The acoustic and daylighting effects of external façade sun shading systems

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Abstract

External sun shading devices are increasingly used in sustainable buildings to reduce the greenhouse effect in the summer and the glare effect due to direct solar irradiation through transparent surfaces. The acoustic effects of these devices have been investigated in recent studies that suggest the possibility of optimising these elements to improve acoustic comfort in indoor environments, even with open windows. Nevertheless, there are few studies that analyse the combined effect of these devices on acoustic attenuation and improved daylighting.
In this paper, the results of acoustics and daylighting simulations are reported, considering different dimensions, distances of the louvres and orientations of the façade. The main results of previous works concerning the effect of lining the bottom side of each louvre with sound-absorbing material are also briefly summarised. The acoustic effects of different configurations of the louvres are evaluated in terms of Insertion Loss in the façade plane. For the lighting simulations (daylight factor, daylighting uniformity and daylight glare probability), the variation of the shielding effect is studied considering the spacing between the louvres and the orientation of the façade for different times and seasons for latitude in the South of Europe.

Keywords

Façade, Indoor comfort, Light shelves, Insertion Loss, Acoustic absorption, Daylighting

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1 INTRODUCTION

Solar shading systems installed on building façades are necessary to reduce the summer energy consumption of buildings, based on the technical standards EN 13363 (EN 13363-1, 2003) and EN 14501 (EN 14501, 2006), received within the Energy Performance Buildings Directive (EPBD) released in 2002 and revised in 2010 (Directive 2010/31/eu, 2010). These standards and the EU directive concern building construction techniques to achieve very high energy-efficient buildings, also known as nearly Zero Energy Buildings (nZEB); buildings that significantly reduce their environmental footprint.

Solar shading devices can influence visual comfort (Cellai, Carletti, Sciurpi, Secchi, Nannipieri & Pierangioli, 2014) (ECBCS Annex 29/SHC Task 21, 2010) negatively by diminishing daylight amount in inner spaces, but also positively by reducing glare effects and improving daylighting uniformity, especially with clear sky conditions. This paper evaluates the effect of variation in daylight availability in a specific period of the year in South Europe. The threshold parameters that define the quality and quantity of natural lighting are regulated by national laws and calculated by international standards such as EN 12464 (EN 12464-1, 2021), EN 14501 (EN 14501, 2005) and EN 17037 (EN 17037, 2018).

The assessment and management of environmental noise are also very important for the well-being of people (Directive 2002/49/ec, 2002). Poorly designed façade shading systems can lower the acoustic comfort and undermine the overall acoustic performance of the façade if the sound coming from the traffic is directed toward the windowpane. This negative effect can be suppressed and converted into a positive effect by proper louvre design that reflects the traffic noise away from the façade surface.

The acoustic performances of building façades have been considered in several studies, which investigated multiple aspects such as their shape (Busa, Secchi & Baldini, 2010), the presence of balconies (Li, Lui, Lau & Chan, 2003), the effects of a green envelope (Van Renterghem, Hornikx, Forssen & Botteldooren, 2013), the influence of the windows (Granzotto et al., 2017) and the flanking transmission (Secchi, Cellai, Fausti, Santoni & Zuccherini, 2015). A comprehensive review related to the acoustic performances of building façades was recently published (Hu, Zayed & Cheng, 2021), including studies on sound insulation, the effect of façade on street noise, and noise reduction techniques. On the other hand, the acoustic influence of façade shading systems has not been widely investigated. Sakamoto and Aoki (Sakamoto & Aoki, 2015) presented a numerical study to examine the sound reduction effects due to the presence of louvres mounted on the building façade, validating the results with experimental measurements on a 1:20 scale model. Numerical analysis and a 1:1 scale model were also used by Zuccherini et al. (Zuccherini, Fausti & Secchi, 2016) and Fausti et al. (Fausti, Secchi & Zuccherini, 2019) to analyse variations in the acoustic sound pressure field on the building façade, considering different sound source positions and changing the configuration of the louvres and their tilt angle. Further investigations of the acoustic effects of building façade shading systems, involving in-situ experimental measurements (Sakamoto, Lee, Ishii, Katayama, Iwase & Takahashi, 2017) (Zuccherini, Fausti, Santoni & Secchi, 2015) and evaluation of the related psychoacoustic effects (Zuccherini, Aletta, Fausti, Kang & Secchi, 2019), highlighted that the louvres can reduce the sound pressure levels across the building façade and the magnitude perception of the noise. The most common indoor shading devices were experimentally analysed by Catalina et al. (Catalina, Ene & Biro, 2019), assessing their influence on both the improvement of the sound insulation performance and the reverberation time of the room. However, in both cases, results showed negligible differences between different shading device systems.

At present, most studies deal with the effect of façade shape and shielding devices, with analyses referring only to acoustics or daylight, whereas the human reaction to sound and light stimuli are strongly correlated, as some studies show (Buratti, Belloni, Merli & Ricciardi, 2018) (Huang, Zhu, Ouyang & Cao, 2012) (Hangzi, Xiaoying, & Yue, 2020). The main aim and the novelty of this work are, therefore, the use of a multi-domain approach to evaluate the acoustic and daylight effects given by the presence of an external shading device made of shading louvres. This study was carried out by means of both simulations and measurements in a real building and in a scale model realised in an acoustic laboratory. In the follow-up to this work, questionnaire-based investigations will make it possible to analyse the reciprocal influence between the daylighting and acoustic parameters currently described by independent parameters and limit values.

A virtual mock-up building was designed as a reference for various evaluations. The building could be assimilated into an 8-storey office building with a flat façade. The shading system was simulated by evaluating various sizes of louvres and the spacing between them. Acoustic and daylight simulations were carried out on the same geometries.

The louvres' tilt angle was not considered in this work for daylight simulations because it was assumed that shading devices with horizontally oriented louvres constitute the best compromise between acoustic and daylight comfort: previous works have shown that louvres tilted towards sound sources can increase the sound pressure level on building façade, offering, on the other hand, the best shading to the building itself (Fausti et al., 2019) (Zuccherini et al., 2019).

Acoustic performances have been evaluated as sound pressure level differences (Insertion Loss – IL) on building façades, between a reference scenario, without shading devices on the façade, and with various shading systems. In previous works, a standard shading system was compared to an acoustically optimised one, having louvres with sound-absorbing properties on the bottom side (Zuccherini et al., 2016) (Fausti et al., 2019) (Zuccherini et al., 2015) (Zuccherini et al., 2019). The conclusions of these studies are assumed in the present work.

The daylighting effect of external louvres is evaluated in many studies for their importance in the reduction of thermal loads but also for the improvement of visual well-being (Technical Report of IEA SHC Task 50.C2, 2016) (Technical Report of IEA SHC Task 61.C1, 2019) (Ahmad, Kumar, Prakash & Amana 2020) (Carletti, Cellai, Pierangioli, Sciurpi & Secchi, 2017). Several parameters have been introduced to assess the quantity, quality and glare of light (Carlucci, Causone, De Rosa & Pagliano, 2015).

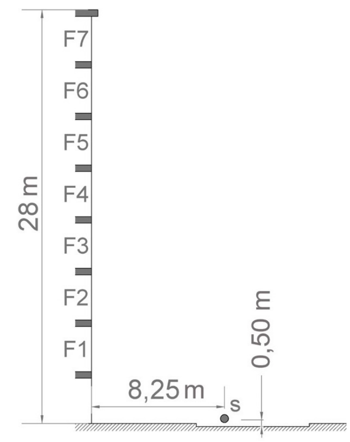
In this study, the daylighting effect is analysed with reference to three parameters, and the relevant results are compared with the corresponding recommended values. In particular, the amount of daylight is evaluated by means of the Daylight Factor (D), described in many national and international standards; the distribution of daylight is analysed with the Daylighting Uniformity (U), as defined in the standard EN 12665 (EN 12665, 2013); the daylighting glare effect is analysed by means of the Daylight Glare Probability (DGP), described in the standard EN 17037 (EN 17037:2018) (Galatioto & Beccali, 2016). Also, the Useful Daylight Illuminance (UDI) is an important parameter to analyse the probability of glare occurrence due to daylight. It is defined as the annual occurrence of illuminances across the work plane where all the illuminances are within the range 100 to 3000 lx; the degree to which UDI is not achieved because illuminances exceed the upper limit is indicative of the potential for occupant discomfort due to glare (Nabil & Mardaljevic, 2005). In any case, as has been shown (Mardaljevic, Andersen, Roy & Christoffersen, 2012), there is a strong correlation between the Useful Daylight Illuminance and the Daylight Glare Probability used in this study.

2 METHODOLOGY

2.1 DESCRIPTION OF THE CASE STUDY

The virtual mock-up considered in the present study is a 28 m tall building with 8 floors (ground floor + floors 1 to 7). Each floor is 3.1 m high, having 0.4 m slabs dividing two consecutive floors.

A road was set in front of the building façade, made up of two lanes (3.5 m each), lateral pavements/ sidewalks and cycling paths, a total of 6.5 m wide (Figure 1). The sound source was set as a traffic lane, 8.25 m away from the building façade.



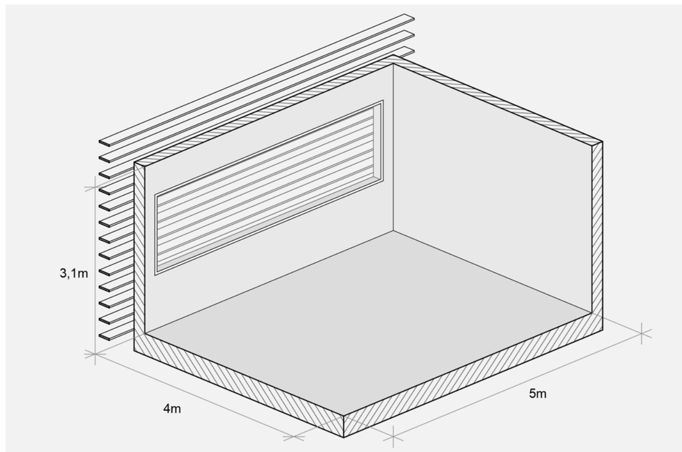


FIG. 1 LEFT: Section of the building façade. Dimensions are in meters (m). Each floor is 3.50 m high, including the thickness of the floor slab. The sound source S is placed at 8.25 meters from the building façade and 0.50 m from the ground, simulating the sound emission of a traffic lane. F1-7 indicates the floor level.

FIG. 2 RIGHT: Axonometry of the inner space. Dimensions in meters.

The third dimension of the test room was only considered with daylight simulations. The inner space was simulated as a room 5 m wide, 4 m long and 3.1 m high (Figure 2), with windows 4.6 m wide and 1.5 m high (34.5% of the floor surface).

Both the acoustic and the daylight simulations consider louvres 3 cm thick and variable between 20 / 30 / 40 cm in spacing.

2.2 ACOUSTIC SIMULATIONS METHODOLOGY

The acoustic effects of external louvres were investigated with a commercial Finite Element (FE) Solver (COMSOL® Multiphysics), whose detailed description is reported in (Fausti et al., 2019). This model was previously validated with reference to a 1:1 scale model analysed in a semi-anechoic chamber (Zuccherini et al., 2016) (Figure 3). The laboratory mock-up used in the cited work was characterised by tiltable louvres, sized 0.2 m x 2 m, 1.8 cm thick: the tilting possibility of the louvres helped study the variability of acoustic Insertion Loss (IL) associated with the tilt angle of sun shading louvres. The IL was calculated as the differences between the sound pressure level (SPL) measured without the shading system (considered as the reference value) and the SPL measured with the shading devices. The IL was calculated first considering a traditional façade shading system (Figure 3 (b)) and then adding sound-absorbing material on the bottom faces of each louvre in the shading system (Figure 3 (c)).

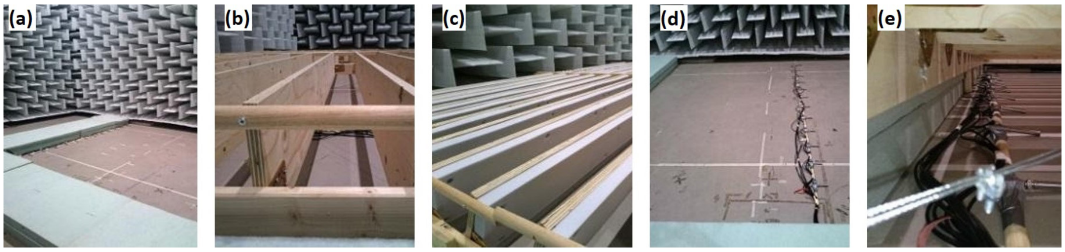


FIG. 3 (a) Empty floor of the semi-anechoic room simulating a flat building façade; (b) non-absorbing shading louvres; (c) sound absorbing louvres; (d) microphones used for measuring SPL without the shading device; (e) microphones used for measuring SPL with the shading devices.

Figure 4 shows measured values (EN ISO 10534-2, 2001) of the normal incidence sound absorption coefficient of the melamine foam used in the experiment.

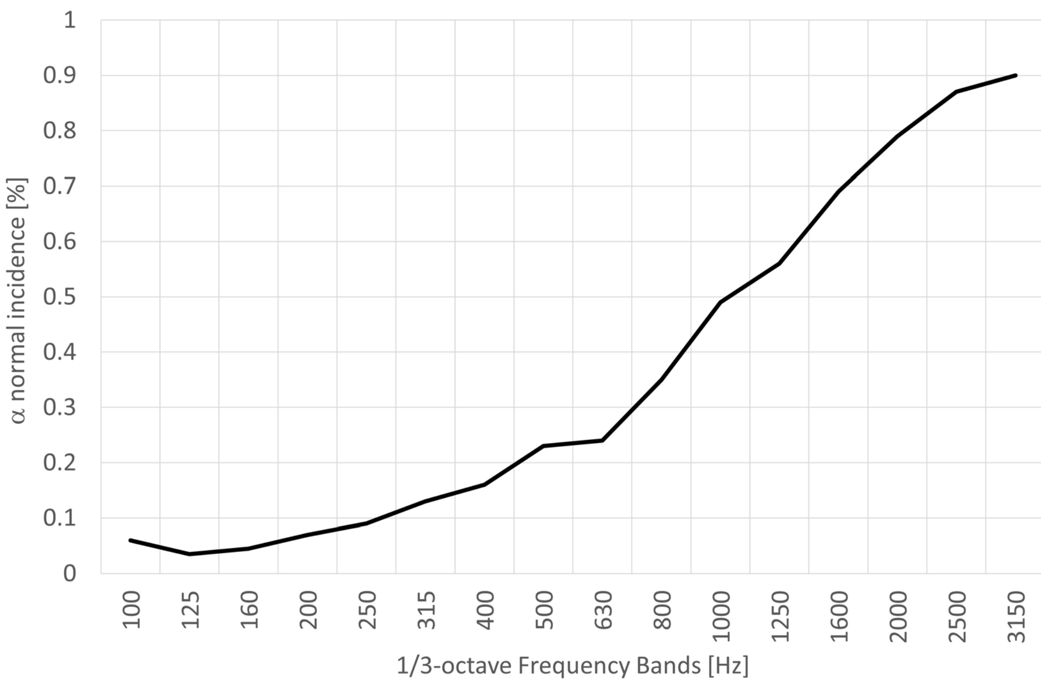


FIG. 4 Measured normal incidence sound absorption coefficient (α) of the material (expanded melamine foam) used in the mock-up.

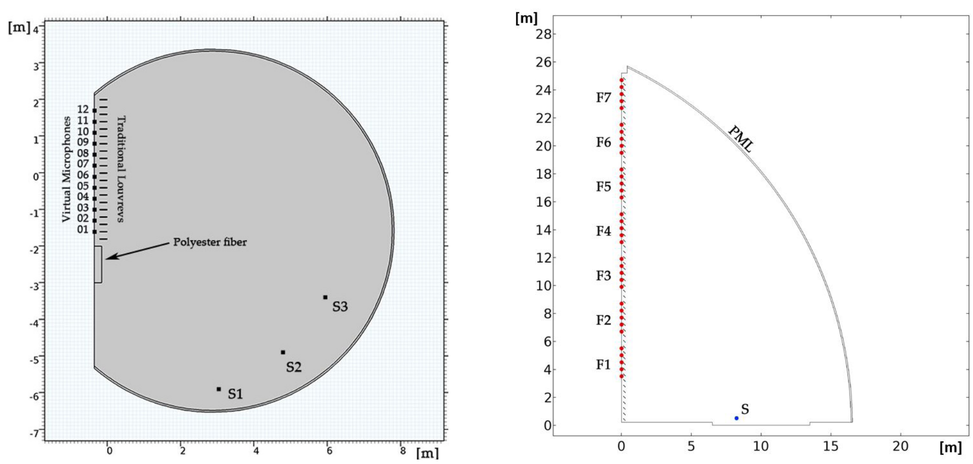
A 2D FE model, representing the experimental mock-up in a semi-infinite acoustic domain, was first validated with laboratory measurements and then expanded to further investigations, simulating urban situations (Fausti et al. 2019).

To exactly reproduce the laboratory condition, the louvre system was modelled with the same geometry as the mock-up, backed by perfectly reflecting boundary conditions representing the floor of the semi-anechoic chamber (as well as the glazing surface in real conditions). The acoustic fluid domain was modelled with a radius of 4.8 m and truncated by using perfectly matched layer (PML) elements to approximate the semi-infinite domain condition (Figure 5 a). The louvres in the standard condition (bare wood material with no sound-absorbing layer) were approximated as rigid boundaries of the fluid domain. The condition representing louvres lined with a layer of sound-absorbing material was simulated with the *Poroacoustic* built-in feature in COMSOL®, applied to sound-absorbing domains: a Delany-Bazley-Miki (DBM) (Delany & Bazley, 1970) (Miki, 1990) equivalent fluid model was used to replicate measured absorption properties.

After the validation of the model, further FE analyses were carried out using an extended model, as shown in Figure 5 b.

The sound source, which reproduced the experimental configuration, was implemented as a monopole (omnidirectional) point source (5 Pa) placed in the middle of the left lane, 0.5 m from the ground, 8.25 m from the building façade.

Although the section of the simulated road includes two traffic lanes, only one was simulated. The acoustic effects of the shading louvres were evaluated in terms of Insertion Loss (evaluation of the effects on a building façade facing the one with the shading louvres). Further details on this modelling approach can be found in the reference (Fausti et al., 2019).



a b

FIG. 5 (a) Bi-dimensional FEM Set-Up reproducing the experimental set-up. (b) Extended FEM model of an entire 7-storey building façade facing a traffic lane at ground level; red dots represent virtual pressure sensors to measure the sound pressure level.

2.3 DAYLIGHTING SIMULATIONS METHODOLOGY

The daylighting parameters described in section 1 (D, U and DGP) were calculated with RELUX® (www.relux.com), a software to simulate artificial light and daylight according to standards EN 12464-1:2021 and EN 17037:2018, one of the most used and advanced lighting simulation tools for daylight and lighting calculation (Maamari, Fontoynont, Adra, 2006) (Bhavani & Khan, 2011) (Kaempf et al., 2016). Relux® is validated (Bouroussis, Nikolaou & Topalis, 2019) regarding the methodology described by the technical report CIE 171:2010 (CIE 171, 2010) that defines and proposes a set of several test cases to validate the calculations accuracy of a lighting simulation software. An in-depth study of the validity of nine different software tools, including Relux®, showed that they can simulate a standard room, also with louvres, with minimal percentage differences between them (Iversenet al., 2013).

In this work, simulations were performed with reference to the CIE sky types 1 (overcast sky, for daylight factor) and 12 (clear sky, low turbidity, for daylighting uniformity and daylight glare probability). The investigated solutions assessed the ability of the software to simulate the influence of an obstruction, like an external horizontal louvre, on the diffuse reflection and on the internal direct illuminance.

The analysed model was placed in a geographical location in the South of Europe with the correct North orientation. The calculation method uses radiosity algorithms to evaluate the lighting characteristics in discrete points of the environment after dividing each surface into meshes with homogeneous photometric properties. Radiosity algorithms require that all surfaces be ideal diffusers that follow Lambert's law.

The following summarises the main lighting properties of the surfaces and the calculation parameters.

- Reflection factor of walls and ceiling in gypsum plaster, white matt: 80%.
- Reflection factor of floor: 40%.
- Reflection factor of external louvres: 80%.
- Transmission factor of window glasses: 80%.
- Position of the calculation surface: 0.75 m from the floor and 0.5 m from the walls.
- Position of the case study: Florence, Central Italy (43° 46' N 011°15' E).
- Orientation of the case study: South and East (West façade in the morning is equal to East façade in the afternoon about the altitude of the sun; therefore, only the East façade has been evaluated).
- Sky conditions: standard CIE overcast sky for daylight factor simulations; standard CIE clear sky with sun and overcast sky for Uniformity factor and Discomfort Glare Probability simulations.
- Percentage of indirect light used in simulations: average.

Reflection factors of internal surfaces were taken from the acceptable ranges described by both EN 12645-1:2021 and EN 17037:2018 (0.7 to 0.9 for the ceiling, 0.5 to 0.8 for walls and 0.2 to 0.4 for the floor). Annex B of EN 17037 recommends using lower values of reflection factors in the above-reported range to take into account the presence of furniture. However, we considered the case of a room furnished with light-coloured furniture.

Simulation refers to the following parameters described in the introduction:

- Daylight factor D.
- Daylight Uniformity U.
- Daylight Glare Probability DGP.

The daylight factor, D, is believed to have been developed by Alexander Pelham Trotter towards the end of the nineteenth century (Mardaljevic, J., 2013) as the ratio of the internal horizontal illuminance to the unobstructed external horizontal illuminance, usually expressed as a percentage. Nowadays, the required levels of daylight factor range between 1% and 5%, depending on building types and activities, and it can be evaluated in standard overcast conditions as under various unobstructed skies (Danny et al., 2018) (Xu, Yuehong, Xin, 2014).

Daylighting uniformity, U, (EN 12665, 2013) is the ratio of minimum illuminance to average illuminance.

The daylight glare probability, DGP, (EN 17037, 2018) is the parameter used to analyse the daylight glare effect that considers both the illuminance at eye level and individual glare sources of high luminance to estimate the fraction of dissatisfied people. Both U and DGP are useful parameters to evaluate the effect of louvres in clear sky conditions (Kose & Kazanasmaz, 2020).

For daylighting purposes, the International Commission on Illumination, CIE, defines 15 different standard sky conditions (CIE S 011/E, 2003) (Darula & Kittler, 2014) that are described by functions, depending on the solar altitude, even when the sun is obscured. In this study, the analysis of the parameters U and DGP was performed with clear sky conditions (less than 30 % cloud cover or none) combined with sunny sky conditions; in this case, the sky distribution corresponds to the standard CIE clear sky condition with additional direct illumination from the sun. This model of the sky is useful when visual glare and thermal discomfort studies are performed (Suk & Kensek, 2011).

Standard EN 17037 (EN 17037, 2018) gives recommendations for the daylight factor D with reference to different locations. Table 1 shows the values of D to obtain a given target illuminance E_T (lx) from 100 (minimum target illuminance) to 750 lx (high target illuminance), referred to the median external diffuse illuminance $E_{v,d,med}$ of Florence and Rome for a fraction of daylight hours $F_{time,\%}$ = 50%.

As an example, in the case of Central Italy (Florence), the value D equal to 2% allows exceeding 300 lx for 50% of the time daylight hours.

TABLE 1 **Values of D for daylight vertical openings to exceed an illuminance level from 100 to 750 lx for a fraction of daylight hours $F_{time,\%}$ =50%**

Place	Latitude (°)	Median external diffuse illuminance $E_{v,d,med}$ lx	D to exceed 100 lx	D to exceed 300 lx	D to exceed 500 lx	D to exceed 750 lx
Florence	43.46	15017	0.67%	2.00%	3.33%	5.00 %
Rome	41.80	19200	0.50%	1.60%	2.60%	3.90%

Table 2 shows the correspondence between values of Daylight Glare Probability and the statistical perception of glare according to the standard EN 17037.

TABLE 2 **Recommended values of daylight glare probability according to annex E of EN 17037**

Criterion	DGP value
Glare is mostly not perceived	DGP ≤ 0.35
Glare is perceived but mostly not disturbing	0.35 < DGP ≤ 0.40
Glare is perceived and mostly disturbing	0.40 < DGP ≤ 0.45
Glare is perceived and mostly intolerable	DGP ≥ 0.45

To assess daylight glare probability, the luminance distribution within the field of view and the size, intensity and location of the glare sources in regard to the line of sight have to be taken into account. Consequently, DGP values have been calculated for the three positions shown in Figure 6: DGP1 and DGP2 are symmetrical but facing the opposite walls, located 2.0 m from the façade and with a view direction parallel to the window, while DGP 3 is perpendicular to the façade and located 3 m away; all points are 1.2 m high from the floor.

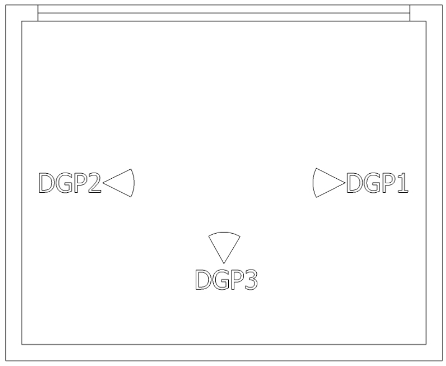


FIG. 6 Position of the points views for the calculation of DGP.

The analysis of DGP was carried out for different configurations of louvres for the same orientations of the façade (South and East), periods of the year (two solstices and equinox) and at the same hours of calculation (09:00, 12:00 and 15:00) as for the daylighting uniformity.

3 RESULTS AND DISCUSSION

3.1 ACOUSTIC RESULTS

Simulations were performed with the above-described FE software and method: they produced a detailed description of the sound distribution across the façade at different frequencies.

Figure 7 shows a sample result obtained by FE simulations: the sound pressure level at 1 kHz across the building façade portion is affected by the presence of the shading louvres; the sound pressure level also appears to be highly reduced by the presence of sound absorbing louvres, with respect to the traditional ones.

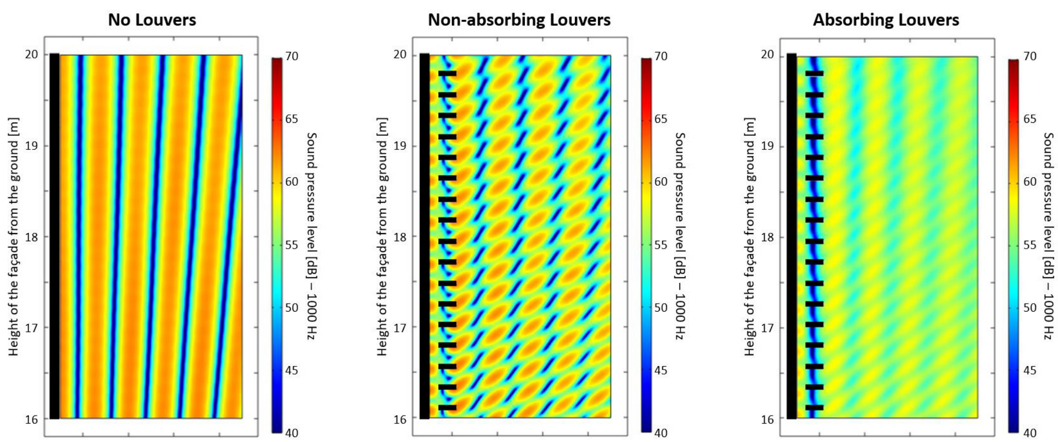


FIG. 7 Sound pressure level simulated in correspondence with the 4th floor of the simulated building façade. The solid thick black vertical line represents the façade surface. Left: without louvres. Center: non-absorbing louvres. Right: sound-absorbing louvres.

As shown in Figure 7, the sound pressure level with louvres present is far from uniform across the façade. The results of the simulations have therefore been further evaluated in terms of arithmetic averages of the Insertion Loss, with each average referring to a single floor. Simulations have been conducted considering five virtual measurement positions on each floor. Each average considers five measurement points across the virtual building façade.

In the FE acoustic model, the effect of the variation of the following parameters was studied:

- Louvres' tilt angle (0, -30°, -45°), considering: 0° for horizontal louvre; -45° for louvre tilted towards the soil and the sound source.
- Louvres' width (20, 30, 40 cm).
- Louvres' spacing (20, 30, 40 cm).

The following summarises the main results.

3.1.1 Tilt angle of louvres

The louvres' tilt angle with respect to the sound source has an impact on the acoustic Insertion Loss: it is shown that tilted louvres offer less acoustic protection than horizontal ones. Therefore, only horizontal louvres have been considered in further daylight analyses.

It is very clear how IL increases with respect to the building height: this consideration can be made while evaluating other geometrical aspects of the shading system.

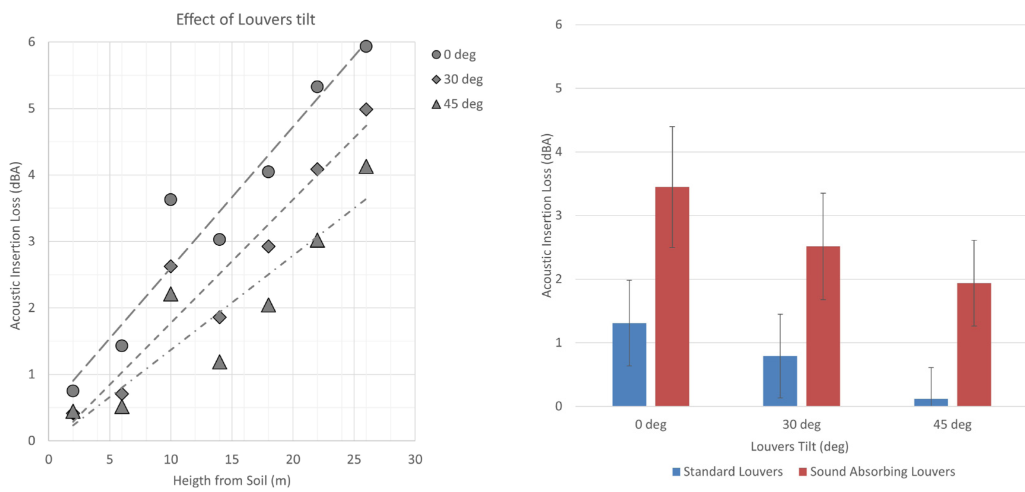


FIG. 8 LEFT: Average of IL in dB(A) considering sound-absorbing louvres' tilt angles (0°, 30°, 45°) with respect to building height. RIGHT: Overall evaluation of the effect of louvre tilt angle on IL: standard versus sound-absorbing louvres results are shown.

3.1.2 Louvre width

In this case, the width of the louvres varied between 20, 30 and 40 cm, with respect to the floor height and an overall average.

Results show that the louvres' section width is not relevant when acoustic IL in dBA is observed: it is important to mention that simulations have been executed considering the spacing between louvres being no shorter than their width. In other words, the ratio between the spacing and width of louvres has been kept equal to 1. This fact can partially explain the minor effects of louvre widths on the acoustic IL.

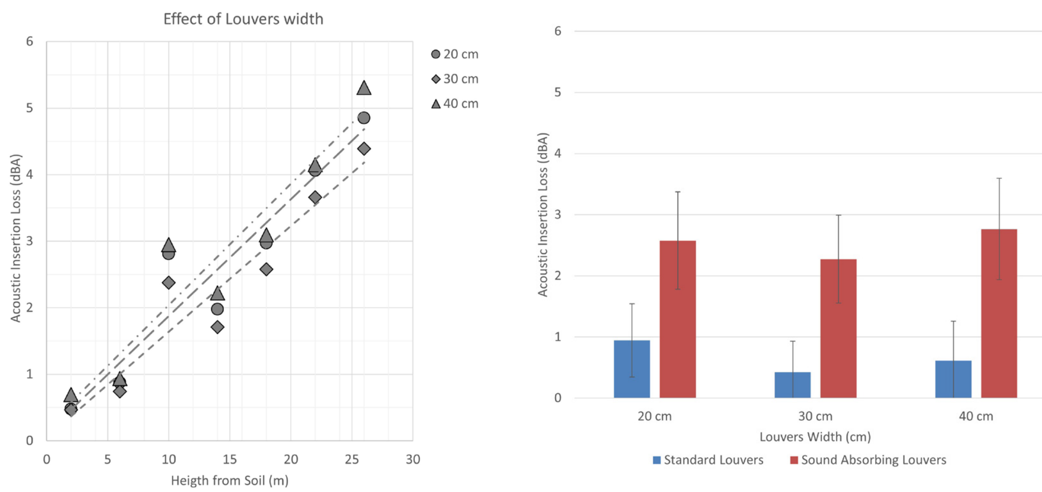


FIG. 9 LEFT: Average of the IL in dB(A) considering sound-absorbing louvres section width (20, 30 and 40 cm) with respect to building height. RIGHT: Overall evaluation of the effect of louvre section width on IL: standard versus sound-absorbing louvres results are shown.

3.1.3 Louvre spacing

Results showed that values of IL in dB(A) are affected by the louvres' spacing: wider distances between louvres give poorer sound protection to the building façade.

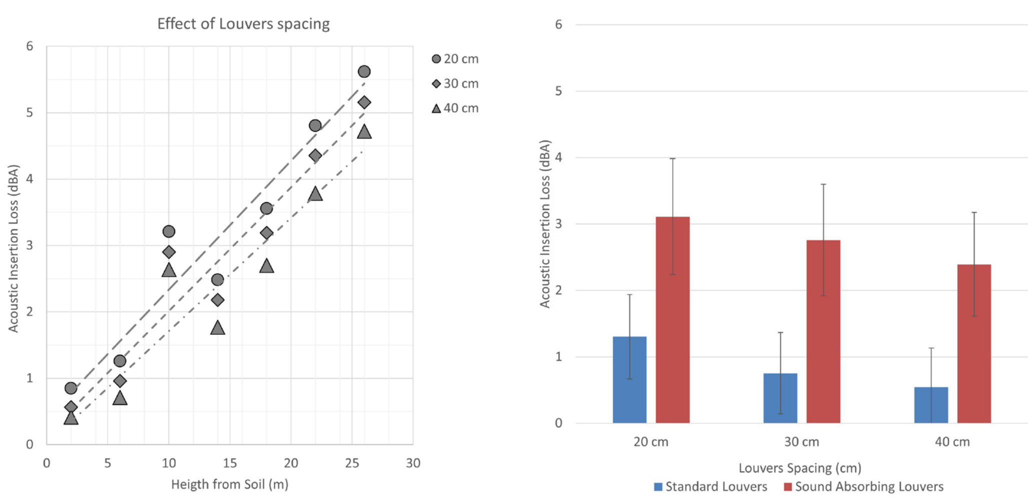


FIG. 10 LEFT: Average of IL in dB(A) considering the spacing between sound-absorbing louvres (20, 30 and 40 cm) with respect to building height. RIGHT: Overall evaluation of the effect of louvre section width on IL: standard versus sound-absorbing louvres results are shown.

3.1.4 Preliminary considerations on acoustic results

Figures 8, 9 and 10 indicate that the acoustic effect of the louvres is mainly influenced by the floor level and by their tilt angle and spacing.

Since these results are the starting point for daylighting analysis, it must be considered that the floor level does not influence the indoor daylighting for a building not obstructed by other buildings, as in the case study analysed. On the other hand, louvres tilted downward (30° or 45°) negatively affect both the reduction of the Insertion Loss and the Daylighting Factor. For this reason, daylighting simulations have been performed with reference to a typical floor level and horizontal louvres (0° of tilt angle) 20 cm wide, spaced 20, 30 and 40 cm from each other.

3.2 DAYLIGHTING RESULTS

Figure 11 shows the results with reference to the values of maximum, average and minimum daylight factor, D, calculated with standard CIE overcast sky, in the conditions expressed in paragraph 2. The second vertical axis in the same graph shows the fraction of the reference plane (F_{plane}) where the target daylighting level (500 lx) or the minimum target daylighting level (300 lx) are achieved, according to annex A of EN 17037:2018.

The reduction of the daylight factor is a consequence of the presence of the louvres and their spacing. With horizontal louvres 20 cm wide and spaced 20 cm from each other, the average daylight factor is 3.1%, and 47% of the reference plane (F_{plane}) reaches the target illuminance level of 500 lx, while 100% of the reference plane reaches the minimum target level of 300 lx for 50% of the daylight hours. According to EN 17037:2018, minimum values of F_{plane} should be 50% for the target level and 95% for the minimum target level. Therefore, it can be deduced that, for the latitude of Southern Europe, even with external louvres spaced 20 cm from each other, the minimum values of daylighting level are achieved with good approximation under overcast conditions (47% instead of 50% can be considered within the uncertainty margin of the method).

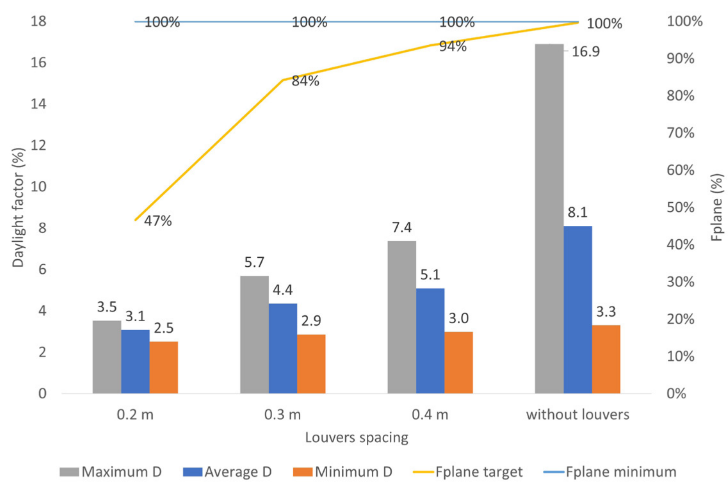


FIG. 11 Variation of the average Daylight Factor as a function of the louvres' spacing with overcast skies.

From Figure 12 it can be observed that the presence of the louvres spaced 20 cm improves the uniformity of daylighting, U, (E_{min}/E_{avg}) with clear sky, at the latitude of Central Italy and with reference to a different orientation of the façade, the two solstices and the equinox, both in the morning and in the afternoon. An important exception to this is the South façade, without louvres, at 12:00 of the winter solstice, when the direct sun radiation involves all the evaluation area of the office. Here, the minimum and the average values of daylighting are very similar (very high uniformity factor). It can also be noted that at the equinox (21 March), the illuminance uniformity with louvres spaced 20 cm is much higher than with louvres more broadly spaced. This is due to the fact that with louvres spaced 20 cm, the direct solar radiation is completely intercepted by the louvres, as can be seen in Figure 13, which compares the luminances of the room surfaces with louvres spaced 20, 30 and 40 cm for 9.00 am on 21 March. We must consider, for this purpose, that the Eastern orientation of the sun's altitude at 9:00 corresponds to the Western orientation at 15:00, while the Eastern orientation at 15:00 corresponds to the Western orientation at 09:00. For this reason, the Western orientation is not considered in these evaluations.

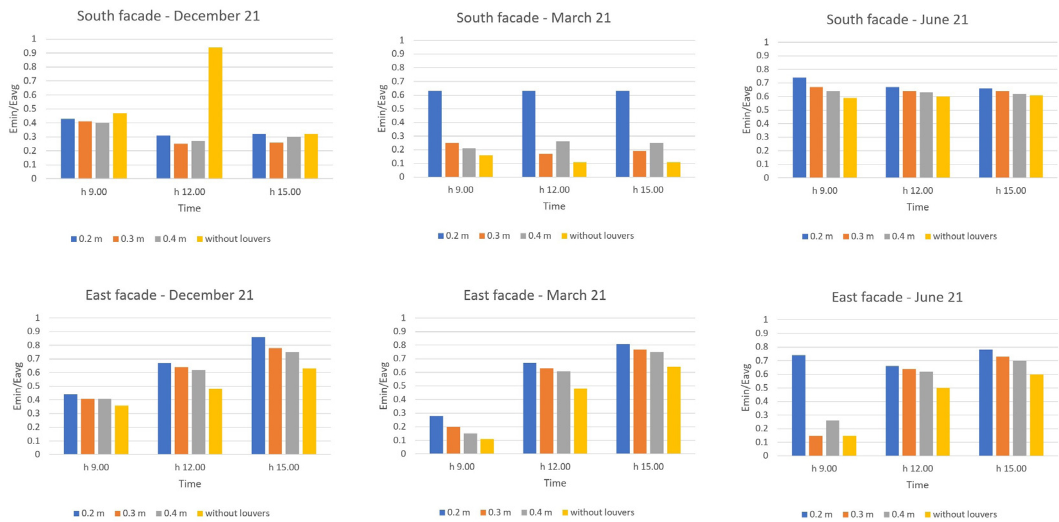


FIG. 12 Variation of the Uniformity factor as a function of the louvres' spacing with clear sky.

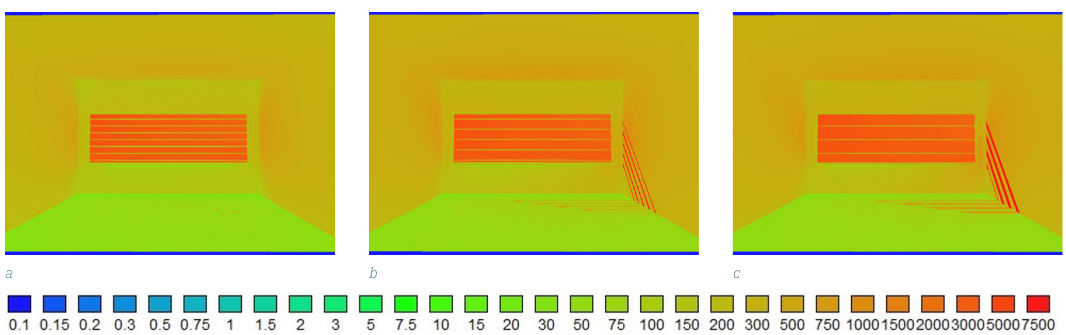


FIG. 13 *Luminance values (cd/m²) as a function of the louvres' spacing with clear sky. From left to right, louvres spaced 20, 30 and 40 cm.*

Also, with overcast skies, when the orientation and the date and hour of the evaluation are irrelevant, a better uniformity factor is achieved with louvres' spacing of 20 cm (Figure 14).

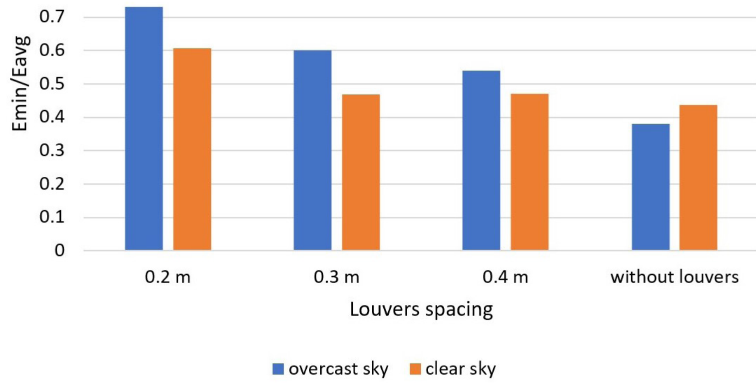


FIG. 14 Variation of the Uniformity factor as a function of the louvres' spacing with overcast and clear sky (average values over the year).

Tables 3 and 4 show the DGP values calculated for the three positions and for East and South exposure.

TABLE 3 **Daylight Glare Probability for South orientation of the façade. The cell colours refer to DGP range of values in Table II**

date	21-December				21-March				21-JUNE			
louvres' spacing	0.20m	0.30m	0.40m	no louvers	0.20m	0.30m	0.40m	no louvers	0.20m	0.30m	0.40m	no louvres
						DGP1						
h 9.00	0.28	0.29	0.29	0.3	0.36	0.4	0.42	0.46	0.31	0.37	0.4	0.45
h 12.00	0.22	0.23	0.23	0.23	0.23	0.24	0.24	0.26	0.23	0.24	0.24	0.24
h 15.00	0.19	0.19	0.19	0.2	0.19	0.2	0.2	0.21	0.19	0.2	0.2	0.21
						DGP2						
h 9.00	0.28	0.29	0.3	0.31	0.37	0.41	0.42	0.46	0.32	0.37	0.4	0.45
h 12.00	0.22	0.22	0.23	0.23	0.24	0.24	0.25	0.25	0.23	0.24	0.24	0.24
h 15.00	0.19	0.19	0.19	0.2	0.2	0.2	0.2	0.21	0.2	0.2	0.2	0.21
						DGP3						
h 9.00	0.37	0.39	0.39	0.41	0.49	0.55	0.57	0.62	0.41	0.5	0.55	0.62
h 12.00	0.28	0.29	0.29	0.29	0.31	0.31	0.31	0.34	0.31	0.31	0.32	0.32
h 15.00	0.21	0.21	0.22	0.23	0.22	0.23	0.23	0.25	0.22	0.23	0.23	0.25

TABLE 4 **Daylight Glare Probability for East orientation of the façade. The colours of cells refer to DGP range of values in Table II**

date	21-December				21-March				21-JUNE			
louvres' spacing	0.20m	0.30m	0.40m	no louvers	0.20m	0.30m	0.40m	no louvers	0.20m	0.30m	0.40m	no louvres
						DGP1						
h 9.00	0.86	0.87	0.88	0.89	0.28	0.31	0.33	0.35	0.24	0.25	0.25	0.26
h 12.00	0.49	0.53	0.54	0.57	0.32	0.37	0.4	0.45	0.25	0.26	0.27	0.34
h 15.00	0.33	0.35	0.35	0.37	0.28	0.32	0.35	0.39	0.23	0.24	0.24	0.29
						DGP2						
h 9.00	0.28	0.29	0.3	0.31	0.26	0.3	0.32	0.35	0.22	0.23	0.23	0.27
h 12.00	0.4	0.44	0.44	0.48	0.31	0.36	0.4	0.45	0.25	0.26	0.27	0.35
h 15.00	0.33	0.34	0.35	0.4	0.3	0.34	0.36	0.4	0.24	0.25	0.26	0.29
						DGP3						
h 9.00	0.37	0.39	0.39	0.41	0.34	0.4	0.44	0.49	0.29	0.3	0.3	0.36
h 12.00	0.54	0.58	0.59	0.63	0.41	0.5	0.55	0.61	0.31	0.34	0.35	0.47
h 15.00	0.44	0.46	0.47	0.49	0.37	0.44	0.48	0.54	0.29	0.3	0.31	0.4

Results of DGP show that the presence of the louvres produces a generalised reduction of glare effects. In particular, horizontal louvres spaced 20 cm from each other produce better results.

For observers in positions DGP1 and DGP2, which are the more usual in office buildings, and louvres spacing 0.2 m, only in the morning of the winter solstice, when the sun altitude is very low for the East orientation of the façade, glare problems occur.
During the summer season, the presence of louvres spaced 20 cm from each other reduces the DGP below the value of 0.35 (glare mostly not perceived according to EN 17037) at each of the hours examined; with the only exception of the observer position DGP3 at 9.00 in the morning with South orientation (DGP = 0.41).

4 CONCLUSIONS

In this work, the effect of external louvers on a case study building 28 meters high, unobstructed by other buildings on the opposite side of the road, is evaluated regarding both acoustic and daylighting parameters. The results of previous works by the authors concerning only the acoustic effect are summarised and recalled here. To better understand the hypothesis and the details of these results, it is necessary to refer to the cited papers ((Zuccherini et al., 2016) (Fausti et al., 2019) (Zuccherini et al., 2015) (Zucherini et al., 2019).

In general, the acoustic effect of an external louvre could be negative, as it can cause an increase in the sound pressure level on the façade. However, if properly designed and with the bottom side of the louvres lined with sound-absorbing material, this effect can become positive and contribute to reducing the façade sound pressure level by some decibels. On the other hand, the presence of these façade devices significantly reduces the amount of daylighting in the interior, especially with overcast sky conditions, and modifies the distribution of daylight, especially with clear sky conditions.

In this study, only fixed horizontal louvres 20 cm wide, with different spacing and with different façade orientations, are considered for both acoustic and daylighting simulations since acoustic simulations showed that this is the better configuration to reduce the façade sound pressure level. Regarding the latitude of Central Italy (Florence) and an office building with large windows (34.5 % of the floor surface), unobstructed by other buildings on the opposite side of the road, in this configuration, the reduction of Daylight Factor with overcast skies is acceptable also with louvres spaced 20 cm from each other. Moreover, results show that the uniformity factor (ratio between minimum and average daylighting level) is significantly improved both with clear and overcast sky conditions with white (80% reflection factor) external louvres 20 cm wide and spaced 20 cm from each other. Moreover, the presence of the louvres produces a generalised reduction of glare effects in sunny sky conditions.

The results presented in this paper demonstrate that a proper design of external louvres, specifically referring to the characteristics of the building and the latitude of the location, can improve both acoustic insulation properties of the façade and the distribution of daylight in the indoor space, reducing the probability of daylight glare.

Further development of this work will involve evaluating the daylighting effect at other latitudes and studying the effect of the reduction of thermal loads in summer conditions.

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