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On Energy Efficiency of Night Window Shutters for a Non-Residential Building in Three Major Romanian Cities

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Abstract: An estimation by simulation of the heating energy saving in the cold season due to heavily insulated exterior window shutters closed at night was performed for a low-rise to mid-rise office building in the following three major Romanian cities: Bucharest, Cluj-Napoca and Iasi. All three locations are in a wet temperate continental climate region. The studied building, whose number of floors was varied from 3 to 22, has a rectangle-shaped floor surface. The considered shutters, covering at night only the pane of the window, were assumed to be EPS panels with various thicknesses. In addition to its height more parameters related to the building were varied: its orientation, the height of the windows, the width of the building and the internal gains produced by building lights and equipment. Finally, some short evaluations were performed for a low-U glazing. For the initial glazing used in the simulation, very good potential savings were found. As the assumed heavily insulated shutters do not exist in the Romanian market, three possible design ideas for such shutters have been sketched at the end, all involving a system of guide rails.

Keywords: low-rise mid-rise office building; temperate continental climate; insulated exterior shutter; heating energy saving

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1. Introduction

Of all the building envelope elements, windows have changed the most in the last four decades or so [1–4]. The driver in this transformation has been the constant goal of making them more energy-efficient. Some developed countries have adopted a mandatory window energy rating system to influence the window market toward more energy-efficient windows: the rating authority is NFRC in the USA [5] and BFRC in Great Britain [6]. It appears there are also some countries of continental Europe that rate windows [7], and there may be others as well.

But windows have always had the very important psychological function for the building occupants of acting as 'openings' to the outside world, to provide a visual connection to it; so, letting natural light, and therefore solar energy, in through them is a must, at least during some time intervals of the daylight period. However, with windows being poor thermal barriers compared to heavily insulated walls, it is of course desired during the night in a cold climate that they better insulate thermally the building interior. Also, in the sunny hot summer days, it is of course desired that windows, especially those facing South, keep solar radiation out of the building interior as much as possible.

It follows that in order to offer building occupants comfort under the mentioned conditions, windows need a remarkable energetic versatility as a building element; their energetic qualities having to differ with the spatial orientation of the window, as well as between seasons and between day and night.

From very old times people solved this problem by inventing the so-called attachments to the building openings. After the invention of glass, they used glazed window attachments. The deployment of the attachments is variable in time, and so, the ensemble of a window and its attachment equip the window with the sought-after energetic versatility.

It appears the window attachments have been overlooked in the same last four decades or so we are talking about, when a great deal of attention and work have been dedicated to designing and manufacturing more energy-efficient windows. Window attachments are players in this game because they are considerably less costly than the replacement windows [8].

The USA seems to be the most advanced as regards the influence of the market for those products: an official energy rating authority similar to NRFC has been created, named AERC [9].

At this moment, AERC already has a quite large range of residential window attachments for which it provides ratings [10]: Roman shades, cellular shades, storm windows, roller shades, solar screens, blinds, pleated shades and awnings.

In the category of commercial window attachments, the only product AERC currently offers an energy rating is secondary windows [11], that is, glazing units attached to the initial windows.

It seems heavily insulated exterior window shutters do not sell in the USA (except maybe in Alaska; see further). These shutters are the window attachments our paper deals with.

Obtaining heating energy savings by using heavily insulated exterior window shutters closed at night is not a new idea for cold and very cold climates [12–15]. But according to our knowledge, it has not been explored for temperate climate regions. A possible reason for that is the fact such shutters should be composed of thick and very thick slats or panels. And because of their bulkiness, compacting the slats or panels when the shutters are open is a problem; it is highly unlikely the very common shutter model having a cassette or box where the slats are rolled is adequate in this case. However, we calculated potential savings provided by ideal shutters (from the operation point of view) that have thick thermal insulation; they are not small, for the current windows of most Romanian buildings. The presented calculations by simulations did not use any technical detail of what the respective shutters look like and how they function; the only assumption was that the desired operation of the heavily insulated shutters, namely being closed at night and open during the daylight period, is accomplished. At the end of the results of this paper, we present a sketch of three conceptual ideas of how the assumed shutters could be realized technically for buildings like those used by us in the simulations.

Further, a context is provided for our choosing of this building heating-energy-saving strategy for temperate climate regions: using, during the cold season, exterior window shutters that are heavily insulated and are closed at night and opened in the daytime.

We believe the right philosophy when designing an energy-efficient building is to first get the most out of the possible passive ways of saving energy and only after that try to optimize the HVAC equipment by design [16,17]. Among the passive ways of saving energy, increasing the efficiency of the thermal barrier between the building's interior and its exterior is a very used one nowadays. The so-called thermal refurbishment of buildings which includes as a major component applying an additional thermally insulating layer to the building envelope has been widely enforced in European Union countries in Central and Northern Europe. Bucharest and Romania in general still experience a longer heating season than the cooling one. In Bucharest (northern latitude for used weather station 44.51° and eastern longitude 26.08°), the heating season is at least 5 months per year while the cooling season is no longer than 4 months per year. In many parts of the country, like in the other two major Romanian cities considered in this study, Cluj-Napoca, and Iasi (please see Figure 1, which uses the map provided in [18]), the cooling season is even shorter, and the heating season is clearly longer.

The energy consumption for heating buildings is the most important. The climate in Bucharest, Cluj-Napoca and Iasi, as well as in much of Romania, is Dfb (wet temperate continental) according to the Koppen classification as issued by the National Meteorological Authority in 2008 [19]; see Figure 2. Thus, temperatures are colder than in the West of

Europe a big part of which is labeled as Koppen Cfb; please see the map presented in reference [20].

Figure 1. The location in Europe of the three studied cities: Bucharest, Cluj-Napoca, Iasi.

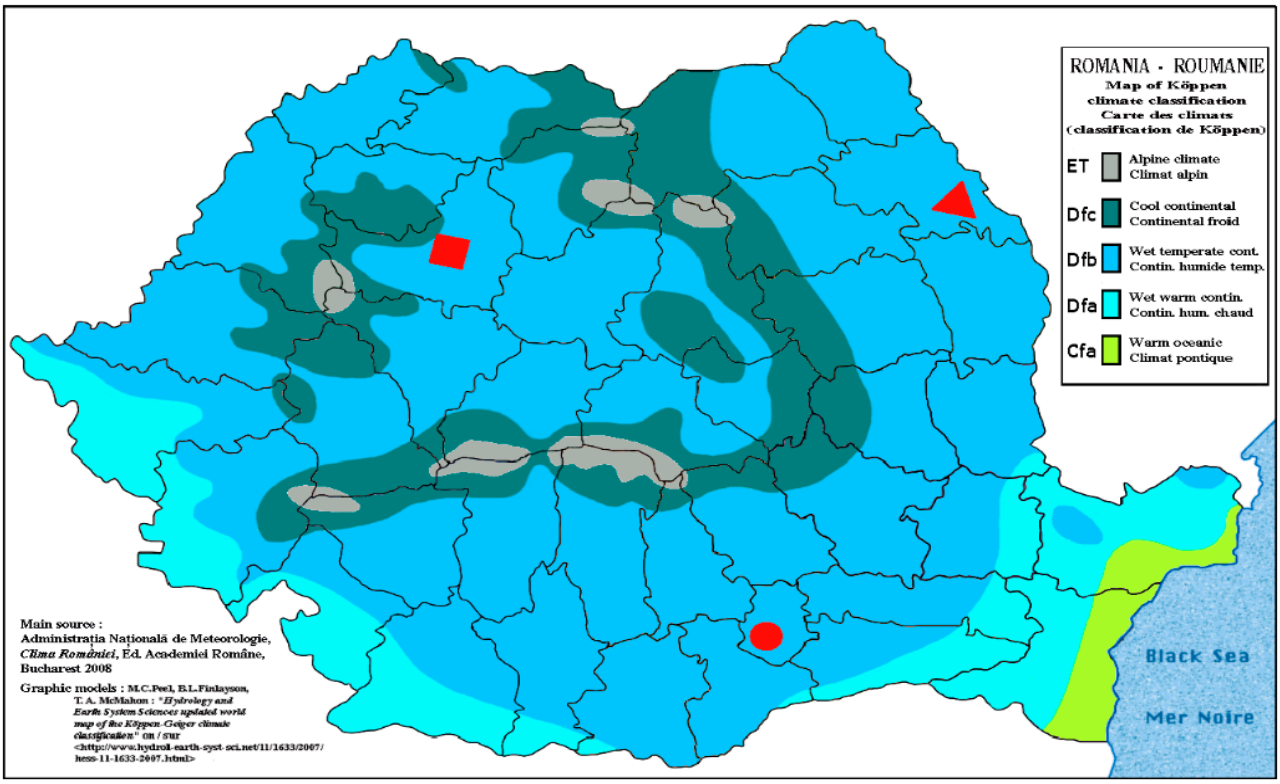
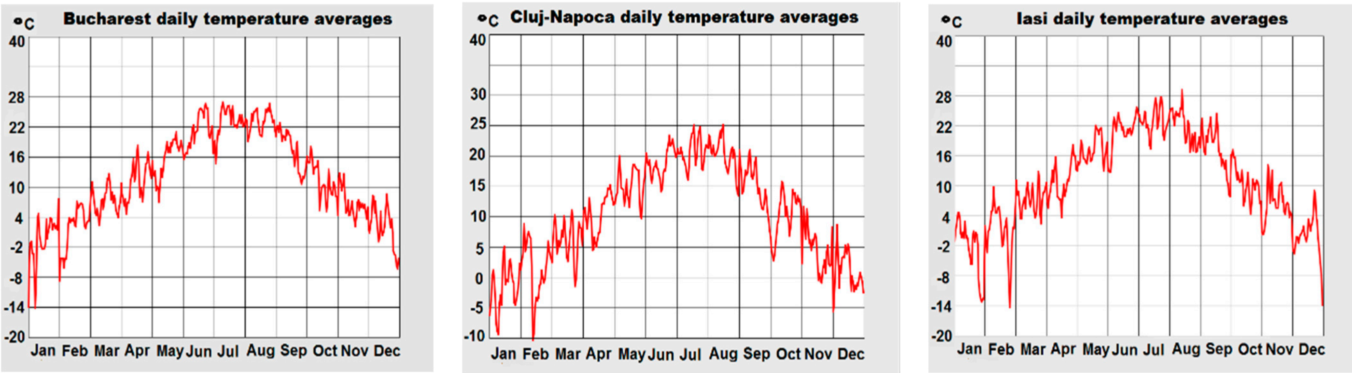


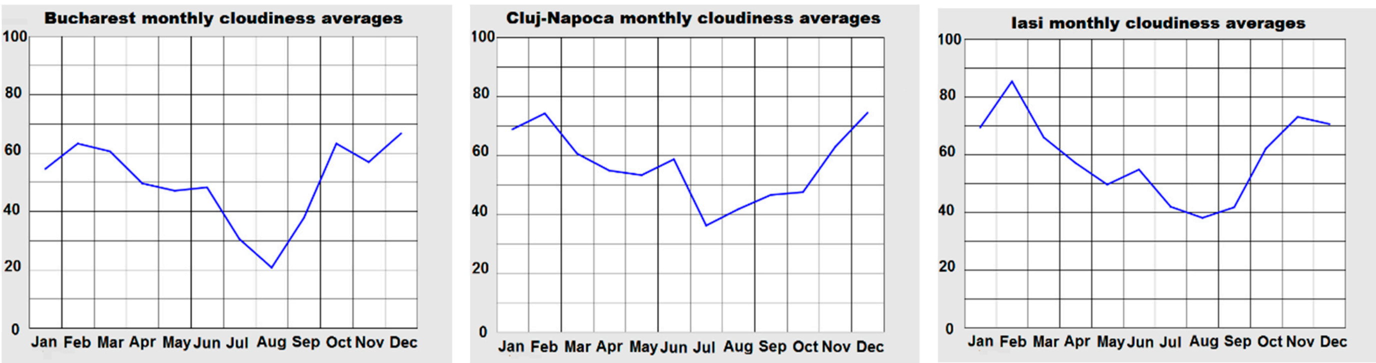
Figure 2. The location of the three cities on the Romanian climate map.

Daily means of dry bulb temperatures for each of the three mentioned cities are shown in Figure 3, taken from the weather files used by us in the following calculations and then averaged in the program Climate Consultant [21]. We also present values for cloud cover, in Figure 4. They show direct sunlight is available during the cold months in quite generous quantities in Bucharest but is not scarce in the other two cities.



(**a**) (**b**) (**c**)

Figure 3. Daily averages of dry bulb temperatures: (**a**) Bucharest, (**b**) Cluj-Napoca, (**c**) Iasi.



(**a**) (**b**) (**c**)

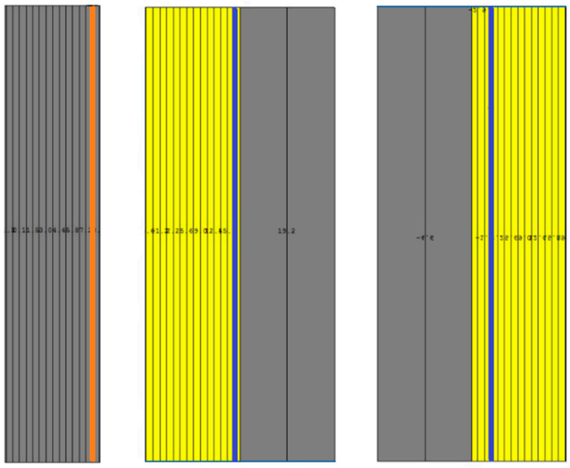
Figure 4. Monthly averages of sky cover (zero value is clear sky): (**a**) Bucharest, (**b**) Cluj-Napoca, (**c**) Iasi.

That is reflected in the considerably lower building heating energy demand for this location when compared to the other two. The respective weather files' data in the format called epw have been downloaded from the resource onebuilding.org [22].

The enumerated climate features of winter in such locations challenge the designers of a building to take advantage of the clear sky periods that may not be short and also mitigate the effect of cold outdoor temperatures. The building element naturally considered to solve the problem is, of course, the window. During the daylight period, the window passively allows solar radiation to enter the building, but it is a weak link within the thermal barrier at night. So, the not-new idea of thermally insulating the window during the night is considered.

Still, what we will probe using some simulations in this paper has not been a so common endeavor in climates that are not very cold: insulating windows heavily. We used insulation for exterior window shutters being at least 1.5 cm thick. Such window attachments have been investigated for very cold climates like Alaska and Canada, and the reported results were very good [12,14]. Adding on the outside of a building a fat insulation layer has been the common improvement of the envelope's performance as a thermal barrier. The common thickness for the exterior insulation in the case of thermal rehabilitation of apartment buildings is 10 cm according to current Romanian building codes.

The reason for adding an insulation layer on the outside, except for special cases like for instance historic buildings whose facade's look has to be preserved, is to avoid low temperatures in the rest of the envelope including the building structure. Such low temperatures could lead to unwanted condensation and even ice within the non-structural envelope and the structure itself of the building. Apart from the very problematic formation of mold, such events could damage the structure when water trapped there freezes and expands and then thaws. Three suggestive images are presented below (Figure 5) for the case of a very simple structure wall made of a concrete layer 15 cm thick and an insulation layer also 15 cm thick. They have been simulated in the program THERM of Lawrence Berkeley Lab [23] for a heat transfer situation between a building interior and exterior assumed to be 2D and steady state. The exterior simulation temperature is −5 °C, and the interior temperature is 20 °C. The 'pushing to the outside' of low temperature values can be seen when the thermal insulation layer is applied on the outside of the (initial) concrete wall. In contrast to that, when the thermal insulation layer is applied on the interior face of the concrete layer, there occurs an 'attraction to the inside' of low temperature values compared to the case of uninsulated concrete.

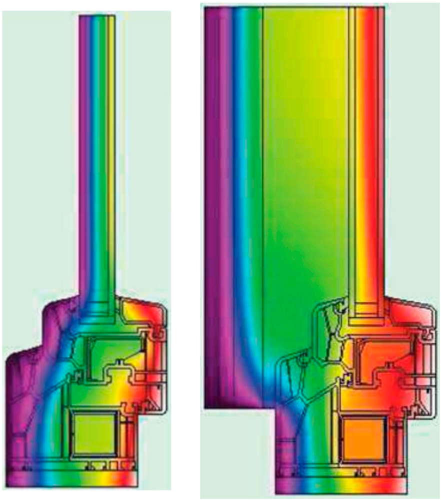


(**a**) (**b**) (**c**)

Figure 5. Equidistant isotherms in a concrete layer (gray color): (**a**) uninsulated concrete, the 7.9 °C isotherm is colored orange; (**b**) exterior insulation yellow color, the 17.5 °C isotherm is colored blue; (**c**) interior insulation yellow color, the 0.5 °C isotherm is colored blue.

Another reason for the outside application of the thermal insulation layer, at least for buildings whose facade details do not pose complicated problems as regards their cover in insulation, is the ease of obtaining an uninterrupted, continuous and quite uniform insulation layer all around the interior space. This is important from the heat transfer point of view as any discontinuity/change in thermal properties of the envelope separating the interior and the exterior of the building creates a so-called thermal bridge region, where the heat transfer is larger than in the surrounding region of the 'normal'/'common' envelope. Such an effect of course needs to be mitigated. Various pieces of metal piercing the initial envelope from inside to the outside before the exterior insulation layer is added will now no longer reach the cold/outside envelope surface after the outside insulation is put in place. Also, as the insulation layer is continuous and quite uniform in thickness and applied overall, thermal bridges caused by important thermal characteristic changes from one envelope region to another are now overwhelmingly attenuated. Examples of such regions are the places having structural elements of reinforced concrete adjacent to aerated concrete blocks.

An important decision that needs to be made concerns insulating that part of the envelope that is the building windows. Being holes in walls that have multiple and important building functions, windows have to be scrutinized carefully. As a thermal barrier, windows are a weak part of the envelope. From this point of view, in this part of the world, they perform poorly when compared to walls, which are difficult to beat while they are a thermal barrier of at least 10 cm of thermal insulation. The value to be considered for the thermal transmittance of a whole window (glazing and frame), installed in or after 1998, is U_{window} = 2 W/m^2 K according to current Romanian building energy performance calculation regulations. In the case a window acts as a passive thermal barrier only, which happens of course at night, when the window is shut, the presence of some additional insulation layer on its exterior side has a similar effect to its effect on the wall, previously described. The temperature value range within the glazing and the frame too is 'pushed to the outside' compared to the case of the uninsulated window (see Figure 6 cut out of an image in [24]). That is beneficial not only to the window itself, which will experience warmer temperatures inside its structure and have less risk of condensation, but also to the comfort of the occupants of the building, who will interact, by air convection and radiative heat exchange, with warmer space surfaces.



(**a**) (**b**)

Figure 6. Simulation cross-section through the frame–glazing join region in a cold night: (**a**) the uninsulated window, (**b**) the window with exterior shutter made of 1 cm wood layer and 3 cm EPS.

In [24], we calculated the energy balance terms of a window, its solar gains and heat losses, for each month of the cold season in Bucharest, considering a steady-state situation for the whole month. That steadiness was for both the interior of the building and its exterior dry bulb temperature and solar radiation. We took into account the present thermal bridges, both for the glazing–frame join and for the frame–surrounding wall join. The result was that in Bucharest, even in the most unfavorable months, namely December and January, a South oriented window completely unobstructed could have a non-negative energy balance.

In this paper, we calculate a quite similar situation, but for the whole building, this time taking into account the various thermal zones of the building interior and the hourly dynamic of the interior and exterior environments of the building. The entire heat transfer through various building envelope elements is now modeled as being 1D in the simulation program used in this paper. Approximating the thermal bridge effect might be performed by thinning some wall layers. To be conservative, we indeed took, without any in-depth calculation, a thickness of 15 cm for the aerated concrete layer of the exterior wall instead of 22 cm.

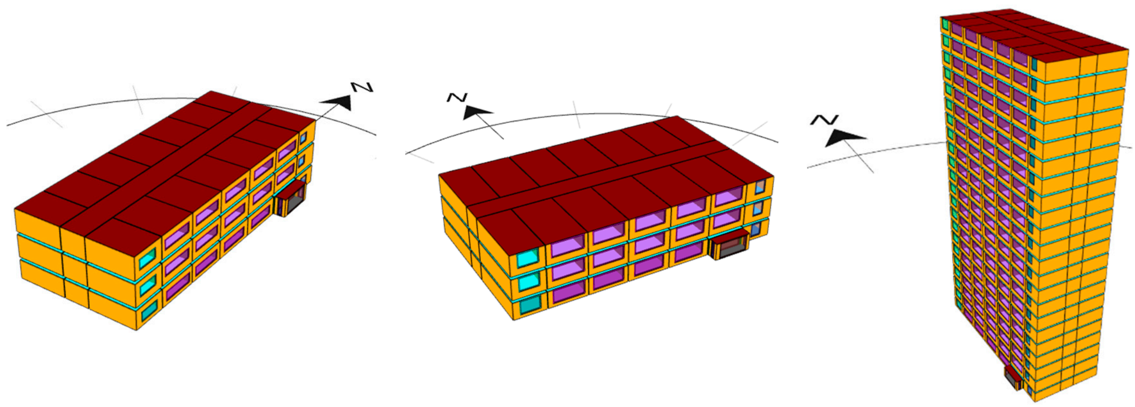
The building in this study is not a residential one but an office building. The essential energy terms in the case of such a building are the internal gains (lights, people and equipment), which can be more important compared to those of a residential building; and the external ones (solar gains entering the building mainly through windows); and the heat losses. Among the heat losses, important are the so-called heat transmittance losses (occurring directly through the entire envelope) and those due to air exchange between the building interior and exterior (the inoperable ones constitute the so-called air infiltration, and those operable, termed ventilation exchanges, are of two types, natural ventilation and artificial, commonly called mechanical, ventilation). The difference between gains and losses, calculated hour by hour in the performed simulation, must be compensated by the heating energy 'injected' in the thermal zone in question, in order to bring it to the required comfort parameters (of which the decisive one is the interior set temperature). In case the internal gains are big, it is possible that decreasing the heat transmittance losses through the envelope will not result in very attractive energy savings. We explored such a possibility at the end of our simulation runs. But we think the internal gains used in most of this paper are quite common values for office buildings. In addition, in recent decades, the trend has always been to have equipment that is more and more energy-efficient, so erring by considering too-small internal gains in the simulations has a quite low chance.

For the office building studied in most of this paper, the heating energy savings that are possible to realize in the cold season by decreasing the heat transmittance losses with heavily insulated shutters closed at night are not small.

We tried to explore if our results are general enough, if they are valid not for a very peculiar building only. For that, we varied some of the significant quantities involved in the physics of the energy transfer for the building in question: the fraction of the transparent part of the building facade, the building's orientation, the building width, its number of floors, its internal gains provided by lights and equipment. Also, a very short assessment of the situation where the building has a significantly more performant U value for its glazing has been performed. Except for this last case, the potential of the proposed strategy (heavily insulated shutters closed at night) to reduce the heating energy demand in the cold season appears to be quite general. As such shutters do not exist in the Romanian market at this time, at the end, we very briefly sketch three possible ideas for their technical design. We think it is unlikely to have roller shutters' slats of the thickness used by us in the simulations performed. All of our proposals at the end involve some guide rail system. If the same rail system used in the cold season for slats or panels of a heavily insulated shutter is also used in the warm season for some shading slats or panels, the strategy might still appear attractive for the case of windows having a very performant U of their glazing.

2. Materials and Methods

Variants of an office building having the very common shoe-box shape were drawn/modeled in the program TAS of EDSL [25]; see Figure 7. The initial building has its long axis oriented true North-South so that the solar access of the two identical facades (facing East and West) is 'democratic'. We call this building V-E-oriented, meaning its facades face West and East, and the East facing facade has the protruding building entrance at its North end. The floor's space is a surface of area 35 m $\times$ 15 m, except for the ground floor where two entrance spaces are added. The floor height is 3 m.



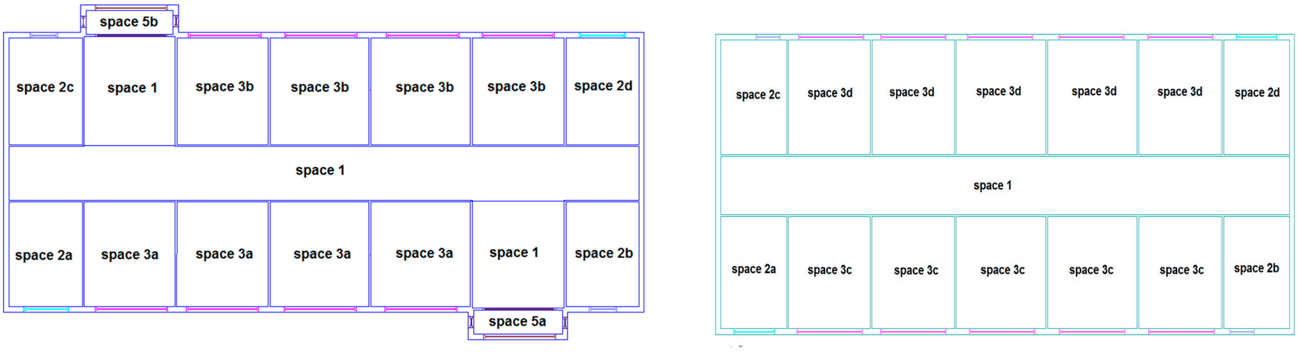
(a) (b) (c)

Figure 7. The 3D building models used in the simulations: (**a**) the 3-floor initial building oriented West-East, (**b**) the 3-floor wide building-oriented West-East, (**c**) the 22-floor thin building.

The transparent surface of the facades was varied by drawing a small-window building, where the window height is 1.2 m, and a large-window building, where the window height is 1.8 m (see Figure 7). For these two situations, the window/facade ratio for a three-floor building is 0.28 and 0.41, respectively.

The simulation results for the two mentioned cases (shown later) clearly show the trend of the heating energy savings when the glazing area of the facade is increased. So, it is quite apparent there is no need to consider another situation for the glazing/wall ratio of the facade, a value between the two extremes already calculated, called the large-window building and the small-window building.

Apart from the pair of protruding double-door entrance spaces, spaces 5a and 5b, there are two main regions inside the building, see Figure 8a,b: hallway and toilets lumped together for simplicity in a single thermal zone, space 1 in Figure 8, and the office Zone, the rest of the spaces of a floor.



(**a**) (**b**)

Figure 8. Building plans: (**a**) ground floor plan, (**b**) last floor plan.

The air infiltration (lumped together with natural ventilation rates) for those two main regions and the internal gains (in W/m^2) are respectively shown in Figure 9a,b for a weekday and in Figure 9c,d for weekends and unoccupied days. They are the same for all building variants unless specified otherwise. The so-called extended schedule consists of work hours from 8am to 6pm for the first five days of the week.

Gain	Value	Factor	Setback Value
Infiltration	0.5 ach	1.0	0.0 ach
Ventilation	0.0 ach	1.0	0.0 ach
Lighting Gain	5.0 W/m²	1.0	1.0 W/m²
Occupancy Sensible Gain	1.2 W/m²	1.0	0.0 W/m²
Occupancy Latent Gain	0.5 W/m²	1.0	0.0 W/m²
Equipment Sensible Gain	2.0 W/m²	1.0	0.0 W/m²
Equipment Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Pollutant Generation	0.0 l(CO2)/hr/m²	1.0	0.0 l(CO2)/hr/m²

(**a**)

Gain	Value	Factor	Setback Value
Infiltration	0.5 ach	1.0	0.0 ach
Ventilation	0.0 ach	1.0	0.0 ach
Lighting Gain	10.0 W/m²	1.0	0.0 W/m²
Occupancy Sensible Gain	9.0 W/m²	1.0	0.0 W/m²
Occupancy Latent Gain	4.0 W/m²	1.0	0.0 W/m²
Equipment Sensible Gain	12.0 W/m²	1.0	0.0 W/m²
Equipment Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Pollutant Generation	0.0 l(CO2)/hr/m²	1.0	0.0 l(CO2)/hr/m²

(**b**)

Gain	Value	Factor	Setback Value
Infiltration	0.2 ach	1.0	0.2 ach
Ventilation	0.0 ach	1.0	0.0 ach
Lighting Gain	1.0 W/m²	1.0	1.0 W/m²
Occupancy Sensible Gain	0.0 W/m²	1.0	0.0 W/m²
Occupancy Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Equipment Sensible Gain	0.0 W/m²	1.0	0.0 W/m²
Equipment Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Pollutant Generation	0.0 l(CO2)/hr/m²	1.0	0.0 l(CO2)/hr/m²

(**c**)

Gain	Value	Factor	Setback Value
Infiltration	0.2 ach	1.0	0.2 ach
Ventilation	0.0 ach	1.0	0.0 ach
Lighting Gain	0.0 W/m²	1.0	0.0 W/m²
Occupancy Sensible Gain	0.0 W/m²	1.0	0.0 W/m²
Occupancy Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Equipment Sensible Gain	0.0 W/m²	1.0	0.0 W/m²
Equipment Latent Gain	0.0 W/m²	1.0	0.0 W/m²
Pollutant Generation	0.0 l(CO2)/hr/m²	1.0	0.0 l(CO2)/hr/m²

(**d**)

Figure 9. (**a**) Weekday info for Zone 1, (**b**) Weekday info for office Zone, (**c**) Weekend info for Zone 1, (**d**) Weekend info for office Zone.

The chosen values in Figure 9 are not very different from those of an older office building example provided by EDSL in their TAS software package [26].

For the office spaces, the lower temperature limit for the heating (where it starts automatically) is 20 °C for work hours and 16 °C for the rest of the day during the work week and during the weekend. For space 1, that lower limit is 18 °C for the work hours and 15 °C for the rest of the time. Spaces 5a and 5b are free-running thermal zones.

As our calculation is an estimation, the so-called constructions of the building (the material layers its building elements are made of) have been mostly chosen for expediency from the Construction database TAS comes with and are quite common. They are shown in Figure 10, while the list of used building elements (the various surfaces of the building, each being assigned a certain construction) is shown in Figure 11.

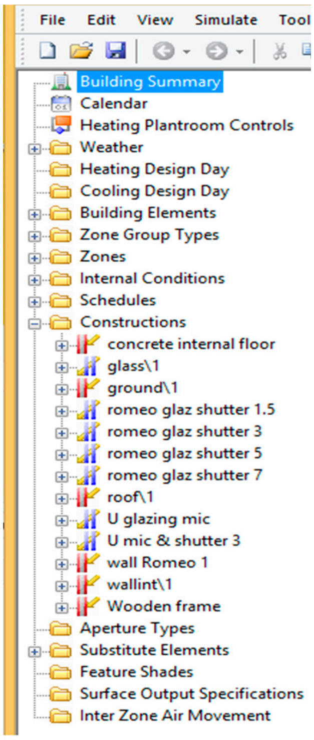
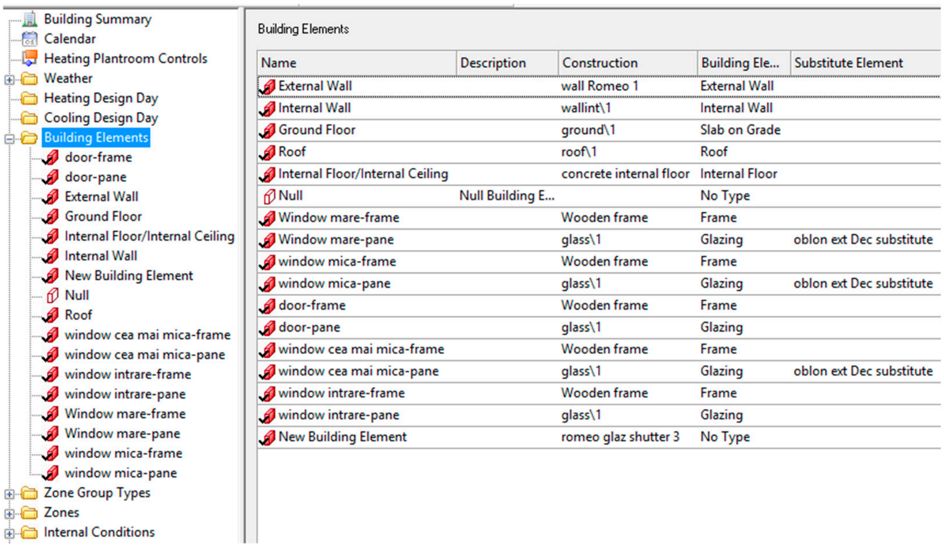


Figure 10. Constructions used.



Name	Description	Construction	Building Ele...	Substitute Element
External Wall		wall Romeo 1	External Wall	
Internal Wall		wallint\1	Internal Wall	
Ground Floor		ground\1	Slab on Grade	
Roof		roof\1	Roof	
Internal Floor/Internal Ceiling		concrete internal floor	Internal Floor	
Null	Null Building E...		No Type	
Window mare-frame		Wooden frame	Frame	
Window mare-pane		glass\1	Glazing	oblon ext Dec substitute
window mica-frame		Wooden frame	Frame	
window mica-pane		glass\1	Glazing	oblon ext Dec substitute
door-frame		Wooden frame	Frame	
door-pane		glass\1	Glazing	
window cea mai mica-frame		Wooden frame	Frame	
window cea mai mica-pane		glass\1	Glazing	oblon ext Dec substitute
window intrare-frame		Wooden frame	Frame	
window intrare-pane		glass\1	Glazing	
New Building Element		romeo glaz shutter 3	No Type	

Figure 11. Building elements used.

The glazing used in the simulations ('glass\1'; see Figure 10) has a U value of 1.82 W/m^{2}K, according to both EN 673 and ISO 15099.

A construction created by us (named 'wall Romeo 1') is that for the building element External Wall. The two main material layers of that construction, from inside to outside, are aerated concrete 15 cm thick and expanded polystyrene 10 cm thick (thus, it is considered the modeled building has been refurbished according to Romanian building energy regulations requiring 10 cm of applied exterior thermal insulation).

The only other constructions we created are those for the ensemble made of a window and an insulated shutter. In TAS, such a thing is called a substitute building element (its name in Figure 11 is 'oblon ext Dec substitute'), and it replaces the pane of the window during the simulation, according to a specified hourly schedule for certain specified days. In this paper, we have the same schedule for the substitute element for both weekdays and weekends. Four types of ensemble constructions were used, named 'romeo glaz shutter 1.5' and so on (see Figure 10), because we had four types of shutters. The shutters considered in the calculation are just expanded polystyrene panels 1.5 cm, 3 cm, 5 cm and 7 cm in thickness.

For every month of the cold half of the year, from October to March included, simulations were run having the building windows with no shutter and with each of the four types of shutters. The shutters covered the windows at night only, between the following exact hours for the months of November, December, January, February and March: from 5 p.m. to 7 a.m., from 5 p.m. to 8 a.m., from 5 p.m. to 8 a.m., from 6 p.m. to 7 a.m. and from 7 p.m. to 7 a.m., respectively. The chosen hours are the closest exact hours to the sunset and sunrise times. Those times were calculated by us using the free online NOAA solar calculator [27]. October is still a warm month for each of the three locations studied; the obtained simulated heating energy demands for the no-shutter case are zero in October for both large-window and small-window 3-floor buildings.

In the run simulations, shutters are not applied to the pair of transparent doors in each of the double-door entrance spaces; also, they are not applied to the narrow windows of the same spaces (spaces 5a and 5b in Figure 8). It must be mentioned too that shutters are applied only to the panes of the windows and not their frames. This is due to a peculiar approach in TAS to handling the so-called substitute element which must only replace a building element having a transparent construction. In reality, of course, exterior shutters cover the window frame. Because of that, our heating energy demand results would be worse than those in real situations, where frames are covered too. But on the other hand, we improved the results by increasing the real shutter capacity to seal the air between it and the glazing; we did that by considering a sealed air cavity between the exterior face of the glazing and the shutter itself.

To not restrict ourselves to a building having certain dimensions, we drew a 6 m wider variant of the initial building; see Figure 7b. The hallway width of the new building, also having 3 floors, is the same as that in the initial building; the extra 6 m width is allocated fifty-fifty to the office regions of the two facades.

With the same idea of searching for a more general result than that provided by the more or less peculiar building variants explored in simulations so far, we varied the orientation of the initial, thin building as well as that of the wide building. In the simulations run for that, the 3 cm insulation shutter was used exclusively.

Then for the Bucharest thin and wide buildings oriented West-East we varied the number of floors between 3 and 7 by adding one at a time. Then, only for the Bucharest thin building, we increased further the number of floors, in steps of 4 or 5 floors; the maximum building height simulated was 22 floors; see Figure 7c. The same representative 3 cm insulation shutter was used exclusively.

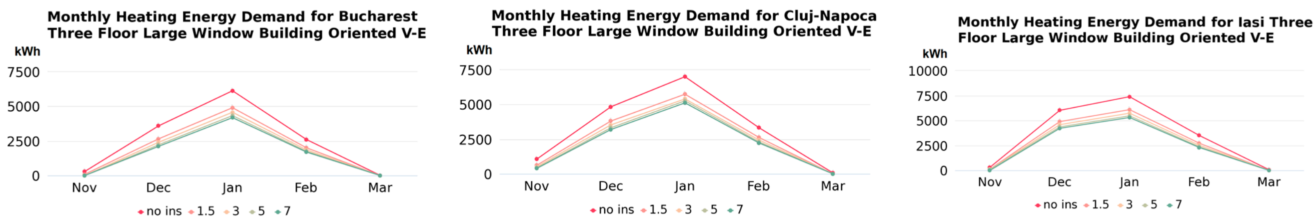
Two important components of the internal gains of the building were also varied: the (artificial) lights and the so-called equipment. The initial building has for the two components the values of 10 and 12 W/m^2 respectively. These values and others used by us for the rest of the gains are not too much different from those in an older example provided by EDSL in a sample project that comes included in their TAS package [26]. In addition, we calculated three cases of different internal gain sets for lights and equipment categories named by us IG1, IG2 and IG3. For IG1, the two values have been multiplied by the factor 0.75; for IG2, by the factor 1.25; and for IG3, by the factor 1.5. So, the values of the two mentioned internal gains are respectively the following for the cases enumerated above: 7.5 and 9 W/m^2 for IG1, 12.5 and 15 W/m^2 for IG2 and the quite exaggerated values of 15 and 18 W/m^2 for IG3. Simulations were run for the Bucharest thin building oriented Westast with 3 cm insulation shutters closed at night for the most severe months of December and January.

Finally, we considered the case of a window with a lower-U glazing. In the UK, for instance, from the summer of 2022, a minimum required flag value of 1.6 W/m^2 K is stipulated for the whole window; according to glazing experts, that may require U values for the glazing/pane itself, of 1.1 W/m^2 K or even 1 W/m^2 K, the contribution of the window frame increasing the overall value for the window [28]. Our initial glazing of U = 1.82 W/m^2 K was replaced by a new glazing having U = 1.02 W/m^2 K according to EN 673 and 1.04 according to ISO 15099. We simulated the Bucharest thin building oriented West-East with the new glazing. Like before, two variants of the building were simulated for the most severe months of December and January: the large-window building and the small-window one. Like before again, only the 3 cm insulation shutter was used in the calculations.

3. Results and Discussion

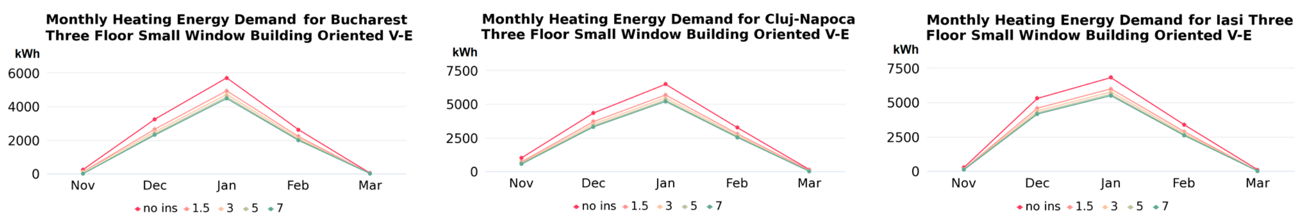
For the month of October, the heating energy demand in all three locations is zero for the three-floor buildings, oriented V-E, when windows have no exterior shutters applied.

For the rest of the five months, for every city, the monthly heating energy demand is shown in Figure 12a–c for the three-floor large-window building and Figure 13a–c for the small-window building. The result for the no-applied-shutter case is the polyline called 'no ins' in the graphs; the other four polylines, named '1.5', '3', '5' and '7' in the graphs, are for the exterior shutters closed at night having an insulation thickness of 1.5 cm, 3 cm, 5 cm and 7 cm, respectively.



(a) (b) (c)

Figure 12. The monthly heating energy demand for large-window buildings.



(a) (b) (c)

Figure 13. The monthly heating energy demand for small-window buildings.

For all three locations, the above graphs clearly show a not small-decrease in the energy demand, important in the most severe three months of the cold season, December, January and to a lesser extent February. They also show the smaller and smaller effect of the newly added insulation layer as the total insulation thickness increases. This is a well-known thing; it is due to the fact the transmission heat flow is proportional to the inverse of the thermal resistance R of the involved material while the R itself is proportional to the material thickness.

As regards the wide building case, the absolute values of the results (see Figure 14a–c) do not differ too much from those of the initial, thin, building. All the trends of the previous result graphs are preserved, and the effectiveness of closing the exterior shutters at night is obvious.

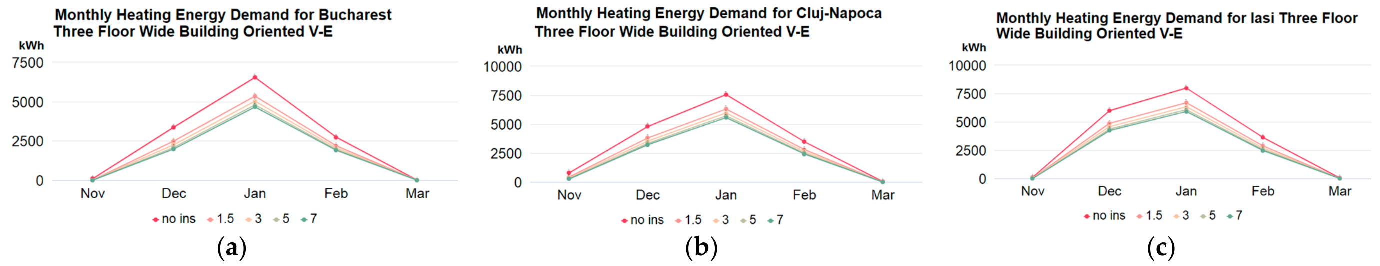


Figure 14. The monthly heating energy demand—wide building case.

Two main conclusions were drawn by us from the simulation results shown so far. The first is not at all surprising: in all three studied cities, the most demanding month as regards the necessary heating energy is January, which is followed by December. The second conclusion was that choosing the 3 cm shutter as the representative for the whole category of heavily insulated shutters seems natural and reasonable. So, in our further simulations, we restricted ourselves to exploring results for the two most severe months and the 3 cm shutter. The respective shutter does not have the inconvenience of being as bulky as the 5 cm and 7 cm shutters. At the same time, it offers a quite significant energy saving when compared with the no-shutter situation. So, the 3 cm shutter 'visually' appears to be the sweet spot for balancing the desire to save energy as much as possible without the troubles very bulky equipment incurs.

The results for varying the orientation are shown in the following tables: Tables 1a,b, 2a,b and 3a,b for the thin building and Tables 3–5 for the wide building.

In Bucharest, for the initial three-floor building with large windows, the monthly energy saving using the 3 cm shutter for the months of December and January varies among all orientations, between 889 and 1555 kWh. In Cluj-Napoca, it varies between 1073 and 1605 kWh. In Iasi, it varies between 1331 and 1659 kWh. For the initial building having small windows, the respective values are as follows: Bucharest, between 623 and 983 kWh; Cluj-Napoca, between 741 and 1014 kWh; and Iasi, between 863 and 1045 kWh.

These values exhibit obvious trends. First, in all cases, the monthly heating energy savings for the most severe months, December and January, are not small, so they cannot be disregarded. Also, for every location and orientation and for both samples of the three-floor thin building (with large windows and small windows), the monthly heating energy demand when no shutters are applied at night is higher for the large-window building.

But the same is true for the absolute values (in kWh) of the monthly energy savings due to closing the 3 cm insulation shutter at night.

For the wide three-floor building with large windows, the monthly energy saving using the 3 cm shutter for the months of December and January varies among all orientations, between 831 and 1512 kWh in Bucharest, between 1021 and 1590 kWh in Cluj-Napoca and between 1284 and 1649 kWh in Iasi.

Then there is a well-shown pattern for the variation in the magnitude of the monthly heating energy demand in the no-shutter case and the magnitude of the energy savings with the building orientation. In all locations and for each of the two most severe cold months (December and January), a variant's energy demand and also energy saving decrease in the following order: V-E, NE-SV, NV-SE, N-S.

Table 1. (**a**) Bucharest three-floor large-window initial building, various orientations; (**b**) Bucharest three-floor small-window initial building, various orientations.

(a)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	3591	2773	2506	3340
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1187	973	889	1121
Monthly Energy Saving as Percent of No Shutter Demand	33	35	35	34
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	6130	5130	4787	5924
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1555	1407	1346	1519
Monthly Energy Saving as Percent of No-Shutter Demand	25	27	28	26
(b)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	3250	2629	2401	3071
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	754	665	623	731
Monthly Energy Saving as Percent of No-Shutter Demand	23	25	26	24
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	5714	4989	4729	5571
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	983	930	903	972
Monthly Energy Saving as Percent of No-Shutter Demand	17	19	19	17

Table 2. (**a**) Cluj-Napoca 3-floor large-window initial building, various orientations; (**b**) Cluj-Napoca three-floor small-window initial building, various orientations.

(a)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	4841	3859	3452	4440
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1307	1174	1073	1271
Monthly Energy Saving as Percent of No-Shutter Demand	27	30	31	29
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	7010	6059	5578	6618
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1605	1486	1411	1583
Monthly Energy Saving as Percent of No-Shutter Demand	23	25	25	24
(b)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	4347	3661	3356	4079
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	822	777	741	810
Monthly Energy Saving as Percent of No-Shutter Demand	19	21	22	20
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	6482	5811	5468	6220
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1014	980	958	1008
Monthly Energy Saving as Percent of No-Shutter Demand	16	17	18	16

Table 3. (**a**) Iasi three-floor large-window initial building, various orientations; (**b**) Iasi three-floor small-window initial building, various orientations.

(a)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	6021	5275	5012	5830
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1438	1371	1331	1418
Monthly Energy Saving as Percent of No-Shutter Demand	24	26	27	24
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	7391	6462	6146	7210
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1659	1587	1540	1640
Monthly Energy Saving as Percent of No-Shutter Demand	22	25	25	23
(b)				
Building Orientation	**V-E**	**NV-SE**	**N-S**	**NE-SV**
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	5296	4774	4581	5169
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	904	877	863	898
Monthly Energy Saving as Percent of No-Shutter Demand	17	18	19	17
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	6815	6164	5940	6693
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1045	1022	1008	1039
Monthly Energy Saving as Percent of No-Shutter Demand	15	17	17	16

Table 4. Bucharest three-floor wide building, various orientations.

Building Orientation	V-E	NV-SE	N-S	NE-SV
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	3372	2615	2373	3140
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1118	905	831	1049
Monthly Energy Saving as Percent of No-Shutter Demand	33	35	35	33
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	6540	5531	5180	6334
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1512	1373	1315	1482
Monthly Energy Saving as Percent of No-Shutter Demand	23	25	25	23

Table 5. Cluj-Napoca 3-floor wide building, various orientations.

Building Orientation	V-E	NV-SE	N-S	NE-SV
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	4796	3834	3443	4396
Monthly Energy Saving using the 3 cm Night Shutter (kWh)	1261	1117	1021	1218
Monthly Energy Saving as Percent of No-Shutter Demand	26	29	30	28
Month of January				
No-Shutter Monthly Heating Energy Demand (kWh)	7555	6607	6123	7156
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1590	1474	1406	1566
Monthly Energy Saving as Percent of No-Shutter Demand	21	22	23	22

Here we must remember that a specific cloudiness distribution that is non-uniform in the sky in a location studied will not be accounted for by the simulation made because the used weather file misses that; the file merely provides a global cloudiness (for the whole sky). The previous remark about quantities' variation with the building orientation also holds for the three-floor wide building (which does not have the small-window variant).

Finally, another obvious trend displayed by the values in the tables is related to the percent values of the heating energy demand for the no-shutter situation the energy savings represent. The variation in the percent values with the building orientation exhibits a trend that is the reversal of the variation with the orientation of the heating energy demand and heating energy savings (in kWh). The percent values decrease in the following order (see Tables 1–6): N-S, NV-SE, NE-SV, V-E.

Table 6. Iasi three-floor wide building, various orientations.

Building Orientation	V-E	NV-SE	N-S	NE-SV
Month of December				
No-Shutter Monthly Heating Energy Demand (kWh)	5987	5244	4982	5800
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1407	1330	1284	1384
Monthly Energy Saving as Percent of No Shutter Demand	24	25	26	24
Month of January				
No Shutter Monthly Heating Energy Demand (kWh)	7985	7062	6748	7807
Monthly Energy Saving Using the 3 cm Night Shutter (kWh)	1649	1573	1531	1630
Monthly Energy Saving as Percent of No-Shutter Demand	21	22	23	21

Besides varying the width of the building, we also varied its height. We did that by varying the number of the thin (initial) building's floors one floor at a time. That was done for Bucharest exclusively for just two orientations: V-E and N-S. The range for the number of floors was between three and seven, something that preserves the initial height category of the building as low-rise. The displayed results in Figure 15 show the same not-small potential for energy saving by closing the 3 cm exterior shutters at night. The savings appear to increase linearly with the number of floors of the building, something not very surprising. Only for Bucharest and the V-E orientation, simulations have been performed for both the thin building and the wide one, using a larger step in varying the building height of four or five floors. Results are shown in Figure 16 for up to a 22-floor building which is already in the mid-rise height category. As noticed before, the taller the building, the bigger the potential energy savings using the adopted strategy (closing at night the 3 cm exterior window shutters).

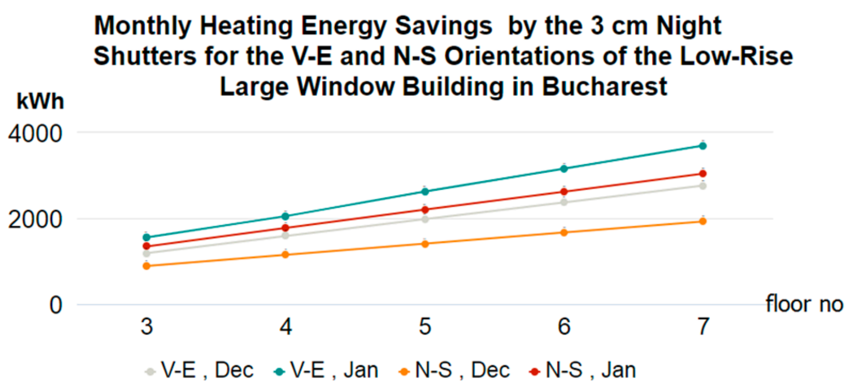


Figure 15. Savings of the Low-Rise Building.

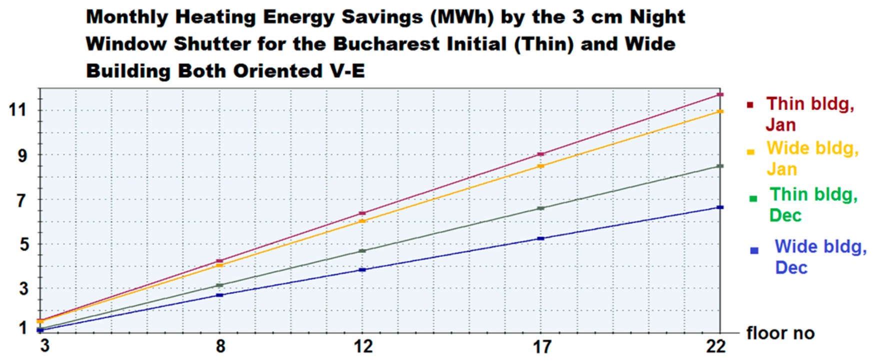


Figure 16. Savings of the Mid-Rise building.

The results for varying the internal gain values for lights and equipment produced the results expected intuitively, as shown in Figure 17a–c; the lower the values of those gains, the higher the energy losses of the whole building that will be either compensated by the heating equipment of the building or first reduced by some passive strategy.

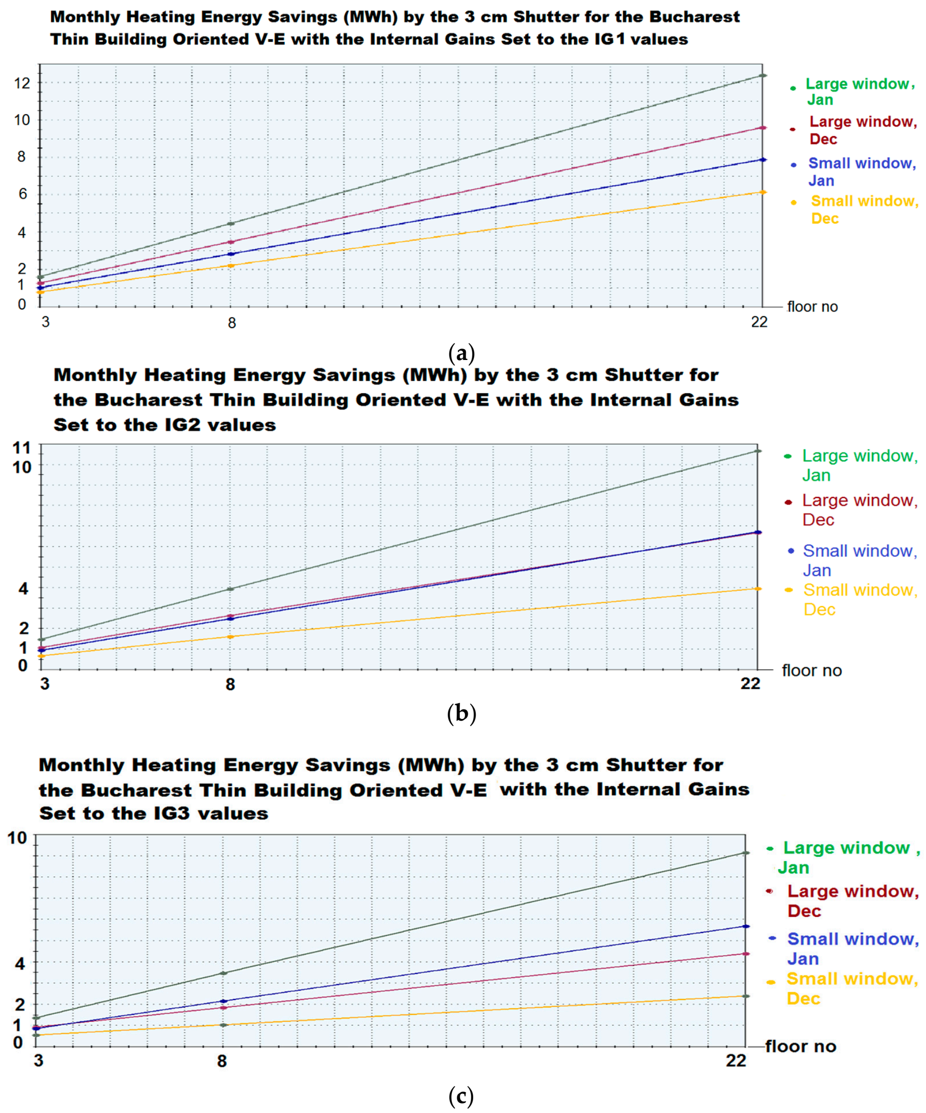


Figure 17. Monthly heating energy savings using the 3 cm shutters for 3 different value sets of internal gains: IG1, IG2, IG3.

Of course, the second way is the desirable one, and closing some heavily insulated window shutters at night may be an option.

The results show, of course, that the potential savings theoretically achievable by such shutters are higher as the modified gains (lights and equipment) are lower. And as the height of the building increases, this functional dependence is linear. Tables 7–9 are shown to enable the reader to judge in detail the magnitude of the new energy savings as a percent of the old savings (obtained with 10 and 12 W/m^2 values for the light and equipment gains).

Table 7. Monthly energy savings using the 3 cm shutter as percent of old savings for the Bucharest thin building oriented V-E with the internal gains set to the IG1 values.

Floor No.	**3**	**8**	**22**
Large windows			
December	**107**	**110**	**113**
January	**104**	**105**	**106**
Small windows			
December	**106**	**110**	**113**
January	**104**	**105**	**106**

Table 8. Monthly energy savings using the 3 cm shutter as percent of old savings for the Bucharest thin building oriented V-E with the internal gains set to the IG2 values.

Floor No.	**3**	**8**	**22**
Large windows			
December	91	83	78
January	95	93	91
Small windows			
December	90	80	73
January	94	92	90

Table 9. Monthly energy savings using the 3 cm shutter as percent of old savings for the Bucharest thin building oriented V-E with the internal gains set to the IG3 values.

Floor No.	**3**	**8**	**22**
Large windows			
December	77	59	52
January	88	82	78
Small windows			
December	73	51	44
January	87	80	76

The new savings (for the IG1 values), as a percent of the old savings, vary among all building heights and window sizes, between 104 and 113 for the two most severe months, December and January, in Bucharest. The new savings (for the IG2 values), as a percent of the old savings, vary among all building heights and window sizes, between 73 and 95 for the two most severe months, December and January, in Bucharest. The new savings (for the IG3 values) as a percent of the old savings, vary among all building heights and window sizes, between 51 and 88 for the two most severe months, December and January, in Bucharest

For the low-U glazing case simulations, the results are shown in Figure 18 and Table 10. The linear dependence on the number of building floors is of course still valid.

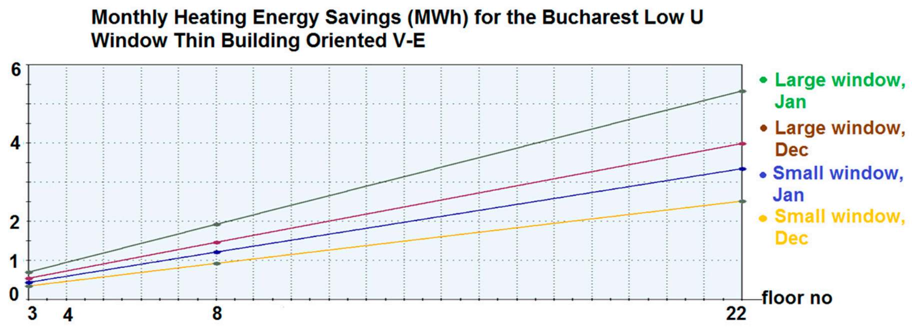


Figure 18. Monthly heating energy savings for low-U-window building.

Table 10. Monthly heating energy savings using the 3 cm shutter as percent of old savings for the Bucharest V-E thin building with a lower $U_{glazing}$.

Floor No.	3	8	22
Large windows			
December	46	46	47
January	45	45	46
Small windows			
December	45	46	46
January	45	45	45

The new savings (for the low-U case) as a percent of the old savings vary among all building heights and window sizes, between 45 and 47 for the two most severe months, December and January, in Bucharest

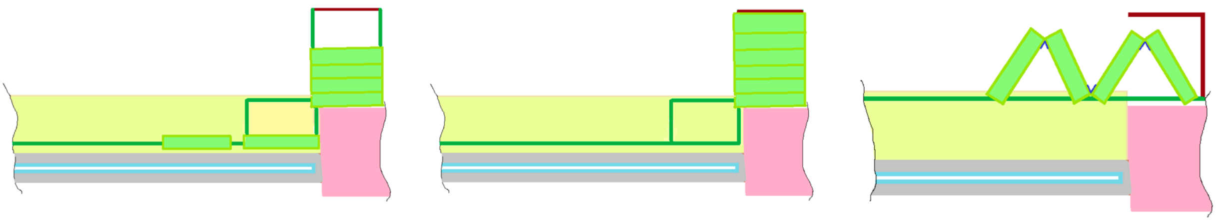
In all the simulations performed, we assumed the heavily insulated window shutters, closed at night, were placed exterior to the windows. In the final report of their study on using various window accessories to increase the thermal resistance (which is the thermal transmittance U reversed) of Alaska home windows, the researchers of Cold Climate Housing Research Center concluded the exterior and interior heavily insulated shutters had by far the best performance [13]. But the very troublesome phenomenon of condensation on the interior surface of the window and inside the window differed strongly for the two. It assessed the condensation resistance provided to the window by the exterior foam shutter as 'very beneficial' but its functionality as 'challenging'. For the interior insulation shutters, the condensation resistance provided by them to the window was assessed as 'problematic' but their functionality was assessed as 'efficient'. If we remember the 'pushing to the outside of low-temperature isotherms' when insulation is applied externally to the respective envelope element, be it a wall or window, then the very good condensation resistance provided by the exterior shutter comes as no surprise. Similarly, the very poor performance in this regard of the interior insulation shutter is expected because the low-temperature isotherms are this time 'drawn to the inside'.

In all the simulations performed, it was assumed the shutters functioned ideally, opening and closing without any problem at the specified times. Now we try to suggest some ideas about what the shutters assumed in the calculations should look like, from a very superficial point of view, one providing a sketch of an idea about their technical design. As we already said, even the not-so-bulky 3 cm insulation shutter is thick enough to make us believe it is highly unlikely to be a roller shutter kind. One attractive idea, not at all original (see, for instance, many possibilities for home shutters in [29]), is of course to have the shutter panels hinged. But our building has more difficulty in accommodating that than a residential building because the wall 'strips' on its facades (see Figure 7) are very narrow compared to the width (the horizontal size) of the windows. That will make it impossible for the opened shutter panels to have a position in the plane of the facade, forcing us to keep them at some opening angle. Such a thing is a major inconvenience. The only option without that drawback we can think of is a sliding panel shutter.

In his book published in 1980, Shurcliff offers many tips and ideas on how to realize a DIY 'thermal shutter' for a home [29], of course with the technologies and the materials of the time.

He lauds the sliding insulation shutter of one of the Zero Energy Homes built and studied at the Technical University of Denmark in the 1970s and describes its mechanism. That highly effective shutter decreased the thermal transmittance U from 3.1 W/m^2 K for the no-shutter window to 0.4 W/m^2 K for the closed-shutter window [30]. But for our simulated buildings, it is too big and too heavy.

In addition, if we choose a sliding shutter, that means some guide rails should be mounted. If the shutters are light enough, the rails will not be too strained when the shutters are operated. We have thought of three possible technical design ideas for such shutters, illustrated in the three images below which are all horizontal cross-sections. In Figure 19a,b, the insulated panels or thick slats the shutter is made of are detached from one another. When the shutter is opened, they are compactly 'parked' in front of the wall (see Figure 19b) to not interfere with the window's visual perspective and solar collection functions. The main disadvantage is likely the requirement to open the window in order to operate the shutter. Another possibility is the accordion shutter, shown in Figure 19c. It is placed in front of the facade's plane, so its sliding range is not between the window reveals. It is possible to operate it from the interior if some actioning system is put in place (as is the case with some roller shutters; some of them have straps for handling). Maybe the best will be some combination, some hybrid between the two where the 'parking' is still performed in front of the facade's wall, but the sliding takes place between the window reveals, thus providing additional protection from the outside to the air space between the window and the shutter.



(**a**) (**b**) (**c**)

Figure 19. Two ideas for designing thick-panel exterior shutters: (**a**,**b**) detached panels, (**c**) accordion shutter.

All images in Figure 19 are views from above a horizontal cross-section through a double-glazed window. The green lines above the yellow sill are light metal guiding rails. When not used, the separated panels in Figure 19a are packed in front of the opaque wall part of the facade; see Figure 19b.

4. Conclusions

In the climate of the three studied Romanian cities and likely in most of Romania or maybe in the whole temperate Dfb Koppen climate region, for a low-rise to mid-rise office building with a widespread shape and a window-to-wall ratio between 0.28 and 0.41 for its facades, exterior window shutters having a thick layer of insulation (1.5–7 cm), when applied at night, provide potential building heating energy savings that are significant for the most severe cold months of December and January. In the case of an office building with walls having 10 cm exterior insulation and window glazing with a U =1.8 W/m^2 K, the ideal monthly energy savings as a percent of the monthly heating energy demand vary for the cities of Bucharest, Cluj-Napoca and Iasi in the following ranges: 17% to 35%, 16% to 31% and 15% to 27%, respectively. Our calculations ideally have not considered any energy consumption for operating the shutters.

At present, such shutters do not exist in the Romanian market. Technically designing them to work effectively and manufacturing them at a low cost seem to be challenges. But the potential energy savings they offer and their low cost compared to replacement windows may make them attractive, and we hope a reliable design will be developed. Our very brief analysis at the end suggests such shutters should rather be of the sliding type. If we replace the glazing with a more performant one whose U value is around 1 W/m^2 K, the new potential energy savings provided by the 3 cm insulation shutter in the most severe months of December and January decrease to 45–47% of the old savings in Bucharest. Even then, such shutters might still appear attractive if they share their guide rail system with other panels or slats to be used in the warm season for shading.

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