On the impact of night ventilation through motorized windows on the energy and thermal performance of office buildings

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ABSTRACT

Global and local climate changes affect the energy performance of buildings, especially during the warm season, with relevant increase of cooling uses in mechanically cooled buildings and discomfort hours in naturally ventilated ones. The ventilative cooling is proved to be a promising strategy to tackle this threat, however installing new ventilation systems in existing buildings is challenging in technical and economic terms. The strategy can be also pursued by motorized windows duly operated. This solution is tested in a living lab in the northern outskirts of Rome, Italy. The living lab consists of seven rooms of an office building, planned to be upgraded to more four rooms and services during the present year. The energy and environmental performances of the living lab are continuously monitored and operated by a smart energy management system. Four of the seven rooms are equipped with motorized windows to provide free cooling and adequate indoor air quality through the implementation of different control rules. These windows are 200cm wide and 160cm high, the width of the manually and monetized sashes are 130 and 67.5cm, respectively. The latter opens/closes thanks a developing chain (30cm long) that allows 30° as maximum angle opening. As the living lab is expanding in the number of rooms, new solutions are screened to exploit the free cooling potential for windows to be replaced. Field measurements were carried out to assess the impact of night ventilation under real operative conditions, as well as to calibrate the living lab model in TRNSYS 17. In this study, starting from the calibrated model, a parametric analysis is carried out to evaluate the impact of different aperture angles of the motorized sash on the ventilative cooling potential. Simulations are run for the case of the active cooling installed in the office rooms. Based on the numerical analyses outcomes, the partner industries designed a prototypal windows, in which the developing chain is stretched so to allow 45° opening angle of the motorized sash. The new windows are currently under production, and it is planned to be installed and tested on site in summer 2024.

KEYWORDS

Energy performance, night ventilation, dynamic simulation, advanced windows

1 INTRODUCTION

As in most European countries, the energy renovation of the building stock is a crucial issue to meet the environmental objective set at Italian and international level (MiSE, 2019). The issue is of particular relevance in Italy, due to the age and the obsolescence of a relevant part of existing buildings (MiSE, 2020). Despite the first target has been to reduce the space heating use for decades, it is now necessary to tackle the recent explosion of space cooling uses, due to thermal comfort expectations by a large portion of the population not able to afford mechanical cooling systems before, as well as increase of the demand induced by global and local overheating phenomena, as the urban heat island.

The trend is bound to increase in most part of the world in the coming years (IEA, 2018). This framework created the condition for international collaborations aimed at identifying and quantifying solutions for efficient cooling, as done under the Energy and Buildings Community

of the International Energy Agency; among the studied ones, the ventilative cooling emerged as one of the most promising passive cooling strategy in several climatic regions (Holzer, 2023). This strategy can be applied by naturally cooling down the building during the cooler hours of the day, typically at night and in the first hours of the morning. Ventilative cooling can be optimised when mechanical ventilation systems are installed, unfortunately most of the existing buildings, either residential or not, are not in such conditions. Windows, and other envelope components, can be thus used to pursue the night ventilation (Hee, 2015).
More in general, windows and transparent surfaces deeply affect the building energy and environment performances (Vanhoutteghem, 2015; Valladares-Rendón, 2017) and the replacement or upgrade of existing fenestration systems is one the most effective solutions to improve the thermal response of the building during the heating and cooling season. During the latter, thermal loads are affected by solar gains through transparent components; consequently, the solar protection is an important solution to achieve energy efficiency, thermal and visual comfort (Al-Masrani, 2019). In addition, dynamic aperture of the building envelope may mitigate the indoor thermal environment via natural ventilation, according to the specific climatic conditions and building use (Zhang, 2021; Chiesa 2015).
Automated dynamic windows can be operated to optimise the thermal response of the building, and, at the same time, ensure comfort conditions for the occupants (Psomas, 2017). Benefits of this technology were quantified in field and numerical studies, aimed at improving the performance of an office building by modulating solar gains and night ventilation through automated windows managed by a smart energy management system (Botticelli, 2023). The here presented study starts from those findings and analyses window design alternatives to increase the ventilative cooling potential and increase the energy and thermal performance of the building.

2 MATERIALS AND METHOD

The activity, here presented, resumes the results achieved in (Botticelli, 2023) and develop a process to upgrade the advanced windows installed in the F40 building of the Casaccia Research Centre of ENEA, as well as to quantify the impact on the built environment. The work is carried out in the following steps:

- Description of the reference building and recap of the model calibration;
- Detailed description of the current windows system and possible upgrade aimed at enhance ventilative cooling;
- Modelling of the new windows' configuration for single side ventilation;
- Numerical analyses to assess the impact of the technology on the building cooling energy performance.

The base case is the building without any night ventilation (windows closed) and the alternatives are compared against both, the base case and the current windows' configuration. The results are then analysed to identify the most effective window aperture configuration as a function of the cooling potential and the technological limitations for the window motorization.

2.1 Description of the building and recap of the model calibration

The test building dates back to the late 80s of the past century. It was a state of art building at those time, in fact the structure is in reinforced concrete and the walls have a double layer of clay bricks with thermal insulation in between, scoring 0.50 W/m^2K thermal transmittance.. The case study is the Living Lab of the building consisting of seven rooms at the second of the three floors; they are west oriented and the dimensions are: width 3.90 m, depth 4.34 m, height 3.20 m. Each room has a hole-in-a-wall window 200 cm wide and 160 cm high, with a window to floor and window to wall are ration of 0.19 and 0.26, respectively. Rooms host one or two workers, with flexible working schedule, mostly in the 08:00-18:00 range. The seven rooms have identical rooms at the lower and upper level with identical thermal regime. The lay-out of the living lab with indicated rooms and window type is reported in Figure 1.

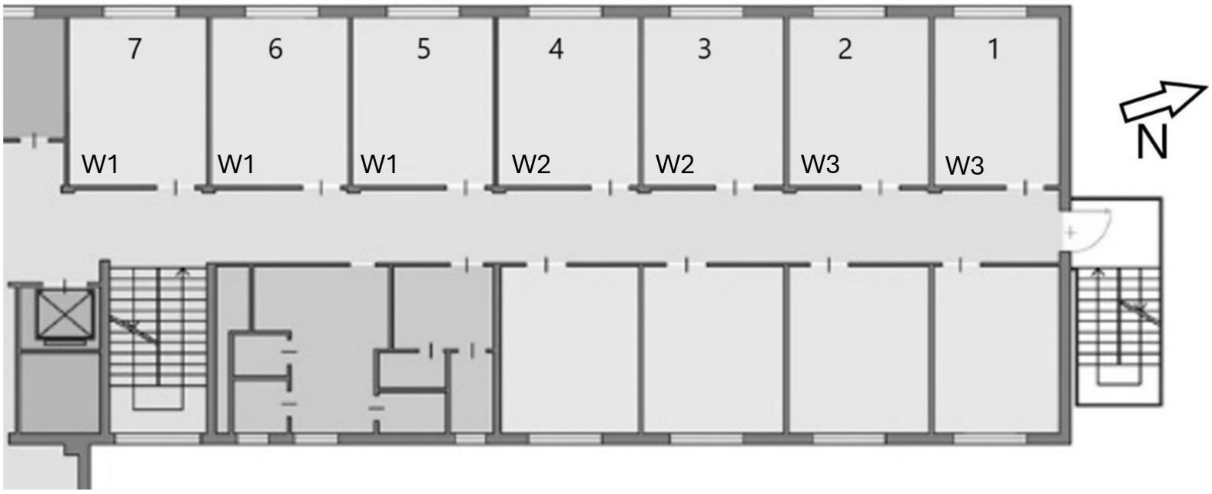

Figure 1: Lay-out of the ENEA living lab. The figure show the office number and the window typology in each room

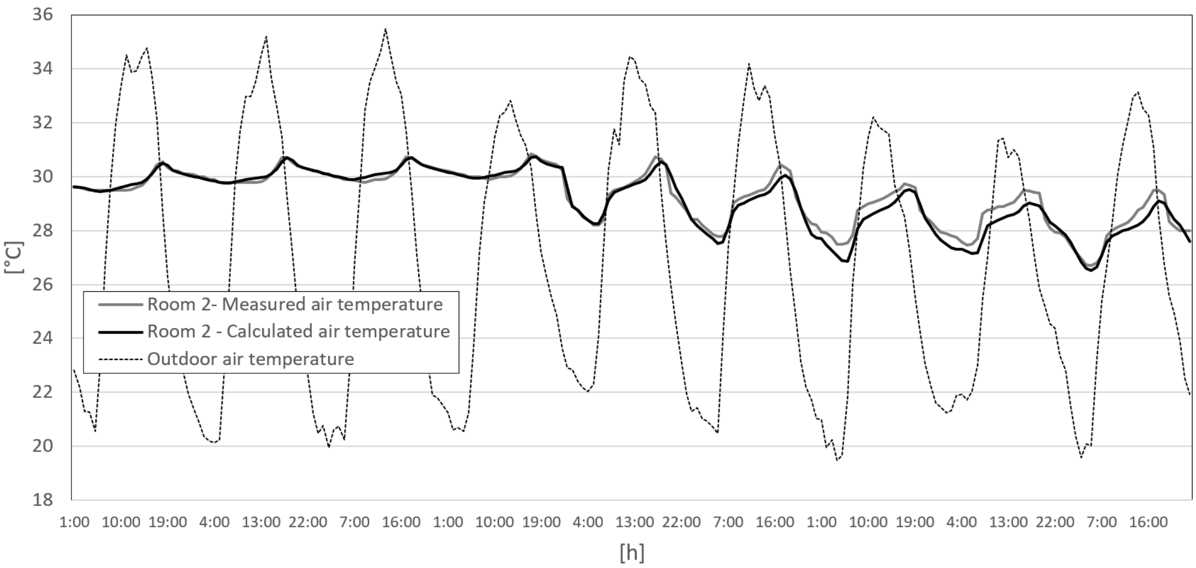

Figure 2: Comparison of measured and calculated air temperature in an exemplary room during 9 days in August 2020. The first 4 days the windows are closed, next the windows are automatically opened during the night-time hours

Rooms 5, 6 and 7 have original windows (W1), equipped with double glazing units with no-thermal break aluminium frame and an external blind for solar control. Rooms 1 and 2 have new windows (W3) with triple glazing unit with low-emissivity solar selective coating and argon in the two gaps, and the frame is in aluminium with thermal breaks. Room 3 and 4 have windows (W2) as W3 but with a double glazing unit. W2 and W3 have moveable venetian blinds in the air gap and a motorized sash. Figure 2 reports an exemplary comparison of the measured and the calculated air temperature, in a TRNSYS calibrated model against thermal free-floating and active cooling conditions according. Accuracy of the temperature sensor 0.5°C in the range of measured temperatures. Figures 2 also reports the outdoor air temperature during the monitoring period.

According to the procedures defined in (ASHRAE, 2002), a thermal model is calibrated when the coefficient of variation of the root means square error is lower than 30% in hourly data are used; in our previous exercise the indicator was slightly above 2% only, in full compliance with the reference method. Full details about measures and calculations can be found in (Botticelli, 2023; Zinzi, 2023).

2.2 Detailed window description and new design options

The new windows (W1 and W2) were designed and installed in the living lab in the framework of a joint activity with shading and fenestration systems manufacturers. The cooperation aimed at testing the potential of advanced dynamic windows in improving the energy performance of an existing building, thanks to the presence of the smart energy management system installed in the building, able to activate the venetian shading system and the sash opening of the windows to ensure solar protection during the day and ventilative cooling at night.

The graph in Figure 2 shows the impact of the window opening from 9pm until 7am (next day) on the temperature level in that exemplary room. Comparing the temperature profile with the windows closed (first four days in the graph) with that of the days with night ventilation it was observed that the maximum temperature reduction was not greater than 1.5°C. In agreement with the manufacturers, it was decided to study new configurations of the windows to enhance the ventilative cooling potentials.

The current new windows have two sashes, see Figure 3, and the net openable areas are as follows: the one on the left is manually operated and is 130cm wide and 154cm high, and the one on the right that is 65cm wide and 154cm high. The latter is motorized and it is activated either by the push-button on the sash or remotely by the building smart system. The motorized opening takes place thanks to a developing-chain, whose maximum length is 30 cm and allows 26cm of maximum aperture – image on the right of Figure 3.

Increasing the ventilation potential is, thus, intimately linked to the length of the chain, which rule the sash opening. Increasing the latter has a number of technical restraints; one of them would be related to the higher position of the button (not-ergonomic), other ones cannot be disclosed because of industrial property. To asses in details the impact of the windows and sash configuration, it was decided to analyse the impact of different apertures configurations on the energy and thermal performance of the calibrated model.

Figure 3: Front view of the new window, left, with the push-button indicated on the right sash; detail of the motorized chain to open/close the sash on the right.

3 CALCULATION

The living lab was implemented in the well known software TRNSYS 17, a model able to calculate the thermal response of buildings and solar systems in transient regime. The overall simulation is carried out by several calculation routines (called Types), each of them with a specific calculation task, and appropriately link each other. The model here used is that calibrated and applied for energy performance analyses in the aforementioned publications. The following routines were used:

- weather data reader, where local measured air temperature, relative humidity and wind speed are inputted (data used for simulation are those from Ciampino Airport as reported in the Meteonorm international database);
- solar processing, where the solar irradiation is calculated for whatever façade starting from the local measured global horizontal irradiation;
- sky temperature calculation routing, to calculate the radiative heat transfer between the building elements and the sky;
- psychometrics to calculate the characteristic of the moisted air;
- building descriptor, where the characteristic of the envelope, energy systems, gains/losses, occupancy are described;
- ad-hoc routine to model the solar shading occupancy, shading and ventilation schedule:
- ad-hoc routine to model the single side ventilation induced by the window opening.

3.1 Thermo-physics characteristics of the building

Each room of the living lab is treated as a thermal zone; all the boundary zones (corridor and rooms above and below) were monitored so they thermal conditions are used as known input. The external wall has U-value 0.5 W/m^{2}K U value; the vertical and horizontal internal structures have U-value 1.6 and 1.67 W/m^{2}K, respectively. Once calibrated, the model was simplified for the sake of the calculation effort, using the window W2 in all the rooms; its main properties are: U-value1.4 W/m^{2}K, g-value of the glazing system 0.35, light transmittance of the glazing system 0.69, the solar properties with the shading activated change as a function of the sun position and the lamellae tilt. With the objective of focusing on the ventilative cooling potential, occupancy and internal gains were simplified and assigned a constant 300W during the occupancy hours from 08:00 until 18:00.

The simulation is run for the cooling season only in line with the scope of the study. Each room is equipped with a direct-expansion air conditioning unit with 4.03 Energy Efficiency Ratio (EER) and 2.5kW as peak power. The summer set-point are 26°C and 55%, and the system run on daily basis during the occupancy hours; the air conditioning is switched-off during the week-end, when the offices are empty. When the night ventilation is activated, fixed 0.1 ACH is considered as infiltration, while the ventilation rates at night are calculated according to the procedure defined in the next sub-section.

Concerning the dynamic behaviour of the windows, the shading systems are activated when the global solar irradiation raised above 150W/m^2 and they are retracted when the irradiation drops below 100W/m^2; for the sake of calculation times the lamellae are not varying the tilt according to the solar position but are kept fixed with 45° tilt against the. The night ventilation is ensured by opening the automated sash when the indoor temperature is 2°C higher than the external one, and they close when the temperature difference is below 0.5°C.

3.2 Natural ventilation through window model

As mentioned above, the external flow rate due to the single-side opening of windows was calculated according to the empiric model developed in (Warren, 1985), which resulted to be sufficiently accurate for the specific case study, as reported in the previous sections. The model provides two equations to calculate the flow rate through the window aperture due to stack effect (1) and to wind (2):

$$Q_s = A \cdot \frac{C_d}{3} \cdot (\Delta\theta \cdot g \cdot \frac{h}{\theta})^{0.5} \quad (1)$$

$$Q_w = 0.025 \cdot A \cdot w_R \quad (2)$$

Being:

Q (m^3/s)	air flow rate for stack effect (s) and wind (w)
A (m^2)	area of the aperture, being h the height of the aperture and b its width
C_d (-)	coefficient of discharged assumed 0.61 for sharp edged windows
g (m/s^2)	acceleration of gravity
θ (K)	mean of the internal and external absolute air temperature
$\Delta\theta$ (K)	difference between internal and external air temperature
w_R (m/s)	wind velocity at reference height

At a given time step, the flow rate entering the room is the greater value between the two obtained with the equations 1 and 2.
Given the objective of the study, we run a set of simulation for different values of the aperture, keeping fixed the height of 154cm and progressively increasing the width of the aperture, starting from the initial value 26cm maximum current opening allowed by the chain and progressively increasing it by 5cm. The geometry of the apertures and the opening to floor area ration for the different chain length is reported in Table 1, together with the results on the building energy performance.

4 RESULTS

The simulations were run for the cooling season and, in particular, they focused on the three hottest months (June, July, August); the performance, in terms of total energy and energy intensity, of the building as a function of the windows opening geometry are reported in Table 1. Figure 4 shows the cooling savings achievable by the different opening sizes of the window with respect to the base case (no night ventilation) and the incremental savings achievable with respect to the current aperture. It can be observed that the current window configuration leads to 2% to aperture to floor area ratio. The additional increase of the chain length by 5cm producess about 5% increase of the aperture to floor area ratio, peaking 4.4% for the maximum chain length (0.51m).
The results report the absolute final energy uses, as well as the energy savings compared with the base case (no night ventilation), whose initial cooling energy is 37.4kWh/m^2 per year. The energy uses as a function of the window opening do not follow a linear correlation, in fact the relative energy savings progressively decrease with the increase of the aperture. The best approximation is reached by a cubic interpolation function, scoring an R^2 of 1. From the simulation results, it can be observed that the window opening with the current aperture halves (57%) the initial energy use, reaching 70% energy savings with the greatest window opening (aperture 0.74m^2). Comparing to the base case, increasing the chain length from 36 to 51cm

brings 5% (1.8kWh/m^2) as additional savings. Increasing the aperture width of 10cm provides an absolute cooling reduction of 3.1kWh/m^2, corresponding to 20% additional savins respect to the current aperture. An additional 15cm of the chain length would provide only 1.5kWh/m^2 cooling use reduction.

Table 1: Window aperture geometry and energy performance for the identified configurations

Chain length [m]	**Aperture area [m^2]**	**Aperture to floor area ratio [%]**	**Energy [kWh]**	**Energy intensity [kWh/m^2]**
0.00	0.00	0.0	4558	37.4
0.26	0.35	2.1	1983	16.3
0.31	0.43	2.5	1762	14.5
0.36	0.51	3.0	1613	13.2
0.41	0.59	3.5	1510	12.4
0.46	0.66	3.9	1445	11.9
0.51	0.74	4.4	1386	11.4

It is observed also that the prevailing ventilation forcing is the stack effect for the current configuration, this ventilation mode applies for 67% of the period. Increasing the size of the opening, a slight increment of the wind effect is observed, even if the stack effect remains the prevalent ventilation mode in all configuration; in fact, the stack effect occurrence drops to 62% for the 0.66m^2 aperture.
The current aperture provides 2.5ACH on average (0.6 and 8.2 as minimum and maximum, respectively) during the opening hours. The 0.51 and 0.66m^2 apertures provide 3.4 and 4.3ACH on average, with a relative increase compared to the current configuration by 40% and 75%, respectively; in both cases the maximum rates peak well above 10ACH.

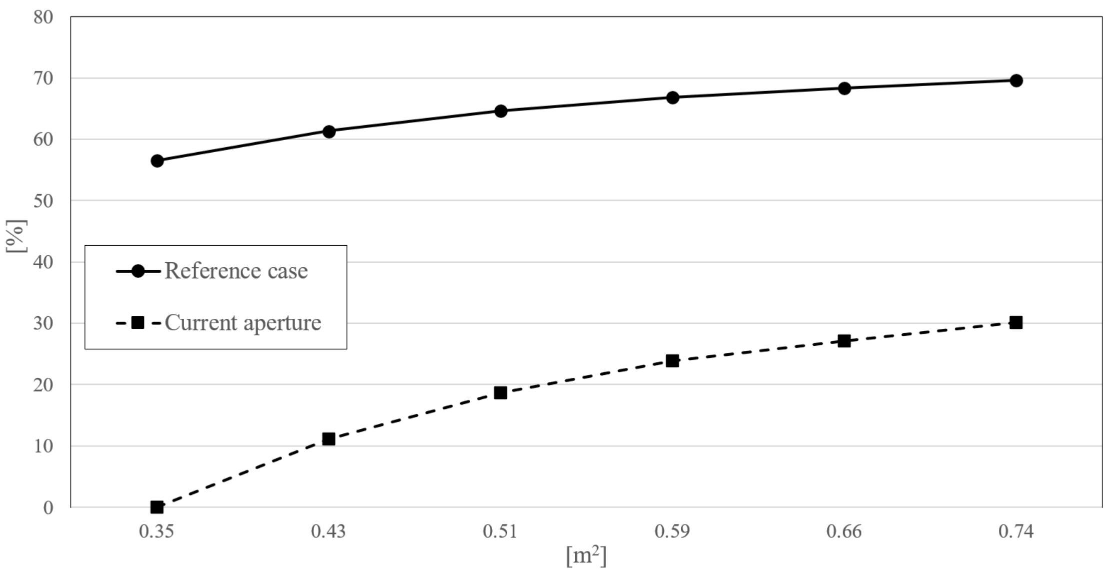

Figure 4: Relative energy savings for different aperture areas; they are calculated with respect to the base case (no night ventilation) and to the current aperture.

As exemplary case, Figure 5 reports the ACHs as a function different aperture areas for an entire week in mid-August. The plots well depict the relation between the two variables and also show the air exchange peaks due to the sudden increase of the wind. It can be also observed that the chosen rule keeps the window opened not only during the night-time, but also during the morning hours. In addition, the increase of indoor temperature, due to the absence of active cooling during the week end, keeps the window opened for entire days, thus mitigating the overheating risk in thermal free floating conditions.

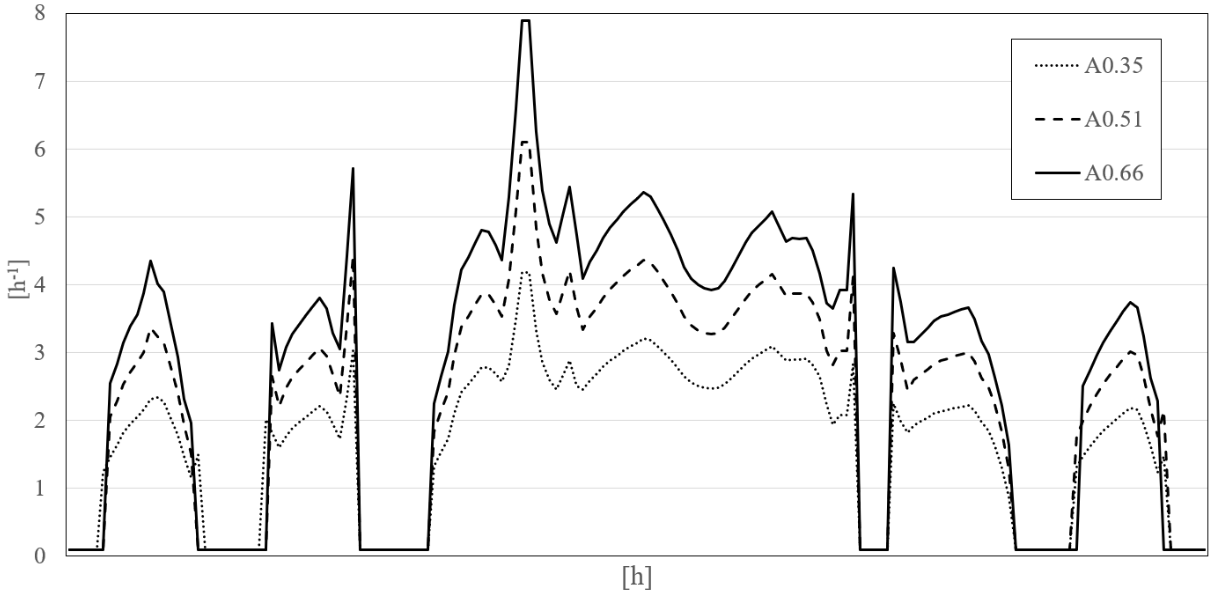

Figure 5: Air exchange per hour for different aperture sizes during a week in mid July

5 CONCLUSIONS

This study aimed at assessing the potential of natural ventilation provided by advanced fenestration systems, whose aperture can managed via a building energy management system to enhance ventilative cooling by night opening. Starting on previous studies, focus was here to provide insight on ventilation potential to upgrade the design of this innovative windows, in particular on the mechanical parts that rule the aperture size. The calculation work was based on a model validate against field measurements and, with the given input, it was found that the current aperture provides 57%; additional savings, up to 70%, can be reached increasing the aperture up to 0.74m^2. Increasing the area, however, implies to substantially increase the metal chain that ensure the automated opening of the moveable sash of the window; this is critical, especially for the usual windows sizes (total height up to 170cm). According to the study, increasing the length of chain by 10cm provide more the 3kWh/m^2 energy savings, with 20% incremental saving respect to the current chain. Further stretching provides lower savings and do not justify the mechanical implications needed to upgrade the current motorization window design.

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