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Indoor conditions study and impact on the energy consumption for a large commercial building

PhD. Tiberiu Catalina, Research Engineer
PhD. Vlad Iordache, Associate Professor
PhD. Florin Iordache, Professor
Technical University of Civil Engineering Bucharest, CAMBI Research Centre
Bucharest, ROMANIA

ABSTRACT

This study is focused on the analysis of indoor conditions for a new commercial building that will be constructed in an East-European country. Based on the initial HVAC design parameters the surface of the building was divided in thermal zones that were studied using dynamic simulations. The article provides interesting insights of the building indoor conditions (summer/winter comfort), humidity, air temperature, mean operative temperature and energy consumption using hourly climate data. A dynamic variation of the PMV (Predicted Mean Vote Index) was obtained for different thermal zones of the building (retails stores, mall circulation, corridors) and in most of the cases the acceptable values of ±0.5 are exceeded Among the most important energy efficiency measures it is mentioned a decrease of the heating set point temperature, increase of the walls and roof thermal resistance and the use of a heat recovery on the ventilation system. In this work it is demonstrated how simple measures can enhance the indoor conditions and reduce the energy consumption for this kind of construction.

INTRODUCTION

Heating, ventilating and air conditioning (HVAC) systems, which consume large quantities of energy, have become a necessity for almost all the buildings (ASHRAE, 1992) to provide a comfortable indoor environment. Knowing the influence of certain design parameters on the energy consumption, it's mandatory to find out what is their correlated impact on the building. With the energy policy and as well its active role putting energy issues on the agenda of the EU, ROMANIA is making big efforts to reduce the energy consumption and the CO_2 emissions for new or refurbished constructions. During the last decade, in Bucharest more than twenty commercial stores were built and other ten are actually in construction.

In a typical retail building, lighting and heating alone represent nearly 70 percent of total energy use, making those systems the best targets for energy savings. Other sources of energy consumption include cooling, ventilation, and refrigeration. These building consume large quantities of energy and a detailed analysis in the design stage is mandatory. In many cases, the architects or engineers do not study carefully the future building and huge amounts of energy are wasted on indoor environments that are not comfortable for the tenants or clients (too hot in winter or too cold during the summer period). In this article the attention is focused on a large commercial store and by using dynamic simulations a better understanding of building systems use and indoor conditions was possible.

Similar studies focused their attention on studying the energy consumption of commercial buildings. (Zhao et al., 2009) find out using simulations and measurements that a retail space is an important source of energy consumption.

(Luo et al., 2007) and (Carvalho et al., 2010) research work was centered on finding measures to decrease the energy consumption for air-conditioning in large commercial buildings. Similar to these studies, our work is intended to show how simple measure can reduce the energy consumption. The particularity of our work is seen from the detailed modeling of the construction and the parametric study on the heat air recovery, along with the economical potential.

The studied building is located in Bucharest and the main destination of this construction is commercial building with retail stores and supermarket area. The heated volume of the building is around 270 000 m^3 (9534960 ft^3) with a use surface of 55 000 m^2 (592015 ft^2). The study provides interesting insights of the building indoor conditions (summer/winter comfort), humidity, air temperature, mean operative temperature and energy consumption using real climate data. The following points were analyzed:

- Indoor conditions in different zones of the building (air temperature, mean radiant temperature, operative temperature, humidity) with hourly values
- The risk of summer overheating in the non-conditioned zones
- Heating and Cooling energy consumptions (hourly, monthly and annual values) for different zones/floors of the building

- Thermal Comfort (PMV and PPD Index)

The research study is accompanied by recommendation points, which provides suggestions on how the energy performance and indoor conditions of the building could be enhanced.

THERMAL DYNAMIC SIMULATIONS

Compared to dynamic simulations, the steady state methods only provide information for one-hour summer and one hour winter design conditions in buildings and thus do not assist the building designer to achieve low environmental impact design solutions.

For better decisions, accurate information is required on the magnitude and duration of internal peak temperatures during the occupational period and this can be only obtained by dynamic hourly simulations of the building.The influence of different loads (e.g. infiltration, solar or casual gains from equipment lighting and occupants) should also be determined accurately. It is only when the main influence on the peak load can be identified that the correct design solution can be found to reduce the peak loads. If this information is not available to the building designer this means that opportunities are being missed to design buildings better in terms of ***environmental quality and energy consumption***.

In predicting the value and occurrence of the peak loads that will occur in buildings it is necessary to consider the chain of several weather variables and their interaction with the building. This is more realistic than using an extreme value of one weather variable (outside air temperature), treating the weather data in an idealized way and omitting the type of building services system to be used. The advantages of designing a building with dynamic simulations are obvious and moreover the data results are more close to the future conditions of the designed building. To account for energy interactions between building subsystems, we used TRNSYS 16 to model the predicted energy performance of the building. TRNSYS 16 computes building energy use based on the interactions between climate, building form and fabric, internal gains and HVAC systems.

In TRNSYS Studio, the weather module that was used for our simulations employs TMY2 climate data files. TMY2 (Typical Meteorological Year 2) data are hourly annual solar radiation and meteorological data readily available from the National Renewable Energy Laboratory (NREL).

It is important to note that the TMY2 data represents a typical year based upon 30 year weather characteristics. It is unlikely that the data accurately represents any single year, but it is representative of the average weather characteristics over the 30 year time frame.

The building was simulated over the winter/summer months using a typical Bucharest weather file which contained hourly values for dry bulb temperature, wet bulb temperature, direct solar radiation, diffuse solar radiation, wind speed and wind direction (see Figure 1).

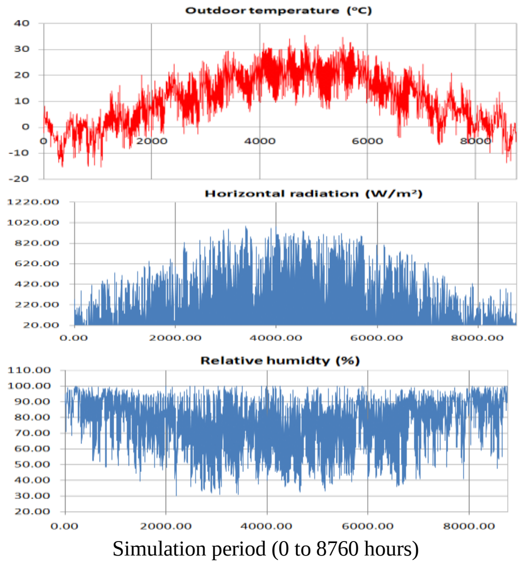

Figure 1. Yearly weather data variation for the Bucharest climate

The mean monthly values obtained from the weather files are very close to those presented by the Romanian National Standard (SR 4839). The information that required producing the thermal study includes:

- the individual spaces or zones in use within the building, and their dimensions (verified from plans and measured).
- the activities conducted within the zones. (in our case we have retail spaces, office spaces, storage, circulation area, etc)
- the heating and ventilation services for each zone (including type of system, metering, controls, fuel used etc.)
- the lighting and controls used for each zone
- the construction of the fabric of the building and thermal efficiency of the materials used: roof, floors, walls and glazing.

Month	Air temperature	Relative humidity	Daily solar radiation - horizontal
	°C/°F	%	kWh/m²/mont
January	-2,5 / 27.5	85,19 %	40,9
February	-0,02 / 31.9	81,99 %	56,4
March	4,8 / 40.6	76,01 %	93,6
April	11,3 / 52.3	69,12 %	133,2
May	16,9 / 62.4	68,25 %	164,7
June	20,0 / 68	69,25 %	196,5
July	21,9 / 71.4	67,62 %	193,7
August	21,2 / 70.1	68,14 %	166,4
September	17,0 / 62.6	73,03 %	125,0
October	10,9 / 51.2	77,20 %	81,2
November	5,2 / 41.3	81,39 %	44,4
December	0,28 / 32.5	85,71 %	28,3
Annual	10,6 / 51.08	75,24 %	110,3

Table 2. Weather monthly values obtained from the simulation data

The building has a very well-constructed shape distributed on six floors (three basements - parking, ground floor, first and second floor). The height between the floors is 6 m/19.68 ft and the building height is around 18 m/59ft. The construction has solid floors, with a concrete slab and fiberglass; insulated external walls ,,sandwich,, type; insulated solid roof with concrete slab; double glazed and aluminum-framed windows. Opaque constructions include roofs, floors, and walls and the thermal properties can be described by a U-value:

Type (roof/floor/wall)	Description	U (W/m^2K)
External walls (type 1)	Plasterboard/Air /Insulation/Air/Al.	0.38
Internal walls (type 1)	Plaster/Aerated concrete/Plaster	0.78
External walls (type 2)	Plaster/Aerated concrete/ Insulation/Plaster	0.28
Internal walls (type 2)	Plaster/Mineral wool/Plaster	0.53
Trafficable roof	Gravel/Insulation/ Slope/Concrete	0.24
Non trafficable roof	Deck/Gravel/Insulation/ Slope/Concrete	0.25
Indoor floors	Glass chips/plate slab	0.45

Table 2.Building elements U-value including thermal bridges

Transparent constructions include windows and curtain walling. The window U-value is 1.5 W/m^2K, the solar absorptance is 0.6; the area/frame window is 0.1% and a g-value of 0.605 %.The building heating is done by using 3 gas fired boilers (capacity 3 x 1600 kW /16.3 $\cdot 10^6$) and the distribution is mainly done by the air handling units (AHU) that supply the air inside the mall area. Only the corridors, storage rooms and toilets are heated with wall mounted radiators. The Ground Floor delivery areas are equipped with a total of 4 aerotherm fans heaters. The facility manager's office, management centre shall also be equipped with panel radiators.

The air conditioning systems generally serve the Mall and Retail areas. This is done with roof top air handling units for the large shops and public areas and a loop system for the small shops. There shall be 3 low height cooling towers rated at 1000kW.

The thermal modeling of the building was done based on the data delivered by the HVAC designer engineer for the heating, air conditioning set point temperatures and ventilation air rates.

Indoor set point temperatures:

- Mall public areas (summer) 26°C / 78.8°F
- Mall public areas (winter) 24°C / 75.2°F
- Shops 24°C / 75.2°F
- Supermarket 22°C / 71.6°F
- Stores (winter) no cooling 17°C / 62.6°F
- Offices 22°C / 71.6°F
- Welfare(winter) no cooling 20°C / 68°F
- Toilets 20°C ± 2K
- Technical rooms 15°C / 59°F

Fresh Air Supplies

- Mall 5 $m^3/hr/m^2$- 29cfm/ft^2
- Shops < 1000m2 5 $m^3/hr/ m^2$- 29cfm/ft^2
- Shops > 1000m2 9 $m^3/hr/ m^2$- 52cfm/ft^2
- Supermarket 9 $m^3/hr/ m^2$- 52cfm/ft^2
- Conference rooms 9 $m^3/hr/ m^2$- 52cfm/ft^2
- Offices 5 $m^3/hr/ m^2$- 29cfm/ft^2
- Food court 9 $m^3/hr/ m^2$- 52cfm/ft^2
- Restaurants 9 $m^3/hr/ m^2$- 52cfm/ft^2
- Toilets 10 ach per hour extract

Only a part of the zones has heat recovery (mall circulation area, shops >10700 ft^2) and there is no humidity control on neither of the zones. Each of the zone has a separate Air Handling Unit (AHU) to supply the fresh air.

Occupational levels

Shops <1000m^2 1 person/6m^2 -65 ft^2
Shops >1000m^2 1 person/3m^2-32 ft^2
Mall areas 1 person/6m^2-65 ft^2
Restaurants/food court 1 person/1m^2– 10.7 ft^2
Offices 1 person /10 m^2-107 ft^2
Management Centre 1 person /10m^2-65 ft^2

Internal heat gains
Offices 60 w/m² - 19.02 Btu/(h ft^2)
Mall 20 w/m² - 6.2 Btu/(h ft^2)
Shops 60 w/m² - 19.02 Btu/(h ft^2)

The thermal modeling and building diving in zones was chosen based on the air set point temperature, ventilation fresh air rate and destination. A global heat gains value was found to be 15W/m^2. Figure 2 shows an example of thermal zoning for the 1st floor of the commercial store.

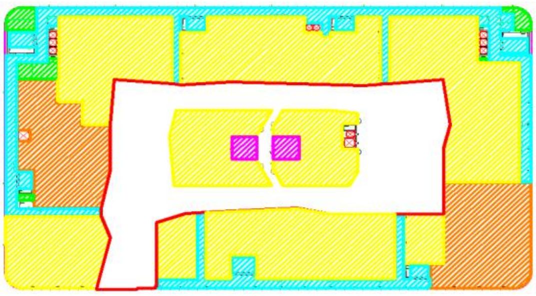

Figure 2.Firstfloor thermal zones (white-mall circulation, yellow – stores < 10700 ft^2, orange–stores > 10700 ft^2, blue- technical, corridors, magenta – toilets)

RESULTS ON ENERGY CONSUMPTION

The energy and peak demand for the HVAC system, as calculated from the hourly annual energy simulations, is used to determine the energy and power cost savings. The calculation of carbon dioxide CO_2 emissions was possible through the following factors: 0.205 kgCO_2/kWh (Gas Heating) and 0.1 kgCO_2/kWh (Chillers-Cooling). As concerns the price for the electricity a mean value of 0.11 €/kWh was chosen and for the gas the price is around 0.04 €/kWh (translated from the price of 0.9 €/m^3 of gas).

The heat losses of the building are divided in heat losses throw the envelope and heat losses by the heated outside air used as fresh air. The building is well insulated (good Ù-value of the walls) and the windows area is relative low compare to the opaque part. Consequently the heat losses by transmission are low compared to the total heat losses. As it was found the air heating energy represent around 80% of the total heat losses.

The total annual heating energy consumption for building was found to be of 26.7·10^9 Btu with an annual cost of 316 768 €/year (450 500 $/year). The total heating CO_2 emission for the construction is 1 623 434 kgCO_2/year.

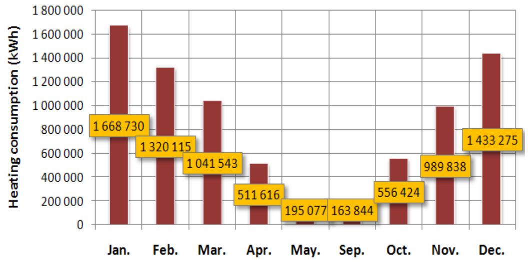

Figure 3.Heating energy consumption for each winter period month

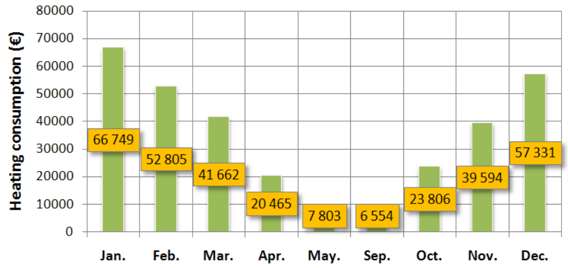

Figure 4. Heating monthly costs for the winter period

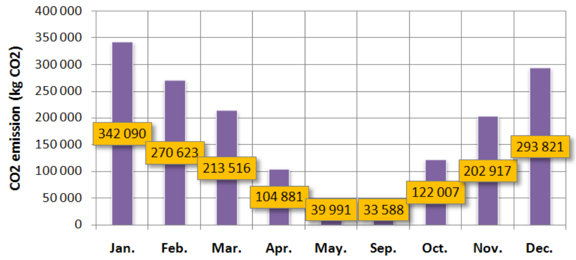

Figure 5.CO_2 monthly emissions for the winter period

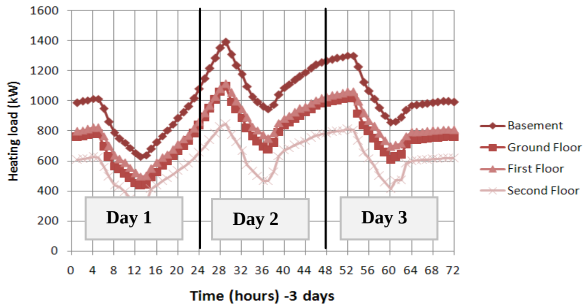

Figure 6.Hourly heating loads during the coldest days of the year for different floors

In Figure 6 it can be observed the maximum heating load for the designed building which is 4447 kW (15.1·10^6 Btu/h). The difference between the steady state calculation and the simulation is 8% (353 kW / 1.2 ·10^6 Btu/h).

The total annual cooling energy consumption for building was found to be 903 510 kWh/year. 3.08 ·10^9 Btuwith an annual cost of 99 386 €/year

(150.500 \$/year). The total cooling CO_2 emission for the construction is 90 351 $kgCO_2$/year.

RESULTS ON INDOOR CONDITIONS

Apart from decoration and the merchandise on offer, numerous other factors strongly influence the customer's feeling of comfort. Principal among these, however, are lighting and the indoor air conditions in the store. Comfort conditions offered to the customer gain more and more importance for better sales. A number of parameters play a high level importance for the indoor comfort of your tenants and future clients.

Good indoor air quality is best achieved through a system approach that considers:

- ventilation,
- moisture control,
- reduction of indoor pollution sources
- monitoring and maintenance

The ideal standard for thermal comfort can be defined by the **operative temperature**. This is the average of the air dry-bulb temperature and of the mean radiant temperature at the given place in a room.In the summer the suggested temperature is between 23.5 and 25.5 degrees Celsius (74.3 ^{o}F to 77.9 ^{o}F), and airflow velocity of 0.18 m/s. In the winter, the recommended temperature is between 21.0 and 23.0 degrees Celsius (69.8 ^{o}F to 73.4^{o}F) with an airflow velocity of 0.15 m/s.

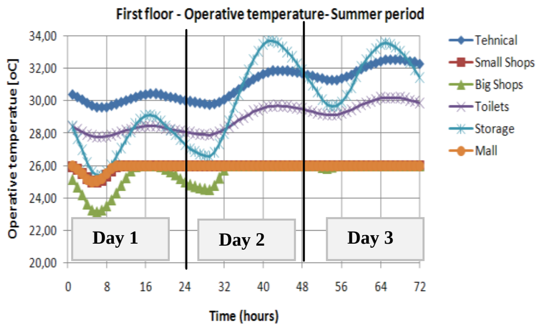

Figure 7.Indoor operative temperature during the warmest 3 days of the year

During the warmest summer days the values are outside the acceptable levels, with values higher than 30^{o}C/86^{o}F (see Figure 7) for the Technical Spaces and Storage Areas. These values are due of course because these spaces are not air conditioned.

For indoor thermal comfort, relative humidity levels up to 70% in summer may be acceptable. But for indoor air quality, the optimal humidity is between 40% and 60%. Poor indoor air quality may lead to an increased incidence of health related symptoms, which in turn may lead to a rise in absenteeism and a loss of productivity. Consistently low humidity levels are also bad for the indoor environment. This tends to occur when the weather is cold outside (winter case) and the heat is turned on in the zone. The most noticeable effects are a sore throat and sinus pain, symptoms that are common at certain times of year.

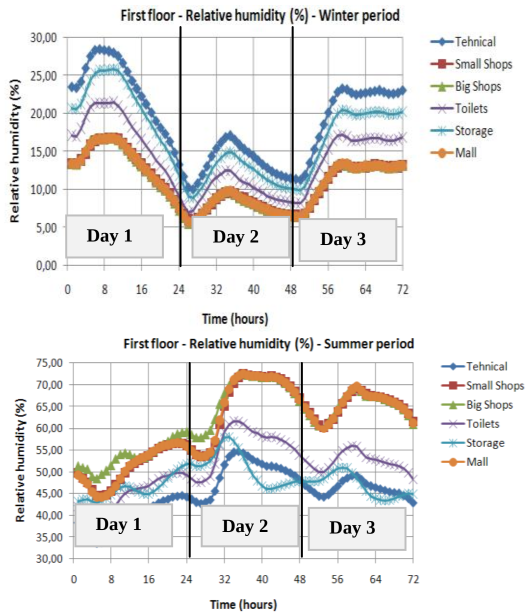

Figure 8.Indoor relative humidity during the coldest/warmest 3 days of the year

As it can be noticed from Figure 8 the levels of indoor humidity are low and the air seems to be dry which can cause certain problems in long term occupational period. These levels can be higher in reality because of different unpredicted indoor humidity sources (higher number of persons, coffee machines, etc) but they will still have low values. During the summer period the indoor humidity levels are higher than the recommended values of 60% for the case of Retail Shops and Mall Circulation. Maximum values of 74% are observed and unfavorable impact on the indoor conditions is evident.

The most common approach to characterizing thermal comfort for the purposes of prediction and building design has been to correlate the results of psychological experiments to thermal analysis variables. The level of comfort is characterized using the ASHRAE thermal sensation scale. The average thermal sensation response of a large number of subjects, using the ASHRAE thermal sensation scale, is called the predicted mean vote (PMV) (ISO 7730).

The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and occupant's metabolism) into an index that can be used to predict thermal comfort. Occupant comfort is computed assuming clothing levels of 1.0 clo (normal winter indoor clothing: pullover) October through April, and 0.5 clo (t-shirt) May through September; and an in-building air velocity of 0.66 ft/s (0.2 m/s).

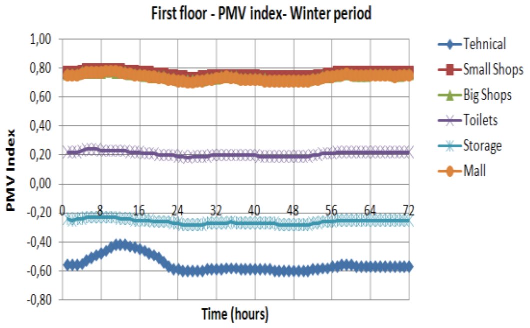

Figure 9.PMV index for the first floor of the commercial store during the coldest days

What can be observed from Figure 9 is that the PMV index is higher than + 0.5 for the thermal zones (Retails Shops, Mall Circulation) while in areas like technical rooms the index is lower than -0.5. The set point temperature of 24°C/75.2 °F as designed for the retails stores will be too high for this and people will tend to get warm. Moreover the 24°C as set point temperature will have a negative impact on the energy consumption and is recommended a lower value.

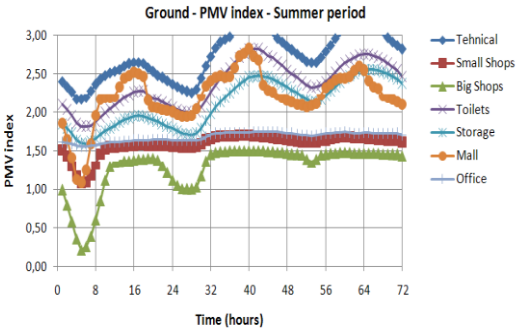

Figure 10.PMV index for the ground floor of the commercial store during the warmest days

What can be observed from Figure 10 is that the PMV index is higher than + 0.5 for the most of the hours and for all areas. Non-conditioned spaces like Technical (Corridors, etc) have the highest value of discomfort, but also the Retail Spaces and Mall Circulation are above the acceptable values with levels of +1 to +1.5. A decrease of summer design temperature is highly recommended to ameliorate the thermal comfort.

To solve the thermal comfort issues of the building a small analysis was done and the data found are shown in the Figures 11 and 12.It can be noticed that for the HVAC summer designed temperature the PMV is 0.92, so the occupants will tend to have a sensation on ,,slightly warm,,.

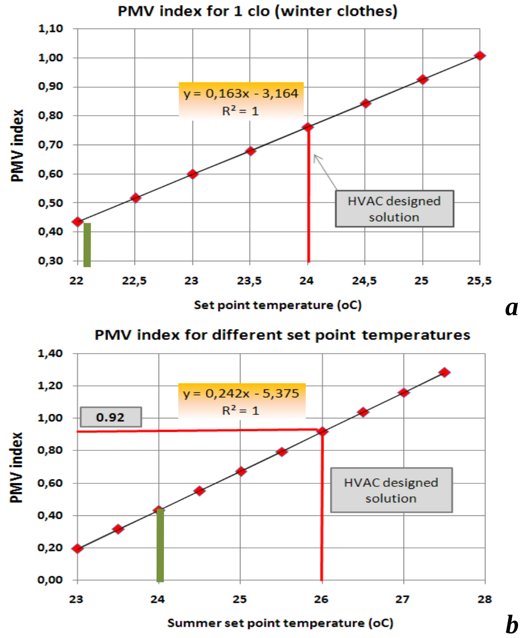

Figure 11.Set point temperature impact on the PMV index (winter/summer)

A value of 23.5 to 24°C (75.2°F) is recommended if the thermal comfort is wanted to be improved (see Figure 11 b). The same conclusions are drawn for the winter period when the set point temperature should take lower value.

ENERGY EFFICIENCY MEASURES

It is recommend adding extra 5 cm insulation (extruded polystyrene) for trafficable/non-trafficable roof and the floor between the 1st Basement and the Car parking Area. The U-value will be 0.25 W/m²K for the roof and 0.31 W/m²K for the floor.

It was found the energy demand for the heating represents the most important part between all consumption. The air heating accounts for more than 75%,so drastic measures on this system would decrease substantially the consumption.

Solution	U-value	Air heat recovery	Winter set point
Designed	Initial	8% global	24°C/75.2 °F
S_1	New	8% global	24°C/75.2 °F
S_2	New	8% global	23°C/73.4 °F
S_3	New	8% global	22°C/71.6 °F
S_4	New	29% global	24°C/75.2 °F
S_5	New	29% global	23°C/73.4 °F
S_6	New	29% global	22°C/71.6 °F
S_7	New	50% global	24°C/75.2 °F

S_8	New	50% global	23°C/73.4°F
S_9	New	50% global	22°C/71.6°F

***S_1-S_9 solutions**

Table 3. Solutions to improve the energy efficiency

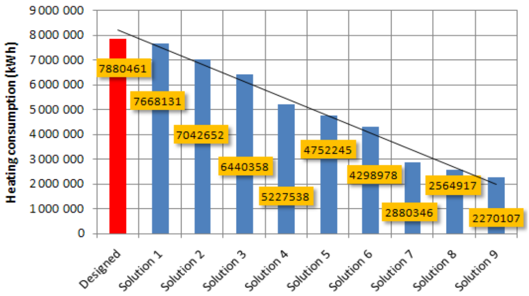

Figure 12.Impact of proposed measures on the annual heating demand of the building

Table 3 summarizes the most important measure to be applied to the mall circulation area and tenants stores. Figure 12 shows the effect of different measures on the heating consumption. The initial designed building has a global air heat recovery of 8%; the measure goes up to 50% which will lead to a significant decrease of the energy consumption (up to 70%).

CONCLUSIONS

The conclusions of this report follow two pathways:

- Indoor conditions of the designed building
- Measures to improve energy efficiency and indoor conditions

The indoor humidity levels are high (>70%) during the summer period and low (<30%) during the winter period. These values will influence the global thermal comfort and complaints from the occupants may appear for longer periods of occupation, especially from the employees. A dehumidification/humidifier system is recommended to be integrated in the AHUs. This solution will increase the initial investment but the indoor conditions will be improved. The air set point temperature for the winter period of 24°C is considered to be too high if the clothing of the occupants are at a level of insulation of 1 clo (indoor winter clothing - sweater). For lighter clothing (e.g shirt) the value is correctly. If the landlord wants an energy efficiency building it is recommended to decrease the value of winter set point from 24°C (75.2 °F) to 21-22°C (69.8-71.6 °F).

On the other part, the cooling design temperature of 26°C (78.8°F) may be considered to be too high for the indoor climate. Even cooling consumption will be higher with a decrease of temperature of set point by 2°C (35.6 °F), the PMV index will be better and the indoor conditions will be highly improved. It must be pointed out the fact that in the non conditioned spaces like Corridors and Technical spaces the indoor air temperature during the summer period can be higher than 30°C. Reducing this peak values will demand that the spaces to be air-conditioned or the air from the Mall area to be introduced in these zones.

A higher value of heat recovery will have a significantly impact on the energy consumption reduction. Moreover a decrease of the air set point temperature for the winter period of 2°C/35.6°F will decrease the heating consumption by 18% (-57 900 €/year or 82 888 $/year)).

ACKNOWLEDGEMENTS

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