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ASSESMENT OF ENERGY PERFORMANCE AND THERMAL BEHAVIOR OF A SINGLE-FAMILY RESIDENTIAL BUILDING

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Abstract

This study provides a comprehensive analysis on the impacts of passive and active design strategies with regard to energy efficiency and thermal comfort of a building in three different climate conditions, over a case study. A single-family building has been simulated to determine energy consumption and internal thermal comfort based on static (ISO 7730:2005) and adaptive thermal comfort (EN 15251:2007) criteria. A serious of simulations were conducted to optimize the building envelope by using Trnsys 17. The study carried out the results of different design options by the implementation of varied thermal mass, natural ventilation, shading, plant system and heat exchanger options for Lystrup, Paris and Rome climates. The results of simulations point out that a single building strategy without a promoter energy-driven strategy, is not enough to obtain an energy efficient building.

Key words*: Thermal Comfort; Building Envelope; Low-energy Residential Building*

1. INTRODUCTION

Buildings, as the keystones of cities, have an important role for the sustainable development. According to European Commission, buildings are responsible for 40% of global energy consumption [1]. Considering this major impact of the buildings within the context of future climate change, it is crucial to understand the energy performance of a building and to take required actions for prevention of the waste of energy. There are also many studies can be found about the impact of climate change on the energy performance of a building since they are linked to each other. Wang et al. [2], analyzed the effect of climate impact on the change of heating and cooling demands of residential buildings. The study shows up to 120% and 530% in total heating and cooling energy requirements depending on the increase in the global temperature for 2°C and 5°C. In this regard, the optimization of the building envelope, in other words the improvement of the building energy performance has become an important step during the design stage to minimize the cooling and heating energy demands, thereby the reduction of energy consumption. To improve the energy performance of a building considering the thermal comfort of the envelope, different building strategies are implied to the building envelope. Pfafferott et al. [3], carried out an experiment aiming the reduction of primary energy consumption of office buildings by utilizing the natural heat sinks such as ambient temperature, ground water, etc. An another study showed that the ventilated roof system can be used to improve the thermal performance of a building by reducing the heat flux up to 50% [4]. The

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building strategies can be classified under the two title; passive design strategies and active design strategies. The direct usage of natural energy, appropriate building orientation, optimized window to wall ratio (WWR), etc., are some of the examples to the passive building strategies [5] and optimization of HVAC system, energy efficient lightening systems can be shown as examples to the active design strategies. However, all the simulations, the energy calculations and energy performance evaluations have no meaning without a building standard. The evaluation of a building makes a sense when the results are acquainted with the specified design criteria [6].

In this study, a series of energy simulations have been operated to better understanding of impact of building technologies, climate conditions, passive and active design strategies on the energy performance of a building. A sustainable single-family building from a real case study, has been analyzed by usage of Trnsys, building energy simulation (BES). Moreover, the study provides the sensitivity analysis of different parameters aiming the most efficient energy performance of the building, such as climate conditions, building technologies (wood, brick, concrete, etc.) with different thermal mass and thermal transmittance, shading devices (intensity and control), ventilation (intensity and use), etc. Evaluation of thermal condition and energy use are the main two stages of the method of work of the study. The building performances and the thermal comfort classes are evaluated according to EN 15251:2007 (adaptive approach) and to the ISO 7730:2005 (static approach) [7], [8].

The building simulations were carried out for both summer period (1st May - 30th September) and winter period (15th October 15th April). According to UNI EN ISO 6946:2008 the thermal mass is described as the mass per unit area of the opaque wall. Thermal mass can also be considered as a passive system because the building components are capable of storing heat, thereby they can provide the heat that is needed for the active systems. For example, walls and floors in the building components are assumed as thermal masses [9], [10]. This heat storage system can be determined by usage time lag (ϕ) and decrement factor (f) [11]. In this study, the mentioned utilization factors referring the internal behavior for the assigned building technologies are evaluated regarding to UNI-EN-ISO-13786 [12].

2. MODEL PREPERATION

The model preparation consists of three steps. Firstly, the required information about the case building was collected. Then the building was divided into the thermal zones which is required for a proper thermal comfort study or sizing of HVAC system. Lastly, the implemented building technologies were defined.

2.1. Building information

The case study building was built in city of Lystrup, 10 km north of Aarhus, Denmark, in 2009. The 190 m2 home is distributed over one and a half story, with a total window area (façade windows and roof windows) is equivalent to 40% of the floor area. The building has been modelled in SketchUp. The next step was to import the 3d model into Trnsys tool with Simulation Studio and using TRNBuild.

2.2. Thermal Zone

The model was divided into a sufficient number of thermal zones and shading objects (Fig. 1). Each of thermal zone represents a space that simulates the energetic behavior of a part of the

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home. In other words, the areas in the same zone share the same load profile. The thermal zones of the building are detailed for each floor respectively:

- The first thermal zone is on the ground floor and mostly oriented to the north. It has one large window on the south facade, two windows on the west facade, five windows on the north facade and two windows on the east facade.
- The second thermal zone is on the south oriented part of the building. It has one window facing to south, one window each the west and the east facades, and it has two roof-windows facing to the south.
- The third thermal zone is on the first floor of the building. It has one window facing to the south, two windows on the west, two windows on the east, one window on the northern part and six windows on the north oriented roof.
- The building has some external shading elements. Balcony and console part of the roof are used to shade the south side of the home. On the east side, the garage, shades one of the two windows of the east side.

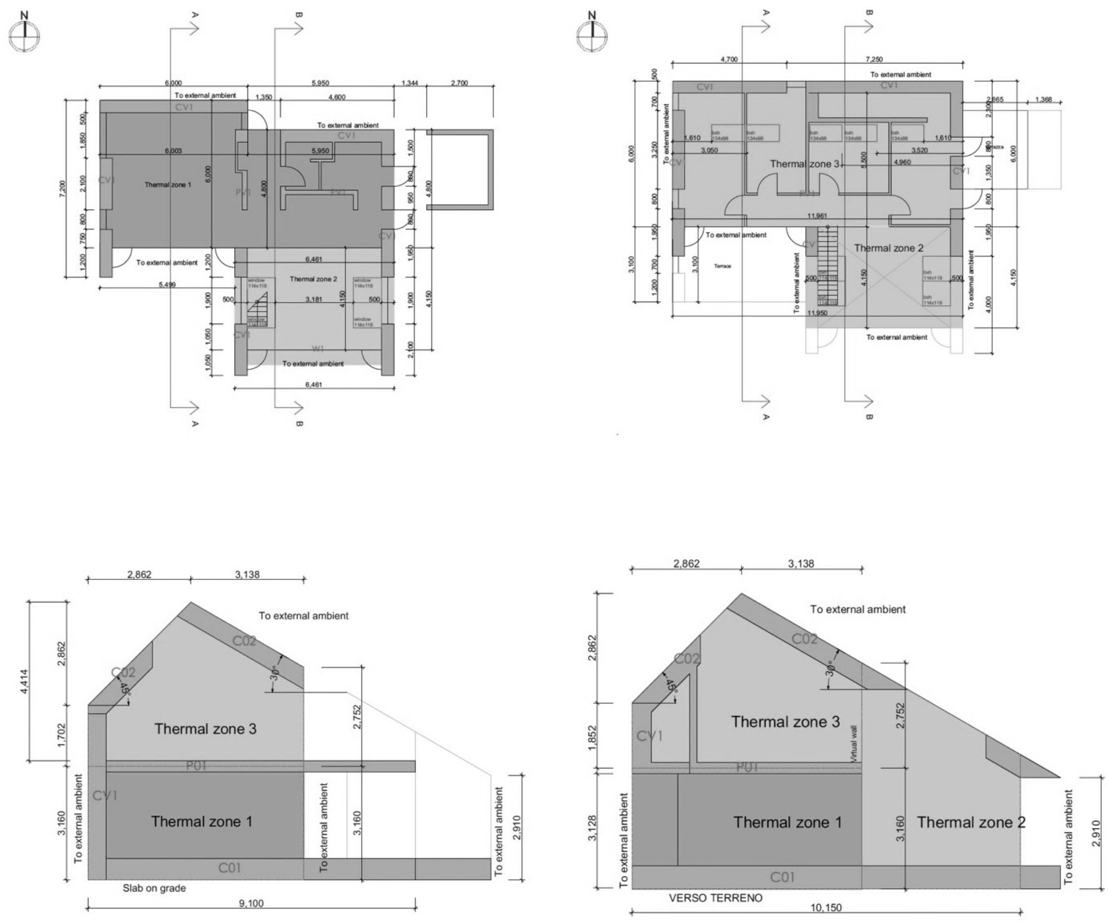

Fig. 1. Ground floor and section A-A on the left and second floor and section B-B on the right

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2.3. Building Technology

The behavior of the building was studied considering the three different building technologies listed below with the constant thermal transmittance, U-value seen in Table 3 and Table 4, in order to evaluate different building materials' behavior and to compare the thermal masses. The cases were tested in this study based on their technologies are listed below.

- Case 1: Light technology
- Case 2: Medium technology
- Case 3: Heavy technology

3. ANALYSIS OF THE DYNAMIC PROPERTIES

The dynamic thermal behavior of the building is analyzed based on UNI-EN-ISO-13786. Verified dynamic-state conditions are utilized to understand the behavior of opaque envelope components taking into consideration the influence of the time in thermal exchanges, between internal spaces and external ambient. According to the Italian code, the building performance is classified in relation to summer operation (Table 1). The analyze of the two important parameters, thermal lag and attenuation factor, can be considered as the fundamental for the thermal performance analyze, especially when the opaque elements are considered as storage in hot seasons. The attenuation factor is analyzed to determine the relationship between the external temperature variation and the heat flow from outside to inside (Fig. 3). The thermal lag is analyzed to determine the time delay for transmitting the heat between the walls.

3.1. Results

Maintaining a constant thermal transmittance, U-value, and analyzing the dynamic properties gave the following indications. It has been observed that the thermal mass value increase causes to decrease of the attenuation factor. In contrary to that, the time shift increases in parallel with the thermal mass value. Comparison of the thermal lag values (Fig. 2) shows that the stratigraphic correlation of the medium technology has a higher value of the time delay. While the thermal lag difference between heavy and medium technologies is around 3 to 4 hours, the difference between light and medium technologies is almost 6 to 7 hours. Overall the medium and heavyweight technologies show a higher level of time shift (>12), compared to the lightweight technologies. The medium and heavyweight technologies in comparison to the lightweight one, have a low decrement factor (< 0.15); which means a higher indoor thermal comfort. The increasing trend is proportional to the increment of the thermal mass. The classification table is used as an instrument of thermal analysis of opaque components, to verify the behavior of the different building technologies' elements as summarized in the Table 5. The medium construction satisfies the requirements to be classified in the first classes of performance. The analysis proved that the lower thermal transmittance alone is not enough to guarantee the optimum indoor thermal comfort considering the utilization factors.

Table 1. Classification of building performance on the basis of Italian regulation (Ministero dello Sviluppo Economico, 2009)

Time Lag [φ]	Decrement factor [f_a]	Performance	Performance quality
$\varphi > 12$	$f_a < 0{,}15$	Excellent	Excellent
$12 > \varphi > 10$	$0{,}15 < f_a < 0{,}30$	Good	Good
$10 > \varphi > 8$	$0{,}30 < f_a < 0{,}40$	Middle	Fair
$8 > \varphi > 6$	$0{,}40 < f_a < 0{,}60$	Satisfactory	Satisfactory
$6 > \varphi$	$0{,}60 < f_a$	Poor	Poor

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Table 2. Window properties

Transparent envelope components	U_w [W/m^{2}K]	*g value* [%]
Vertical windows	1.0	0.45
Roof facing South windows	1.0	0.3
Roof facing North windows	1.0	0.45

Table 3. U-value [W/m^{2}K] of different building technologies

Element	Lightweight	Medium	Massive
External wall	0.38	0.39	0.40
Horizontal slab	1.04	0.55	0.76
Slab on grade	0.21	0.23	0.31
Roof	0.65	0.14	0.14
Party wall	0.24	0.29	0.28

Table 4. Building physic characteristics of the simulation model

Case Study	Building Component	Thickness [m]	Heat capacity (kJ/m2K)	Attenuation Factor [F]	Thermal Lag [φ]
Case 1	External wall (CV1)	14.60	23.46	0.92	3.25
	Horizontal slab (PO1)	14.00	46.18	0.83	3.88
	Slab on grade (CO1)	14.60	46.82	0.11	17.33
	Roof (CO2)	57.40	31.18	0.69	5.74
	Party wall (PV1)	26.60	48.20	0.49	8.19
Case 2	External wall (CV2)	32.20	32.35	0.08	16.80
	Horizontal slab (PO2)	27.00	47.46	0.21	12.52
	Slab on grade (CO3)	116.50	51.12	0.10	12.52
	Roof (CO4)	48.10	31.52	0.21	12.92
	Party wall (PV2)	24.60	47.90	0.22	10.84
Case 3	External wall (CV3)	60.10	120.80	0.17	7.18
	Horizontal slab (PO3)	31.50	36.44	0.44	6.20
	Slab on grade (CO5)	66.50	34.33	0.42	6.97
	Roof (CO6)	50.10	121.63	0.28	8.96
	Party wall (PV3)	41.60	78.40	0.34	10.00

Table 5. The building performance rating according to the Italian regulation (Ministero dello Sviluppo Economico, 2009)

Element	Lightweight		Medium		Massive	
	φ [h]	fd [-]	φ [h]	fd [-]	φ [h]	fd [-]
Vertical wall	3.25	0.92	16.80	0.08	7.18	0.17
Horizontal slab	3.88	0.83	12.52	0.21	6.20	0.44
Slab on grade	17.33	0.11	14.52	0.10	6.97	0.42
Roof	5.74	0.69	12.92	0.21	8.96	0.28
Party wall	8.19	0.49	10.84	0.22	10.00	0.34

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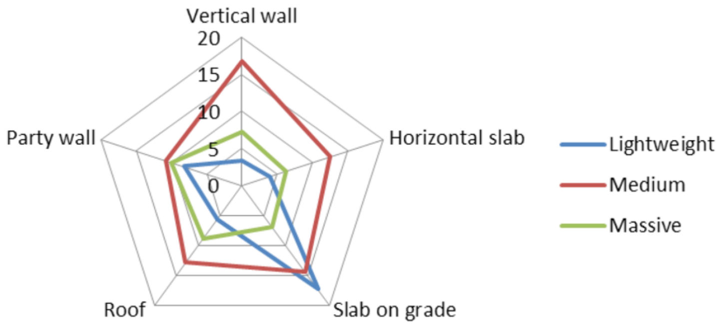

Fig. 2. Thermal time shit

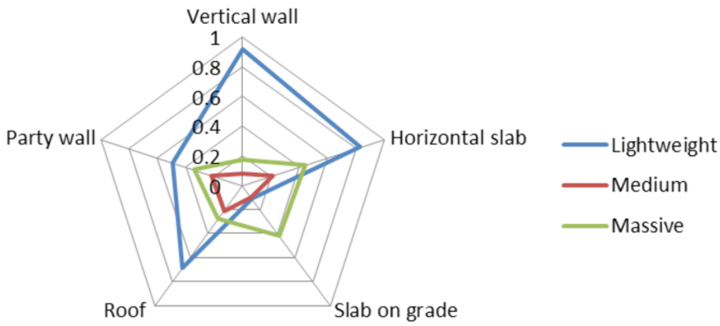

Fig. 3. Decrement factor

4. CLIMATE ANALYSIS

Preliminary design solutions considering the orientation and the aspects related to the building form can be deduced by analysing the annual/seasonal distribution of solar radiation, air temperature, wind direction and relative humidity. The defined building technologies were assigned in the simulations of TRNBuild and TRNEdit. The different climate properties were added the model through the Simulation studio. The climate data was collected by using the Meteonorm software which generates the accurate database from the weather station of a demanded location. The simplified Trnsys model was conducted with the input database of the different cities. In this study, the air temperature (°C), relative humidity (%), direct solar radiation (kWh/m2), wind velocity (m/s) and wind direction (orientation) were used as database.

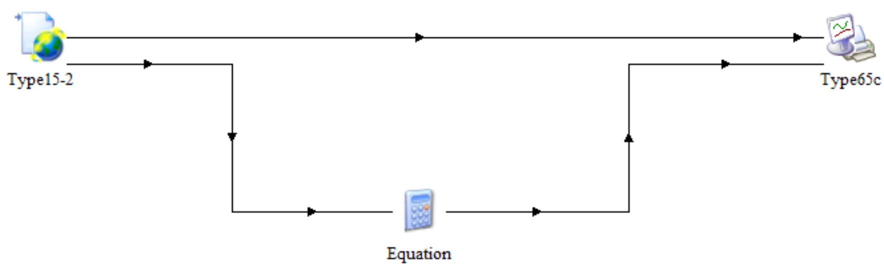

Fig. 4. The scheme of climate analysis

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To verify the behaviour of the building performance with different sets of external conditions, three different climate conditions were analysed. The purpose of this step was to determine the most efficient technology and climate that is consistent with Air temperature and Relative humidity values.

4.1. Climate type

The locations were decided so as to be analysed for hot climate, mild climate and cold climate conditions. The cities were selected as listed below.

- Lystrup climate data for cold climate condition
- Paris climate data for mild climate condition
- Rome climate data for hot climate condition.

The maximum and minimum temperature values of the three cities can be followed from Fig. 5. The maximum ambient temperature value highlights the fact that the range of variation is almost parallel for the Paris climate and the Lystrup climate. But on the other hand, the minimum average temperature can be tracked for the Lystrup climate. Given that the thermal comfort depends on the external climate conditions. In every location, the variation of the temperature causes the similar difficulties from the design point of view. The following indications can be deduced from the monthly average temperature graph in Fig. 6. Among of the three cities, the Rome represents the warmest climate in overall and the Lystrup represents the coldest climate throughout a year. The information of minimum and maximum temperature values and monthly average temperature values clue in about the cooling and heating demands (caused by the climate condition) of the building.

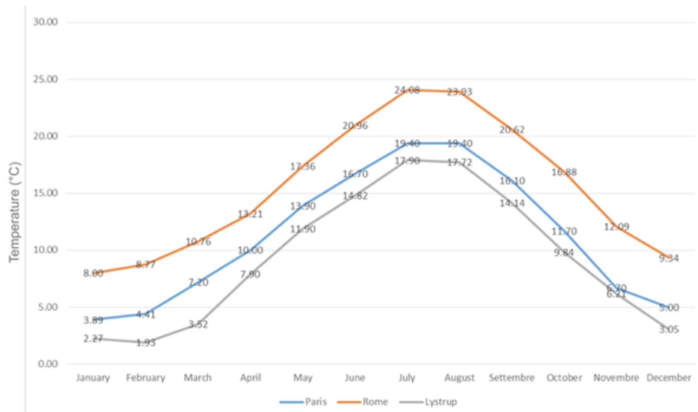

Fig. 5. Ambient temperature - Minimum and maximum values

IJESG International Journal of Energy and Smart Grid
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Fig. 6. Ambient temperature - Month average

The humidity and temperature have different ranges of variation for the three cities (Fig. 7, Fig. 8 and Fig. 9). It is observed that while the hot summer is in Rome where the average temperature is 23°C and relative humidity is 74.7%, the driest summer is in Paris where the average is temperature 18.5°C and relative humidity is 70.3%. Also, a variety of intermediate conditions between the hot, dry and cold climate conditions are traced for the two cities. The situation for Lystrup climate is also similar with a different range of variations. In winter period, the coldest climate is in Lystrup with the average temperature 2°C and relative humidity 85.5%. The minimum relative humidity is seen in Paris with 36% in April. Lystrup has more humid climate than others. The maximum relative humidity (100%) can be seen for the all three cities.

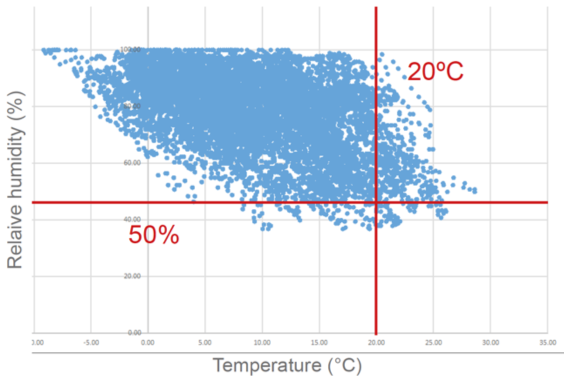

Fig. 7. Lystrup, Denmark

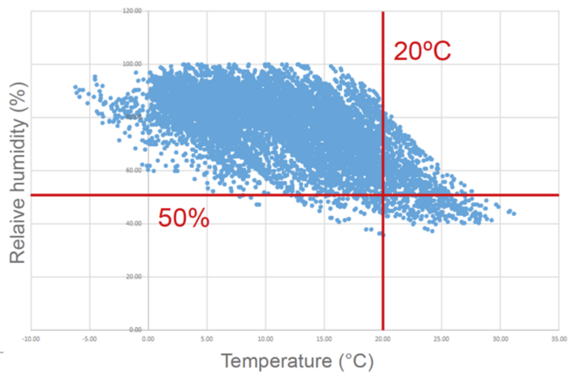

Fig. 8. Paris, France

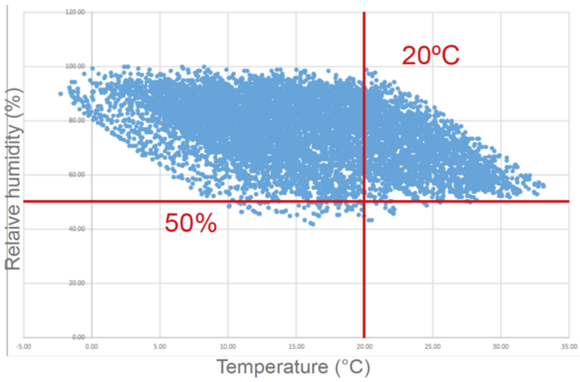

Fig. 9. Rome, Italy

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5. SOLAR RADIATION

The monthly average of the Direct Solar Radiation for the mentioned cities can see tracked from the Fig. 11. Considering that all the cities are located in the boreal hemisphere, the direct solar radiation trend for each location seems similar. It is interesting to observe that the monthly average direct solar radiation is the lowest in Paris while it is expected to be seen in Lystrup. Regarding the maximum direct solar radiation, it has been observed that for each location, the result shows a rather constant value during the year (Fig. 10). However, the maximum values are relatively close for all three locations and eventually the solar system installed in this location would provide a rather constant gain at an energetic level. The highest direct solar radiation values are seen for Rome climate. The result of the solar radiation analyse was utilized to evaluate the efficiency of the eventual solar and shading system.

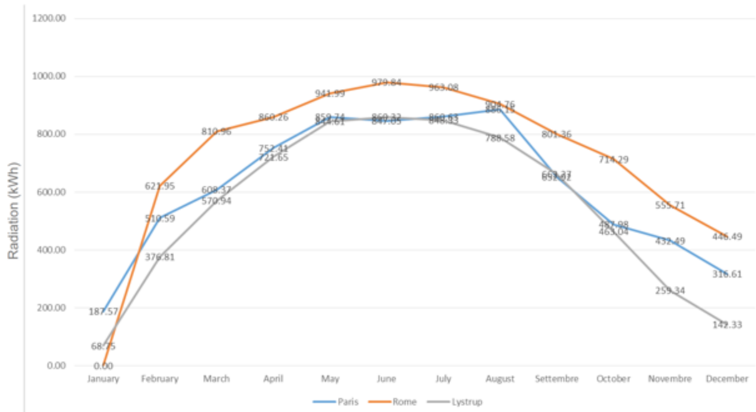

Fig. 10. Solar radiation - Maximum per month

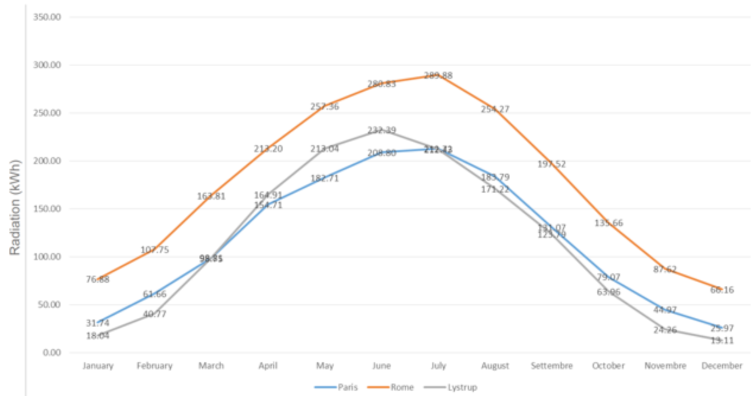

Fig. 11. Solar radiation - Monthly average

Considering all the climatic analyses so far, some specific conclusions could be drawn regarding the influence of the climate shift. From the series of comparative analysis previously illustrated, substantial differences emerged between the climates taken into consideration. The hypothetical displacement of the building in the three different cities shows that the climate change has a high influence on the subsequent analysis results.

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6. IMPACT OF CLIMATE ON THE DIFFERENT BUILDING TECHNOLOGIES

The main purpose of the following simulations is to test the building with all the possible combinations of applicable passive strategies, in order to obtain the best combination in terms of energy efficiency and thermal behavior. The best combination is used as a base case to implement, where needed, the all necessary active strategies.
After creating the model on SketchUp and opening it in Simulation studio component of Trnsys, it was necessary to set up some starting point conditions that were kept fixed in all the simulations as shown in Table 6, Table 7 and Table 8. The TRNBuild component of Trnsys was used for giving the initial inputs of the simulation. The tool was conducted to define the different layering and to set the parameters.

Table 6. Initial point conditions

Thermal zones	Schedule	Internal heat gains (light and appliances) [W/m2]
Thermal zone 1	7:00-8:00; 11:00-13:00; 17:00-22:00	4
Thermal zone 2	7:00-8:00; 11:00-13:00; 17:00-22:00	4
Thermal zone 3	7:00-7:30; 22:00-23:00	1.5

Table 7. Initial point conditions

Thermal zones	Schedule	Internal heat gains (persons) [W/m2]
Thermal zone 1	7:00-8:00; 11:00-13:00; 17:00-22:00	2
Thermal zone 2	7:00-8:00; 11:00-13:00; 17:00-22:00	1
Thermal zone 3	22:00-7:00	2
Air infiltration [ACH]	0.1	

Table 8. Initial point hygrometric values

Thermal zones	Starting point temperature [°C]	Relative humidity [%]
Thermal zone 1, 2, 3	5	50

The comfort is evaluated for each thermal zone separately with the three building technologies for three different climate conditions. The analyses have been done to understand how the operative temperature changes depending on the building technology correlated with the ambient temperature for the different climate conditions. From the annual simulation, it was seen that the three thermal zones present some differences in terms of behaviors. For thermal zone 1 and thermal zone 3, the maximum temperature was tracked around 40°C in Rome. Moreover, for all three climates thermal zone 2 presents higher values of maximum temperatures. The most efficient performance for the building technology was massive technology, namely C type for all types of climates as it allows slightly higher temperatures in cold days and lower temperatures in hot days. In Fig. 12 shown as an example, an accurate zooming for Paris climate on the hottest month over a typical year (July) narrowed the result down by the purpose of emphasizing the role of building technologies in determination of the internal operative temperatures. The same procedure was implemented for Rome and Lystrup climate data as well. Considering the hottest month (July), the lightweight and medium technologies perform similar in comparison to the massive technology. The massive technology

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showed a better performance than the other two technologies as it permits the presence of sensible lower temperatures in the hotter days for all climate conditions.

As the conclusion of the impact of the climates and technologies on the building performance, the following results were observed.

- The preferable technology for Lystrup climate is the massive technology;
- The preferable technology for Paris climate is the massive technology;
- The preferable technology for Rome climate is the massive technology.

Regarding the simulation results, the massive technology is used as the best solution for the all chosen climates. The following simulations were done by using the massive technology strategy.

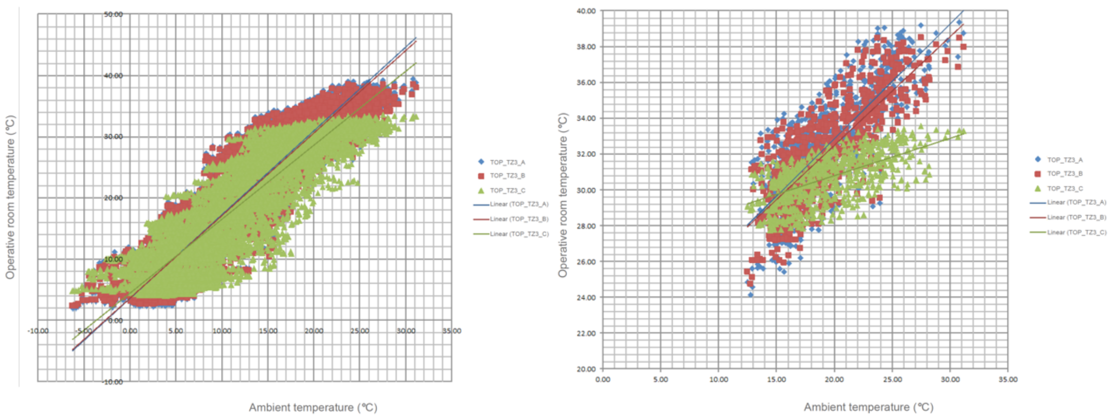

Fig. 12. Paris - Influence of technologies - Thermal zone 3 - Annual Simulation on the left and July on the right

- ***TOP_TZ1,2,3_A - operative room temperature [°C] for thermal zone 1,2,3 with lightweight technology;***
- ***TOP_TZ1,2,3_B - operative room temperature [°C] for thermal zone 1,2,3 with medium technology;***
- ***TOP_TZ1,2,3_C - operative room temperature [°C] for thermal zone 1,2,3 with massive technology;***
- ***Linear (TOP_TZ1,2,3_A,B,C) – interpolation of the TOP_TZ1,2,3_A,B,C data.***

7. IMPACT OF SHADING STRATEGIES

In this part of the study, the influence of shading devices on the building performance are analyzed. The different shading strategies were applied to the simulation model and observed the results. Proceeding in that way, three types of shading strategies were introduced. The shading strategies were defined by the percentage of shading factor and applied to the glazed components of the envelope.

Initially, 0.6 Vol/h ventilation rate was adopted through the building envelope as a constant value. All the simulations were performed considering the summer behavior (July) of the building since it is the most variational parameter and the simulations were strictly related to the solar radiation for every single context introduced in this study. The data analyzed is related to the operative room temperature, since it is considered as the most relevant energy data for

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defining the thermal comfort conditions of the inside envelope of the building. The simulation results with the different shading strategies, following the order of Table 9 were evaluated. The operative room temperature of each three zones was obtained with the different shading options for the climates of Lystrup, Paris and Rome.

Table 9. Shading strategies

Location	Thermal zone	Shading strategy	Percentage of shaded surface
Lystrup, Paris, Rome	Thermal zones 1, 2, 3	Low shading strategy	20%
		Medium shading strategy	50%
		Hight shading strategy	80%

7.1. Results

Proceeding in this way, the remarkable changes on the operative room temperatures were obtained with the mentioned percentages of the shaded surface. The following deductions were made for all types of climate conditions. The peak operative room temperatures have been decreased to 20°C to 25°C from 30°C to 38°C for the thermal zone 2 by adopting to the 80% shading strategy. In the case of 20% and 50% shading strategies, the operative room temperature of the three thermal zones varies between 23°C and 38°C. The highest uncomfortable temperature was obtained with 20% shading strategy for all thermal zones. The 80% shading strategy shows the best results with regard to the comfort temperature in July. The analysis confirmed the strong relationship between the operative room temperature of each thermal zone including the roof windows and incident solar radiation. In case of Rome, the comfortable operative room temperature could not be achieved for most of the analysis period, even though the high shading strategy (80%) was adopted for each thermal zone. The analyses can be summarized as that adaptation of shading solutions alone on the glazed components of the envelope is not enough to obtain desired results in terms of internal thermal behavior. The strategies were chosen to follow for the further steps are listed below.

- The preferable shading strategy for Lystrup is medium (50%);
- The preferable shading strategy for Paris is medium (50%);
- The preferable shading strategy for Rome is high (80%).

8. IMPACT OF VENTILATION STRATEGIES

The ventilation systems provide the passive cooling in buildings and correspondingly the thermal comfort and improved of energy performance. In this step the ventilation strategies were performed by TRNbuild component of TRNSYS simulation tool. The strategies were applied on the three thermal zones. All the strategies were associated to a schedule shown in Table 10. The data used in this section are the operative room temperature and the outside temperature since they are considered as the most relevant energy drivers to determine the comfort condition inside the building. All the simulations were performed for the summer season (July) as the most variable results were obtain in summer season for the previous simulations too.

IJESG International Journal of Energy and Smart Grid
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8.1. Results

The study mostly focuses on thermal zone 2 and thermal zone 3 for the all climates in the context of ventilation strategy since the impact of ventilation system is more crucial when the temperature ranges are considered. Regarding behavior of thermal zone 2 in Rome case (Fig. 13), the high ventilation strategy shows the most effective operative room temperature range, in comparison to the other cases. In Paris climate, implementation of the high ventilation strategy shows a reasonable solution, as it permits to maintain an intermediate range for the comfort temperature which varies between 22°C and 30°C. For the analysis of thermal zone 3 in the Rome climate, the lowest mean operative temperature was obtained when the ventilation rate was the highest. To sum up, the analyses proves that with introducing the appropriate ventilation system to the building envelope reduces the demand for a cooling system, therefore decreases the overall energy consumption of the building without activation of a plant system. As a conclusion of the analyses, the following strategies have been chosen:

- The preferable ventilation strategy for Lystrup case is high (1.5 Vol/h);
- The preferable ventilation strategy for Paris case is high (3 Vol/h);
- The preferable ventilation strategy for Rome case is high (3 Vol/h).

Table 10. Ventilation strategies

Location	Thermal zone	Schedule	Ventilation strategy	
Lystrup, Paris, Rome	Thermal zones 1, 2, 3	7:00-18:00	Low ventilation	0.6 Vol/h
			Medium ventilation	1.5 Vol/h
			High ventilation	3.0 Vol/h

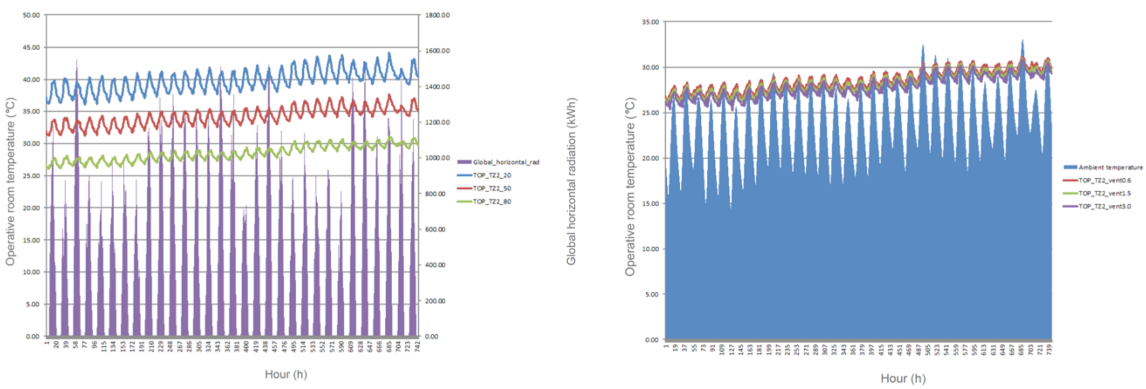

Fig. 13. Implementation of shading and ventilation strategies on thermal zone 2 for Rome climate, as an example

9. COMFORT ANALYSIS

In this section, the hygrothermal comfort of internal spaces of the building is analyzed. The study so far determined the simulation results with the intent of energy consumption reduction by selecting the best strategy. The analysis and the evaluations till this section were done mainly by considering the operative room temperature and ambient temperature. To obtain a robust analysis, in this section the building is analyzed according to the static comfort and the adaptive

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comfort analysis since both are crucial for comfort rating. The following analyses in this section were done to find out the best building technology among of the ones described in the previous sections (lightweight, medium, massive) with the fixed building strategies for ventilation and shading as indicated in the Table 11, by making use of the static and adaptive comfort criterion.

Table 11. Scheme of best solutions

Location	Shading strategy	Ventilation strategy
Lystrup	Medium (50%)	High ventilation (1.5 Vol/h)
Paris	Medium (50%)	High ventilation (3.0 Vol/h)
Rome	High (80%)	High ventilation (3.0 Vol/h)

9.1. Static Model (UNI EN ISO 7730) and Adaptive Comfort Model

Both the static thermal comfort model and adaptive model were used to evaluate the percentage of occupants satisfied with thermal environment according to ISO 7730 and UNI EN 15251respectively. The adaptive comfort categories is shown in Table 12. The charts below for Lystrup case are shown as an example. The same evaluations were done for each climate conditions separately. The colored dots for both charts represent the zone temperatures of the hours for the related thermal zone, grey the lines show the upper limits and the dark grey lines show the lower limits classes (Fig 14).

Table 12. Thermal comfort categories by UNI EN 15251

Category	Applicability/Level of expectancy	Limit equations
I	High: Buildings with high expectancy for sensitive occupants	Upper limit: θi,max = 0.33×θrm+18.8+2 Lower limit: θi,max = 0.33×θrm+18.8-2
II	Normal: New buildings and renovations	Upper limit: θi,max = 0.33×θrm+18.8+3 Lower limit: θi,max = 0.33×θrm+18.8-3
III	Acceptable: Existing buildings	Upper limit: θi,max = 0.33×θrm+18.8+4 Lower limit: θi,max = 0.33×θrm+18.8-4
IV	Low: Expectancy only for short periods	-

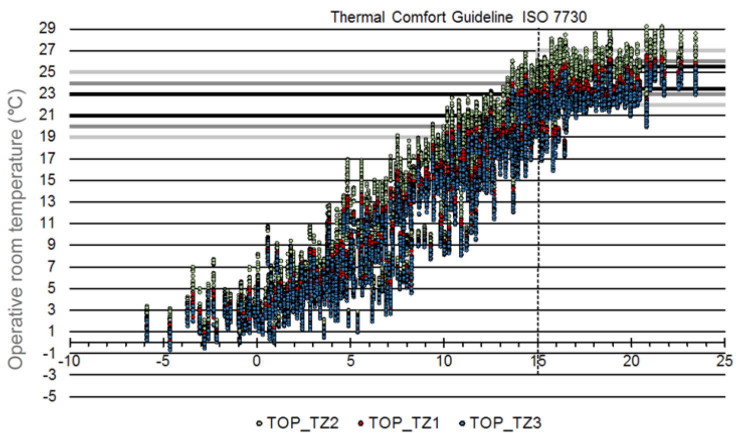

Fig 14. The static thermal comfort model based on ISO 7730 for medium

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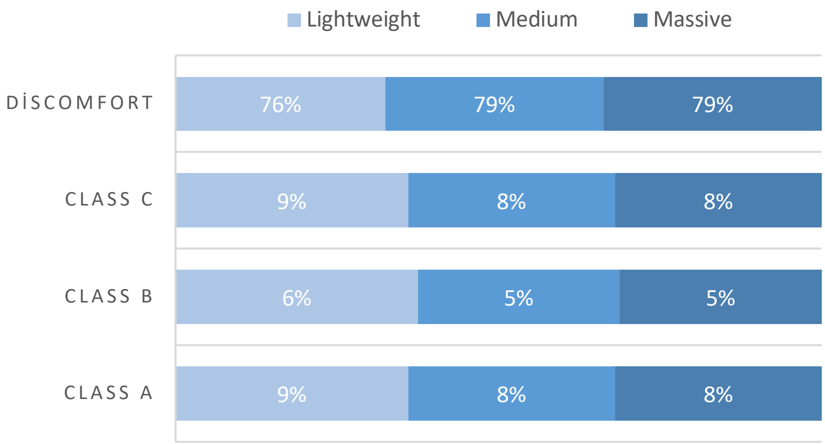

Fig. 15. Static comfort analysis result for Lystrup technology in Lystrup

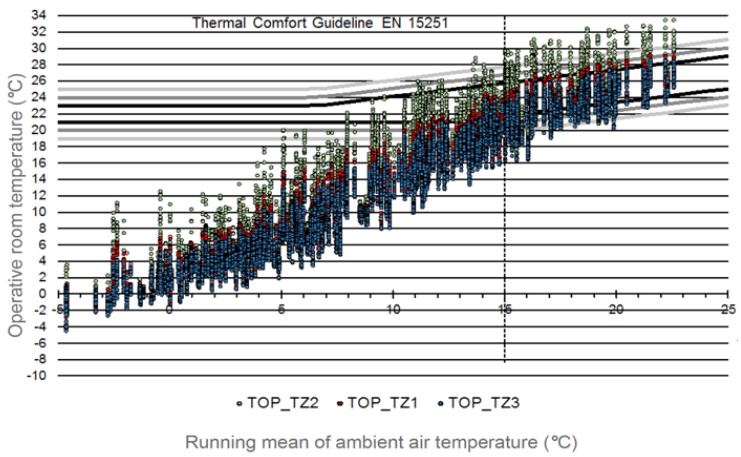

Fig. 16. The adaptive thermal comfort chart based on UNI EN 15251

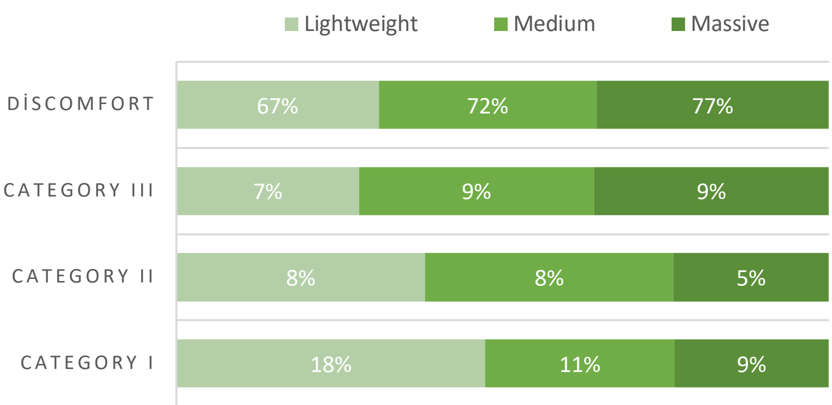

Fig. 17. Adaptive comfort analysis result for Lystrup medium technology for Lystrup

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9.1.1 Lystrup Climate

Regarding the static comfort analysis, the largest number of unsatisfied users was defined as 76% when the lightweight technology was adopted. The medium technology and massive technology presented a similar trend with 79% occupants satisfied. From the comparison analyses, the operative room temperature of thermal zone 2 was higher than other two thermal zones. In the case of adaptive model, the operative room temperature trend was similar in the case of lightweight and medium technologies. Thermal zone 1 provided a better overall behavior in comparison to the other two thermal zones. Considering the two comfort models, the results showed that the highest efficient performance solution was for the lightweight technology justified by the fact that it provided an increase as twice much, in the percentage of the satisfied users in category I.

9.1.2 Paris Climate

In the Paris case, the range of operative room temperatures was obtained between -3°C and 30°C. Due to the location and the zone geometry, thermal zone 2 represented a higher operative room temperature range between 30°C and 35°C. Regarding the static comfort analysis, the percentages of satisfied users were similar for the lightweight and the medium technologies. The least number of unsatisfied users was defined as 74% in the case of the massive technology. According to adaptive comfort model, the massive and medium technologies showed similar percentages of discomfort category. The lightweight technology appears as the most performing one, as in summer period the operative room temperatures are totally in comfort class range. The lightweight technology has been chosen for Paris climate as solution because of the least percentage of unsatisfied users (65%) shown in the adaptive model.

9.1.3 Rome Climate

The range of operative room temperatures for Rome climate was obtained between 2°C and 28°C. It is deduced from the evaluations, the passive strategies applied for the climate of Rome are effective mainly in summer season. Comparing the previous context for the Rome climate, the operative room temperatures are less scattered and thermal zone 3 has the highest values for the operative room temperature. The largest number of unsatisfied users was obtained in the case of the lightweight and medium technologies as 79%. According to static comfort analysis, the massive building technology is the one with highest efficiency among the other technology options for Rome climate.

In the context of adaptive model, the envelope solutions can be considered as similar. The medium technology appeared as the highest efficient technology with 59% occupants satisfied with the thermal environment, as in summer period the operative room temperatures for most of the days were in comfort class range limit.

9.2. Results for Static and Comfort Analysis

According the hard data of the comfort analyses, the numerical outputs were deduced. The results showed the necessity of a plant system, providing both heating and cooling services aiming to increase the internal comfort conditions. The working on the performance of envelope components alone was not enough to guarantee acceptable comfort conditions, especially in winter period for all the climates. The further simulations were conducted by adopting following technologies:

- Lystrup - Lightweight technology;

IJESG International Journal of Energy and Smart Grid
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- Paris - Lightweight technology;
- Rome - Medium technology.

10. IDEAL PLANT SYSTEM

After the optimizations with the passive strategies i.e. envelope technologies, natural ventilation and solar shading, there was still a percentage of discomfort inside the building. Therefore, plant systems i.e. heating and cooling systems, are introduced to the model aiming to improve in the indoor thermal comfort. Type 91 was inserted to the simulation as an air ventilation system and heat exchanger combined. The plant system is set by taking in consideration the boundary climatic conditions of each location (Lystrup, Paris, and Rome). The heating schedules depending on degree days parameters (HDD) are defined based on Italian regulations (Table 13). Lystrup and Paris are located in climate zone E and Rome is located in climate zone D. The performed simulations are indicated step by step in Table 14 for the following analyses.

Table 13. Schedule of heating and cooling systems

			Heating schedule		Cooling schedule	
Climate zone	Location	Degree days	Days	Daily schedule	Days	Daily schedule
E	Lystrup	2100-3000	15th Oct-15th April	07:00-12:00 16:00-19:00	1st May-30th Sep	10:00-18:00
E	Paris	2101-3000	15th Oct - 15th April	07:00-12:00 16:00-19:00	1st May-30th Sep	10:00-18:00
D	Rome	1401-2100	1st Nov – 15th April	07:00-12:00 16:00-19:00	1st May-30th Sep	10:00-18:00

Table 14. Scheme of the performed simulations

			Passive strategy	
Type of simulation	Location	Active strategy	Shading/Surface Percentage	Ventilation Rate
Step 1. Heating and cooling systems	Lystrup, Paris, Rome	Heating (20°C) Cooling (26°C)	-	0.3 Vol/h
Step 2. Heating and cooling systems	Lystrup, Paris, Rome	Heating (21°C) Cooling (26°C)	-	0.3 Vol/h
Step 3. Heating and cooling systems + Shading strategies	Paris	Heating (21°C) Cooling (26°C)	20% 80% Adaptive (South, West-50%, East-20%)	0.3 Vol/h
	Rome	Heating (21°C) Cooling (26°C)	20% 80% Adaptive shading (South, West-50%, East-20%) Adaptive shading (South, West-80%, East-20%)	0.3 Vol/h
Step 4. Heating and cooling systems + Passive strategies	Rome	Heating (21°C) Cooling (26°C)	20% for Thermal zone_1,3 + Adaptive shading (South, West-50%, East-20%) for Thermal zone_2	0.3 Vol/h (08:00-22:00) 1.5 Vol/h (22:00-08:00)
	Rome	Heating (21°C) Cooling (26°C)	20% for Thermal zone_1,3 + Adaptive shading (South, West-50%, East-20%) for Thermal zone_2	0.3 Vol/h (08:00-22:00) 3.0 Vol/h (22:00-08:00)

IJESG International Journal of Energy and Smart Grid
Vol 4, Number 1, 2019
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10.1. Step 1. Heating and cooling systems
Implementation of a plant system decreased the percentage of unsatisfied users. By observing the quantitative definition, it is possible to derive that in Rome case the number of unsatisfied users is decreased from 59.94% to 30%. It is seen also in Lystrup and Paris with 50% and 48% respectively, for unsatisfied users. In Paris and Lystrup cases the comfort level depended on the heating system. For this reason, the energy consumption of the building was heavily influenced by the winter energy demand. On the other hand, the need of cooling system in Rome climate plays a fundamental role in defining the comfort level and at the same time causes a higher energy consumption during summer season. It is important to see that the 90% of heat gains were associated to solar so the cooling system. The losses were associated to infiltration through the envelop. The total energy consumption for heating and cooling was 53.13 kWh/m2 for his step.

10.2. Step 2. Heating and cooling systems
The same strategies implied for step 1, here the heating system set to 21°C to improve the energy performance. That was resulted with increase on the number of occupied satisfied with thermal environment according to adaptive comfort analysis. 12%, 14% and 2% decreases on the percentage for the number of occupants in discomfort, were deduced for Lystrup, Paris and Rome cases respectively. The heating and internal gains was 17% less comparison to the previous simulations due to the increase of heating set point temperature. Total energy consumption for heating and cooling for this step was 55.94 kWh/m2.

10.3. Step 3. Heating and cooling systems with shading strategies
In this step, the building performance was improved by combination of passive strategies with the idealized plan system. Addition to the 20% and 80% shading strategies, different adaptive systems were introduced to minimize the cooling load. The shading systems were tested with different percentages for south, east and west facades. The scheme of performed strategies can be followed from Table 15.

Table 15. Scheme of performed simulations in the Step 3

Location	Thermal zones	Shading strategy	Percentage of shaded surface
Paris	Thermal zones 1, 2, 3	Low shading strategy	20%
		High shading strategy	80%
		Adaptive shading strategy 1	South, West 50%, East 20%
Rome	Thermal zones 1, 2, 3	Low shading strategy	20%
		High shading strategy	80%
		Adaptive shading strategy 1	South, West 50%, East 20%
		Adaptive shading strategy 2	South, West 80%, East 20%

In the Paris case, adopting the fixed shading devices with 20% of the covered glazed resulted with a better performance than 20% of shading as increasing the number of satisfied users: Thermal zone 1; Category I from 0% to 30.11%; thermal zone 2: Category I from 0.91% to

Vol 4, Number 1, 2019
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31.10%; thermal zone 3: Category I from 0% to 24.34% increased by transferring the 80% shading to %20 shading. The results from adaptive shadings showed efficient results in thermal zone 2, but for thermal zone 1 and 3, 20% of shading was a better solution. From the analysis of energy demand on Paris case, the solution of fixed shading elements with 80% of the covered glazed surface resulted with the least performing solution, as it caused an increase in the sensible heat in winter means the amount of energy needed to increase the indoor temperature. The low shading and the adaptive strategy were resulted as the best performing strategy, since it reduced the winter energy demand from 11399.45 kWh, to 10587.39 kWh and 11399.45 kWh, respectively. In the Rome case, reduction of the glazing percentage was a better option as in the case of Paris. The number of satisfied users in Rome case increased as; thermal zone 1: Category I from 0.43% to 62.15%; thermal zone 2: Category I from 16.8% to 33.4%; thermal zone 3: Category I from 13.36% to 51.53%. The results from adaptive shadings strategy showed a similar result with the Paris case. The adaptive shade strategy 1 showed 5096.19 kWh energy demand while the adaptive shade strategy showed 6947.02 kWh energy demand. In comparison to the low shading strategy and the adaptive shade strategy 1, the energy demands obtained as 6947.02 kWh, to 3866.36 kWh respectively. In conclusion, the following shading strategies have been chosen taking into account the results related for both to comfort and energy consumption.

- The preferable shading strategy for Thermal zone 1 - Low (20%);
- The preferable shading strategy for Thermal zone 2 - Adaptive (South, West facades-50%, East facade-20%);
- The preferable shading strategy for Thermal zone 3 - Low (20%).

10.4. Step 4. Heating and cooling systems with passive strategies

The previous step proved that the most efficient climate for the building results were obtained for the Rome climate conditions. Hence, the further steps were conducted with the Rome climate data. In addition to that, the optimum shading strategy was defined for each zone separately. The performed simulations are listed in Table 16. The purpose of this stage to deduct the optimum ventilation strategy that would work efficiently with the ideal plant system. For this purpose, different ventilation rate values are introduced; 0.3 Vol/h, 1.5 Vol/h and 3.0 Vol/h.

Table 16. Scheme of performed simulations in the Step 4

Location	Thermal zones	Strategies		Ventilation strategies
		Active strategies	Shading strategies	
Rome	Thermal zones 1, 3	Heating (21°C) Cooling (26°C)	Low shading strategy (20%)	0.3 Vol/h (08:00-22:00)
	Thermal zone 2		Adaptive shading strategy (S, W-50%, E-20%)	1.5 Vol/h (22:00-08:00)
Rome	Thermal zones 1, 3	Heating (21°C) Cooling (26°C)	Low shading strategy (20%)	0.3 Vol/h (08:00-22:00)
	Thermal zone 2		Adaptive shading strategy (S, W-50%, E-20%)	3.0 Vol/h (22:00-08:00)

IJESG International Journal of Energy and Smart Grid
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The results showed that optimization of natural ventilation system regarding the thermal zone increased the number of satisfied occupants. The comfort level increased to 53% in Category I with introducing 1.5 Vol/h rate of ventilation to the thermal zone 2 while the other option also represented a good amount of satisfied occupant with 51%. For the energy the demand analysis, the results determined for the summer season. The energy demand analysis showed 3.0 Vol/h ventilation rate as the most efficient solution. Total energy consumption for heating and cooling was 41.43 kWh/m2.

11. HEAT EXCHANGER

In this section, the impact of the heat exchanger, classified as a hybrid device, was investigated for the climate data of Rome aiming the reduction of energy demand for plant system. The heat exchanger was introduced into the TRNSYS simulation model. The ground heat exchanger is an underground heating that can work as passive heating and cooling system. By introducing the controlled ventilation, the contribution of the natural ventilation and infiltration were neglected. Initially, the main parameters of ground heat exchanger were optimized. The relationship between ground heat exchanger efficiency and the depth, length and diameter of the exchanger system was evaluated (Table 18) by determining the load side outlet temperature. Firstly, the depth of the duct was investigated to find the appropriate depth in terms of the load out temperature for both winter and summer seasons. The 60 m duct length and the 0.3 m duct diameter were used initially. As result, the 6 m and 10 m duct depths showed similar temperature trends. Both duct depths provided 10°C temperature difference between load outlet and ambient temperature in the summer season. Due to the constructive reasons, 6 m length has been chosen. Secondly, the duct diameter was simulated for 0.2 m, 0.3 m and 0.6 m with the 6 m duct length and 60 m duct length. The highest temperature difference (12°C) was obtained with 0.3 m duct diameter. As third and the last step, the duct length was simulated for 20 m, 40 m and 60 m. The 14°C temperature difference was obtained with 60 m duct length. As final result, the following duct characteristics have been chosen.

- The preferable depth of the duct - 6 m;
- The preferable diameter of the duct - 0.3;
- The preferable length of the duct - 60 m.

By introducing the heat exchanger to the building envelope, the total energy consumption for heating and cooling was obtained as 35.53 kWh/m2.

Table 17. Parameters of Ground Model (Type 77)

Amplitude of surface temperature [°C]	Time shift [day]	Soil thermal conductivity [kJ/hmK]	Soil density [kg/m3]	Soil specific heat [kJ/kgK]
5	30	8.72	2000	0.84

Table 18. Options for defining the depth of the duct

Location	Duct length [m]	Duct diameter [m]	Duct depth [m]
Rome	20 40 60	0.2 0.3 0.6	1.5 3.0 6.0 10.0

Vol 4, Number 1, 2019
ISSN: 2548-0332 e-ISSN 2636-7904
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12. CONCLUSION

The main purpose of this research is investigation of the thermal behavior buildings depending on the passive and active strategies implemented to the building envelope. With this aim, a building energy simulation tool was conducted for a case study building constructed in Lystrup, Denmark. The research study determines the thermal lag and the attenuation according to Italian code, to evaluate internal thermal behavior of the building.
The results of the study show that with the right passive strategy, the amount of the energy consumption can be considerably reduced. In particular, controlled shading system minimized the solar gains. The impact of thermal mass over the different building technologies are analyzed with combining the passive strategies. It was important to consider the different climate conditions during the analysis. Therefore, the study was carried out for three cities; Lystrup, Paris and Rome. Even though the initial analyses showed the massive strategy as the most effective design strategy, the further simulations, when the building technologies were combined with the other passive design strategies, showed the lightweight technology for the Lystrup and Paris climate and the medium technology for Rome climate. The building with free running (only with passive strategies) represented only 40% thermal comfort in the category III for Rome case as the highest result. The lowest comfort conditions were observed for the Lystrup case. The study showed that the passive strategies was not enough to achieve for the different climate conditions. The analysis was conducted for whole year with taking into account occupied hours.
The energy benchmarks used in this research to determine how efficiently the building used the energy, are not discussed in this paper. The energy benchmarking method as an effective tool to identify the building properties, will be analyzed in a further research paper.

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Vol 4, Number 1, 2019
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