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Thermal performance of office building envelopes: the role of window-to-wall ratio and thermal mass in Mediterranean and Oceanic climates

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Abstract

Tertiary sector buildings and office buildings in particular are heavy users of energy and hence have the potential to make significant improvements in their energy efficiency. To achieve this there needs to be a rethinking of the building design process leading to an optimization of the building's energy demand and good indoor environmental quality conditions. The right decisions have to be taken in the early stages of design in order to achieve the best possible energy performance of the building. The main objective of this paper is to present the results of research on the parameters that most influence the building envelope's energy performance for Mediterranean and Oceanic climatic conditions, according to the Köppen climate classification. The study investigates how two factors—thermal mass and window-to-wall ratio—influence a building's energy performance. A parametric study on those variables is carried out through a dynamic simulation in order to evaluate their influence for Thessaloniki, Greece, and Nicosia, Cyprus—which both feature a Mediterranean climate—and London, United Kingdom, and Munich, Germany—which both feature an Oceanic climate. The results are discussed and conclusions drawn on the influence of each parameter.

Keywords: Office buildings, Window-to-wall ratio, Thermal mass, Energy simulation

1. Introduction

Many studies have been carried out over the last forty years to evaluate energy usage by office buildings from the early design phase. Numerous parameters that influence the design of an urban office building have been considered, accompanied by measures and effective ways to achieve thermal, optical and acoustic comfort and indoor air quality, as well as ways to improve conditions in existing buildings [1, 2].

Thermal mass and the window-to-wall ratio are two of the crucial parameters for the energy performance of buildings in both Mediterranean and Oceanic climates; therefore a dynamic simulation program has been applied to derive quantitative results and compare these parameters in relation to building envelope and energy performance.

A parametric study on those variables was carried out through a dynamic simulation in order to evaluate their influence for Thessaloniki, Greece, and Nicosia, Cyprus, (Mediterranean climate) and London, United Kingdom, and Munich, Germany (Oceanic climate). This study is followed by a deeper investigation of them depending on the re-

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spective climate. A parametric analysis is conducted with the use of simulation tools in order to evaluate the parameters that influence the typical modern office building. A research protocol is finally performed on the effect of such measures in each respective climate.

2. Literature review

A brief presentation of some recent studies, always bearing in mind the scope of this paper, throws up some interesting aspects. Design factors like the geometry of an office building were examined by Adnan Al-Anzi et al. in a detailed parametric analysis [3]. This study looked at buildings in Kuwait. A number of different shapes and floor plans were investigated such as Rectangular shape, L-shape, T-shape, Cross-shape, H-shape, U-shape and Cut-shape. The results of the analysis showed that in desert climates three factors are affected by the form of the building. Specifically, relative compactness, the window-to-wall ratio and the glazing type as described by its solar heat gain coefficient. It was proven that, independently of the shape, the total energy use is conversely proportional to the building's relative compactness when it has low window-to-wall ratios. Additionally, there is a correlation between the aforementioned parameters and annual total building energy use.

The window-to-wall ratio and its effect were investigated by Farshad Nasrollahi in the "warm and dry" climatic region of Iran [4]. Iran's climate ranges from arid or semiarid, to subtropical along the Caspian coast and the northern forests. On the northern edge of the country (the Caspian coastal plain) temperatures rarely fall below freezing and the area remains humid for the rest of the year. The results showed that the best window ratio for heating, cooling and lighting is 80%, 10% and 40% respectively. In order to decrease the total energy consumption, the optimum window-to-wall ratio is 50% and these percentages are different if there are shading devices.

The impact of thermal mass of a low, medium and heavy mass office building was investigated by Bojan V. Anđelković et. al. [5] for Belgrade through a dynamic simulation and using the Energy Plus program. Belgrade lies on the transition zone of humid subtropical (Cfa) and humid continental (Dfa) climate zones, according to the Köppen climate classification, with four seasons and uniformly spread precipitation. The study considered the use of concrete only in the floors and ceilings (light weight construction), in the floors and exterior walls and roofs (medium weight) and also in other building elements, in combination with insulation (heavy weight construction). The results proved that in all of the cases annual space heating energy requirements were reduced and in 67% of the simulated cases, annual space cooling energy requirements were reduced. In 83% and 50% of the cases the peak space heating and cooling demands were reduced respectively.

In another research that was carried out for the tropical savanna climate (Aw) of Jakarta, Indonesia, heat transfer was also investigated together with air flow. Two office buildings with the same orientation and location with double skin façades but with a different building envelope were simulated. The role of wind—thermal performance and behavior of the wind—on the building design was proved to have an influence on heat transfer and energy savings [6].

K. J. Chua and S. K. Chou [7] studied a variety of parameters that affect the energy performance of commercial buildings in the tropical rainforest climate of Singapore (Af). It was revealed that the Envelope Thermal Transfer Value (ETTV) had a strong correlation with the annual cooling energy requirement (Ec); specifically it was demonstrated that a reduction of ETTV from 50 to 45 $W/m^2/yr$ would yield a reduction of around 2.5% in cooling energy.

Solutions that may be used in practice to design energy efficient office buildings with a good thermal interior climate were suggested by Elisabeth Gratia and André De Herde [8]. Where the influence of various parameters, like: insulation level, ventilation strategies, thermal mass, etc. was studied, it was proved that the window area and orientation had to be fixed. In the second case, in a very well insulated building, where the influence of orientation, solar gains, shadowing devices, ventilation strategies, etc. were studied, it was proved that the insulation level and internal gains should be fixed. The whole study took place in the northern Europe, in Belgium to be precise. The climate there, like most of northwest Europe, is maritime temperate, with significant precipitation in all seasons (Cfb).

For the same climate but in a different country, namely Germany, and for a location with low temperatures, Jens Pfafferott et al. [9] aimed to design, monitor and evaluate a low energy office building with passive cooling by night ventilation. The concept was to use architectural solutions to minimize HVAC and artificial lighting from the design phase. With the required thermal insulation and moderate window dimensions a low heating and cooling energy demand was succeeded. With the design of an atrium acting as a buffer zone, a yielding of solar energy gains—and natural lighting—was achieved. Both natural and mechanical ventilation was used in the offices. During the evaluation, the building was found to have internal heat gains that were higher than the solar heat gains for the period from 16th July 2001 to 12th August 2001. The strategy was to optimize night ventilation and to have the additional mechanical ventilation controlled without human interference. The results showed that there was a great need for hybrid ventilation strategies to be implemented carefully, in order to avoid disturbance of the natural ventilation by additional, mechanically driven air flows. In warm climate regions though, thermal storage mass can be utilized as a cooling strategy to reduce the required power loads throughout the daily working period in office buildings. R. Becker and M. Paciuk [10] insisted that the most effective strategy for lowering the required power loads is night pre-cooling.

3. Methodological approach

The methodology applied in this study has a multidisciplinary character. Its main objective is to understand how a typical modern office building is affected by the building thermal mass and window-to-wall ratio and to study the importance of these parameters in temperate/mesothermal climates [11]. Having a typical lineal geometry and using specific architectural features, the building is studied in two Mediterranean and two Oceanic climate locations; Greece, Cyprus and UK, Germany respectively. The study is approached in a quantitative method through simulation, and a set of construction characteristics are given in accordance with each country's legislation [12–15]. The dynamic simulation software Energy Plus is used for the needs of this study [16]. The main complexity is to find the appropriate combination of factors that achieve an optimized design solution for an office building in each of the four different climates.

3.1. *Office model*

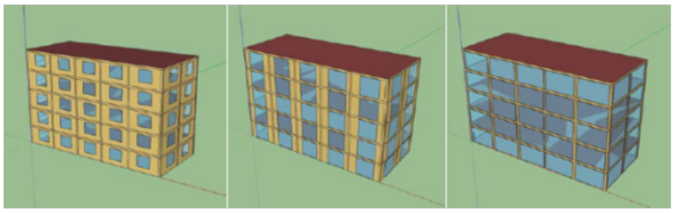

Figure 1: Exterior appearance of the building office model for the respective window-to-wall ratio: 25%, 50% and 75% WWR respectively

The building model is typical five-storey linear office building with dimensions 28 m wide, 12 m deep and 3.50 m floor-to-ceiling height. The total floor area is 336 m^2 with a height of 16 m. The building has a typical composite construction, which has a number of advantages such as high building standards, freedom of architectural design, earthquake proofing, and lower foundation costs. In Fig. 1, the model of the office building is shown in the OpenStudio plug-in environment in Google SketchUp.

The wide face of the building is south oriented which is thought to be the best orientation for gaining solar heat in winter and airflow rate in summer. The building is divided into five thermal zones, one for each level. The north side of the building is identical to the south and the east side is similar to the west.

Table 1: U-values that used for each city according to each country's existing legislation [12–15]

U-Value, W/m^{2}K	Greece	Cyprus	UK	Germany
Ext. walls	0.45	0.72	0.35	0.28
Beams/Props	0.45	0.72	0.35	0.28
Ground floor	0.75	1.6	0.25	0.28
Flat roof ext.	0.40	0.63	0.25	0.20

As already mentioned, the proposed model is that of a contemporary office building with a compact construction. The characteristics of the building elements are based on each country's existing legislation. The U-values within the limiting requirements that were used for each city are given in Table 1.

The selected openings are chosen according to each country's required U-values. The frame type is the horizontal sliding frame, which has the advantage that the open area can be adjusted so as to canalize the drift to a specific area.

The office building model was simulated using the Ideal Loads Air System HVAC Template provided by Energy Plus. This object provides an ideal system to supply conditioned air to the zone that meets all the load requirements. It is often used for load calculations, an evaluation where the load components of the building are all that is being investigated, or as the first step to a more realistic model of a building.

This component can be operated with infinite or finite heating and cooling capacity. For either mode—infinite or finite capacity—the user can also specify on/off schedules for heating and cooling and outdoor air controls. There are also optional controls for dehumidification, humidification, economizer, and heat recovery. This component can be thought of as an ideal unit that mixes air at the zone exhaust condition with the specified amount of outdoor air and then adds or removes heat and moisture at 100% efficiency in order to produce a supply air stream at the specified conditions [16].

For the needs of the simulations some basic assumptions have been made: the indoor design temperatures are 20°C in winter and 26°C in summer, the relative humidity is 40% during winter and 60% during summer, the lighting level is 500 lux. The office working hours, the office occupancy schedule and the metabolic rate of the building users are based on ASHRAE standards.

3.2. Climatic conditions

Four different cities are selected in order to investigate two climates of the temperate/mesothermal climates (C). These climates have an average temperature above 10°C in their warmest months and a coldest month average between −3°C and 18°C. The chosen climates are the Dry-summer subtropical or Mediterranean (Csa) and the Maritime Temperate climates or Oceanic (Cfb).

Mediterranean climates usually occur on the western sides of continents between the latitudes of 30° and 45°. Those climates are in the polar front region in winter, and thus have moderate temperatures and changeable, rainy weather. Summers are hot and dry, due to the domination of the subtropical high pressure systems, except in the immediate coastal areas, where summers are milder due to the nearby presence of cold ocean currents that may bring fog but prevent rain. In order to evaluate the effect of the selected parameters two cases are selected to be examined; the case of Thessaloniki in Greece as typical for a humid warm and Nicosia in Cyprus as typical for a dry warm Mediterranean climate. They have an overall temperate climate and are located at the Southeast end of Europe.

Oceanic climates usually occur on the western sides of continents between the latitudes of 45° and 55°; they are typically situated immediately poleward of the Mediterranean climates. In Western Europe, this climate occurs in coastal areas up to 63°N latitude in Norway. These climates are dominated all year round by the polar front, leading to changeable, often overcast weather. Summers are cool due to cool ocean currents, but winters are milder than other climates in similar latitudes but usually very cloudy. London in United Kingdom as humid cold and Munich in Germany as dry cold selected to be investigated.

The meteorological data used for the simulation are taken from the EnergyPlus simulation program. The climatic data that are used for the buildings' simulation in EnergyPlus cover a typical year for the energy consumption calculations. The typical climate year used is the IWEC (International Weather for Energy Calculations) form and is the result of ASHRAE Research Project 1015 implemented by ASHRAE Technical Committee 4.2.

3.3. Simulation scenarios

Direct solar radiation produces a huge variability in loads making window design optimization vital in increasing the building energy efficiency. The window-to-wall ratio of the building in conjunction with the envelope thermal mass is a factor that significantly affects the energy performance of an office building in terms of heating, cooling and lighting demand and therefore energy consumption. In this study the model office building is simulated for a window-to-wall ratio ranging from 25% to 75%.

Thermal mass is considered one of the powerful tools designers can use in order to control diurnal temperature changes and achieve thermal comfort. In buildings where solar gain is used as a heating strategy, diurnal effects can be managed by absorbing the heat of the winter sun during the day, while keeping the air temperature moderate, and releasing the heat at night to prevent the air temperature from plummeting. The results of the model office building simulated for various thermal mass levels, ranging from 110 kJ/m^2K to 290 kJ/m^2K, are presented.

4. Results

In this section will be presented the results from the parametric analysis carried out. They will be presented and discussed for each separately by evaluating the effect of each parameter examined.

The energy consumption for the countries studied was calculated by keeping the parameter of Window-to-wall ratio (WWR) constant. Three scenarios were developed based on the WWR. The cases studied were: a) WWR=25%, b) WWR=50% and c) WWR=75%.

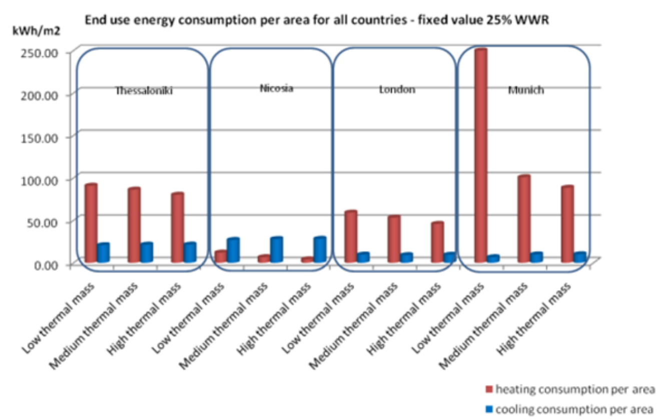

Figure 2: End use energy consumption per area for the countries studied—fixed value 25% WWR

The energy consumption was also calculated by changing the building thermal mass criteria. Therefore, three scenarios were developed for: a) Low

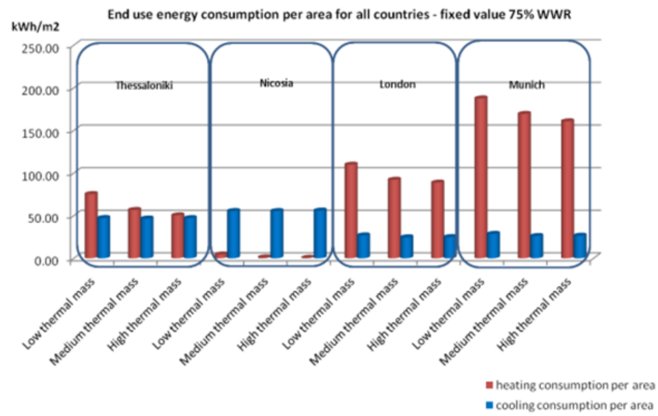

Figure 3: End use energy consumption per area for the countries studied—fixed value 75% WWR

Thermal Mass, b) Medium Thermal Mass and c) High Thermal Mass. The end use energy consumption per area for the countries studied and the WWR parameter on 25% and 75% is presented in the Figs 2 and 3.

The scenarios developed, taking into consideration the thermal mass increase of the building, concluded to heating energy consumption being reduced in all four countries considered. The most significant reduction is noticed for Munich, as it was expected, due to the prevailing climate conditions: Munich has the lowest temperature conditions compared to London, Nicosia and Thessaloniki and therefore the building thermal storage capacity affects significantly the building's thermal needs. Providing by means of design an increased thermal storage potential, which is best utilized in a thermally well insulated, continually operating building, leads therefore to greater reductions in heating energy demand. Those results are in agreement with previous findings [17–19].

On the other hand, the energy consumption for cooling is not affected dramatically. The parameter of thermal mass cannot affect the cooling loads, therefore the natural or mechanical ventilation during the night should also be included in the scenarios studied [20, 21].

The thermal mass is a key factor for building's thermal performance because indicates the amount of heat absorbed from the construction elements of the building. This heat can be emitted to the internal areas of building and contribute to energy reduction for heating and cooling. It is generally accepted that more precise predictions of the energy consumption derive when the building's thermal performance has been calculated on a hourly base, as this depicts the changes occurring during the day.

Moreover, the WWR parameter has been studied in relevance to energy consumption keeping this time constant the thermal mass criteria. The results presented concern the low thermal mass scenario because low thermal mass conditions do not affect the energy consumption significantly and therefore the WWR impact to energy consumption is more obvious.

The results demonstrated that the WWR impact differs in the different cities and is depending on climate condition. In Thessaloniki, for example, which has a rather mild climate if the openings' percentage is increased from 25% to 50% there is significant reduction of energy consumption for heating because the building utilizes the solar gains. On the other hand, if solar protection, by means of shading and the use of appropriate glazing, is not adequate the energy consumption for cooling is increased. The opposite is happening to cities like London which have mild but rainy climate conditions, with high levels of humidity. In these types of climate the opening percentage is not leading to a decrease of energy consumption for heating as the solar profit is negligible. There are, however, positive effects with respect to lighting, as natural lighting can be utilized, reducing the demand for artificial one. A detailed lighting study is needed in any case, to determine the optimum dimensioning of window surfaces, also with respect to their orientation.

5. Summary/Conclusions

Considering the optimal scenario for cooling energy consumption for both climates accrued to be the building model with 25% window-to-wall ratio, as it was expected, given the fact that enough incoming solar radiation can be achieved in this way to ensure lighting and optical comfort, without leading to excessive solar loads in summer and therefore to increased cooling demands. With this as a constant, the best performance is observed for Mediterranean climates for lightweight buildings, while in

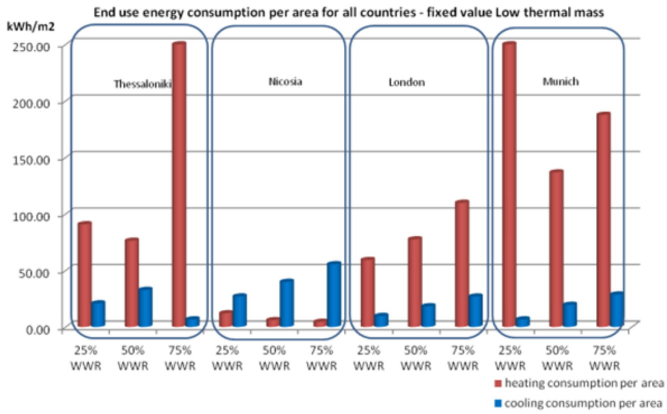

Figure 4: End use energy consumption per area for the countries studied—fixed value for low thermal mass

Oceanic ones the best performance is observed in heavyweight buildings. This situation can be explained given that the storage mass of the building is used to mitigate the indoor air temperature releasing the stored heat during the night. In both climates, the best results are observed for low use buildings since increasing the building internal loads leads to an increase on the building cooling loads as expected. Still, one has to keep in mind that those results concern mechanically ventilated, fully air-conditioned office buildings. They may differ considerably when naturally ventilated buildings are considered.

With respect to the building's heating energy consumption, the worst case scenario is the same for both climates: Specifically, buildings with 50% WWR and medium thermal mass result to have the worst efficiency. On the other hand, the best case scenario differs. Specifically, for Mediterranean climates the best case is observed for 75% WWR, high thermal mass, while for Oceanic ones it occurs in buildings with 25% WWR and high thermal mass.

On the other hand, the results of the total primary consumption showed that the best performance has the examined scenario with 25% WWR, high thermal mass and high internal loads for the Thessaloniki, London and Munich. Cyprus which is southern enough to feature high air temperatures and significantly higher solar radiation values, calls for a 25% WWR, high thermal mass and low internal loads office building. In Oceanic climates the best performance in terms of total primary energy performance occurs when the heating energy consumption is minimum, whilst for the Mediterranean climates of Thessaloniki and Cyprus the situation appears to be more complicated since the minimum total primary energy performance does not coincide with the best scenarios for heating and cooling energy consumption. In terms of total primary energy consumption the best performance occurs for scenarios with low WWR and high thermal mass showing the importance to mitigate the internal air temperature using high thermal mass in buildings while keeping the WWR as small as possible minimizing the thermal losses regardless the climate.

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