Façade design through parametric modelling for environmental noise mitigation in a courtyard

Elena Badino, Louena Shtrepi, Arianna Astolfi

Department of Energy, Politecnico di Torino, Italy
elena.badino@polito; louena.shtrepi@polito.it; arianna.astolfi@polito.it

Abstract
The reduction of environmental noise in cities is essential to protect public health. Architectural design can support the mitigation of environmental noise in cities, by means of a performance-aware design decisions. Starting from a reference courtyard in Turin characterized with in-situ measurements, this study explores through a parametric approach how the design of a double skin applied to the façades of the courtyard can reduce the environmental noise levels within the courtyard. The proposed double skin façade is composed by a pattern of protruding wedges whose geometry and material properties are varied parametrically. The sound pressure level is predicted for the different geometric and material design options of the double skins in outdoor spaces at the courtyard level and over the façade, and in indoor spaces with open windows to identify the most beneficial design strategies. The results evidence the noise reduction potential of sound absorbing materials applied to the double skin, and that the performances of the totally absorbing double skin are comparable to those achieved with the sound absorbing material applied to the lower sides of the wedges.

Keywords: façade design, urban acoustics, performance-based design, courtyard, leisure noise

1 Introduction

Environmental noise pollution is a rising problem in worldwide cities. As evidenced by the World Health Organization (WHO), the well-being of urban populations is threatened by the increased health risks due to environmental noise pollution (e.g. cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus and annoyance) [1]. In order to protect the public health in cities, the WHO has suggested thresholds of outdoor sound pressure levels not to be exceeded [1]. Low outdoor environmental noise levels would allow dwellers to stay comfortably indoors with open windows and in private open spaces, such as balconies and terraces. A further benefit of lower outdoor environmental noise is the energy saving resulting from the ability of dwellers to use natural ventilation to achieve indoor thermal comfort in summertime, reducing the use of air-conditioning. This has also been evidenced by the Acoustics, Ventilation and Overheating Guide [2], which promotes an integrated design approach to combine acoustic requirements with natural ventilation and thermal comfort in indoor spaces.
Environmental noise levels in cities are influenced by the morphologic and material properties of the surrounding urban fabric. The compact layout of urban environment and the sound reflective properties of common construction materials cause the environmental noise levels in cities to increase due to multiple reflections. Therefore, performance-aware architectural design choices can provide an effective and long-lasting contribution to the enhancement of acoustic comfort in urban settings [3]. However, despite the growing awareness on the importance of addressing urban noise pollution, acoustic concerns are hardly considered during design processes [4,5].

Nowadays, retrofit interventions on existing buildings are commonly carried out to enhance the thermal insulating properties of the building envelopes or to modify the functionality of the existing construction. Such measures, if opportunely conceived, can also mitigate environmental noise pollution. Previous studies have investigated the potential of the geometrical and material features of façades [6–11] as environmental noise reduction strategies. A recent review article has collected the main findings of the studies related to façade design features [12]. Based on previous works, sound absorbing materials applied to urban facets can lower environmental noise levels by reducing the amount of sound reflections occurring in the urban environments. Moreover, the geometry of the façade can help shielding the receivers from the incoming sounds, although this contribution is generally limited compared to that obtained with sound absorbing strategies.
Although vehicular traffic noise is the most common noise source worldwide, in certain contexts leisure noise, i.e. the noise generated by people talking, can be considered the major noise source [6,13]. Moreover, it must be highlighted that the relevance of leisure noise has increased due to the restrictions of COVID-19 pandemic, that have limited the ability of bar and restaurants to host clients indoors while promoting the use of outdoor spaces. An example of scenario where leisure noise plays a crucial role is that of courtyards that host the outdoor terraces of restaurants, that are surrounded by residential or office buildings. In such scenarios, the noise generated by the clients within the courtyard may compromise the acoustic comfort of dwellers, especially during nighttime.

1.1 Objectives

This contribution analyzes a case-study courtyard to be retrofitted with double skin façades to couple acoustic performance and functional ones. The work aims to analyze the influence of different geometric and material design options of the double skin façade on the environmental noise level perceived in outdoor positions over the façades of the buildings and at the ground level. Some further estimation of sound pressure level (SPL) in indoor spaces with open windows is also provided, based on the SPL difference measured in-situ. The work presents an application of acoustic performance-based design approach for a retrofit intervention, and the findings can provide guidance for similar design scenarios.

2 Method

This work takes into consideration an intervention of the façades of two buildings facing an existing courtyard, which are meant to be retrofitted with a double skin façade.
Pachyderm Acoustics [14] is used to predict the variation of outdoor and indoor A-weighted SPL occurring over the façades of the courtyard resulting from different design options of the double skin, regarding both the geometric and material features of the structure. The double skin aims to combine the creation of new functionalities with the reduction of environmental noise. It is composed by a pattern of protruding wedges, that enables the creation of a series of balconies in place of the windows of the pre-existing building, providing the users with small private open spaces. The material and geometric properties of the structure are tested in different configurations to analyze the extent to which such design variations can reduce environmental noise levels. While the main design concept of the double skin remains unaltered, the geometric variations inform the inclination of the sides of the wedges and their depth; moreover, the application of sound absorbing materials to different portions of the double skin was investigated.

2.1 The case-study

The case-study is an existing courtyard of the Politecnico di Torino in Turin, Italy; a picture of the courtyard is presented in Figure 1a. The courtyard is 18.7 m wide and 29.7 m long and is located between 4 educational buildings. The fronts on three sides are between 15.4 and 17.1 m high, while the remaining front is lined by a small building (7.25 m high and 5 m deep), backed by a 7 stories building (about 25 m high). At the present state, the buildings facing the courtyard host laboratories and offices of the university and no activity such as bar or restaurant is present, however, the scenario can be considered representative of a courtyard hosting the open spaces of restaurants and bars located at the ground floor of residential or office buildings. The retrofit proposal is the addition of a wedged double skin to the two opposite building on the longest sides of the courtyard. The two buildings, shown at the two sides of Figure 1a, will be referred to as building A and building B in the following. Figure 1b presents an example of double skin façade design option for the two buildings.

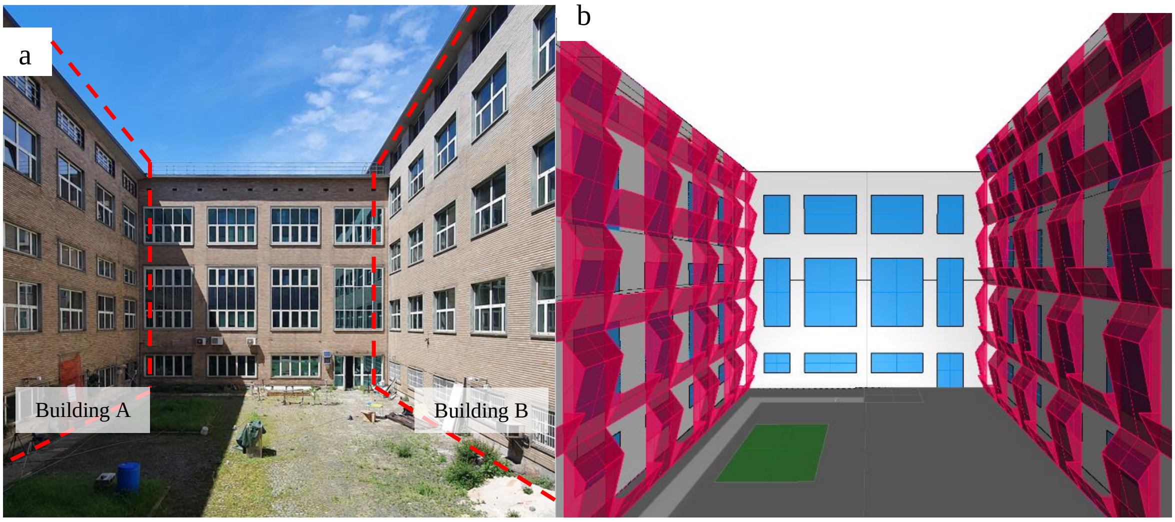

Figure 1 – a) Picture of the courtyard adopted as case-study, with the identification of buildings A and B and the position of the double skin (red dashed line); b) parametric model of the double skin to be applied to the side buildings (in red color).

The double skins are meant to reduce environmental noise while also creating a series of small balconies in place of the windows. Some slight changes to the existing buildings were implemented to host the double skins. The acoustic performance of the double skin, i.e. its ability to lower environmental noise level in outdoor positions, are the focus of the present contribution.

2.2 The parametric model of the double skin

The double skins are applied to the buildings lining the longest sides of the courtyard. The base plane of the structures is placed at a distance of 1 m from the existing façades, and the double skins are composed by a series of protruding wedges with the inter-storey height and variable depth. While the wedges that covers an opaque portion of the building are complete, those located in correspondence of the windows of the façade present only the lower sides of the wedges, whose height is fixed at 1.1 m, while the upper portions are absent to create balcony-like elements. The inclined sides of the wedges interact with the sound propagation within the courtyard by redirecting the incident sound waves in different directions. In order to analyze how different geometric configurations of the two double skins perform, a parametric model of the structures was created in Grasshopper for Rhinoceros. Figure 2a shows reference configuration, i.e. a flat double skin with sound reflective finish, and the geometric parameters of the wedges that were controlled by the parametric model, i.e. the wedge depth and the relative tip height. Both variations result in different tilting of the wedges' sides. The depth of the wedges was varied in all the floors and was either set at 0.3 m, 0.6 m or 0.9 m, respectively identified as d_03, d_06, d_0.9. Moreover, it was also varied according to an increasing/decreasing gradient, i.e. 0.3 m at ground and first floor, 0.6 m at second floor, 0.9 m at third and fourth floor for the increasing gradient option (d_incr), and vice-versa for the decreasing one (d_decr). Besides the depth, also the position of the wedge tip was altered, as it was set at either 25% or 75% of the inter-storey height, identified in the following as t_25% and t_75%, respectively. This variation results in either greater or smaller angles of

inclination of the lower sides of the wedges, and vice-versa for the tilting of the upper sides. Moreover, it also results in a variation of the area of the lower and upper sides of the wedges. It must be noted that the design variations shown in Figure 2 are representative of the wedges located in front of an opaque portions of the façade. Indeed, those located in front of the windows present only the lower wedge sides that work as the balcony parapets; in these cases, the wedge tip position was fixed at 1.1 m, which corresponds to the height of the balcony parapet, and only wedge depth is varied parametrically.
Besides the geometric variations, also material variations were tested, as shown in Figure 2b. The surfaces of the double skin were treated with a sound reflective finish, i.e. glass, and with sound absorbing materials, i.e. a commercial sound absorbing solution with a perforated metal finish suitable for outdoor applications. The sound absorbing material was either used over all the surfaces of the double skin (i.e. totally absorbing), or applied to the lower sides of the wedges, that are oriented downward, while the upper parts were sound reflective (i.e. partially absorbing). This has been done in the attempt to absorb the sound coming from the sound source located in the courtyard impinging on the lower sides of the wedges, while also promoting the redirection of the incident sound towards the sky with the upward oriented sides of the wedges, to reduce sound trapping. Moreover, this may also increase the durability of the sound absorbing panels, which are partially shielded from the weather elements.

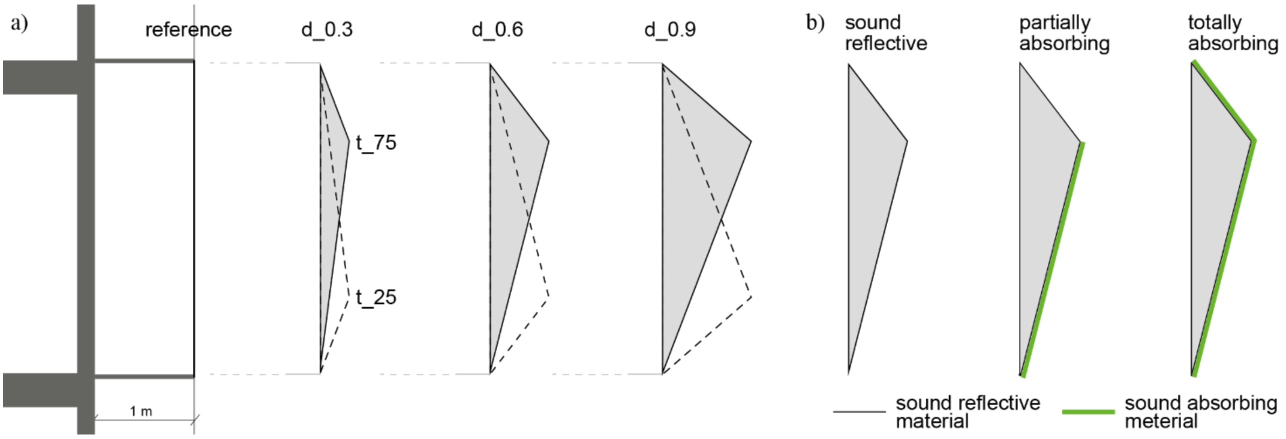

Figure 2 – a) section of the reference configuration and examples of geometric variation of the wedges, considering wedge depth and tip position; b) material options tested, i.e. sound reflective, partially absorbing and totally absorbing.

In total, 30 design configurations of the double skin were evaluated, resulting from 10 geometric variations, each considered with the 3 different acoustic treatments. An option with a flat sound reflective double skin façade was also tested as a reference condition.

2.3 Acoustic measurements and model calibration

The acoustic model of the courtyard was calibrated with respect to in-situ measurement of reverberation time conducted in May, 2021. A measurement campaign was carried out in order to measure the reverberation time (T_{20}) in 8 different positions in the courtyard level and in outdoor positions at the 1st, 2nd and 3rd floor over the façade of building B. The measurements were carried out with an omnidirectional sound source emitting a sine sweep signal in the range 50-20000 Hz with a duration of 6 s, that was repeated three times for each sound-receiver position. The source was placed in a central position at a height of 1.5 m. During the measurements, the equivalent sound pressure level of background noise was 60.5 dB while the equivalent sound pressure level at 1 m distance from the source was 92.6 dB. Two calibrated Class 1 sound level meters (model NTI XL2) were used to record the signals, while Audacity [15] in combination with Aurora plug-in [16] was used to estimate the reverberation time (T_{20}) from the impulse response.

An acoustic model was set in order to reproduce the measurement conditions and the acoustic properties of the materials applied to the surfaces of the courtyard. The sound absorbing and sound scattering coefficients of the surfaces were initially set according to values collected from published databases and articles, such as those in [17–19]. The mean octave-band values of the T_{20} measurements in the courtyard and over the façade was used as reference for the model calibration. The calibration of the model was performed in order to ensure that the difference between the mean measured and simulated T_{20} was smaller than 10%. The sound absorption and sound scattering coefficients of the surfaces of the model were then weighted (up to ± 20%) in order to fit the measured reverberation time as much as possible. After the model calibration, the difference between the mean simulated reverberation time and the measured one at the courtyard level is less than 5%, i.e. the Just Noticeable Difference (JND) for reverberation time [20], in the frequency range between 125 Hz and 500 Hz, and less than 10% in the range 1000 to 4000 Hz. The difference between the mean simulated and measured T_{20} over the façade is below 10% with the exception of the value at 2000 Hz, for which it is 14%.
During the measurement campaign, also the variation of SPL in different locations was evaluated. Measurements were taken in different positions at the courtyard level and in outdoor positions (2 m distance from the façade) and indoor positions at the 1st, 2nd and 3rd floors of building B (1 m distance from the façade, with open windows) to assess the sound insulation provided by the façade.

2.4 Acoustic simulation set-up

The acoustic simulation was performed using the Grasshopper version of Pachyderm Acoustics (v 2.0.0.2) [14]. The simulation procedure is based on geometric acoustic principles, and combines image source and ray-tracing. The acoustic simulations have been performed with transition order 2 (i.e. reflection order after which ray-tracing is used to collect results in place of image-source method), and a cut-off time of 5000 ms. The number of rays shot is determined by Pachyderm based on the convergence of the simulated results.
The acoustic parameter used to describe the variation of environmental noise perceived by the people located in the courtyard and in the balconies is the A-weighted SPL, which accounts for the frequency-dependent intensity perceived by the human ear. An omnidirectional sound source was positioned at the center of the courtyard, at a height of 1.5 m from the ground. The source represents a group of people talking in the courtyard: its frequency spectrum is based on the ICRA noise [21], and presents an overall Sound Power Level of 80.0 dB. The octave-band and global sound power level [dB] of the source is reported in Table 1.

Table 1 - octave band sound power level of the omnidirectional sound source used to simulate the presence of a group of people talking at the center of the courtyard

	Octave-band center frequency (Hz)								global
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	
Sound Power Level	60.8	65.5	76.6	76.6	64.8	58.1	55.1	46.3	80.0

The sound receivers were initially located in correspondence of the baricenter of the windows of the façade of both buildings A and B, at a distance of 2 m from the base-plane of the double skin (i.e. 3 m from the existing façade). Since the results obtained on the two façades were comparable on a floor basis, it was chosen to consider only those of the receivers on building B, that are shown in Figure 3. It must be highlighted that even though the results have been collected on building B only, the proposed design variations investigated are applied to both buildings A and B. Three receivers were placed at each of the 5 floors of the design building. The receivers located at the ground floor of the building are used to estimate the variation of A-weighted SPL perceived by pedestrians in the courtyard, while that of those located from the 1st to the 4th floors are used to estimate that of dwellers in the balconies.

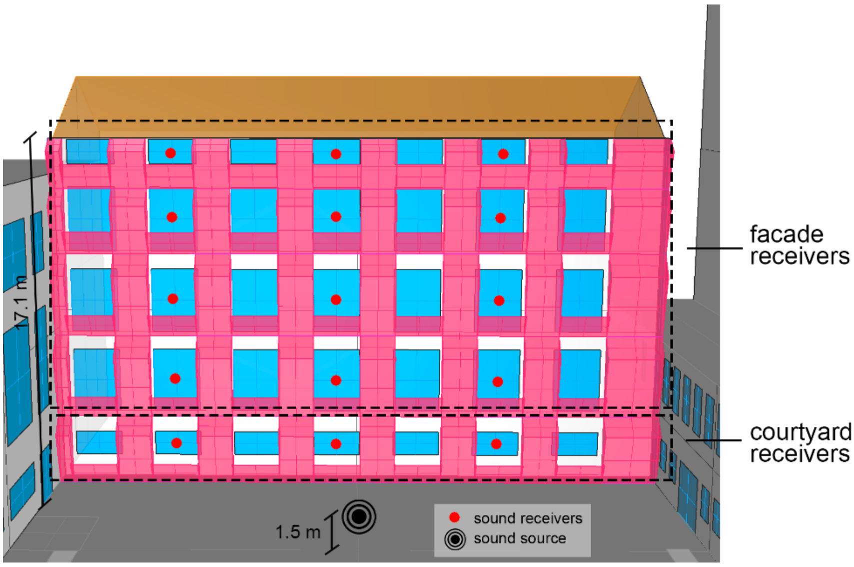

Figure 3 – virtual model of building B showing the position of sound receivers at the courtyard level and over the façade and the position of the sound source

As regards material properties, the surfaces of the double skin are tested with three material configurations presenting different acoustic properties (see Figure 2b). In the sound reflective configuration, all the surfaces are made of glass, in the partial sound absorbing configuration, the inferior sides of the wedges are treated with a commercial sound absorbing panel with a perforated metal finish, while in the sound absorbing configuration all the surfaces are treated with the sound absorbing solution. The octave-band sound absorption and sound scattering coefficients of the two cladding options are detailed in Table 2.

Table 2 - octave band sound absorption (a) and sound scattering (s) coefficients of the sound reflective and sound absorbing materials used for the double skin façades

		Octave-band center frequency (Hz)							
		63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Perforated metal (sound absorbing)	a	0.09	0.09	0.14	0.38	0.67	0.85	0.88	0.88
	s	0.03	0.03	0.05	0.05	0.06	0.07	0.1	0.15
Glass (sound reflective)	a	0.15	0.15	0.05	0.03	0.03	0.02	0.02	0.02
	s	0.03	0.03	0.05	0.05	0.06	0.07	0.1	0.15

3 Results

As previously evidenced, the variation of SPL resulting from the design variations of the double skin at the different floors of building A and B was comparable. Therefore, for the sake of simplicity, the results reported in the following refer to the receivers on building B, although the design variation are applied to both façades.

3.1 Variation in outdoor SPL

The A-weighted SPL results collected by the receivers located in outdoor positions over the façade of building B for the different design configurations of the double skin are plotted in Figure 4, while the SPLs at the courtyard levels are shown in Figure 5. The simulated A-weighted SPL values for the flat double skin option with sound reflective finish are considered as reference. The sound reflective, partially absorbing and totally absorbing material options are shown with a color gradient, from the lighter to the darker green respectively.

The results collected by the receivers are reported using boxplots to provide the reader information on the statistic distribution of the simulated A-weighted SPLs over the façade. Besides the quartile thresholds, the arithmetic mean values for the façade and courtyard receivers are marked by a cross. The highest values reached by the boxplot can be considered representative of the closest receivers to the sound source, i.e. 1st floor, while the lower values are those of the receivers located at the 4th floor of the building.

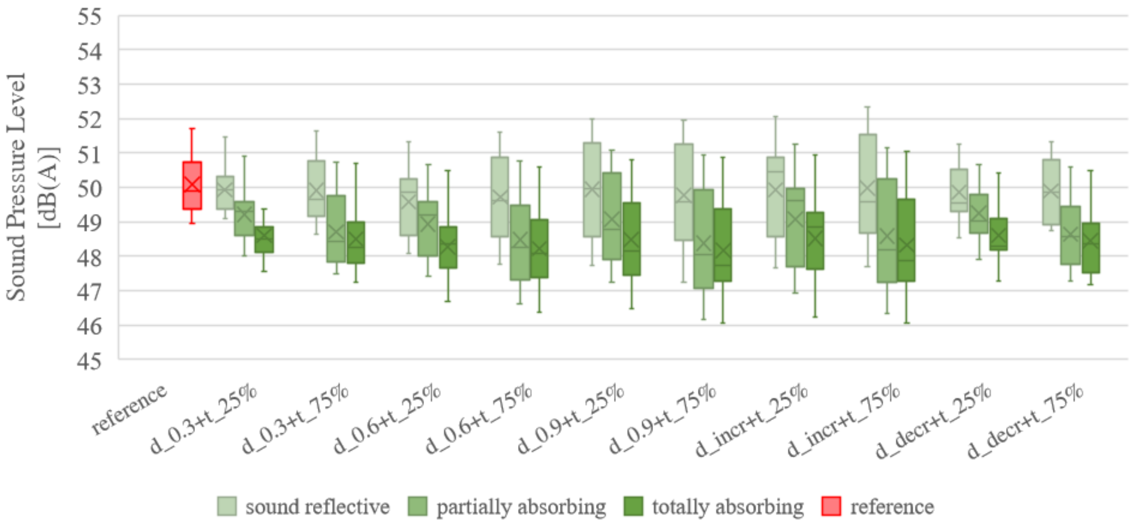

Figure 4 - Variation of A-weighted SPL over the façade of building B resulting from the different material and geometric configurations tested, in comparison to the reference configuration (in red).

The variation of SPL over the façade due to the tested geometric variations of the double skin are limited. The mean value is close to 50 dB(A) for all design options and for the reference configuration, i.e. flat double skin, showing variations smaller than the JND_{SPL} (i.e. 1 dB). This highlights the minor influence of geometric variation on the mean outdoor SPL. On the other hand, it must be noted that the lowest values, i.e. the value perceived by the receivers at the 4th floor, vary more markedly based on the geometric configurations. The SPLs of receivers at the last floor (i.e. lowest values) seem to decrease for increasing depth of the wedges. Indeed, the configurations that reach the lowest values, i.e. around or inferior to 48 dB(A), are those presenting a depth of 0.6 m or 0.9m and an increasing wedge depth at the highest floors, i.e. d_0.6+t_25%, d_0.9+t_25%, d_0.9+t_75%, d_incr+t_25%., d_incr+t_75%. This is likely to be due to the more effective noise screening shown by the deeper wedges. Conversely, the geometric solutions where the wedge depth decreases with increasing floors present SPLs comparable to those obtained when settings all the wedges with a depth of 0.3 m. The wedge tip position does not have a noticeable contribution on the SPL in case of a sound reflective treatment.

When the surfaces of the double skin are treated with sound absorbing materials, a noticeable decrease in the mean SPL over the façade is reported, that is about 1.5 dB. This is coherent with the findings of other studies [12]. When considering the minimum values reached by the SPLs, the geometric trends previously observed for the reflective finish are confirmed. The lowest values obtained in case of the sound absorbing treatment are around 46 dB.

With respect to the results obtained by the partially absorbing and totally absorbing configurations, it must be highlighted that the mean, maximum and minimum results reported for the two solutions are comparable for almost all configurations (i.e. differences smaller than the JND_{SPL} of 1 dB [20]). This trend is emphasized for the solutions with the wedge tip at 75% of the height present mean SPLs values, probably due to the resulting greater area of the inferior sides of the wedges treated with sound absorbing materials. Therefore, the treatment of the lower sides of the wedges with sound absorbing materials is a viable solution as it maintain good performances while allowing to reduce the intervention cost and increasing the durability of the sound absorbing materials, that are more protected from the weather elements.

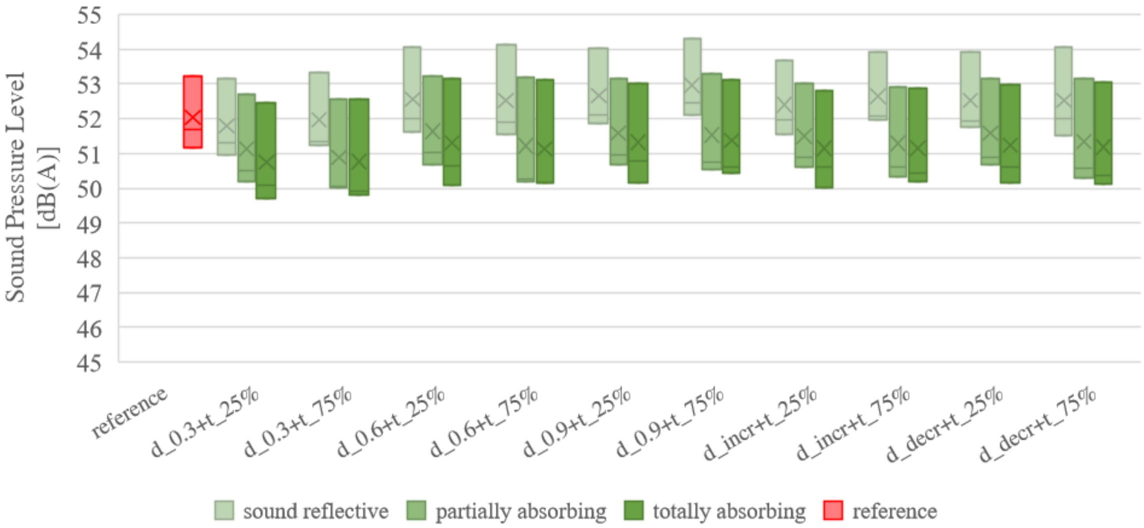

Figure 5 - Variation of A-weighted SPL for courtyard receivers (i.e. at the ground level of building B) resulting from the different material and geometric configurations tested.

The A-weighted SPL at the courtyard level is just marginally influenced by the geometric and material variations of the double skin. The maximum, minimum and mean value show a negligible variation for the geometric options tested (differences smaller than 1 dB), while a more marked variation occurs due to the application of sound absorbing materials, that is in the order of 1 dB. As for the receivers over the façade, the difference between the partially absorbing and totally absorbing options is negligible.

3.2 Variation in indoor SPL

Based on the results collected during the measurement campaign, the difference between the SPL in an outdoor position at 2 m from the façade of building B and that measured in an indoor position at 1 m distance from the façade with open windows is on average 8.3 dB. This information was used to estimate the mean SPL in indoor positions for each design configuration; these results are shown in Table 3. In order to assess the SPL variation with the double skin, the receivers were placed at a distance of 2 m from the double skin base-plane, i.e. at 3 m from the existing façade, while the measurements were taken at a distance of 2 m from the existing façade. Therefore, the difference between the mean SPL for a receiver placed at 2 m and 3 m from the existing façade was assessed without the double skin (existing scenario), finding negligible differences (around 0.1 dB). Therefore, it was considered acceptable to estimate the mean indoor SPL based on the SPL predicted at 2 m from the double skin, i.e. 3 m from the existing façade. It must be however noted that the estimation of the indoor SPL does not take into consideration the contribution of the double skin to the insertion/transmission loss, but only its influence on the outdoor SPLs.

Table 3 - mean A-weighted SPL in indoor spaces of building B for the different design configurations analyzed

	Refer-ence	**d_0.3+ t_25%**	**d_0.3+ t_75%**	**d_0.6+ t_25%**	**d_0.6+ t_75%**	**d_0.9+ t_25%**	**d_0.9+ t_75%**	**d_incr+ t_25%**	**d_incr+ t_75%**	**d_decr+ t_25%**	**d_decr+ t_75%**
sound reflective	41.8	41.6	41.3	41.6	41.6	41.6	41.6	41.4	41.5	41.7	41.6

partially absorbing	-	40.9	40.6	40.8	40.8	41.0	40.4	40.2	40.1	40.3	40.3
totally absorbing	-	40.3	40.0	40.2	40.2	40.3	40.2	39.9	39.9	40.0	40.2

The results collected in Table 3 are coherent with those in outdoor settings over the façade: geometric variations tend to have a negligible effect, while the application of sound absorbing materials result in a mean reduction of about 2 dB, ranging from about 42 dB in case of the sound reflective double skin to 40 dB in case of the totally absorbing solution.

4 Conclusions

This study analyses the effect of different design options for a double skin to be applied to two opposite façades of a courtyard on environmental noise levels. The geometric and material properties of the double skin are varied parametrically, and the variation of A-weighted sound pressure level is evaluated in outdoor positions at the courtyard level and over the façade. Moreover, also the indoor noise levels are estimated for the different design configurations. The results highlight that the tested geometric variations are generally associated to negligible noise reduction difference, as regards the façade-mean values. However, the geometries with deeper wedges they seem to have an influence on the SPLs predicted at the highest building floors with up to about 2 dB of reduction, that is likely due to the screening effect provided by the protruding elements. With respect to the material variation, it was confirmed the noise reduction potential of the application of sound absorbing materials to the surfaces of the double skin, that in this study lead to a mean SPL reduction over the façade up to 1.5 dB. Moreover, such reduction results comparable between the case of an acoustic treatment applied to all the surfaces of the double skin and that of its application on the downward oriented sides of the wedges. The variation of SPLs at the courtyard level is limited, and is only sensitive to the different materials applied to the building façade.
Further development of this work includes a systematic evaluation of the outdoor and indoor SPLs on a floor basis, in order to evidence the extent to which the proposed solutions can benefit dwellers at the different building levels. Moreover, the evaluation of the effect of the double skin applied to different façades of the courtyard (e.g. single façade, all façades) may be considered. Finally, a more advanced estimation of the sound insulation provided by the double skin can be implemented to present more reliable information of the indoor SPL resulting from the tested design configurations.

Acknowledgements

The authors are grateful to Giuseppe Vannelli for the support during the measurement campaign in the courtyard.

References

1. World Health Organization *Environmental Noise Guidelines for the European Region*; World Health Organization: Copenhagen, Denmark, 2018; ISBN 978-92-890-5356-3.
2. *Acoustics Ventilation And Overheating: Residential Design Guide*; Association of Noise Consultants: Northallerton, NJ, USA, 2020;
3. Strømann-Andersen, J.; Sattrup, P.A. The Urban Canyon and Building Energy Use: Urban Density versus Daylight and Passive Solar Gains. *Energy and Buildings* **2011**, *43*, 2011–2020, doi:10.1016/j.enbuild.2011.04.007.
4. Alves, S.; Estévez-Mauriz, L.; Aletta, F.; Echevarria-Sanchez, G.M.; Puyana Romero, V. Towards the Integration of Urban Sound Planning in Urban Development Processes : The Study of Four Test Sites within the SONORUS Project. *Noise Mapping* **2015**, *2*, 57–85, doi:10.1515/noise-2015-0005.

5. Naboni, E.; Milella, A.; Vadalà, R.; Fiorito, F. On the Localised Climate Change Mitigation Potential of Building Facades. *Energy and Buildings* **2020**, *224*, doi:10.1016/j.enbuild.2020.110284.
6. Badino, E.; Manca, R.; Shtrepi, L.; Calleri, C.; Astolfi, A. Effect of Façade Shape and Acoustic Cladding on Reduction of Leisure Noise Levels in a Street Canyon. *Building and Environment* **2019**, doi:10.1016/J.BUILDENV.2019.04.039.
7. Echevarria Sanchez, G.M.; Van Renterghem, T.; Thomas, P.; Botteldooren, D. The Effect of Street Canyon Design on Traffic Noise Exposure along Roads. *Building and Environment* **2016**, *97*, 96–110, doi:10.1016/j.buildenv.2015.11.033.
8. Lee, P.J.; Kim, Y.H.; Jeon, J.Y.; Song, K.D. Effects of Apartment Building Façade and Balcony Design on the Reduction of Exterior Noise. *Building and Environment* **2007**, *42*, 3517–3528, doi:10.1016/j.buildenv.2006.10.044.
9. Wang, X.; Mao, D.; Yu, W.; Jiang, Z. Acoustic Performance of Balconies Having Inhomogeneous Ceiling Surfaces on a Roadside Building Facade. *Building and Environment* **2015**, *93*, 1–8, doi:10.1016/j.buildenv.2015.06.027.
10. Wang, X.; Yu, W.; Zhu, X.; Jiang, Z.; Mao, D. Effects of Ceiling Phase Gradients on the Acoustic Environment on Roadside Balconies. *J. Acoust. Soc. Am.* **2017**, *141*, EL146–EL152, doi:10.1121/1.4976192.
11. Crippa, T.; Dagnini, E.; Davies, G.; Rees, H. Façade Engineering and Soundscape.; Bern, Switzerland.
12. Yang, W.; Jeon, J.Y. Design Strategies and Elements of Building Envelope for Urban Acoustic Environment. *Building and Environment* **2020**, *182*, doi:10.1016/j.buildenv.2020.107121.
13. Ottoz, E.; Rizzi, L.; Nastasi, F. Recreational Noise: Impact and Costs for Annoyed Residents in Milan and Turin. *Applied Acoustics* **2018**, *133*, 173–181, doi:10.1016/j.apacoust.2017.12.021.
14. Van der Harten, A. *Pachyderm Acoustics*;
15. The Audacity Team *Audacity*;
16. Farina, A. *Aurora for Audacity*; ISBN http://pcfarina.eng.unipr.it/Aurora_XP/index.htm.
17. Vorländer, M. *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*; RWTHedition; 1st ed.; Springer International Publishing: Cham, 2008; ISBN 978-3-030-51201-9.
18. Building bulletin 93 *Acoustic Design of Schools: Performance Standards*; 2015;
19. Yang, H.-S.; Kang, J.; Cheal, C. Random-Incidence Absorption and Scattering Coefficients of Vegetation. *Acta Acustica united with Acustica* **2013**, *99*, 379–388, doi:10.3813/AAA.918619.
20. ISO 3382-1:2009 *Acoustics - Measurement of Room Acoustic Parameters. Part 1: Performance Spaces*; International Organization for Standardization: Geneva, Switzerland, 2009; ISBN 9782832214961.
21. International Collegium of Rehabilitative Audiology ICRA Noise Available online: https://icra-audiology.org/Repository/icra-noise (accessed on 6 August 2021).