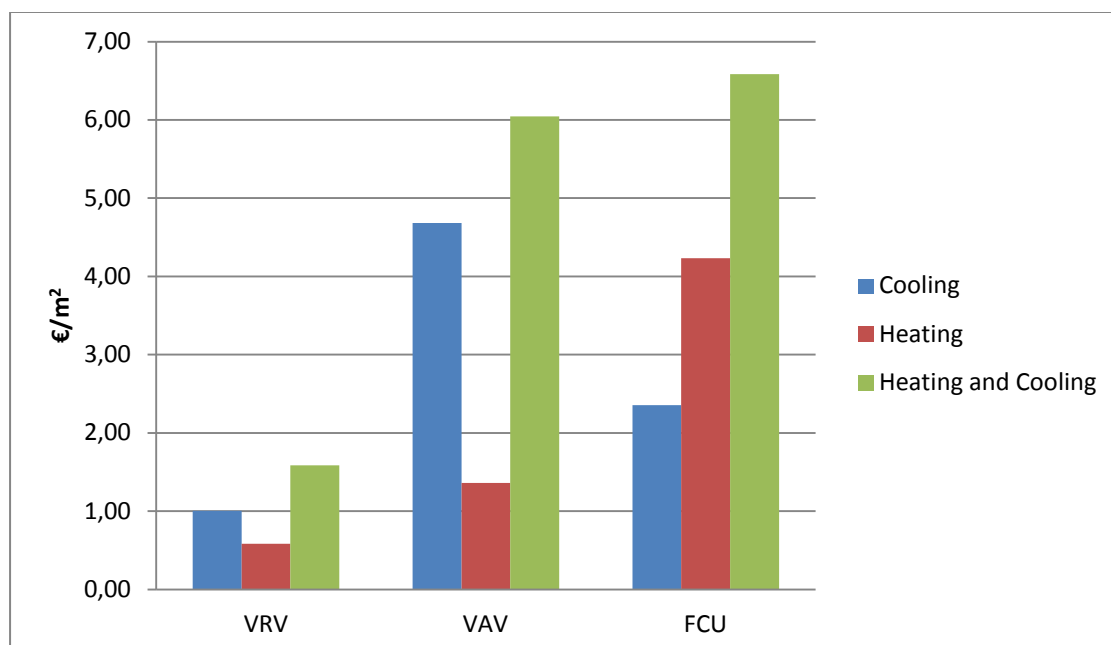
**Table 50 – Total cost of energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU system**



**Figure 67 – Total cost of energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU system**

Looking Figure 67 it is noticed that, differences in annual cost of energy consumption between VAV, needs 6.04 €/ m<sup>2</sup>, and FCU, needs 6.59 €/ m<sup>2</sup>, have been normalized. While, VRF system has the lowest operating cost, almost three times less that the other two, of 1.59 €/ m<sup>2</sup>.

Figure 68 shows the annual cost of energy consumption for heating, cooling and the combination of these in each alternative scenario:



**Figure 68 – Heating, cooling and total cost of energy consumption in Athens, bounded to the surface of the building, using VRF, VAV and FCU**

Looking Figure 68 it is noticed that, using the VAV system the cost of energy consumption for cooling is almost triple than the cost needed for heating. While VRF system, has twice as much as cost for cooling than for heating. On the contrary, FCU system has twice as much as cost for heating than for cooling. Also, as it has been mentioned before, FCU system has the largest total annual cost, while VRF the lowest.

#### **6.4. Conclusions**

So far, we have presented simulation's results referring a) to comparison of heating/ cooling loads and thermal gains/ losses between Athens, Andravida and Thessaloniki and b) to comparison of energy consumption and operation cost between three different HVAC systems, VRV, FCU and VAV. As far as the first one, while in partial results were not always as expected, the final and total results conclude in something reasonable, i.e. Thessaloniki consumes the largest heating loads of all three cities, Andravida consumes almost same amount for cooling and heating loads and Athens consumes, slightly, the largest amount of cooling load between all three cities.

For the second one, results were the expected; with VRV system has the lowest energy consumption, as well as, the lowest operation cost. While FCU system has the largest energy consumption, which is reasonable, since, it is a heavy system, more often be used for industrial installations. As far as VAV system, has slightly less energy consumption than FCU system, but it is remarkable to mention that VAV system has largest energy consumption for cooling between all three HVAC systems.

## Chapter 7 Sizing and Installation cost of three HVAC systems

In this chapter, we will analyze the installation cost of basic components of each of the three HVAC systems. It has been assumed that all three systems are going to be installed in Athens in Greece (N37°54', E23°43'). In order to achieve this, first we need to make a primary sizing of the three systems that could cover the building's needs as presented in the previous section. It should be mentioned that, calculation data are not considered as accurate, since as an air conditioning system that is intended to cover a building's needs to be further studied.

### 7.1. HVAC systems sizing

We will begin by sizing the Variable Refrigerant Volume (VRV) system by thermal zones of the building. We also need to clarify that in systems that offer both cooling and heating sizing is based on the period with the most demanding needs. Taking into account what has been said the table below follows:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.26	0.16	0.26
Thermal zone 3	0.51	0.31	0.51
Thermal zone 4	0.21	0.13	0.21
Thermal zone 6	0.07	0.04	0.07
Thermal zone 8	0.22	0.13	0.22
Thermal zone 9	0.16	0.10	0.16
Total	1.44	0.86	1.44

Table 51 – VRV system sizing in Athens

Then, Variable Air Volume (VAV) system sizing follows:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.67	0.03	0.67
Thermal zone 3	1.31	0.06	1.31
Thermal zone 4	0.55	0.03	0.55
Thermal zone 6	0.19	0.01	0.19
Thermal zone 8	0.56	0.03	0.56
Thermal zone 9	0.42	0.02	0.42
Total	3.69	0.18	3.69

Table 52 – VAV system sizing in Athens

Last, Fan Coil Unit (FCU) system sizing table follows:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.46	1.03	1.03
Thermal zone 3	0.90	2.01	2.01
Thermal zone 4	0.38	0.85	0.85
Thermal zone 6	0.13	0.29	0.29
Thermal zone 8	0.38	0.85	0.85
Thermal zone 9	0.29	0.65	0.65
Total	2.54	5.67	5.67

**Table 53 – FCU system sizing in Athens**

## 7.2. Components

After sizing all three HVAC systems, the individual components must be selected. The components choices, based on the cooling and thermal loads required by the conditioned thermal zones of the building, are based on the technical specifications defined by the manufacturers.

### 7.2.1. VRV system components

First, for the VRV system, we need a heat pump with refrigeration fluid that takes care of the cooling and heating of the building and terminal units in each of the air-conditioned thermal zone of the building. Also, the same heat pump with built-in adapters is the one that assumes the circulation of refrigeration fluid without the need for circulators.

#### 7.2.1.1. VRV system terminal units

In the table below, the terminal units for the VRV system are selected:

A/A Thermal zone	Use	Type	Quantity	Heating [kW]	Cooling [kW]
1	Kitchen	wall mounted	1	2.5	2
3	Living room	wall mounted	1	2.5	2
4	Bedroom 1	wall mounted	1	2.5	2
6	Bathroom	wall mounted	1	2.5	2
8	Bedroom 2	wall mounted	1	2.5	2
9	Bedroom 3	wall mounted	1	2.5	2
Total			6	15	12

**Table 54 – VRV system terminal units**

### 7.2.1.2. VRV system heat pump

The choice of power of the central heat pump of the VRV system depends not only on the total maximum load of the building, but also on the installed power of the terminal units as well as on their total number. All of the above contributes to eventually selecting a heat pump which is significantly stronger than the total loads of building or even the installed power of the terminal units. The following table shows the technical characteristics of the selected heat pump:

	Heating	Cooling
Power [kW]	15.5	15.5
Refrigerant fluid	R – 410A	

**Table 55 – VRV system heat pump**

According to the manufacturer, the above information applies to the following conditions:

- Cooling from -5°C to +52°C
- Heating from -20°C to +15.5°C

### 7.2.2. VAV system components

VAV system requires a heat pump to cover thermal load and a chiller to cover cooling load of the building. Also, terminal units needed for each of the conditioned thermal zone of the building.

#### 7.2.2.1. VAV terminal units

VAV system uses boxes as terminal units. For this study, single duct boxes were chosen. The following table shows the technical characteristics of chosen boxes for VAV system:

A/A Thermal zone	Use	Type	Quantity	Pressure [Pa]	Air flow [m <sup>3</sup> ]
1	Kitchen	Single duct box	1	69	150
3	Living room	Single duct box	1	69	150
4	Bedroom 1	Single duct box	1	69	150
6	Bathroom	Single duct box	1	69	150
8	Bedroom 2	Single duct box	1	69	150
9	Bedroom 3	Single duct box	1	69	150
<b>Total</b>			6		900

**Table 56 – VAV system terminal units**

### 7.2.2.2. VAV system heat pump and chiller

For VAV system we will use an air heat pump for heating loads and a water chiller for cooling loads, as it is determined in Energy Plus®. Following tables show the technical characteristics of selected boiler and chiller for VAV system:

	Heating
Power [kW]	6.02
Refrigerant fluid	R – 410A

**Table 57 – VAV system heat pump**

	Cooling
Power [kW]	17.40
Refrigerant fluid	R – 410A

**Table 58 – VAV system chiller**

### 7.2.3. FCU system components

As VRV system, FCU system will, also, require a single heat pump to cover the thermal and cooling load of the building and terminal units for each of the conditioned thermal zone of the building. Or we can have an alternative scenario, using a boiler for heating loads and a chiller for cooling loads. Again there are individual terminal units for each conditioned thermal zone.

#### 7.2.3.1. FCU system terminal units

In the table below, the terminal units for the FCU system are selected:

A/A Thermal zone	Use	Type	Quantity	Heating [kW]	Cooling [kW]
1	Kitchen	floor standing	1	2.46	2.46
3	Living room	floor standing	1	2.46	2.46
4	Bedroom 1	floor standing	1	2.46	2.46
6	Bathroom	floor standing	1	2.46	2.46
8	Bedroom 2	floor standing	1	2.46	2.46
9	Bedroom 3	floor standing	1	2.46	2.46
Total			6	14.76	14.76

**Table 59 – FCU system terminal units**

It should be mentioned that, FCU floor standing terminal units which were selected are 4 – piped and inverter.

### **7.2.3.2. FCU system heat pump**

The choice of heat power will be based on the thermal and cooling loads of the building as calculated in the previous chapter and not based on the installed power of the terminal units. According to these, the following table shows the technical characteristics of the selected inverter heat pump for the FCU system:

	Heating	Cooling
Power [kW]	17	16.60
Refrigerant fluid	R – 410A	

**Table 60 – FCU system heat pump**

### **7.2.3.3. FCU system boiler and chiller**

As an alternative scenario we can use a hot water boiler for heating cooling and a chilled water chiller for cooling loads. Following tables show the technical characteristics of selected boiler and chiller for FCU system:

	Heating
Power [kW]	6.1 – 21.00
Refrigerant fluid	R – 410A

**Table 61 – FCU system boiler**

	Cooling
Power [kW]	17.40
Refrigerant fluid	R – 410A

**Table 62 – FCU system chiller**

## **7.3. Installation costs analysis**

In this paragraph, we will calculate the total installation cost of all three HVAC systems. Prices were taken from Daikin’s price catalogue for 2017 [17]. It should be mentioned that prices are suggested by the manufacturer and may differ from market prices. Also, cost does not include human labor.

According to what mentioned above, total installation cost of the VRV system is analyzed in table Table 63:



A/A	Components	Quantity	Cost (€)
1	Heat pump	1	6846
2	Wall mounted unit	6	317
Total cost including VAT (24%)			8748

**Table 63 – VRV system installation cost**

Next, total installation cost of the VAV system is analyzed in Table 64:

A/A	Components	Quantity	Cost (€)
1	Heat pump	1	5848
2	Chiller	1	13349
3	Single duct box unit	6	1625
Total cost including VAT (24%)			28947

**Table 64 – VAV system installation cost**

Following, scenario with a single heat pump for both heating and cooling loads for FCU system total installation cost is analyzed in Table 65:

A/A	Components	Quantity	Cost (€)
1	Heat pump	1	14387
2	Floor standing unit	6	729
Total cost including VAT (24%)			18761

**Table 65 – FCU system installation cost, scenario A**

Last, scenario with a boiler for heating load and a chiller for cooling load for FCU system total installation cost is analyzed in Table 66:

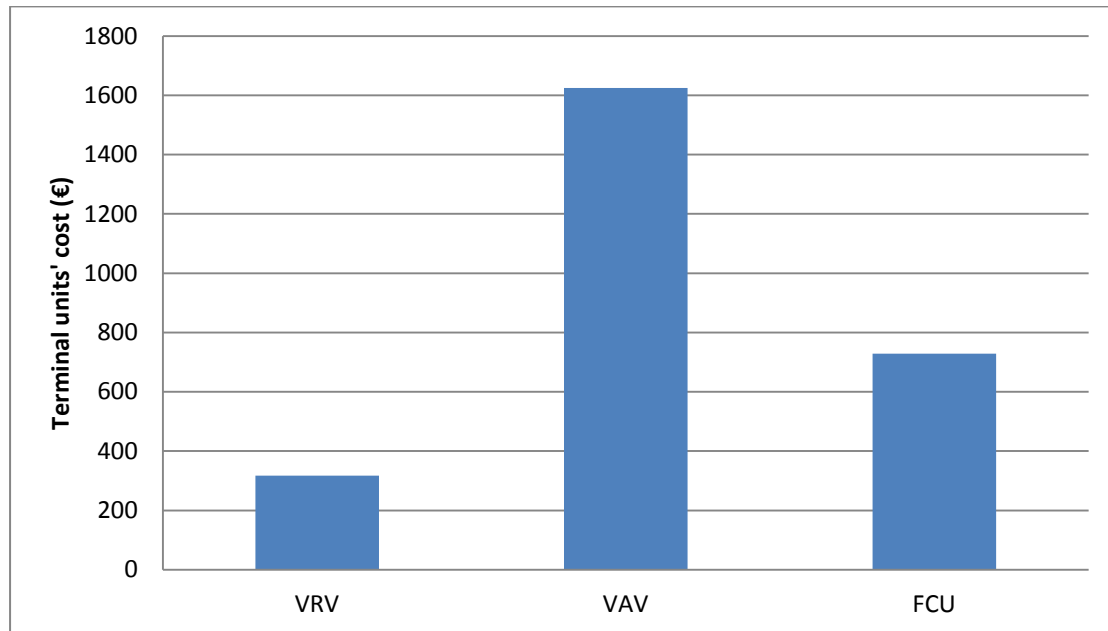
A/A	Components	Quantity	Cost (€)
1	Boiler	1	13349
2	Chiller	1	2155
3	Floor standing unit	6	729
Total cost including VAT (24%)			19878

**Table 66 – FCU system installation cost, scenario B**

#### 7.4. Comparison of installation costs

Following are figures comparing the installation cost of either the individual components or the HVAC systems as a whole, according to prices were calculated on paragraph above.

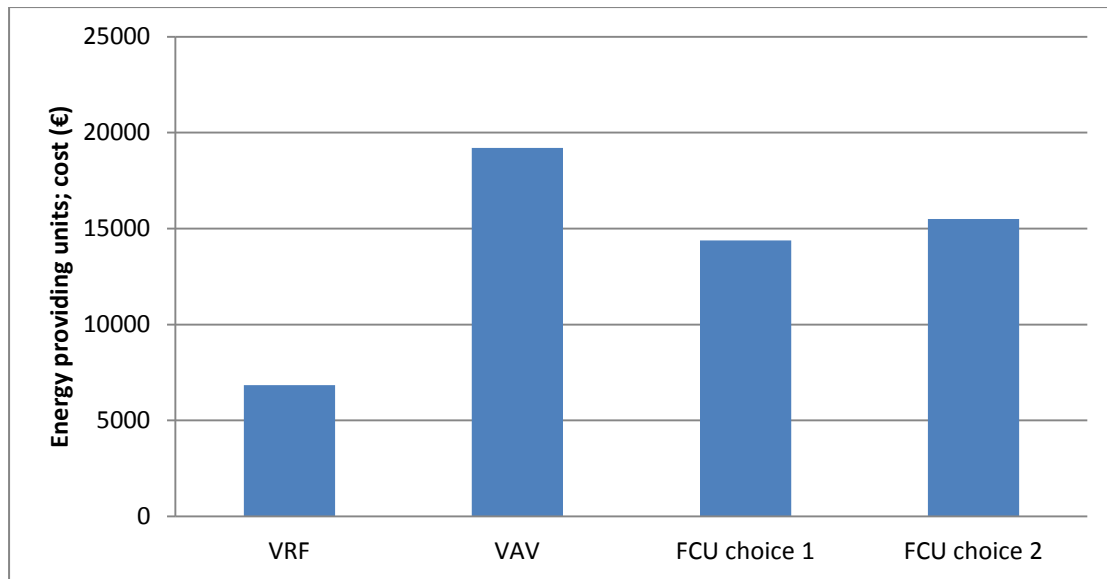
First, Figure 69 shows installation cost comparison between the terminal units of all three HVAC systems:



**Figure 69 – Comparison of terminal units' installation cost of the three different HVAC systems when the building is placed in Athens**

We can see that VAV system has the most expensive terminal units' installation cost. This is because of the technology used for VAV system is way to different from the technology used for the other two systems. The cheapest option is wall mounted units of VRV system.

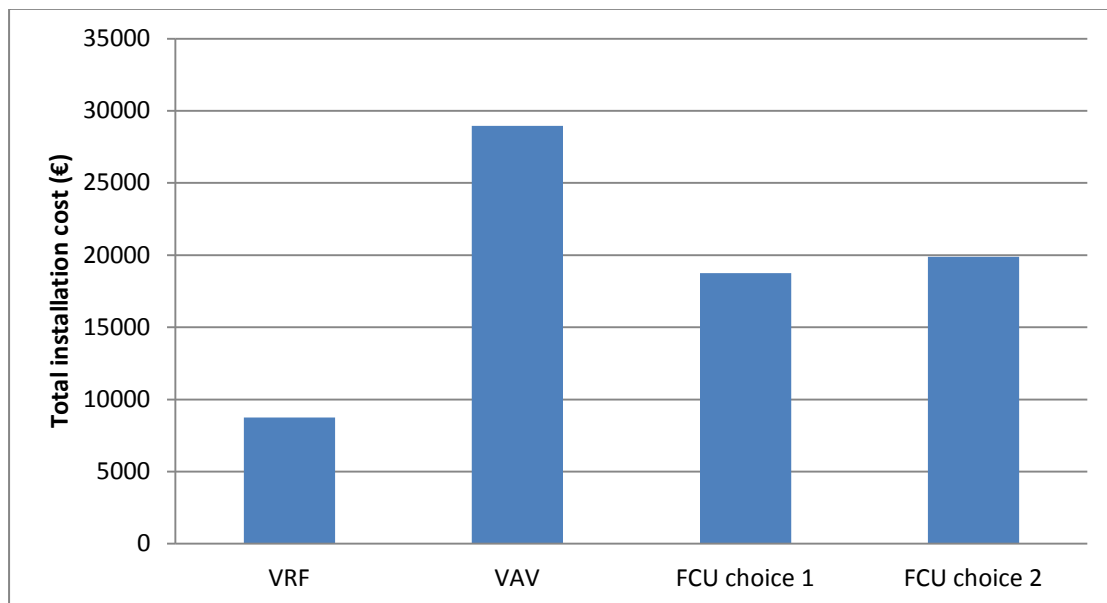
Then, shows installation cost comparison between the energy providing units of all three HVAC systems. Remember that, for FCU system case there are two different scenarios presented:



**Figure 70 – Comparison of energy providing units' installation cost of the three different HVAC systems when the building is placed in Athens**

Again, the cheapest option is the single heat pump of VRV system, cost less than the half price of the three other options. This is because VRV system chosen for this study is the simplest of all, since it is was design to be an all air system.

Last, Figure 71 shows the total installation cost of all three HVAC systems:



**Figure 71 – Comparison of total installation cost of the three different HVAC systems when building is placed in Athens**

As expected, VRV system has the lowest total installation cost of all three HVAC systems. While, VAV system has the most expensive total installation cost which is mostly due to terminal units' cost, as it was mentioned before.

## Chapter 8 Conclusions

### 8.1. Conclusion

In this diploma, a HVAC system is modeled. A double-storey house is designed and studied in three different Greek cities, Andravida (N37°55', E21°16'), Athens (N37°54', E23°43'), and Thessaloniki (N40°31', E22°58'). We found that the three cities have different thermal load requirements. Through different scenarios were simulated in Energy Plus®. This context some very basic conclusions about the energy behavior of buildings have been issued.

Based on the methodology applied and analyzed in the previous chapters, it is calculated that Thessaloniki has the largest thermal load consumption, needs 27.10 W/ m<sup>2</sup> annually, when Athens needs 20.92 W/ m<sup>2</sup> and Andravida 18.27 W/ m<sup>2</sup>. It is also worth mentioning that Andravida needs the same amounts of cooling and heating loads, Athens needs twice as much as cooling load than heating load, while for Thessaloniki is vice versa, twice as much as heating load than cooling load. This demonstrates the fact that in a place like Greece, with a temperate climate, but without overriding a season (e.g. winter or summer) attention should be paid to the behavior of each building in both heating and cooling.

The observations resulting from the presentation and analysis of the results refer to the overall assessment of the simulation calculation process applied in each case. The results are generally considered satisfactory; however, the individual results were unexpected. So, buildings should be considered in their overall operation for needs in heating and cooling loads, as this separation does not serve anything, nor does it reflect the real requirements of the building, in essence. Also, as part of a more general energy approach, importance should be given to any other form of energy consumed by the building for its operation, i.e. electric equipment.

Assessing the results further, it is a clear that in areas with temperate climates, such as Greece, where there are not seasons, winter or summer, the use of HVAC systems seems needless during the months of April, May and October, when there is the lowest energy consumption in all three cities. Since the saving and rational use of energy in the building sector is now imperative, it can be said that the use of HVAC systems can be an economical and non-energy-consuming solution for heating and cooling buildings, when used in moderation.

Next in this study we had, also, a look at thermal gains and losses. That was a way to understand how the external environment affects in the internal temperature of the building. For Athens and Thessaloniki, results showed that thermal losses have greater impact than thermal gains. While, for Andravida this works vice versa, with thermal gains have greater impact than thermal losses. It should also be mentioned that as far as the thermal gains greater affect have all fenestration surfaces, in percent 55%, then is electric equipment, in percent 22%, and also human activity in percent 13%. While, as far as thermal losses greater affect has the infiltration of the building, in percent 52% and also all fenestration surfaces in percent 14%. According to this we can conclude that fenestration surfaces have a great affect in both thermal gains and losses.

Now, as far as the comparison of the operating costs of the three different HVAC systems, VRF system has the lowest energy consumption and therefore the lowest operating cost of 1.59 €/ m<sup>2</sup>. The other two systems, VAV and FCU, have almost the same operating cost with the second one have slightly higher cost of 6.59 €/ m<sup>2</sup>, while VAV's operation cost is 6.04 €/ m<sup>2</sup>. At this point it should be mentioned that for this study VRF system was designed to be an all air conditioning system, FCU was design to be an all water system and VAV was designed as an air – water conditioning system. According to this and, also, having in mind the results, we can come to the general conclusion that all air conditioning systems have the lowest operation cost, which is reasonable, since they do not use any chillers or boiler for heating or cooling water, which are also energy consuming devices.

Last in this study is seen the installation cost of the three different HVAC systems. Different individual components were selected according to the needs and specifications of each HVAC system. Prices were calculated according to Daikin's price catalogue for 2017 and may differ from other manufactures. Results showed that VRV system has the lowest installation cost of all three systems, of total value of 8748 €, while VAV has the greatest installation cost, of total value of 28947 €. For FCU system case two different installation scenarios were made. The first one, with a single heat pump for both cooling and heating has total cost of 18761 €, while, the second one, with a boiler for heating and a chiller for cooling, has slightly greater cost of 19878 €. This time results cannot come to a general conclusion, because installation cost does not only depends in the technology of each HVAC system but also has to do with the power offered and needed.

For the specific building in study we can consider that VRV system option is the best choice, since it has both the lowest operation and installation cost. In this point it should be mentioned that the other two systems, VAV and FCU, are usually used in large industrial or business facilities where great amounts of power needed. So, VAV and FCU systems are not suitable for the building in study, because their rated output power is greater than the power needed.

Finally, it must be acknowledged the incompleteness of this diploma thesis and the need for further study. The present study was at a primary stage of research, but if having more data and details needed for such simulations and studies, the result would certainly be the most realistic.

## References

### Books:

- [1] Clarke, J.A. Energy Simulation in Buildings Design; Second Version; Butterworth-Heinemann; Glasgow, Scotland; 2001
- [2] ASHRAE Handbook, "2008 HVAC Systems and Equipments", 2008 Revision
- [3] ASHRAE Handbook, "2007 HVAC Applications", 2007 Revision
- [4] McQuiston, Parker, Spitler, "Heating, ventilation and Air conditioning – Analysis and Design", Wiley student publication. 6th Edition, 2014
- [5] Carrier Air Conditioning Company, "Handbook of Air conditioning system design", McGraw Hill New York. 2000 Edition
- [6] Edward G. Pita, "Air conditioning Principles and systems", Prentice Hall India publication. 4th Edition, 2012
- [7] Vaughn Bradshaw. The Building Environment: Active and Passive Control Systems, 3rd Edition, Wiley

### Papers:

- [8] International Journal of Innovative Research in Science, Engineering and Technology; Basic Classification of HVAC Systems for Selection Guide, April 2016
- [9] Dandan Zhu, Tianzhen Hong, Da Yan, Chuang Wang. Comparison of Building Energy Modeling Programs: Building Loads, June 2012
- [10] EnergyPlus™ Engineering Reference, September 2017
- [11] Da Yan and Yi Jiang, An Overview of an Integrated Building Simulation Tool – Designer's Simulation Toolkit (DeST)
- [12] Drury, Crawley; Hand, Jon W.; Kummert, Michael; Griffith, Brent, Contrasting the Capabilities of Building Energy Simulation Software tools. Energy Performance Simulation Software tools, U.S. Department of Energy, Energy Systems Research Unit, University of Wisconsin-Madison; National Renewable Energy Laboratory; Version 1.0; July 2005
- [13] DOE-2 Engineers Manual Version 2.1A
- [14] DOE-2 Basics Version 2.1 E
- [15] Getting Started, EnergyPlus™ version 8.8.0 (2017)
- [16] T.O.T.E.E. 20701 – 1/2017, "Detailed national parameter specifications for calculating the energy performance of buildings and issuing the energy performance certificate", 1st Edition (in Greek)
- [17] Daikin 2017 Price List

### **Websites:**

- [18] Applications of air conditioning; available from <http://www.allsubjects4you.com/applications-of-air-conditioning.htm>
- [19] European commission – Topics, Energy Efficiency of Buildings; available from <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>
- [20] Greek ministry of environment, energy and climate change – Article 6, Climate zones; available from <http://www.opengov.gr/minenv/?p=189> (in Greek)
- [21] EPPO Standard PP1/241(1), Guidance on comparable climates; available from [https://www.eppo.int/PPPRODUCTS/ppp\\_standards/comparable\\_climates.htm](https://www.eppo.int/PPPRODUCTS/ppp_standards/comparable_climates.htm)
- [22] HVAC DESIGN: SELECTING AIR CONDITIONING SYSTEMS; available from [http://servicesconsultant.blogspot.gr/2011/03/hvac-design-selecting-air-conditioning\\_08.html](http://servicesconsultant.blogspot.gr/2011/03/hvac-design-selecting-air-conditioning_08.html)
- [23] HVAC machinery; Single duct, constant volume, multi zone system; available from <http://machineryequipmentonline.com/hvac-machinery/multiple-zone-air-systemssingle-duct-zoned-reheat-constant-volume-systems/>
- [24] HVAC machinery; Multiple Zone Air Systems: Constant Volume; available from <http://machineryequipmentonline.com/hvac-machinery/multiple-zone-air-systemsconstant-volume-dual-duct-all-air-systems/>
- [25] Variable Refrigerant Flow or VRF Systems - HVAC system; available from <https://www.linkedin.com/pulse/variable-refrigerant-flow-vrf-systems-hvac-system-s-m-ali>
- [26] Air conditioning installation; available from <http://www.designproductsrca.com/tag/air-conditioning-installation/>
- [27] Basic components of air conditioning; available from <https://www.slideshare.net/servproofgreatneck/hvac-basic-concepts-of-air-conditioning>
- [28] Understanding noise control; available from <http://www.citysoundproofing.com/index.php/library/23-hvac-applications>
- [29] University of Strathclyde, Glasgow, ESP-r Overview; available from [http://www.esru.strath.ac.uk/Programs/ESP-r\\_overview.htm](http://www.esru.strath.ac.uk/Programs/ESP-r_overview.htm)
- [30] TRANSSOLAR software – TRNSYS Overview; available from [http://www.trnsys.de/docs/trnsys/trnsys\\_uebersicht\\_en.htm](http://www.trnsys.de/docs/trnsys/trnsys_uebersicht_en.htm)
- [31] TESS – Thermal Energy Systems Specialists, TRNSYS Overview; available from <http://www.tess-inc.com/trnsys>
- [32] <https://www.worldweatheronline.com>
- [33] <https://www.zenith.gr>
- [34] EnergyPlus weather data; available from <https://energyplus.net/weather>

## Appendix A Normalized diagrams

Following diagrams Figure 72 – Figure 78 present normalized values of thermal loads needed in different cities and energy consumption of different HVAC types in Athens:

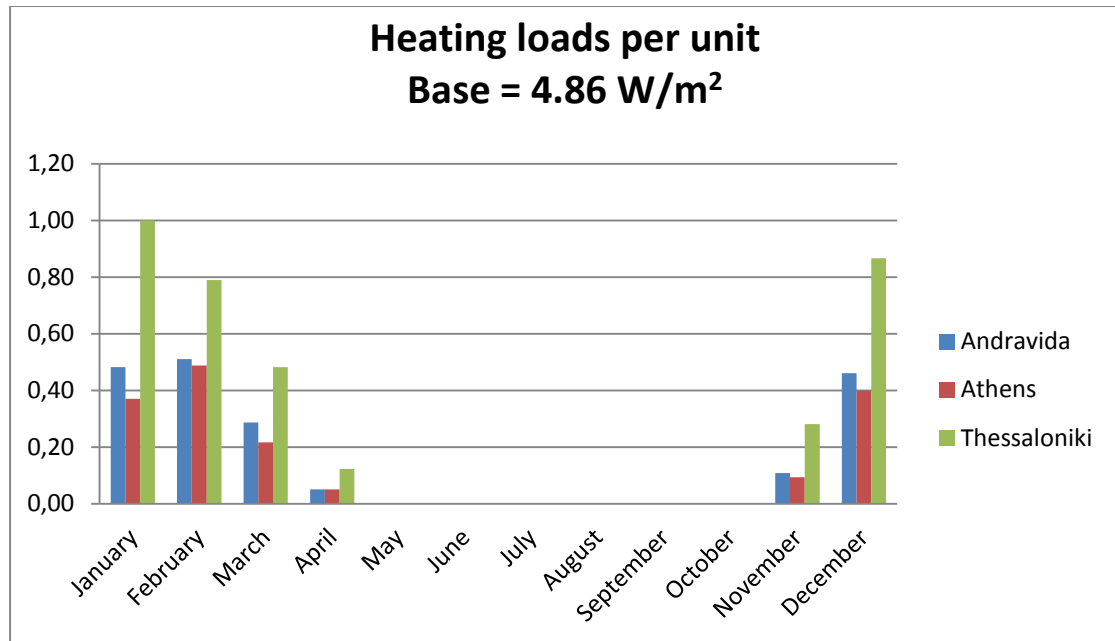


Figure 72 – Heating loads per unit in three different cities

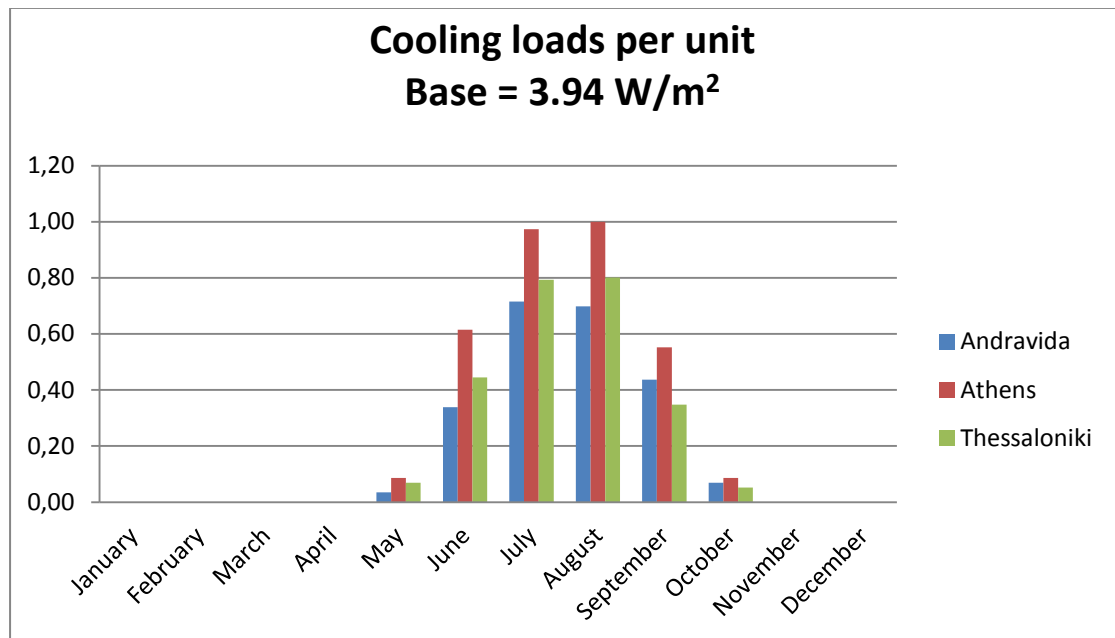


Figure 73 – Cooling loads per unit in three different cities



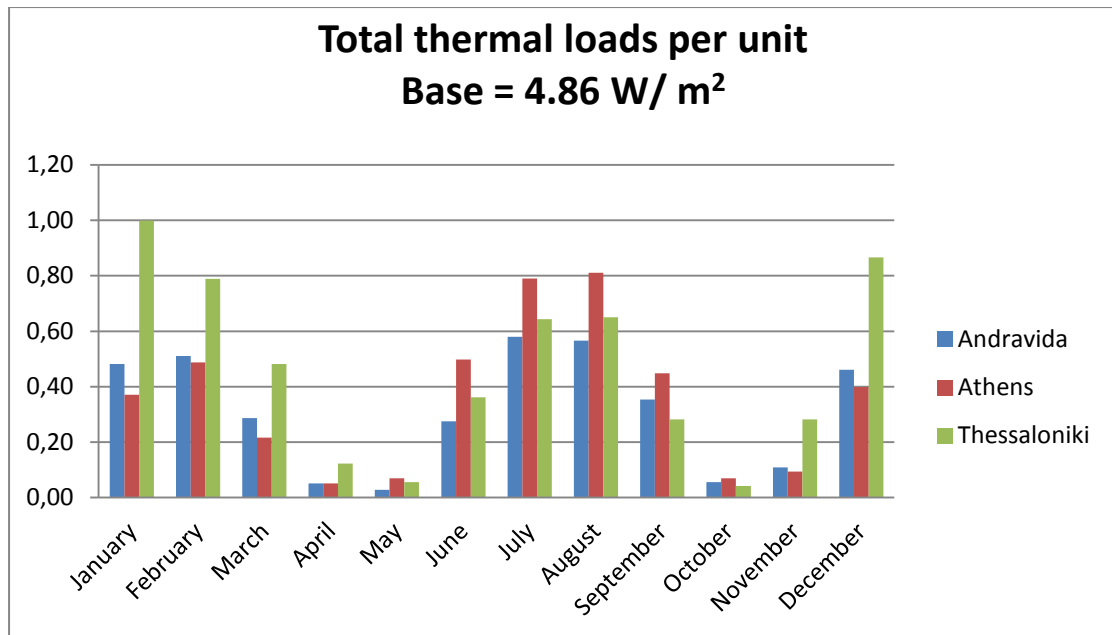


Figure 74 – Total thermal loads per unit in three different cities

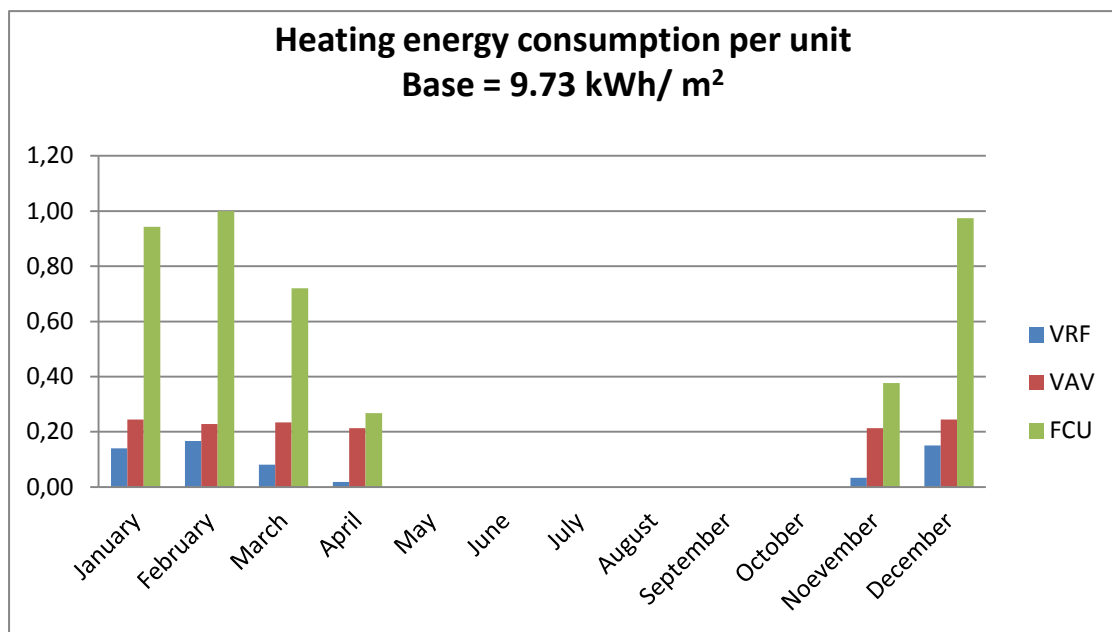
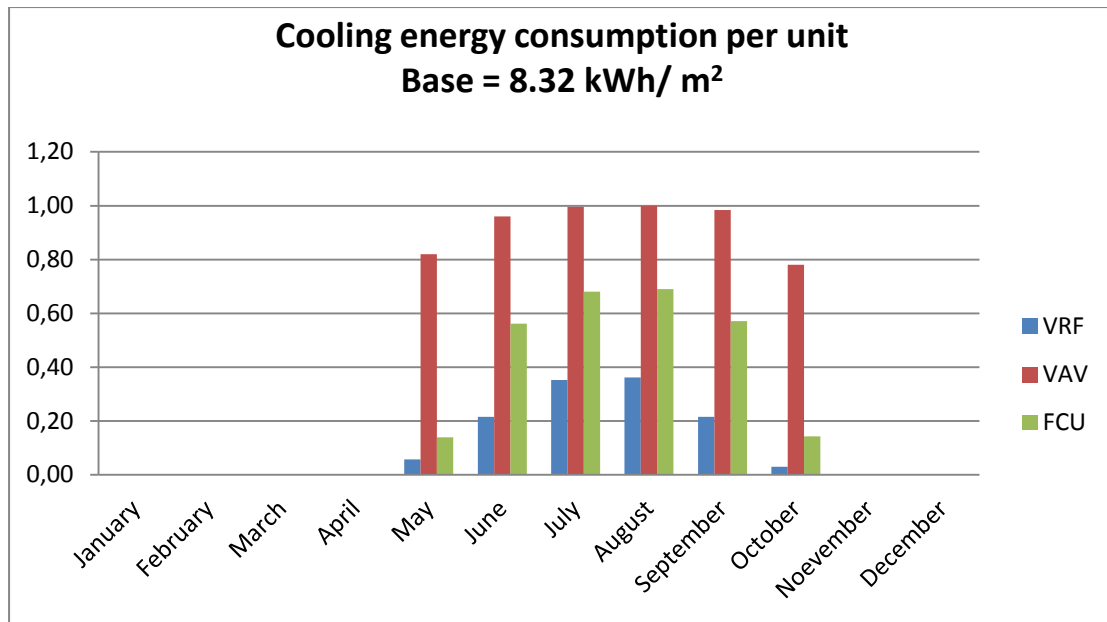
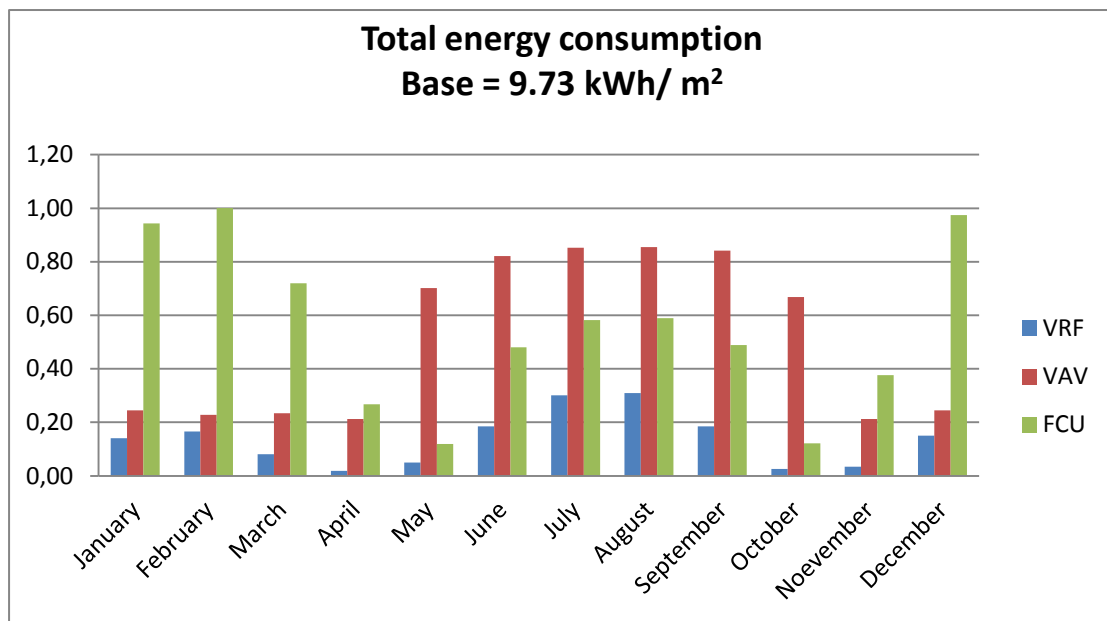


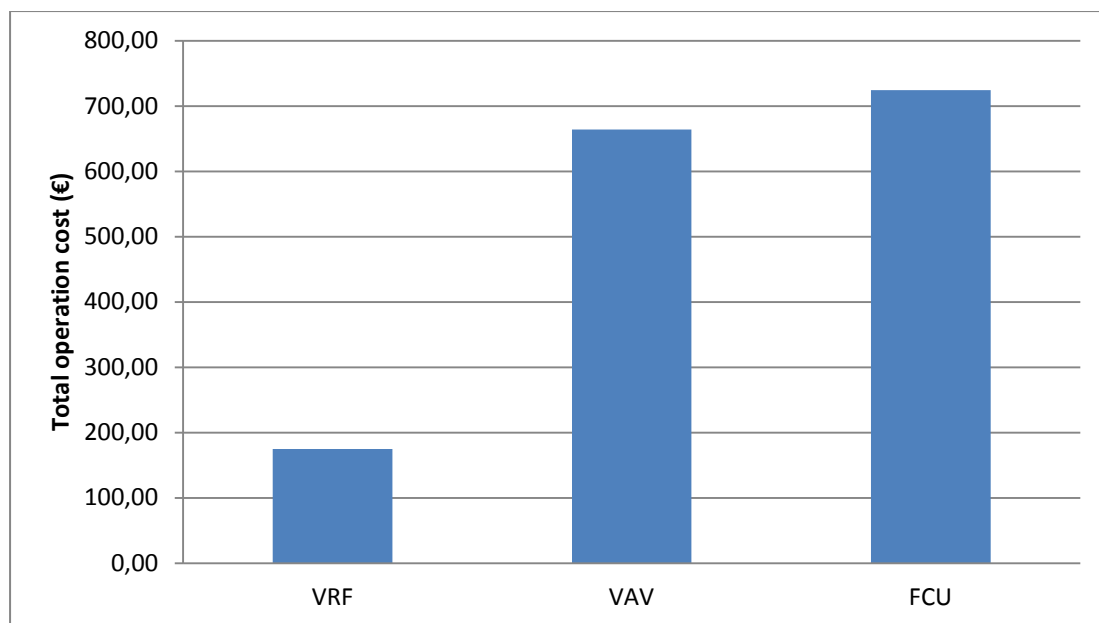
Figure 75 – Heating energy consumption per unit for different HVAC types in Athens



**Figure 76 – Cooling energy consumption per unit for different HVAC types in Athens**



**Figure 77 – Total energy consumption per unit for different HVAC types in Athens**



**Figure 78 – Total operation cost of different HVAC types in Athens**

## Appendix B Comparison of HVAC types in Thessaloniki

Now, we will compare three different types of HVAC systems: a. Variable Refrigerant Flow (VRF), b. Variable Air Volume (VAV) and c. Fan Coils Unit (FCU) when they are put in the same building in Thessaloniki city. Comparison follows same steps as we did for the city of Athens in Chapters 6 and 7. In details, first we compare the energy consumption of these different systems, then we calculate the total operation costs and last we compare installation costs.

### a. Energy consumption comparison

Following diagrams Figure 79 – Figure 81 show heating, cooling and total energy consumption of different HVAC types in Thessaloniki:

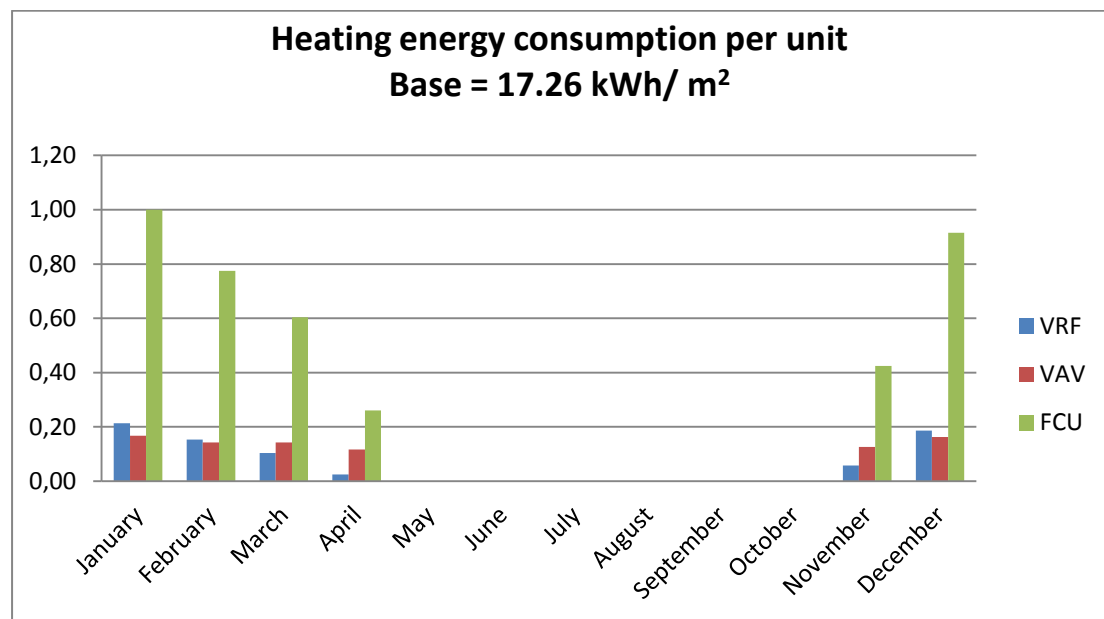
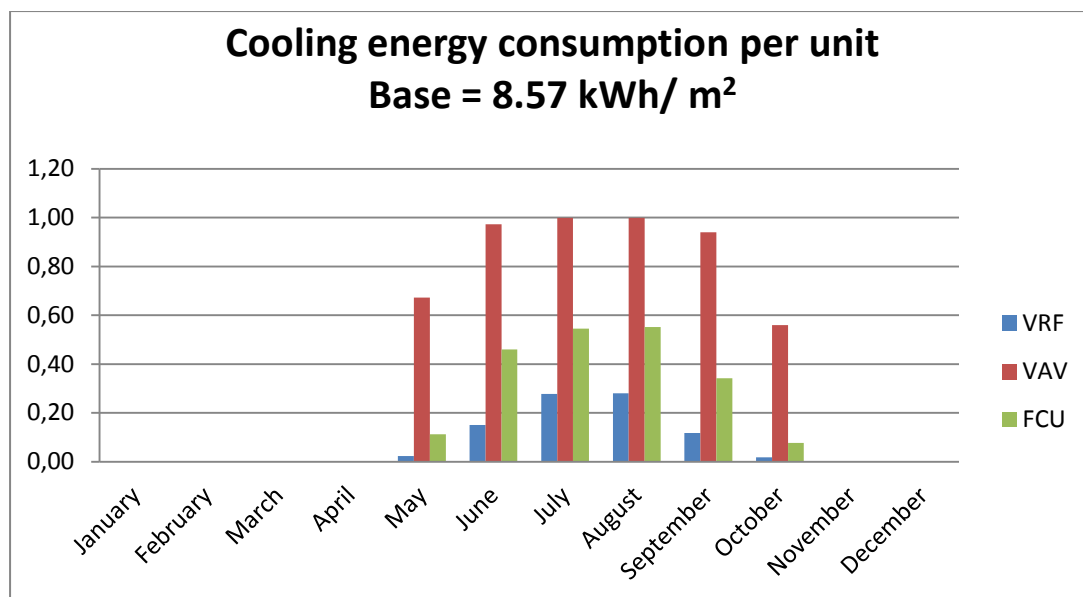


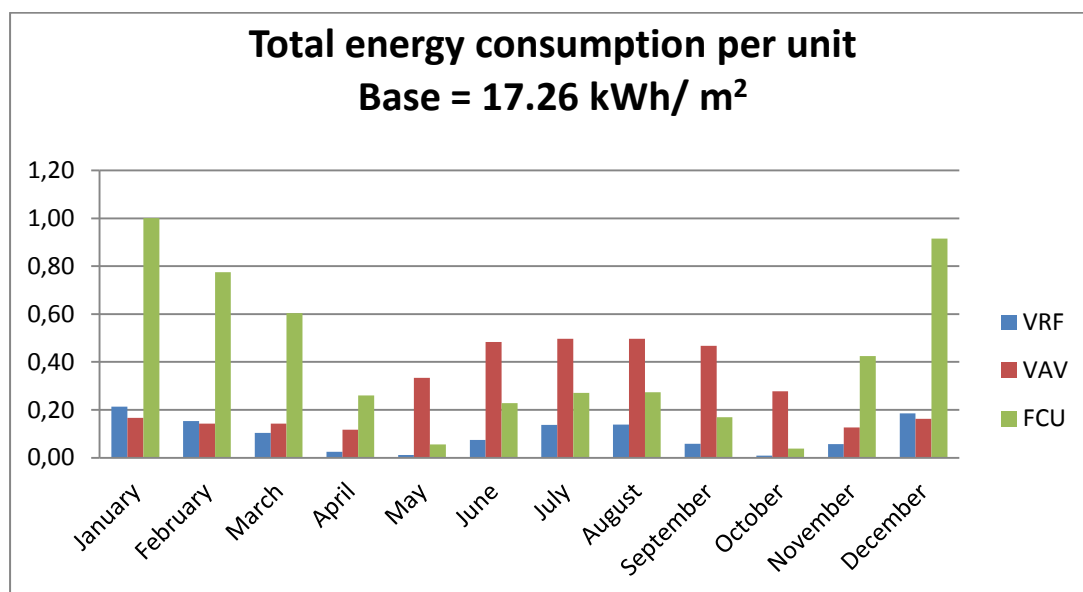
Figure 79 – Heating energy consumption for different HVAC types per unit in Thessaloniki

Looking at Figure 79 we observe that FCU system consumes the largest amount of energy for heating in Thessaloniki, especially in January, February, March and December.



**Figure 80 – Cooling energy consumption for different HVAC types per unit in Thessaloniki**

Looking Figure 80 we observe that VAV consumes almost the double amount of energy for heating in Thessaloniki than FCU. VRF consumes, again, the lowest amount of energy.



**Figure 81 – Total energy consumption of different HVAC types in Thessaloniki**

Looking Figure 81 we observe that VAV consumes more energy for cooling than heating, while FCU vice versa consumes more energy for heating than cooling. VRF consumes almost same amounts of energy for both cooling and heating.

## b. Operation costs comparison

Following diagram shows the comparison of total operation costs of three different HVAC systems through a whole year. Results were taken after calculate multiplication of energy consumption, showed above, times cost of 1 kilowatt-hour = 0.10158 €.

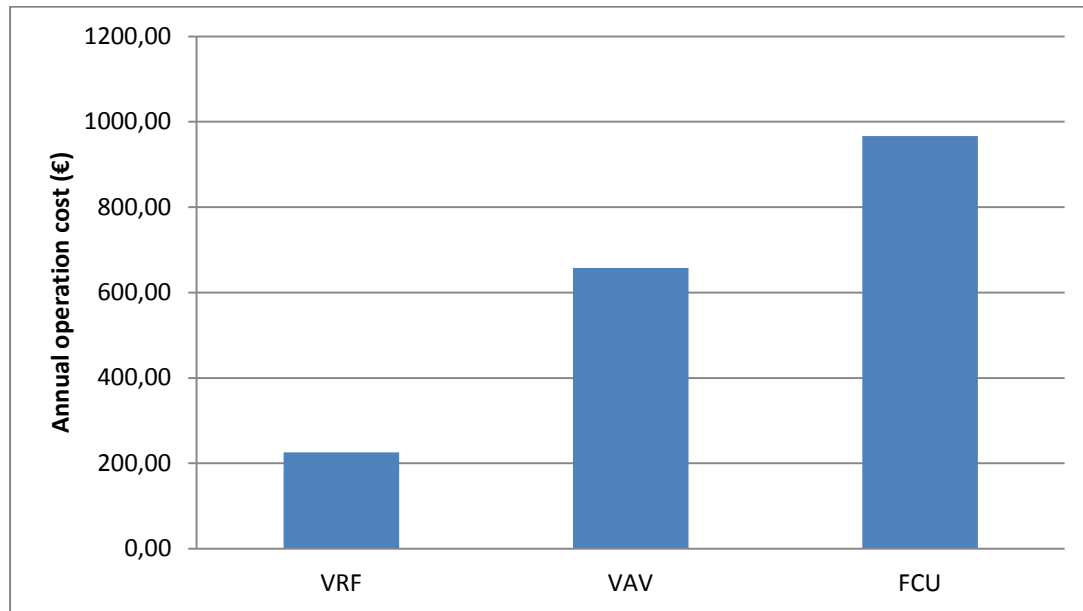


Figure 82 – Total operation costs of different HVAC types in Thessaloniki

Looking Figure 82 is easy to conclude that FCU system has the biggest operation cost of 966.49 € in a year, while VRF has almost four times less cost of 225.47 € in a year. VAV has operation cost of 657.49 € in a year.

## c. Installation costs comparison

As in the case of Athens, in order to compute installation costs we will begin by sizing the air condition systems by thermal zones of the building. Starting with Variable Refrigerant Volume (VRV) system:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.20	0.34	0.34
Thermal zone 3	0.38	0.67	0.67
Thermal zone 4	0.16	0.28	0.28
Thermal zone 6	0.06	0.10	0.10
Thermal zone 8	0.16	0.28	0.28
Thermal zone 9	0.12	0.22	0.22
Total	1.09	1.89	1.89

Table 67 – VRV system sizing in Thessaloniki

Then, Variable Air Volume (VAV) system sizing follows:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.66	0.09	0.66
Thermal zone 3	1.28	0.17	1.28
Thermal zone 4	0.54	0.07	0.54
Thermal zone 6	0.18	0.02	0.18
Thermal zone 8	0.54	0.07	0.54
Thermal zone 9	0.41	0.05	0.41
<b>Total</b>	3.60	0.48	3.60

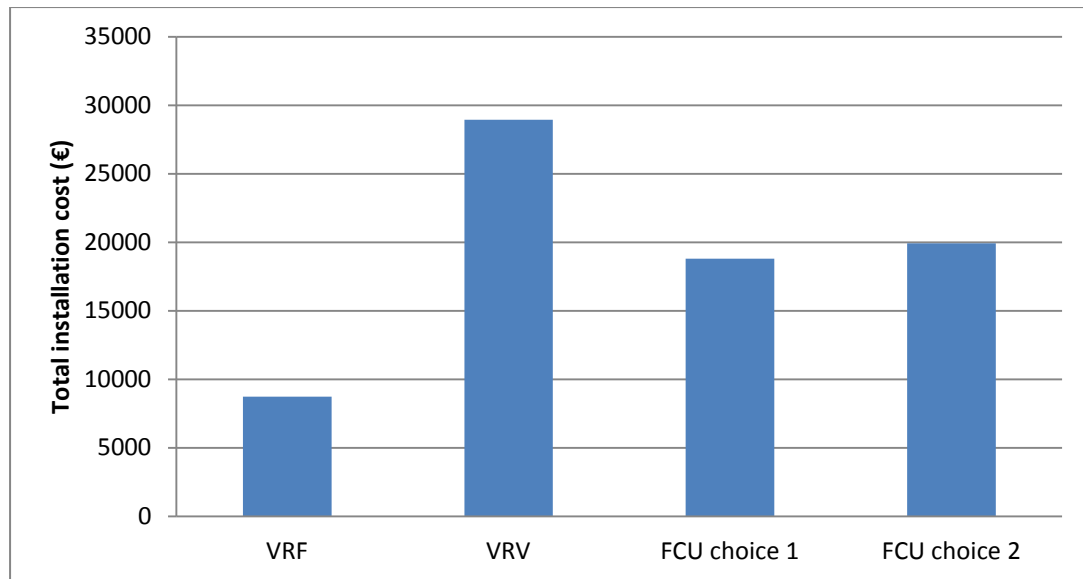
**Table 68 – VAV system sizing in Thessaloniki**

Last, Fan Coils Unit (FCU) system sizing follows:

	Cooling [kW]	Heating [kW]	Sizing [kW]
Thermal zone 1	0.35	1.76	1.76
Thermal zone 3	0.68	3.41	3.41
Thermal zone 4	0.29	1.44	1.44
Thermal zone 6	0.10	0.49	0.49
Thermal zone 8	0.29	1.45	1.45
Thermal zone 9	0.22	1.10	1.10
<b>Total</b>	1.91	9.65	9.65

**Table 69 – FCU system sizing in Thessaloniki**

Compare Table 67 – Table 69, systems' sizing in Thessaloniki, with Table 51 – Table 53, systems' sizing in Athens, we can see only small differences. That is also seen in installation costs, as shown below:



**Figure 83 – Comparison of total installation cost of the three different HVAC systems when building is placed in Thessaloniki**

As in the case of Athens, by looking Figure 83 we can see that VRV system has the lowest total installation cost of all three HVAC systems. While, VAV system has the most expensive total installation cost which is mostly due to terminal units' cost, as we was mentioned in chapter 7.



## Appendix C Life Cycle Cost Analysis

Here, we will calculate the life cycle cost (LCC) of each HVAC system during first 15 years of its operation, in order to take our final decision for the optimum choice between VRF, VAV and FCU. The life-cycle method we have chosen associate measures of net savings, saving to investment ratio, and payback.

The general formula for the LCC present-value is as follows:

$$LCC = \sum_{t=0}^N \frac{C_t}{(1+d)^t}$$

Where:

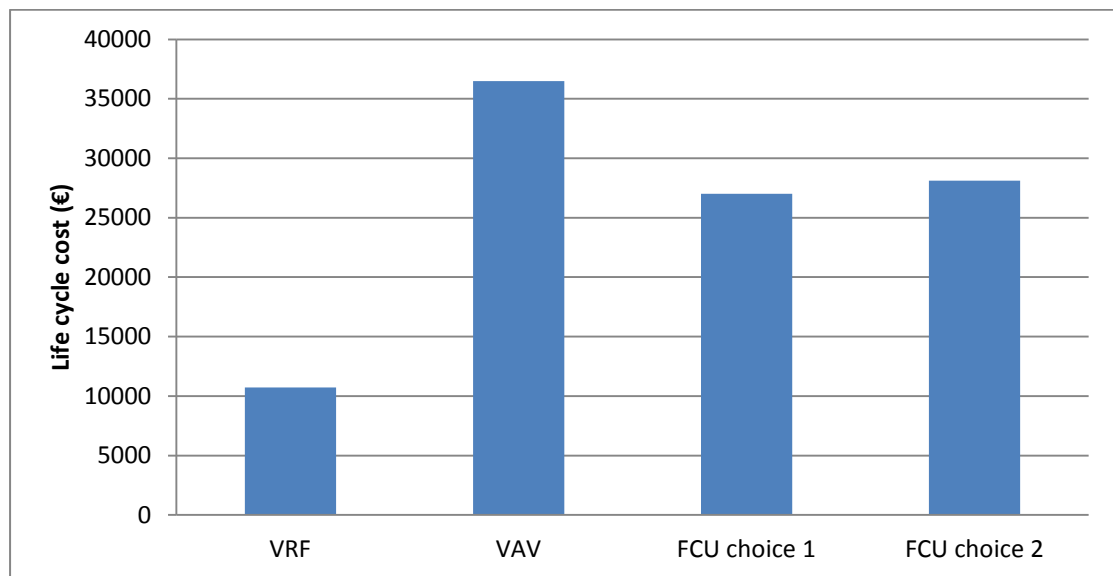
LCC = total LCC in present value of a given alternative,

$C_t$  = sum of all relevant costs, including initial and future costs, less any positive cash flows, occurring

N = number of years in the study period, and

d = discount rate used to adjust cash flows to present value.

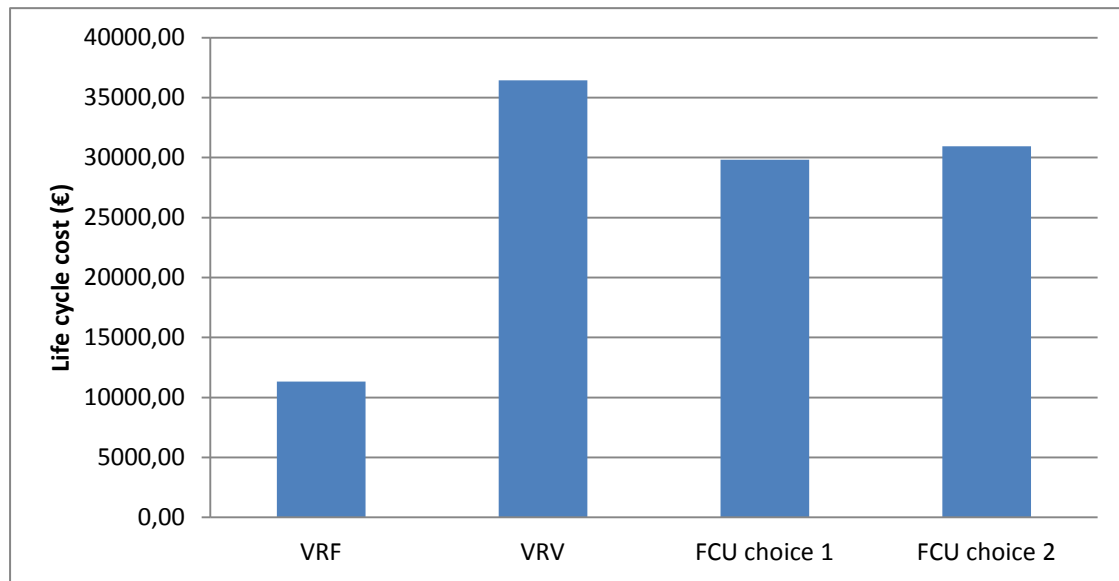
Figure 84 shows life cycle cost of the three different HVAC systems when the building is placed in Athens:



**Figure 84 – Comparison of life cycle cost of the three different HVAC systems when the building is placed in Athens.**

Looking Figure 84 we can conclude that VRF system is the cheapest choice, cost 240% less than the most expensive one, which is VAV. While, FCU cost 61% more than VRF.

Figure 85 shows life cycle cost of the three different HVAC systems when the building is placed in Thessaloniki:



**Figure 85 – Comparison of life cycle cost of the three different HVAC systems when the building is placed in Thessaloniki.**

Looking Figure 85 we make similar conclusions as in the case of Athens. That is, again, that VRF system is the cheapest choice cost 220% less than the most expensive one, which is VAV. While, FCU cost 63% more than VRF.