Dynamic Simulation of the Influence of Fenestration on Buildings Energy Consumption. A Comparison Between Northern and Southern Europe

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Abstract

Dynamic simulation allows us to foresee the actual behavior of a building as a whole, namely of the envelope, its occupants, and HVAC equipments. This approach requires a huge amount of data of current inhomogeneous variables related to local climate, shelter's shapes and materials, fenestration and lighting technologies, mechanical and electrical facilities, air quality needs, etc. Consistency and accuracy of input data, together with a comprehensive and integrated knowledge of the performance of all the parts involved, act as the crucial points of the process. The paper, by means of a proprietary simulation SW proposed and used in the past by one of the Authors, shows first results in terms of impact of different degrees of buildings fenestration on needs of energy for either lighting and air conditioning. Conflicting opportunities when comparing locations in Southern (Rome) and in Northern (Berlin) Europe are found. A focus on crucial points is made using a case study as a reference.

1. Introduction

The correct evaluation of energy consumption of buildings is a necessity either to fulfill legal obligations, either to find the fittest improvements for existing buildings. Dynamic simulation models allow us to enhance the representation of the physical characteristics of the materials and to deeply forecast the effects of any change of the envelope and/or the plant facilities (Hensen and Nakahara, 2001; Hensen and Lamberts, 2011; Reddy, 2006). In the present paper we will stress a basic aspect often underestimated: the study of the lighting system with respect to the daylighting contribution (Fontoynont, 1999). This actually influences the overall energy consumption of buildings, as much as they are highly performing from the merely thermal point of view (Bazjanac, 2004; Fumo et al., 2009).

2. Aim of the Work

The purpose of the work is to evaluate and compare the different energy needs of an overall building-plant system (in terms of thermal, cooling, and electric demand) when varying both fenestration and climatic conditions, through the implementation and execution of a computer code (Spena, 1984) acting as a dynamic simulation model. The comparison will be carried out on different scenarios referring to a base-case, focusing on the influence of different kinds of glass of the frames, as follows:

- Fenestration:
    - Double glass, low emissivity (base-case)
    - Single glass, low emissivity
    - Triple glass, low emissivity.
- Locations and scenarios:
    - South Europe (city of Rome), standard building broadly exposed to insolation (base-case)
    - South Europe (Rome), building with smaller window's areas, and actually sun-shaded
    - South Europe (Rome), fully shaded building (no direct sunlight)
    - North Europe (city of Berlin), standard building broadly exposed to insolation
    - North Europe (Berlin), building with smaller windows areas, and actually sun-shaded

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- North Europe (Berlin), fully shaded building (no direct sunlight).

The case study is the model of a real building located in Rome, used as an office from Monday to Friday in the daily range of 7 am–8 pm. The characteristics of the overall building-plants system together with the input data considered will be displayed in § 4, 5, 6.

3. Climate Simulation

3.1 The Stabilized-Periodic Regime

In order to get a correct energy need for HVAC plants, a detailed knowledge of the thermal behavior of the building during time is necessary. For this purpose, the study of heat transfer must be taken considering the stability of a harmonic thermal fluctuation (Clarke, 2001; Fisher and Pedersen, 1997). The temperature-response of the system was obtained from the Fourier's general equation resolution under realistic boundary conditions. For the wall's temperature on the inner face we used:

$$Tpi(s, t) = \overline{Te} + \theta * e^{-\beta s} * sen(\omega t - \beta s) \qquad (1)$$

Inside the wall, anywhere at an x-distance from the outer face, we supposed a temperature periodic oscillation delayed and damped when compared with the fluctuation acting on the outer side.

Both damping and phase-delay are functions of the parameter β: it depends on material's properties, according to the expression:

$$\beta = \sqrt{\frac{\pi}{a * \tau 0}} \qquad (2)$$

This assumption, valid for a single-layer, may be extended to multi-layer walls by introducing (Tabunschikov, 1993) an equivalent homogeneous wall. Solar radiation on the outer surface is also taken into account, by means of the "sun-air temperature" (ASHRAE, 2000).

3.2 Insolation and IR Radiation

Solar radiation on the building surfaces affects both the thermal loads due to transmission through opaque and transparent walls, and the loads due to solar gains by transparency (Gugliermetti et al., 2004). The radiation intensity on the building surfaces not only depends on geographical coordinates, hour of the day, and sky conditions, but also varies according to the exposure of the lighted area (Spena et al., 1997). Calculations of the three components of global solar radiation have been performed following the semi-empirical model of atmosphere provided by Spena et al. (2010).

No IR radiative transfer is considered at nighttime, assuming all windows as fully shaded.

4. Building Simulation

Fig. 1 - The case-study building (Google Earth)

The architecture of the simulated building (Fig. 1) fits well with both sites (Rome and Berlin). It is 8 floors tall, with a total height of 27 m and an aspect ratio of roughly 0.3. The window/total wall surface ratio varies along the three main building facades, with values: 0.48, 0.28, 0.20.

5. HVAC Facilities Simulation

5.1 Air Conditioning

Thermal comfort within the building is provided by a fully conditioned air system (air-water mixed type, namely primary air + fan-coil) that controls: ambient temperatures, relative humidity, airflow, and renewal. Primary air is treated in several AHU (Air Handling Units) and sent to spaces to balance latent-heat loads. Sensible-heat loads are balanced by the fan-coil water system. Space inner temperatures were set according to the current standard comfort requirements. External air handling acts as follows:

- winter: pre-heating, humidification, post-heating
- summer: cooling & dehumidification, post-heating.

Renewal air flow-rates were calculated as:

$$\dot{V} = n * V \left(\frac{m^3}{h}\right) \qquad (3)$$

$$n = 0.15 * \left(\frac{24-toc}{24}\right) + \frac{toc*\phi*ia*Ap}{2400*Va} \qquad (4)$$

5.2 Inner Lighting

The lighting system is designed to guarantee and maintain given levels and uniformities of light on the work-field; to this purpose, according to UNI EN 12464, for offices and connecting spaces lighting levels were respectively averaged to 300 and 50 lx. Current standards on natural lighting in Italy (UNI 10840: 2000) impose an "average daylight factor" to be higher than 2 %, and the fenestration area to be greater than 1/8 of the floor area. It is then possible to evaluate the artificial lighting needs during time. The case study actual lighting system was based on halogen incandescent lamps with an efficiency of 22 lm/W. It was roughly assumed that 90 % of the electrical lighting power was released into the rooms, and the remaining 10 % wasted to the outer environment through the windows.

6. The Input Data of the Model

The listing of the code (Spena, 1984) is composed of a main routine and of four different subroutines operating iteratively to be applied simultaneously to the different scenarios, while composing a unique code that can inherently generate the results of each comparison. In order to correctly take into account the radiation and sun-air temperatures dependence on both time and exposure, in the iterative control procedures the execution of paths was stepped with reference to:
- day of the year (one reference day per month)
- surfaces exposure
- hourly building usage range (7 am – 8 pm).

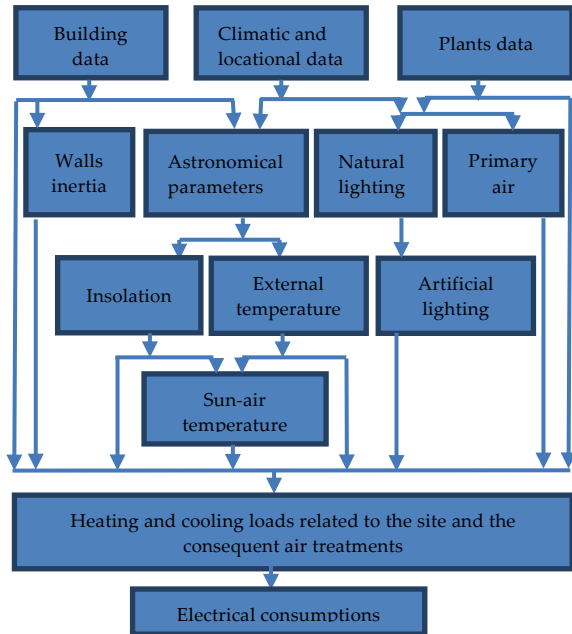A lean flow-chart is given in Fig. 2.

Fig. 2 – Simulation flow-chart

The daily results were then extended prior monthly and then yearly in terms of total heating, cooling, and electrical energy loads. Heating and cooling loads are supposed to be respectively covered by boilers, and electrical chillers. The corresponding electrical needs are then computed in the overall electrical energy (Spena, 1984; Spitler, 2009; Pedrini et al., 20002).

The following main input quantities are considered.

- Weather data:
  - Daily maximum and minimum external air temperatures; sunny hours per day; maximum and minimum shading; urban surfaces albedo;
- Building data:
  - Total area of walls, roof, windows, floor, connective, inner surfaces; inter-storey height; total building volume; thermophysical characteristics of walls, roof, floors; characteristics of the windows; solar radiation absorptance from walls and from the roof;
- Facilities data:
  - airflow-rates; room temperature setpoints; performances of the major components; conversion efficiencies of the plants.

7. Simulation Results

7.1 The Base-Case: South Europe, Rome

7.1.1 Site

The reference site for the base-case is Rome.

The windows have the following properties (Table 1):

Table 1 – Base-case windows properties

Properties	Values
Glass type	Low-emissivity double glass
Transparency	0.64
Window factor	0.35
Alignment factor	0.8
Shading factor	0.5
Solar factor	0.32
Chassis factor	1.17
Transmittance	1.3 kcal/(h*m²*K)

7.1.2 External conditions, inner lighting

The hourly outside temperature maximum value is attributed to 3 pm of each day. The absolute maximum was recorded in August (31.9 °C), the absolute minimum (2.5 °C) in December. As far as insolation is concerned, when clear sky is recorded we assume for the considered building that the maximum values are reached before midday for exposures that include South, after midday for exposures that include West (Gugliermetti et al., 2004). The cover receives maximum insolation at noon. The artificial lighting needs are closely related to the contribution of the sunlight, due to their intrinsic complementarity; so lighting needs occur mainly at sunrise and at sunset, while lacking around the midday (Pedrini et al., 2002; Li and Wong, 2007). This range is wider in summer.

7.1.3 Energy loads

As a matter of main interest, the amounts of the fan-coil loads of each different exposure are reported in Fig.s 3 and 4.
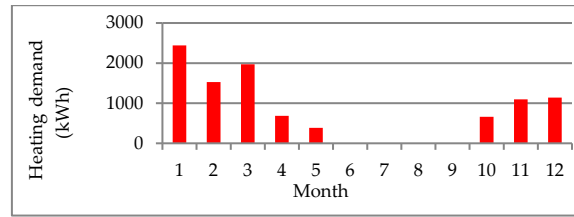
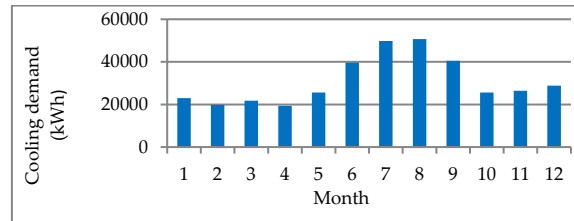

Fig. 3 – Fan-coil loads, heating demand

Fig. 4 – Fan-coil loads, cooling demand

The month requiring more local heating is January (2441 kWh), while the higher demand for local cooling occurs in August (50 676.5 kWh). The entity of those loads shows that relatively low thermal dissipation and high internal loads characterize the considered building. Monthly electrical requests are dominated by the use of lighting systems and chilling units.

Adding AHU demand, and reassuming:

- Thermal energy required: 391 765.8 kWh/year
- Cooling energy required: 624 801.9 kWh/ year
- Electrical energy required: 778 846.3 kWh/ year

7.1.4 Glass sensitivity

The kind of glass (Tables 2 and 3) influences either thermal and daylighting contributions (due to different transparencies), either loads due to the transmission through the glass (due to different transmittances).

Single glass

Table 2 – Single glass properties

Properties	Values
Transmittance	2.6 kcal/(h*m²*K)
Transparency	0.8
Solar factor	0.4

The monthly thermal needs keep on growing (the higher transmittance and the lower artificial lighting contribution prevail over the higher transparency to insolation); the cooling requests decrease in winter and rise in summer (the combination of greater

transmittance and transparency prevail over the low artificial lighting contributions). Electricity is mostly influenced by the lower cooling demand.

The annual need relative departures (%) from the base-case are as follows:

- Heating: +8.7 %; Cooling: -6.4 %; Electricity: -2.9 %.

Triple glass

Table 3 – Triple glass properties

Properties	Values
Transmittance	1.1 kcal/(h*m²*K)
Transparency	0.51
Solar factor	0.25

The heating demand results lower in all months. The cooling demand increases in winter and decreases in summer, because of the lower transmittance and transparency. Electrical consumption increases, following the artificial lighting needs.

Departures from the base-case:

- Heating: -1 %; Cooling: -0.37 %; Electricity: +1.1 %.

7.2 Lower Fenestration: The Case of Rome

In the reference site of Rome, the building was modified by reducing the window surfaces and their outer shield (shading factor = 0.9). The new window/total wall surfaces ratios are respectively equal to 0.05-0.10-0.20. The glass type of the initial configuration is the base case one. The reduction of the glass surfaces affects both the loads due to radiation and the loads due to artificial lighting, as the average daylight factor diminishes. Departures from Case 1 in standard configuration are:

- Heating: -2.28 %; Cooling: +8.8 %; Electricity: +10 %.

Single glass

Departures from the initial configuration:

- Heating: +1 %; Cooling: -4.6 %; Electricity: -3.4 %.

Similarly to the previous case, the transition from double to single glass leads to a greater heat consumption (due to greater transmittance) and to a lower electrical (related to lighting devices) and cooling request: the latter due to the lower dissipa-

tion by internal light that prevails over the greater solar gain. Departures from Case 1 with the same kind of glass:

- Heating: -9.2 % ; Cooling: +10.9 %; Electricity: +9.4 %.

These departures show how the same kind of glass over greater surfaces (and greater outer shield) requires: less cooling and electricity, more heating.

Triple glass

Departures from the initial configuration:

- Heating: -0.1 %; Cooling: +1.1 %; Electricity: +1.1 %.

For this different building configuration the effect of the triple glass gives a greater cooling request.

Departures from Case 1 with the same kind of glass:

- Heating: -1.4 %; Cooling: +10.4 %; Electricity: +11.9 %

7.3 Total Shading: The Case of Rome

The new outer condition accounts for the lack of direct radiation on the building surface in the standard configuration. The presence of solely diffuse radiation implies a lower global radiation intensity that leads to both sun-air temperature and solar gain reductions. Spaces inner lighting doesn't undergo any changes. Departures from Case 1 in the standard configuration:

- Heating: +0.3 %; Cooling: -9.8 %; Electricity: -2.9 %.

Single glass

For this scenario we considered true to evaluate the relative departures only from Case 1. In the standard configuration they resulted in:

- Heating: +9.7 %; Cooling: -18.2 %; Electricity: -6.48 %.

Departures from Case 1 with the same kind of glass:

- Heating: +0.9 %; Cooling: -12.6 %; Electricity: -3.7 %.

The lower insolation leads to smaller cooling and electricity request, and to higher heating

Triple glass

Departures from Case 1 in standard configuration:

- Heating: -0.72 %; Cooling: -8.4 %; Electricity: -1.3 %.

The general reduction of all annual loads enable us

to conclude that using a triple glass in the absence of direct radiation performs better than using a double glass in standard insolation conditions.

Departures from Case 1 with the same kind of glass:

- Heating: +0.28 %; Cooling: -8 %;
  Electricity: -2.4 %.

7.4 The Case of North Europe: Berlin

7.4.1 Site, insolation, outer daylighting

The selected site is Berlin. The building is assumed to be the same of base case, in the standard configuration.

A different siting involves variations of climatic conditions such as temperature, insolation, duration of the day and of actual hours of sunshine, external average illumination values. In Berlin, temperatures are always lower than in Rome. As the absolute maximum temperature is recorded in summer in Rome (31.9 °C), the absolute minimum occurs in winter in Berlin (-2 °C). The irradiation trend for the different exposures is similar to that of Rome, while the intensity values are in general lower. A higher latitude also means that days are shorter in winter and longer in summer (Fig. 5).
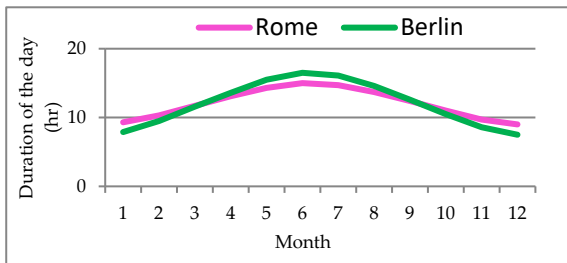

Fig. 5 – Durations of the reference days vs. months of the year

7.4.2 Energy loads

The maximum fan-coil heating demand occurs (see Fig. 6) in February, with a value of 12 085 kWh (almost 5 times the maximum monthly in Rome). The chilling fan-coil request (Fig. 7) is highest in July, namely up to 43 378 kWh (lower than the maximum cooling load occurred in Rome); high values are also recorded in January and December as the consequence of a high artificial lighting demand. The results reflect what above exposed in terms of climatic diversity between the two

locations. The electrical energy performance (peak of 88 656 kWh in December, mainly due to lighting need) corroborates what said until now.

Adding AHU demand, and reassuming:

- Thermal energy required: 567 271.6 kWh/year
- Cooling energy required: 390 216.5 kWh/year
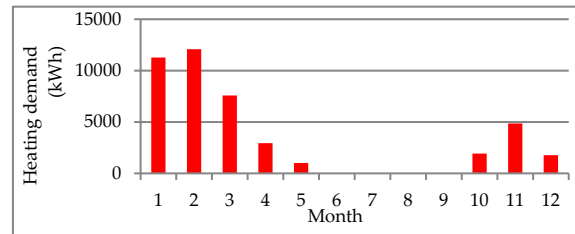- Electrical energy required: 703 721 kWh/year.
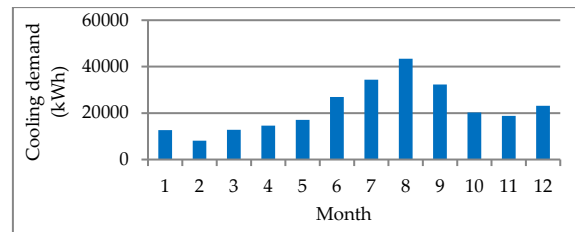

Fig. 6 – Fan-coil loads, heating demand

Fig. 7 – Fan-coil loads, cooling demand

Departures from Case 1 in standard configuration:

- Heating: +44.8 %; Cooling: -37.5 %;
  Electricity: -9.6 %.

7.4.3 Sensitivity to the kind of glazing

Single glass

Heating demand keeps on growing; cooling request is instead always decreasing, the highest departures occurring in months with low external solar radiation (in other months higher solar gains are offset by low lighting devices thermal dissipation).

Departures from initial configuration:

- Heating +15.6 %; Cooling: -17.3 %;
  Electricity: -4.7 %.

Departures from Case 1 with the same kind of glass:

- Heating: +53.9 %; Cooling: -44.8 %;
  Electricity:-11.3 %

Lower outdoor temperatures, lower radiation and external lighting lead to: a greater demand for heating; a lower demand for cooling and electricity.

Triple glass

Heating needs departures are again negative, but lower in absolute values. Cooling requirements instead grow in colder months and decrease in warmer months (due to lower heat transmission and lower transparency).

Departures from the initial configuration:

- Heating: -2.2 %; Cooling: +2.5 %;
  Electricity: +2.1 %.

We can observe that, unlike Rome, triple glazing leads to an increase of the cooling need (the lower external insolation makes the artificial lighting dissipation dominant in the overall energy balance).

Departures from Case 1 with the same kind of glass:

- Heating: +43 %; Cooling: -35.7 %;
  Electricity: -8.8 %.

7.5 Lower Fenestration: The Case of Berlin

Still in Berlin; reference building the same of Case 2. Departures from Case 4 in the standard configuration:

- Heating: -2.3 %; Cooling: +8.9 %
  Electricity: +17 %.

Single glass

Departures from the initial configuration:

- Heating: +3 %; Cooling: -12.5 %;
  Electricity: -6 %.

The trend is similar to the previous cases of single glazing. Departures from Case 4, same kind of glass:

- Heating:-16.6 %; Cooling:+31.8 %;
  Electricity: +15.5 %

Departures result similar to those of Case 2.

Triple glass

Departures from the initial configuration:

- Heating: -0.4 %; Cooling: +4.6 %;
  Electricity: +2.1 %.

The use of a more insulating and less transparent glass, in this site reduces the transmission and solar gain loads; but globally amplifies the effect of the other inner loads. Departures from Case 4 with the same kind of glass:

- Heating: -4.8 %; Cooling: +27 %;
  Electricity: +19.9 %.

7.6 Total Shading: The Case of Berlin

Still in Berlin; outer conditions changed as in Case 3. Departures from Case 4 in the standard configuration:

- Heating: +0.6 %; Cooling: -8.1 %;
  Electricity: -1.7 %.

Single glass

Departures from Case 4 in the standard configuration:

- Heating: +17.1 %; Cooling: -26.4 %;
  Electricity: -6.6 %

Using the single glass instead of the double one, when adverse changes in insolation occur, involves: higher heating demand; lower cooling demand; lower electrical demand. Departures from Case 4 with the same kind of glass:

- Heating: +1.3 %; Cooling: -11 %;
  Electricity: -1.9 %.

Triple glass

Departures from Case 4 in the standard configuration:

- Heating: -1.7 %; Cooling: -4.2 %;
  Electricity: +0.7 %.

Departures from Case 4 with the same kind of glass:

- Heating: +0.5 %; Cooling: -6.5 %;
  Electricity: -1.3 %.

8. Discussion

Consistently with the results reported in § 7, in the following pictures it may be observed, as a consequence of the transmittance and transparency reductions (transition from single to triple glass), a general heating (fan-coils+AHU) needs decrease (Fig. 8) together with a cooling (fan-coils+AHU) needs increase (Fig. 9).
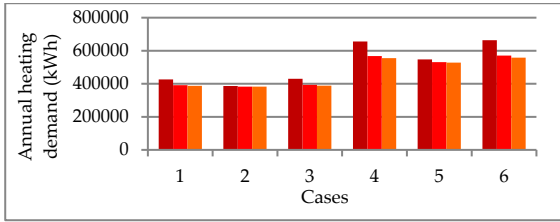
Fig. 8 – Heating overall demand for different glasses (from left: single, double, triple) in the 6 analyzed cases
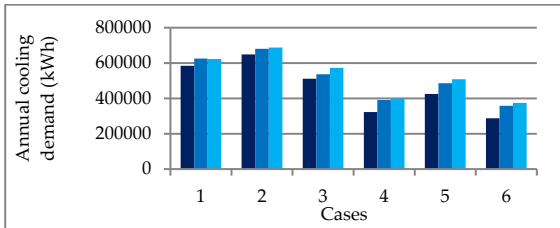

Fig. 9 – Cooling overall demand for different glasses (from left: single, double, triple) in the 6 analyzed cases
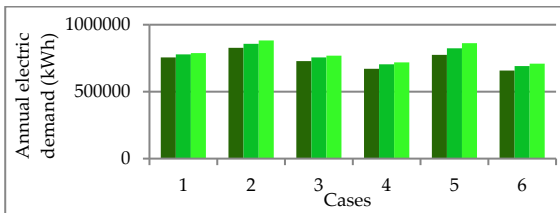

Fig. 10 – Electricity demand for different glasses (from left: single, double, triple) in the 6 analyzed cases

The highest thermal needs for the same site are recorded in case of lack of direct radiation; while the highest cooling needs occur in case of reduced windows area (electrical needs trends follow the cooling ones). The merely electrical demand (which inherently compounds all the HVAC facilities) is represented in Fig. 10, while in Fig. 11 the total energy required for the overall building performance is shown.
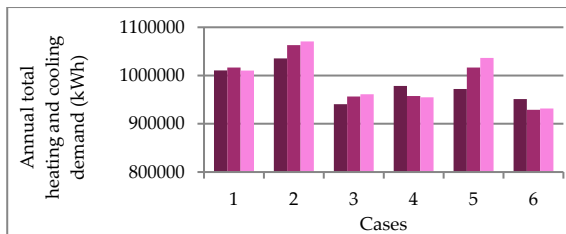

Fig. 11 – Annual total heating and cooling demand for different glasses (from left: single, double, triple) in the 6 analyzed cases

In this last picture we can observe that the overall heating and cooling demand doesn't follow a predictable trend. Considering the scenarios #1 and #4 (Rome and Berlin in standard configuration), and

not taking into account the final building system electrical consumptions, we could conclude that by replacing single glasses with triple ones (of the given properties) could be beneficial to both the sites of Rome and Berlin. A general assessment of this kind, however, is not always predictive for the actual suitability for dedicated, specific solutions. As a matter of fact, a more comprehensive analysis should consider indeed the global amount of the final energy requirement, especially if energy for the HVAC service is partly electrical (chillers, fans, pumps) and partly thermal (boilers), while the energy used by the lighting systems is merely electrical (Spena, 1984; Zhu, 2006). This could correctly lead to assess the solution that – the same comfort levels given - involves smaller overall values of both terms. And, in case of conflicting demand trends, the choice of the best solution would require an additional analysis in terms of primary energy, to be expressed in economic terms (Fumo et al., 2009). It appears necessary, as an example, in the two previously mentioned cases when, moving from single to triple glazing, thermal and electrical performances oppose.

9. Conclusion

Methodology appears validated by the intrinsic coherence of the results, and the tool fit for building comprehensive simulations. Actions and retro-fittings on fenestration made with the aim of optimizing the building performance not always lead to intuitive goals: as a matter of fact, with respect to the site we can obtain different performances for the same category of glass. The critical issue of glasses resides in their wide field of influence on building energy consumption: mainly inner room HVAC (due to the influence on heat transmission, solar gains, artificial lighting) together with lighting system energy needs. The mere assumption that single, double, triple glasses can undoubtedly - in this order – increasingly reduce building energy needs in any climatic condition, has been demonstrated to be not self-evident. Further insights will explore the sensitivity of the results to the use of led lamps at a user's level, and of heat pumps at a central level.

Nomenclature

Symbols

Tpi	Internal wall temperature (°C)
$\overline{Te}$	Average outside temperature (°C)
θ	Fluctuations half-amplitude (-)
t	Time (s)
ω	Frequency of fluctuations (s^{-1})
s	Wall thickness (m)
β	Damping factor (m^{-1})
a	Thermal diffusivity ($m^2 * s^{-1}$)
τ^0	Time of oscillation (h)
$\dot{V}$	Ventilation air flow-rate ($m^3 * h^{-1}$)
n	Renewal air rate (h^{-1})
V	Room volume (m^3)
t^{oc}	Room occupancy time (h)
ϕ	Specific flow-rate ($m^3 * h^{-1} * person$)
ia	Occupancy ($person * (100\ m^2)^{-1}$)
Ap	Useful floor area (m^2)
Va	Air volume in HVAC service (m^3)

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