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Chapter 9

APPLICATION OF BUILDING ENERGY SIMULATION IN THE SIZING AND DESIGN OPTIMIZATION OF AN OFFICE BUILDING AND ITS HVAC EQUIPMENT

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ABSTRACT

The reduction of energy consumption in buildings is of central importance in the North America's and European Union's energy policy. Following the adoption of legislative measures, methodologies are developed and employed to calculate the year-round energy performance of buildings. A number of computational tools are already available, however, the specific procedures of incorporating their use in the building shell and HVAC system's design process are not yet agreed. Energy performance standards for new buildings and large existing buildings subject to major renovation, are set at national level, but the process of translating these standards to shell and HVAC system sizing and design is not yet clear. This paper demonstrates the application of TRNSYS building energy simulation to produce design optimization directions for a new Department building under study contract. Sensitivity runs are employed to assess the effect of certain design parameters on the transient building's energy performance. The simulation process is demonstrated for two different levels of detail, with the higher level involving detailed simulation of the main HVAC equipment. The results of energy simulation runs are presented in the form of designer friendly diagrams, with special emphasis on the transient performance during critical periods of the year. The role of building shell insulation and design, HVAC system size, (heating and cooling), ventilation strategy, equipment performance characteristics and climatic conditions is studied. Based on the results, a methodology can be assembled for the incorporation of building energy simulation on the building shell and HVAC design process. Reasonable criteria for the degree of modeling complexity to be implemented, based on the available manpower, computing and other resources are discussed.

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Index Terms: Building Energy Simulation, HVAC Equipment, Design Optimization.

Keywords: Building Energy Simulation, Optimization, HVAC Systems Design.

Nomenclature

g:	solar gain factor at 0^o incidence angle
R_{sol}	Solar reflectivity of the glazing layer
R_{vis}	Visible spectrum reflectance of the glazing layer
U*	heat transmission coefficient – window panel area
U**	heat transmission coefficient – including frame
ε_l	Infrared (longwave) emissivity of the glazing layer
λ	Thermal Conductivity of glass (W/m-K).
τ_{sol}	Solar transmissivity of the glazing layer
τ_{vis}	Visible transmittance of the glazing layer
τ_{ir}	Thermal infrared (longwave) transmissivity of the glazing layer.
ACH	Air changes per hour
COP	Coefficient of performance
SHGC	Solar heat gain coefficient
TMY	Typical Meteorological Year
VLT	Visual light transmission

1. Introduction

The following four goals are set by ASHRAE in the Advanced Energy Design Guide for Small Office Buildings [1], for achieving energy savings in a new construction:

- Reducing internal and external loads
- Matching the capacity of HVAC and other systems to the reduced loads (because oversized systems cost more and do not operate at their optimum efficiency)
- Using higher efficiency equipment that will use less energy to meet any given load.
- Integration of building systems to increase energy savings potential.

Application of the recommendations in the Guide should result in small office buildings with 30% energy savings when compared to those same office buildings designed to the minimum requirements of ASHRAE Standard 90.1-1999 [2].

Following the example of the US, the European Union demonstrates an intensive legislative effort during the last decade, addressing the reduction of fossil fuels consumption (oil, gas, solid fuels). An important tool in this direction is the management of energy demand, which allows the EU to affect the world energy market, in order to safeguard energy supply for its member states, which lack adequate fossil fuel deposits. The residential, commercial and industrial building sectors are responsible for more than 40% of the final energy consumption in the EU. They also produce more than 30% of CO_2 emissions [3, 4]. According to recent studies, space heating energy consumption in residential buildings accounts for 57%, and water heating for 25% of the total energy consumed. The conclusion from specialized studies as well as real world experience, indicates that a great energy efficiency improvement capacity exists in the above sectors [5]. For the above reasons, the reduction of building energy consumption is of crucial importance internationally. A significant European development in this frame was the adoption of the Directive 2002/91/EC [4]. Following this directive, Member States are gradually applying methodologies for the calculation of the energy performance of buildings. Also, they are applying minimum requirements on the energy performance of new buildings and large existing buildings that are subject to major renovation. Energy certification of buildings is based on the above as well as the regular inspection of heating, ventilation and air-conditioning systems. When buildings are constructed, sold or rented out, an energy performance certificate is made available to the owner or by the owner to the prospective buyer or tenant. The above requirements enhance the involvement of advanced engineering tools in the building construction, maintenance, refurbishing and certification sector.

According to this directive, each EU member state needs to develop or adapt to its local needs, a methodology for calculation of the integrated building energy performance, which must at least cover the following aspects:

i. thermal characteristics of the building (building shell, internal walls etc), infiltration characteristics
ii. heating installation and hot water supply, including their insulation characteristics,
iii. air conditioning installation,
iv. ventilation,
v. integrated lighting installation (especially in the commercial building sector),
vi. building position and orientation, including local climatic conditions,
vii. passive solar energy utilization,
viii. natural ventilation,
ix. indoor conditions including the required thermal and environmental comfort conditions. The computational methodology must be able to take into account the positive effect of active solar and other renewable energy systems, electricity generated by cogeneration, district heating and cooling systems in various scales and natural lighting.

The computations must differentiate for the following basic categories of buildings: low and high-rise residential buildings of various types, office buildings, school and University buildings, hospitals, hotels and restaurants, athletic facilities, commercial buildings. Based on the developed building energy efficiency computation methodologies, the directive proceeds to suggestions for the application of minimal energy efficiency requirements for new buildings, as well as large existing buildings being refurbished [6]. In addition, energy certification of buildings is legislated. This ambitious step of European Legislation is aimed at following the pioneering North American legislation that is in use since the nineties. The actions taken for fast implementation of the new Directive's requirements, were delayed by significant gaps in a number of technical standards and guidelines related to building energy performance computation [7]. Around 30 European (CEN) standards have been developed to provide Member States with the necessary tools for developing the framework for an integrated calculation methodology of the energy performance of buildings [8]. Should voluntary compliance with the standards not be forthcoming, then mandatory standards should be considered in a future amended version of the buildings directive [9]. Especially with regard to electrical energy, it is important to minimize also peak demand, thus avoiding equipment oversizing.

Traditionally, building energy simulation studies were being carried out on simplified building shell designs and schedules, producing indicative results to provide general directions for the architect [6, 10], but also for complex geometries and systems [11, 12]. This type of studies is not only carried out by specialized University or Research Labs, but also by some specialized Architectural and Engineering Offices [13]. The significant requirements in terms of man-hours for input data, pre-processing and post-processing, but also the lack of unanimous computation protocols, delays the incorporation of this type of calculation procedures in the building design studies carried out by engineering offices. In most cases, indicative building energy simulations have been carried out, without the close interfacing with the detailed building design procedures. However, during the recent years, large software producers are incorporating in their architectural and engineering drawing software, innovative system design and analysis solutions, based on building information modeling (BIM). Thus, the new software versions may support in a certain degree sustainable designs, by analyzing building performance using integrated tools as well as partner applications [14].

As regards the required detail and complexity of computations, according to the Directive, for the small residential buildings a simplified steady state energy calculation procedure is sufficient, for the estimation of heating energy consumption on a monthly basis. However, for larger buildings over 1000 m^2, a detailed computation of the transient thermal behavior of the building on an hourly basis is required. Such a computation can be supported by one of the in-use certified building energy simulation programs, such as TRNSYS, DOE-2 or EnergyPlus [15]. The hourly base computation allows for sufficient accuracy in the calculation of solar gains that contribute significantly to the energy consumption for cooling, and also affect heating energy consumption. Moreover, the hourly base calculation is normally required for the optimization of the building automation and control systems.

The role of building energy simulation in supporting the design optimization of the building envelope and energy subsystems is demonstrated in this paper by studying an office building with the aid of the TRNSYS simulation suite. Input data to the code are presented and discussed and sensitivity analysis of the effect of certain design parameters on the yearly energy consumption of the building is carried out by means of multiple building energy simulation runs.

2. Building Design Parameters Affecting Energy Consumption

Well-documented simulation runs are required to predict energy savings produced by specific building design choices, in order to draw key decisions with respect to any energy efficient building design project. For example, the Advanced Energy Design Guide for Small

Office Buildings[1] that was recently published by ASHRAE, is intended to provide a simple approach for contractors and designers who create small office buildings. A large number of building energy simulation runs have been required to confirm the adequacy of the proposed design approaches to fulfill the intended energy savings over Standard 90.1-1999. To quantify the expected energy savings, the authors of this guide selected potential envelope, lighting, HVAC, and service water heating energy-saving measures for analysis, based on typical products that are commercially available. Each set of measures was simulated using an hour-by-hour building energy analysis computer program for two small office prototypes in representative cities in various climates. Simulations were run for reference buildings, designed to Standard 90.1-1999 criteria, compared to buildings built using selected energy-saving measures to determine that the expected 30% savings target was achieved. This approach is workable for small office buildings using unitary heating and air-conditioning equipment. Buildings of this size with these HVAC system configurations represent a large fraction of commercial office space in the United States and Europe.

However, for the study of larger office buildings with dedicated heating and HVAC equipment, it is becoming increasingly necessary to extend the building design study to include an hour-by-hour energy simulation, for typical climatic conditions of the site. For this reason, according to European Legislation, if the characteristic value of energy consumption of a building exceeds a specified mean value for the specific building category, a detailed analysis should be carried out to highlight existing deficiencies and suggest measures for improvement [16]. Building energy simulation is being increasingly employed to support this process.

In this section, the basic building design parameters that significantly affect energy consumption for heating, cooling, lighting and other operations are discussed.

Table 1. Building architectural, shell and equipment characteristics that significantly affect yearly energy consumption

BUILDING SHELL – ORIENTATION	HVAC INSTALLATION	OFFICE EQUIPMENT/ LIGHTING
Building position related to the sun's path. Shading by neighboring buildings. Building shell materials: walls, frame, windows Shell insulation materials	Design and control of HVAC system Efficiency of specific HVAC system components Energy / heat recovery Exploitation of solar energy	Lighting intensity per workspace, exploitation of solar lighting Lighting equipment technology, energy efficiency characteristics Efficiency of specific office equipment

Table 1 summarizes certain characteristics of the building architecture and shell that significantly affect energy consumption. They have been categorized as follows:

- Geometrical, constructional shell and frame characteristics, including orientation,
- Main characteristics of HVAC installation and
- Main characteristics of lighting and office equipment.

3. Building and HVAC System Simulation Levels

The numerous building energy simulation methodologies in-use today, can be categorized in the following two levels of simulation detail [17]:

- Level I: simulation mainly of the building envelope with simplifying assumptions regarding operation of the HVAC equipment and
- Level II: detailed transient simulation of the building envelope and the HVAC equipment and its control.

Due to increased complexity and need for additional performance and control system data, most studies employ the first approach [18]. On the other hand, simulations of the, so-called, “typical day operation” type, are nowadays carried out with advanced HVAC control system modelling [19]. A few years ago, a “level I” simulation of a single zone house, combined with a component model of an air-to-air (split type) heat pump, was carried out to study performance optimization of heat pump operation by varying refrigerant pressure levels to minimize outdoor unit temperature differences [20]. The results of this study suggested that the attainable gains in heat pump COP were not readily transferable as gains in total yearly energy costs. The study was based on the assumption of ideal control of zone temperature. Nowadays, more detailed investigation with “level II” system simulations is increasingly employed to assess the overall effects of COP improvements. They are usually based on software with standardized modules, like the DOE-2 [19]. However, fully transient simulations are also possible [21, 22]. As demonstrated in this paper, “level II” simulations enable realistic prediction of reduction in yearly heating and cooling energy costs for a typical residential building by improved building, HVAC and equipment design and how this is affected by equipment sizing, climatic conditions, operating schedule and specific control system implementation.

4. The Role of Building Automation Systems

The wide application of building automation systems allows for important energy savings in modern buildings. This can only be accomplished by well designed automatic or manual control system practices for the various building operations. As an example, Table 2 summarizes a number of characteristic control parameters for building subsystems that significantly affect energy consumption.

Three different levels of control can be discerned here:

- The first level is realized by suitable programming of the building automation system
- the second level can be realized by suitable education of the building safety/ cleaning personnel, while
- the third level is realized by the employees themselves, again by suitable education that develops an energy saving culture among them.

Table 2. Characteristic control parameters for certain building subsystems affecting yearly energy consumption

BUILDING AUTOMATION SYSTEM	SAFETY – CLEANING PERSONNEL	BUILDING PERSONNEL
Optimal tuning of HVAC system control parameters Optimal scheduling of equipment shut-off by means of BMS software or individual controllers - timers.	Switching off the lights Closing of doors – windows Switching off the heating or cooling of specific rooms Adjustment of the shading mechanisms	Shutting off of equipment and lights at exiting the room Keeping heating set point at 20 ^{o}C or lower in winter, cooling set point at 26 ^{o}C or higher in summer Use of shading mechanisms Performing the required air changes per hour without keeping the windows open all day long.

In practice, there is a tendency to transfer most of the second and third level of control to the building management system [23-25], which is becoming more and more sophisticated (Figure 1).

However, the real-world assessment of the performance of low energy buildings indicates that it is not an easy task to exploit the full capabilities of building management systems. For example, the results of a comparative assessment made in 5 low energy school buildings in England [26] indicate that, although heating energy consumption for these buildings was successfully reduced, electrical energy consumption was much greater than in the existing stock of schools.

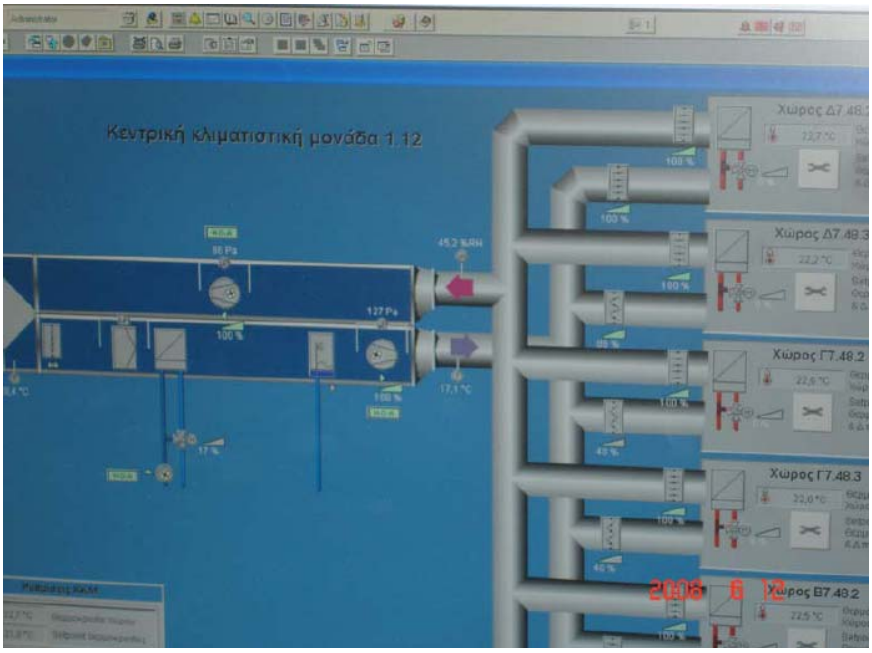

Figure 1. Building management system: monitoring of a central HVAC unit.

This could be due to increased use of computers and related activities in schools, as well as more stringent indoor air quality settings and a lack of building management training for “intelligent” buildings that resulted in not optimal control settings. In another comparative study with two library buildings in England and Sweden [27], both buildings have been reported to experience difficulties in getting some of their advanced building service systems to work as intended. However, it is also due to the haste with which buildings are usually handed over from the procurement teams, under pressure from the users, to the operators, which had not been directly involved in the commissioning and handover procedures. The role of the building manager in looking for further improvements in performance requires an increasing degree of expertise and knowledge. Monitoring of the transient performance of the building energy systems is a demanding process that requires good engineers to be involved. Moreover, a comparison of measured with predicted transient performance is valuable to the building design engineer, because it supplies useful feedback for future design improvements in subsequent design tasks. Also, the use of the building management system with respect to building performance diagnostics is a demanding task that requires significant engineering effort.

5. TRNSYS AS A BUILDING ENERGY SIMULATION SOFTWARE

TRNSYS is a transient systems simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components. TRNSYS components (referred to as "Types") may be as simple as a pump or pipe, or as complicated as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, and building input data is entered through a dedicated visual interface. In the simulation studio, the user specifies the components that constitute the system and the manner in which they are connected. The simulation engine solves then the resulting set of algebraic and differential equations. In addition to a detailed multizone building model, the TRNSYS library includes components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc. The modular nature of TRNSYS facilitates the addition of new mathematical models to the program. In addition to the ability to develop new components in any programming language, the program allows to directly embed components implemented using other software (e.g. Matlab/Simulink, Excel/VBA, and EES). The TRNSYS library, written in Fortran source code, includes many of the components commonly found in energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The software is well suited to detailed analyses of any system whose behaviour is dependent on the passage of time and has become reference software for researchers and engineers around the world. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells. TRNSYS is one of the listed simulation programs in the recent European Standards on solar thermal systems (ENV-12977-2). The level of detail of TRNSYS' building model, known as "Type 56", is compliant with the requirements of ANSI/ASHRAE Standard 140-2001. The level of detail of Type 56 also meets the general technical requirements of the European Directive on the Energy Performance of Buildings [4]. During the last two decades, TRNSYS is widely employed in building energy systems simulations [11, 12, 28-30]. There exist systematic studies comparing the performance of this software against experimental results, as well as comparing the results of TRNSYS to other industry standards for building energy simulation [15, 31].

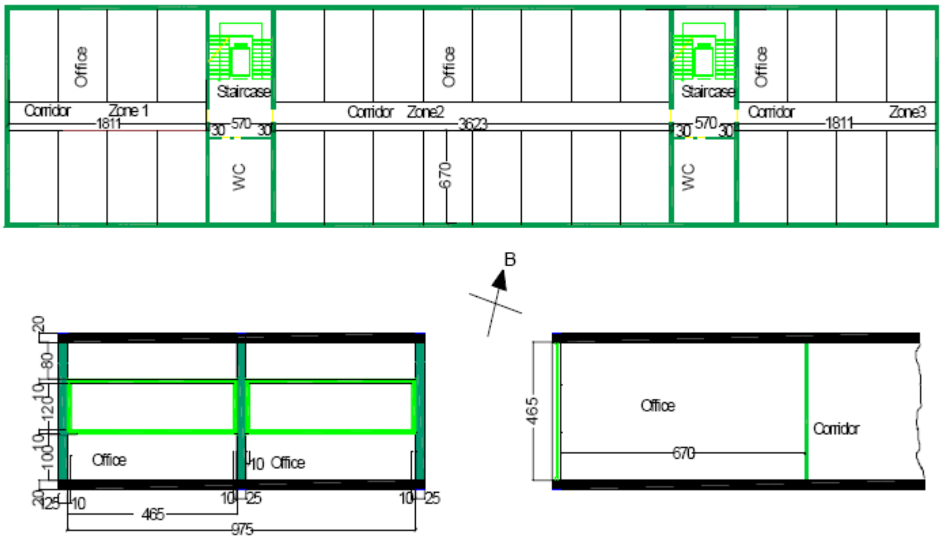

Figure 2. Typical plan and elevation of the office building employed in the simulations.

6. LEVEL I SIMULATION DETAILS FOR AN OFFICE BUILDING

TRNSYS 16 software was employed in the building energy simulation study to predict thermal performance and economic aspects of the reference building of Figure 2, which is located in Volos, Greece. It is an office building that covers a land area of 1340 m^2 and consists of a ground level and 4 higher levels, plus an underground parking. The building is elongated along an east-west axis. This leads to significant solar energy gains, that are favorable in winter, but unfavorable during summer. The southeastern part of the building is partially blocked by a neighboring building. Each level consists of 3 zones (For example, zones 5.1, 5.2 and 5.3 for the 4th floor are shown in Figure 2). Zones 5.1 and 5.3 of the 4th floor (along with the respective zones of the other levels), comprise 8 independent office rooms each, while zone 5.2 and the respective zones of the other levels (4.2, 3.2, 2.2 and 1.2) consist of 14 office rooms each. Each level includes 2 staircases and 2 groups of WC. The WC spaces of all building are grouped in a single zone (WC) and all staircases in another zone (SC). In addition, the underground parking is modeled as an additional zone. Thus, a total of 18 zones exist in the building. The basic diagram of building simulation in the TRNSYS environment is presented in Figure 3. The values of the basic building design and control parameters are presented in this section.

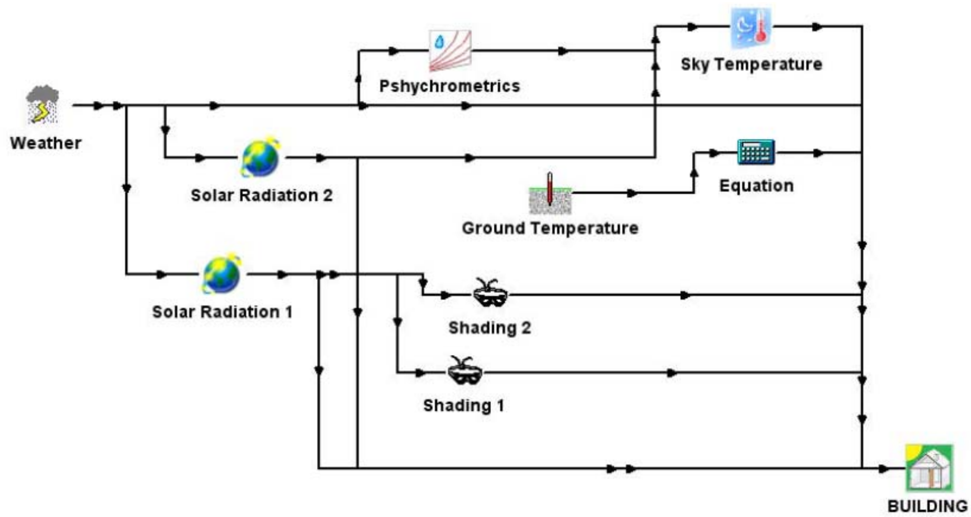

Figure 3. Basic diagram of building simulation in the TRNSYS environment.

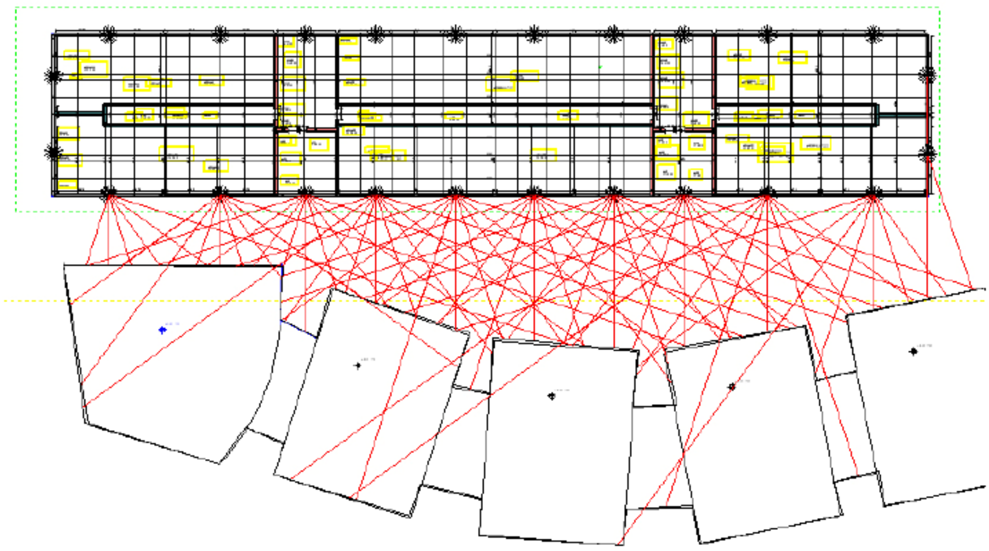

Figure 4. Calculation of shading by neighbouring buildings.

A. Building Geometry and Construction Materials

As regards the building envelope characteristics inserted in Type 56 building model, insulation values are inserted based on the Greek Standard under preparation (Table 2). These values cover the characteristics of all building envelope components, including the Roofs, Walls, Floors, Slabs, Doors, Vertical Glazing and Skylights. The basic building geometry was introduced by means of the SIMCAD 1.3 software [32]. This software is capable of incorporating input files from standard architectural drawing software like AutoCAD [33].

After the introduction of the basic building geometry, the building materials are input to SIMCAD, which performs the required pre-processing to produce the necessary input files for TRNSYS type 56 subroutine (multi-zone building), see Figure 3.

B. Shading by Neighboring Buildings

Shading by neighboring buildings is taken into account as shown in Figure 4. The calculations are carried out by a specialized TRNSYS module (Type 68).

C. Building Shell and Frame Characteristics

The main characteristics of the building shell and frame are summarized in Table 3. More details of European building shell material properties can be found in [34].

Table 3. Insulation data for the building envelope of the house under study

Building shell component	Total Thickness [m]	U-value [W/m^{2}K]	Layers	Layer thickness
Floor, parking space	0.25	2.944	Industrial floor	0.05
			Reinforced concrete B240	0.2
Floor, utility space	0.25	3.336	Marble	0.03
			Plaster	0.02
			Reinforced concrete B240	0.2
Floor, office space	0.223	2.399	Linoleum tiles	0.003
			Mosaic	0.02
			Reinforced concrete B240	0.2
Floor, WC	0.225	3.385	Ceramic tiles	0.005
			Plaster	0.02
			Reinforced concrete B240	0.2
Walls, outside building shell	0.28	0.559	Plaster	0.02
			Brick	0.09
			Polystyrol insulation	0.06
			Brick	0.09
			Plaster	0.02
Frame, outside beams	0.33	0.592	Plaster	0.25
			Reinforced concrete B240	0.06
			Polystyrol insulation	0.02
			Plaster	0.02

Table 3. (Continued)

Building shell component	Total Thickness [m]	U-value [W/m^{2}K]	Layers	Layer thickness
Walls, inside	0.074	0.620	Plasterboard	0.012
			Polyurethan foam	0.05
			Plasterboard	0.012
Deck	0.35	0.375	Plaster	0.02
			Reinforced concrete B240	0.2
			Polystyrol insulation	0.06
			Plaster	0.02
			Deck tiles	0.05
Frame, inside beams	0.27	3.167	Plaster	0.02
			Reinforced concrete B240	0.25
Frame, inside walls	0.22	3.434	Plaster	0.02
			Reinforced concrete B240	0.2
Doors, inside	0.05	1.808	Processed wood chips	0.05

D. Windows

Suggested values for window-to-wall ratio vary from 20-40% in [1]. In the specific building, this ratio is 39%, that is, ample window area is supplied, according to the usual practice for an office building.

A well established approach to heating and cooling energy saving is the application of advanced technology window glass with selective coatings. Because of its energy efficiency, daylighting, and comfort benefits, low-e coated glass is now used in more than 30% of all fenestration products installed in the United States and a similar trend is developing in Europe. There are two types of low-e coating: High-solar-gain coatings for cold climates, mainly reduce heat conduction through the glazing. Low-solar-gain coatings, for hot climates, reduce solar heat gain by blocking the admission of infrared solar radiation.

For the case of a mild climate like ours, there are two ways of achieving low solar- gain low-e performance: with a special multilayer solar infrared- reflecting coating, or with an outer glass that absorbs infrared solar radiation. Of course, in the second case, part of the absorbed heat would be emitted towards the inner glazing. Thus, we need to additionally install a protective low-ε coating also in this case.

A preliminary assessment of the effect of the use of such technologies is important in the techno-economic study preceding the selection of building shell materials. This process requires performing level I, hour-by-hour building simulation runs.

In the building studied here, the south - facing outside windows (6 mm panel thickness) may be coated with special solar protection coating in their internal face, while the internal window panes, with 4 mm thickness are uncoated (see Table 4). The modeling of thermal and optical performance of these windows is supported by the specialized software WINDOW 5.2 [35], which includes an extensive database from a variety of windows manufacturers.

Table 4. Characteristics of typical window panels studied for the building

Manufacturer /Type	Panel thickness (mm)	τ_{sol}	R_{sol1}	R_{sol2}	τ_{vis1}	R_{vis1}	R_{vis2}	τ_{ir}	ε_1	ε_2	λ
Pilkington / Solar E	6	0.456	0.074	0.113	0.607	0.074	0.097	0.00	0.840	0.161	1.0
Manufacturer /Type	Panel thickness (mm)	τ_{sol}	R_{sol1}	R_{sol2}	τ_{vis1}	R_{vis1}	R_{vis2}	τ_{ir}	ε_1	ε_2	λ
Pilkington / Optifloat Clear	6	0.774	0.072	0.072	0.883	0.081	0.081	0.00	0.840	0.840	1.0
Pilkington / Ever Green	6	0.338	0.051	0.051	0.667	0.064	0.064	0.00	0.840	0.840	1.0
Pilkington / Energy Advantage Low-E	6	0.662	0.113	0.100	0.819	0.108	0.102	0.00	0.157	0.840	1.0
Clear_3.dat	3	0.834	0.075	0.075	0.899	0.083	0.083	0.00	0.840	0.084	1.0

Explanations to Table 4:
$\tau_{sol:}$ Solar transmissivity of the glazing layer
R_{sol1}/ R_{sol2} :Solar reflectivity of the glazing layer, exterior-facing side/ interior-facing side
$\tau_{vis:}$ Visible transmittance of the glazing layer
R_{vis1}/ R_{vis2} Visible spectrum reflectance of the glazing layer, exterior-facing side/ interior-facing side
$\tau_{i:}$ Thermal infrared (longwave) transmissivity of the glazing layer.
ε_1/ ε_2 : Infrared (longwave) emissivity of the glazing layer, exterior-facing side/ interior-facing side
λ: Thermal Conductivity of glass (W/m-K).

Table 5 summarizes the main window heat transmission characteristics due to conduction, convection and radiation, including the aluminium frame.

Table 5. Characteristics of alternative window types examined here (including frame)

Window type		U* (W/m^{2}K)	U** (W/m^{2}K)	g-value	τ_{sol}	$R_{f\text{-}sol}$	τ_{vis}
Pilkington Solar Control	SOLARE6.LOF 12 mm air CLEAR4.LOF	1.893	3.490	0.461	0.365	0.091	0.452
Pilkington Low-e Glass	EVGRN6.LOF 12 mm air LOW-E_6.LOF	1.887	3.486	0.369	0.246	0.071	0.460
Common double window/ 6 mm air gap	CLEAR_3.DAT 6 mm Air CLEAR_3.DAT	3.167	4.460	0.713	0.703	0.128	0.681

Explanations to Table 5:
U*: heat transmission coefficient – window panel area
U**: heat transmission coefficient – including frame
g: solar gain factor at 0^o incidence angle
$R_{f\text{-}sol}$: reflectivity at 0^o incidence angle, solar radiation spectrum
τ_{sol}: transmissivity at 0^o incidence angle, solar radiation spectrum
τ_{vis}: transmissivity at 0^o incidence angle, visible solar radiation spectrum

The use of high-performance and selective low-ε glazing reduces the visual light transmission (VLT) proportionately less than do reflective coatings or tints. Dividing the VLT by the solar heat gain coefficient (SHGC) is a good rating of the performance of the glass. If the result is less than 1.0, then the glass is a poor choice for visual quality and daylighting. If the result is higher than 1.55, it is a high-performance option [1].

E. Building Schedules

The following building operation schedule was assumed: Daily schedule 07:30 – 19:30 (Monday to Friday) and 09:00 - 14:30 (Saturday). Table 6 presents the heating and cooling control system set points in the office spaces during the winter and summer period. It should be noted here that this is the level I simulation stage which pertains to the preliminary study of the building. At the specific simulation level, the ideal assumption is made that the HVAC system is capable of supplying the required heating or cooling power for meeting the instantaneous loads with perfect control (without dead bands or hysteresis effects). A more detailed study of HVAC system performance will only become capable with a level II simulation at a later stage, which pertains to the main study.

Table 6. Space heating and cooling set points

Space	Temperature set point		Relative humidity set point		Ventilation
	Heating	Cooling	Heating	Cooling	Air changes per hour
HVAC operation only during working hours – see building operation schedule					
Parking	-	-	-	-	1*
Zones 1 to 15 (offices)	21 °C	26 °C	20%-30%	50%-60%	1, 2 ACH or 2.5 l/s per person
Staircases	20 °C	26 °C	-	-	1*
WC	20 °C	26 °C	-	-	1*

F. Lighting

Energy consumption for lighting is estimated at 17 W/m^2 for office spaces and at 5 W/m^2 for service spaces (staircases, WC, parking spaces). The building uses daylighting combined with daylight sensors that could automatically adjust when artificial lighting is not needed. Fluorescent lights supplement the natural lighting. As another option, lighting controls could be ordinary switches controlled by occupancy sensors in areas with intermittent use.

G. Office Equipment

Each office room is equipped with 2 pc's and 1 printer, operating depending on the number of occupants existing in the room. The number of occupants at each hour of the day is calculated based on the building operation schedule and averages 1 - 2 persons per room.

H. Climatic Conditions

Climatic data in the form of a Typical Meteorological Year (TMY) for the city of Volos are employed. The TMY is a basic input file for the TRNSYS and other dynamic building simulation software. The TMY employed in this study is approximated based on the monthly data available for the city of Volos by the National Meteorological Agency, for the period 1956-1988, as well as the period 1996-2006 (Figure 5). Hourly values of the following data for the full TMY (8760 hours) are employed in the simulation: Dry Bulb temperature, Relative Humidity, wind direction and speed, total and direct solar horizontal radiation.

I. Ventilation Strategy

As regards ventilation, 1 Air Changes per Hour (ACH) are assumed, a figure which surpasses the requirements of ASHRAE 62.2-2004 [36]. Internal heat gains are taken according to ASHRAE [37]. Ventilation is only applied during the working hours prescribed in the building operation schedule. An option with night ventilation will be examined in a subsequent section.

J. Sizing Of Heating – Cooling Equipment

Initial sizing of heating equipment was done according to DIN 4701[38]. Maximum heating power was set to 308 kW.

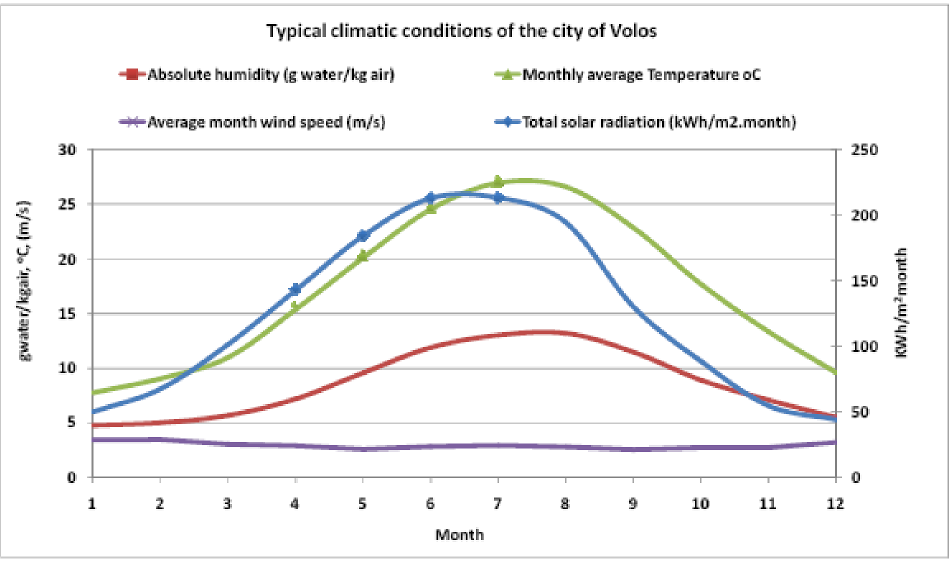

Figure 5. Basic climatic data for the city of Volos.

7. RESULTS OF PARAMETRIC STUDY – LEVEL I SIMULATION

The specific level I simulation study, based on the modeling details described above, is aimed at the assessment, at a preliminary study level, of the effects of the variation of the following building design and control parameters on the yearly heating and cooling energy requirements:

- Windows' area
- Windows' insulation properties and technology
- Ventilation strategy
- Building shell insulation strategy
- Building heat capacity

Typical transient results for the reference building design are presented in Figure 6 (heating season, the week – 168 hours duration - with the lowest ambient temperature levels) and Figure 7 (cooling season, the week with the highest ambient temperature levels).

This part of the study takes into account the basic design parameters of the preliminary design stage. The available data at this stage do not include details on the specific HVAC equipment to be employed. These details are going to be studied in the frame of a level II simulation, presented at a subsequent section of this paper, that will take into account the type of equipment employed, efficiency characteristics of individual components (boilers, chillers, pumps, fans, fan coils etc) and control system operation details. To assist a better understanding of the simulation runs, Table 7 summarizes the range of variation of the main parameters studied by means of the level I simulation runs.

Table 7. Range of variation of various parameters in the specific parametric study

Parameter	Reference value	Range of examined values	Results
Window area	Window height 1.2m	Window height 2.4 m	Figures 10,11
Windows – selective coatings	Window height 1.2m, K=4.5 W/m^2K	W|indow height 1.2m, K=3.5 W/m^2-K	Figures 12,13
Ventilation strategy	1 air change per hour	1-2 air changes per hour, or 2.5 l/s per person	Figures 14,15
Night ventilation	No	Night ventilation, 4 air changes per hour, whenever $\Delta T>5^oC$.	Figures 16,17,18
Insulation	Insulation thickness 6 cm	Insulation thickness 12cm	Figures 21,22
Building heat capacity	Reference values of a lightweight construction	Up to double of the reference value (heavyweight construction)	Figures 23,24,25

In this section, typical results are presented and briefly discussed, to demonstrate the role of energy simulation in the preliminary design phase. For the sake of a wider usefulness of the results, yearly heating and cooling loads are expressed normalized per m^2 of heated or cooled space. To this end, total heating and cooling energy consumption is divided by the total zone area, excluding the parking space which is only ventilated, but neither heated nor cooled.

We have started with the presentation of the variation of the temperatures of typical zones during the coldest week of winter (Figure 6). The week starts with Monday and ends up with the weekend. During the working days' schedule, the heating control (assumed ideal in this level I simulation), keeps indoor temperatures fixed at 21^{o}C in all zones. During the night, as well as during the weekend, indoor temperatures are left to drift to low values because the heating is off. Ambient temperatures reach a -5^{o}C low at Thursday and Friday evening. However, indoor temperatures do not below 14^{o}C, even in the zones of the ground level, which receive reduced solar radiation due to the blocking by the neighboring building.

Next we present the variation of the temperatures of typical zones during the hottest week of summer (Figure 7), with a maximum outdoor temperature of 45^{o}C on Monday at noon. Again, the cooling control system, considered ideal, keeps indoor temperatures fixed at 26^{o}C during the working hours (including Saturday morning). During the rest of the day and the weekend, indoor temperatures are climbing to high values, especially at the 4th floor, which bears the solar load of the roof. An indoor temperature high of 31^{o}C is predicted for Sunday at noon, when the air conditioning is off.

Further to the computation of zone temperatures, it is very useful to study the transient variation of heating loads during the same winter week. This can be seen in Figure 8. According to this figure, the peak heating load calculated by means of the specific level I building energy simulation reach the value of 317 kW on Tuesday morning. Apparently, the combination of sudden outdoor temperature drop to -4^{o}C and a reduced solar gain, lead to the maximization of the total building heating load. Two additional peaks of the same level of about 300 kW are predicted during the same week. The first on Monday morning, due to the high transient thermal load required for heating up the building that has cooled off during the weekend and the second one on Friday morning, with outdoor temperatures below zero.

The study of transient heating load predictions is necessary as a first approximation of the heating equipment size. In the specific case, our first guess would be a boiler of 300 kW nominal heating power. However, during this preliminary design phase, one would study the predicted building performance during the rest of the winter and see how many incidences of heating loads higher than 300 kW exist. If there exist very few (as is the case here), an effort should be taken towards reducing these peaks by design changes. Also, a calculation of the total number of hours requiring, say, more than 250 kW would be very helpful in the process of preliminary sizing of the boiler. Of course, a better sizing will be made with the aid of the level II simulation, as will be presented in a subsequent section.

In an analogous manner, the variation of cooling load during the high temperatures' summer week shown in Figure 9, may help the designer in the preliminary sizing of the cooling equipment. The maximum cooling load reaches 460 kW, on Monday at noon, with outdoor temperature exceeding 45^{o}C. At a first glance, this would mean that the specific building, in the specific climate, is more demanding in cooling than in heating. This is not exactly the case, as will be obvious by a closer look at Figure 9, as well as at the results of the rest of June and August. The predicted peak cooling load occurs during only one day of the summer. During the rest of the summer, the cooling load is less than about 360 kW. According to the specific Typical Meteorological Year, the highest temperature that produced the extreme cooling load is observed at about the 20th of June. However, the probability is higher for these temperature levels to occur inside the typical vacation period of mid-July to mid-August. The usual practice in such cases would be to install a chiller of lower capacity (less than 300 kW) and try to manage the cooling load demand during peak temperatures in a more economical way – that is, minimize the percentage of outdoor air, shut off air conditioning in unoccupied spaces etc. The effect of such measures will be better understood with the level II simulations that follow in a subsequent section.

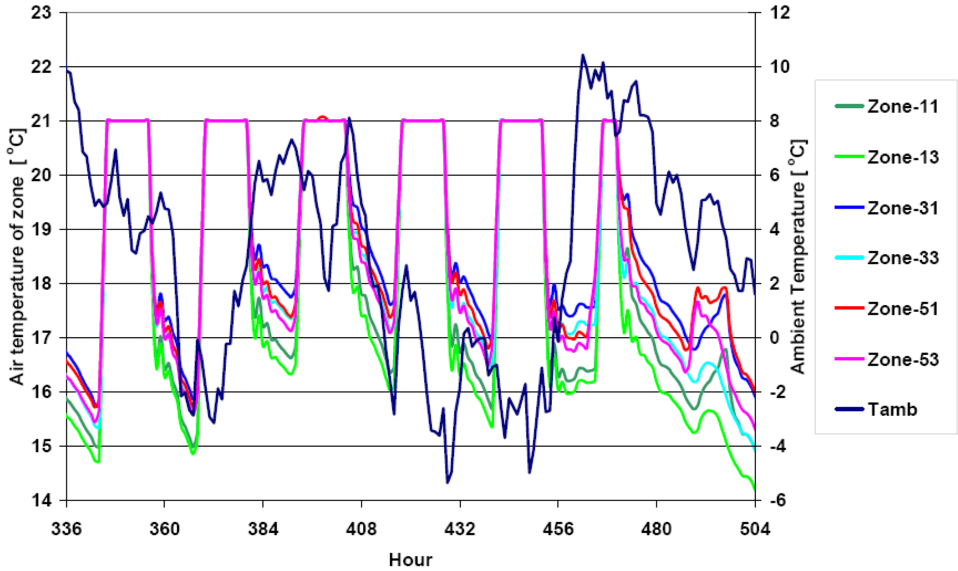

Figure 6. Simulation of typical winter operation (1 week, hours 336-504) zone temperatures for typical zones belonging to the ground, 2nd and 4th floor.

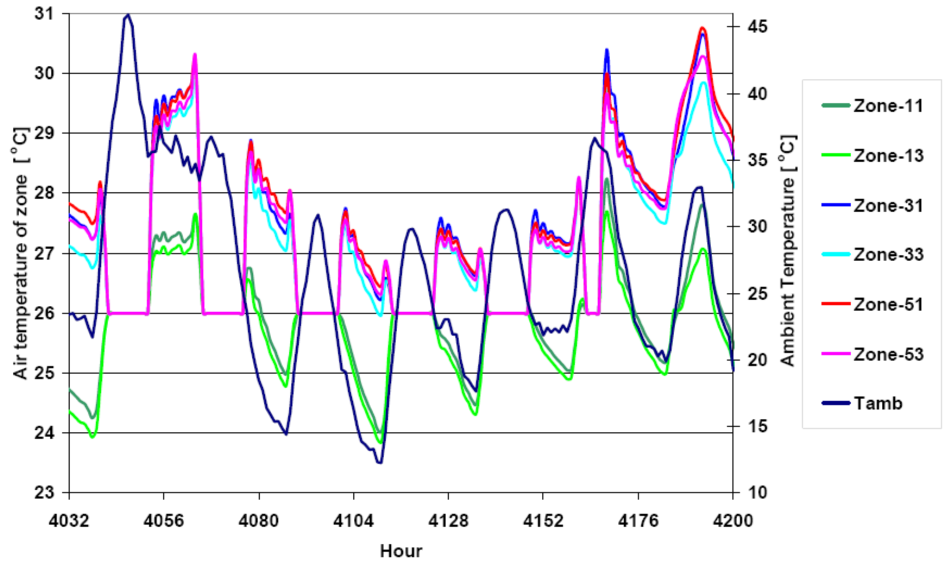

Figure 7. Simulation of typical summer operation (1 week, hours 4032-4200), temperatures for typical zones belonging to the ground, 2nd and 4th floor.

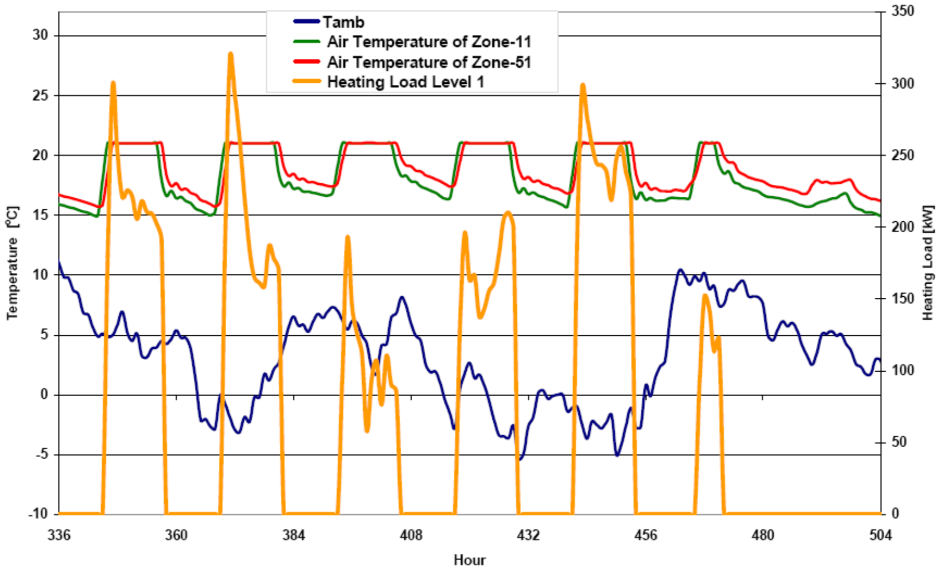

Figure 8. Instantaneous building heating load variation during the worst winter week.

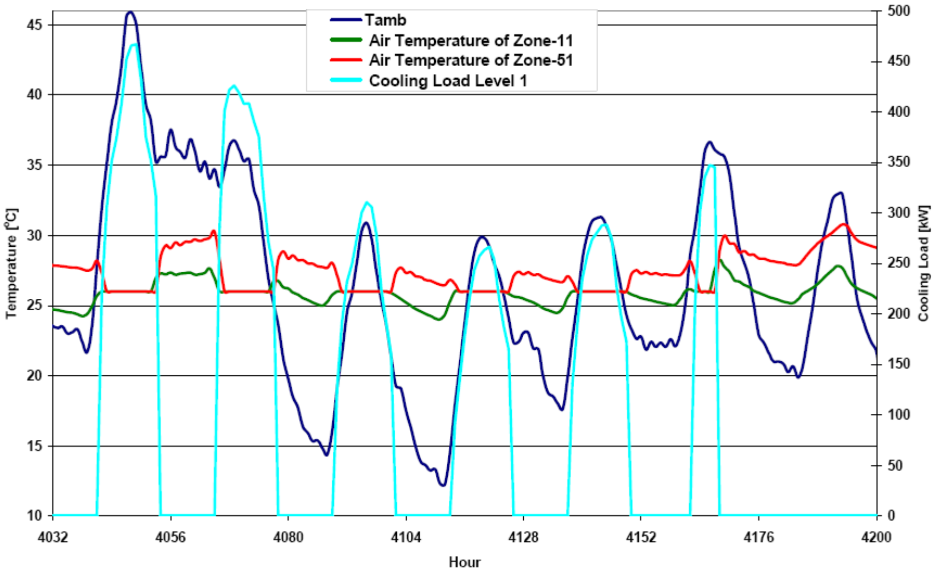

Figure 9. Instantaneous building cooling load variation during the worst summer week.

A. Effect of Window Area, Insulation and Radiation Exchange Details

Next we study the effect of increasing window area in the building studied. Due to the specific design concept, only an increase in window height can be envisaged. A simulation is performed with an increase of the standard window height of 1.2 m of the reference building design to 2.4 m. The width of the windows is assumed to remain constant in both alternative cases. According to the results of the simulation runs, the increase of total window area with standard window technology is predicted to significantly increase the yearly cooling loads, (Figure 10) with a parallel increase of the yearly heating loads (Figure 11).

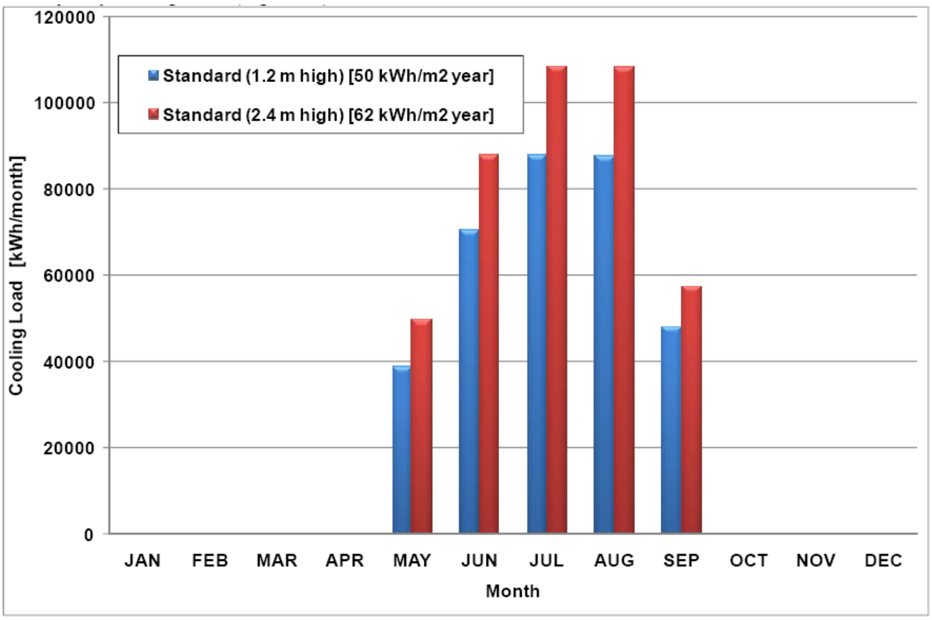

Figure 10. Effect of Window area on the annual cooling energy consumption.

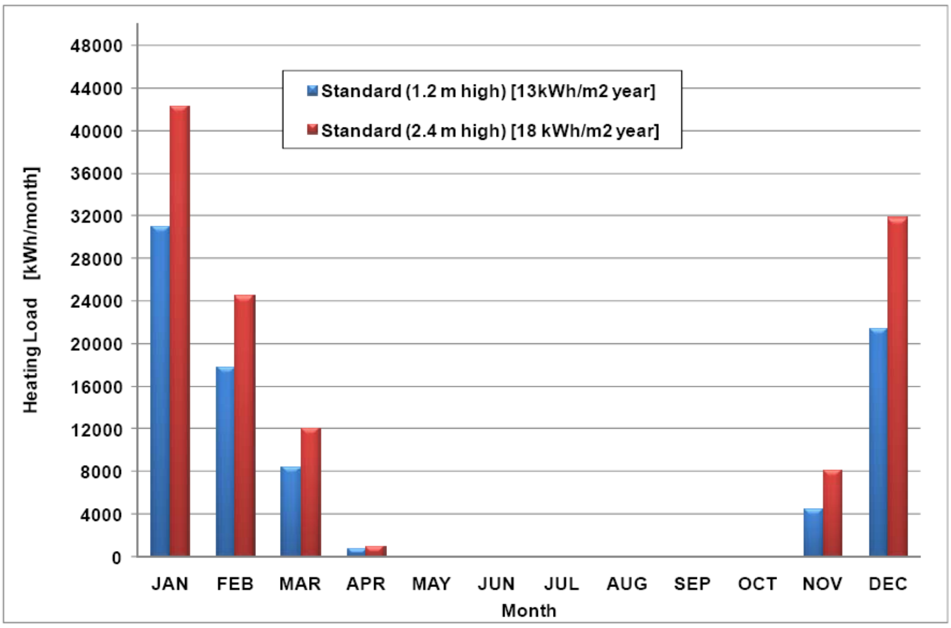

Figure 11. Effect of window area on the annual heating energy consumption.

The estimated increase in the annual heating energy consumption is 43%, whereas the respective increase in the annual cooling energy consumption is only 24%. The increase of window area is expected to increase solar heat gains, especially during the winter. However, the lower insulation capacity of the windows compared to that of the well insulated walls is proven to have a more important effect and lead to an overall significant increase in heating loads. As regards summer operation, to improve summer operation with the bigger windows of standard technology, it will be necessary to introduce overhangs or shading mechanisms. The position and size of these mechanisms is going to be studied by means of further hour-by-hour simulation runs. On the other hand, in addition to thermal behavior, the position and size of the windows, along with the performance of the shading mechanisms, affects the levels of natural daylighting. This should be additionally studied by specialized photo-technical calculations [39].

However, the above-mentioned results are based on the use of standard technology windows. During the last decade, significant developments in window technology have led to the introduction of advanced windows in the market. The assessment can be extended to the effects of the use of such advanced technology windows.

Figure 12 presents the results of a simulation of the same building using the low-ε windows of Table 5, in place of the standard double windows of Table 4. As expected, an important reduction to the annual cooling energy consumption is predicted with the low-ε and solar control - coated windows. It must be mentioned that the simulation takes into account the complex radiation exchange phenomena through the window panels, that is, the differences in reflected, transmitted, absorbed and emitted radiation in the different wavelength bands, stemming from the differences in the related properties of Tables 4 and 5. The solar control panels are predicted to be more beneficial in winter, (they have a higher solar gain factor), whereas the low-ε panels are expected to attain the lowest cooling energy consumption in summer.

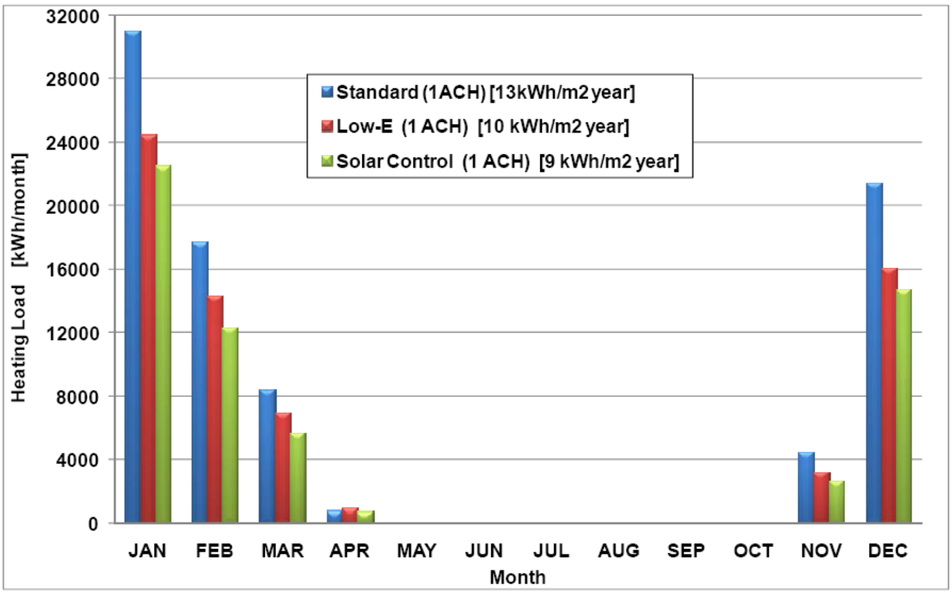

Figure 12. Effects of window technology on the yearly heating energy consumption.

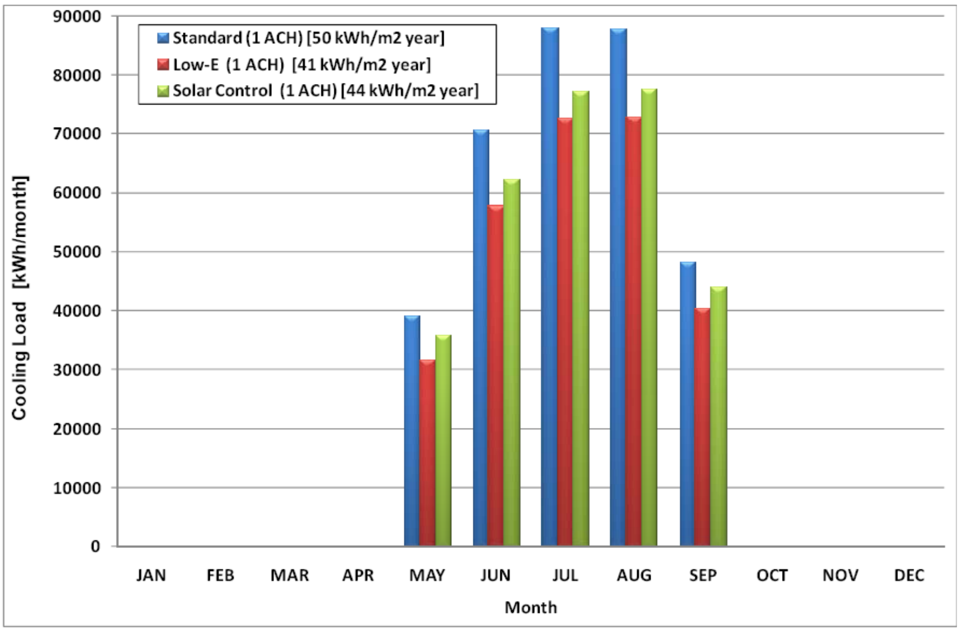

Figure 13. Effect of window technology on the yearly cooling energy consumption.

The standard double pane windows are characterized by a higher overall heat transmission coefficient (4.5 W/m^2K instead of 3.5 W/m^2K of the advanced technology windows of Table 5), but also they present no selectivity to the radiation wavelength – that is, their emissivity is nearly constant both for the maximum solar radiation wavelength and the infrared. The evaluation of advanced window technologies requires the use of advanced dynamic simulation software like TRNSYS that can process the radiation exchange property data of Tables 4 and 5.

B. Effect of Ventilation Strategy

Space ventilation aims at offering the building occupants, on the one hand comfort conditions and on the other hand to minimize the cumulative health effects from bad indoor air quality.

Continuing efforts to replace existing European standards at National level by a commonly accepted European Standard have not succeeded so far, because it came out that the estimation of the required outdoor air quantities in the various categories of indoor spaces differs significantly from country to country, especially between the European North and South [40]. An important reason for this lies in the high energy cost of ventilation in Northern climatic conditions. Of course, each building, apart from the mechanical ventilation, can rely on the natural infiltration through its windows and doors. In the specific simulations, standard air leak properties of windows and doors have been assumed to calculate infiltration.

As regards the mechanical ventilation requirements, with the introduction of outdoor air in the HVAC system, three alternative ventilation strategies have been examined at this stage, corresponding to 1 and 2 air changes per hour or 2.5 l/s per occupant in all main spaces (offices – zones 1 to 15). The remaining 3 service zones (staircases, WC and underground parking space), keep a constant ventilation rate of 1 ACH (Table 6). In the simulations, it is assumed that external air with the outdoor temperature and humidity conditions is entering the mechanical ventilation (that is, no ground or other heat exchangers are employed for pre-conditioning of the air, as is usual in the Northern climates).

The reduced ventilation rates of 2.5 l/s per person are more representative of reality in Greece, where mechanical ventilation is rare. Especially the specific site in Volos, with its proximity to the harbor and the Pagasitikos Gulf, has a temperate climate with outdoor temperatures that rarely exceed 35°C. Thus, the building is contemplated to feature operable windows and natural ventilation, which is further encouraged because of the shallow floor plates that place occupants close to windows.

According to the monthly results of Figure 14 and Figure 15, the increase of external ventilation rates affects quite significantly the heating and cooling energy consumption. Based on the reference case of 1 ACH , an increase of about 100 % and a decrease of 53% is predicted respectively for the 2 ACH and the 2.5 l/s per person cases, respectively, in the annual heating energy loads.

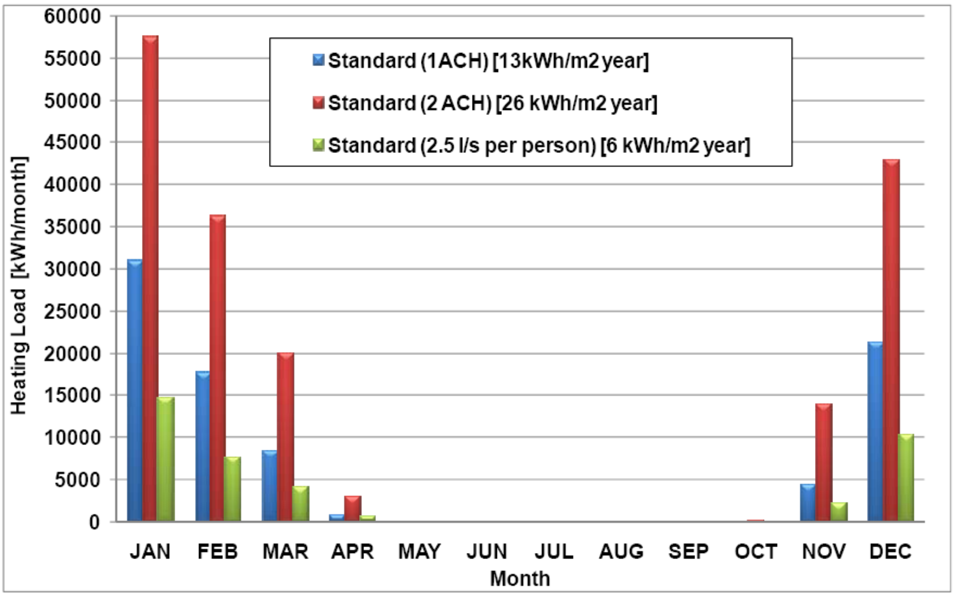

Figure 14. Effect of the external ventilation air quantity on the yearly heating energy consumption.

Apparently, the building is adequately insulated and the introduction of big quantities of outdoor air significantly affects heating energy consumption. On the other hand, during the cooling season, the percentage increase of the annual cooling energy loads with increased outdoor air ventilation is not significant. This is attributed to the lower average difference between indoor – outdoor temperatures during the summer, which is due to the mild climate of the place.

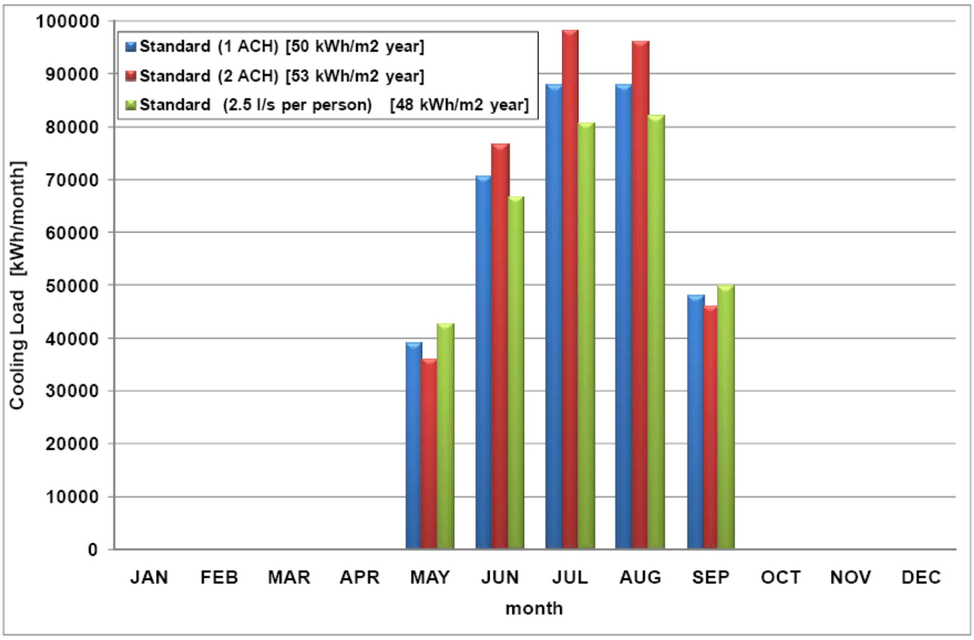

Figure 15. Effect of the external ventilation air quantity on the yearly cooling energy consumption.

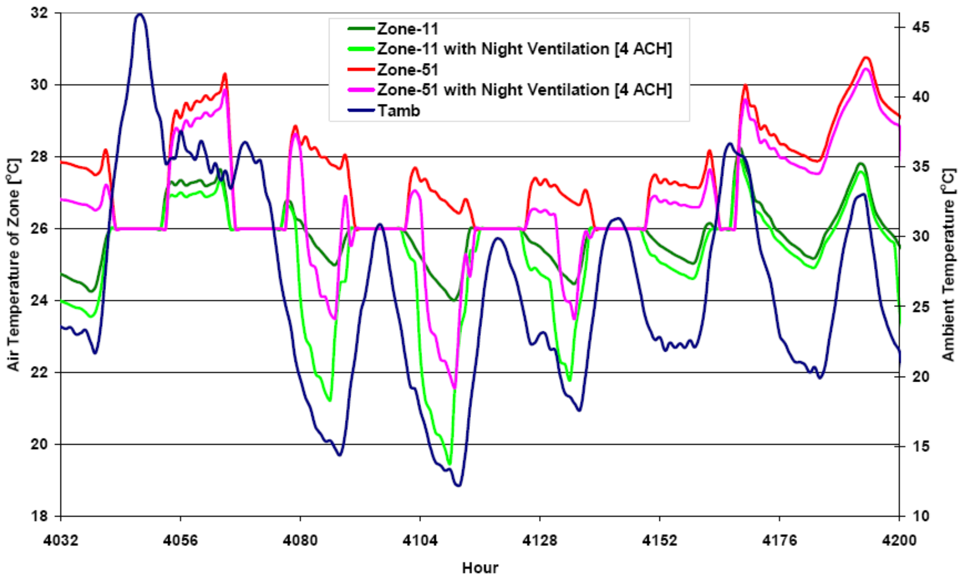

Figure 16. Effect of night ventilation for the worst summer week (ground floor vs 4th floor).

C. Effect of Night Ventilation

The night ventilation is a well established measure for the reduction of cooling energy consumption during summer. It consists of circulating outdoor air in the building during the night, where the outdoor temperature is significantly lower than the indoor temperature. In order to demonstrate the effect of night ventilation in our building, the following strategy and schedule is applied: During summer nights, outdoor air is circulated in the building at a rate of 4 ACH, whenever the indoor - outdoor temperature difference higher than 5°C or (see Table 7). The transient effect of night ventilation during the worst week of summer, for different zones of the building, is presented in Figure 16 and Figure 17. In some days, a significant gain is observed compared to the reference case. The overall improvement in cooling loads is presented in Figure 18. The gains are not so remarkable because of the specific climate of the site that is near the sea and the daily temperature variation is not high as in the continental climates.

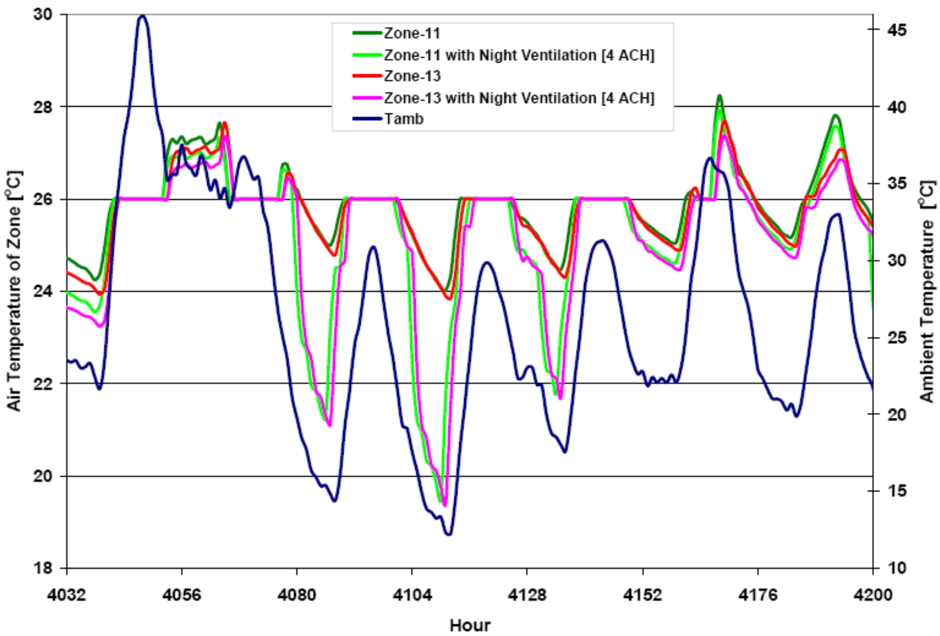

Figure 17. Effect of night ventilation for the worst summer week (2 zones of the ground floor).

D. Effect of Building Shell Insulation Characteristics

The insulation material employed in the specific building (external walls, roof and floor above the underground parking), consists of wrought polystyrol panels of 6 cm thickness. The effect of doubling the average shell insulation thickness from the reference value of 6cm to 12cm is also studied. It is worthwhile to mention here that in Northern Europe, shell insulation thickness values of 30-40 cm are not uncommon [41]. In order to better demonstrate the effect of increasing insulation thickness in the transient thermal behavior of the building, Figure 19 presents the variation of zone temperatures in 3 zones belonging to the ground, 2^{nd} and 4^{th} floor, respectively, along with the outdoor temperature variation during one very cold week of winter, for 6cm and 12 cm insulation thickness. If we examine the variation of the relative parameters in this figure for zone 3.1, it can be concluded that zone temperature, when the heating system is off, drops significantly lower in the reference building than in the building with the 12 cm insulation thickness.

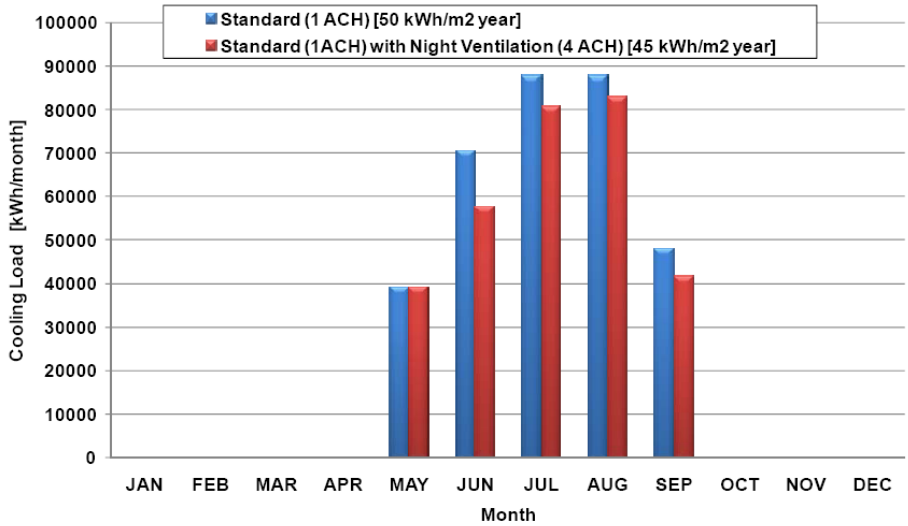

Figure 18. Effect of night ventilation (total cooling load during summer).

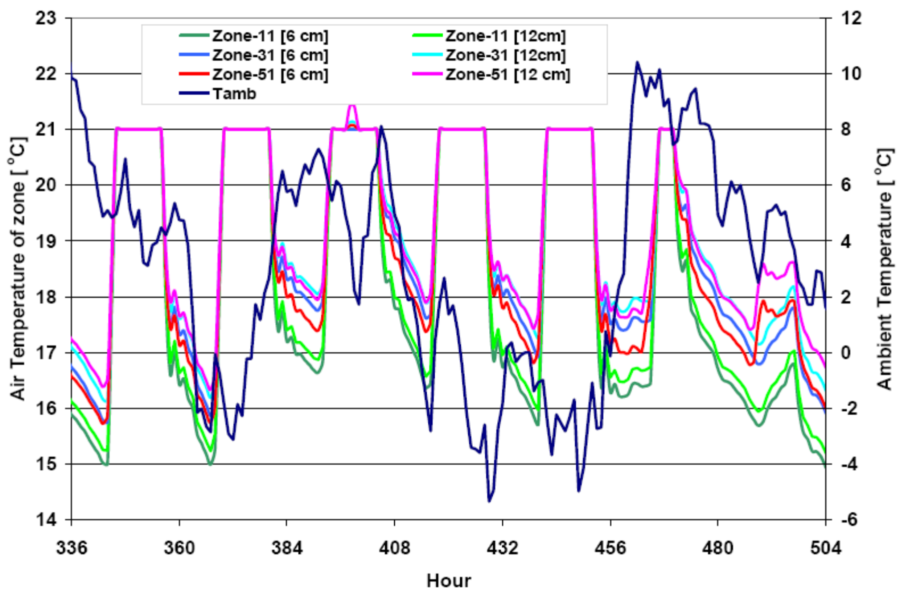

Figure 19. Variation of zone temperatures in 3 zones belonging to the ground, 2nd and 4th floor, respectively, during one week of winter, for different values of insulation thickness.

This fact significantly affects the maximum instantaneous heating load, and the required heating equipment size respectively. The same is true for the instantaneous cooling load variation during summer (Figure 20). If we extend our inspection to the transient system performance during the 8760 hours of the year, it can be seen that the maximum instantaneous heating load is 295 kW with 12cm insulation, instead of 317 kW with 6 cm insulation. That is, the required nominal heating load drops by 22%. On the other hand, the monthly and annual heating energy consumption of the building is presented in Figure 21. If we extend our inspection to the summer operation of the building, we can see that the required maximum cooling load is not affected by the 12cm insulation (Figure 22). This is attributed to the fact that the specific peak in cooling load, already discussed in the context of Figure 9, is not significantly affected by insulation. Overall, a small reduction in cooling loads is also observed. Thus, an additional advantage of better shell insulation stems from the reduction in the heating and cooling equipment size, which reduces the building construction and operation cost.

E. Effect of Building Heat Capacity

Building heat capacity can be significantly increased by use of the so-called, mass walls, that is, walls with heat capacity exceeding 7 Btu/ft^2·°F. This type of walls, with insulation placed on the outside of the masonry wall, pose the greatest advantages in energy performance, because the mass absorbs internal heat gains that are later released in the evenings when the building is not occupied. Mass walls could be combined with thicker slabs etc. This type of heavy building construction can be profitably combined with the application of night ventilation techniques discussed above.

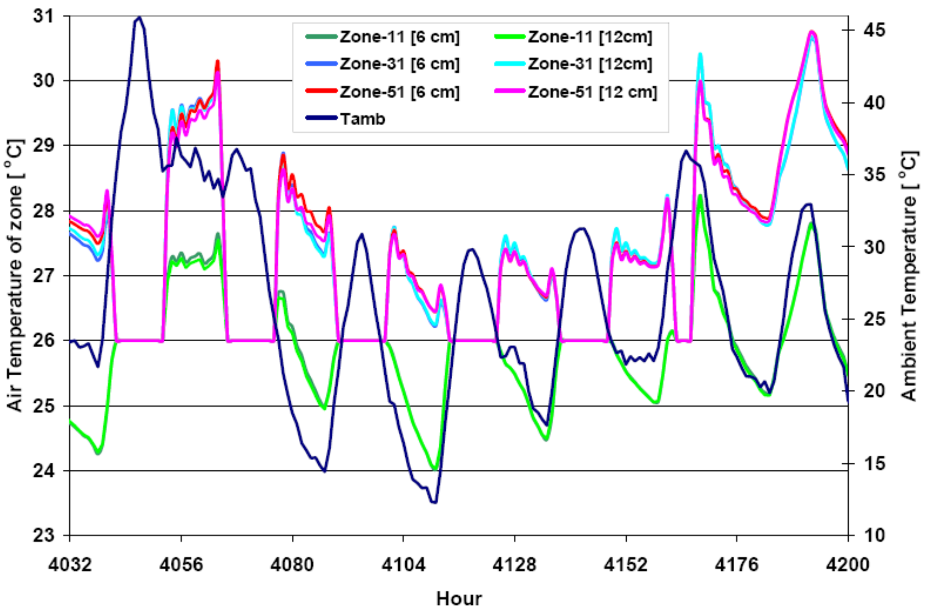

Figure 20. Variation of zone temperatures in 3 zones belonging to the ground, 2nd and 4th floor, respectively, during one week of summer, for different values of insulation thickness.

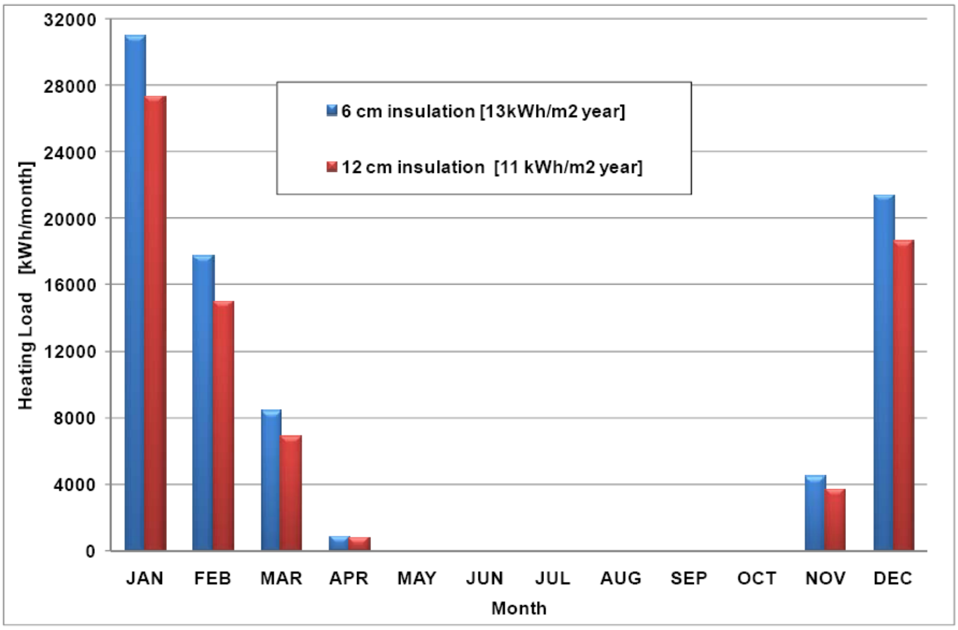

Figure 21. Effect of insulation thickness on the annual heating energy consumption (winter months).

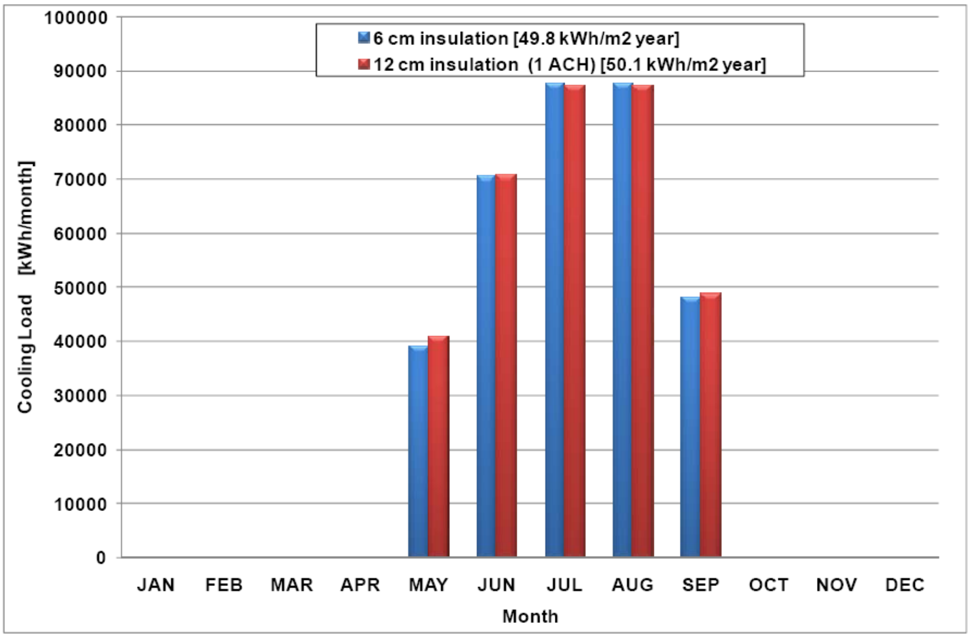

Figure 22. Effect of insulation thickness on the annual cooling energy consumption - summer months.

In order to study the effect of the heat capacity of the building materials (heavyweight –vs- lightweight construction) on the annual energy consumption, a comparative run is made, with a building of the same geometry, but with a heavier construction which results in a doubling of the total heat capacity of the building walls and frame.

According to the results of Figure 23, where the variation of characteristic operation parameters of the heating systems in 3 zones belonging to the ground, 2nd and 4th floor, respectively, during a cold week of winter, for a lightweight and a heavyweight building construction are presented, a significant reduction is observed to the maximum instantaneous heating load with the heavyweight construction.

The same behavior is observed in Figure 24 with the variation of the cooling loads during a hot summer week. Again, the maximum cooling load is reduced with the heavyweight construction. As a consequence of the above-described effect, the required maximum heating load is reduced by 23%, and the required maximum cooling load is reduced by 7%. Thus, the heavyweight construction results to a reduced heating and cooling equipment sizing, which reduces by its turn the investment cost for boiler, chiller, fan coils, air ducts etc, thus allowing system operation closer to nominal, reduced maintenance costs.

As regards the operation costs, according to the total annual results presented in Figure 26, the annual heating energy consumption is estimated to be reduced by 8%, while the annual cooling energy consumption is reduced by 2%. Based on practical experience [42], one could assume that the model underestimates the effect of building heat capacity on the thermal behavior. Research is on-going to further improve modeling performance in this direction.

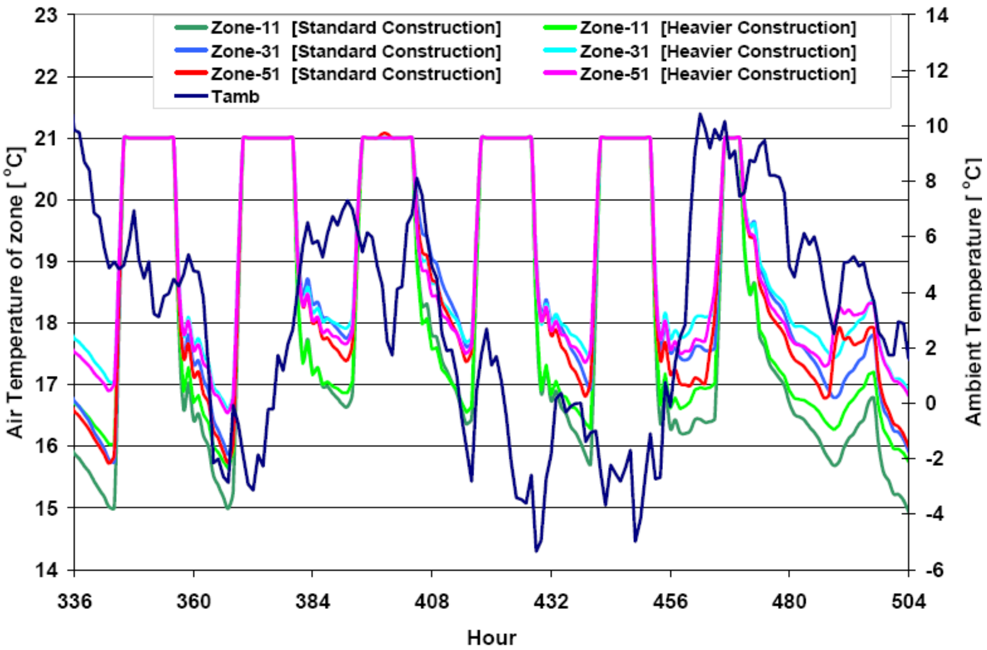

Figure 23. Variation of characteristic operation parameters of the heating system in 3 zones belonging to the ground, 2nd and 4th floor, respectively, during a cold week of winter, for a lightweight and a heavyweight building construction.

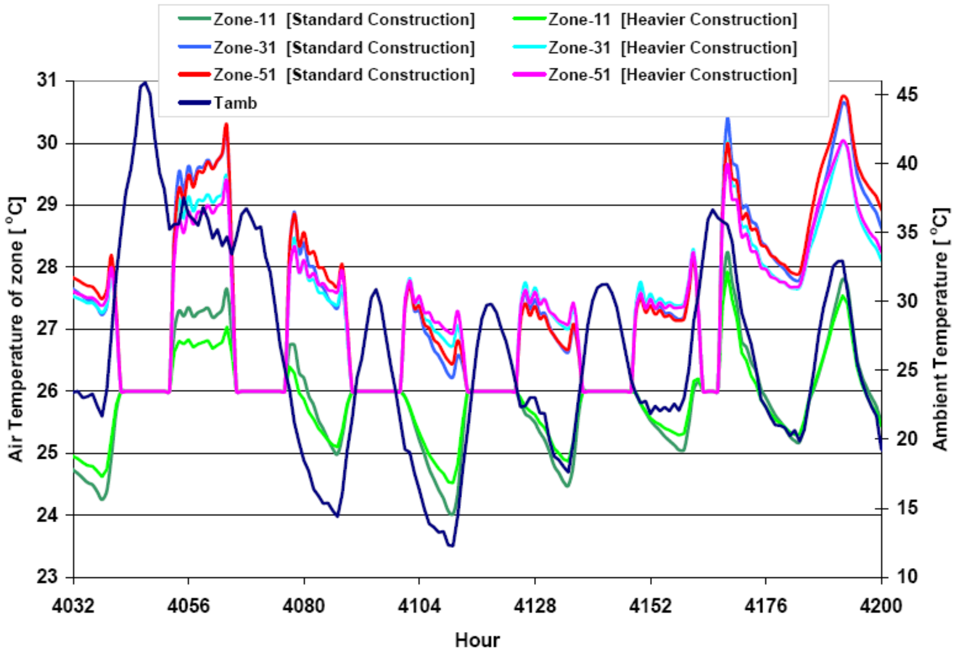

Figure 24. Variation of characteristic operation parameters of the heating systems in 3 zones belonging to the ground, 2nd and 4th floor, respectively, during a hot week of summer, for a lightweight and a heavyweight building construction.

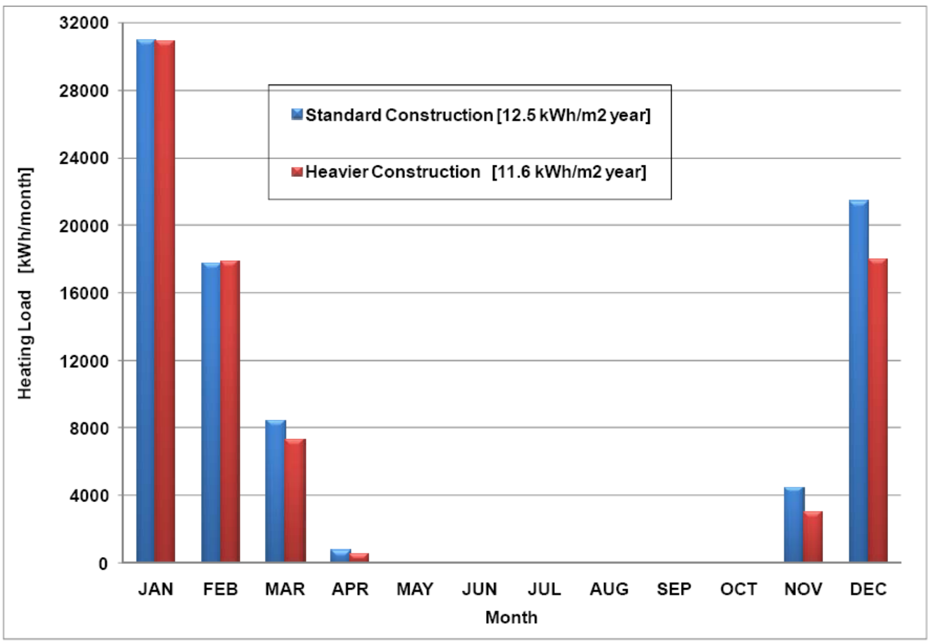

Figure 25. Effect of building heat capacity on the annual heating energy consumption of the reference building.

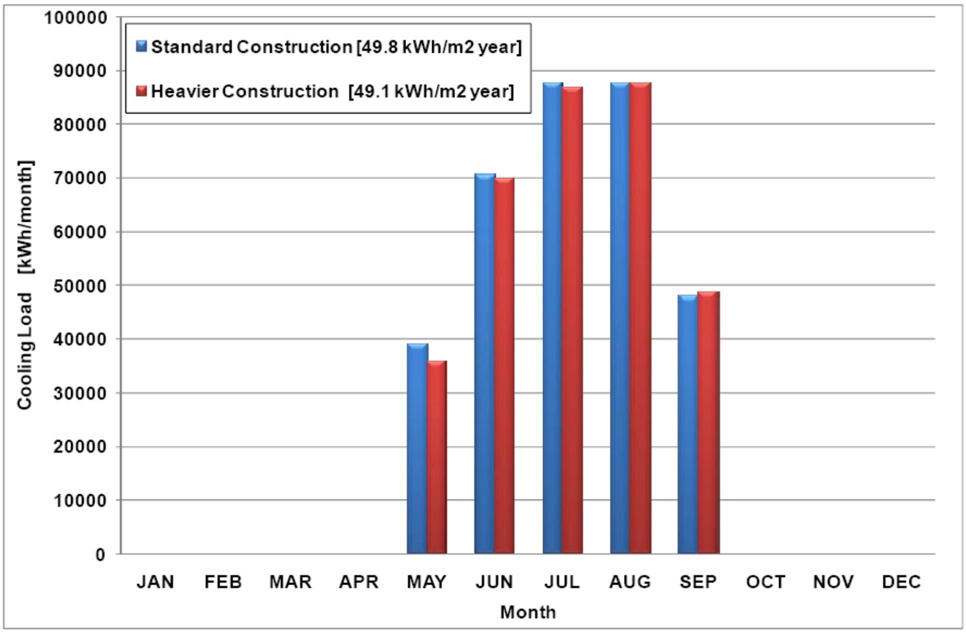

Figure 26. Effect of building heat capacity on the annual cooling energy consumption of the reference building.

8. LEVEL II SIMULATION DETAILS

In this section, the computational study for the reference office building of Figure 2 will be extended to level II detailed HVAC system modeling. To this end a HVAC system equipped with fan coils and a chiller/boiler 2-pipe system, along with a separate duct ventilation system, along with its control system, are going to be added to the building model. Comparative energy simulation runs will be carried out with this more advanced building model, aiming at the assessment, at a detailed modeling level, of the effects of the variation of the following HVAC equipment and system design and control parameters on the yearly heating and cooling energy requirements:

- Boiler and heating system sizing
- Boiler efficiency
- Heating control settings
- Chiller and cooling system sizing
- Chiller efficiency
- Cooling control settings
- Ventilation strategy
- Supply Fans
- Ducts

The required modelling detail will be demonstrated in the following.

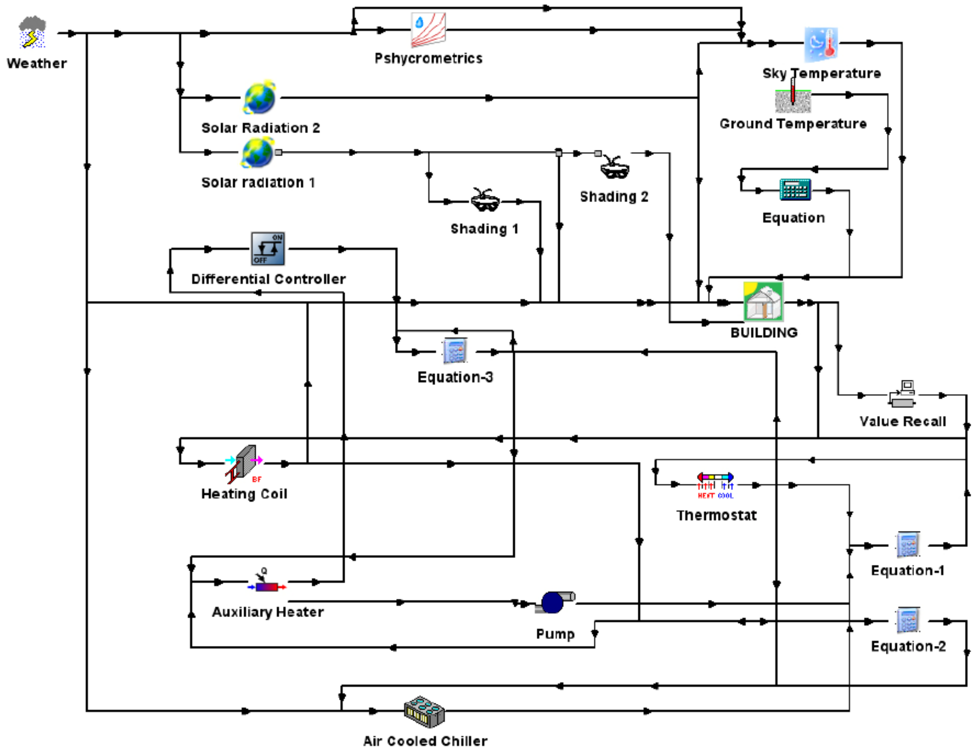

Figure 27. Level II simulation: TRNSYS 16 project file components, (Types): (fan coils, chiller/boiler system).

The level II system model (Figure 27), comprises the 18-zone reference office building with a boiler, an air-cooled chiller model and its HVAC control system. The system uses fan coils to distribute heating and cooling in the different parts of the house.

Apart from the standard utility components of the program, the following TRNSYS component models (Types) were employed in the simulations:

Type 56, Multi-Zone Building
Type 2, ON/OFF Differential Controller
Type 6 Boiler (modified Auxiliary Heater to model a standard oil-fired boiler)
Type 108, Five-stage Room Thermostat
Type 54, Weather Generator
Type 16, Solar Radiation Processor: Total Horizontal Only Known
Type 33, Psychrometrics: Dry Bulb and Relative Humidity Known
Type 69, Effective sky temperature for long-wave radiation exchange
Type 68, Shading Mask
The following TRNSYS types belonging to the TESS library [43] are employed:
Type 753a Heating Coil Using Bypass Fraction Approach - Free Floating Coil (modified),
Type 655 Air Cooled Chiller (modified). The specific chiller is modeled based on a lookup table that contains the COP variation as function of the chilled water exit temperature and the ambient air temperature (see Figure 37).
Type 654, Single Speed Pump

The modification to certain types indicated above, was necessary to add dynamic characteristics that are essential to the realistic simulation of the control system and start/stop operation.

A. HVAC System Modeling Details

The main components of the HVAC system are modeled by means of the boiler's model (modified type 6), the pumps (Type 654), the air cooled chiller (Type 655) and the fan coils (Type 753a).

B. Control System Modeling Details

The control system details employed for heating operation is as follows: the boiler's exit temperature is set to 60^{o}C±5^{o}C. The room thermostat controls zone temperature to 20^{o}C with a tolerance of ±1^{o}C. This is accomplished by switching on and off the fan coils of each zone. For cooling operation, the air-cooled chiller's water exit set-point temperature is 6.5^{o}C. Again, the room thermostat controls zone temperature to 26^{o}C within a tolerance of ±1^{o}C. A full year's performance simulation with a time step of 0.1 h, takes about 10 minutes total computation time on an AMD Phenom PC.

9. Results of Parametric Runs – Level II Simulation

A typical graph of simulated winter operation for the worst week of winter of the TMY is presented in Figure 28. The HVAC system's and is control operation in heating mode is apparent in this figure. As long as the room thermostat is on, demanding hot water from the boiler, the boiler's operation is managed by its own aquastat, which is set to 60^{o}C. After an initial heating-up period, following standby due to non-working hours, the room thermostat starts to cycle on/off, keeping the room's temperature to 21^{o}C within ±1^{o}C. During the very cold days, the room thermostat stays always on, and the boiler's operation is controlled by its own aquastat. On days with higher temperatures, the room thermostats cycle quickly on and off and do not allow the boiler to stay on for enough time to reach its aquastat setting of 60^{o}C. Of course, it is possible to model a variable aquastat setting, to produce the usual practice of lowering aquastat's setting with increasing outdoor temperature levels in winter. If one compares the level II simulated variation of indoor temperature in the specific zone, with the ideal one produced by the level I simulation, in the same figure, the difference between the real, on/off operation from the ideal one is apparent. The effect of the real, on/off operation on the transient heating load variation can be readily seen in Figure 29. If we compare the instantaneous heating loads calculated by the level I versus level II simulations, it becomes apparent that the level II simulation produces a fluctuating response to the heating load, above and below the ideal values calculated by the level I simulation.

Next, a typical graph of simulated summer operation of HVAC system is presented in Figure 30, for the hottest week of the Typical Meteorological Year.

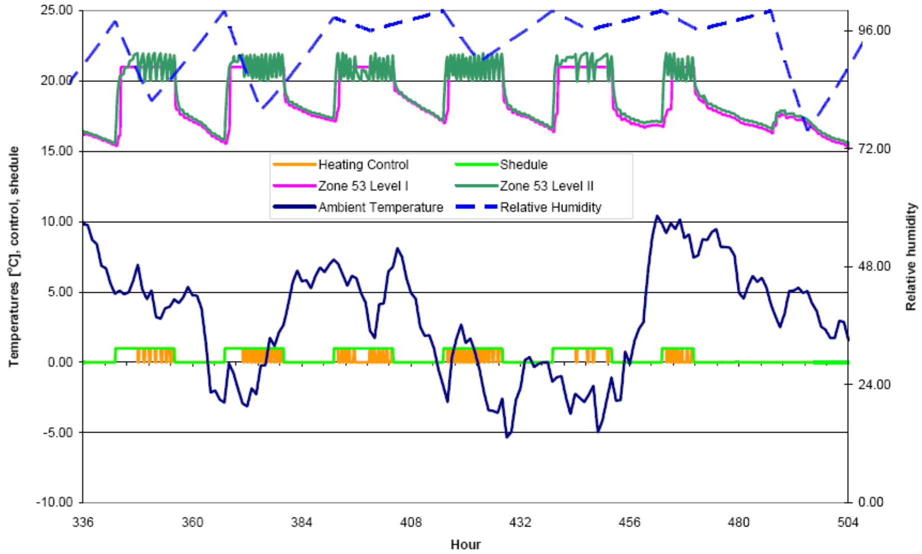

Figure 28. Level II simulation: Transient performance of HVAC system (fan-coil, chiller-boiler), during the coldest week of Winter. Room thermostat, which controls furnace operation, is set to 21°C. Boiler thermostat is set to 60°C.

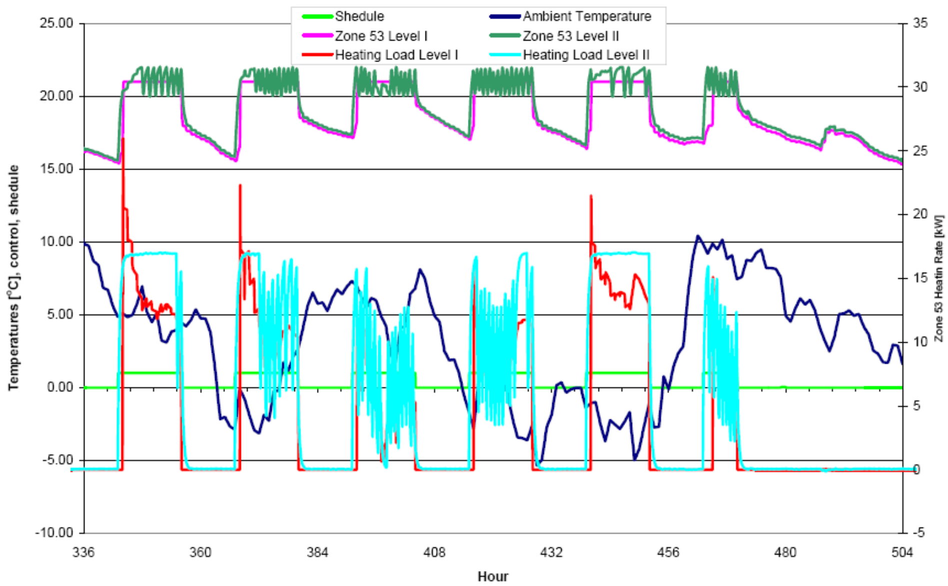

Figure 29. Transient heating loads with the level I –vs- level II simulation, during the coldest week of Winter. Room thermostat, which controls furnace operation, is set to 21°C. Boiler thermostat is set to 60°C.

The system's and control operation in cooling mode is apparent in this figure. The onset of high outdoor temperatures at about 4040 h will require, after a small time lag, the starting up of the chiller operation. The chiller stays on during the hot hours of each day, until the ambient temperature levels drop after 4080 h. The undersized chiller selected for the reference runs is responsible for the presence of the reduced on/off cycling during Monday and Tuesday (in contrast to the frequent boiler cycling).

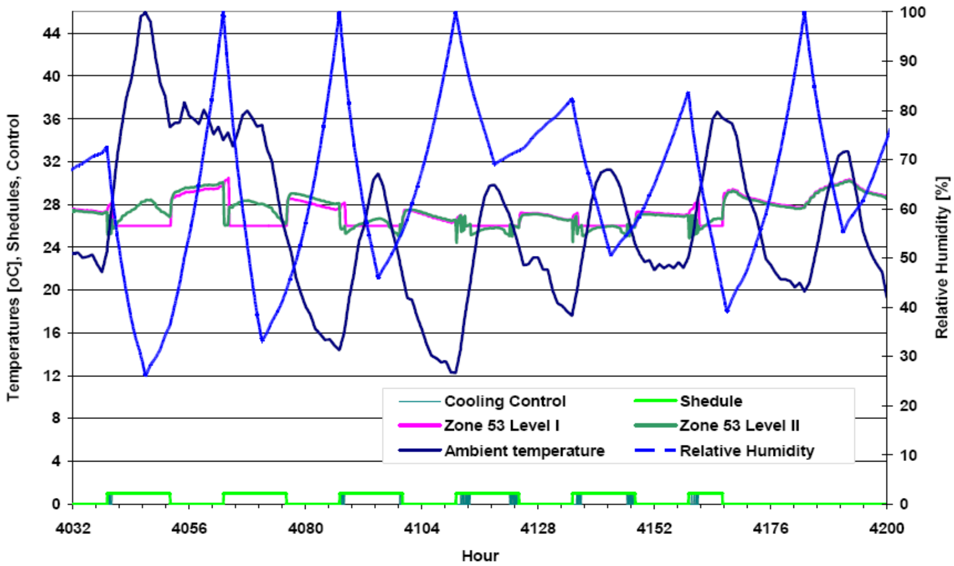

Figure 30. Transient performance of HVAC system during the worst week of Summer. Room thermostat, which controls chiller operation, is set to 26^{o}C.

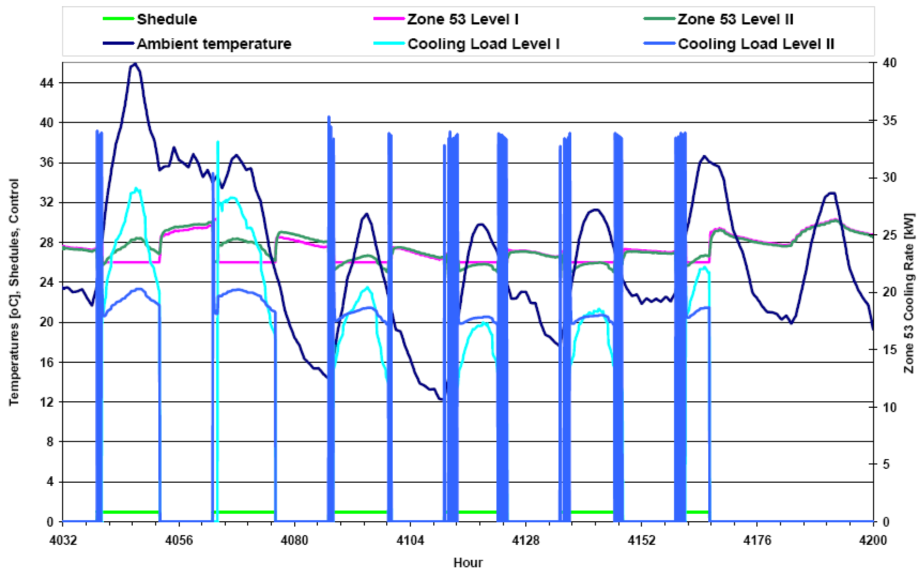

Figure 31. Transient cooling loads with the level I –vs- level II simulation, during the worst week of Summer. Room thermostat, which controls chiller operation, is set to 26^{o}C.

Due to the undersized chiller, the system cannot keep the set zone 5.3 temperature levels of 26°C during the working hours of Monday and Tuesday. Temperature peaks of about 28°C are predicted instead. However, the specific simulation is based on heavy assumptions regarding the phasing of the loads, that is, all offices are assumed to be occupied according to the schedule. If we look at the respective variation of the cooling loads, as they are computed by the level I and the level II simulation, again it becomes apparent that the response to cooling load in the level II simulation is reduced during Monday and Tuesday, due to the undersized chiller.

Figure 32 and Figure 33 presents a summary of heating and cooling energy data of zone 5.3, respectively, for the year-round simulation of the reference building and HVAC system. As regards the heating loads, it is apparent in Figure 32 that the heating loads predicted with the more realistic, level II simulation are increased, presumably due to the imperfect control of boiler operation. On the other hand, a comparison of the respective cooling loads met by the level I and level II simulation in Figure 33, shows that a reduced cooling load is met by the level II simulation. As already mentioned, this is due to the undersized chiller that fails to meet the required cooling load in certain cases with high outdoor temperatures. Energy consumption data are also included in these two figures. In interpreting the energy data of the level II simulation, we should keep in mind that boiler consumption kWh's are thermal, while chiller consumption kWh's are electrical.

In the following, the detailed equipment model will be employed in various simulations supporting design optimization of the HVAC system.

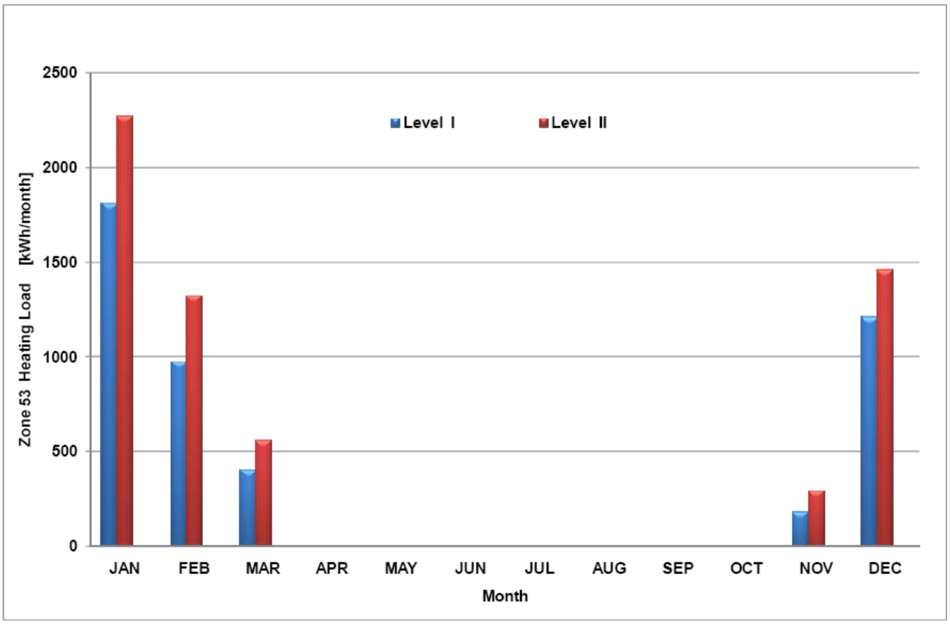

Figure 32. Yearly reference system heating performance energy data.

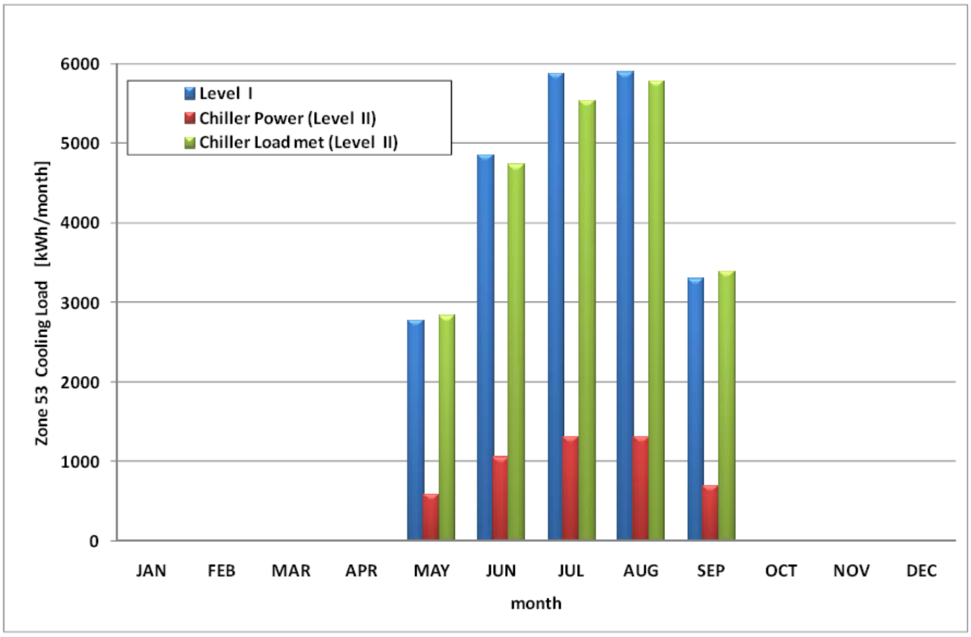

Figure 33. Yearly reference system cooling performance energy data.

A. Equipment Sizing

Level II simulation can be readily employed to support heating equipment size optimization. As an example, the effect of reducing the nominal size of the boiler is checked by means of monthly energy loads of zone 5.3 in Figure 34. The 10% undersized boiler is predicted to result in better fuel economy (6.02 instead of 5.86 kWh/m^2 year). Of course, this is an indicative figure. The detail of simulation of boiler operation in the specific model does not take into account starting losses of the boiler, which would further increase fuel consumption penalty of an oversized boiler.

In a similar way, the level II simulation results during the cooling season, allow an optimal sizing of the chiller. As already mentioned, the specific chiller installed on the reference building configuration is undersized. Figure 35 compares the monthly loads and total energy consumption for the reference chiller with those of a chiller with 10% increased capacity.

Good engineering practice suggests normal area per cooling unit of about 25-35 m^2 per ton (3.6 kW) for commercial buildings in Greece. However, building HVAC systems designers tend to overdimension the equipment. Obviously, apart from the operation expenses, this practice penalizes installation and maintenance cost, and could damage the overall payback time advantage of ground source heat pump. “Level II” systems simulations, as those demonstrated here, allow optimal sizing of the equipment with good estimates of percentage of failure to cover heating and cooling load peaks. In this way, they can be a valuable tool for the building design process [42].

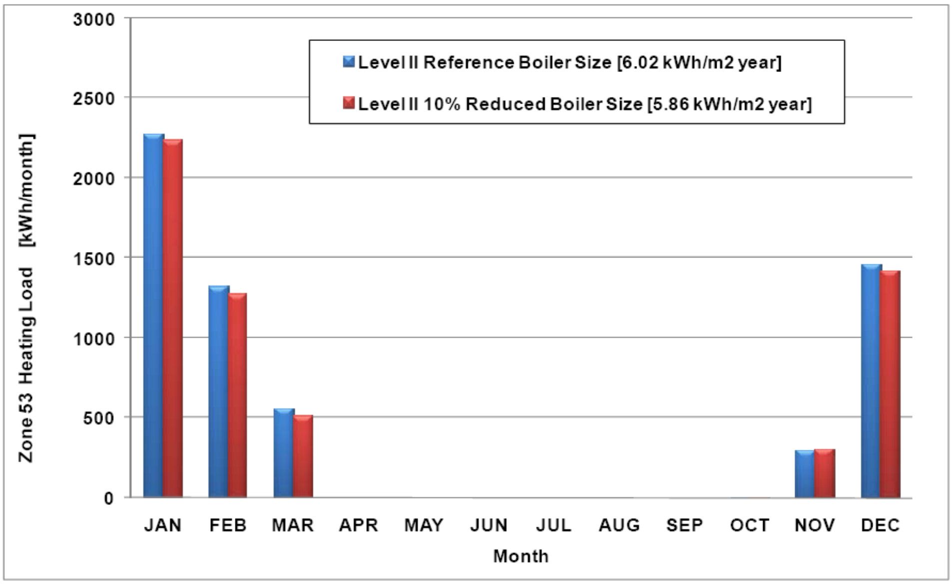

Figure 34. Heating performance during winter: effect of boiler size.

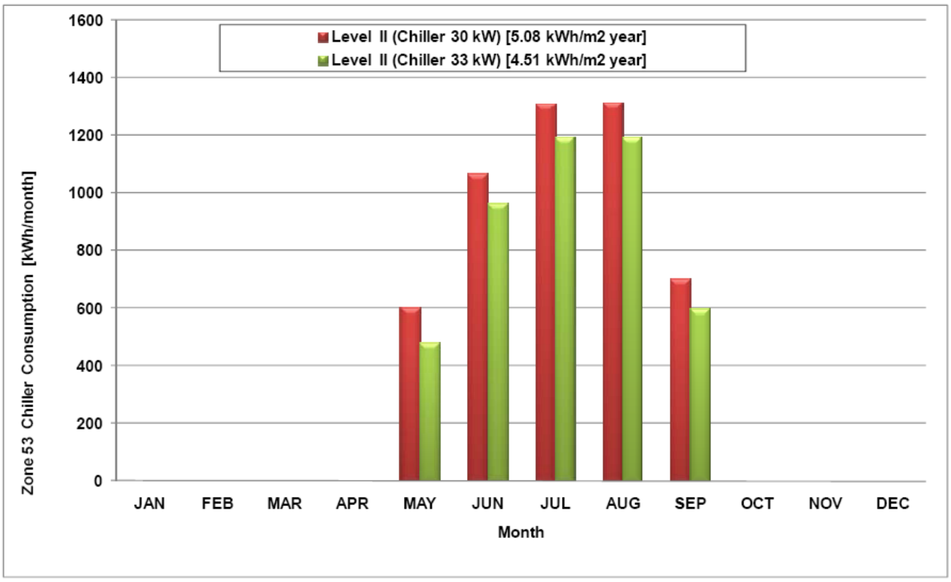

Figure 35. Cooling performance during summer: effect of chiller size.

B. Sizing of HVAC Ducts

The minimization of cooling energy requirements affects also the sizing of HVAC ducts. The sizing and routing of ducts is a critical issue in office buildings, because of the current, strict energy saving requirements of 1 Pa/m friction rate (0.08 in w.g./100 ft), that result in big duct sizes that cannot be easily accommodated in the limited plenum space available in office buildings. Whenever the designer succeeds in a reduced chiller size, additional energy savings are produced by the reduced fan sizes for a given duct size selection.

C. Effect of Boiler Efficiency

The effect of employing a boiler of increased efficiency can be readily assessed with the level II modeling. For example, in case of a natural gas – fired boiler, instead of employing a standard boiler of 0.92 efficiency, we could employ a condensing furnace of 1.09 efficiency [44]. Moderate efficiency improvements can be attained even by retrofitting a stainless steel heat exchanger to the boiler's exhaust line [45].

According to the results of Figure 36, a significant fuel economy improvement can be attained with the use of a high efficiency boiler. This improvement is mainly feasible whenever we use natural gas-fired boilers. Moderate economy improvements are also possible with oil fired boilers of improved efficiency.

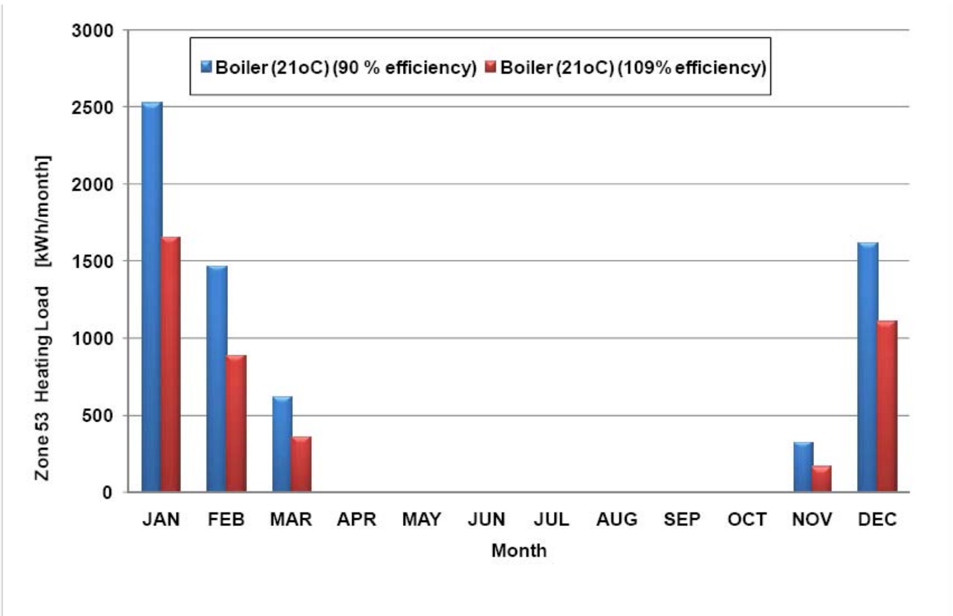

Figure 36. Effect of installing a condensing boiler with 109% efficiency on fuel consumption.

D. Effect of Chiller COP

The chiller employed in the reference runs is a standard efficiency, state of the art chiller with a reference COP value of 3.0. In the market, there exist chillers of inferior performance (down to reference COP value of 2.5, especially older models, and also there exist modern, high efficiency chillers reaching a reference COP as high as 3.5. The overall effect of employing different chiller technologies is tested by means of the respective modifications in the lookup tables for COP (see Figure 37) and capacity ratio [46, 47].

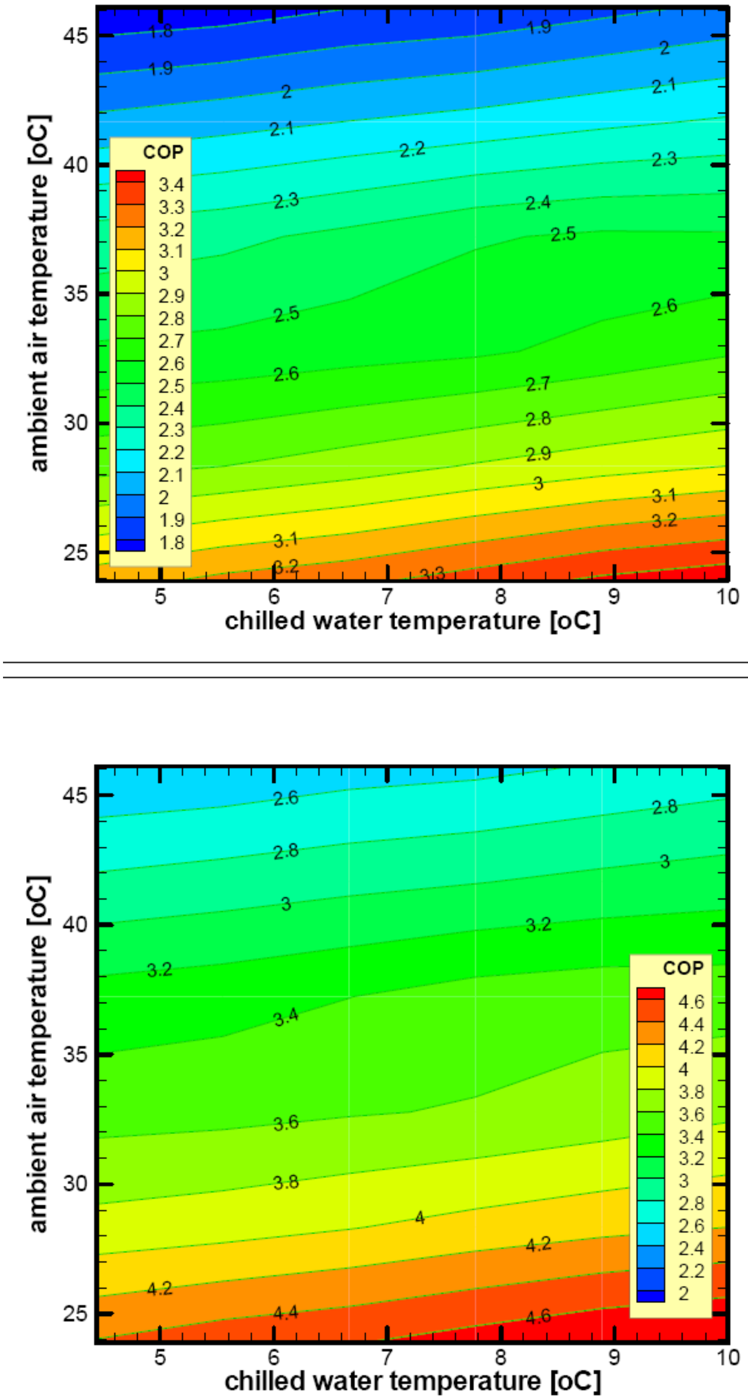

Figure 37. COP characteristics of a low (upper graph) versus a high efficiency chiller.

A high efficiency chiller is expected to significantly improve system's performance. The upper part of Figure 37 presents a map of COP characteristics of a low efficiency air-cooled chiller, as function of chilled water temperature level and ambient dry bulb temperature levels. Standard COP, measured at 35°C air temperature and 7°C chilled water exit temperature, is 2.5 in this old fashioned chiller. On the other hand, a map of COP characteristics for a state of the art air-cooled chiller with the highest efficiency available on the market is presented in the lower part of Figure 37.

The results of comparative runs of the cooling performance of the reference building, with the three alternative chiller installed (standard, low and high efficiency as above), is presented in Figure 38. According to the results presented in this figure, the use of the highest efficiency chiller available in the market instead of an old, low efficiency chiller, may reduce total electricity consumption by 30% in the specific building. In making these comparisons one should keep in mind that we already have reduced the size of the chiller in the course of sizing with the aid of level II simulation.

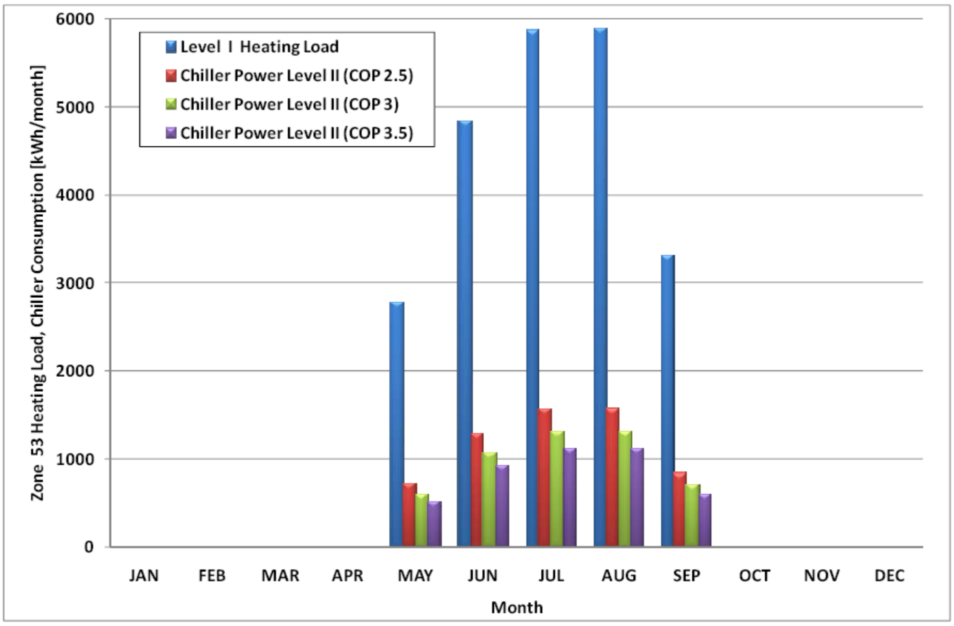

Figure 38. Summary of performance in cooling mode: standard –versus- high efficiency chiller.

E. Effect of HVAC Control Settings

The effect of control system details and settings is well known to affect the heating and cooling energy consumption [48]. Here we demonstrate this effect by performing comparative runs with three different room thermostat settings for winter: 20, 21 and 22°C respectively. The results are presented in Figure 39 in the form of comparative total heating load per month. A 53% increase in total heating load is predicted with a shift of thermostat setting from 20 to 22°C. For the sake of comparison, it may be stated that the total fuel consumption for the standard 20°C case would be 0.5 l. Diesel/m^2 year (4.86 kWh/m^2 year), whereas the total heating load is 4.37 kWh/m^2 year, taking into account an oil-fired boiler efficiency of 90%.

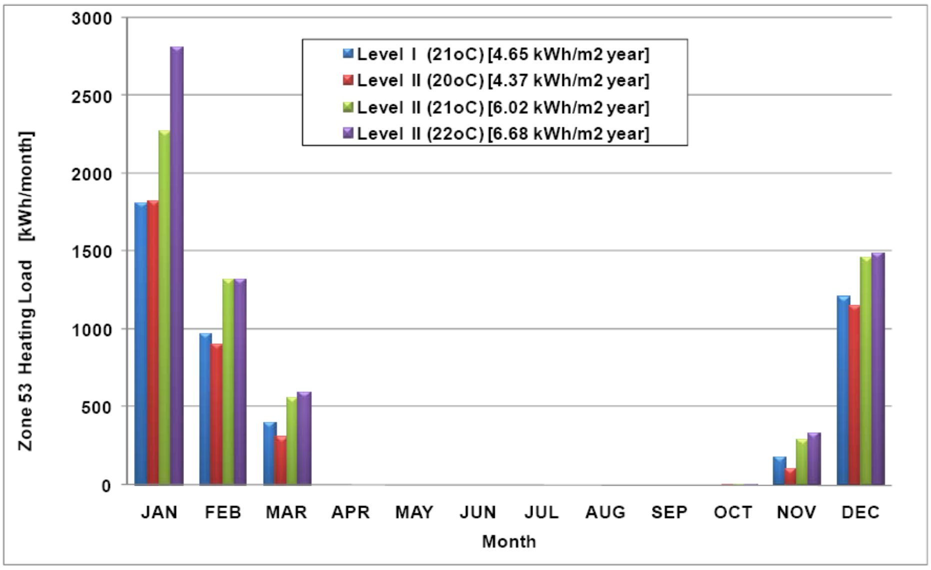

Figure 39. Summary of heating performance: effect of thermostat setting (20 versus 22 ^oC).

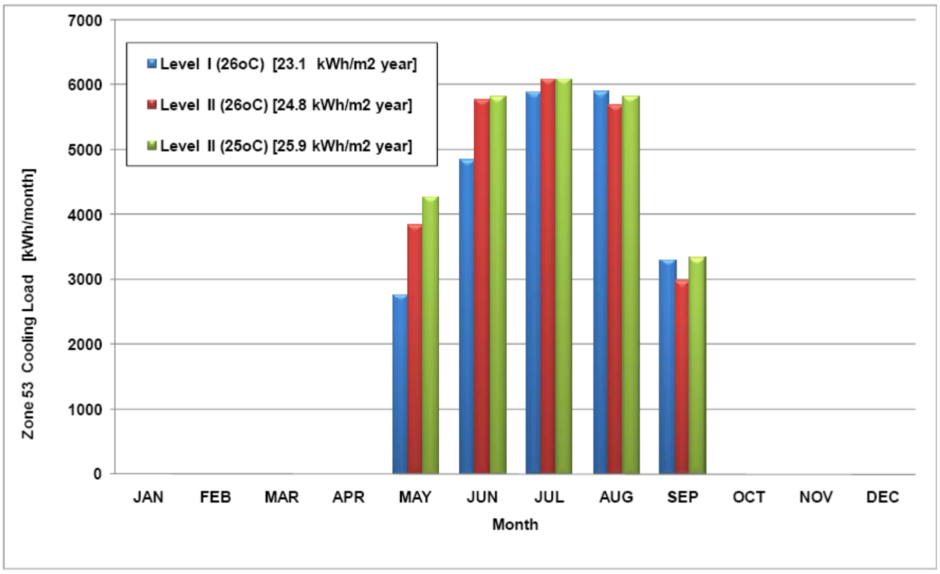

Figure 40. Summary of cooling performance: effect of thermostat setting (25 versus 26^{o}C).

In an analogous manner, Figure 40 presents a comparison of cooling loads for two different thermostat settings: 25 and 26^{o}C. Again, an increase of the total cooling load from 24.8 to 25.9 kWh/m^2 year is predicted (and an analogous increase in electricity consumption – according to the specific type of chiller applied – see Figure 38), can be expected with the decrease of thermostat setting from 26 to 25^{o}C. Of course, heating and cooling energy consumption depends on the specific location of the zone.

The above computations allow a better assessment of the effect of changing control settings in the different zones of the building. This type of investigations is useful in analyzing recordings of the building management system during the first period of commissioning of a new building. Temporarily changing the control settings may become part of an effective strategy for building operation costs reduction. For example, increasing space temperature heating and cooling offsets, performed by the building management system in response to the electrical real-time price reaching a certain level, is a well known load shedding strategy [49]. The effect of applying such strategies to the building management can be assessed at a preliminary level based on the level II building energy simulation presented above. It should have become clear from the above demonstrations that a better understanding of the effects of building design and control modifications can be realized by means of level II building energy systems simulation. This may lead to further design and control improvements that will reward the additional modelling effort and improve the state of the art building design optimization methodologies.

CONCLUSIONS

- Detailed simulation of the building envelope and HVAC equipment, despite its added complexity, is increasingly applied in building HVAC systems design optimization.
- A demonstration case study is presented here by means of a case study with a multistory office building.
- The preliminary design of the building shell and HVAC system of the building is supported by energy simulation in the TRNSYS environment, in two different levels of modeling detail.
- Typical results of the level I simulation are presented and discussed, aiming at the study of the effect of design parameters like the window area, window technology, ventilation and night ventilation strategy, insulation characteristics and the heat capacity of the building frame and walls. To this end, transient simulation results in the form of zone temperatures versus ambient temperature and relative humidity during typical periods of the year, as well as monthly and yearly heating and cooling loads.
- The specific building energy simulation tools can predict the effect of more parameters as the building position, orientation, existence of neighboring buildings, local climatic conditions, construction materials and building operation schedule.
- The methodology is extended to level II that takes into account HVAC system details and the specific equipment and installation efficiency values.
- Typical results of a level II simulation are presented and discussed, that support HVAC system and components sizing, control system optimization and optimization of other parameters pertaining to the detailed design of the building and its HVAC and other subsystems. Moreover, application of level II modeling allows a better assessment of the effect of chiller efficiency characteristics, boiler efficiency, fan and duct design approaches and friction rates.

- Based on the results of this study, it can be concluded that the building energy simulation is a valuable tool in the hands of the building design engineer, which further advances the building design and construction methodologies, because it allows the economic evaluation of different design approaches and concepts.
- To succeed in the diffusion of these methodologies, a careful selection of the necessary depth in analysis and modeling, pertaining to the respective design phase, must be effected, to avoid unnecessary complication in the design tools. The methodology being demonstrated in this paper is a step in this direction.
- The methodology is readily extensible to economic analysis and optimization of the building and HVAC subsystems, and it is expected to lead to significant energy savings in the building sector, that is worthwhile the added modeling complexity.

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