Thermal Performance of Retrofitted Envelopes with Internal Insulation:

A Comparative Analysis

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ABSTRACT: The paper discusses two main points; first is the validity of steady state analysis in assessing buildings' heating and cooling loads, as well as the internal air and surface temperatures (T_{AIR}, T_{SI}) using UNI TS 11300-1:2008 compared to TRNSYS dynamic simulation software. The second aim is to understand how internal insulation affects the building envelope thermal inertia. Insulation is important to conserve heat in the heating season; however, it may contribute to space overheating in the summer. Thermal capacity is important in increasing human comfort in the space, limiting overheating in summer and managing peak temperatures due to internal or solar gains. Inside insulation can alter the dynamic behaviour of the existing envelope, and the aim is to understand the consequences of this intervention. The work presents an analysis of different internal envelope retrofitting solution, and deal with the climate of Milan and Palermo cities in Italy. The results show that steady state analysis for the heating and cooling loads calculation in cold climates is sufficient, while in hot climates, dynamic simulation is of major importance. They also discuss the importance of the thermal capacity and thickness of the finishing layers in moderating T_{AIR} and T_{SI}.
Keywords: Internal envelope retrofit, Thermal mass, Thermal comfort, Steady and dynamic simulation.

INTRODUCTION

The building sector accounts for about 35.8% of the final energy consumption in Europe. Globally, statistics show that about 50% of today's building stock will remain in use beyond 2050. In Europe, almost 80 million buildings were built between 1925 and 1975, which require envelope retrofitting to guarantee their future exploitation [1]. Internal Insulation Solutions (IIS) comprise an insulation layer fixed to the inside of the perimeter walls of buildings, using either single or multi-layer solutions. While external insulation seems more efficient in terms of energy performance, internal insulation is sometimes the only solution; i.e. in heritage buildings with listed facades, in cases where distance between buildings does not allow increasing the external walls thickness, or if its adoption depends on single owners thus it is subjected to different decision criteria. Internal insulation also exhibits a number of issues such as reducing inside space, risk of condensation and thermal bridges, among others [2, 3].

Objectives

The study deals with the impact of internal insulation on existing residential buildings envelope. The paper features two main objectives:

- To conduct a comparison between the steady state and dynamic energy simulation for a set of cases, using CENED certification program, DIATHERM and TRNSYS, accordingly. The results will be demonstrated through the assessment of the heating and cooling loads, as well as the average internal surface temperatures (T_{SI}) in different seasons.
- To understand the impact of added insulation and finishing layers on the effective thermal capacity of existing building envelopes, which in turn may affect the indoor comfort conditions. Therefore, the study forms a comparative analysis of a number of building envelopes with various thermal inertia values, and different added insulation and finishing layers. The results will be demonstrated through comparing internal air and surface temperatures (T_{AIR} and T_{SI}) of the simulated space.

BUILDING MODEL ANALYSIS

Building Description

The study is carried out on a residential building model. The building's overall height is 12 m; composed of 4 floors, each floor hosts 6 rooms. The building has no basement and no surrounding masses that cast shadows on it. The only shading elements are outside vertical shutters, which function automatically with a value of 70% in weekdays and 85% in weekends; during daytime in the summer period. The shutters are only simulated in TRNSYS. Windows are placed equally on the longer facades of the building, and they occupy 20% of these external walls surface area. The rooms vary in dimensions (four rooms with an area of 4x4 m^2, and two of 4x8 m^2) and in position. The zone of focus in this paper is Room R01, which represents the master bedroom (as in Fig. 1).

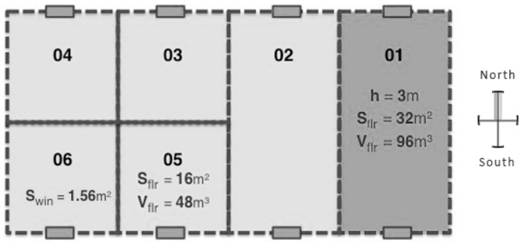

Figure 1: Room No. 01 on the second floor, the focus of the study, represents the master bedroom [2,3].

Varying Parameters

A number of variables were defined which compose the different combinations in order to understand how the building envelope performs in each simulated case. The varying parameters are described as follows:

1- Climate

Two climates are defined according to Köppen climate classification [4]. One is represented in the city of Milan in Italy, which is described as warm temperate climate, fully humid and warm summer, abbreviated as 'Cfb'. The other is represented in the city of Palermo in Italy as well, described as warm temperate climate with dry and hot summers, abbreviated as 'Csa'.

2- Building Envelope Configuration

A matrix of four base building envelope configurations, six different insulation layers, and three finishing layers are studied and presented in this paper. A summary of the layers is found in Table 1.

Table 1: Base envelopes - sensible properties (U = 1 W/m²K).

Code	Elements	ϱ Kg/m³	Cp KJ/KgK	λ W/mK	≠ Cm
W.1	Plaster	1400	1	0.7	1.5
S. Masonry	Brick	1540	1	0.46	37.5
	Plaster	1400	1	0.7	1.5
W.2	H. bricks	775	0.84	0.35	8
Cavity Wall	Air gap	1	1.04	0.24	5
	H. Bricks	717	0.84	0.34	12
	Plaster	1800	1	0.9	2
W.3	OSB	600	1.7	0.12	1.8
Light wall	Mineral wool	40	1.03	0.036	2
	OSB	600	1.7	0.12	1.5
W.4	OSB	600	1.7	0.12	1.8
Light wall	Wood fibre	40	2.1	0.036	2
	OSB	600	1.7	0.12	1.5

Table 2: Base envelopes - sensible flux characteristics.

	Yie W/m²K	S.M. Kg/m²	φ h	fa
W.1	0.095	598.50	15.21	0.09490
W.2	0.668	169.11	5.51	0.64728
W.3	0,950	22,40	1,22	0,97336
W.4	0,949	22,40	1,25	0.97233

The four base envelopes have the same U-value, which is 1 W/m²K. Each of the insulation layers, when added to any of the base wall types, reduces the U-value to 0.34 W/m²K, compliant with the value required by the Italian regulation D.Lgs. 311/06. The base walls, insulation and finishing layers differ in dimension, material density and thermal capacity. Reducing the thickness of the internal intervention in envelope retrofitting is of high importance, therefore insulation materials used are chosen based on their ability to reach the required U-value with the least thickness possible. Table 2 shows the sensible characteristics of the envelopes, defined as the periodic transmittance (Yie), superficial mass (S.M.), thermal phase shifting (φ) and thermal wave attenuation (fa). These characteristics are important in evaluating the thermal performance in summer periods.

Table 3: Insulation materials alternatives.

Code	≠ m	λ mW/mK	ϱ Kg/m³	Cp KJ/KgK
INS.1 Cork + Aerogel + Cork	0.027	(44+14+44)	(225+150+225)	(1+1+1)
INS.2 Mineral Wool	0.068	35	100	1.03
INS.3 Mineral Wool + Aerogel	0.037	19	180	1.03
INS.4 Glass wool	0.060	31	50	1.03
INS.5 PET + Aerogel	0.027	14	150	1
INS.6 VIP	0.008	4.2	160	0.7

3- Ventilation Rate

Two ventilation rate alternatives are applied on the simulated cases. In TRNSYS, the first scenario uses a constant 0.5 Ach/h, and the other a 1.5 Ach/h at night in summer time, with a constant 0.5 Ach/h in winter. This allows understanding the impact of night ventilation in reducing overheating in the summer season. The schedule of the two scenarios can be seen in Table 5.

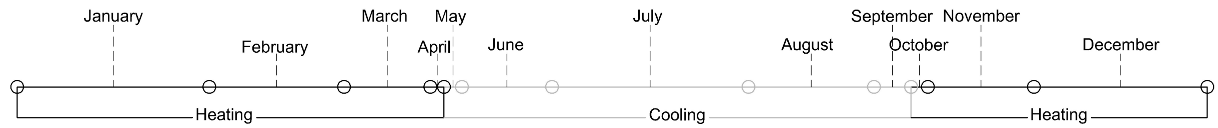

Figure 2: Heating and cooling periods in the city of Milan. The segments length is in proportion to the energy consumed per month.

When using the steady-state calculation method, values for the two cases are constant all year long.

Table 4: Finishing layers alternatives.

Code	≠ m	λ mW/mK	ρ Kg/m^3	Cp KJ/KgK
F.1 Plasterboard	0.0125	2	760	0.837
F.2 Fiber cement	0.012	36	1800	0.9
F.3 Plywood	0.012	2	780	2

Table 5: Ventilation rate alternatives.

VENTILATION RATE 0.5Ach/h I Constant	
Summer and Winter	
All Days	Ach/h
00.00 - 24.00	0.5
VENTILATION RATE 1.5Ach/h I Night Ventilation	
Summer	
All Days	Ach/h
00.00 - 08.00	1.5
08.00 - 20.00	0.3
20.00 - 24.00	1.5
Winter	
All Days	Ach/h
00.00 - 24.00	0.5

Simulation Software

The steady-state analyses for the heating and cooling loads are performed through average monthly values using CENED Ver. 1.08.06.19. This software is used in the Lombardy Region (Italy) for evaluating the energy classes of buildings in accordance with the "prEN ISO 13790 rev: Thermal performance of buildings – calculation of energy use for space heating and cooling" [5]. The steady state analysis software used for evaluating the T_{SI} is called DIATHERM. For the dynamic simulations, TRNSYS software is used.

Comparison between CENED and TRNSYS

Following are the main differences between the two predefined software used for the heating and cooling loads calculation. This allows understanding the general potentials and limitations of each software used.

In CENED, it is only possible to insert the U-value of the whole envelope regardless of the layers composing it, and only one input for the ventilation rate all year long. The internal gains cannot be set when evaluating the energy demand in the buildings, since they are attributed standard values. TRNSYS on the other hand enables to identify the thermo-physical properties of each layer composing the building envelope. The ventilation rate can be defined with different values for each hour, and the internal gains depend on users' activity and occupancy schedule, PC type and usage, as well as the lighting consumption and schedule. The results in the steady condition are in monthly balances, while in dynamic simulations the results are on an hourly or fraction of hourly basis. The heat flux, in the steady-state condition follows a single direction; while in the dynamic simulations the direction of heat flow depends on the variation of temperature between inside and outside the space, and within the building envelope.

Approach Limitations

The simulations did not take into consideration the effects of thermal bridges. Different urban environments or different orientations for the building were not simulated either. The ventilation rates used for calculations assimilate mechanical ventilation, while in reality adaptive window opening and ventilation seems more realistic, especially in hot climates. Finally, the inputs used in TRNSYS vary in complexity and number of parameters compared to those used in CENED.

COMPARISON BETWEEN STEADY STATE AND DYNAMIC SIMULATION RESULTS

Heating and Cooling loads analysis comparison

A comparison between dynamic and steady state simulation software has been conducted. The comparison of the heating and cooling loads calculation is conducted in the city of Milan, due to the fact that CENED only works within the Lombardy Region in the north of Italy. Fig. 3 and Fig. 4 show the results of the heating and cooling energy demand for the whole building, in the case of 0.5 Ach/h ventilation and 1.5 Ach/h. Generally, the behaviour of W.3 and W.4 is identical whether using CENED or TRNSYS. The first section of each table shows a comparison between the results of the steady state and dynamic simulation, while the lower section only shows the result from CENED software. The heating and cooling periods in Milan are shown in Fig. 2.

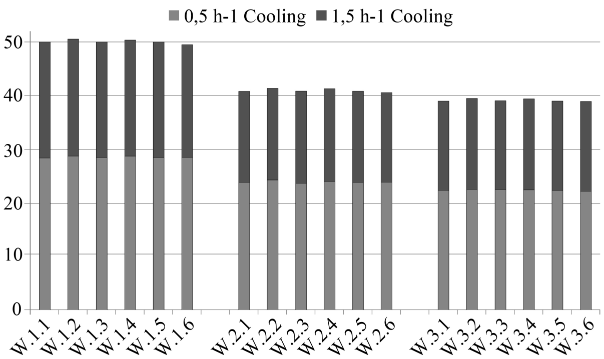

Figure 3: Steady-state comparison of cooling energy need among the envelopes with different insulation levels.

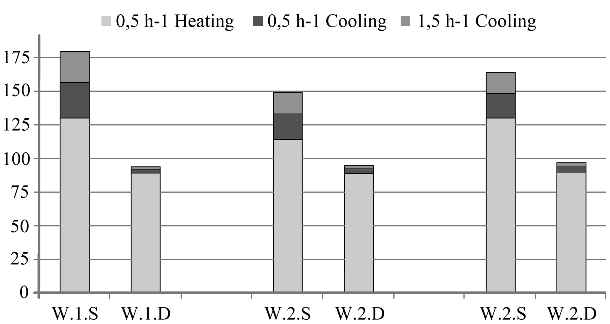

Figure 4: Dynamic and steady-state comparison of net energy need among the various envelopes.

A considerable difference can be noticed in the results: this is due to the fact that CENED fixes the internal gains, while in TRNSYS calculates them based on an amount of information including schedule and activity of occupancy, PC type and usage, as well as the lighting system used and its schedule, which were defined by the authors. The internal gains calculated by TRNSYS are 7.6 kWh/m^2, while in CENED they reach up to around 30 kWh/m^2. This explains the main gap between both results, while the remaining difference is divided between the other gains and losses contributors. The steady state simulation shows a considerable difference in the heating and cooling results when comparing the base envelopes: around 5 kWh/m^2 when comparing the heating demand of W.1 and W.2, and up to 20 kWh/m^2 when comparing W.1 to W.3/4. For the cooling loads, the difference between the four cases is around 5 kWh/m^2. TRNSYS, on the other hand, shows an identical heating demand in W.1 and W.2, and a slightly different from W.3 and W.4 with only 0.2 kWh/m^2 annually. The cooling loads difference between W.1 and W.2 is 0.5 kWh/m^2 and is 1.3 kWh/m^2 when compared to W.3/4. When adding insulation, the change in the loads due to the variation in the insulation material is insignificant, and it is only noticeable when the cases are compared between different base walls. This is the case in the results of both CENED and TRNSYS.

Internal surface temperature (T_{SI}) comparison

Fig. 5 shows the impact of the thickness of the wall and its sensible characteristics evaluated both in steady state – using DIATHERM software – and in dynamic conditions. The results of the comparison show a difference in the T_{SI} evaluated. In summer, DIATHERM shows a 4°C higher value than TRNSYS for W.1 in Milan. This value increases up to 8 °C in Palermo. The difference slightly increases in W.3 and W.4 where in the case of Milan, the difference reaches 4°C and in Palermo it goes up to 9 °C. Based on these notices, it seems that dynamic analysis are of major importance in simulating buildings in warm and hot climates, while in cold and temperate climates, steady state simulation can be sufficient for the evaluation.

IMPACT OF ADDED INSULATION AND FINISHING ON EXISTING ENVELOPES

The analysis in this section is conducted using TRNSYS software only. The aim is to understand the impact of the insulating materials and finishes on the effective thermal capacity of existing building envelopes and their impact on users' comfort. A matrix of combinations of the layers introduced in Table 1, Table 3 and Table 4 is analysed. The result of the comparison can be presented in the following points.

Envelope Comparison Without Insulation

Four types of non-insulated walls (W.1, W.2, W.3, and W.4) were compared. The envelopes have the same U-value and were compared in the two predefined ventilation modes. Simulations were conducted for the cities of Milan and Palermo in Italy.

Generally, the behaviour of W.3 and W.4 is exactly the same in all the simulated cases. Therefore, the comparison will be presented mainly on the first 3 wall types, i.e. W.1, W.2 and W.3. The analysis is explained as follows:

a) Milan city, V0.5 and V1.5N:

Daily temperature fluctuations are at their maximum in W.3, which decreases in W.2 and reaches its minimum in W.1. The difference in T_{AIR} between W.1 and W.2 is around 1°C, and it increases to around 2°C when comparing W.1 to W.3. This difference reduces in autumn and spring, and it becomes almost negligible in winter. In terms of T_{SI}, it is very stable in W.1, showing very little fluctuation (≤ 1°C); this increases to ≤ 2°C, with a time lag of 6-7 hours. The largest temperature fluctuation can be seen in W.3, where the difference in T_{SI} reaches 4°C – 6°C in the summer, autumn and spring, and decreases to around 2°C in winter, with zero time lag. These notices are the same in the constant or variable ventilation modes, with a reduction of around 0.5°C in the peak temperatures in summer, and with an increase in the temperature difference between day and night of around 1°C.

b) Palermo city, V0.5 and V1.5N:

Similar results are deduced with a larger range of T_{AIR} difference between the 3 envelopes, which reaches around 1.5°C and 2.5°C when comparing W.1 to W.2 and W.3 respectively. T_{SI} fluctuations are more intense. Difference in TSI increases up to ≥ 3°C in the summer period when comparing W.1 and W.2, and up to ≥ 5°C when compared to W.3.

Fig. 5 shows a comparison between the non-insulated existing envelopes in the solstices and equinoxes, simulated in DIATHERM and TRNSYS. This shows the difference in temperature (ΔT), which indicates the importance of dynamic simulations in considering the thermal mass to assess T_{AIR} and T_{SI} when the outdoor temperature is high.

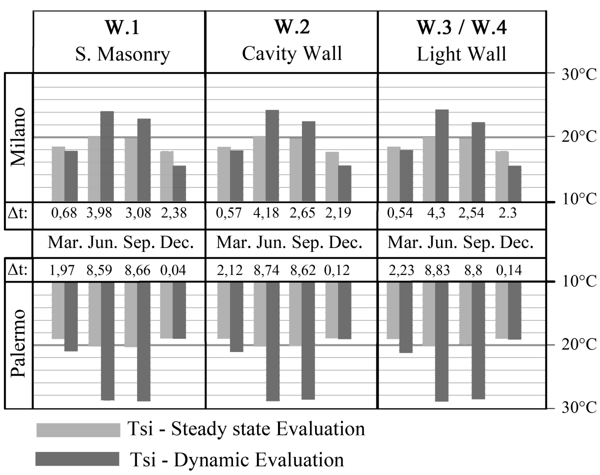

Figure 5: Inner surface temperature, Milano and Palermo.

External and Internal Insulation Comparison

A comparison between internal and external insulation for the massive and light solution (W.1, W.3) was conducted. The authors hypothesized an insulation layer similar to mineral wool in order to understand the impact of the density on the internal comfort. The added layer is 6 cm thick. The simulations took into consideration two different densities, one of 50 kg/m^3 (INS.50) and the other of 150 kg/m^3 (INS.150). No finishing layer was used. The ventilation rate used is 1.5 Ach/h at night.

In both cases (W.1, W.3), there is no difference between T_{AIR} and T_{SI} whether using INS.50 or INS.150; inside or outside of the building envelope, in Milan or Palermo.

In the case of W.3, external insulation results in less T_{AIR} and T_{SI} than internal insulation of ≤ 0.5°C in the summer solstice and spring equinoxes. In the case of W.1, when simulating in Milan, a difference of T_{AIR} or T_{SI} of about 1°C is noted in the summer solstice, and almost no difference in the winter solstice. In Palermo the same is deduced for T_{AIR}, with a higher T_{SI} difference of about 2°C. A more thorough comparison between internal and external insulation in terms of T_{AIR}, T_{OP}, T_{SI} and DDH is presented in [2, 3].

Comparison between different insulation types

A comparison between different insulation layers has been conducted. The analysis matrix included the four base wall-types plus the six insulation layers defined earlier. The analysis was conducted according to the following scenarios:

1- Different insulation layers with no finishing layer.
2- Different insulation layers with one common finishing layer (Plasterboard).

In all the simulated cases related to W.1 and W.2, the result shows no difference in T_{AIR} or T_{SI}. However, when the insulation layers are attached to W.3 or W.4, a very small difference in T_{AIR} and T_{SI} can be noted. This difference is < 0.2°C in the summer and spring, and decreases to 0°C in the winter and autumn.

Generally, it appears that, when using small insulation thicknesses attached to massive walls, the impact of insulation material's density or thermal capacity on T_{AIR} or T_{SI} is not as influential as its thermal transmittance. This impact increases to a certain extent when dealing with thin and light building envelopes.

Regardless the impact of the results, the most performing insulation layers due to their ability to moderate T_{AIR} and T_{SI} were equally the mineral wool (INS.2) and mineral wool + aerogel (INS.3), while the least performing solution was the VIP panels (INS.6).

Comparison between different finishing layers

A comparison between three finishing types has been executed. The comparison was performed on 4 levels:

1- Analysis of one finishing layer on the internal side of the building perimeter walls.
2- Analysis of one finishing layer on the perimeter walls, ceiling and internal walls implemented on the analysed floor only.
3- Analysis of one finishing layer on the perimeter walls, ceiling and internal walls implemented in all the floors of the building.
4- Analysis of two finishing layers on the internal side of the building perimeter walls.

In all the simulated cases, fluctuations were the least when using the 1.2 cm fibre cement (F.2) finishing; the 1.2 cm plywood (F.3) showed almost the same performance, while the 1.3 cm plasterboard (F.1) exhibited the highest fluctuations. Also, the temperature fluctuations are at the highest in summer and spring, and they decrease in autumn reaching the least variation value in winter.

In the first case, when combining W.1 and INS.1, the difference in T_{AIR} and T_{SI} between the three finishing layers is < 0.1°C at its highest value, whether in Milan or Palermo. However, when working with W.3, the temperature differences in Milan remains the same, while they increase to around 0.2°C for T_{AIR}, and T_{SI}. When increasing the finishing surface for one floor apartment only, as in the second case, the values remain the same when working with W.1, and increases to 0.3°C difference in T_{SI}, while the T_{AIR} variation is the same as the first case when working with W.3. In the third case, T_{AIR} and T_{SI} difference jumps to 0.3°C when working with W.1, and reaches up to 0.4°C difference of T_{SI} when working with W.3. When doubling the finishing layers, as in case four, the difference between The fibrecement (F.2) and plasterboard (F.1) is around 0.3°C. When working with W.3, the difference between F.2 and plywood (F.3) diminishes. If the surface of the finishing layer increased as in cases two and three, the difference in T_{AIR} reaches 0.6°C, and the T_{SI} reaches 0.7°C.

Comparison between best and worst solutions

A comparison of the most and least performing insulation and finishing layers was conducted. The most performing insulating layer is the mineral wool or mineral wool + aerogel, while the least was the VIP layer; and the most performing finishing layer is the fibre cement or plywood and least is the plasterboard. Four cases were compared as a result. The simulations showed that there is a difference in T_{SI} of around 0.5 °C, and in T_{AIR} of around 0.4°C, between the best and the worst combination when working on W.3 in Palermo (as shown in Fig. 6). This is in the case of using one finishing layer of 1.2 cm.

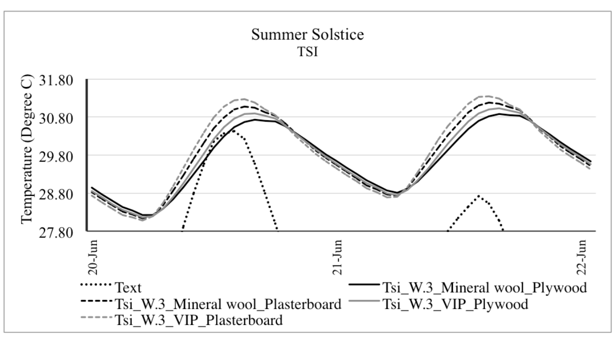

Figure 6: Comparison between the T_{SI} of the most and least performing insulating materials and finishing layers.

CONCLUSION

A parametric study was conducted on a residential building, with the aim of comparing steady-state and dynamic analyses in determining the heating and cooling loads; as well as understanding the impact of internal thermal insulation on the thermal behaviour of the existing envelope and on occupants' comfort. The study is focused on the cities of Milan and Palermo in Italy.

The results show that internal insulation of the building envelope is beneficial in all cases in terms of heating and cooling loads reduction. When having low outdoor temperature, thermal capacity of the existing envelope or the added insulation and finishing layers does not show a significant effect on T_{AIR} and T_{SI}. In this case, thermal transmittance is the property that drives the enhancement of the thermal comfort. Therefore, the thermal performance of the intervention layer can be estimated using steady-state analysis. However, when the outdoor temperature is high, the approach is more complex, because of the need to carefully evaluate all the envelope layers, i.e. existing wall, insulation and finishing materials applied internally. The choice of the internal intervention needs to be made in relation to the existing wall, i.e. when intervening with a high mass envelope, the importance of the internal insulation and finishing layers thermal capacity can be neglected; while in a lightweight envelope, the thermal capacity of the intervention layers is important and can influence the parameters of comfort. Dynamic analysis can describe accurately the effect of changing thermal capacity.
Although the temperature differences in the analyses presented are quite limited, the effect of thermal capacity on users' comfort should prove larger under different conditions such as occupancy schedules, wall to window ratio and amount of available thermal mass. These parameters will be the object of future studies.

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