Optimisation criteria of an active transparent façade based on IEQ and energy efficiency issues: results from an experimental campaign in a full-scale mock-up

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ABSTRACT
Active transparent façades are building envelope systems largely used in new office and public buildings, whose optimization (e.g. types and number of glass panes, of shading device, integration with HVAC) is a complex problem with a multidisciplinary perspective.
As far as the energy and indoor environmental performance are concerned, thermophysical, optical and acoustic properties need to be taken into account through a synergic approach so that an optimal overall behaviour is achieved.
The research activity presented herewith was aimed at supporting the contractor's decision process about the layout of an Active Transparent Façade (Climate Façade typology) for a high-rise office building. An extensive monitoring on a full scale office room mock-up was thus designed to compare two ATF solutions, assessing the most viable trade-off between high performance and costs, taking not only energy efficiency but also thermal, visual and acoustic comfort into account. Two ATF modules with slightly different configurations (type of inner skin) were tested in the mock-up. The energy efficiency analyses showed that, as predictable, the ATF module equipped with the best inner skin was able to significantly increase the thermal resistance, reducing the winter heat loss and the summer heat gain, though this impact was not so relevant when the overall energy balance at building level was considered.The inner skin played, instead, a relevant role when considering thermal comfort, especially during summer peak conditions. From a visual comfort perspective, the two technologies did not perform in a significantly different way in the presence of the screen, but differences were observed in winter (with retracted screen), since the higher luminance values measured for the single skin could cause glare. Considering sound insulation, the façades presented comparable values and no significant differences were measured.

KEYWORDS
Active transparent façade, optimisation criteria, real scale mock-up, energy performance, IEQ.

INTRODUCTION
Active transparent façades (ATFs) are a particular type of responsive façade characterized by a certain degree of integration with the HVAC equipment. The main functioning principle of this façade is based on a ventilated cavity positioned between two glazing surfaces, where the shading device is hosted. This type of technology has been largely investigated and adopted in high-rise office buildings because it combines a fully transparent façade with a good energy and comfort performance. Being a dynamic façade, the design phase of these façade systems is not a trivial task because of two reasons: firstly, the façade system needs to be accurately designed to perform according to the desired targets when in real operation conditions (i.e. under the climate and indoor conditions of the specific location/building), and this can only be

done through advanced simulations; secondly, due to its higher degree of complexity, costs constrains are a relevant variable of the problem, often leading to non-optimal compromises, where the efficacy of the solution is decreased because of the search for lower investment cost. The optimization of the ATF configuration thus needs to take several criteria into account and to combine various performances that are often difficultly to compare.
The research activity presented in this paper originated in the framework of the construction of a high-rise office building and it was aimed at supporting the contractor's decision process about the final layout of the façade of the building. Preliminary simulations of different façade layouts were carried out by the engineering consulting firm and the façade manufacturer, with a focus on energy performance and maintenance issues. These led to the design of a specific active façade system, which was proposed to the contractor with two different configurations. A full scale mock-up of an office room was built and ATF configurations tested.
This paper is based on the analysis of data collected during an extensive and continuous monitoring that was carried out in the mock-up for more than a year. The paper is aimed at highlighting how the façade configuration might be not fully optimized if the focus is placed on one particular aspect of the problem only (i.e. the energy performance), and that a multicriteria analysis can lead to different optimal solutions.

MATERIALS AND METHODS

Active transparent façade configurations

The ATFs investigated in this paper belong to the subcategory of Climate Façades. These are double skin façade characterized by a mechanically ventilated cavity, used to extract exhaust air from the room and convey it to the return of the ventilation plant. The air flows from the room to the façade's cavity through an inlet, positioned at the bottom of the façade. The optimal solution of Climate Façade configuration was identified by an engineering consulting firm through a modelling activity, considering mainly energy and maintenance issues.
It consisted of a high performance outer skin, a roller screen in the ventilated cavity and an inner transparent skin. Given the high performance of the external selective glazing and of the reflective roller screen a question aroused about the performance level required for the internal glazing, two different configurations for the inner layer were proposed: both modules presented the same outer skin, screen and ventilation air flow rate, whilst the inner side skin (layer 4) was different: for the module called "A", it was made of a single extra-clear pane, and for the module called "B" it is made of a double glazed unit with low-e coating.
An experimental activity was thus designed and a long term monitoring on a full scale mock-up was carried out. The main features of the mock-up are presented in Table 1. Given the characteristics of modules A and B, it is straightforward to assume that the latter would have presented a better energy and comfort performance. The scope was instead to verify whether the solution A, having a very high impact on the reduction of the overall cost, would be nonetheless considered acceptable from energy and users perspective or not.

Table 1. Assemblies of the two configurations of ATF.

	ATF module A	ATF module B
1. External skin -	double glazed unit with a selective external glass, 20/16/10 mm	
2. Ventilated cavity	240 mm depth with an air flow rate of 20 m^3/h	
3. Shading	reflective roller screen	
4. Inner skin	single extra-clear glass pane of 10 mm	double glazed unit with clear glass, argon cavity and low-e coating glass 10/16/10 mm

a) b) c)

Figure 1 a) The mock-up with façade modules A and B b) Acoustic measurement c) Light measurement.

Experimental test rig, data collection

An experimental campaign, based on both a continuous monitoring and spot measurements, was designed and carried out to evaluate the difference between the two façade module configurations in terms of energy, thermal comfort, visual comfort, and acoustic comfort performances. The two ATF configurations were tested, in parallel, on the south façade of a 1:1 office room mock-up . The mock-up was positioned at the building site of a new high-rise building in Turin, Italy (45.05 N, 7.70 E), sub-continental climate.

The indoor air temperature of the mock-up was maintained by means of a combined air system and radiant panels, at the following set-point temperature: 20 C in winter, 23 C in spring and autumn, 26°C in summer. Over 70 sensors were installed: thermocouples for air and surface temperature measurement, heat flux meters and pyranometers for solar radiation. Physical quantities were recorded with a time step of 15 minutes (average of 30s samplings).

Spot measurements were carried out to acquire vertical illuminance values (both inside and outside the façade modules). An Imaging Luminance Measuring Device (equipped with both a 4.5 mm lens and a fish-eye lens; accuracy ±3%) was used to obtain a series of luminance maps within the mock-up and to assess the daylight distribution. The measurements were repeated in 3 different positions (close to the modules; at the center of the room; in the back of the room, far away from the modules), positioning the lens of the instrument at a height of 1.20 m (that of a sitting person). For each ATF module the transmitted sound level was also evaluated by means of an intesimetric probe measure (Brüel & Kjær), in accordance with the standard UNI EN ISO 15186-2 – 2010. This measurement was carried out using an external sound source with a pink noise of 80 W, placed in front of the two ATF modules.

Direct measurement of thermal comfort, visual comfort and energy consumption were not possible because the two façade configurations were sharing the same indoor environment. For this reason thermal comfort was evaluated through simulations using the measured data as input.

Energy performance assessment

Synthetic performance parameters were assessed for each module, with both the screen displaced and retracted. Following the methodology presented in (Goia et al., 2014 and Bianco et al. 2015), the thermal transmittance (U-value), the equivalent value of (g-value*), the solar transmittance (τ_s) and the visible transmittance (τ_v) were assessed. The winter and summer performance was assessed through the evaluation of the daily energy crossing the façade modules (i.e. the integral over the 24 h of the hourly values of the surface heat flux and of the transmitted solar irradiance). A week with the screen displaced and a week with the screen retracted were selected, for summer and winter season respectively.

IEQ analysis

Thermal comfort

The thermal comfort evaluation was carried out by means of a software, using the surface temperatures measured at each façade module during the experimental activity as input. Instead, the surfaces temperatures of the floor, walls and ceiling were assumed to be equal to the indoor air temperature. Two office rooms with the same sizes of the office mock-ups (3.25 x 6.25 x 4 m) were modeled, fully equipped with the module A façade and with the module B façade, respectively. PMV values (UNI EN ISO 7730/2006) were calculated for a grid of points evenly distributed over the surface floor of the office room. Although thermal comfort analyses were carried out for both the summer and winter season, for long periods, results of the simulations under peak summer conditions are presented in this paper because of their relevance. Analyses were carried out for the configuration with screen displaced, which presented higher temperature at the indoor surface of the glazing, and thus a more critical condition for thermal discomfort. Further input data for the model for summer simulation were: a metabolic rate of 1.2 [met], a clothing resistance of 0.5 [clo], humidity ratio of 50% [-] and air velocity of 0.25 [m/s]. Following the standard UNI EN ISO 7730/2006, the PMV results were classified in three classes: class A for $-0.2 < PMV < +0.2$, class B for $-0.5 < PMV < +0.5$ and class C $-0.7 < PMV < +0.7$.

Visual comfort

The visual comfort potentially perceived by an occupant in the mockup was analyzed through measurements of the luminance distribution within the occupant's visual field, rather than illuminances acquisition on the work plane. Different daylight distributions were actually produced in the room through the glazing A and B, resulting in a different perception for the future occupants of the office. The luminance distributions were measured through a series of luminance maps taken by the instrument positioned close to the entrance door and at 4 m distance from the façade. The luminance measurements were taken for some spot days in summer and in winter, under overcast and clear skies. The evaluation of the potential visual comfort associated with each of the two technologies was done comparing the luminance values over the glazing surface (both with displaced and retracted screen) as well as over surfaces on the ceiling, the walls and the work plane on the desk. It is important to stress that a direct comparison cannot be done, as the two glazing technologies were installed side by side; as a result, it was not possible to identify the contribution of each technology to the luminous environment inside the room, as the daylight in the space was determined by the combined effect of the two technologies. To overcome this problem, two measurements were taken for each setting, using a black opaque curtain to shade one of the two glazing and then the other one so as to avoid parasitic contribution of daylight. The two luminance images were eventually merged into a single one, which showed the luminance values of the two technologies and allowed a direct comparison to be done.

Sound transmission

The difference between the transmitted sound level and the incident level (L_1-L_2) was assessed for both ATF modules. L_1 is the level (in dB) produced by the external source which is subtracted of the L_2 the sound level monitored by the intensimetric probe. The higher the (L_1-L_2) difference, the higher the sound insulation level of the façades evaluated according to the standard ISO 717-1:2013.

RESULTS

Energy performance assessment

Synthetic performance parameters are reported in Table 2. An equivalent U-value of 0.62 W/m^{2}K was found for module A, against 0.33 W/m^{2}K for the module B. This means that module B presented a higher thermal resistance than module A, as expected. The calculated values of the equivalent solar factor (g-value*) were in the range of 0.12 to 0.22 for module A, and 0.07 to 0.15 for module B (for screen displaced and retracted, respectively). When the screen was displaced, the difference in energy performance between the two technologies became more evident. Module B (equipped with the low–e double glazed unit) presented lower values of solar and visible transmission than module A – see Table 2.
On the contrary, no relevant differences were found between the two modules when the screen was displaced, in terms of both visual and solar transmittance. Module A always presented higher values of daily energy than the module B, regardless of the season (Figure 2). In winter, module B had, on average, 40% lower values of transmitted energy than module A. In summer, when the screen was retracted, the energy transmitted through Module A was 26%-32% higher than that entering through Module B. This showed that the extra glass in the inner skin of the Module B allowed both heat loss during winter and heat gain during summer to be decreased. For both façades configurations no risk of overheating within the ventilated cavity was recorded, since the highest air cavity temperature (measured in module B) was below 60 °C (a value well below the range where risk of durability for PVB sealing increases).

Table 2. Synthesis of the performance metrics related module A and B.

	ATF module A	**ATF module B**
1. U-value [W/m^{2}K]	0.62	0.33
*2.1 g-value * screen ON* [-]	0.12	0.07
2.2. g-value screen OFF* [-]	0.22	0.15
3.1 τ_s screen ON [-]	0.03	0.02
3.2 τ_s screen OFF [-]	0.20	0.13
4.1 τ_v screen ON [-]	0.06	0.05
4.2 τ_v screen OFF [-]	0.50	0.42

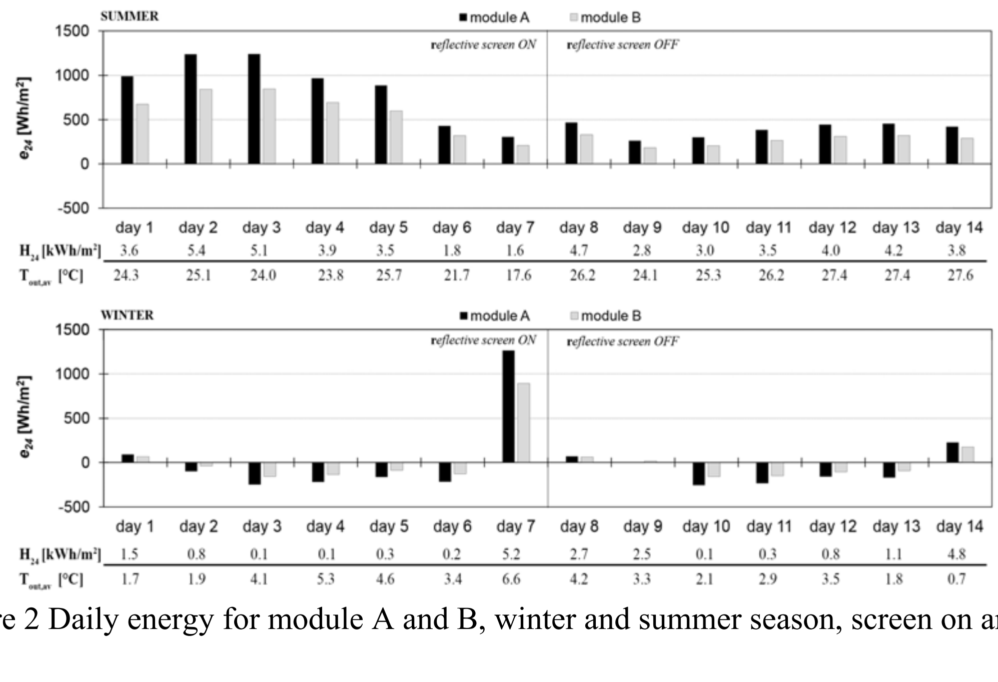


Figure 2 Daily energy for module A and B, winter and summer season, screen on and off.

IEQ

Thermal comfort

The results of the thermal comfort analysis are reported for the summer season because no critical conditions were observed during the winter period for any of the two configurations. For the summer day selected as representative of design conditions (high outdoor air temperature and clear sky), the peak solar radiation was 656 W/m^2 and the maximum external air temperature was 33°C, while the maximum internal temperature was 26.9°C. In Figure 3 the internal surface temperature are plotted for the two façade modules at different height.
The peak internal surface temperatures were recorded at 17.00 for module B and 2 hours earlier for module A, both at the level 3 (+3.00 m), showing the higher inertia of the configuration with double glazed unit, which shifts by 2 hours the peak of the transmitted heat flux. The maximum internal surface temperature was 39.1°C and 32.4°C, for module A and for module B, respectively. During the analysis day, 8% of the floor area near the façade of module A was in discomfort condition while for module B no discomfort was registered. 79% of the floor area of module A was in comfort class B and the remaining in class C.
For module B the 5% of the floor only was in the lowest comfort class (C), while the rest was in the class B. Module A shows slightly worse thermal comfort conditions, but these occur in an area very unlikely to be occupied, and thus with little influence on the user.

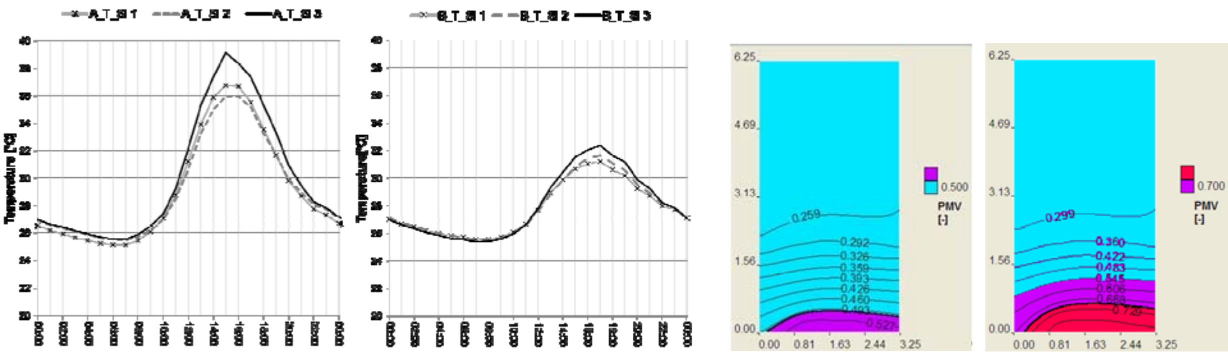


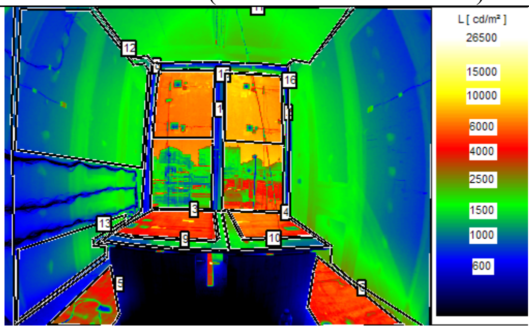
Figure 3 Indoor surface temperature and PMV floor distribution for modules A and B.

Visual comfort

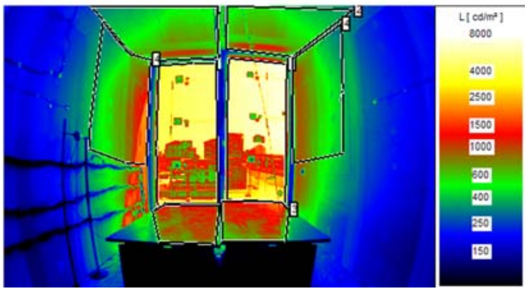
For the sake of brevity, the results for the farthest point apart from the windows under a clear sky are presented only. Table 3 shows the luminance maps measured in winter as well as the results found under summer and winter design day conditions.
As far as the winter design day is concerned, higher luminance values were observed for module A compared to module B. This difference is consistent with the higher visible transmittance (τ_v) of the module A (τ_v = 0.50 and τ_v = 0.42, A and B, respectively – both in the absence of the shading system). The comparison between the mean luminance values measured on the same surfaces for the two technologies showed a similar ratio, regardless of the presence of the shading system (L_A/L_B = 1.21 without shade, L_A/L_B = 1.23 with shade).
This magnitude is confirmed when the luminance values of the two glazed surfaces are considered (module A had ≈ 19% higher luminance values than module B).
As expected, a higher difference between the cases of presence/absence of the shading system was observed for the summer design day. When the shade was retracted (which is a not a realistic case in a sunny day, under direct solar irradiation), the ratio of the mean luminance over the glazing A to the mean luminance of the glazing B is 1.88. When the shade was displaced, the luminance ratios were constantly close to the unity, showing that the glazing type does not play a role on the light distribution within the space - this can be explained considering that the screen becomes the dominant component of the system).

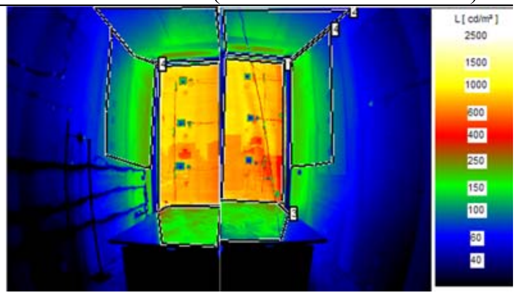
Table 3 Example of L values of the two glazing A and B. Winter and summer season.

	WINTER DAY (SHADE: RETRACTED)			WINTER DAY (SHADE: DISPLACED)		
surface	L_B [cd/m^2]	L_A [cd/m^2]	L_A / L_B	L_B [cd/m^2]	L_A [cd/m^2]	L_A / L_B
glazing	L_{15} = 1268	L_{16} = 1531	1.21	L_{12} = 265	L_{13} = 326	1.23
desk (daylit area)	L_3 = 1225	L_4 = 1471	1.20	L_3 = 93	L_4 = 168	1.81
desk (non daylit area)	L_9 = 319	L_{10} = 484	1.52	L_9 = 64	L_{10} = 74	1.16



	SUMMER DAY (SHADE: RETRACTED)			SUMMER DAY (SHADE: DISPLACED)		
surface	L_B [cd/m^2]	L_A [cd/m^2]	L_A / L_B	L_B [cd/m^2]	L_A [cd/m^2]	L_A / L_B
glazing	L_1 = 1914	L_1 = 3606	1.88	L_1 = 598	L_1 = 622	1.04
ceiling	L_2 = 382	L_2 = 456	1.20	L_2 = 80	L_2 = 82	1.03
desk (daylit area)	L_3 = 883	L_3 = 914	1.04	L_3 = 259	L_3 = 268	1.04
Side wall	L_4 = 656	L_4 = 400	0.61	L_4 = 89	L_4 = 89	1.00





Acoustic

In Figure 4 it is possible to observe that the module B presented a slightly better insulation level than the module A for high sound frequency. For low frequency, below 800 Hz, the sound insulation level of the two façade configurations had a very similar trend. The global sound insulation of the façade was 39 dB for module A and 40 dB for module B. The values are very similar (furthermore, the measured difference is in the uncertainty interval). It appears clear that, for this kind of ventilated façade, a very important role in the sound transmission is played by the outer skin more than the inner skin.

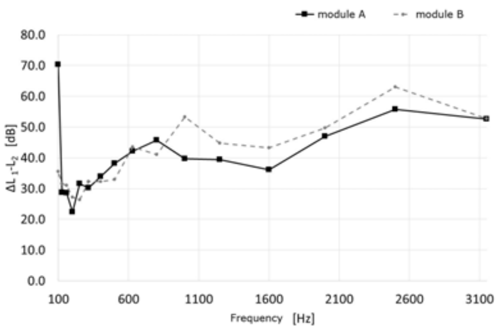


Figure 4 Acoustic results, difference of level, module A and B.

DISCUSSION AND CONCLUSIONS

A long term monitoring campaign was carried out in a full scale mock-up, aimed at assessing the impact of two slightly different configurations of ATFs on the transmitted energy and on the IEQ related issues. The difference is concerned with the inner skin (a double glazing low-e coated, module B, versus a single glazing, module A).

The analyses related to the energy efficiency showed that, as predictable, the double glazed unit in the inner skin of module B was able to significantly increase its thermal resistance compared to module A, noticeably reducing the winter heat loss and summer heat gain. The selective glazing, the reflective shading device and the ventilated cavity (the same for both the modules), were able to remove the solar gains entering the office, reducing the risk of overheating and the energy crossing the façade. The inner skin played thus a negligible role. It is important to stress that the energy reduction that was measured may appear relevant (30%), but this is just related to the energy crossing the façade, and this difference can be significantly lower when the overall energy balance at building level is performed.

The inner skin played a relevant part when considering thermal comfort, especially during summer peak conditions. In winter days, internal surface temperatures for both modules were quite similar to the indoor temperature and no discomfort occurred. In summer, the low-e glazing was able to maintain lower the internal surface temperature (32°C vs. 39°C), with a relevant impacting on the discomfort for the users when the workplace is located very near the façades (however, a situation unlikely to occur). The PMV values maps showed that no floor area was indeed in discomfort condition for module B, which means that all the floor area could be potentially used, while adopting the module A, in the zone near the façade discomfort conditions were registered.

To draw some conclusions from a visual comfort perspective, the two technologies did not perform in a significantly different way in the presence of the screen in summer. Higher differences were observed in winter, with higher luminance values in the presence of the glazing A (≈ +20% compared to the glazing B over the same surfaces). When the screen was retracted, the difference became more significant: this means that due to the higher τ_v of the glazing A, discomfort problems (glare in winter, overheating in summer) may be experienced by the occupants. As far as visual comfort is concerned, it is worth noticing that the low-e glass of the Module B produced a slight color shift of the daylight transmitted toward the green, which may be associated to a lower comfort by the occupants.

Considering sound insulation, the façades presented comparable values and no significant differences were measured.

Another key point of the analysis was related to the maximum temperature registered in the cavity that can increase maintenance costs (i.e. malfunctioning of electrical motors for blinds, durability of materials). The most performing façade, from the energy point of view, revealed to be more critical when considering this aspect, since higher temperatures were measured, though these seemed to remain within an acceptable range where safety is assured.

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