MODELING AND ANALYSIS OF ENERGY CONSUMPTION FOR DATA CENTER SPACE

by

IOANNIS FANTAOUTSAKIS

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

DEPARTMENT OF INFORMATICS ENGINEERING

SCHOOL OF APPLIED TECHNOLOGY

TECHNOLOGICAL EDUCATIONAL INSTITUTE OF CRETE

2016

Approved by:

Assistant professor
Spyros Panagiotakis

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Abstract

This work investigates thermal performance of buildings with emphasis on data center spaces. Literature review reveals that 44% of all energy consumed is used in buildings in the EUs and in the U.S., 40 billion kilowatt-hours (kWh) of electricity are used annually for cooling. In parallel, power consumption in Data Centers, nowadays, is constantly increasing. Data Centers provide the world community with an invaluable service: almost unlimited access to all kind of information imaginable with the support of most Internet services, such as Web Hosting and e-commerce services. Data Centers include, sometimes thousands of Servers and cooling infrastructure support. Research on power management in Servers can ease the installation of a Data Center, cost reduction, and environmental protection. Power Usage Effectiveness (PUE) is a metric that characterizes the way the total energy consumed is distributed over the Data Center facilities. A reduced PUE allows for more efficient energy usage in a Data Center. In that context, hosting a data center in a building that assures minimal energy requirements, can save huge amounts of energy (and money) providing green-friendly administration. In order to evaluate the thermal performance and energy efficiency of buildings and building sub-sectors, several simulation tools have been proposed. In this work, the researcher exploits the potential of EnergyPlus software. EnergyPlus is a software platform that is used in relation to other tools in order to create a user friendly simulation environment. In order to develop a modeling procedure, the researcher studied the simulation tools and used them in order to simulate the Educational building in Heraklion, Crete that hosts the data center of TEI Crete. In order to evaluate the developed model, measurements were performed at specific periods, and the indoor air temperature of the Educational building's spaces was calculated. Main objective of this work is to assure that the model built for the Data Center space confirms the measurements obtained about temperature variation. If this is achieved to a great extent, the loads and the required temperature as measured in the space of the Data Center can be set in our model, and through the EnergyPlus to calculate the required cooling energy and therefore the PUE. Subsequently, various interventions are evaluated in terms of PUE reduction for upgrading energy efficiency of the Data Center space.

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Acknowledgements

I would like to thank my supervisor, Dr. Spyros Panagiotakis, for the opportunity he gave me to deal with such an interesting and modern science subject, for the crucial guidance, and his patience and Dr. Michalis Vourkas for his assistance in the measurements process. Also, I would like to express my deepest love and gratitude to my family for supporting and encouraging me during the elaboration of this master thesis.

Ioannis Fantaoutsakis

June 2016

Chapter 1 - Introduction

1.1 Background of the research

Green technologies of information and communication (Green ICT) include the study and practice of environmentally sustainable IT. San Murugesan notes that this might include the design, manufacture, use and disposal of computers, Servers, and associated subsystems, such as monitors, printers, storage devices, and networking and communications systems - efficiently and effectively with little or no impact on the environment. According to Bernard Aebischer et al (2011), research into the socio-technical system of ICT and its energy consumption currently faces several methodological challenges:

- The distributed nature of the ICT systems providing the final service to the user and the increasing share of embedded ICT make the definition of the system boundary of a study a non-trivial task with decisive consequences for the results.
- There is an increasing need to consider the life cycles of end-user devices, network components, servers and supporting infrastructures, spanning the extraction of raw materials to end-of-life treatment of obsolete hardware. The collection of data on the life cycle of each component, the creation and validation of models for each phase of the life cycle (including user behavior in the use phase) are issues calling for interdisciplinary efforts.
- Understanding ICT energy demand also requires a better understanding of the influence of software products on the demand for hardware capacity, on usephase energy consumption and on the obsolescence of ICT components.

Figure 1 presents computing energy efficiency (in computations per kWh) from 1945 to 2010.

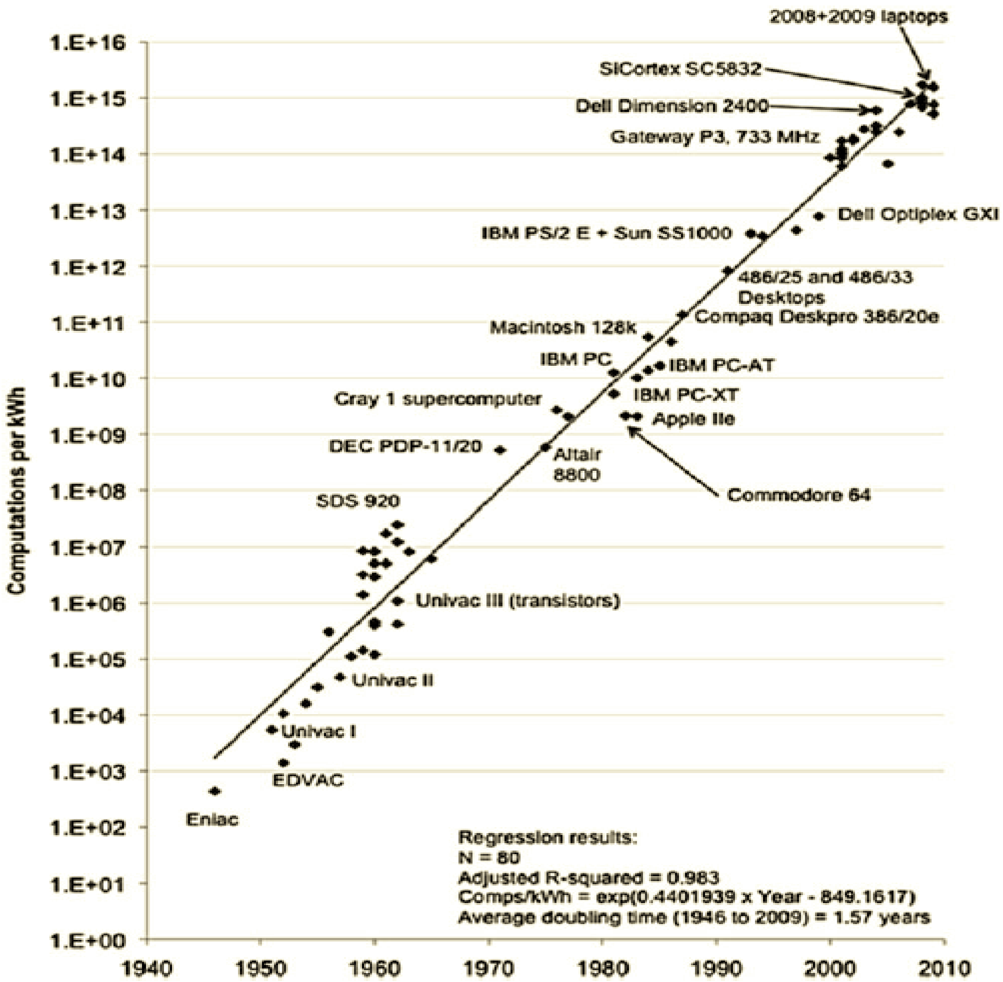


Figure 1: Computing energy efficiency (in computations per kWh) from 1945 to 2010 (Source: IEEE Computer Society)

The goals of green computing are similar to those of green chemistry, ie, reducing the use of hazardous materials, maximize energy efficiency during the product's life, and the promotion of recycling or biodegradability of products and factory waste. Many corporate IT departments have received green IT initiatives to reduce the environmental impact of its activities. Green ICT and their services present opportunities for reducing carbon dioxide emissions, because of its unique ability to make energy consumption and GHG emissions visible through its products and services.

The ecological computing is defined as the study and practice of design, construction, use and disposal of computers, Servers, and subsystems- such as monitors, printers, storage devices, networking and communications systems - efficiently and effectively with minimal or no impact on the environment. Four directions in which the environmental impact of computers should be addressed: Green use, green disposal, green design, green construction. Green IT can also develop solutions that offer benefits of aligning all IT processes and practices with the principles of sustainability, which is to reduce, reuse, recycling and finding innovative ways to use IT in business processes to afford the benefits of sustainability throughout the company and beyond.

Modern IT systems rely on a complex mix of people, networks and hardware. Therefore, a green initiative should cover all these areas. One solution may also need to address end-user satisfaction, management restructuring, regulatory compliance, and return on investment (ROI). There are also considerable fiscal incentives for companies to take control of their own energy consumption. From the power management tools available, one of the most powerful may still be simple common sense in monitoring and managing the energy use with advanced software tools.

Data Center facilities are large energy consumers, representing between 1.1% and 1.5% of total world energy consumption in 2010. The US Department of Energy estimates that the premises of Data Centers consume by 100-200 times more energy than conventional office buildings. Energy efficient Data Center design should address all aspects of the use of energy contained in a Data Center: from the IT equipment as the HVAC equipment to the actual location, configuration and construction of the building.

The US Department of Energy defines five key areas in which we focus on the energy efficient design of Data Centers:

- Information technology (IT)
- Environmental conditions
- Air management
- Cooling Systems
- Power systems

Additional energy-efficient design features that are defined by the US Department of Energy include on-site electricity and recycling of waste heat. Energy efficient Data Center design should contribute to a better use of space and increase performance and efficiency. Algorithms can also be used to route data to a Data Center, where electricity is less expensive. Researchers from MIT, the Carnegie Mellon University, and Akamai have tested an energy allocation algorithm that successfully directs traffic to a site with cheaper energy costs. The researchers predict up to 40 % savings in energy costs, of the proposed algorithms. However, this approach does not actually reduce the amount of energy used. It only reduces costs for the company and their use. Nevertheless, a similar strategy could be used to direct the traffic to be based on energy produced in a more environmentally friendly and efficient manner. A similar approach has also been used to reduce energy consumption by routing traffic away from Data Centers experiencing warm weather. This allows computers to be closed so as to avoid the use of air. Larger Server centers are sometimes in places where energy and land is cheap and readily available. The local availability of renewable energy, climate allowing the outside air used for cooling, or placing them in places where the heat they generate; can be used for other purposes could be factors in green location decisions.

The power supplies have a desktop computer performance for 75% and the remaining amount of energy is heat. A program called 80 Plus certification, certifies power supplies have an efficiency of at least 80%. From July 2007, all new Energy Star 4.0 - certified desktop power supplies must have a minimum efficiency of 80%. Smaller size and shape of the hard discs, often consume less power per gigabyte of the leading drives. Unlike hard drives, the solid-state drives store data in flash memory or DRAM. With no moving parts, power consumption can be reduced somewhat for flash-based low-capacity devices. In a recent case study, the company Fusion - io, manufacturer of solid-state storage devices, managed to reduce the cost of energy use and operation of MySpace Data Center by 80% and achieved increase in performance speeds beyond that achieved through multiple hard drives in Raid 0. In response, MySpace was able to withdraw several of their Servers. As hard drives have reduced the storage farms have increased in capacity to make available more data online. These include archival and backup data that previously would have been saved on tape or other offline media. The increase in online media has increased power consumption. Reducing the power consumed by large storage arrays, as still provide the benefits of direct connection, is the subject of continuing research.

A fast GPU may be the largest consumer of electricity in a computer. Energy efficient display options include:

- Computers without video card - use a shared terminal, shared thin client, or share the desktop software if display required.
- Using the output motherboard video - usually low 3D performance and low power.
- Select GPU based on low power idle, average power, or performance per watt.

LCD displays typically use a cold cathode fluorescent lamp to provide illumination for the display. Newer displays use an array of light emitting diodes (LED) in place of the fluorescent lamp, which reduces the amount of electricity used by the display.

The Advanced Configuration and Power Interface (ACPI), an open industry standard, allows an operating system to directly control the energy saving aspects of the underlying hardware. This allows a system to automatically disable components such as monitors and hard drives after certain periods of inactivity. Furthermore, a system may be inactivated when most components (including the CPU and system RAM) are turned off. The ACPI standard is the successor to an earlier model of Intel - Microsoft called Advanced Power Management, which allows the computer's BIOS to control power management functions. Some programs allow the user to manually adjust the voltages supplied to the CPU, which reduces the amount of heat generated and power consumed. This process is called undervolting. Some CPUs can automatically reduce the voltage of the processor depending on the workload. This technology is called "SpeedStep" processor Intel, "PowerNow!" / "Cool'n'Quiet" in AMD chips, LongHaul for VIA processors, and LongRun Transmeta processors.

The energy consumption of information and communication technologies (ICT), in the US and around the world, has been estimated respectively at 9.4% and 5.3% of the total electricity produced. The energy consumption of ICT is now an important even in comparison with other industries. Recently a study has attempted to identify the key energy indicators that allow a relative comparison between different devices (data network) .The analysis focuses on how to optimize the consumption of the device and network carrier in telecommunications alone. The goal was to allow direct understanding of the relationship between network technology and its environmental impact. These studies are at an early stage and further research is needed.

The inaugural Green500 list was announced on 15 November 2007. As a complement to the TOP500, the appearance of the Green500, technology ushered in a new era where supercomputers can be compared with the performance per watt. The center Tsubame - KFC - GSIC at Tokyo Institute of Technology currently has a big advantage over the second, the Top 1 supercomputer in the world with 4,503.17 MFLOPS / W and 27.78kW total power.

1.2 Research problem and/or hypothesis

The research problem of this dissertation is to improve energy efficiency of an operating Data Center space, in order to address the problem of improving energy efficiency while preserving expected life and stated mission of the facility and/or other (economic) criteria. Energy efficiency is calculated in terms of Power Usage Efficiency index (PUE) and the scope of this work is to propose interventions that can reduce PUE. First, the developed modelling procedure will be applicable to a case study that relates to a Data Center, a building sub-sector that is a huge energy consumer. The work presented here will explore the feasibility of this problem by studying the modelling of Educational building in Heraklion, Crete. This is achieved by modelling the building using the energy simulation software EnergyPlus.

1.3 Justification of the research including aims

The energy market in the European Union includes energy sources such as coal, oil, nuclear power, natural gas, etc. The current energy mix in the EU represents the decisions, at national level, made decades ago by the individual Member States, at a time, where there was no intent or thought of coordination of all these energy policies into a single European regulatory framework (Parissi, 2009). In France for example, nuclear energy accounts for 40% of the country's primary energy needs, contributing 80% of electricity generation. In Great Britain, however, nuclear power plays only a limited role with 9% contribution in energy needs, generating 20% of electricity (Lannoye et al., 2012).

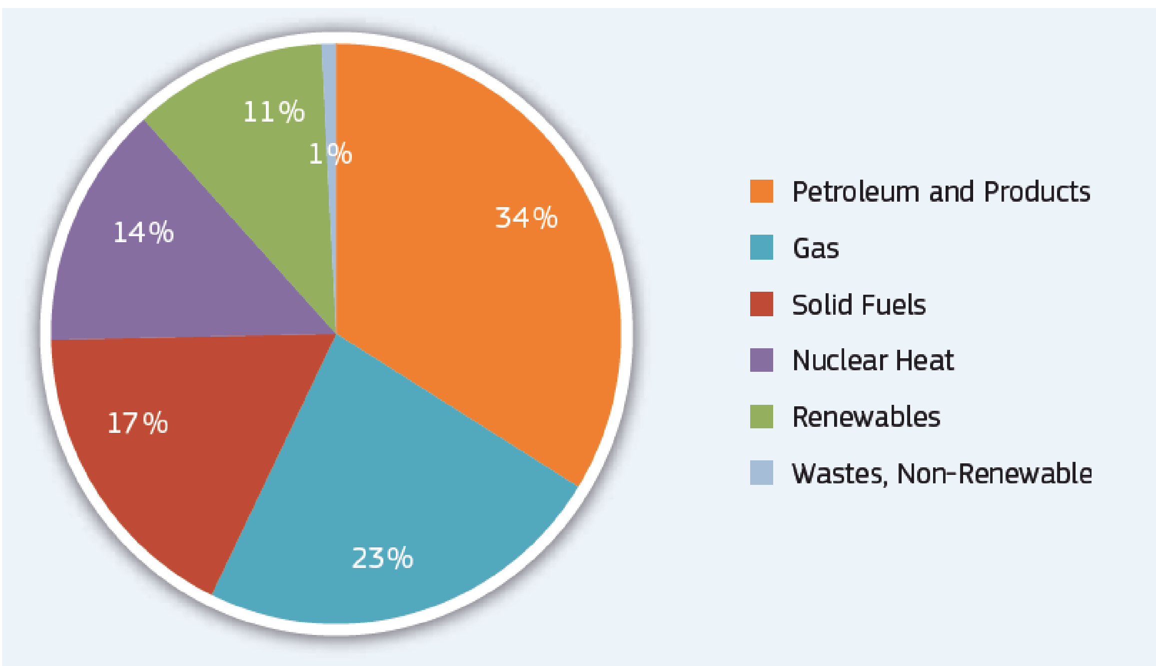


Figure 2: EU-28 Gross Inland Consumption – Energy Mix (%) – Primary Products Only (Total Primary 2012: 1 682 Mtoe / Total Primary and Secondary 2012: 1 683 Mtoe) (Source: Eurostat Pocketbook, 2014)

Other countries, such as Austria, have a clear anti-nuclear energy policy. Nevertheless, the main sources of most European countries are coal, oil and natural gas. In Poland, for example, the dominance in energy production is attributed to coal, accounting for 85% of energy needs, with the participation in electricity at 92% (Lannoye et al., 2012). Moreover, oil covers about 40-50% of primary energy needs in nearly all 27 EU states. Renewables rarely exceed 10% of the energy mix, with the average for the EU reaching hardly 6%. There are of course exceptions such as Austria, where the rate reaches 21%. Finally, dependence of the EU on hydrocarbon fuel imports is expected to increase as the European stocks in the North Sea are declining rapidly. This dependence is expected to reach 90% for oil and 80% for gas by 2030 (Parissi, 2009). The following diagram presents the overall picture of the energy mix in EU level (Eurostat Pocketbook, 2014).

Transportation is the biggest energy consumer in almost all EU countries, with the European average to exceed 30%. The final consumption for the industrial, transportation and household consumers is calculated cumulatively at over 80% in 2004 (Parissi, 2009). In the transport sector, the vast majority - about 83% - of energy use takes place in roadway transport. However, aviation, currently has reached 13% of consumption, it grows quickly, unfortunately at the same time contributing to increased greenhouse gas emissions. In the following diagram, energy consumption per sector is shown graphically for the EU. The 'other consumers' category includes a relatively small amount of energy use in the agricultural sector, which accounted to about 2.5% of total final consumption in 2004 (Parissi, 2009).

Electricity consumption is dominated by the industry, by 41%, while residential consumers reach 29% and the services sector 27%. The fact that the consumption of electrical energy in industry still exceeds much the same consumption in the service sector, points to the high importance of industrial economy, despite the growing importance throughout the EU for one services-oriented economy. In industrial energy consumption some sectors are presented with strong consumption, ie iron and steel, chemicals, engineering and building materials. The energy intensity of these fields is already under close investigation, because of concerns about competitiveness, as well as emissions of greenhouse gases. The aim is to reduce carbon loads and to introduce new improved and energy-efficient processes (European Commission, 2015).

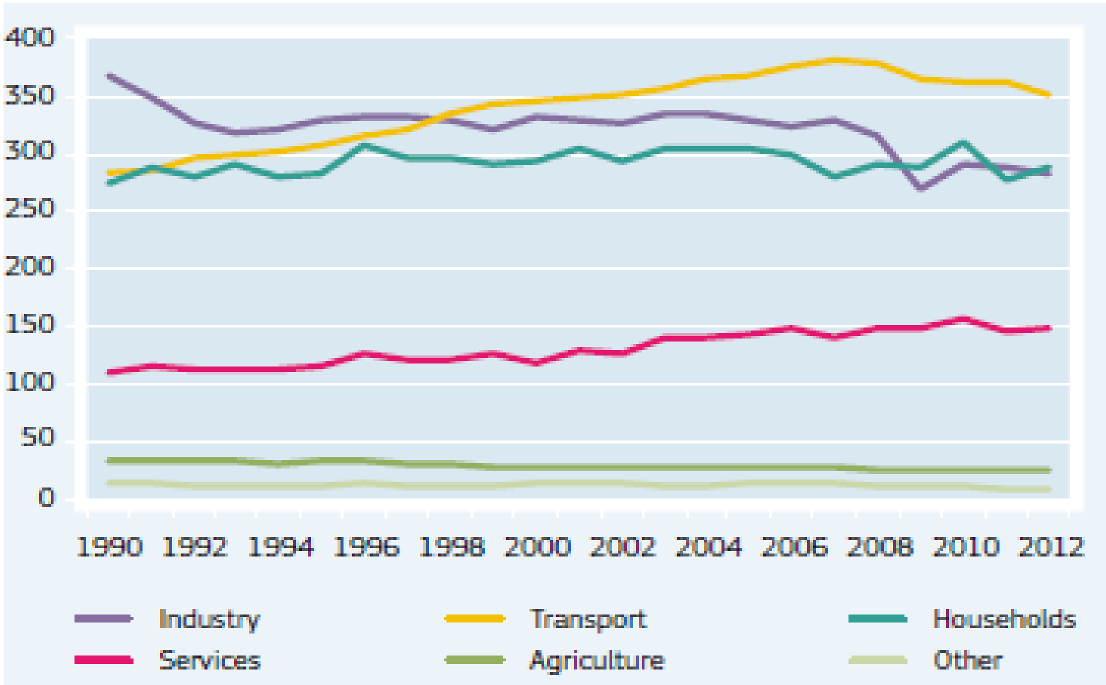


Figure 3: Final Energy Consumption By Sector – EU-28 – 1990-2012 (Mtoe) (Source: Eurostat Pocketbook, 2014)

Each year, 44% of all energy consumed in the EU is used in buildings, domestic, tertiary or industrial buildings. The vast majority of this energy is produced by burning fossil fuels such as oil, natural gas and coal - with serious environmental impacts in terms of greenhouse gas emissions. Today, the social, environmental and economic costs of climate change underline the urgency of the transition to a new energy scenario. In 2011 Energy Information Administration (EIA) estimated that about 440 billion kilowatt-hours (kWh) of electricity were used in the U.S. for cooling, by the residential and commercial sectors, or about 11% of total U.S. electricity consumption. Simultaneously, countries are struggling to keep up with peak power demand in hot weather. Even if this estimation was about the residential and commercial sector, while this project will focus on cooling of an outside area, the amount of energy that is spent every year for cooling is obvious.

Figure 4 shows that cooling needs are increasing dramatically in Greece due to climate change and that Greece presents the highest energy demand in homogeneous climatic data relative to other EU countries (IENE, 2011). These facts lead scientists to believe that there is a wide field for energy saving interventions in the building sector.

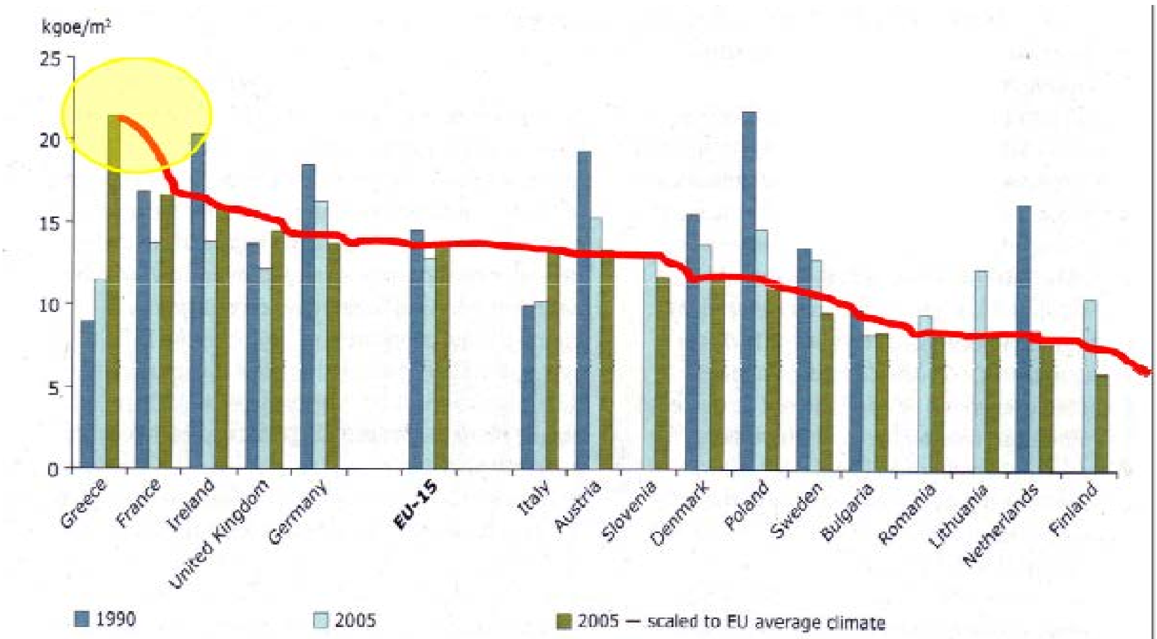


Figure 4: Energy consumption in homogeneous climatic conditions (European Environmental Service, 2006)

1.4 Methodology

When undertaking a research study to find out answers to some specific questions, we are implying that the whole process is being undertaken within a set of techniques, methods and approaches that have been already tested for their reliability and validity and are created to be objective and unbiased. Categorization of the research into the various types, are explained by Skittides and Koilliari (2006) for the context of the dissertation.

Initially this research study should be classified as primary research. The reason is that at the end of the research, new results and conclusions will be added to the problem of Data Center modelling inside a building with thermal zones. The results and conclusions could also be compared with data measured in real conditions and provide conclusions relative to the validity of this work. The results of investigating temperature variation in simulation time and conclusions will also be drawn for the efficiency of the equipment. As a result the factors affecting the operating thermal conditions of Data Centers will be assessed. Moreover, the current research can be characterized as an empirical one. According to Robson (2002), “empirical research is characterized by the fact that knowledge or theory that is derived from it, is arrived at as a result of observations or experiments. In this class of research methods empirical observations or data are collected in order to answer specific research questions”. Therefore there are some basic principles of empirical research, which are also applied in the present one

This research is a deductive case as it aims to check the theory through a detailed study of a specific case. Van Wynsberghe & Khan (2007) after combining various definitions from many scientists conclude that a case study can be defined as “A transparadigmatic heuristic that enables the circumscription of the unit of analysis’’. Moreover they state that “the circumscription is accomplished by providing detailed descriptions of the case, bounding the case temporally and spatially and engagement between the case and the unit of analysis’’. Based on definitions, my research could be characterized as a case study research. The main advantage of using a case study research is that offers a great opportunity for innovation and a good method to challenge theoretical assumptions (Gerring, 2004).

Regarding the technique of this research, it belongs to the area of case studies. This is because separate case studies will take place and the results of them will guide us to a more general conclusion. Ambient temperature and power consumption sensors will be installed at site and a data logging system will archive these measurements. Moreover through this investigation some variables will be changed in order to have a more accurate idea of the performance of the system. Expectation will be to study the results of a system which will be close to thermal comfort conditions.

1.5 Outline of the dissertation

In the first chapter, an introduction is made about the current study. The reader is introduced to the background of the research and the research problem is defined. The justification for this research study is given and the aims are outlined. Finally, the type of the methodology that the research will perform is described and the reasons for the strategic plan are clarified.

In the second chapter, the theoretical problem is identified concerning the significance of energy consumption analysis in the building sector. The researcher outlines the need for self-sustained and low CO_2 emission buildings, while introducing the basic parameters of energy consumption in Data Centers.

The third chapter contains information relative to thermal performance and analysis of buildings, including structural materials and occupational patterns. It is utilized as an introduction to the next chapter of thermal modelling.

The fourth chapter contains the explanation of the collected data and the presentation of the simulation tools that are used for the thermal analysis of the Educational building in

Heraklion, Crete. Here the measurements are also presented regarding the design of Sketcup 3D model and EnergyPlus/Openstudio model and the technology and technics of the software and hardware that are used. Moreover in the fourth chapter the evaluation section illustrates the comparison of the simulation results with measurements of the site in order to demonstrate the applicability of the model.

The fifth chapter presents the estimation of the PUE of the Data Center space and considerations for potential interventions for reduced values. A distinct simulation was made for each proposed intervention of the building model according to measured temperatures in comparison with the recommended envelope proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Power consumption, and therefore PUE comparison results are presented between the previous and new situation.

The sixth chapter presents a thorough discussion and the conclusions of the research work. The conclusions demonstrate how this research study fills out the gap in knowledge from the results.

1.6 Summary

This chapter introduced the reader to the elements of this research, such as what is the energy conservation and thermal modelling in the building sector and how this can be implemented while at the same time presented relevant work from the literature in order to identify the background of the research. The justification why this study is significant was specified and the aims were outlined. Based on the background and justification, the research problem was defined, and the methodology of how this study will address it was described.

Chapter 2 - Energy consumption in buildings

2.1 The need for Energy Sustainability in Europe

Climate change is a major incentive for saving energy due mainly to the high energy consumption in industries and the buildings sector by the end of the 19th century till our time. The main causes of climate change are the production of energy for transport, industrial processes, use of solvents and other chemicals, waste etc. The crisis of the financial system in the last five years has helped reduce energy consumption resulting through significant reductions in greenhouse gas emissions to combat climate change. At the same time, it significantly increased the use of renewable energy sources (RES) increased by 8.3% (except biomass). The largest emission reductions made in industrial processes reflecting lower levels of activity in the cement, chemicals, iron and steel (EEMO, 2009). As a consequence, and in Greece, the decline in industrial production and processing of approximately 9% in 2009 resulted in the reduction of emissions of greenhouse gases by 11.6% compared to 2008. This decrease is desirable but may be undone abruptly from a possible recovery of Greek economy, particularly the industrial sector if no measures are taken for the most rational use of energy and introduction to the energy mix of alternative energies (EEMO, 2009).

The greenhouse effect is one of the major problems of the planet after the industrial revolution. Essentially it is a phenomenon in which the planet's atmosphere retains heat and helps to increase the surface temperature. The greenhouse effect is due to the rapidly growing industries primarily releasing carbon dioxide and other pollutants in the air, such as methane and nitrous oxide (Muslu, 2004). Based on previous observations on climate change agreed by the Kyoto Protocol measures to tackle climate change. The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits the parties to setting internationally binding targets to reduce greenhouse emissions (Sakka and Psarras, 2010) . Recognizing that developed countries are principally responsible for the current high levels of GHG emissions in the atmosphere as a result of over 150 years of industrial activity, the Protocol gives greater weight in developed countries, under the principle of "common but differentiated responsibilities" (Muslu, 2004). The Kyoto Protocol was adopted in Kyoto, Japan on December 11, 1997 and entered into force on 16 February 2005. The detailed rules for the implementation of the Protocol were adopted at COP 7 in Marrakesh, Morocco, in 2001. The first commitment period started in 2008 and ended in 2012. On December 21, 2012, the amendment was circulated by the United Nations Secretary-General, acting in his capacity as Depositary to all Parties to the Kyoto Protocol, in accordance with Articles 20 and 21 of the Protocol. During the first commitment period, 37 industrialized countries and the European Community committed to reducing greenhouse gas emissions by an average of 5% from 1990 levels. During the second commitment period, the parties committed to reducing greenhouse gas emissions by at least 18% below 1990 levels during the period of eight years from 2013 to 2020. However, the composition of the parties in the second commitment period is different from the first one. Under the Kyoto Protocol, the EU-15 has a common commitment to reduce emissions by an average of 8% between 2008 and 2012 compared to the base year emissions. Note that unlike the EU-15, EU-27 has no obligation to achieve a common goal under the Kyoto Protocol by 2012. This, however, applicable to the EU-27 is a unilateral commitment to achieve at least a reduction 20% of greenhouse gas emissions by 2020 compared to 1990.

The combustion of fossil fuels causes urban air pollution leading to respiratory health problems (CARB, 2012) and also the emission of Greenhouse gases (CO_2). During 2010, the energy consumption led to the emission of about 4.6 billion tonnes of CO_2 equivalent (Eurostat, 2012). The world is facing serious environmental impacts like ozone layer depletion, global warming and climate change. Moreover, scientists are concerned about the scarcity of resources and the security of supply (Perez-Lombard et al, 2007). The increasing energy demand in developed regions like Europe has caused higher level of Greenhouse gas emissions and significant increase in fuel prices (Banos et al., 2010). For these reasons, renewable energy sources have grown significantly. Figure 5 presents the increase of the share of RES to electricity generation.

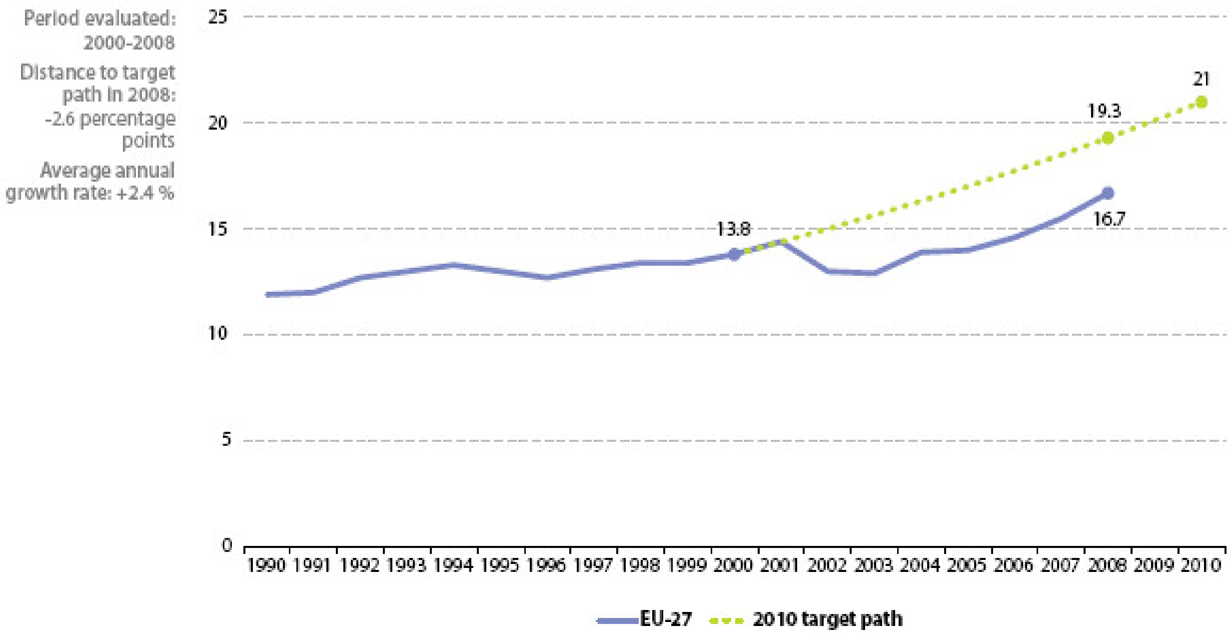


Figure 5: Electricity generated from renewable sources, 1990-2008 (source: Eurostat, 2012).

As it can be seen, the share of RES to electricity generation from 12% in 1990, reached 16.7% in 2008 and 18.2% in 2009 (Eurostat, 2012). Despite not achieving the goal for 2010, the growth of renewable energy sources is still remarkable. Renewable energy sources are part of an overall strategy for sustainable development. The aim is to gradually become independent from fossil fuels, ensuring a sustainable security of supply (EREC, 2004). Besides the integration of RES the whole world is concerned about energy savings and energy conservation. The concept of sustainability or sustainable development was first reported in the United Nations report in 1987 as a vision of progress that links economic development with environmental protection and social justice. Agenda 21 and the Rio Declaration on Environment and Development provided the basic framework for the discussion and political action on issues related to industry and sustainable development. Although the role of business and industry, as a major group, is specifically addressed in chapter 30, issues related to industry and economic growth, consumption and production patterns, social development and environmental protection, develop across the whole Agenda 21, including Section 4, means of implementation. Chapter II of Johannesburg Implementation Plan also calls for the strengthening of industrial development in order to tackle poverty eradication and sustainable natural resource management.

In order to achieve the objectives of sustainable development, governments must integrate economic, social and environmental issues in developing policy and promoting economic growth and international competitiveness of industry through macroeconomic policies. In order to stimulate domestic private enterprise, boost the economy at the level of competitiveness and attract foreign direct investment, policy reforms should aim at creating a favorable policy environment, improvements in infrastructure and education, encouragement of research and development, facilitate exports and the liberalization of the domestic market. In this context, the development of SMEs should be given special attention. The industry plays a critical role in technological innovation and research and development activities, which are vital for the economic and social development of each country, and the development, dissemination and transfer of environmentally friendly technologies and environmental management techniques, which are a key element of sustainable development. There is a reciprocal relationship between social and industrial development, and industrialization has the ability to promote, directly and indirectly, a variety of social objectives such as job creation, poverty eradication, gender equality, labor standards, and greater access to education and health care. In this context, the overriding policy challenge is to promote the positive impacts while limiting or eliminating the negative impacts of industrial activities on social development.

As the world has become more industrialized, there have been increasing environmental pressures, such as harmful emissions and waste, which had global, regional or local impacts. These include, at a local level, urban air pollution, contamination of soils and rivers and land degradation, regionally, acid rain and water pollution of coastal areas and globally, climate change, the destruction of the ozone layer, loss of biodiversity, increased movement of hazardous waste and increased land marine pollution. The primary task facing governments is to maximize the positive impact of industrial activities on economic and social development, while minimizing the negative impacts of production and consumption on the environment. To this end, governments should review regulatory policies and systems of financial incentives and disincentives and undertake other actions as capacity building, collecting environmental data and execution supporting efforts to protect the environment and industry civil society. Governments should encourage the wider dispersion and implementation of voluntary initiatives and agreements of industry and sharing best practices.

To develop more sustainable societies, industry, we need to understand better how to respond to environmental, social and economic challenges and transform industrial behavior. Knowledge should therefore be developed and tools that help accelerate the transition to a sustainable industrial system. Based on the data of the Sustainable Development Center for Industry of the University of Cambridge, there are three lines of action for sustainable development in the industry:

- Improving environmental performance without changing existing products and processes
- The development and introduction of new technologies,
- Change the industrial system.

Therefore interventions that can be made in the industrial process to give direction to sustainable development are focusing on:

- Products
- Production processes,
- Factories,
- Business,
- Manufacturers
- National and international policy frameworks.

Aggregated, the main objectives of sustainable development are the following:

- Balanced and equitable economic development
- High levels of employment and social development
- The high level of environmental protection and the responsible use of natural resources
- The active international cooperation to promote the goals of sustainable development worldwide.

Energy savings (and generally increasing energy efficiency) is a modern and promising tool to achieve these objectives. Especially in industry, as recited above, they are a strategic sector for the prosperity of societies sustainable development through the efficient use of energy, which will positively affect all of the above sectors. Strategies and technologies that surround energy saving policies are the most basic, structural elements in the design of current energy -and not only- policies. Energy savings in industry is not a method that should concern each industry separately. It is a strategic social objective which should be supported by political decisions in the context of sustainable development. Local technical measures to monitor and reduce energy consumption, the introduction of policies that will enhance the implementation of these local measures and interventions in the regulatory framework as presented and reduce total cost of electricity for the Greek industry are cost saving measures and sustainable policy.

2.2 Energy consumption in the building sector in Europe

One of the most significant steps that have been made in the direction of protecting the environment and ensure the global energy supply is the Protocol of Kyoto. In accordance with that, greenhouse gas emissions reduction by at least 5% during the period 2008-2012 was agreed among the states comparing with the emissions of 1990 (United Nations, 2008). European Commission (2011) presented in their recent Statistical Pocketbook some interesting information about the energy situation in Europe. In 2008, the primary energy import dependency of the EU-27 was 54.8%. Particularly, Europe of 27 imported the 41.2% of solid fuels, the 82.6% of oil and the 60.3% of natural gas. It is obvious that such dependence on unstable political countries decreases the security of energy supply. Thus, it is necessary for Europe to increase the share of renewable energy sources. Moreover, during the last two decades scientists were concerned about the high level of CO_2 emissions. The combustion of fossil fuels in order to cover the energy needs causes Greenhouse gas emissions, which are responsible for the global warming effect (Ramanathan and Feng, 2009). Figure 6 presents that despite the efforts to decrease the total CO_2 emissions, there is no significant reduction since 1990. The total CO_2 emissions of Europe for 2010 were 4.7 billion tonnes (Eurostat b, 2012) and extra measures and policies are already decided to be taken.

Greenhouse gases are considered as a new commodity. Each committed country has an allowed amount of emissions which are the "assigned amounts", over a certain period. The allowed emissions are divided into "assigned emissions units" (AAUs). So, countries that may have an excess can sell their spare units to a country that did not manage to fulfill its target. Except from buying emissions, countries have more actual emissions to trade:

- A removal unit (RMU) on the basis of land use, land-use change and forestry (LULUCF) activities such as reforestation
- An emission reduction unit (ERU) generated by a joint implementation project
- A certified emission reduction (CER) generated from a clean development mechanism project activity

All countries have to maintain reserve of all these units in its national registry and it is known as the commitment period reserve. The emissions trading schemes may be established as climate policy instruments heat at a national level and a regional level (United Nations, 2008).

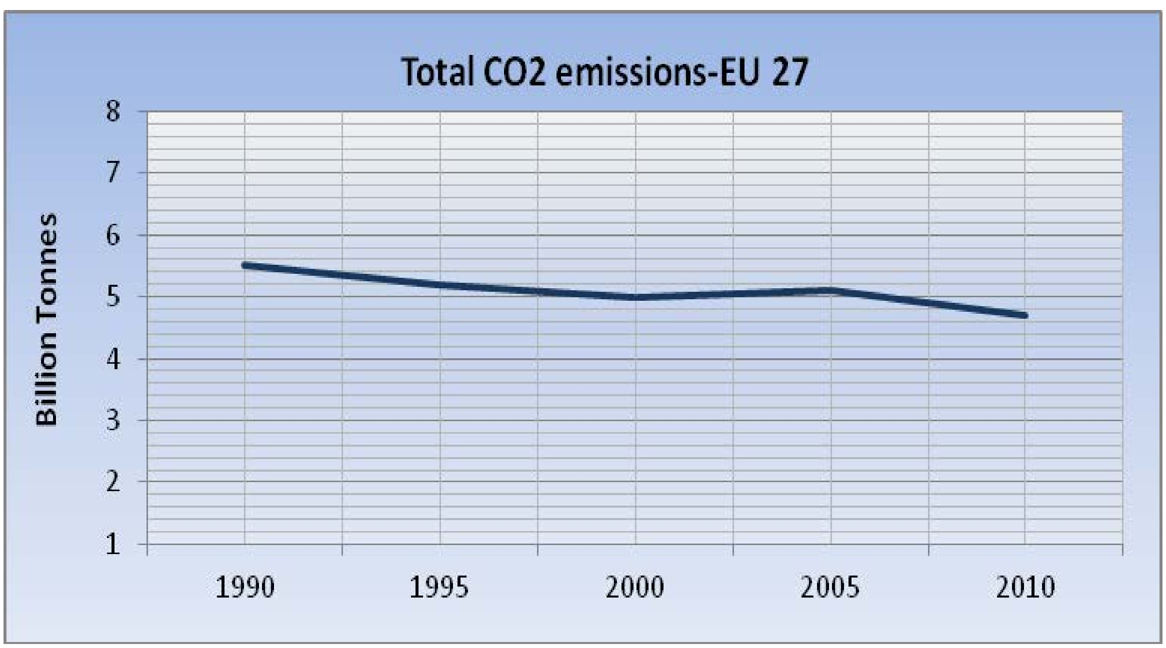


Figure 6: The total CO2 emissions of EU-27 since 1990 (Source: Eurostat, 2012).

All these measures target to secure the energy supply and mitigate the Greenhouse effect. The European Commission has set a target of 30% reduction of its GHG emissions by 2020 and 20% increase in the share of renewable energy (CEC, 2007). Moreover, their latest policies and plans promote the idea of the ‘Post Carbon Society’ (EC, 2008). The main principles of the ‘Post Carbon Society’ as they were presented by Carvalho et al. (2009) are:

- Renewable Energy
- Buildings as power plants
- Energy Storage
- Smart Grids

It is clear that the building sector, which accounts for almost 40% of the total energy consumption with a share of 20% in the Green-House Gas emissions (Shahriar, 2008), could play an important role to achieve the targets for 2020. The possibility of minimizing Green House Gases from building sector to zero levels is one of the most vital and essential issues that need to be addressed in the European energy agenda.

The fuel mix of gross inland energy consumption shows that more than half of energy consumed is produced from fossil fuels like coal, oil and natural gas (Eurostat, 2012). Figure 7 shows that since 1999 the consumption of solid fuels and oil has remained unchanged and Europe faced the increase in demand using natural gas and renewable energy.

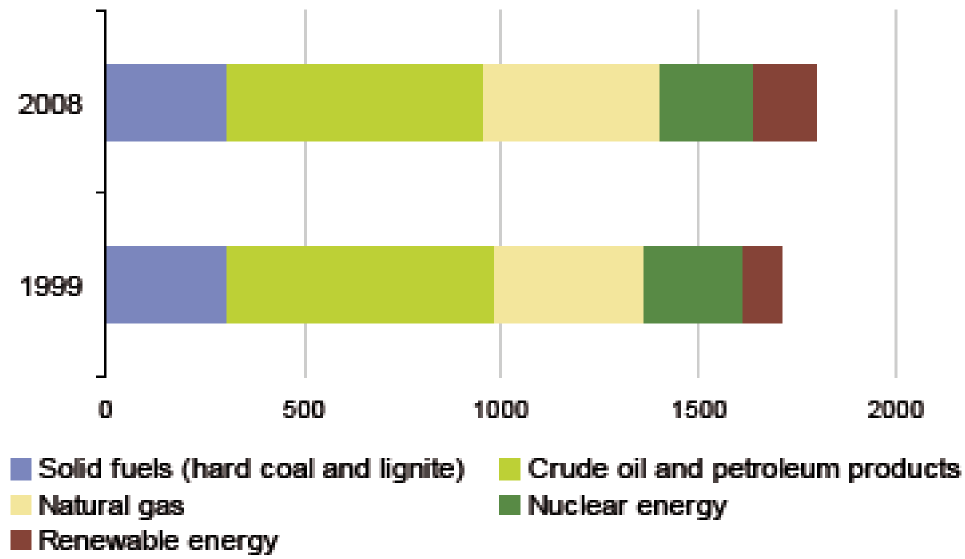


Figure 7: Europe's energy consumption by fuel (million tonnes) in 1999 and in 2008 (source: Eurostat c, 2012)

The combustion of fossil fuels causes urban air pollution leading to respiratory health problems (CARB, 2012) and also the emission of Greenhouse gases (CO_2). During 2010, the energy consumption led to the emission of about 4.6 billion tonnes of CO_2 equivalent (Eurostat b, 2012). The world is facing serious environmental impacts like ozone layer depletion, global warming and climate change. Moreover, scientists are concerned about the scarcity of resources and the security of supply (Perez-Lombard et al, 2007). The European Commission has set a target of 30% reduction of its GHG emissions by 2020 and 20% increase in the share of renewable energy (CEC, 2007). In order to fulfil this target, the European Commission and industries support research on sustainable development for the EU construction sector. One of these initiatives, the 'Energy-efficient Buildings' (EeB) is a 1 billion programme which can help to radically reduce buildings' consumption and CO_2 emissions (EC, 2010). The three main principles of the programme are:

- Reducing the energy use of buildings
- Buildings covering their own energy needs
- Transformation of buildings into energy providers

Consequently, buildings of the future will be designed to cover their own energy needs (using RES) and even to provide energy (using fuel cells) to the local district community.

2.3 Energy consumption in Data Centers

Nowadays Data Centers provide the world community with an invaluable service: almost unlimited access to all kind of information imaginable with the support of most services Internet, such as hosting Web and e-commerce services. The power consumption and energy are key concerns of Internet Data Centers. Benchmarked 22 Data Centers buildings, determined that Data Center can be over 40 times as energy intensive as conventional office buildings. The huge energy consumptions of data centers demonstrate the significant potential of energy saving, and make them the desired target of energy conservation measures (Yiqun Pan et al, 2007). Data Centers include, sometimes thousands of Servers and cooling infrastructure support thereof. Research on power management in Servers can ease the installation of the Data Center, cost reduction, and environmental protection. Given these benefits, researchers have made great strides in energy savings in Servers. Inspired by this initial progress the researchers are looking deeper into this topic (Sawyer, 2004).

World Data Center electricity use doubled from 2000 to 2005, but that rate of growth slowed significantly from 2005 to 2010. This slowing was the result of the 2008-9 economic crisis, the increased prevalence of virtualization in Data Centers, and the industry’s efforts to improve efficiency of these facilities since 2005. If we take the midpoint between the Low and High cases in this analysis, US and world Data Center electricity use grew by about 36% and 56%, respectively, from 2005 to 2010, totaling about 1.3% of World electricity use and 2% of US electricity use in 2010. The US Data Center market appears to have been hit harder than the world market by the economic crisis, with growth slowing more noticeably in that market than in the world as a whole. Finally, while Google is a large user of Data Centers, that company’s facilities represent less than 1 percent of all Data Center electricity use worldwide (Koomey, 2011).

Lizhe Wang and Samee U. Khan (2011) categorized green computing performance metrics in Data Centers as presented in Figure 8 and presented the formal process for benchmarking a Data Center using developed software tools, including EnergyPlus, for benchmarking and designing energy efficient buildings and Data Centers.

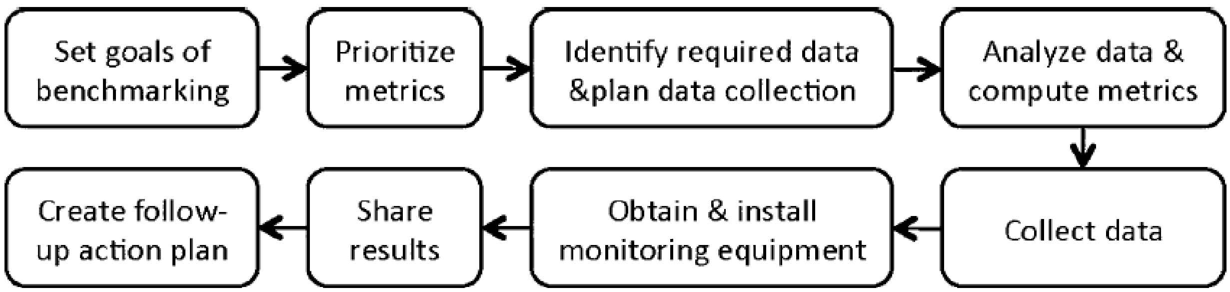


Figure 8: Formal process for designing energy efficient Data Center (Source: Lizhe Wang et al 2011)

The first step in prioritizing opportunities for energy saving is to get a solid understanding of Data Center energy consumption and energy indicators in Data Centers. The indicators can be used to shape strategies for saving energy, and to determine the effectiveness of the measures taken to reduce energy consumption. In the work of Iulia et al. supervised two major indices covering energy efficiency (Sawyer, 2004). In a Data Center, there are many elements that consume power (Rasmussen, 2003). The visible elements that consume power are: Servers, network equipment and UPS, but what is not visible is the function of CPUs that run programs and continuous flow of information in and out of the system (Fichera, 2006).

Figure 9 illustrates a typical power consumption of a Data Center. This is a resolution power of a typical Data Center high availability dual - power- path with N +1 air conditioners (CRAC), operating at a typical load of 30% of design capacity.

Using the analysis and synthesis of information systems with the help of the technological process, the requirements for developing the IT architecture in terms of hardware and software can be determined, and the model to the Data Center can be obtained. A Data Center as presented in Figure 10 is divided in IT equipment such as Servers and equipment non -IT, like air conditioning, UPS, etc. The energy is required as input data to the Data Center and an output is obtained that should bring satisfaction to the customer. The final action is the combination of energy from the grid and renewable energy sources. The output is also accompanied by heat that can be reused. In the output the energy losses are also included. Since the natural environment (for example, the position in a cold area) is a large factor of the input power to the system it is also incorporated in the model (Rasmussen, 2003).

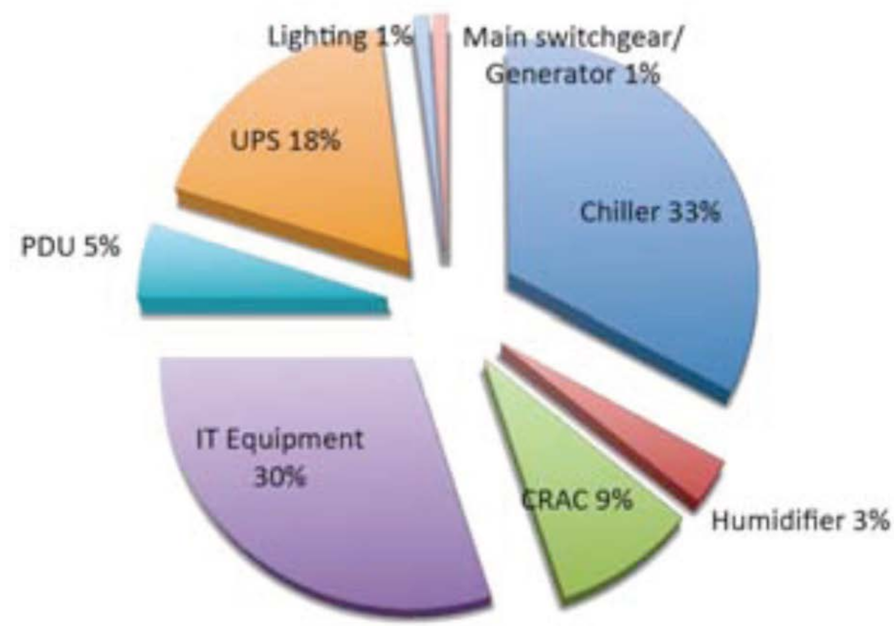


Figure 9: Energy consumption in a typical Data Center (Rasmussen, 2003)

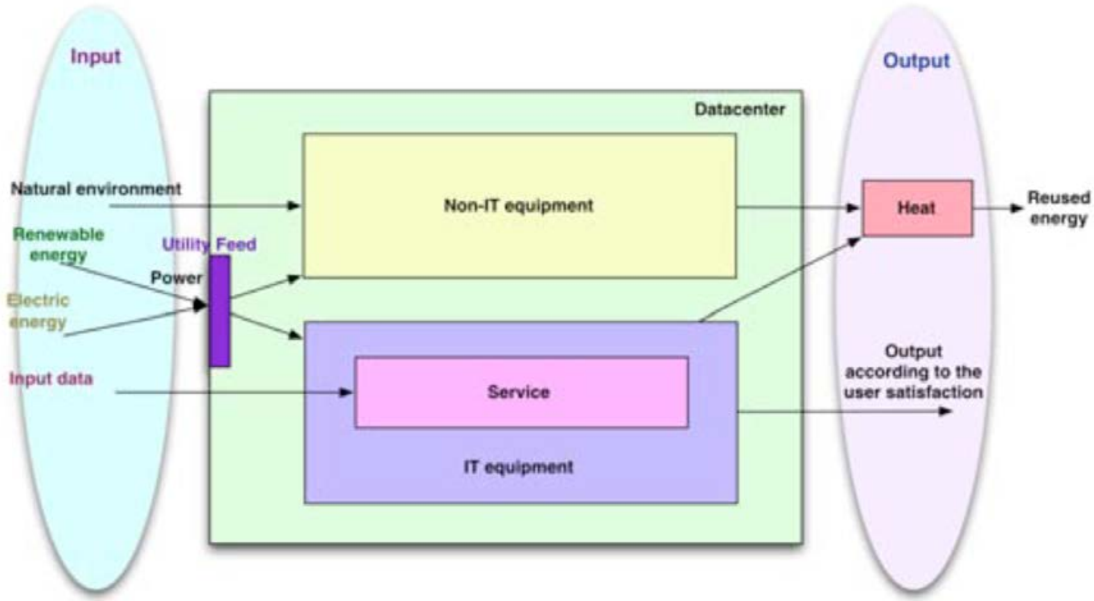


Figure 10: A standard Data Center (Green IT Promotion Council)

In Figure 11, we propose an energy distribution scheme in a typical Data Center. The amount of P01 represents the final energy (electricity) that enters the Data Center. Renewable energy sources (so-called free energy) are also a final energy component. The amount P10 is lost in conversion and energy transfer after it passes through the Utility Power and uninterruptible power systems (UPS). Also, the remaining power may be divided into electricity P11, non-free energy of the end user P12 (as in a cold climate), free electricity P13 (such as photovoltaic energy, thermal energy) and another free energy P14 which may captured from heating, ventilation, and air conditioning systems (HVAC). All this energy that passes through the power distribution unit (PDU) leads to useful energy P21, as well as some energy losses. The useful energy can be divided into two parts: the energy used by the IT equipment and the energy used by devices not -IT (McFarlane, 2005). Since the energy consumed by the equipment non -IT, a part can be reused (P91). It can be reused, for example, for heating in a building connected to the Data Center. We call useful energy consumed by the equipment IT, energy used to only perform the work required by users. The useful energy IT is the energy used to perform the tasks related to user requests. This output should meet the Service Level Agreement (SLA) (McFarlane, 2005).

We can say that the two parties involved in the application development are the users and the Data Center. Between the two approved a Service Level Agreement (SLA). An SLA defines the expectations between the consumer and the provider. It helps determine the relationship between the two parties. It is the cornerstone of how the service provider sets and retains an obligation for the consumer of the service. A good SLA sets five key aspects (McFarlane, 2005).

- the obligations of the provider
- How will the provider offer its services
- Who will measure the quality of provision, and how.
- What happens if the provider fails to deliver as promised.
- How will the SLA changed over time.

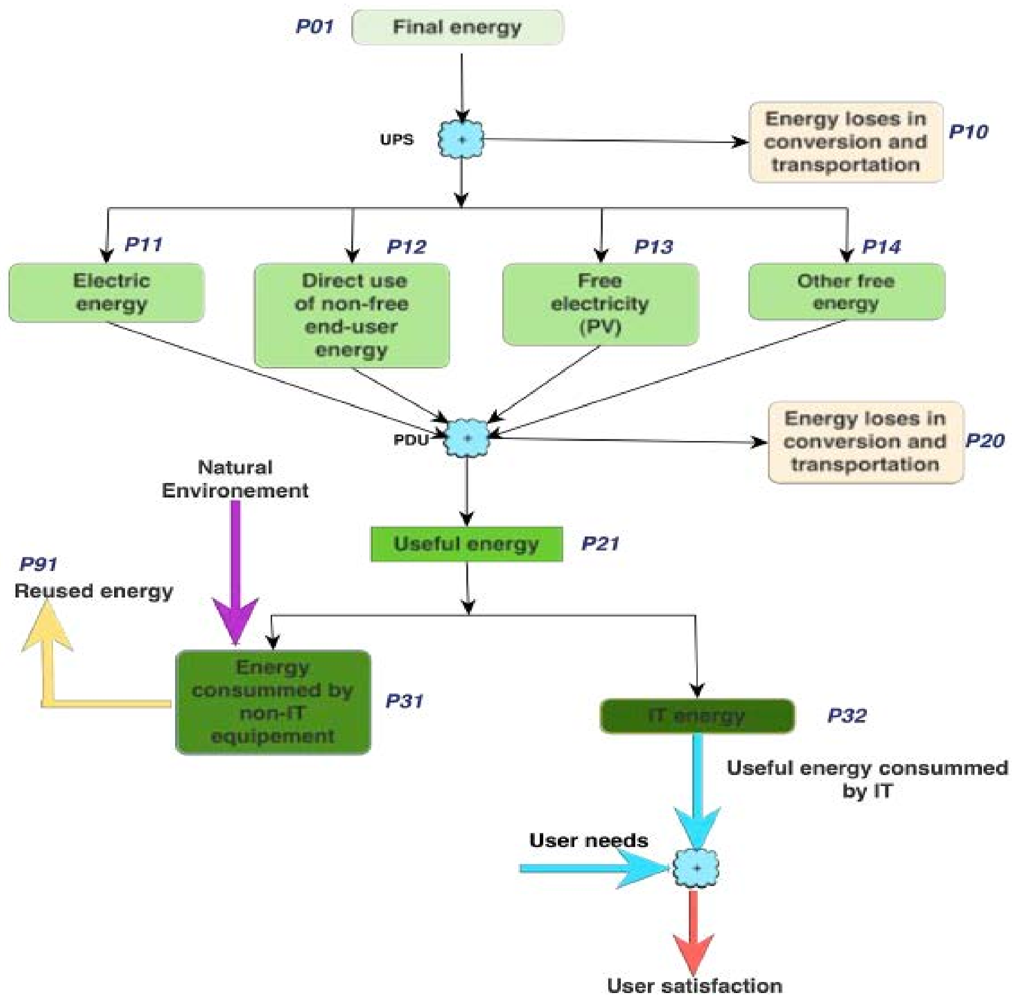


Figure 11: Energy distribution in a typical Data Center (McFarlane, 2005)

The SLA encapsulates many secondary factors that contribute to energy consumption. Also, the SLA represents user satisfaction. The power consumption is not constant over time, but varies depending on various parameters. The main factor affecting the consumption is a Data Center workload and the external environment. The modelling of energy efficiency and the losses of Data Center equipment is a complex task and important cases generate large errors (Dunlap and Rasmussen, 2005). First of all, the assumption that the losses associated with power and cooling equipment is stable over time is wrong. It has been observed that energy consumption is a function of IT load and non -IT equipment (devices responsible for cooling and power supply) (Green IT promotion council).

2.3.1 Degrees of freedom in energy efficiency

We call degrees of freedom, the number of independent pieces of information that can be found in an equation. The plant benefits from degrees of freedom from: energy transmission and transformation, cooling and draining heat from the construction of the Data Center. On the other hand, many degrees of freedom can be secured from its use. Then, we will analyze each degree of freedom (Dunlap and Rasmussen, 2005). When searching for the highest yield in the cooling system, it is imperative for the Data Center to operate at the correct temperature. The pursuit of this objective should include assessments of the energy spent in the cooling process and the power supply fan, and should also be considered the best cooling solution flow and management techniques. One of the degrees of freedom that had been proposed in the literature is the increasing temperature of the Data Center (Dunlap and Rasmussen, 2005).

Some of the major manufacturers of Servers and experts for performance Data Centers share the view that Data Centers can operate at much higher temperatures than those operating today without sacrificing the uptime, and huge savings in both cooling costs and CO_2 emissions. According to (Dunlap and Rasmussen, 2005) Data Centers can save 4-5% in energy costs for every degree increase in single inlet temperature in Server. The air temperature must be raised but only after consideration of the effects on each piece of IT equipment. If a Data Center is successful in raising the temperature, there is a big saving in energy with the chiller, potential savings in humidity control, with the possibility of increasing the number of hours that can be used economizer.

There are several different methods for free cooling in Data Centers, which can be used instead of / in conjunction with traditional refrigeration for full or partial free cooling (Sophia Flucker et al, 2011):

1. Direct air free cooling: Ambient air is treated (filtered, humidified and refrigerated where necessary) and brought into the data hall. The cooling system (and therefore electrical plant) needs to be sized for the worst case maximum refrigeration load.
2. Indirect air free cooling: Ambient air is passed through a heat exchanger and hot / cold air transferred with the data hall internal air stream. Adiabatic humidification on the external air

stream allows evaporative cooling at hot dry ambient conditions. Any refrigeration capacity required is minimal (supplementary only), allowing reduced sizing of mechanical and electrical plant and therefore capital cost saving.

3. Quasi-indirect air free cooling (thermal wheel): Similar to indirect air free cooling except constant volume of fresh air brought in to data hall which requires treatment.

4. Water side free cooling: Heat is rejected to ambient without the use of a refrigeration cycle, for example using cooling towers or dry coolers. This is often an easier retrofit option compared with air side free cooling designs as this method usually requires modification to external plant only and is typically less demanding in terms of plant footprint

According to (Steve Greenberg et al, 2006) the following best practices have emerged through the study of 22 data centers:

• Improved air management, emphasizing control and isolation of hot and cold air streams.
• Right-sized central plants and ventilation systems to operate efficiently both at inception and as the data center load increases over time.
• Optimized central chiller plants, designed and controlled to maximize overall cooling plant efficiency, including the chillers, pumps, and towers.
• Central air-handling units with high fan efficiency, in lieu of distributed units.
• Air-side or water-side economizers, operating in series with, or in lieu of, compressor based cooling, to provide "free cooling" when ambient conditions allow.
• Alternative humidity control, including elimination of simultaneous humidification and dehumidification, and the use of direct evaporative cooling.
• Improved configuration and operation of uninterruptible power supplies.
• High-efficiency computer power supplies to reduce load at the racks.
• On-site generation combined with adsorption or absorption chillers for cooling using the waste heat, ideally with grid interconnection to allow power sales to the utility.
• Direct liquid cooling of racks or computers, for energy and space savings.
• Reduced standby losses of standby generation systems.
• Processes for designing, operating, and maintaining data centers that result in more functional, reliable, and energy-efficient data centers throughout their life cycle.

Other authors (Patel and Shah, 2005), show how the equipment is placed in the Data Center in order to be as effective as possible, the release of heat. The way in which the Data Center was constructed affects the energy efficiency of the Data Center. The goal of all researchers in this area is to find the best location and construction of the Data Center space to ensure efficient release of heat that produced by the electrical equipment installed and operate. In conclusion, the development of a smoother cooling controller and additionally with intelligent placement of equipment can minimize cooling consumption and can support energy optimization and management process in a Data Center.

The energy transfer is not dynamic degrees of freedom because; reliability and solution to optimize the consumption of such equipment can not be affected by designer / Data Center operator (Hughes, 2005). The energy optimization is satisfied with the size and configuration, which can guarantee an effective relationship between the various infrastructure of Data Center.

If we look at performance, we can state that a promising approach to increasing energy efficiency could be virtualization and Server Consolidation (Hughes, 2005). The Consolidation and Virtualization may introduce additional degrees of freedom that are not available in traditional operating models (Anthes, 2005). Furthermore, another degree of freedom can be achieved if the integration Server is associated with scalable dynamic voltage and frequency provided by conventional processors, for even better results. Remarkable work has been done also in terms of data storage, including the variation in the speed of the disc to allow saving energy in fatigue and a rapid recovery in terms of performance (Anthes, 2005).

2.4 Power usage effectiveness

The Power Usage Effectiveness index (PUE) is a Unit of measurement that was established by the Green Grid organization, and expresses the energy performance of a Data Center, namely a central computing facility, in terms of basic infrastructure conditions. PUE expresses the ratio of the total energy required to the energy actually consumed by the computing resources. Total energy is calculated from all the resources needed to support the load under normal conditions, such as UPS, air conditioners, etc. For example, in a Data Center where 1000 watts of total power are consumed and 500 watts on IT equipment, PUE obtained has a value of 2 (1000/500 = 2). The closer the value is to 1, ideally 100% of the energy supplied to the computing infrastructure, the more energy efficient is the Data Center, which in turn means lower operating costs (EPSET, 2016). The precise measurement of PUE allows for the evaluation, control and better compliance to even better (“greener”) energy technologies.

PUE is calculated by taking energy use measurements close to the utility meter. If the Data Center is a mixed-use Data Center or office, the measurement should be taken only to the extent that supplies the Data Center. If the Data Center is in a separate utility meter, the amount of energy consumed by the non-given center portion is estimated and removed from the equation. The IT equipment load should be measured after the power conversion, switching, and the air conditioning. According to The Green Grid, the more likely measurement point would be the output of computer room Power Distribution Units (PDUs). This measurement should represent the total power delivered to the Server racks in the Data Center.

The Uptime Institute has an average PUE of 2.5. This means that for every 2,5 watt measured at the meter, only one watt is delivered to the IT load. Uptime estimates that more facilities could achieve 1,6 PUE using the most efficient equipment and best technologies. These include measures to reduce the IT load, such as decommission or repurposing of Servers, powering down Servers when they are not in use, enabling of power management, replacement of inefficient Servers, virtualization and consolidation. According to Nolimits (2011) PUE is a great tool for the facilities side of the Data Center. It allows facility engineers to measure the impact of changes they make to the infrastructure, things like raising the Data Center temperature, upgrading to a higher efficiency UPS, increasing voltage to the rack and so on. In their Whitepaper Nolimits (2011), they state that Virtualization and consolidation, while reducing the overall energy usage, will actually increase the PUE unless the power and cooling infrastructure are downsized to align with the IT load. Raising the Server inlet temperature may reduce the PUE, but the overall energy usage may actually increase if the increased power required for Server fans is greater than the cooling savings. Hence, we conclude that PUE should not be the only metric for energy efficiency in a Data Center. Making the IT equipment operation more efficient, would not decrease PUE, if the power and cooling equipment are not optimized to adapt to the new IT load. Tripplite (2016) also argues that to decrease PUE one should concentrate first on cooling, which is often the biggest consumer. Cooling load can be reduced by organizing cables, installing banking panels, isolating and removing hot air.

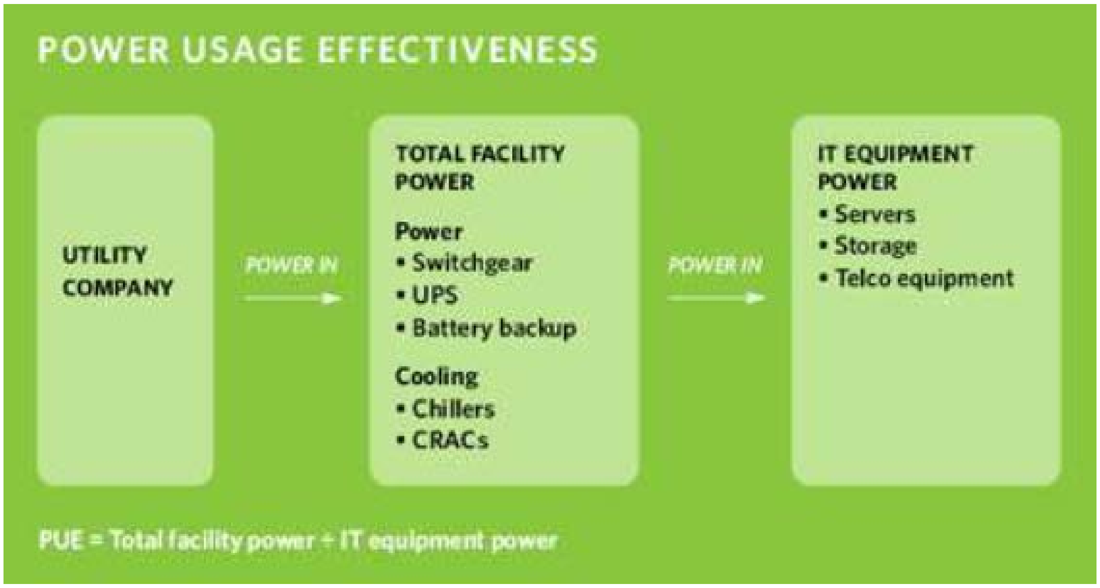


Figure 12: PUE parameter flow

Worldwide according to Uptime Institute's Data Center Survey (UI, 2016) the average PUE of the largest Data Center ranges between 1.8 and 1.89. Best PUE is achieved by companies such as Yahoo, Google, Facebook, and Microsoft that have values close to unity and less than 1.2. The reason why they have achieved such values is that they specially designed facilities which are often placed in very favorable climates for operation of an efficient Data Center. In many cases, the external cold air is used to entirely cool the Data Center avoiding one of the most intensive parts of the traditional Data Center, air conditioning, while in specially designed Data Centers water cooling uses the cold ocean water with positive effects also on resulting value of PUE. Cold Isle Containment systems, i.e. passive separation system of air flow between the cold and hot isle, are used for PUE enhancement. The hot and cold isle ensures both the introduction of cold conditioned air from the front of the system and the extraction of hot air from the back of the Rack and other more efficient system operation. Simultaneously, air conditioners positioning can be set for more efficient channeling of cold air in the cold area at the lowest possible cost.

Also climatic sensors can be installed and configured that are responsible for the immediate notification and the calculation of useful metrics to forecast future improvements in infrastructure. Virtualization / consolidation reduce costs, since reduce capacity requirements and the use of machines and the number of physical machines required. Typical Server utilization ranges from 5% to 30%, which allows accommodating more than one Server on one physical machine. Another popular metric, namely performance per watt attempts to capture performance-power tradeoff. However, a related problem is that characterizing the impact of power on performance is often very challenging and there is little in the way of formal models to address this gap and in a virtualized environment, it should be possible to estimate power and thermal effects of individual VM’s, but this can be very challenging since the VMs can interact in complex ways, for example, a poorly behaved VM can increase the power consumption of other VMs. (Krishna Kant, 2009)

2.5 Summary

In the second chapter, the theoretical problem is identified concerning the significance of energy consumption analysis in the building sector. The researcher outlines the need for self-sustained and low CO_2 emission buildings, while introducing the basic parameters of energy consumption in Data Centers.

Chapter 3 - Thermal behavior of buildings

In this chapter the basic factors affecting the thermal performance of buildings will be thoroughly analyzed. Special attention will be given to non-residential, educational buildings that are the case study of this research. This chapter serves as a basis to the model development procedure in Chapter 4.

3.1 Building envelope/archetype

During the last decades there has been significant research in the area of energy use in the non-domestic sector at a national and international level but it is limited, mainly because there is no 'typical' building (Isaacs, N. and Steadman, P., 2014). Buildings vary widely in terms of use, activities, and ownership structures within them, thus it is difficult to categorize them. As discussed, research in this field is limited. The UK and US are the main two countries that have investigated the non-domestic sector (Choudhary,R., and Tian,W., 2014). Thus this section will present the databases that are used in them.

Research is primarily based on national data sources of each country. Building stock modelling is highly dependent on the amount and type of buildings, along with their floor areas. The UK's system of property taxation is based on buildings and not on land, and this has formed one of the most important databases which are administered by the Valuation Office Agency (VOA). The unit of VOA is the hereditament. (Isaacs, N and Steadman, P.,2014;Isaacs, N., and Hills, A.,2014). The complexity of modelling the non-domestic stock has been thoroughly examined by many researchers (Bruhns,H.,et al.,2000a;2000b;Steadman,P.,et al.,2000a;2000b) , with Bruhns, H. (2008) explaining that there is a significant difference between stock modelling and building modelling. Generally, there are two different types of energy stock models, the top down (or simple statistical models) and bottom up (or physical) models. Each one has a diverse array of criteria (Bruhns, H.,2008; Kavgic, M.,et al.,2010). Simple statistical models give information about stock energy use and end-users, and their aggregation level depends on the quality of information. They provide little technical information about the determinants of energy use or the explanation behind the trends. On the contrary, physical models can predict the energy use mainly according to thermal physics and building services data. It has been proved that factors such as local temperatures, wind and lighting significantly affect the patterns of energy use in a building (Santamouris,M. and Asimakopoulos,D.N.,2001). The main drawback of bottom-up models is that they require a significant amount of information.

In the past decades, many researchers have developed different models which can usually vary in data input requirements, disaggregation levels and socio-technical assumptions. This results in a different type of results and predicted scenarios. In the US, building stock modelling raised by the formation of archetypes, which were introduced in 1991 by Huang et al. Authors developed an energy model that was based on non-domestic building archetypes. Archetypes are building areas selected on the physical characteristics such as insulation levels, but also on the heating and ventilation system. Each archetype was represented by a priori selected average representative characteristics. The scope was to investigate the suitability of cogeneration units across the States but they used unrepresentative data. The model was re-used by Huang,Y.J. and Brodrick,J. (2000) in order to estimate the impact of new technologies on the energy consumption across the entire US building stock. The main added value of this survey was about the contributing factors of energy use, and the quantification of energy savings from efficiency improvements for different building characteristics by region, vintage, and building type. Nevertheless, more research should be done regarding the characterization of prototypical buildings, as well as their better calibration in energy terms.

A study carried out on UK office building stock (Korolija, 2013) aimed to define archetypes by developing models (not actual buildings), by studying several different factors selected through an extensive literature review such as: built form (day lit cellular, artificially lit cellular, day lit hall, artificially lit hall, day lit open-plan, and artificially lit openplan) based on the Steadman work (Steadman, 2000), glazing ratio (25%, 50%, 75%), building envelope construction (5 types according to the level of insulation: from none to U-values lower than UK regulations), solar shading and heat gains control measures (2 measures: reflective glazing and overhangs) and indoor environment (indoor thermal condition, indoor air quality, internal heat gains from occupants, internal heat gains from office electrical equipment, internal heat gains from artificial lighting and daylight control). By running simulations in modelling software for thermal performance and by parameterising construction elements, components, design features, occupancy and activities the authors came out with 3840 typical office buildings.

A research carried out on a Greek school building stock (Gaitani, 2010) studied 1100 buildings in order to develop an energy classification and determine the environmental quality of school buildings. Although this research does not develop building archetypes, the variables considered in its research process are equivalent to those which do, as the final aim is also to develop a classification. The variables considered were: heated surface, age of the building, insulation of the building (0=non insulated / 1=insulated), number of classrooms, number of students, school's operating hours per day and age of the heating system. Developing a cluster analysis determined 5 different energy classes for space heating purposes, from which was identified a representative building for each class. This study presents a robust methodology which shows clearly the process of developing an archetype.

3.2 Building materials

Each building material is characterized by a U coefficient. The heat transfer coefficient or film coefficient, in thermodynamics and in mechanics is the proportionality coefficient between the heat flux and the thermodynamic driving force for the flow of heat. It is used in calculating the heat transfer, typically by convection or phase transition between a fluid and a solid. The heat transfer coefficient has SI units in watts per square meter kelvin: $W/(m^2 \cdot K)$. Heat transfer coefficient is the inverse of thermal insulance. This is used for building materials (R-value) and for clothing insulation.

There are numerous methods for calculating the heat transfer coefficient in different heat transfer modes, different fluids, flow regimes, and under different thermohydraulic conditions. Often it can be estimated by dividing the thermal conductivity of the convection fluid by a length scale. The heat transfer coefficient is often calculated from the Nusselt number (a dimensionless number). The calculation U coefficients of opaque building materials is denoted by the letter U and is calculated by the combination of the resistance of each material part in the component. Usually the walls are created by various vertical layers of construction materials with different resistance to heat flow, as presented in Figure 13.

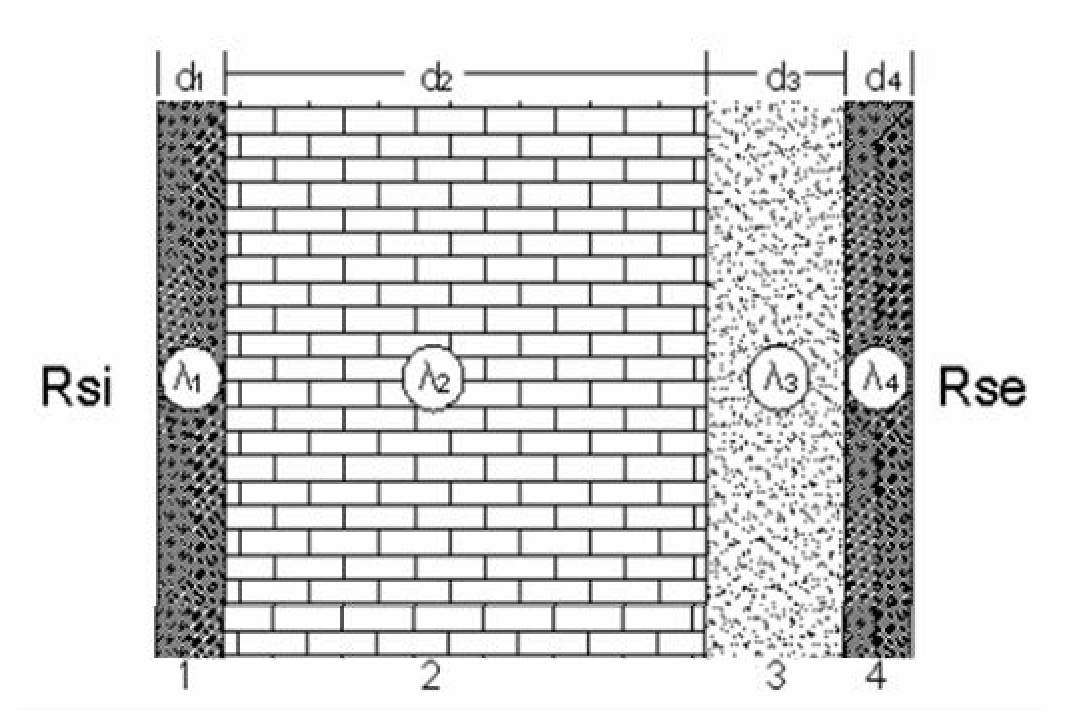


Figure 13: building structure combining building materials

The heat transfer coefficient of the structure resulting from the following formula, wherein the R denotes the resistance of each material that is inserted in the component and the total resistance of the structure.

$$U_i = \frac{1}{R_T} = \frac{1}{R_{si} + R_1 + R_2 + \ldots . R_n + R_{se}}$$

Alternatively, if it is known the thickness of each material d (m) and the typical thermal conductivity k (W / mK) can be used the following formula to calculate the U.

$$U_i = \frac{1}{R_{si} + \boxed{\sum \frac{d_i}{\lambda_i}} + R_{se}} \quad [W / m^2K]$$

Typical thermal conductivity is the value of the coefficient of thermal conductivity of a building material or product under specified internal and external conditions that may be considered typical for the behavior of the material when incorporated into a structural element.

Where there is a trapped layer of air between opaque building materials the following relationship is used:

$$U_i = \frac{1}{R_{si} + \sum \frac{d_i}{\lambda_i} + \boxed{R_a} + R_{se}}$$

3.3 Building air flow and heat transfer

Infiltration and ventilation are two key parameters for energy efficiency of every building structure. Infiltration is defined as the unintentional and uncontrolled flow of outdoor air into a room, which takes place due to openings in the building envelope or pressure differences among indoor and outdoor environment. For example, the air coming in a room through open doors and windows is considered infiltration although it might be considered an intentional form of air flow into the inside of the enclosed space (ventilation) (Hernandez et at., 2008).

In winter, it is more usual to have infiltration when the air outside is colder and heavier than the air inside due to the pressure differences. The factors that affect infiltration are mainly wind velocity, air-tightness of the building envelope and wind direction. Infiltration may also be caused by the stack effect in high-rise buildings. Infiltration (as well as ventilation) is set in ach units which stand for Air Changes per Hour (ACH). This method determines how many times the room air is replaced with outdoor within an hour. The effects of infiltration in non residential building efficiency have been studied by Bull et al. (2014) and Caruana et al. (2011). .

Ventilation could be natural or mechanical, but it is used commonly for mechanical systems. In TAS this parameter is used for determination of mechanical system efficiency in spaces where these systems are present. Unlike infiltration, ventilation is the intentional and controlled entry of outdoor air into a room. Fans and other mechanical systems can provide ventilation. As mentioned above, outdoor air coming through an open door or window is considered infiltration and not ventilation. Recirculation of uncontrolled outdoor air supply to a space is not ventilation either (Hernandez et at., 2008).

In many state regulations for buildings, such as the UK's Building Bulletin 101, ventilation should be provided to limit the concentration of carbon dioxide, ie to enhance the safety and comfort of the building occupants. The maximum concentration of carbon dioxide should not exceed 5000 ppm during the teaching day. At any occupied time, the occupants should be able to lower the concentration of carbon dioxide to 1000 ppm. Intentional ventilation should provide the capability of achieving a minimum of 8 l/s per person at any occupied time. Additional ventilators could be used to provide this extra ventilation e.g. supplementing windows with the addition of louvres or stacks. This ventilation may not be required at all times of occupancy, but it should be achievable under the control of the occupant. When fresh air is supplied at a rate of 8 l/s per person, the carbon dioxide concentration will generally remain below 1000 ppm. For office accommodation, in the absence of tobacco smoke or other excessive pollutants, a supply rate of 10 l/s per person is recommended. This outdoor air-supply rate is based on controlling body odors and typical levels of other indoor-generated pollutants (Building Bulletin 101).

Infiltration and ventilation have been studied extensively in building energy consumption and benchmarking studies. Hong et al. (2013) developed a multiple linear regression model to investigate various determinants of energy use across English schools. Similar trends were found by Godoy et al. (2011), whose data date back in 1999. Difference was found in the impact of ventilation techniques on the energy use. Both studies showed that controlled ventilation strategies increase the building's energy demand leading to environmental and economical impacts. The UK has developed regulations (30 Building Bulletins in total) that cover all the energy efficiency aspects, like ventilation rates, acoustics, environmental design and indoor air quality. They are of significant importance in retrofit scenarios as they can determine the viability of the energy management strategies, eg ventilation system. Both mechanisms, infiltration and ventilation, use fresh, outdoor air to supply the needs of building occupants. The temperature of outdoor air is a determining factor for the efficacy of indoor cooling. The types of cooling techniques that have been proposed in the literature are multiple and vary from passive systems to mechanical – controlled systems. Heat and temperature are distinct but often liable to confusion concepts. The temperature is a statutes size which depends solely on the state of a system. In contrast, the concept of heat results in thermal interactions between bodies, so a system can not be said to "have" a heat value (just like a mechanical system does not "have" a work value). The inflow of heat in a system may result in an increased internal energy or production of work.

The heat transmission often occurs in practical applications with which engineers are correlated. The cost and size of a device or the various components through which a certain amount of heat flow transacts at a certain time, necessitates an analysis of the phenomenon of heat flow. According to the existing literature and even due to the complexity of the phenomenon, there are three heat transfer mechanisms that are divided as below:

1. conductance
2. coconductance
3. radiation

Taking into account the general definition of heat transfer, namely considering the appearance of the phenomenon under the condition of being dynamic temperature difference between systems, only the thermal conductivity can be classified as pure heat transfer process, while the thermal coconductance presupposes the existence of mass flow and radiation temperature of the system. Despite this, and because there is energy transfer from a high temperature system to a low temperature system, this has been accepted to be studied as a heat transfer mechanism.

Thermal conductivity is defined as the heat transfer mechanism in a region or high temperature system to another or other lower temperature through a solid, liquid or gas medium at rest, provided that there is physical contact. This transfer is accomplished either by molecular interaction, either through concentration of free electrons in purely metallic solids. Specifically, when the molecules of a region of matter acquire a mean kinetic energy greater than that of the molecules of the adjacent region, this manifests itself in the form of a temperature differential. So the energy or part thereof is transferred to the molecules of the area with lower temperature, which verifies the definition of the thermal conductivity. The transfer of heat by conduction takes place by elastic shock or by diffusion of molecules during their random motion in gases and fluids. In the case of solid media, the corresponding thermal energy is transferred through the oscillation of the molecules of the matrix and the moving electrons from regions of high to low temperature regions. A typical example is the phenomenon of heat loss that occurs in enclosed space heated during the cold season, which is mainly due to the conductivity of the walls, windows, roof, etc.

The rate of change of the thermal conductivity through a medium is dependent on the geometry of the medium, the material, and the temperature difference between the thresholds. The flow of heat through a wall is proportional to the temperature difference of the limits of the instrument and the vertical surface in the direction of heat transfer, and is inversely proportional to the thickness of the medium. Therefore:

$$Q_{cond} = -k \cdot A \frac{\Delta T}{\Delta x}$$

Wherein the constant amount A is the thermal conductivity of the medium and the characteristic physical property of the material, indicating its ability to transfer heat. In the limited case where the thickness of the medium Dx tends to 0, the equation can be written in differential form:

$$Q_{cond} = -k \cdot A \frac{dT}{dx}$$

This relationship is called Law Fourrier. The negative sign of the equation is the consequence of the second law of thermodynamics which ensures that heat is transported in the opposite direction to the temperature dial.

Thermal coconductance defined as the heat transfer mechanism between a solid surface and an adjacent moving fluid, and is a combination of conductivity and transport of fluid. The mechanism of operation of coconductance heat transfer depends not so much on the temperature difference, but following a series of natural processes as explained below. Initially, the heat flux carried by convection from a solid surface to adjacent molecules of the fluid. Therefore the temperature is increased and the internal energy of the molecules of the fluid, resulting in the molecules moving in the lower temperature region. The thermal energy is stored in the molecules of the fluid and transferred to the movable mass. The process of this kind of heat transfer is called heat coconductance.

The greater the movement of the fluid, the greater the flow of heat through coconductance. If the fluid is stationary, then the heat transfer is realized only by conduction. The thermal coconductance is sorted in accordance with the nature of fluid flow. We have forced coconductance when fluid moves due to external factors. In contrast, free or physical coconductance occurs when the movement of fluid is due to buoyancy forces caused by the temperature distribution.

Despite all the complexity of the phenomenon, the transfer rate of thermal coconductance expressed through the law of Newton.

$$\dot{Q}_{conv} = hA(T_w - T_\infty)$$

wherein A is the area of the surface while TW and T∞ is the surface temperature of the solid wall and the temperature of the free stream of the adjacent fluid, respectively. The term h is the coefficient of thermal coconductance and is not a property of the fluid, but depends on the conditions of the boundary layer affected by the geometry of the surface, the thermodynamic properties of the fluid and the type of flow. The use of the equation exists provided that heat transfer takes place from the higher temperature of the surface to lower the fluid, whereby the heat flow has a positive sign.

Heat propagates in a vacuum. A known example in nature is the heating of the Earth from the Sun, where there is a transmission medium. This method of propagation of heat by radiation is called diffusion. The thermal radiation propagates in space by electromagnetic waves (similar to bright), absorbed by the various colleges and the heats. The radiation heat transfer is usually considered negligible at low temperatures and thus not taken into account. For metals, e.g. not counting for temperatures lower temperature metal. Thermal radiation is defined as the phenomenon of heat flow from the material through the space or through the gap in the form of electromagnetic waves as a result of changes in the array of atoms, or molecules, which is solely due to the temperature of the substance or agent. The transferred amount of energy , defined as radiant heat, is transferred in the form of quanta, whose size mainly depends on the nature of the surface. All bodies which are at a temperature above absolute zero emit thermal radiation. Instead, heat transfer by radiation is more efficient in vacuum and depends on the temperature and nature of the radiation emitting surface. The radiated heat is transferred to the speed of light, and replaces phenomenologically irradiation of light, while according to the electromagnetic theory, the light and thermal radiation vary only in correspondence of the wave length. The heat transferred by a body carried in the form of quanta, and as the temperature increases both the radiated quantities increase. The movement of the radiant heat in the space of the same type and parameter attributes of light and, therefore, can be described by the wave theory.

The maximum transfer rate of thermal radiation emitted by a surface area A and absolute temperature Tw may be determined by the equation:

$$\dot{Q}_{rad,max} = \sigma A T^4_w$$

defined as law Stefan-Boltzmann. The ideal surface which emits maximum thermal radiation transfer rate defined black or black body, while the actual surfaces in the same temperature emit a lower rate, such as:

$$\dot{Q}_{rad} = \varepsilon \sigma A T^4_w$$

wherein the parameter e is defined as emission coefficient, and is a property of the surface. It takes values between 0 and 1.

A special case occurs often in practical applications, includes the existence of a relatively small surface area A and the temperature Tw, which is completely surrounded by a much larger isothermal surface temperature Tsur> Tw, whereby the transported radiation is expressed by the relation:

$$\dot{Q}_{rad} = \varepsilon \sigma A (T^4_w - T^4_{sur})$$

The dimensioning of boilers, heaters, cold rooms, refrigerators and heat exchangers, like turbine blades operating successes, combustion chamber walls, require precise determination of heat transfer amount or metal cooling flow amount, respectively, which implies detailed phenomenon analysis of the heat flow in relation to time. Some other examples are the study of electrical machines, transformers, bearings and support bearings, machine tools and even electrical circuits, electrical resistors, inductance capacitors and provisions and other practical problems that require an understanding of the physical phenomenon of heat flow, the admission requirements and expression of the problem, in the form of equations, the solution of which requires methodology and often computational and / or approximation techniques.

Simple exemplary methods of solving problems thermal efficiency and sizing problems are not generally provided, but imported conditions and approaches should be based not only on understanding the physical state of the problem, on the laws and mechanisms of the phenomenon of heat transfer, but also on the laws of science of fluid mechanics, physics and mathematics. Thermal design problems that require heat transfer studies is the insulation in buildings, airplanes, cooling nozzles, motors and electronic devices, in transistors, diodes, batteries, in optics and alignment. The heat transfer between fluids studied in alternators, car refrigerators, energy conversion systems, boilers and condensers. Also in cooling cycles performed in evaporators and condensers, process industries for heat treatment of metals and glass or forming mechanics. The chemical industries also rely on heat transfer to exploit the waste heat rejecting heat in cooling towers. The heat transfer is studied in meteorology. The heat transfer occurs by transfer of the presence of fluid or surface to fluid conductance and movement.

3.4 Summary

The third chapter contains information relative to thermal performance and analysis of buildings, including structural materials and occupational patterns. It is utilized as an introduction to the next chapter of thermal modeling

Chapter 4 - Proposed methodology for assessing the thermal performance of a Data Center space

In this Chapter the proposed methodology for assessing the thermal performance of a Data Center space will be presented based on the analysis of Chapters 2 and 3. All the software utilized for the analysis will be thoroughly described and all the limitation concerning the research will be discussed. We will proceed in the implementation of the 3-D geometry of the case study building in Sketchup using Sketchup 2015 version, we will describe the input parameter selection and modeling procedure, and we will present and discuss the simulation results and then draw some conclusions based on this analysis.

4.1 Case study building

Figure 14: The case study building

The building of interest in this study is a building of TEI of Crete in Heraklion. It is a 3-story building that has study rooms, classrooms, offices and IT rooms. On the 2nd floor there are two rooms, one data/Data Center and one Hardware Laboratory. We measured the indoor air temperature of the Hardware Laboratory and Data Center as well as the IT equipment and non IT equipment (UPS) electric power consumption of the Data Center. The next step was to compare simulation and measures of the indoor air temperature of the Hardware Laboratory in order to validate our model. As the Data Center and Hardware Laboratory are both spatial and structural the same spaces, we can define in our model the characteristics of the Data Center space in order to have a report about electric energy and cooling capacity required to cool the space regarding the temperature measured in the Data Center. Having the electric energy needed for cooling, the PUE can be estimated. Subsequently we will propose ways to improve the PUE of the Data Center making changes in our model. Figure 15 presents third floor plan with HVAC, sensors and computer with Emoncms software.

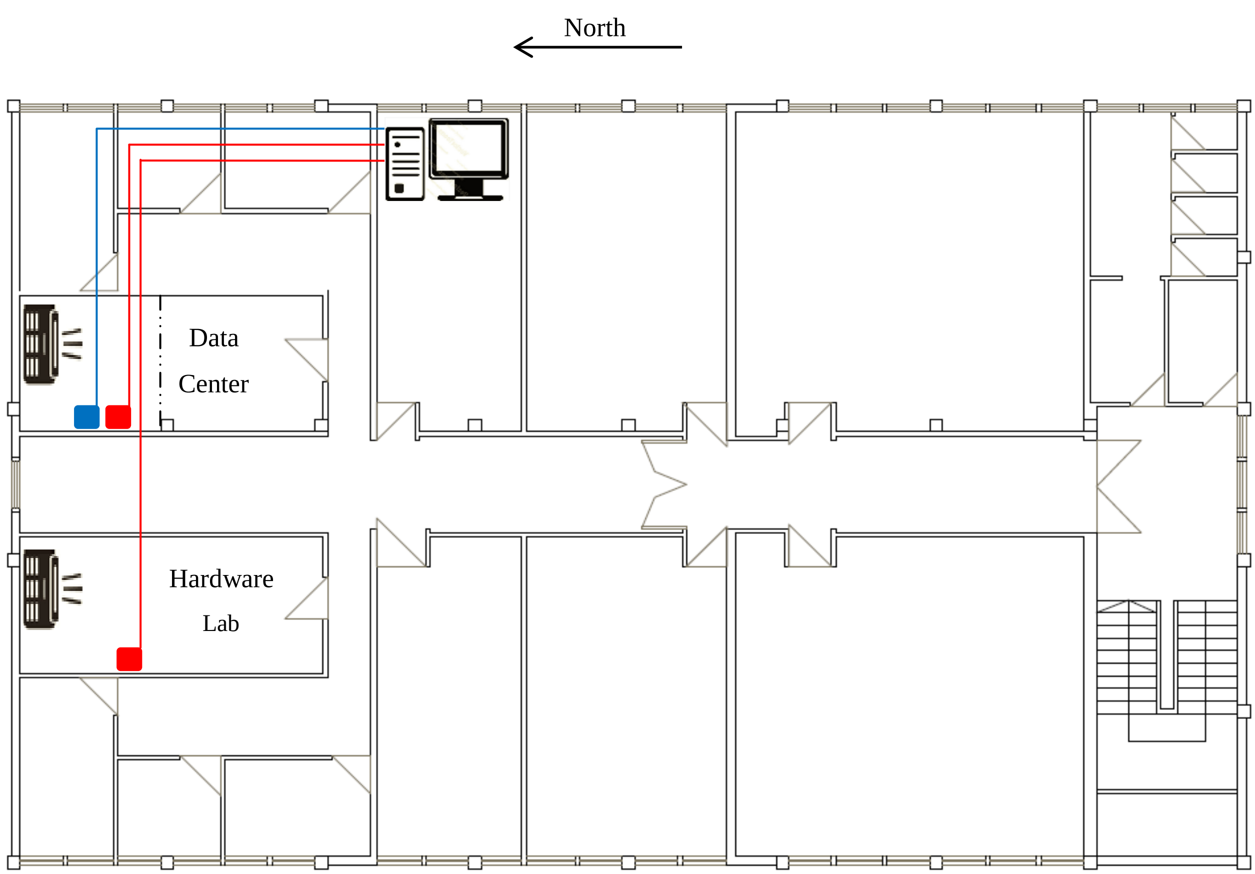


Figure 15: Third floor plan with two air conditions, temperature sensors (red), electricity consumption sensors (blue) and computer with Emoncms software.

4.2 Software tools for simulation

In this section will be presented the simulation tools that was used for the thermal analysis of the Educational building in Herakleion, Crete.

4.2.1 EnergyPlus Software

EnergyPlus is a thermal analysis software that allows engineers to simulate the thermal behavior of buildings. EnergyPlus is a dynamic simulation modelling tool (DSM) and is used to simulate the thermal performance of new and existing buildings. The software is primarily used by engineers, architects, and academics. A popular application lies in producing Energy Performance Certificates, overheating studies, and running heating and cooling design days. Dynamic simulation traces the building's thermal state through a series of hourly snapshots, providing a detailed picture of the way the building performs under extreme design conditions and throughout a typical year. Results consist of several data points for each variable that is output. EnergyPlus allows for preparation of a model in 3-D geometry in a third party software (Sketchup) based on already existing building plans and detailed photos and then guides the user to set up the internal condition zones and structural element characteristics that will describe the building model (by relative plugins). The simulation process calculates annual hourly data that can be examined in detailed and filtered for each zone and variable.

4.2.2 Sketchup Software

Sketchup is a 3D modeling computer program for a wide range of drawing applications such as architectural, interior design, civil and mechanical engineering, film, and video game design — and available in a freeware version, SketchUp Make, and a paid version with additional functionality, SketchUp Pro. There is an online open source library of free model assemblies (e.g., windows, doors, automobiles, etc.), 3D Warehouse, to which users may contribute models. The program includes drawing layout functionality, allows surface rendering in variable "styles", supports third-party "plug-in" programs hosted on a site called Extension Warehouse to provide other capabilities (e.g., near photo-realistic rendering), and enables placement of its models within Google Earth. SketchUp 4 and later support software extensions written in the Ruby programming language, which add specialized functionality. SketchUp has a Ruby console, an environment which allows experimentation with Ruby. The free version of SketchUp also supports Ruby scripts, with workarounds for its import and export limitations. Since Sketchup 2015 Trimble for the first time ever, offering a 64-bit version.

4.2.3 Legacy OpenStudio SketchUp Plug-in

The Legacy OpenStudio Plug-in for SketchUp makes it easy to create and edit the building geometry in your EnergyPlus input files. This free plug-in also allows you to launch EnergyPlus simulations and view the results without leaving the SketchUp 3D drawing program. Active development has moved from the Legacy OpenStudio Plug-in to the more comprehensive OpenStudio suite of tools and libraries. Changes to the Legacy OpenStudio Plug-in will be limited to bug fixes and compatibility updates for new versions of EnergyPlus. The Legacy OpenStudio Plug-in was created by the National Renewable Energy Laboratory for the U.S. Department of Energy (www.nrel.gov) as an interface to the EnergyPlus simulation engine.

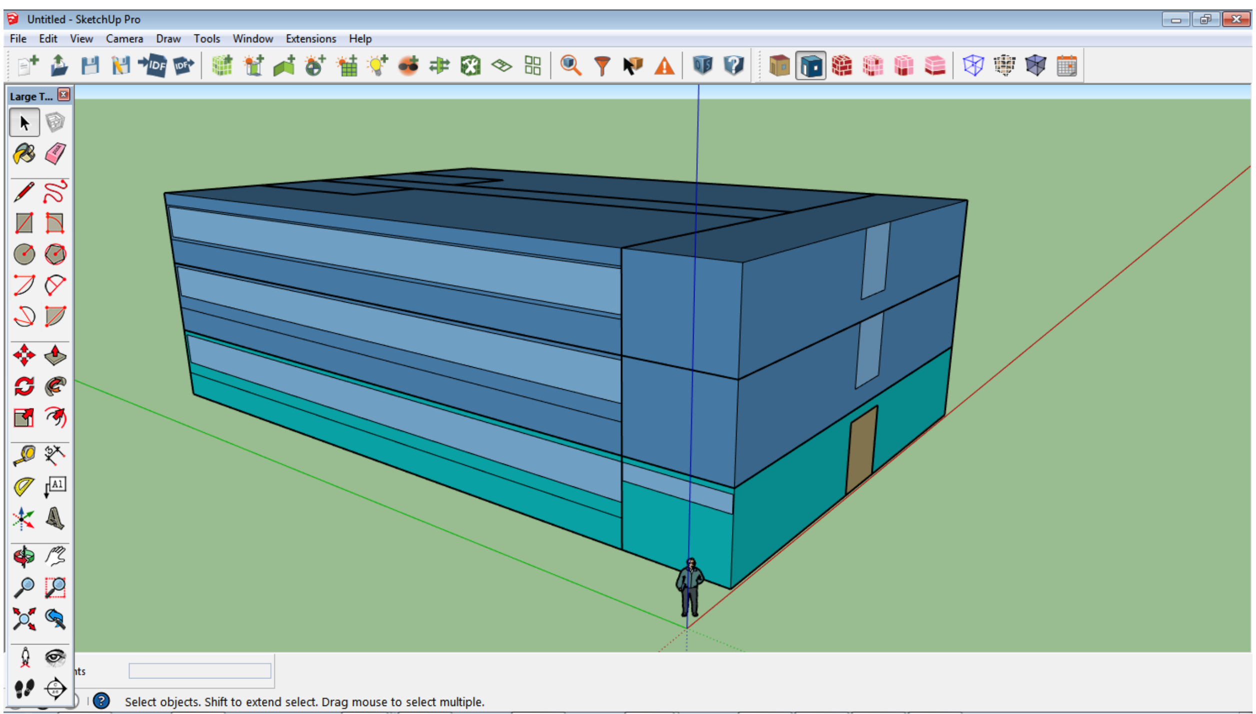


Figure 16: 3D model view in Sketchup rendering by Boundary Condition

4.2.4 OpenStudio Application Suite

The OpenStudio Application Suite combines all the plug-ins for modeling, simulation and results viewing with EnergyPlus and SketchUp. It is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modelling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK). It is the next version of Legacy Openstudio plug-in that incorporates all the necessary tools for EnergyPlus simulations.

OpenStudio enables potential developers to write their OpenStudio measure (henceforth referred to as a "measure"). Measure is a program (or 'script', or 'macro') that can access and leverage the OpenStudio model and API to create or make changes to a building energy model, as defined by an OpenStudio model (.osm). Typically, a measure modifies an existing .osm in order to implement a given Energy Conservation Measure (ECM). For example, a measure might change the insulation rating of the exterior walls, change the window-to-wall ratio of a specific facade, or modify operational or occupancy schedules. Measures may also generate reports on the input and output of a given energy model; as such, these are referred to as reporting measures. Measures may be linked together in a workflow in order to implement complex ECMs, or to repeatably implement ECMs across building types or climate zones; measures can even generate entire - code - compliant and climate - zone specific - building models solely from user inputs. Measures are written in Ruby, which allows the measure author to access OpenStudio directly as well as through the SketchUp plugin. Measures can be created from scratch, but existing measures may also be used as a starting basis. More details one can find in OpenStudio Measure Writer's Reference Guide at http://nrel.github.io/OpenStudio-user-documentation/reference/measure_writing_guide. In our model we created and used a reporting measure “Fan Electric Power” so as to export the cooling fan consumption results and to be able to calculate the total cooling power consumption. Figure 17 presents the measure tab. The measures are located by default in C:\Users\user\OpenStudio\Measures folder. A measure consists of the measure.rb, measure.xml files and the measure_test.rb file in the test sub folder.

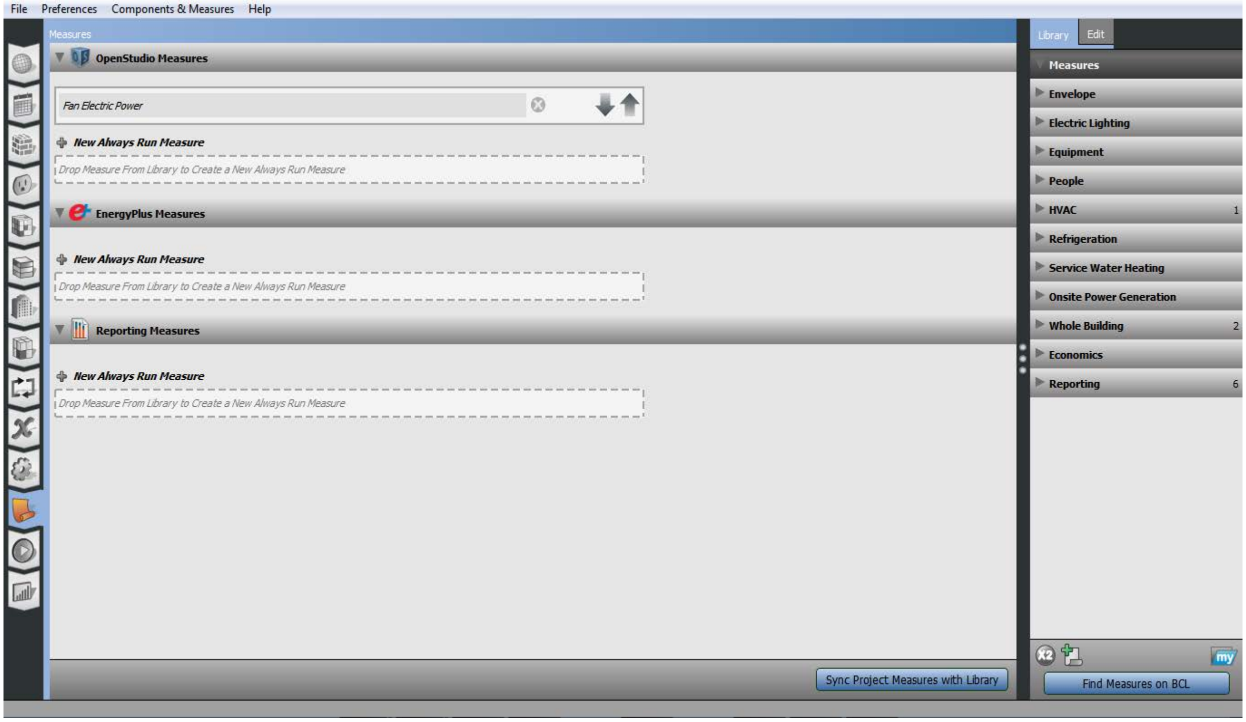


Figure 17: OpenStudio Measure tab

The measure.rb file is the main measure program. It may contain the entire program or may rely on additional functionality defined in one or more resource files, located in the resources directory. The measure.xml file contains metadata that allow the measure to be filed into an organizational structure, provide an explanation about what the measure does and how it works, and inform the GUI where in the workflow the measure can go. The measure_test.rb file is the default test that is automatically created when one make a new measure and contain the Ruby Classes and Modules necessary for all measures to function. All measures submitted to the NRELs Building Component Library (BCL) include a series of functional and unit tests, for integration with the Continuous Integration (CI) system.

Software testing is a means to code quality assurance and output validation, and allow the authors to test their work:

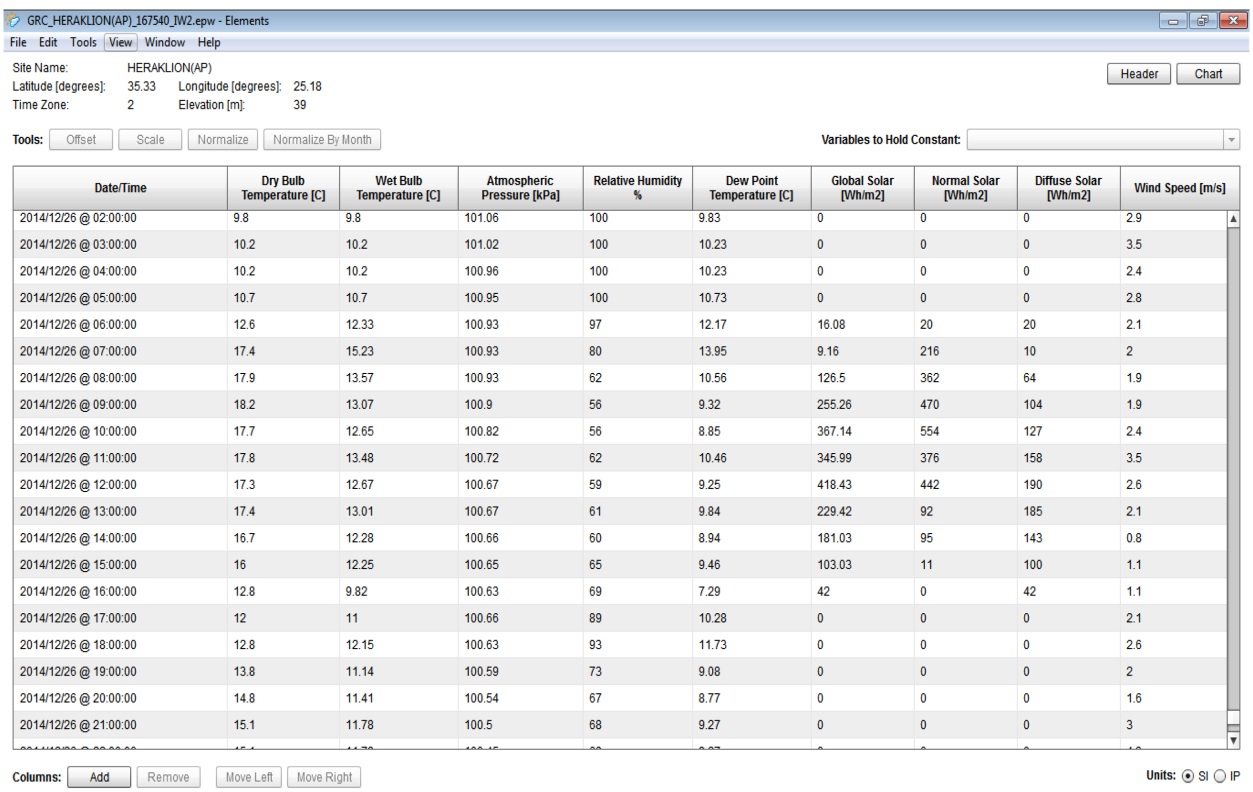
- against various versions of Ruby
- against various versions of OpenStudio
- using combinations of argument values
- against a variety of permutations of input models
- for general runtime errors

- for valid IDF output (may even run EnergyPlus to confirm)
- for reporting measure output quality

More details one can find in OpenStudio Measure Writer's Reference Guide at http://nrel.github.io/OpenStudio-user-documentation/reference/measure_writing_guide/

4.2.5 Elements software

For greater accuracy the weather file edited and updated by the **Elements software,** Version 1.0.4, a free, open-source, cross-platform software tool for creating and editing custom weather files for building energy modeling. Elements software tool was developed by Big Ladder Software with the generous funding and collaboration of Rocky Mountain Institute



GRC_HERAKLION(AP)_167540_IW2.epw - Elements

File Edit Tools View Window Help

Site Name: HERAKLION(AP)
Latitude [degrees]: 35.33 Longitude [degrees]: 25.18
Time Zone: 2 Elevation [m]: 39

Header Chart

Tools: Offset Scale Normalize Normalize By Month Variables to Hold Constant:

Date/Time	Dry Bulb Temperature [C]	Wet Bulb Temperature [C]	Atmospheric Pressure [kPa]	Relative Humidity %	Dew Point Temperature [C]	Global Solar [Wh/m2]	Normal Solar [Wh/m2]	Diffuse Solar [Wh/m2]	Wind Speed [m/s]
2014/12/26 @ 02:00:00	9.8	9.8	101.06	100	9.83	0	0	0	2.9
2014/12/26 @ 03:00:00	10.2	10.2	101.02	100	10.23	0	0	0	3.5
2014/12/26 @ 04:00:00	10.2	10.2	100.96	100	10.23	0	0	0	2.4
2014/12/26 @ 05:00:00	10.7	10.7	100.95	100	10.73	0	0	0	2.8
2014/12/26 @ 06:00:00	12.6	12.33	100.93	97	12.17	16.08	20	20	2.1
2014/12/26 @ 07:00:00	17.4	15.23	100.93	80	13.95	9.16	216	10	2
2014/12/26 @ 08:00:00	17.9	13.57	100.93	62	10.56	126.5	362	64	1.9
2014/12/26 @ 09:00:00	18.2	13.07	100.9	56	9.32	255.26	470	104	1.9
2014/12/26 @ 10:00:00	17.7	12.65	100.82	56	8.85	367.14	554	127	2.4
2014/12/26 @ 11:00:00	17.8	13.48	100.72	62	10.46	345.99	376	158	3.5
2014/12/26 @ 12:00:00	17.3	12.67	100.67	59	9.25	418.43	442	190	2.6
2014/12/26 @ 13:00:00	17.4	13.01	100.67	61	9.84	229.42	92	185	2.1
2014/12/26 @ 14:00:00	16.7	12.28	100.66	60	8.94	181.03	95	143	0.8
2014/12/26 @ 15:00:00	16	12.25	100.65	65	9.46	103.03	11	100	1.1
2014/12/26 @ 16:00:00	12.8	9.82	100.63	69	7.29	42	0	42	1.1
2014/12/26 @ 17:00:00	12	11	100.66	89	10.28	0	0	0	2.1
2014/12/26 @ 18:00:00	12.8	12.15	100.63	93	11.73	0	0	0	2.6
2014/12/26 @ 19:00:00	13.8	11.14	100.59	73	9.08	0	0	0	2
2014/12/26 @ 20:00:00	14.8	11.41	100.54	67	8.77	0	0	0	1.6
2014/12/26 @ 21:00:00	15.1	11.78	100.5	68	9.27	0	0	0	3

Columns: Add Remove Move Left Move Right Units: SI IP

Figure 18: Elements software tool

4.2.6 xEsoView Results Viewer

Openstudio has auxiliary software such as Results Viewer. Results Viewer displays the results of simulations in graphs. However, it does not export the resulting values. To be able to extract the simulation values, we used xEsoViev software. xEsoView is a file viewer for EnergyPlus .eso output files which gives the user a very fast overview of the simulation results. xEsoView uses the Qwt extension of the Qt toolkit from Trolltech Inc. xEsoView presents all reported variable names in a list, which can be sorted and filtered, on the left hand side. On the right hand side it presents the graphical representation of the selected variable. The time axis can be changed using predefined ranges (hour, day, week, month, total) with zooming support. With a selection box you can switch between the available environments, e.g. summer design day and run-period. A simple CTRL+C copies the variable data to the clipboard. So you can easily paste the data into a spreadsheet for further analysis. The Figure 19 presents a snapshot of xEsoView results viewer. xEsoView author is Christian Schiefer from Vienna, Austria. http://xesoview.sourceforge.net/

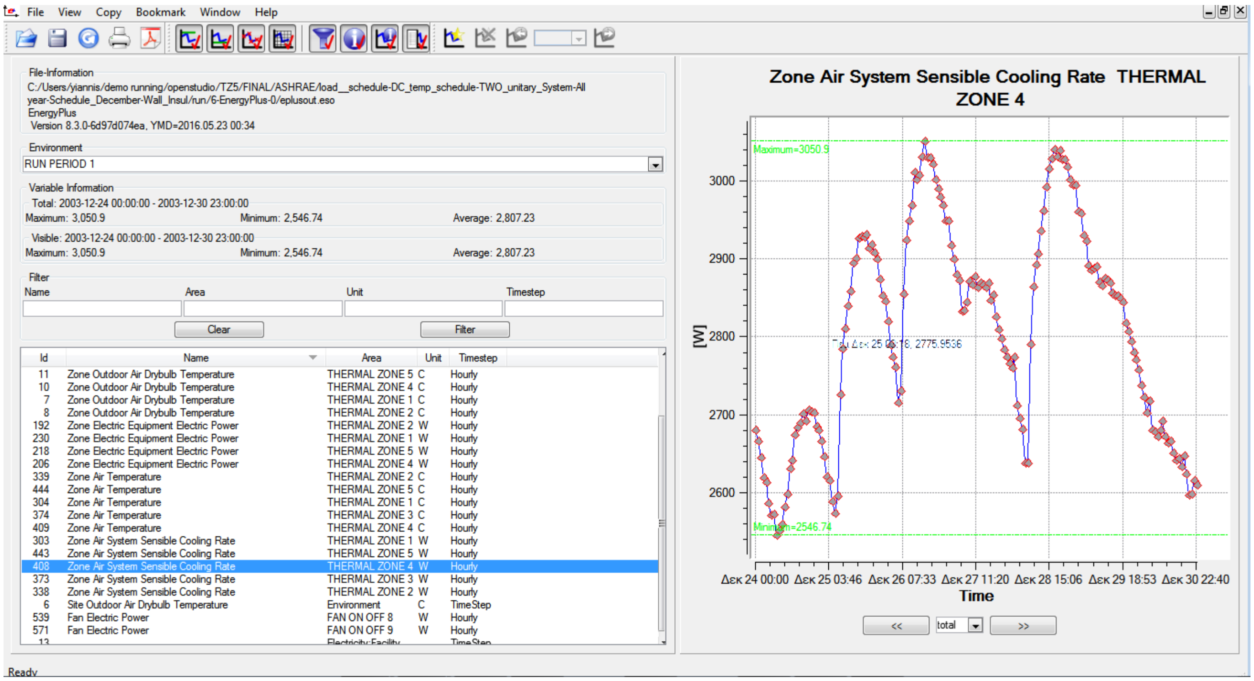


Figure 19: xEsoView results viewer

4.3 Creating the 3D Geometry in Sketchup

In this work, we use the Openstudio 1.8 platform and the SketchUp 15 trial version for 3D modelling. We created the 3D model based on an Autocad 3D model. If importing from Cad drawing all blocks must be “exploded” first. If blocks have no name, there is no way to select them all, so all blocks must be exploded one by one. This was a problem for all internal and external doors and windows in our drawing. Additionally, the CAD model must be a thin line diagram in order to be functional in Sketchup. In our case, a detailed 3D model was available, which was not suited for Sketchup. Hence, a simple thermal 3D model was developed from scratch, and all surfaces was “matched” and linked to each other as presented in the following according to the boundary conditions.

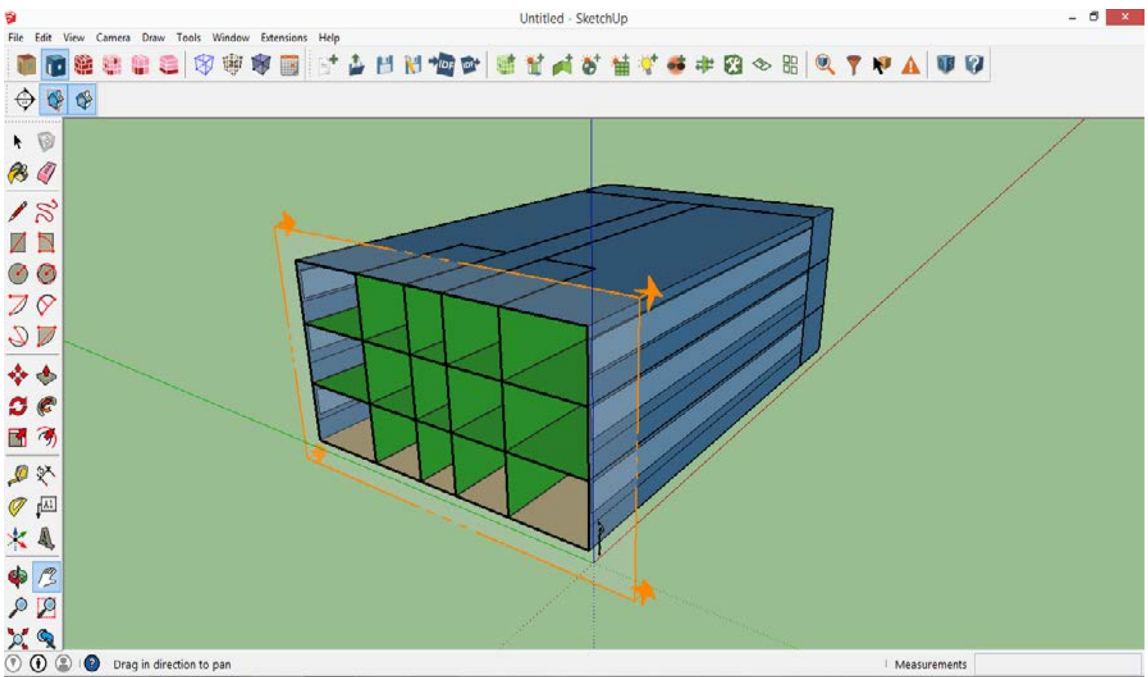


Figure 20: Rendering by boundary conditions view of Sketchup 3D model.

Before creating the geometry, a basic template of a Large office building was imported in the design in order to allow for the basic construction and thermal characteristics to be determined automatically. Changes and adaptations were made to account for the specificities of our application later in the modeling process. The basic design of the floor was expanded using the “Create Spaces from Diagram” command. Three floors were created, the ground floor, 1st and 2nd floor. In the 2nd floor, two spaces are created, which account to the Data Center and the Hardware Laboratory.

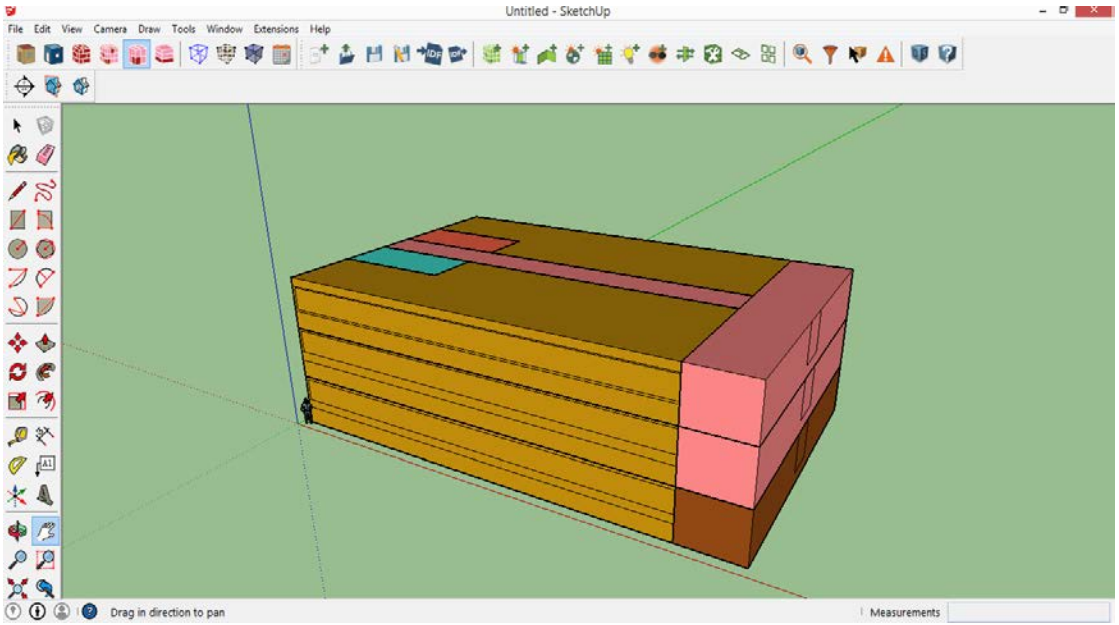


Figure 21: Assignment of thermal zones in Sketchup 3D model.

The basic space types and thermal zones can be set in the 3D geometry, while further details are imported later in the .osm model. First the space types are set as large open office areas for all the areas except the corridors, the stairs and the spaces which are of interest for this study. All office areas are imported in the same thermal zone. The corridors and the stairs area of the upper floor, create a second thermal zone. The stairs area of the ground floor is a separate thermal zone. The areas of the Data Center and the Hardware Laboratory are in different thermal zones and was set as IT spaces in the .osm model.. Hence five different thermal zones are set the .osm file is created. The thermal simulation and all further data are imported in the Openstudio suite environment.

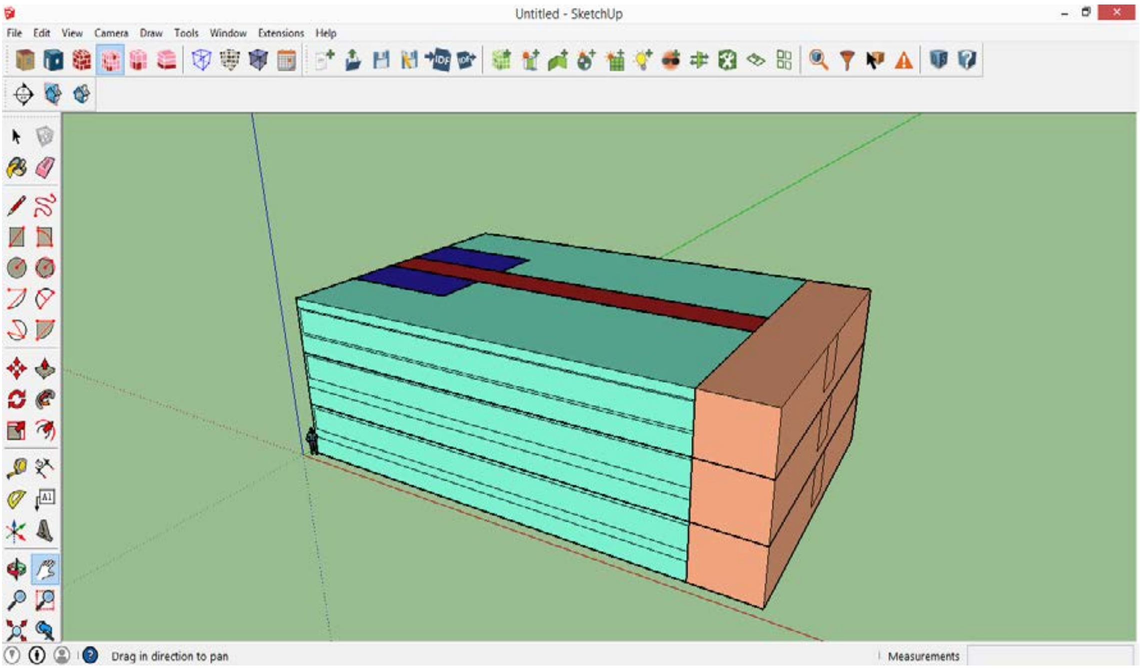


Figure 22: Assignment of space types in Sketchup 3D model.

4.4 Measurements

For temperature and power consumption measurements used Arduino technology and Emoncms open-source web application used for storage, real time representation and treatment of measurement data archived, which were collected from wire-connected Arduino.

4.4.1 Arduino

In particular, for temperature measurements used Arduino equipped with ds18b20+ temperature sensor and for power consumption used Arduino with three noninvasive current sensor 30 A for one of the three phases. Arduino equipped with power consumption sensor was measuring the total consumption of the Data Center. The data of the IT equipment consumption are provided from the UPS which provide electrical power to IT equipment. Arduino layout is presented in figure 23.

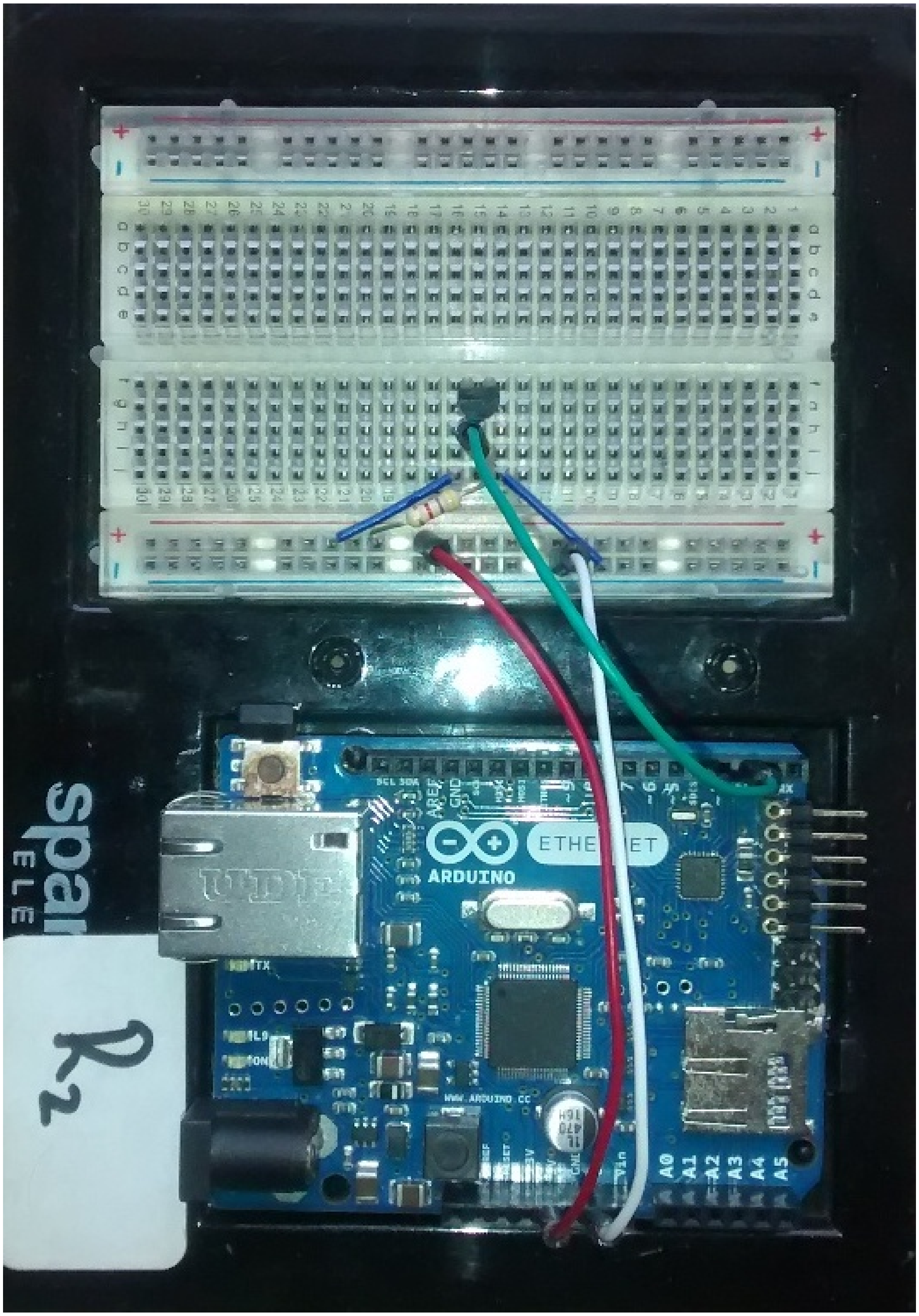


Figure 23: Arduino layout

Two Arduino with ds18b20+ temperature sensor were placed in the hardware lab and the Data Center respectively, for space temperature measurement and one Arduino with three noninvasive current sensor 30 A was placed in Data Center, for measuring the total consumption except the consumption of the air conditioner.

4.4.2 Emoncms

Emoncms was used for storage, real time representation and treatment of measurement data archived which were collected from wire-connected Arduino. Emoncms is an open-source web application for processing, logging and visualising energy, temperature and other environmental data and is part of the OpenEnergyMonitor project. The next Modules can be installed by downloading or git cloning:

- Dashboards module, required for creating, viewing and publishing dashboards:
- App Module - Application specific dashboards e.g. MyElectric, MySolar
- Config - In-browser emonhub.conf editor and emonhub.log log viewer. git clone
- Wifi Module - Wifi configuration interface designed for use on the emonPi

There are many other modules such as the event module and openbem.
Emoncms can be installed in:

- Recommended: Ubuntu / Debian Linux via git
- Raspberry Pi
- Pre built emonSD SD-card Image
- Shared Linux Hosting
- Windows

The basic design of emoncms is that you have client side html, css, javascript code that makes up your user interface and is loaded from the Server when a page is initially requested. With the client up and running the client side javascript queries the Server API via AJAX requests with data passed back and forth in JSON format. The Server API is a HTTP API to internal models which carry out things like data storage, processing and validation. Energy monitoring equipment directly interface with the Server side API. In brief the emoncms architecture is a combination of a front controller on the Server and model-view-controller design pattern and a directory structure that makes adding features in a self contained modular way easy. One of the core features of emoncms is input processing and therefore separation between inputs and feeds. The need for input processing arose initially from the need to calculate kWh per day data from raw power data. Doing a small bit of processing every time an input is updated, means that the kWh/d data can be loaded really fast for visualization rather than having to wait for kwhd data to be calculated on the fly from power data every time you want an overview. As time has moved on however input processing has expanded to allow Server based calibration of inputs, multiplying inputs together, histogram data creation and quite a few other things. Figure 24 presents the main concept

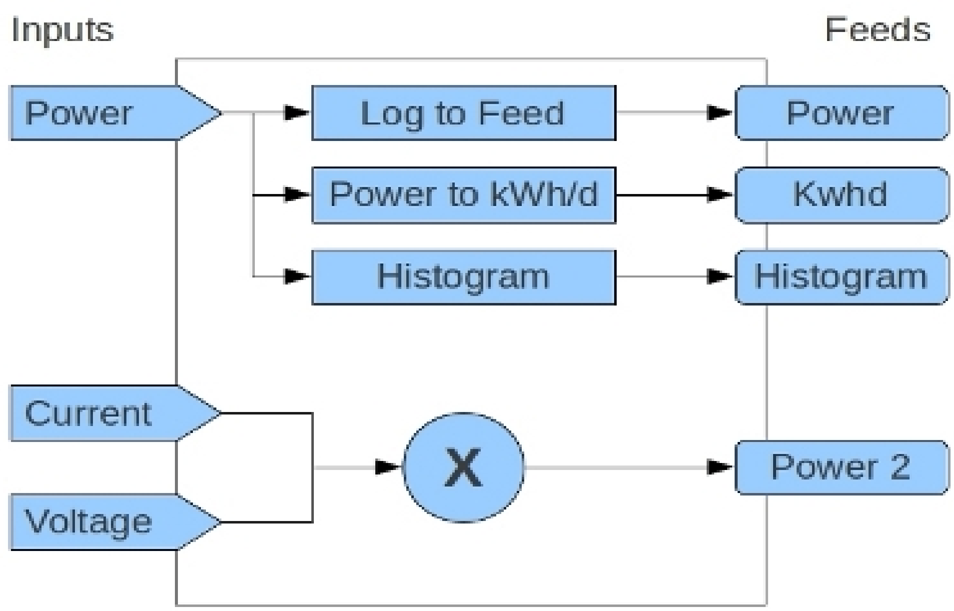


Figure 24: emoncms inputs and Input processing

Temperature and Energy Monitoring achieved through dashboard, the web app and which runs on Emoncms and is also available as a native Android app. Through dashboard we can Explore - visualize Site temperature in Degree Celsius and power consumption in Watts, daily energy consumption in KWh and PUE calculations. Figures 25 to 29 present the dashboard main window with different dashboards.

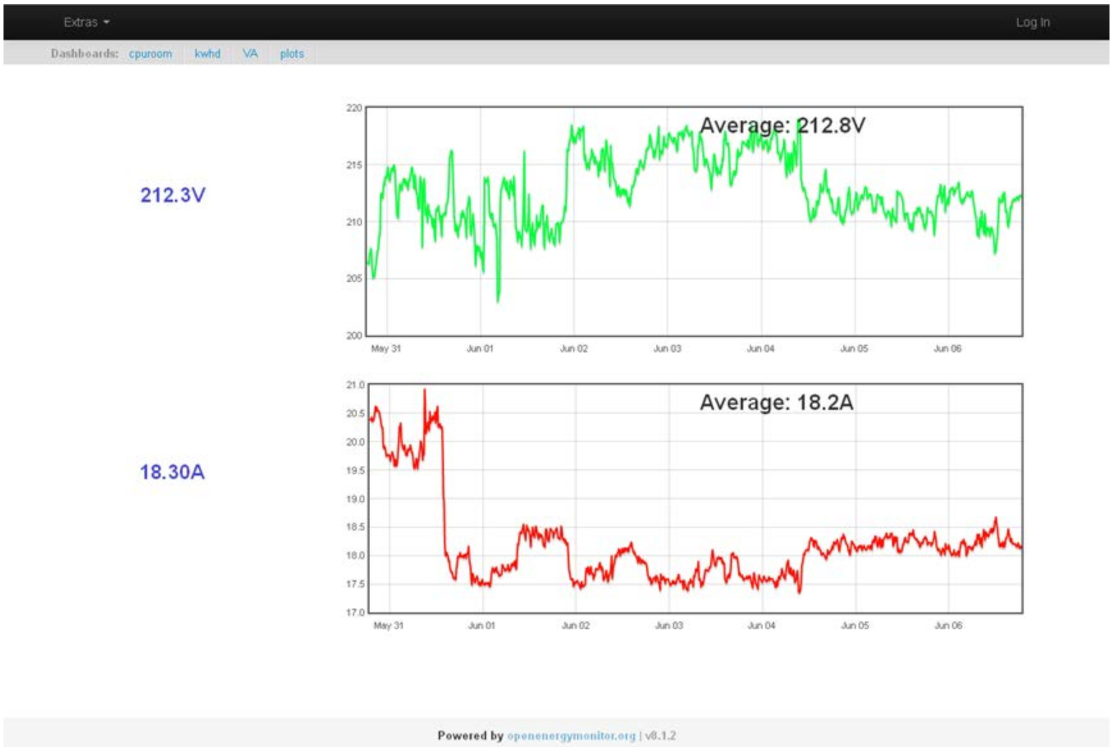


Figure 25: Current and Voltage dashboard in graphical representation.

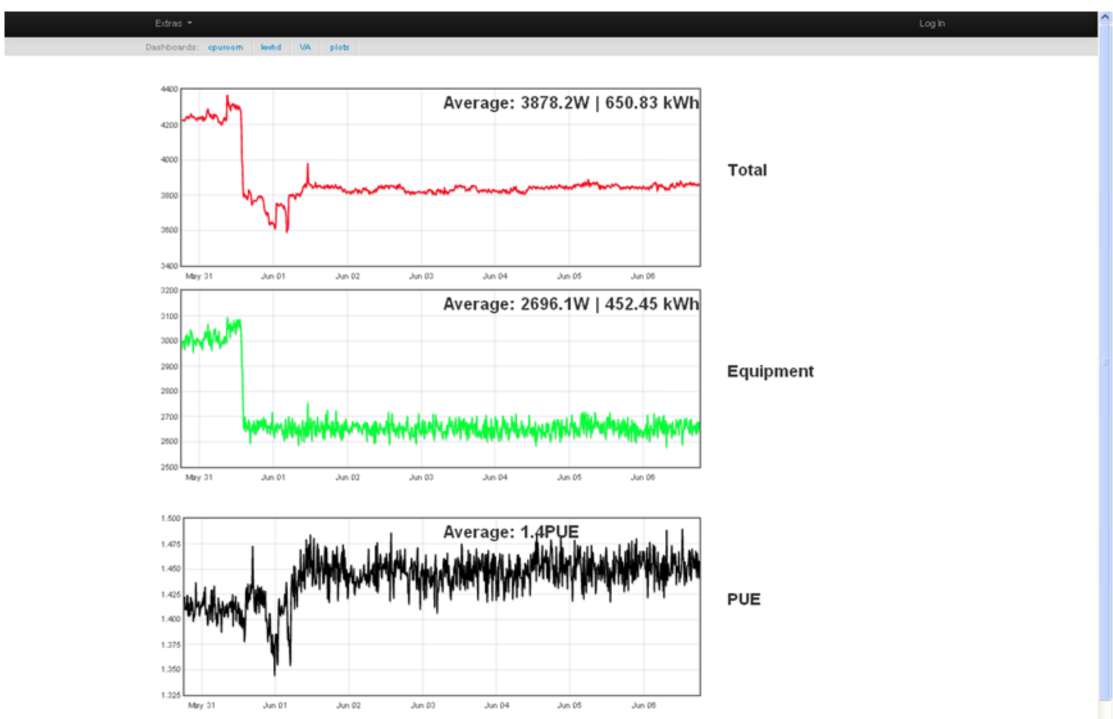


Figure 26: Total and Equipment consumption and the calculated PUE in graphical representation.

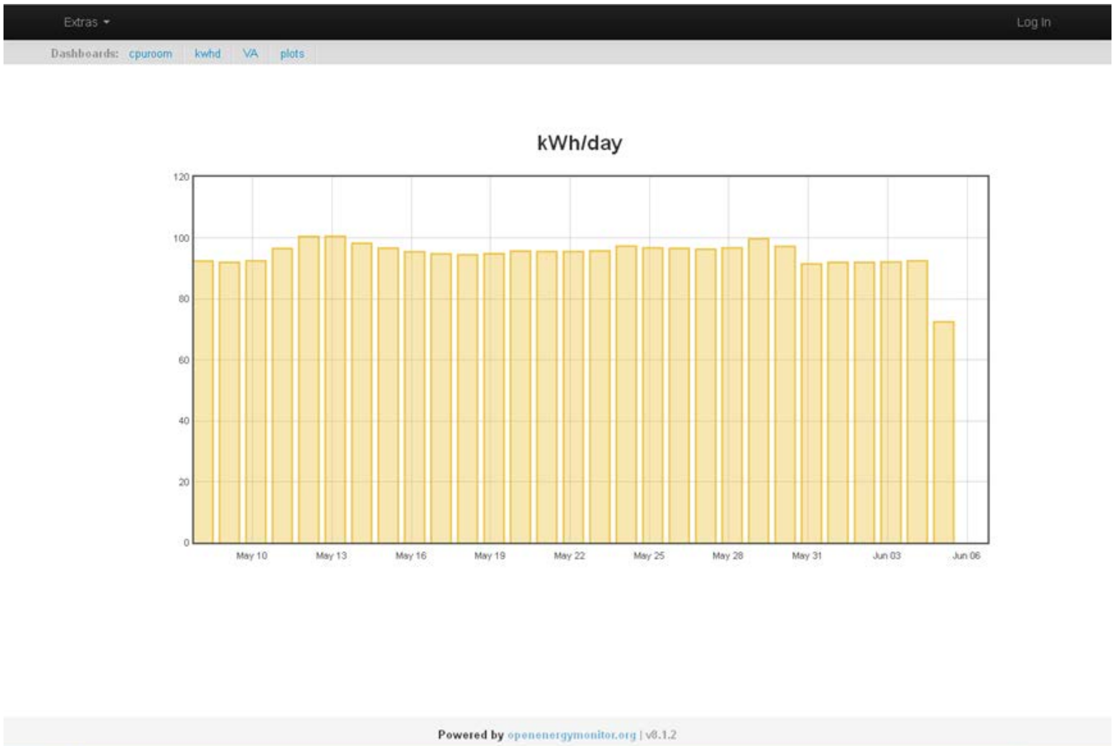


Figure 27: Consumed Energy in KWh/day in graphical representation.

Figure 28: Real time visualization of the power consumption.

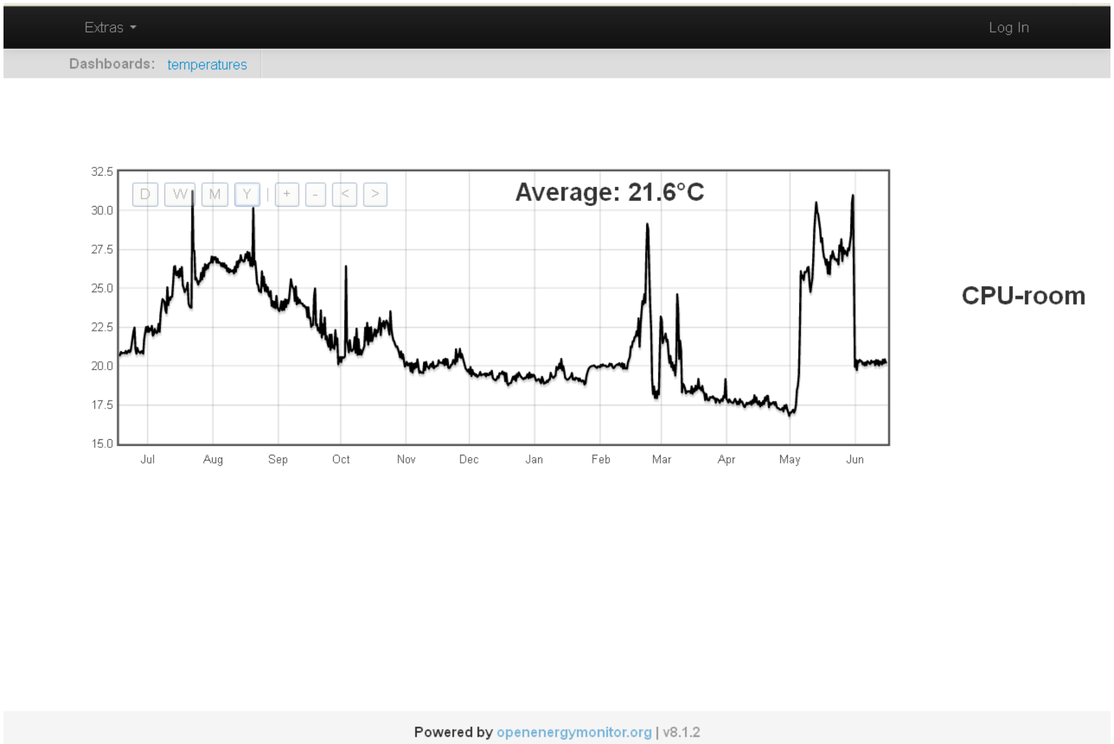


Figure 29: Ambient Temperature in graphical representation.

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4.4.3 Obtained measurments

Figures 30 and 31 present measurements obtained for the Data Center and the hardware lab air temperature respectively, from December 25th to December 30th. Measurements show that Data Center temperatures deviate in the range of 21,4 – 22,7 ^{o}C and at the same time, hardware lab air temperature deviates in the range of 19,4 – 20,8 ^{o}C.

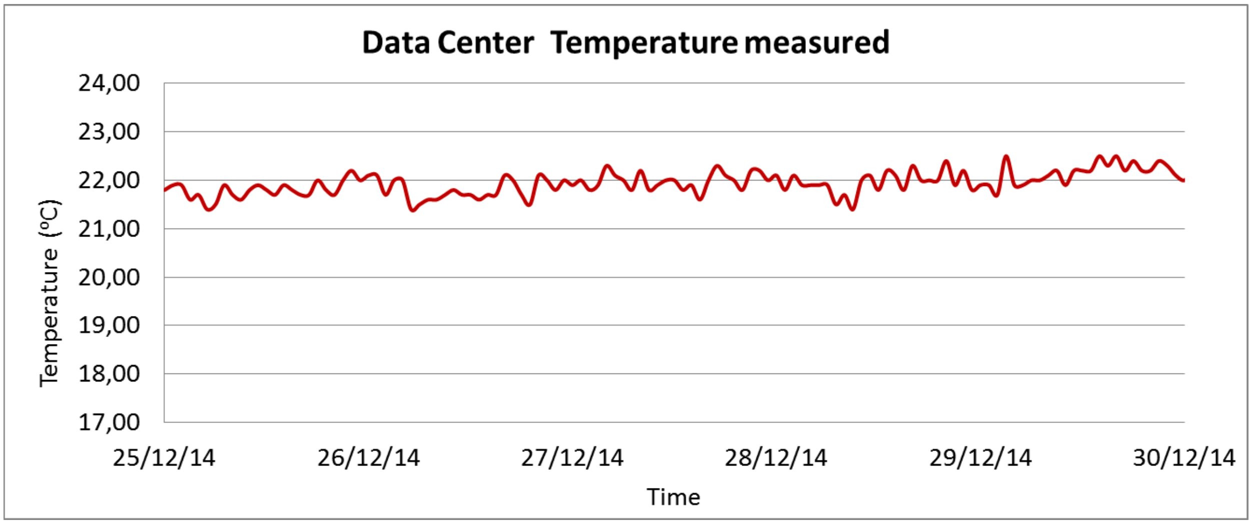


Figure 30: Data Center temperature measured

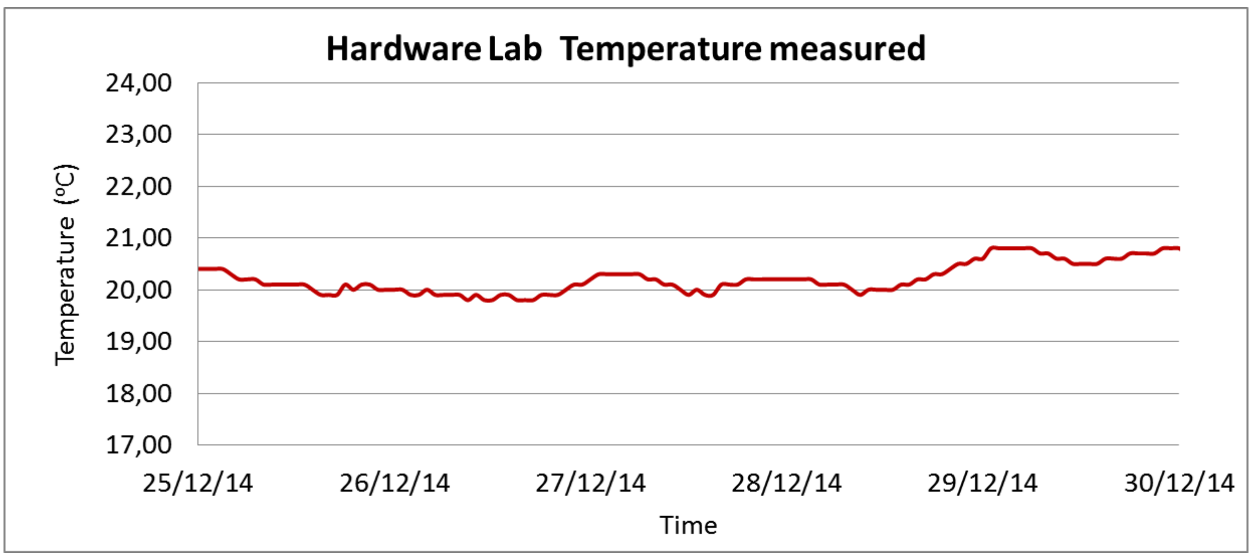


Figure 31: Hardware Lab temperature measured

4.5 Setting model parameters in Openstudio .osm file

In the Site tab we set the path of the .epw weather file for simulation. The weather data has been provided by Weather Station of TEI of Crete which is located in the area of TEI and about 700 meters from the case study building. Weather file has to be in .epw format for simulations in EnergyPlus. A weather file in .epw format was purchased from White Box Technologies Company (http://weather.whiteboxtechnologies.com). The data of the weather file of White Box Technologies Company was edited and updated by the **Elements software** with the weather data from Weather Station of TEI of Crete.

The weather data which were provided by the Weather Station of TEI include atmospheric station pressure (Pa), dry bulb temperature (˚C), global horizontal radiation (W/m2), Liquid Precipitation Depth (mm), relative humidity (%), wind direction (◦) and wind speed(m/s). All these data was in ten minutes time step.

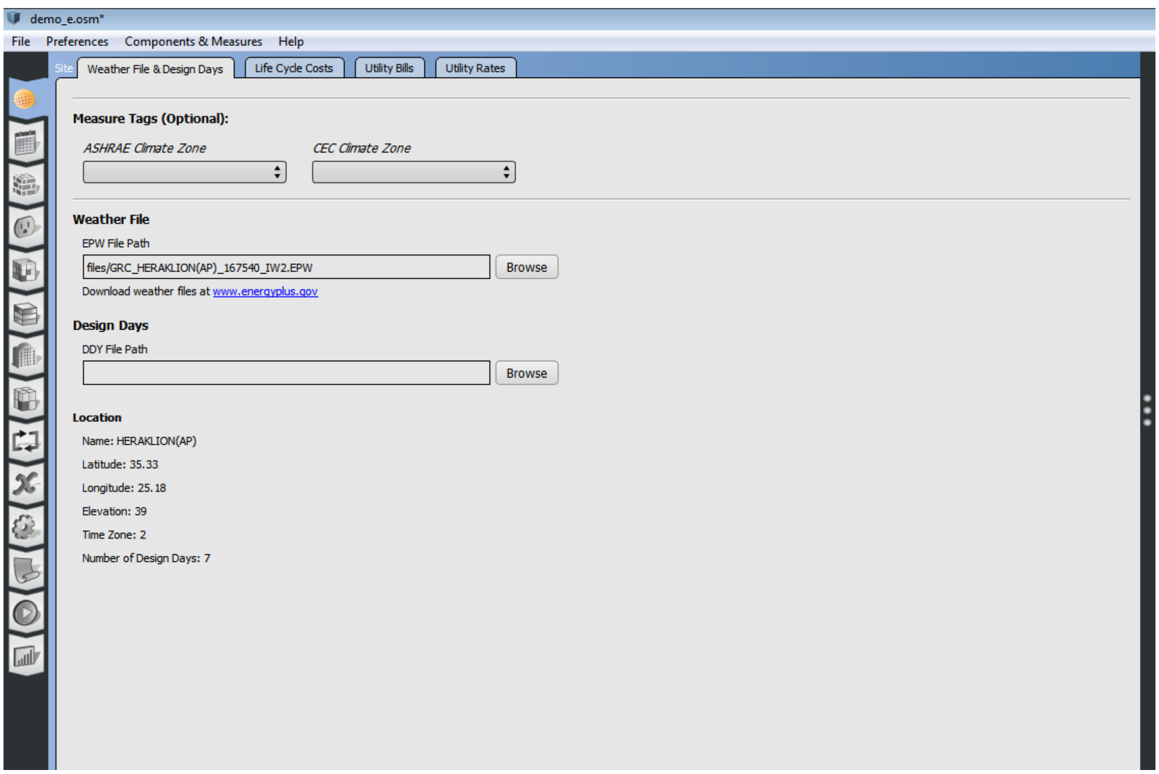


Figure 32: OpenStudio Site tab

In the .osm file we have to make some changes in order to adapt to the case study of the building that we are referring to. The Building is located in an ASHRAE 2 thermal zone, so all materials to the construction tab of the Openstudio suite have to be adapted to that condition. We select the appropriate materials from the Library tab and drag and drop them to the relative position. The materials and their attributes were set according to Technical Guideline 20701-2/2010 of Technical Chamber of Greece (Technical Chamber of Greece, 2010).

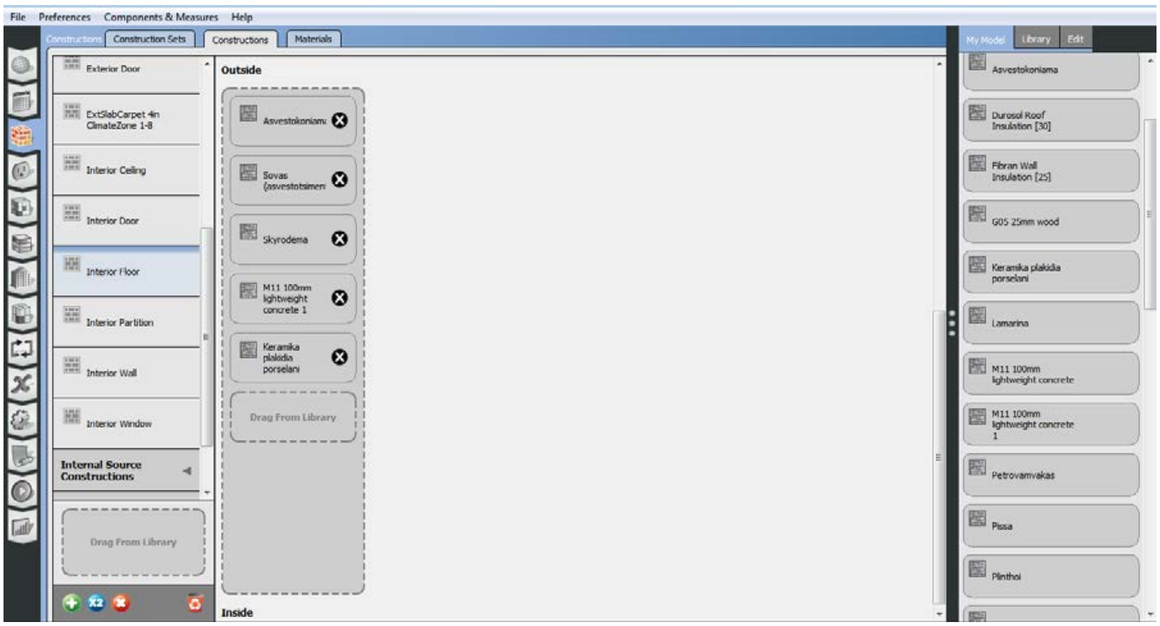
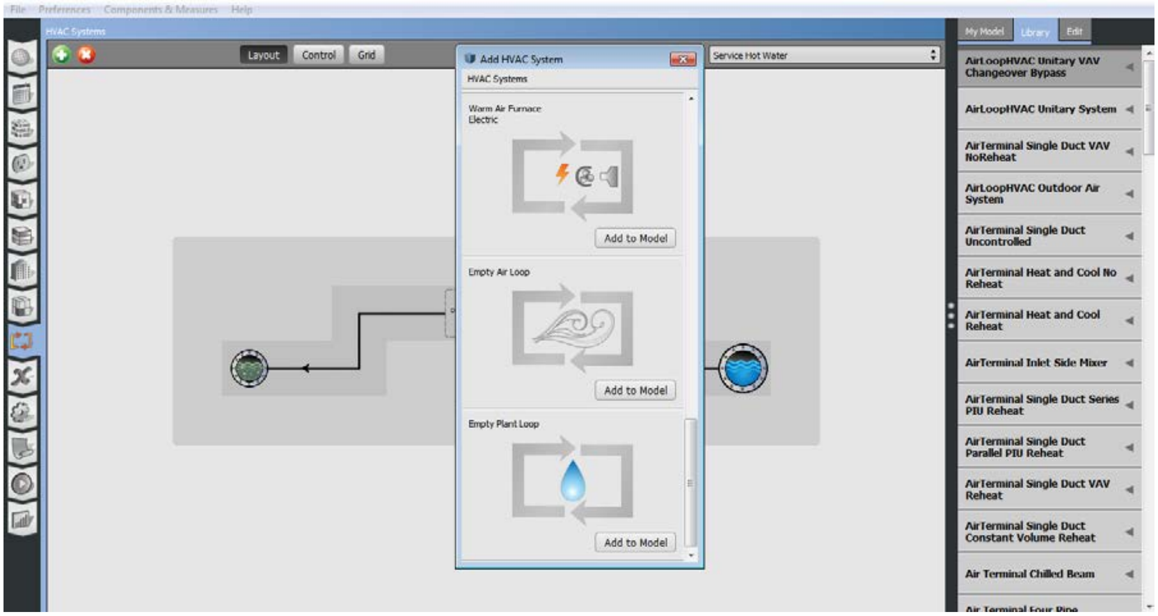


Figure 33: Constructions and their materials

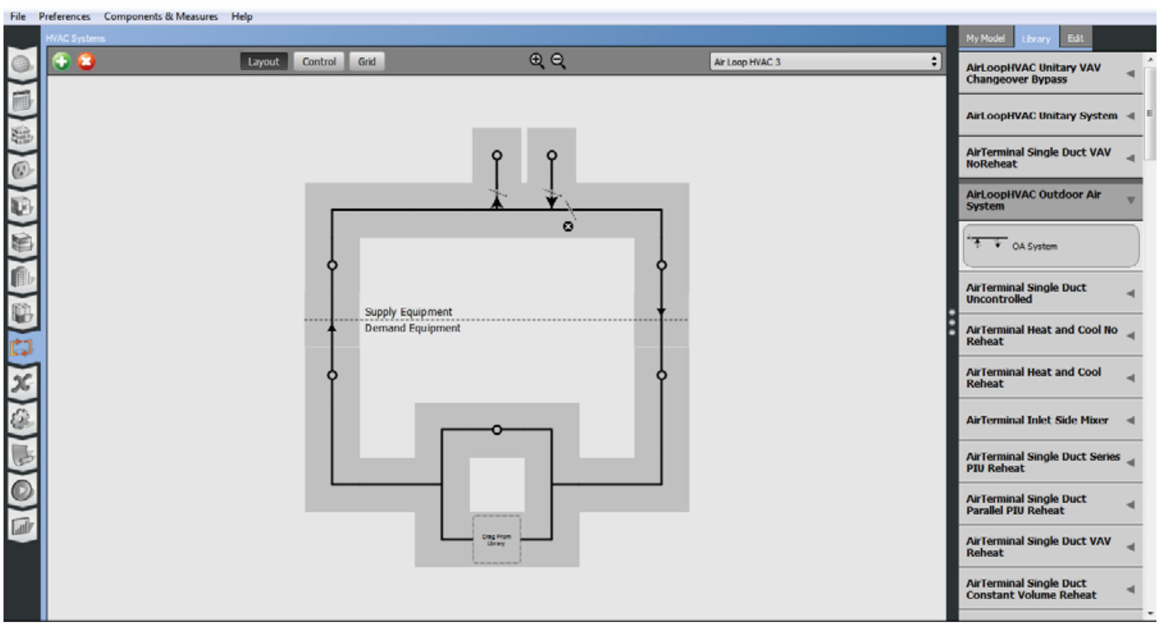
Apart from the materials, we set two HVAC systems for heating and cooling. As the openstudio does not provide a template for a standard split air condition, standard components from the library were used to build up a simple split AC system. As the thermal zone of Hardware Laboratory and Data Center was set to conditioned thermal zones the other three thermal zones were set to not conditioned and left drifting during simulation.

Figure 34 presents the steps to build up a simple split air condition, one for Hardware Laboratory and one for Data Center:

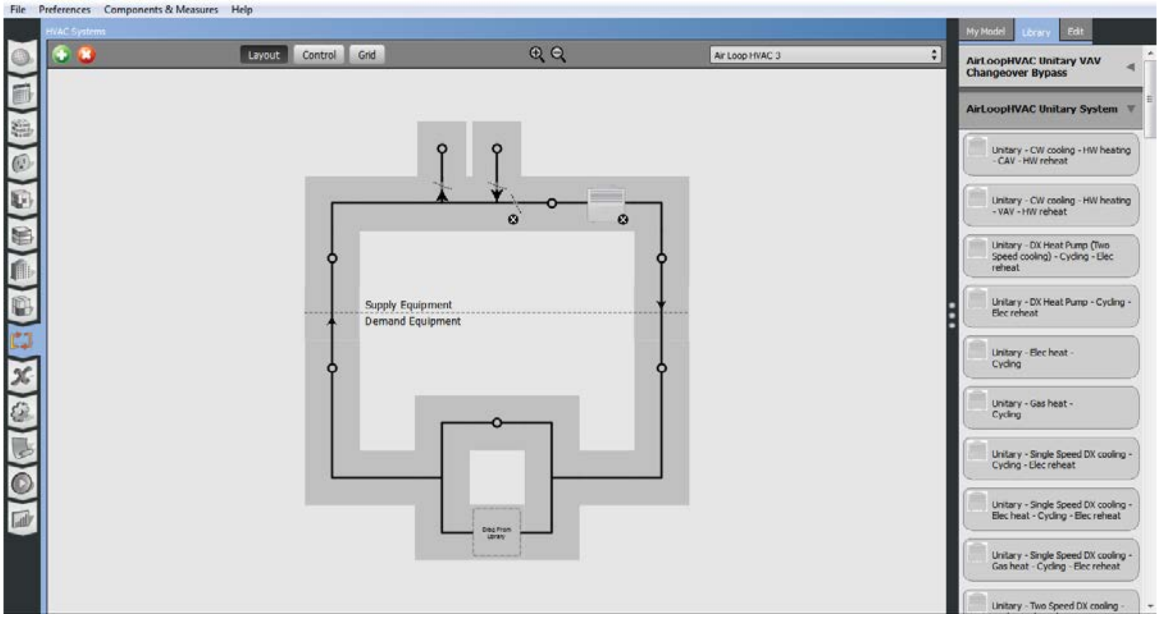
a) Create a new empty AirLoopHVAC system.



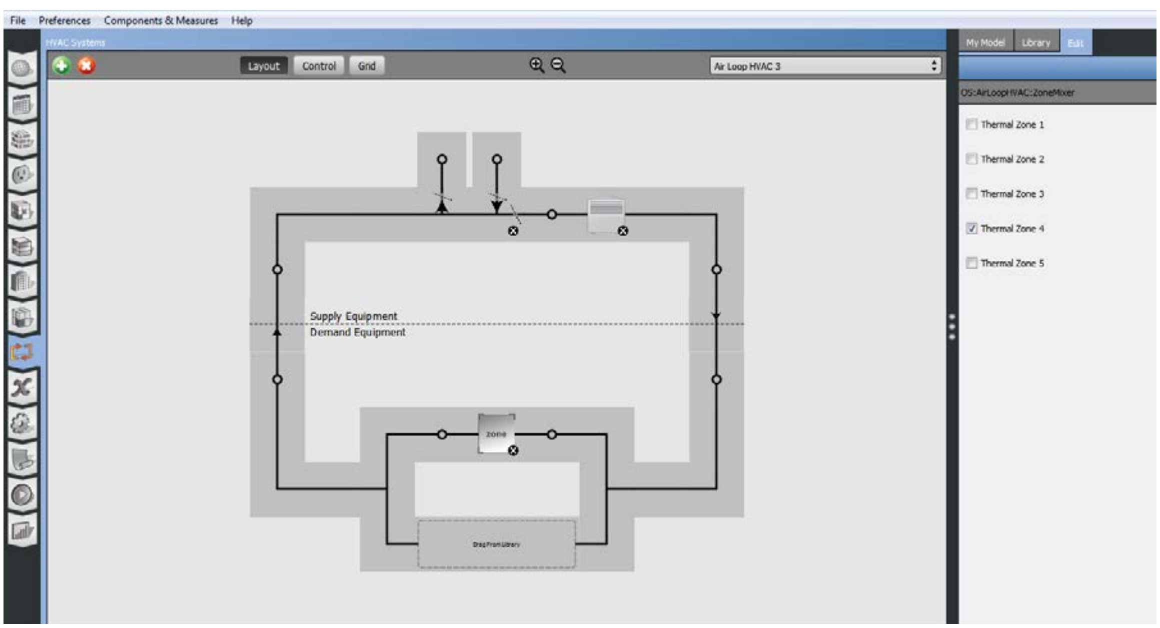
b) Add an OA system.



c) Add an AirLoopHVACUnitarySystem, DX cooling, cycling, and electric "reheat"



d) Attach zone



e) Add an uncontrolled terminal.

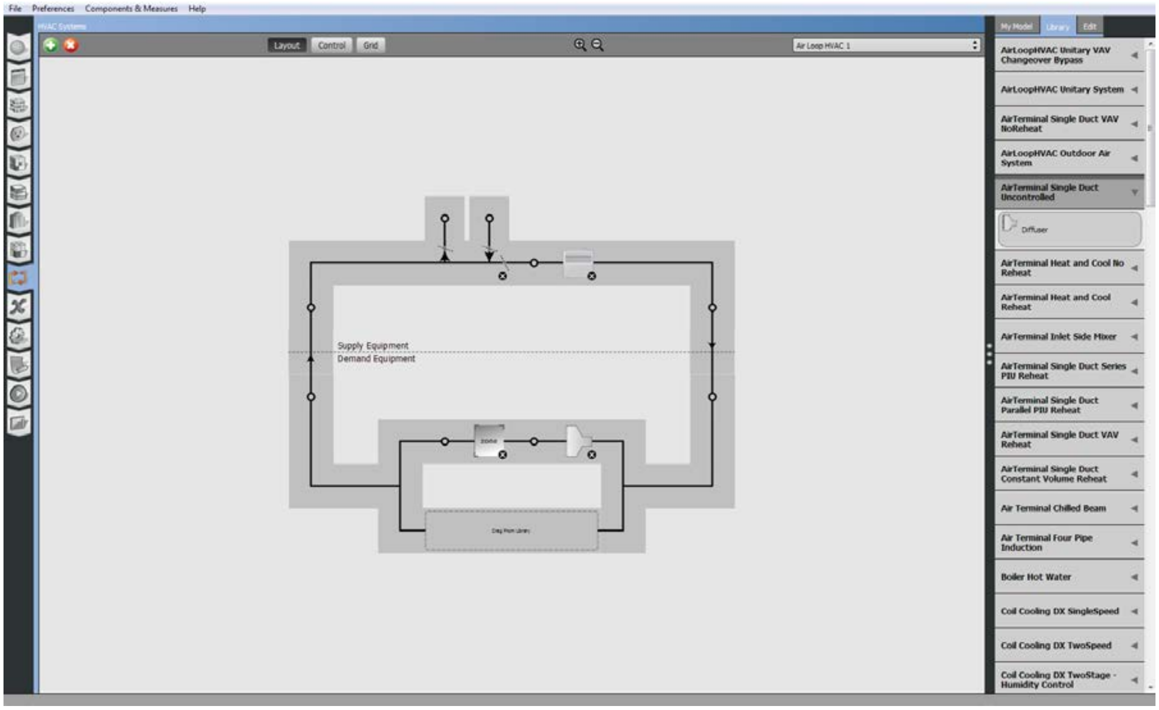


Figure 34: Building up a simple split AC system from standard components

In the Data Center the air condition which is actually operating is an INVENTOR A1PSI-24 wall mounted mini split air condition and its technical data was provided from Inventor official site. Figure 35 presents the technical data of the INVENTOR A1PSI-24 AC.

4.5 Hardware Lab and Data Center model creation and evaluation

A main objective of this work is to study the spaces of the Data Center and Hardware Laboratory, as they are both spatial and structural the same spaces, in order to confirm that the model for the Hardware Laboratory space confirms the measurements about the temperature variation in comparison to the measurements obtained. If this is achieved to a great extent, the next step is to set the operating temperature and the loads as measured and operating in the space of the Data Center, in order to confirm that the model for the Data Center space confirms the measurements about the temperature variation in comparison to the measurements obtained.

Finally, and through the EnergyPlus, it is able to calculate the required cooling energy and therefore the PUE for the Data Center space.

MODEL	A1PSI-24 A1PSO-24
Cooling Capacity (Btu/h)	21.000
Heating Capacity (Btu/h)	22.178
Voltage/ Frequency / Phase	230V/50Hz/1PH
Rated Current Cooling / Heating (A)	11.3/11.7
Power Input Cooling / Heating (W)	1.900 / 1.900
EER for Cooling (W/W)	3.21
COP for Heating (W/W)	3.42
Energy Class Cooling / Heating	A / A
LRA (A)	40
Air Circulation (CMH Max)	850
Noise level Indoor unit High / Low (db (A))	44/38
Noise level Outdoor unit High / Low (dB (A))	56
Compressor Type	Rotary
Liquid line	1/4"
Gas line	1/2"
Dimensions Indoor WxHxD (mm)	940x298x200
Dimensions Outdoor WxHxD (mm)	913x680x378
Net weight Indoor / Outdoor (kg)	13/46
Refrigerant	R410A/1.450g

Figure 35: Technical data of the INVENTOR A1PSI-24 A/C

4.5.1 Hardware Laboratory model creation and evaluation

In the .osm model we can set the loads in each space. The loads for the Hardware Laboratory (Space 303) are set as IT Room space type. A maximum load of 300W was set as a PC was always running for calculations purpose in the space of Hardware Laboratory. Figure 36 presents the space loads for Hardware Laboratory

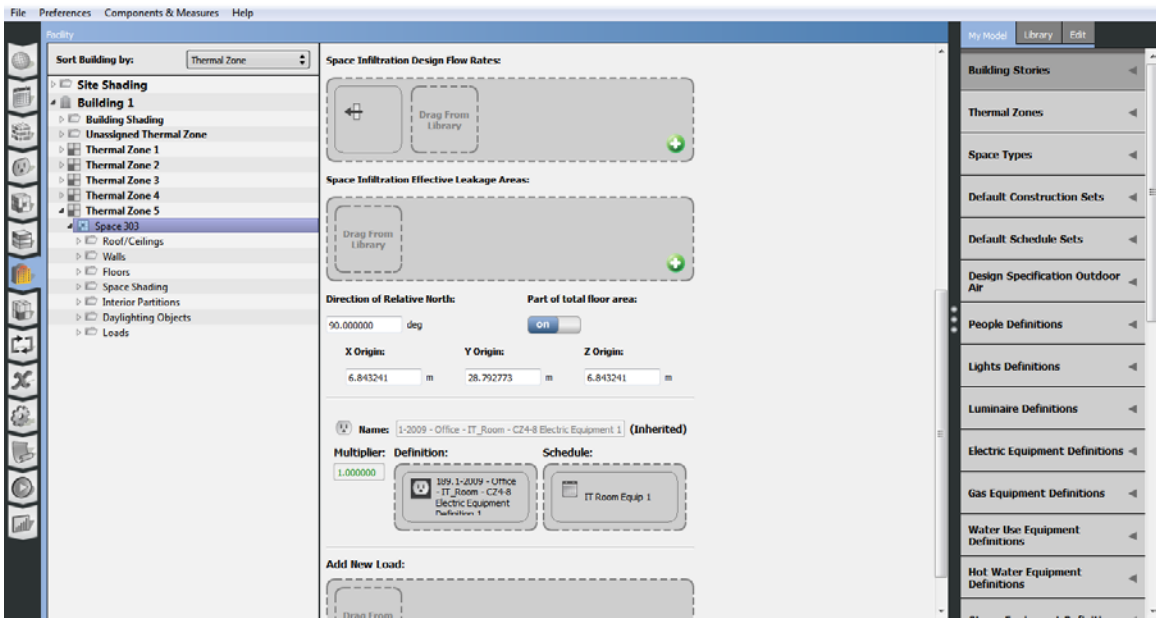
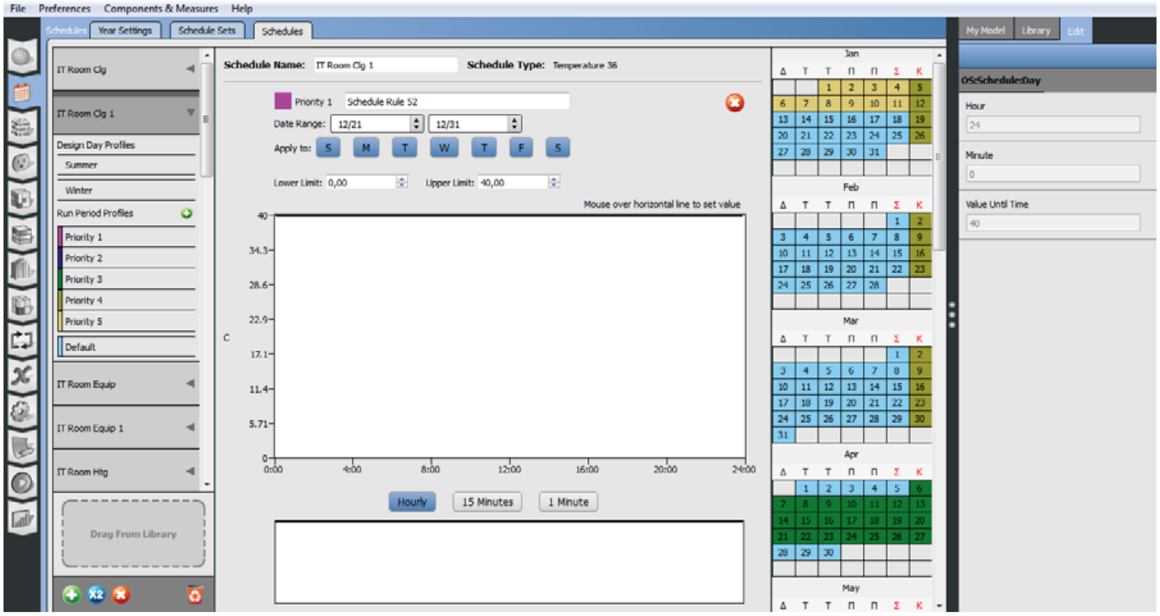
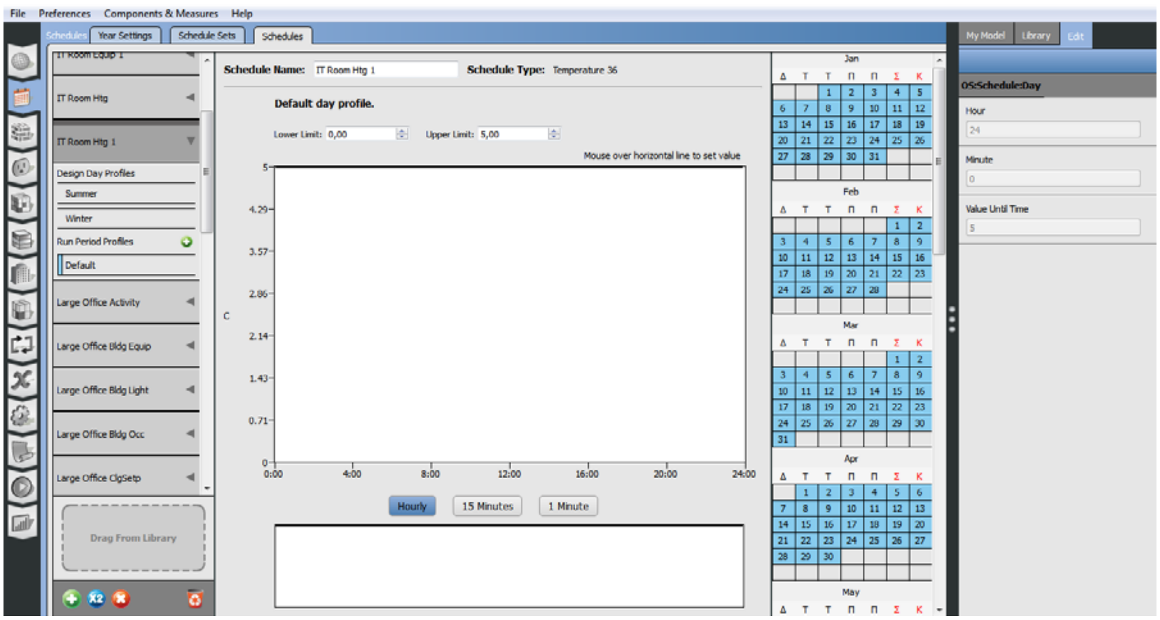


Figure 36: Hardware lab loads

In the .osm model was set the temperature schedule for the Hardware Laboratory. The temperature set points for heating and cooling for the Hardware Laboratory (Space 303) are set as “IT Room Htg 1” and “IT Room Clg 1” respectively. The set points were set for heating at 5 ^{o}C and cooling at 40^{o}C so as the simulated HVAC for Hardware Laboratory to be off, and the Data Center to be the only airconditioned space in the whole building. Figure 37 present the schedules for cooling and heating for Hardware Laboratory.



(a)



(b)

Figure 37: schedules for cooling (a) and heating (b) for Hardware Laboratory

4.5.2 Hardware Laboratory Simulation results

The following figure presents the simulated results relative to the air temperature in the Hardware Laboratory. Simulation Results show that hardware lab air temperature deviates in the range of 19,3 – 20,6 ^{o}C

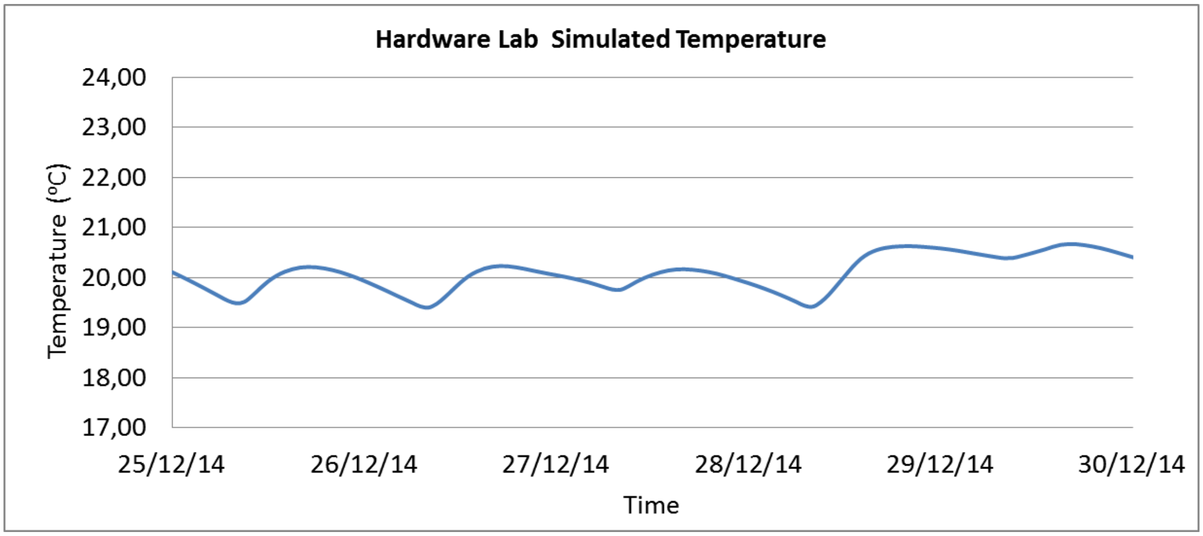


Figure 38: Hardware Lab hourly simulated results from December 25th to December 30th

Continuing the analysis, we will examine the results of EnergyPlus model to real data.

4.5.3 Hardware Laboratory Evaluation of results

The evaluation is realized during Christmas holidays, so that no activity or internal gains are perturbing the results. Figure 39 present measurements obtained for the hardware lab air temperature, the temperature from simulation and the outdoor temperature from December 25th to December 30th 2014

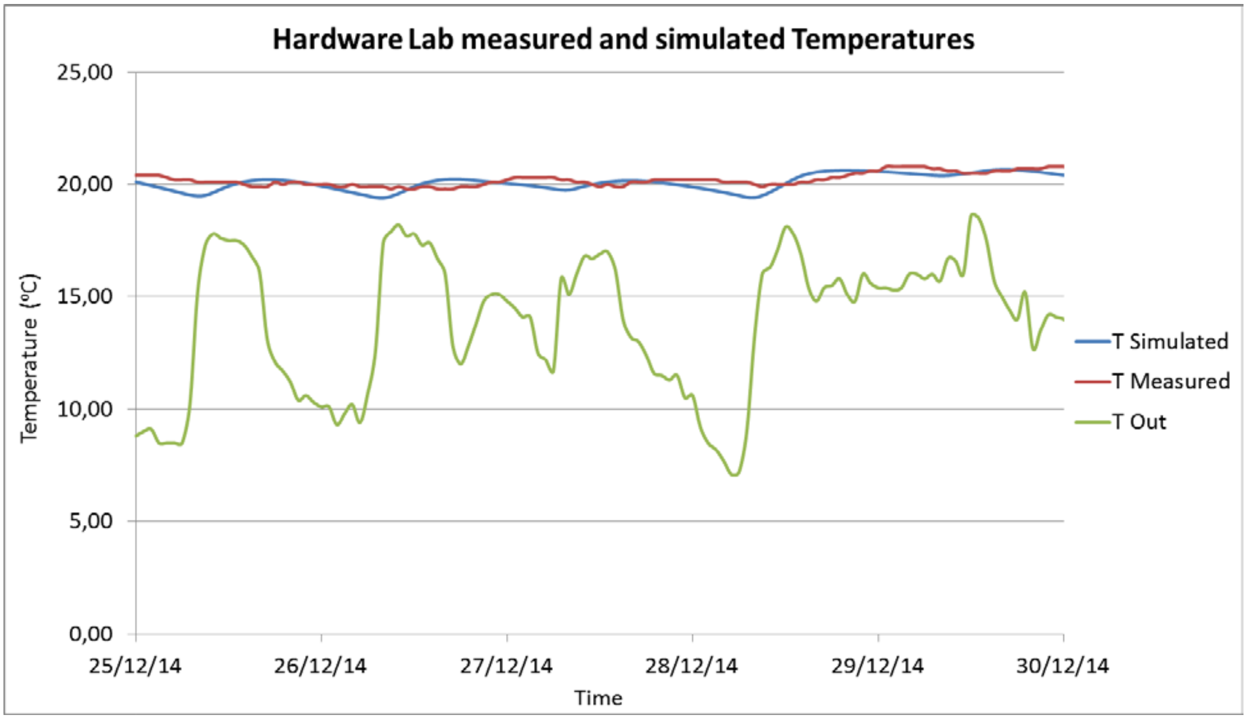


Figure 39: Temperatures measured, simulated and the outdoor temperatures from December 25th to December 30th for Hardware Lab.

Measured temperatures deviate in the range of 19,80 – 20,80 ^{o}C and the simulated temperatures deviate in the range of 19,31 – 20,62 ^{o}C. The standard deviation of the difference between simulated and measured temperatures is roughly 0,2 ◦C. So we can say that the EnergyPlus model gives satisfying results.

4.5.4 Data Center model creation and evaluation

The loads for the Data Center (Space 306) are set according to measurements about the IT and non IT equipment power consumption in the closet of the Data Center and the loads of the equipment was operating at the same period in the Data Center. The Data Center space was set as IT Room space type. A maximum load of 3640W was set in the space of the Data Center according to measurements and a load of 3200W was set as the rest of the equipment outside of closet of the Data Center.

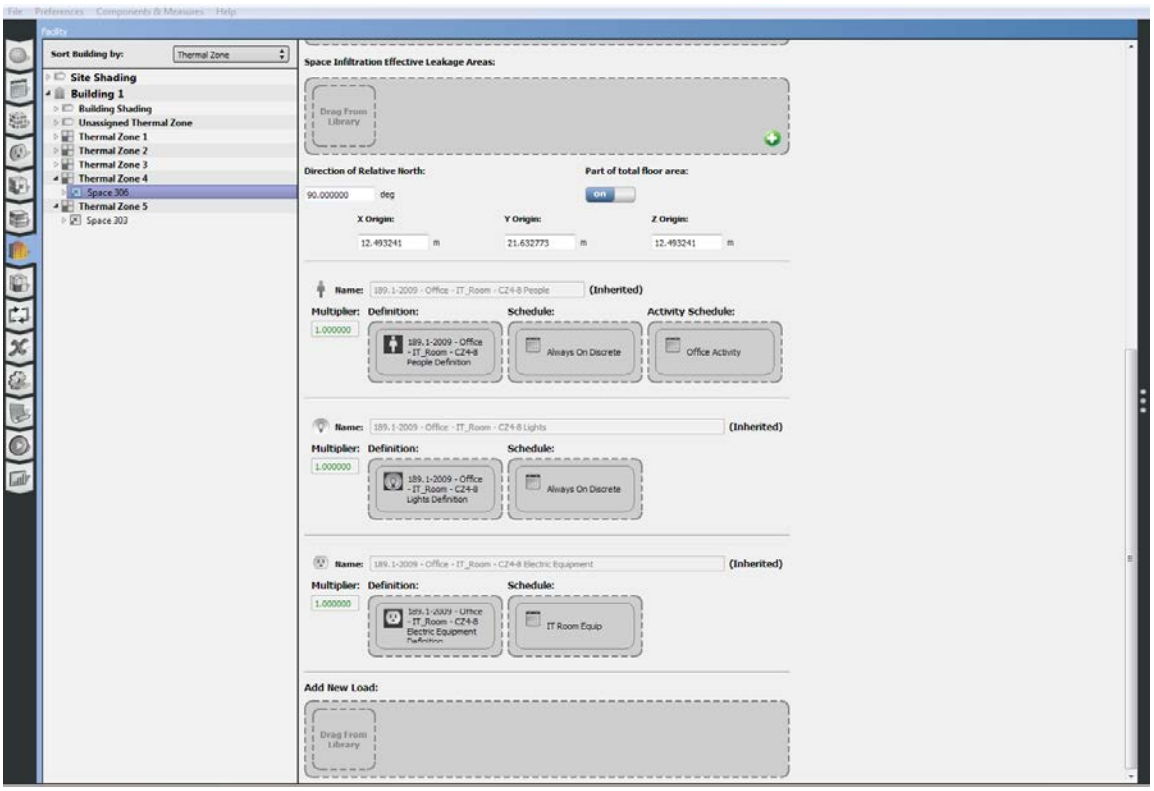


Figure 40: Data Center loads

The loads for the Data Center (Space 306) are set as “IT room Equip” according to measurements about the IT and non IT equipment power consumption in the closet of the Data Center. The schedule consists of a series of fraction rules. The fraction was calculated by dividing the power which measured in the corresponding time step, to the maximum power which measured in the total simulate time. Each rule or profile applied from December 25th to December 30th. Figure 41 presents the fractional rules for the Data Center loads

In the .osm model was set the temperature schedule for the Data Center. The temperature set points for heating and cooling for the Data Center (Space 306) are set as “IT Room Htg ” and “IT Room Clg” respectively. The set points were set for heating at 10 ^{o}C and cooling at the operating temperature which was set at 19^{o}C. Figure 42 present the schedules for cooling and heating for Data Center.

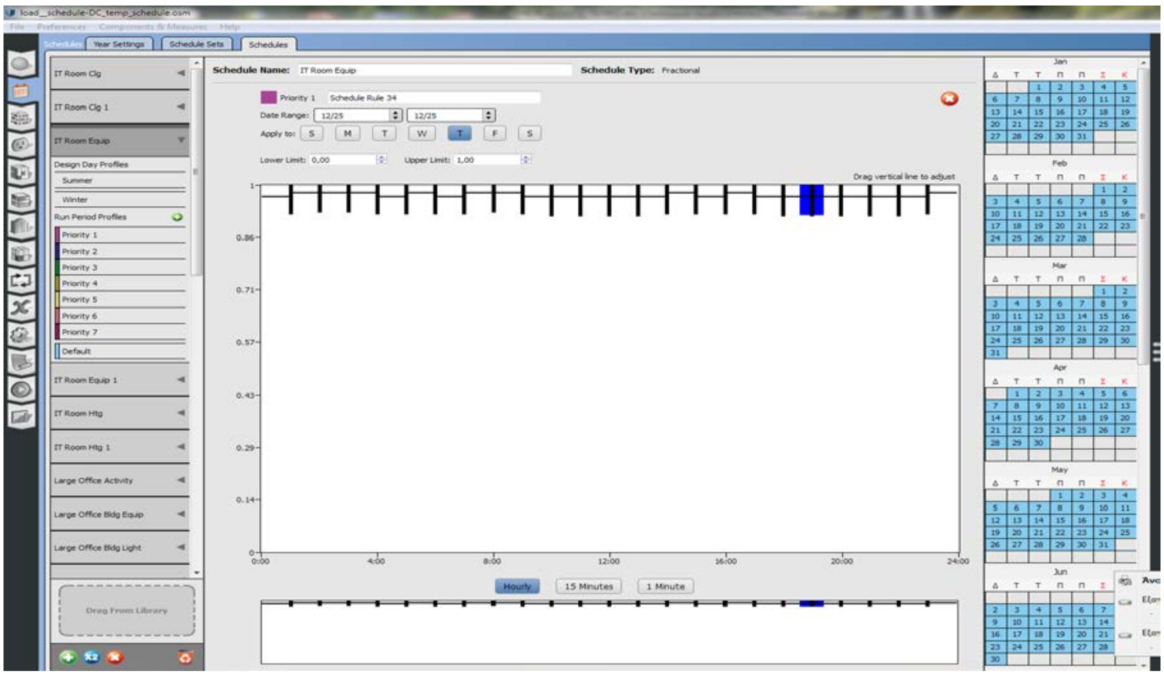
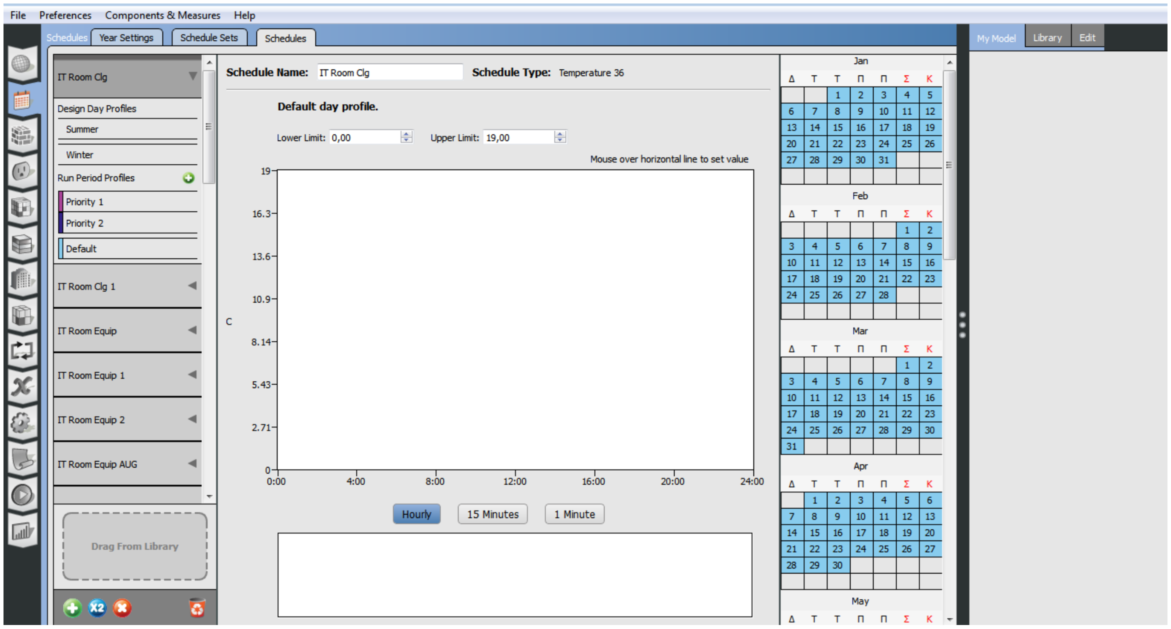
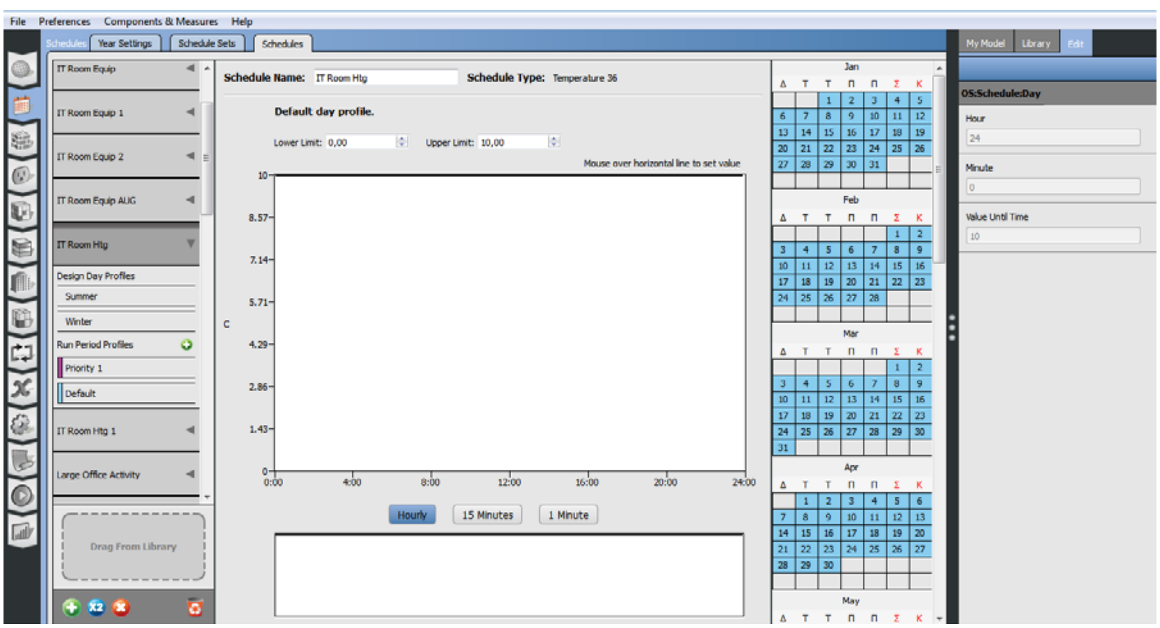


Figure 41: Fractional rules for the Data Center loads



(a)



(b)

Figure 42: schedules for cooling (a) and heating (b) for Data Center

4.5.5 Data Center Simulation results

The following figure presents the simulated results relative to the air temperature in the Data Center. Simulation Results show Data Center air temperature deviates in the range of 21,3 – 22,7 ^{o}C. Continuing the analysis, we will examine the results of EnergyPlus model to real data.

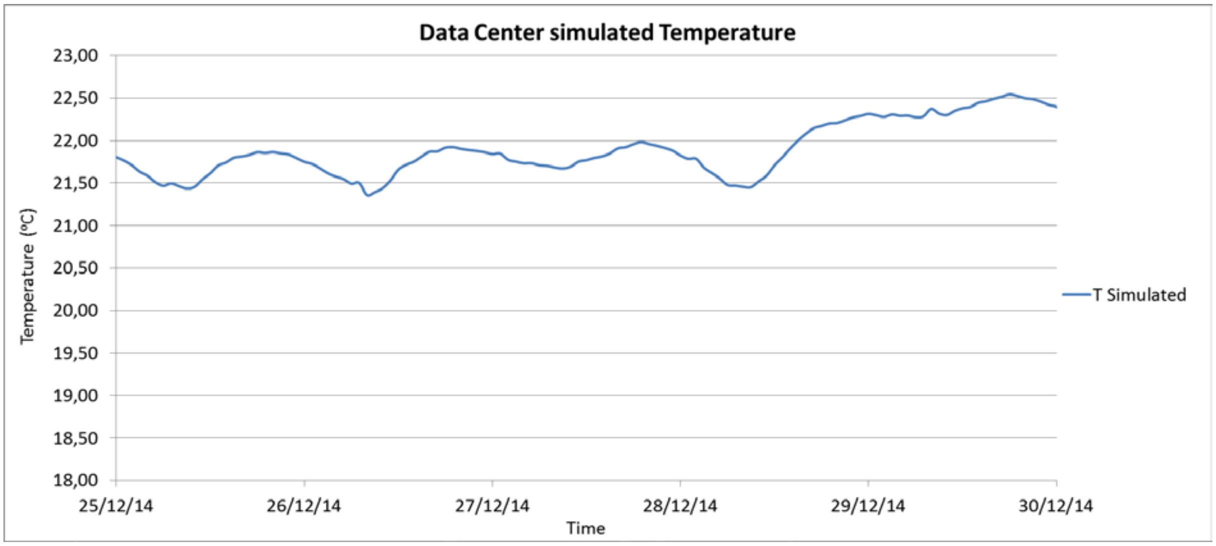


Figure 43: Data Center hourly simulated results from December 25th to December 30th

4.5.6 Data Center Evaluation of results

The evaluation is realized during Christmas holidays, so that no activity or internal gains are perturbing the results. Figures 44 present measurements obtained for the Data Center air temperature, the temperature from simulation and the outdoor temperature from December 25th to December 30th 2014.

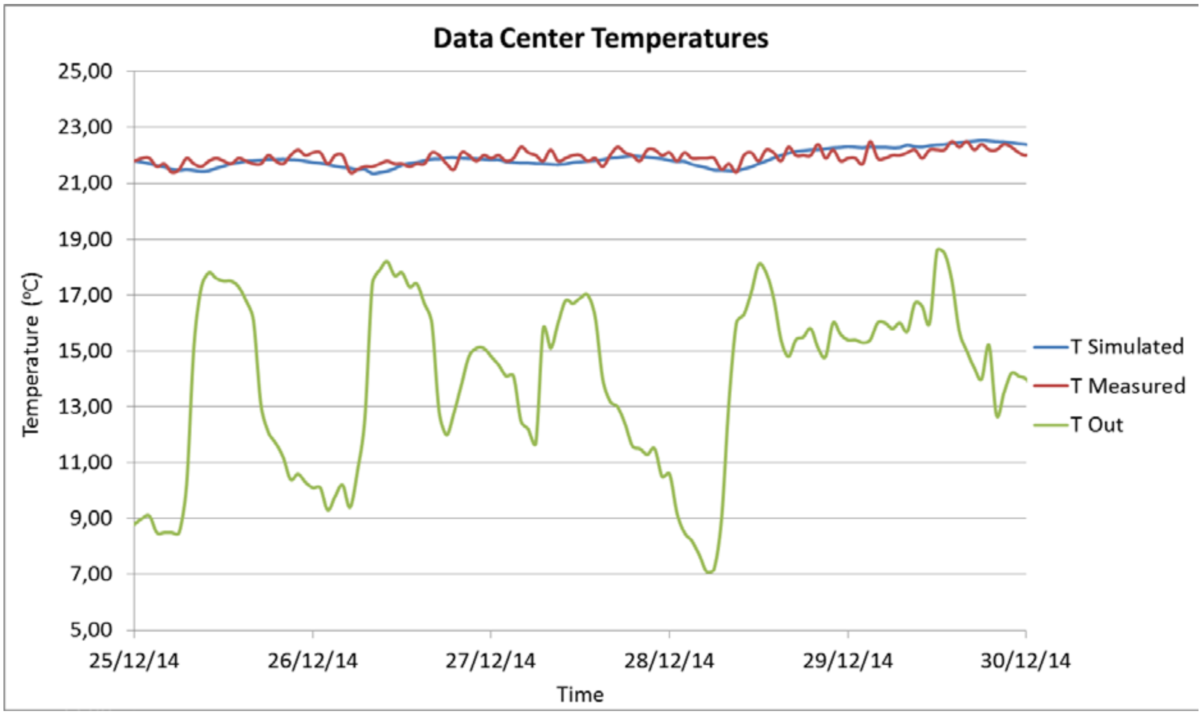


Figure 44: Temperatures measured, simulated and the outdoor temperatures from December 25th to December 30th for Data Center.

Measured temperatures deviate in the range of 21,3 – 22,7 ^{o}C and the simulated temperatures deviate in the range of 21,4– 22,5 ^{o}C. The standard deviation of the difference between simulated and measured temperatures is roughly 0,2 ◦C. So we can say that the EnergyPlus model gives satisfying results.

4.6 Summary

The fourth chapter contains the explanation of the collected data and the presentation of the simulation tools that are used for the thermal analysis of the Educational building in Herakleion, Crete. Here the results are also presented regarding the design of Sketcup 3D model and EnergyPlus/Openstudio model. The evaluation section presents the comparison of the simulation results with measurements of the site in order to demonstrate the applicability of the model.

Chapter 5 - PUE calculation and interventions for reduced values

In this Chapter the procedure of estimating the PUE of Data Center and the interventions in the building model result to a reduced value of PUE will be presented, based on the model created and evaluated in Chapter 4.

In ASHRAE TC 9.9 2011 Thermal Guidelines for Data Processing Environments (2011) introduced major changes in the Data Center classes to ITE used in Data Center applications. Prior to the formation of TC 9.9, each commercial IT manufacturer published his own independent temperature specification. Typical Data Centers were operated in a temperature range of 20 to 21°C with a common notion of “cold is better”. Most Data Centers deployed IT equipment from multiple vendors resulting in the ambient temperature defaulting to the IT equipment having the most stringent temperature requirement plus a safety factor. TC 9.9 obtained informal consensus from the major commercial IT equipment manufacturers for both “recommended” and “allowable” temperature and humidity ranges and for four environmental classes, two of which were applied to Data Centers. Another critical accomplishment of TC 9.9 was to establish IT equipment air inlets as the common measurement point for temperature and humidity compliance. Previously there were two classes applying to ITE used in Data Center applications: Classes 1 and 2. The new environmental guidelines have more Data Center classes to accommodate different applications and priorities of IT equipment operation. This is critical because a single Data Center class forces a single optimization whereas each Data Center needs to be optimized based on the operator’s own criteria (e.g. fulltime economizer use versus maximum reliability). The new guidelines of ASHRAE TC 9.9 2011 were developed with a focus on providing as much information as possible to the Data Center operator to allow them to operate in the most energy efficient mode and still achieve the reliability necessary as required by their business. Two new Data Center classes are created to achieve the most flexibility in the operation of the Data Center. Table 1 presents 2011 and 2008 Thermal Guideline Comparisons. The new classes and the Equipment Environmental Specifications are presented in the Table 2.

2011 classes	2008 classes	Applications	IT Equipment	Environmental Control
A1	1	Datacenter	Enterprise servers, storage products	Tightly controlled
A2	2		Volume servers, storage products, personal computers, workstations	Some control
A3	NA		Volume servers, storage products, personal computers, workstations	Some control
A4	NA		Volume servers, storage products, personal computers, workstations	Some control
B	3	Office, home, transportable environment, etc.	Personal computers, workstations, laptops, and printers	Minimal control
C	4	Point-of-sale, industrial, factory, etc.	Point-of-sale equipment, ruggedized controllers, or computers and PDAs	No control

Table 1: 2011 and 2008 Thermal Guideline Comparisons (Source: ASHRAE TC 9.9 (2011), Thermal Guidelines for Data Processing Environments)

Classes (a)	Equipment Environmental Specifications							
	Product Operations (b)(c)					Product Power Off (c) (d)		
	Dry-Bulb Temperature (˚C) (e) (g)	Humidity Range, non-Condensing (h) (i)	Maximum Dew Point (˚C)	Maximum Elevation (m)	Maximum Rate of Change(˚C/hr) (f)	Dry-Bulb Temperature (˚C)	Relative Humidity (%)	Maximum Dew Point (˚C)
Recommended (Applies to all A classes; individual data centers can choose to expand this range based upon the analysis described in this document)								
A1 to A4	18 to 27	5.5ºC DP to 60% RH and 15ºC DP						
Allowable								
A1	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
A3	5 to 40	-12˚C DP & 8% RH to 85% RH	24	3050	5/20	5 to 45	8 to 85	27
A4	5 to 45	-12˚C DP & 8% RH to 90% RH	24	3050	5/20	5 to 45	8 to 90	27
B	5 to 35	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29
C	5 to 40	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29

Table 2: ASHRAE classes and the Equipment Environmental Specifications for Data Centers (Source: ASHRAE TC 9.9 (2011), Thermal Guidelines for Data Processing Environments)

The four Data Center classes including the two new ones (A3 and A4) are presented in the psychrometric chart in Figure 45.

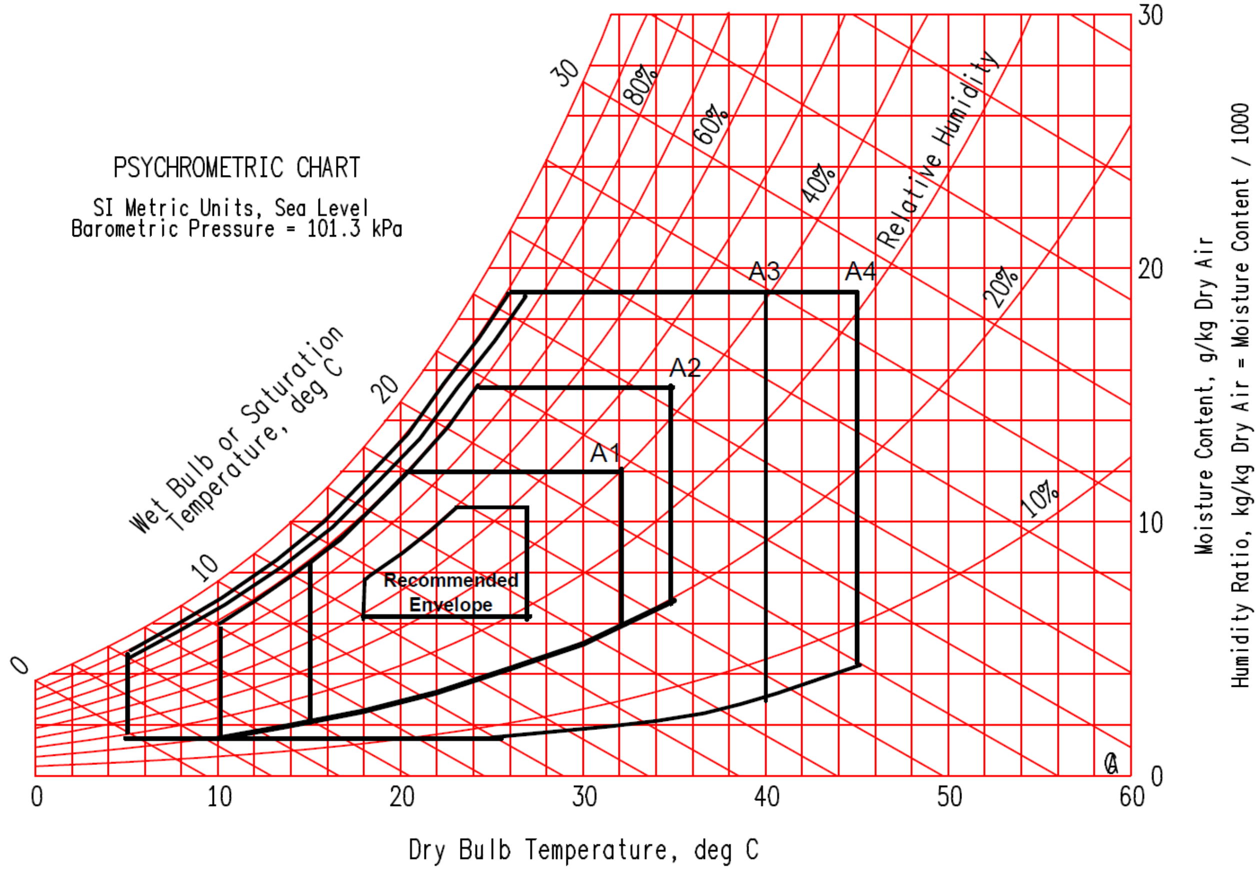


Figure 45: ASHRAE Environmental Classes for Data Centers (Source: ASHRAE TC 9.9 (2011), Thermal Guidelines for Data Processing Environments)

In Chapter 4 were presented the software tools and the steps for creating a building model and the simulation and evaluation process of the building model according to the operator‘s temperature options in the Data Center space. A main objective of this work is to study the areas of the Data Center and Hardware Laboratory, as they are both spatial and structural the same spaces, in order to confirm that the model for the Hardware Laboratory space and its simulation results agree with the measurements about the temperature. As this is achieved to a great extent, both the loads and the required temperature as measured in the space of the Data Center was set, and through the EnergyPlus we can have the results of the required cooling energy and therefore the PUE. Subsequently, we will consider potential interventions in order to achieve reduced values for PUE according to the operator‘s temperature options in the Data Center space and ASHRAE environmental classes.

5.1 PUE calculation

The EnergyPlus model was excited during the period of 25th to the 30th of December 2014 as there was no activity or internal thermal load to perturb the results. The cooling energy needed in the Data Center deviates in the range of 1525,43 W – 1586,88 W. PUE deviates in the range of 1,64 – 1,76 while the average rate is 1,71. The same procedure was followed for the period of 10th to the 15h of August 2014 as we had measures for power consumption, in order to estimate the PUE for summer and the benefits of the interventions in this period which has extended sunshine and high temperatures. The cooling energy needed in Data Center for the period of 10th to the 15h of August 2014 deviates in the range of 1655,41 – 1870,96 W and PUE deviates in the range of 1,74 – 1,79 while the average rate is 1,77 resulting significantly higher consumption values and therefore also for the PUE. Figures 46, and 47 present each type of consumptions and the calculated PUE of the Data Center for December and August Period.

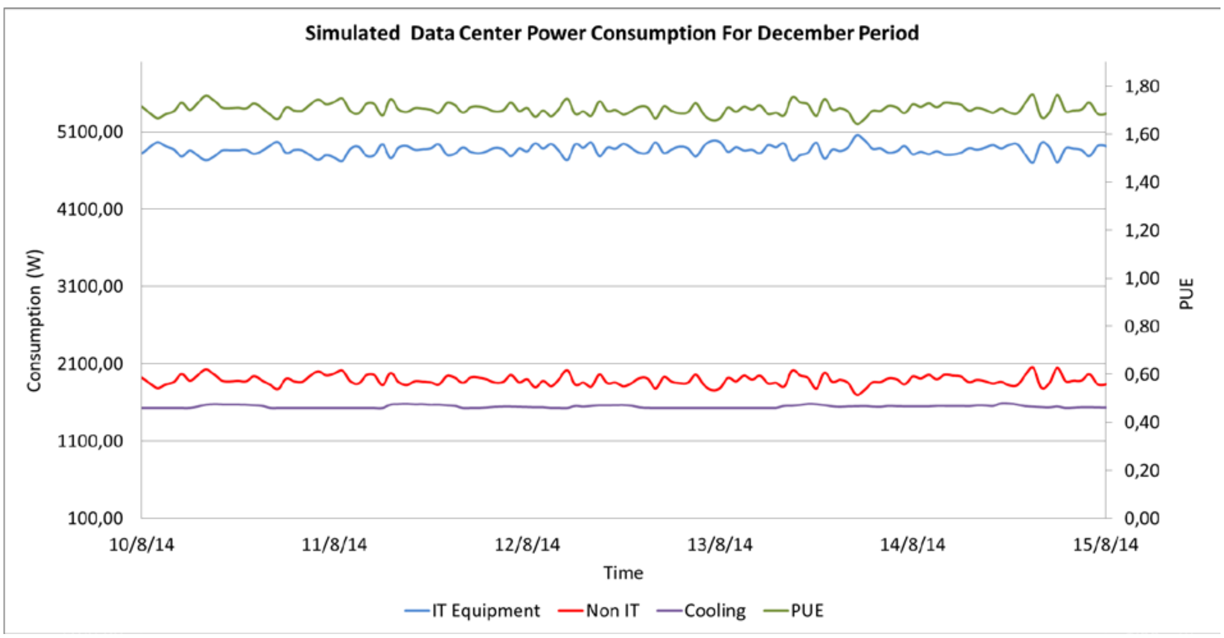


Figure 46: Cooling energy in Data Center (thermal zone 4) and the calculated PUE for December Period

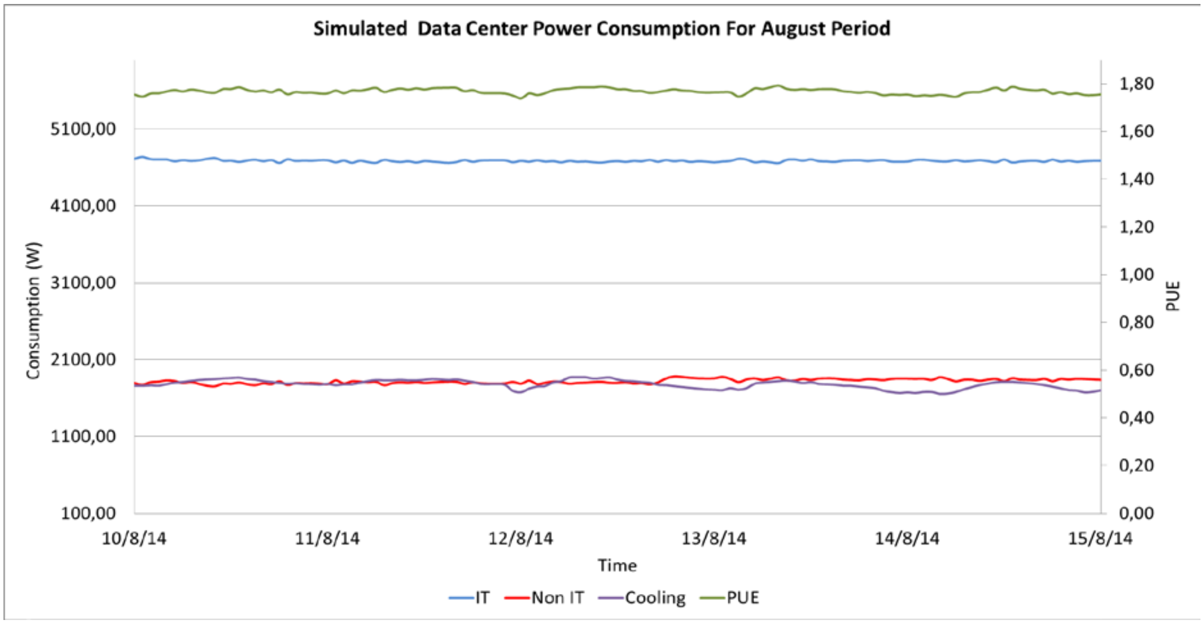


Figure 47: Cooling energy in Data Center (thermal zone 4) and the calculated PUE for August Period

The next figure presents the PUE calculated values of the measurements that were fed to emoncms web application. In the graph have been interpolated the simulated PUE values of our model.

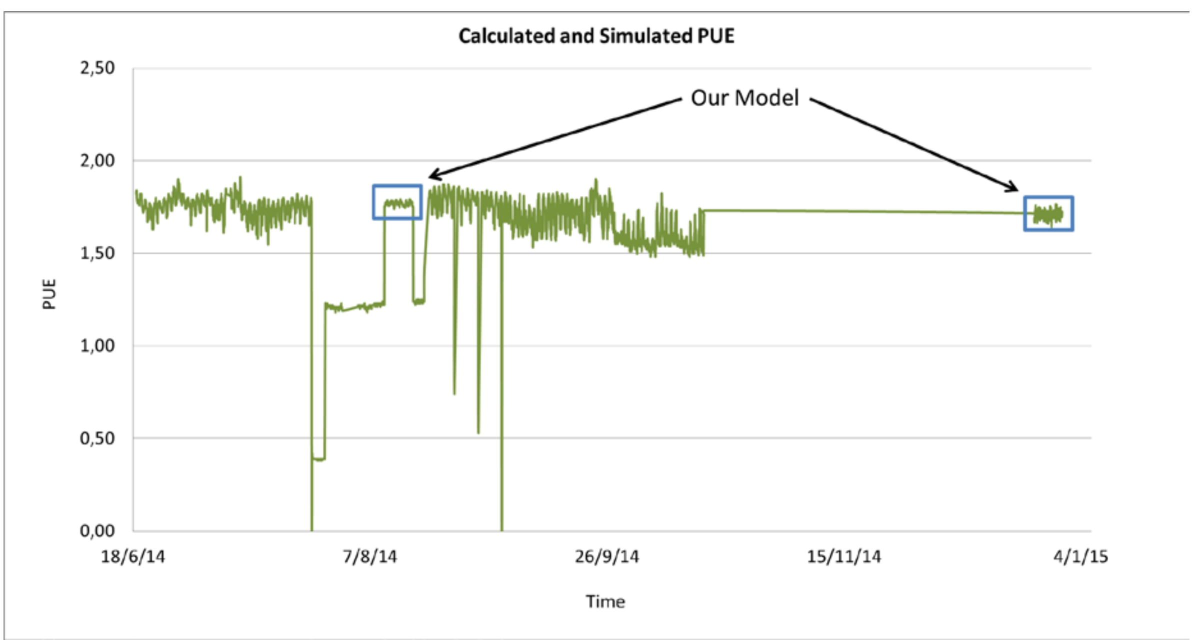


Figure 48: PUE calculated values, of the measurements that were fed to emoncms web application

5.2 PUE interventions for reduced values

In this section we consider the possible interventions that can be done in our building in order to improve energy performance of the Data Center space. A distinct simulation was made for each proposed intervention of the building model according to measured temperatures in comparison with the recommended envelope proposed by the ASHRAE for Data Processing Environments. Power consumption, and therefore PUE, comparison between the previous and new situation was made.

5.2.1 Recommended Dry Bulb temperature limit

According to ASHRAE TC 9.9 - Thermal Guidelines for Data Processing Environments, typical Data Centers are operated in a temperature range of 20 to 21°C with a common notion of “cold is better”. The cooling setpoint of the Data Center we are considering is set from the operator at 19 °C and this is an indication that this apply in respect of the cooling setpoint. The the upper limit temperature value for the recommended envelope proposed by the ASHRAE for Data Processing Environments is at 27^{o}C. Setting the cooling setpoint at 27^{o}C during the period December, resulted in a change of cooling consumption reduced by 9,98% and therefore the PUE reduced from 1,71 to 1,68. Setting the cooling setpoint at 27^{o}C during the period of August resulted in a change of cooling consumption reduced by 8,67% and therefore the PUE reduced from 1,77 to 1,74.

5.2.2 Installing insulation in external facades of Data Center space

In openstudio model and in materials tab we added two new objects: Durosol Roof Insulation [30] and Fibran Wall Insulation [25]. Durosol Roof Insulation [30] is a roof insulation material that can be found on the market. Its technical data are:

Thickness: 0,03 m

Conductivity: 0,034 W/mK

Density: 28 kg/m^3

Fibran Wall Insulation [25] is a wall insulation material that can be found on the market. Its technical data are:

Thickness: 0,025 m

Conductivity: 0,034 W/mK

Density: 28 kg/m^3

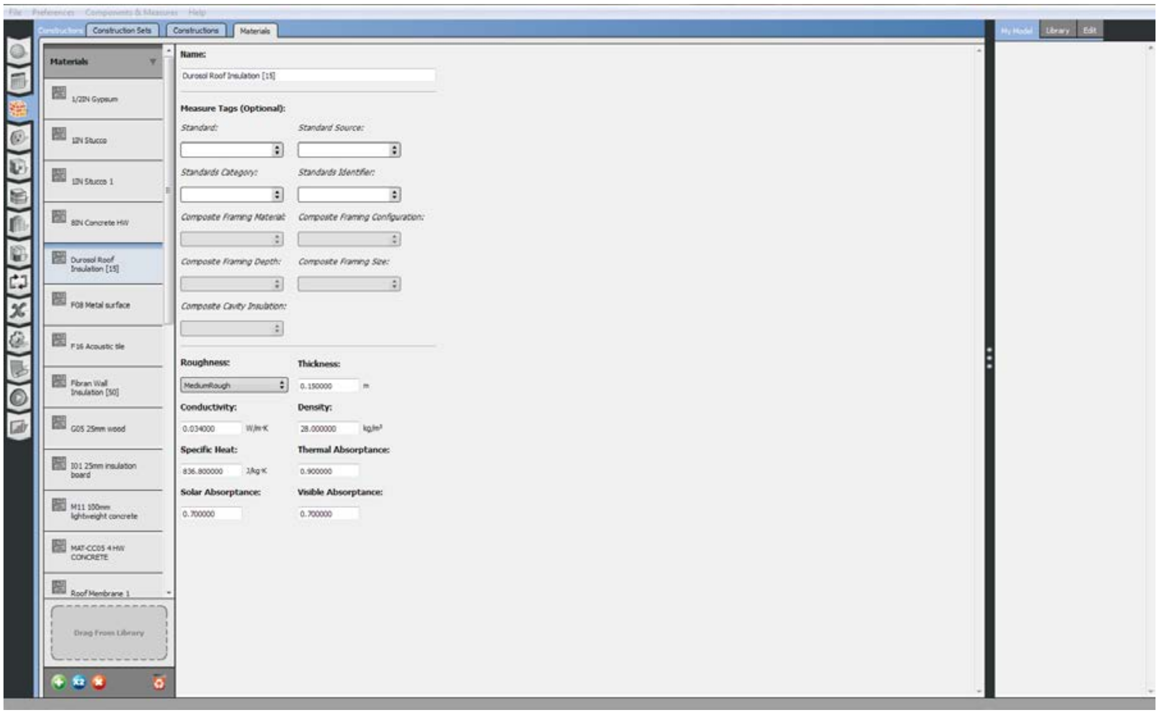


Figure 49: OpenStudio materials tab

The use of the roof insulation during the period of December while the cooling setpoint was set at 19 ^oC, imposed no change in cooling consumption. Similarly, the use of the roof insulation during the period of August, while the cooling setpoint was set at 19 ^oC, imposed no change in cooling consumption. On the other hand we see an increment of the average ambient temperature from 21,86 ^oC to 22,09 ^oC for the Period of December and a reduction of the average ambient temperature from 24,21 ^oC to 24,01 ^oC for the Period of August.

The use of the wall insulation during the period of December while the cooling setpoint was set at 19 ^oC, imposed no change in cooling consumption. The use of the wall insulation during the period of August, while the cooling setpoint was set at 19 ^oC, resulted in a change of cooling consumption reduced by 0,01%. On the other hand we see an increment of the average ambient temperature from 21,86 ^{o}C to 22,38 ^{o}C for the Period of December and a reduction of the average ambient temperature from 24,21 ^{o}C to 24,17 ^{o}C for the Period of August.

While the cooling setpoint was set at 27^{o}C, the upper limit value for the recommended envelope proposed by the ASHRAE for Data Processing Environments, the use of the roof insulation during the period of December, resulted in a change of cooling consumption, reduced by 9,35% and therefore the PUE reduced from 1,71 to 1,68. The use of the roof insulation, while the cooling setpoint was set at 27^{o}C during the period of August, resulted in a change of cooling consumption, reduced by 8,67% and therefore the PUE reduced from 1,77 to 1,74.

The use of the wall insulation, while the cooling setpoint was set at 27^{o}C, the upper limit value for the recommended envelope proposed by the ASHRAE for Data Processing Environments, during the period of December resulted in a change of cooling consumption reduced by 8,48% and therefore the PUE reduced from 1,71 to 1,68. The use of the wall insulation, while the cooling setpoint was set at 27^{o}C during the period of August, resulted in a change of cooling consumption, reduced by 7% and therefore the PUE reduced from 1,77 to 1,74.

5.2.3 Installing shading on external facades of the Data Center space

In openstudio model and in Facility tab we changed Sun Exposure value to NoSun for both Roof and External Wall Surfaces. The use of the space shading during the period of December, while the cooling setpoint was set at 19 ^{o}C, imposed no change in cooling consumption. Similarly, the use of the space shading during the period of August, while the cooling setpoint was set at 19 ^{o}C, imposed no change in cooling consumption. On the other hand we see a reduction of the average ambient temperature from 21,86 ^{o}C to 21,42 ^{o}C for the period of December and from 24,21 ^{o}C to 23,14 ^{o}C for the period of August

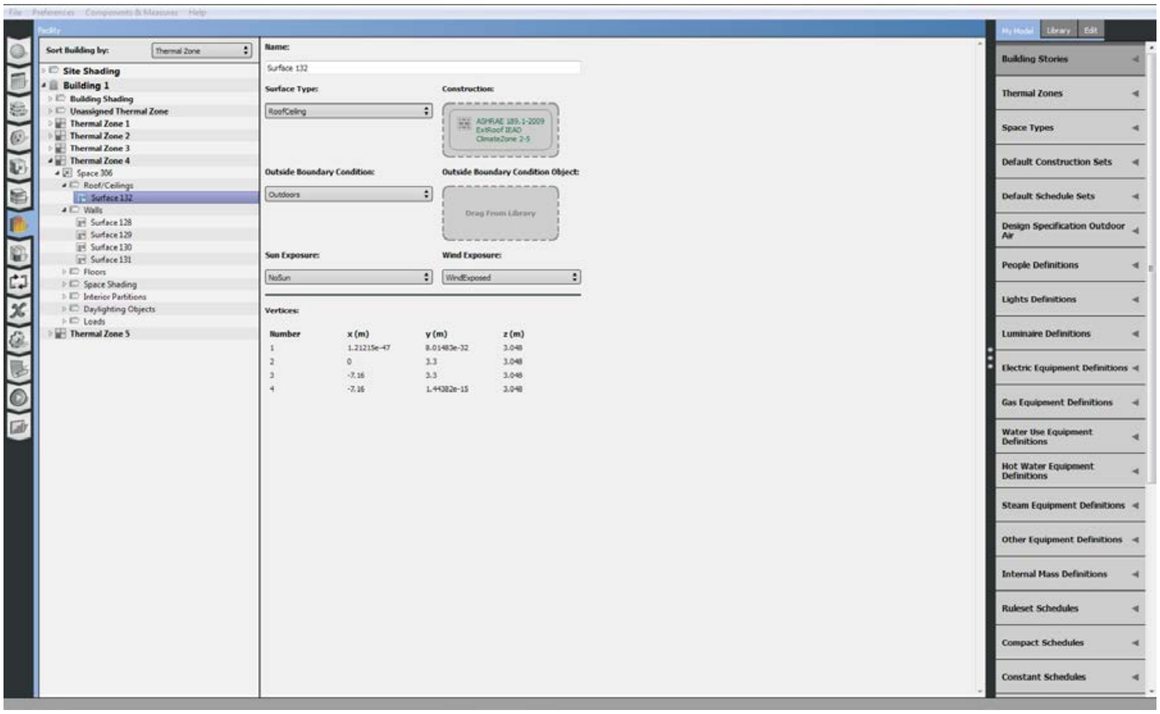


Figure 50: OpenStudio Facility Tab

While the cooling setpoint was set at 27^{o}C, the upper limit value for the recommended envelope proposed by the ASHRAE for Data Processing Environments, the use of the space shading during the period of December, resulted in a change of cooling consumption reduced by 10,66% and therefore the PUE reduced from 1,71 to 1,68. The use of the space shading, while the cooling setpoint was set at 27^{o}C during the period the period of August, resulted in a change of cooling consumption reduced by 10,65% and therefore the PUE reduced from 1,77 to 1,73.

5.2.4 Basement simulation of Data Center space

Usually, buildings have a basement. However, before taking the decision to locate a Data Center in a basement we have to consider some major factors. The Data Center must be protected from water and high moisture. In any case of leakage from hydraulic systems, fuel tanks, activation of fire suppression systems or natural flooding, the basement is the most vulnerable space. Consequently, basements must be equipped with high-capacity sump pumps to protect Data Center from flooding and well isolated from ground moisture.

In openstudio model changes were made in order to simulate and have relevant results on whether the Data Center space is located in a basement. In Facility tab we changed Outside Boundary Condition value to Ground, for Floor and Walls. For Roof and in Outside Boundary Condition value we set the value Surface, in Construction we set the value Interior Ceiling and in Outside Boundary Condition Object we set the value Surface according to surfaces of the Building Story 1 floor as these surfaces are part of the building lowest Floor. These changes were done as the Energyplus to simulate the Building Story 3 as it was a basement.

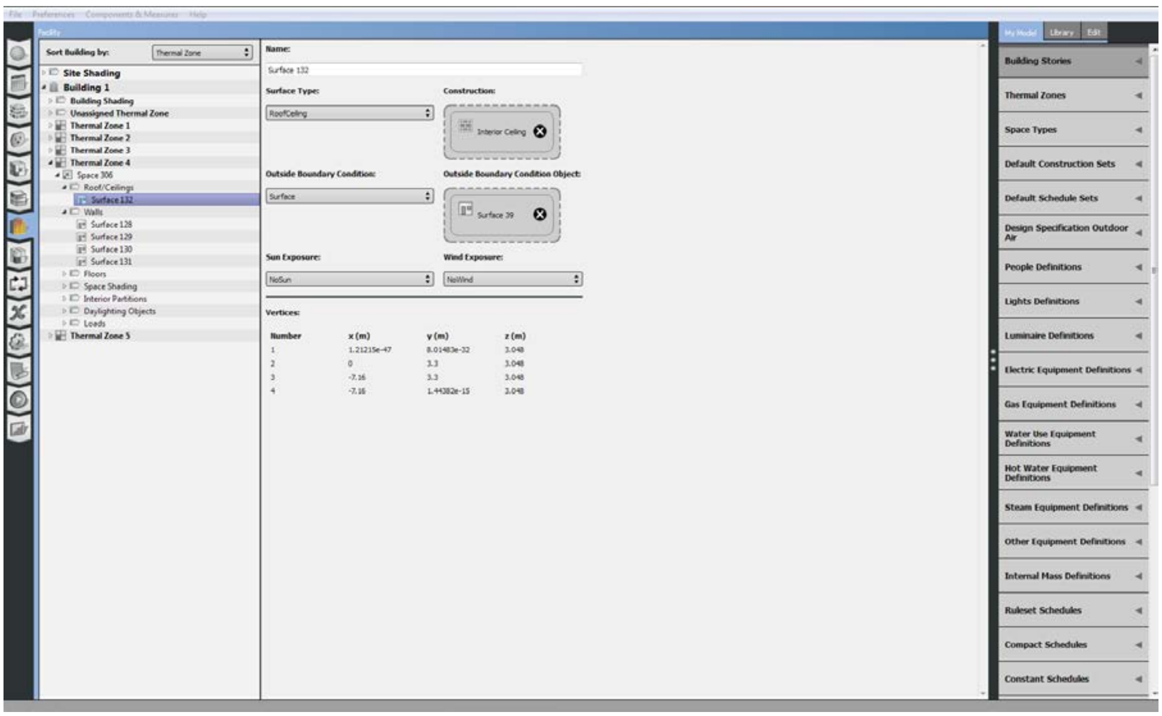


Figure 51: Changes in Facility tab for Outside Boundary Condition

Basement simulation during the period of December, while the cooling setpoint was set at 19 ^{o}C, resulted in a change of cooling consumption reduced by 6,29% and therefore the PUE reduced from 1,71 to 1,69, while achieved constant temperature of 19 ^{o}C. Similarly, basement simulation during the period of August, resulted in a change of cooling consumption reduced by 7,69% and therefore the PUE reduced from 1,77 to 1,74, while achieved constant temperature of 19 ^{o}C.

While the cooling setpoint was set at 27^{o}C, the upper limit value for the recommended envelope proposed by the ASHRAE for Data Processing Environments, basement simulation during the period of December, resulted in a change of cooling consumption reduced by 27,18% and therefore the PUE reduced from 1,71 to 1,64. Basement simulation during the period of August, while the cooling setpoint was set at 27^{o}C, resulted in a change of cooling consumption reduced by 39,70% and therefore the PUE reduced from 1,77 to 1,66

5.2.5 Airside economizer simulation

Airside economizers take advantage of favorable outside air conditions, such as at nighttime and during mild winter conditions. This approach is typically the lowest-cost option to cool Data Centers. Control strategies to deal with temperature and humidity fluctuations must also be considered along) with contamination concerns over particulates or gaseous pollutants (Ian Metzger et al, 2011). A number of Data Centers currently operate without any active humidity control and still maintain a high level of reliability and a higher Relative Humidity (RH) setpoint potentially reduces the need for dehumidification, offering significant energy savings. However, an excessively high RH setpoint can cause a number of problems: conductive anodic filament (CAF) growth; head fly-ability and corrosion in disk drives; and head wear and head corrosion in tape drives. Conversely, low RH increases the risk of electrostatic discharge (ESD) (Michael Sheppy et al, 2011). ASHRAE, in 2014, released the #1499 research study according to the danger to IT equipment from static generation and discharge in the Data Center environment. The conclusion of this research is that relative humidity (RH), can be dropped to 8% RH with only minor precautions. Economizers are most commonly used in cooler climate zones, such as Zones 5 and higher per older versions of the energy code and, hypothetically, the expanded range of the Thermal Guidelines permits economizer mode in any climate zone, but only if the data center is operating in the allowable ranges or with higher class ratings of the installed hardware. (Donald L. Beaty, 2015)

The choice of whether or not to use an economizer and what type to use, depends on a variety of factors including:

- Stated mission of the facility, especially those classified as mission critical;

- The total cost of ownership evaluation;
- Geographic locations;
- Existing building constraints on available space;
- Limitations on reliable water supplies;
- Poor air quality;
- Expected life of the facility;
- Technology refresh rates; and
- Freeze protection considerations

In most climates the switchover from chiller operation to air-side economizer mode for Data Centers should be based on enthalpy controls, not on dry-bulb temperature alone (Donald L. Beaty, 2015).

Utilizing free air cooling or air-side economizers in Data Center may have harmful environment resulting from the ingress of outdoor particulate and/or gaseous contamination increase the rate of hardware failures in data centers high in sulfur-bearing gases—due to copper creep corrosion on printed circuit boards and corrosion of silver in some miniature surface mount components, it is recommended that in addition to temperature-humidity control, dust and gaseous contamination should also be monitored and controlled. These additional environmental measures are especially important for data centers located near industries and/or other sources that pollute the environment and it is incumbent on data center managers to do their part in maintaining hardware reliability by monitoring and controlling dust and gaseous contamination in their data centers (ASHRAE TC 9.9 white paper, 2011).

In openstudio model and in HVAC Systems, the Air Loop HVAC 1 is the relevant HVAC System for Data Center. We changed the settings for the OA System from defaults according to AHRAE recommended envelop proposal:

- Economizer Control Type: DifferentialDryBulbAndEnthalpy
- Economizer Maximum Limit Dry-Bulb Temperature: 27 ^{o}C
- Economizer Maximum Limit Dewpoint Temperature: 17 ^{o}C
- Economizer Minimum Limit Dry-Bulb Temperature: 14^{o}C

- Lockout Type: LockoutWithCompressor

The airside economizer simulation during the period of December, while the cooling setpoint was set at 19 °C, resulted in a change of cooling consumption reduced by 0,17% and minor change of the PUE, while the average ambient temperature reduced from 21,86 °C to 21,33 °C. The airside economizer simulation during the period of August, while the cooling setpoint was set at 19 °C, resulted in a change of cooling consumption reduced by 0,01% and minor change of the PUE, while the average ambient temperature reduced from 24,21 °C to 23,81 °C.

Changing the cooling setpoint at 27 °C for the dry bulb temperature, which is the upper limit of the recommended envelope proposed by the ASHRAE for Data Processing Environments, we see that the simulation of the airside economizer during the period of December, resulted in a change of cooling consumption reduced by 27,16% and therefore the PUE reduced from 1,71 to 1,64, and during the period of August, resulted in a change of cooling consumption reduced by 8,78% and therefore the PUE reduced from 1,77 to 1,74. Figure 52 and Figure 53 present simulated Data Center PUE for the period of December and August respectively. Figure 54 presents average PUE reduction of the December and August period.

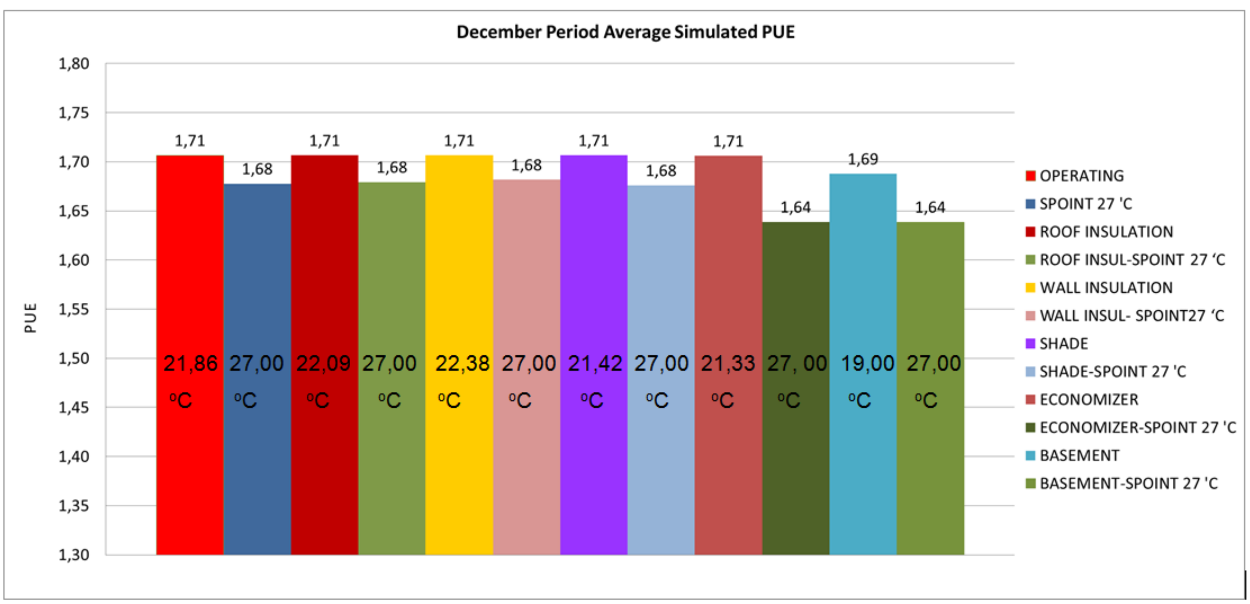


Figure 52: December Period Average Simulated PUE for all Interventions and relevant average ambient temperatures

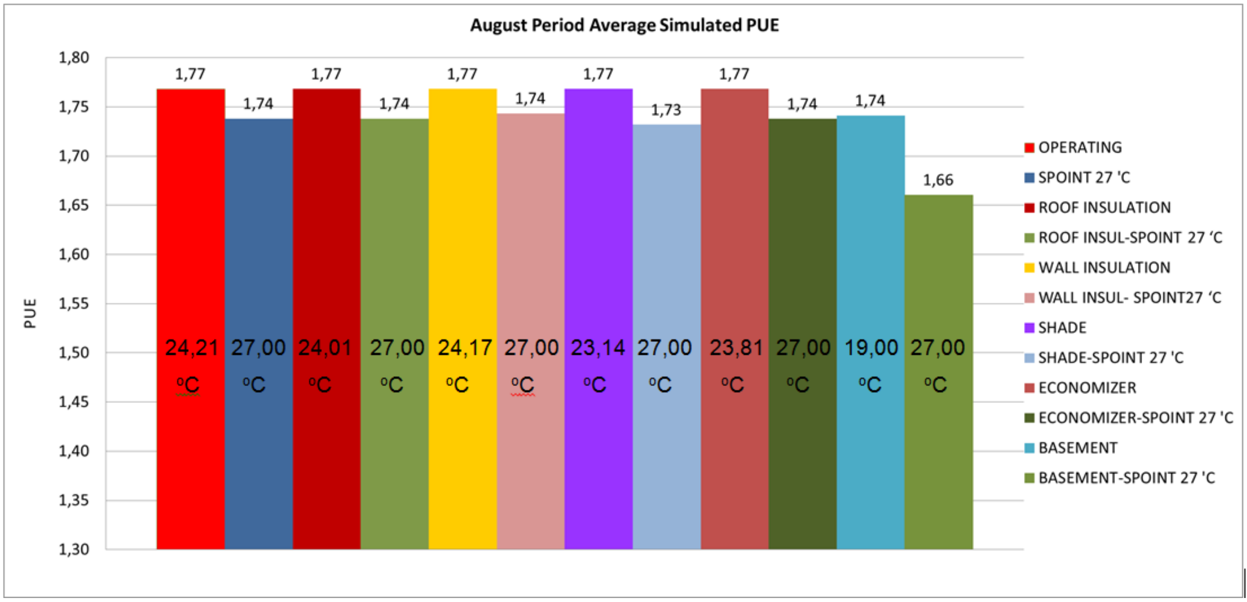


Figure 53: August Period Average Simulated PUE for all Interventions and relevant average ambient temperatures

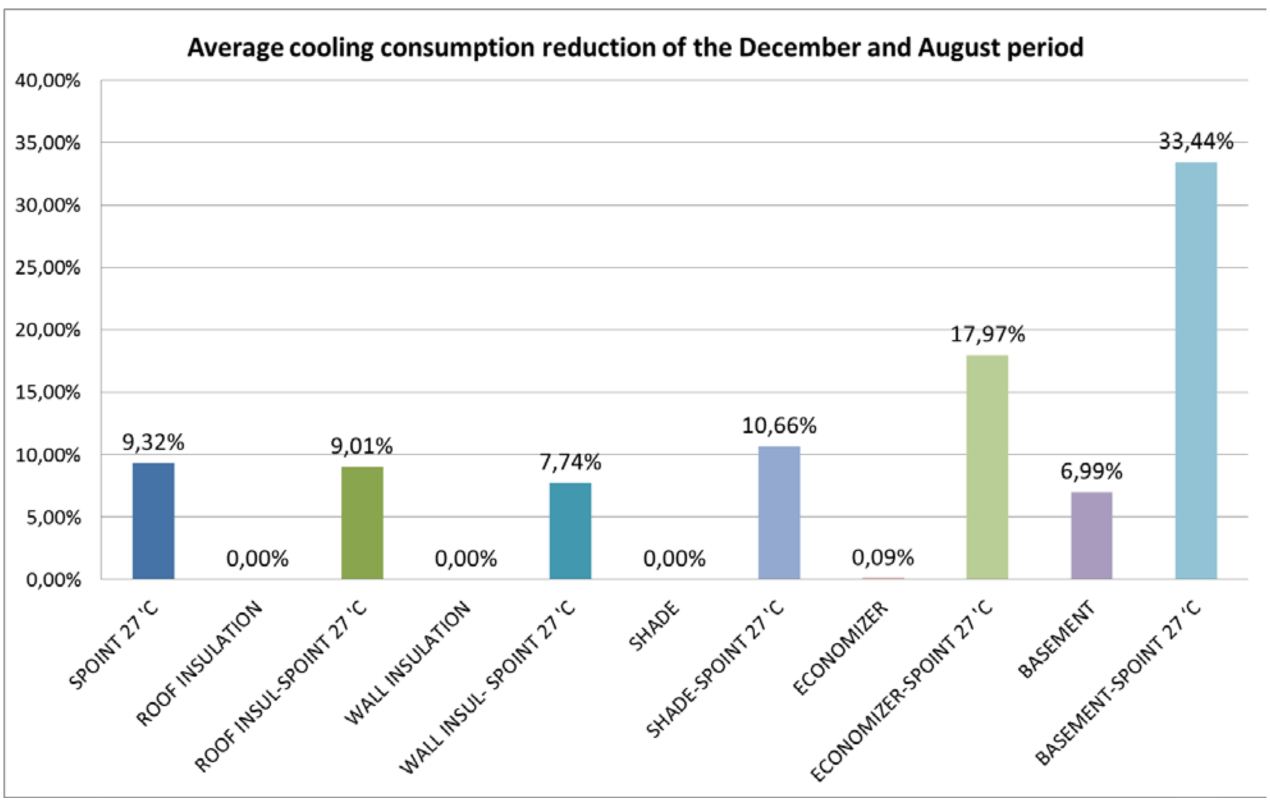


Figure 54: Average cooling consumption reduction of the December and August period for all Interventions

Chapter 6 - Discussion and Conclusions

In this work the researcher investigated thermal performance of an operating Data Center space, in order to address the problem of improving energy efficiency while preserving expected life and stated mission of the facility and/or other criteria. The researcher investigated the literature in order to address the significance of energy conservation in Data Centers. It was found that each year, 44% of all energy consumed in the EU is used in buildings, domestic, tertiary or industrial. The vast majority of this energy is produced by burning fossil fuels such as oil, natural gas and coal - with serious environmental impacts in terms of greenhouse gas emissions. Also in U.S., 40 billion kilowatt-hours (kWh) of electricity are used annually for cooling (EIA, 2011). Hence, there is a global need for energy savings in the building sector. Also, the building sector, which accounts for almost 40% of the total energy consumption with a share of 20% in the Green-House Gas emissions (Shahriar, 2008), could play an important role to achieve the EU targets for 2020.

Nowadays Data Centers provide the world community with an invaluable service: almost unlimited access to all kind of information imaginable with the support of most services Internet, such as hosting Web and e-commerce services. The power consumption and energy are key concerns of Internet Data Centers. These centers include, sometimes thousands of Servers and cooling infrastructure support. Research on power management in Servers can ease the installation of the Data Center, cost reduction, and environmental protection. In a Data Center, there are many types of IT elements that consume power. The IT elements that consume power are: racks, Servers, network cables and power cords, but what is not visible is the function of CPUs that run programs and continuous flow of information in and out of the system. Several degrees of freedom exist (increasing inlet temperature to the manufacturer's limit) that may be exploited in order to reduce Data Center energy consumption, but they should be evaluated according to the efficiency and life-span of the Data Center.

In order to evaluate the thermal performance and energy efficiency of Data Center Spaces considering ASHRAE TC 9.9 2011 Thermal Guidelines for Data Processing Environments, innovative technologies proposed such as airside economizers. Airside economizers take advantage of favorable outside air conditions, such as at nighttime and during mild winter conditions. This approach is typically the lowest-cost option to cool Data Centers.

Several simulation tools have been proposed in order to simulate and evaluate the thermal performance and energy efficiency of Buildings. In this work, the researcher exploits the potential of EnergyPlus as a base simulating software. EnergyPlus is a software platform that is used in relation to other tools in order to create a user friendly simulation environment. These tools are constantly developing due to the emerging need of easily accessible, free thermal performance simulation suites for building energy performance. Sketchup 15 is the latest version of Google's 3D modeling application that can be used with EnergyPlus. Openstudio 1.8 is also the latest version of the application suite that contains all other simulation tools for ruby scripts, model creation, parameter setting, simulation, results viewing. In OpenStudio extra “measure” was added and used in order to extend the report capabilities of OpenStudio. Furthermore EnergyPlus auxiliary software used, such as xEsoView and Elements software tools.

In order to develop a modelling procedure, the researcher studied the simulation tools and used them in order to simulate an Educational building in Herakleion, Crete. The 3D model was developed in Sketchup 15 and based on that model, the .idf and .osm files were created. The .idf file is the EnergyPlus file that can be imported to Sketchup and re-open the 3D model maintaining all features except the space types. The .osm file, is the Openstudio file that can be run and changed independently from Sketchup, once the basic geometry is complete. Openstudio suite calls EnergyPlus, so the user does not have to open other interfaces.

For temperature and power consumption measurements, Arduino technology and Emoncms open-source web application were used. Emoncms is part of the OpenEnergyMonitor project, for storage, real time representation and treatment of measurement data archived which collected from wire-connected Arduino.

In order to evaluate the developed model, specific period simulations were performed, and the indoor air temperature of the Educational building's spaces was calculated. A main objective of this work is to study the areas of the Data Center and Hardware Laboratory, as they are both spatial and structural the same spaces, in order to confirm that the model for the Hardware Laboratory space confirms the measurements about the temperature variation in comparison to the measurements obtained. If this is achieved to a great extent we can set the loads and the required temperature as measured in the space of the Data Center, and through the EnergyPlus to calculate the required cooling energy and therefore the PUE. Subsequently, we can propose interventions for upgrading energy efficiency of the Data Center space.

Simulating proposed innervations, exported the following results for average cooling consumption reduction of the December and August period, sorted in increasing order:

1	Roof Insulation – Setpoint at 19 ^oC	0,00 %
2	Wall Insulation - Setpoint at 19 ^oC	0,00 %
3	Shade - Setpoint at 19 ^oC	0,00 %
4	Economizer - Setpoint at 19 ^oC	0,09 %
5	Install Equipment in a Basement - Setpoint at 19 ^oC	6,99 %
6	Wall Insulation and ASHRAE recommended envelope - Setpoint at 27 ^oC	7,47 %
7	Roof Insulation and ASHRAE recommended envelope - Setpoint at 27 ^oC	9,01 %
8	ASHRAE recommended envelope - Setpoint at 27 ^oC	9,32 %
9	Shade and ASHRAE recommended envelope - Setpoint at 27 ^oC	10,66 %
10	Economizer and ASHRAE recommended envelope - Setpoint at 27 ^oC	17,97 %
11	Install Equipment in a Basement and ASHRAE recommended envelope - Setpoint at 27 ^oC	33,44 %

Table 3: Exported results for average cooling consumption reduction of the December and August period, sorted in increasing order

As one can see the most beneficial option is to increase the cooling temperature limit according to the envelope proposed by ASHRAE, without incurring the life of the equipment. Subsequently, it should be considered which option, among the others, is applicable and most beneficial on the prices of the local market.

The goal of this work is to search ways is to improve energy efficiency of an operating Data Center space, using Openstudio a cross-platform software to support whole building energy modelling using EnergyPlus simulating software, in order to address the problem of improving energy efficiency while preserving expected life and stated mission of the facility. Energy efficiency is calculated in terms of Power Usage Efficiency index (PUE) and the scope of this work is to propose interventions that can reduce PUE. First, the developed modelling procedure will be applicable to a case study that relates to a Data Center, a building sub-sector that is a huge energy consumer.

Conventional interventions proposed as the insulation and shading of exterior surfaces, changing the Data Center location and new, innovative and promising use of economizer. The simulation results of the specific insulation of exterior surfaces show no change or minor cooling consumption reduction because the insulation degrades the transfer of heat to the external colder environment during the cold or cool periods. Shading of exterior surfaces simulation results show satisfactory results. Setting the cooling setpoint at 27 ^{o}C, the upper limit value for the recommended envelope proposed by the ASHRAE and in combination with all conventional interventions, shows significant reduction of the cooling consumption. Similarly, basement simulation shows significant reduction of the cooling consumption because the outside surfaces are in contact with the ground which usually has a cool temperature. The use of economizer at the operating cooling setpoint shows minor reduction for cooling consumption. In combination with the cooling setpoint at 27 ^{o}C shows satisfactory results. The results of the use of economizer are related to the economizer limitations and local climate.

Energy prices are predicted to continue to increase which puts more pressure on Data Center operators to reduce their energy consumption. There are huge energy savings to be made in Data Center cooling systems. Data Center cooling design is driven by the IT hardware it serves. It is difficult to predict how this will change but trends suggest that densities and exhaust temperatures will continue to increase, resulting in even hotter temperatures in the hot aisle. Air performance metrics are a useful tool to assist operators in their understanding of the effectiveness of their Data Center cooling system. They can be used to quantify inefficiencies and to benchmark improvements and may be considered as a first step towards optimization.

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