Building façades optimization at preliminary design stage for outdoor noise mitigation

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Summary
Noise pollution is one of the main issues affecting the inhabitants of contemporary cities, and architects are among the ones that are asked to find innovative solutions to the problem. However, outdoor noise mitigation is tackled only at the final stages of the design. The present study explores the possibility of integrating optimized façades design for outdoor noise mitigation into the preliminary building design phases through performance based design.
Analysis have been conducted on a case-study building located in Torino (IT) through Rhinoceros 3D models, Grasshopper algorithms and Pachyderm Acoustic Simulation plug-in. The optimization algorithm allowed testing 3600 different façade materials combination, in order to maximize the environmental noise mitigation. A reduction of 1.2 dB was obtained by the optimization of materials in compliance with realistic constraints that are present when designing a building façade. Results of further simulations proved that sound absorbing materials on the street pavement and at the ground floor of the building have negligible effects for receivers placed above the ground floor, while variations in balconies geometries have a significant effect.

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1. Introduction

Noise pollution is one of the main environmental issues for contemporary cities, constituting a relevant and widespread cause of disturbance and leading to several health problems [1-3] that affect citizens' life quality and duration [2,4,5] and have a high economic impact. The World Health Organization estimates that over one million of years of healthy life are lost every year in Europe due to environmental noise [6,7] and Harding, Frost, Tan & Tsuchiya [8] value the cost of effects of environmental noise on human health to be 1,34 billion euros per year in the United Kingdom. Moreover, additional costs are due to increase of cognitive load in noisy environment [9] and to productivity loss due to sleep deprivation [10].

The European Commission Green Paper [11] specifies that environmental noise is "caused by traffic, industrial and recreational activities" and the Environmental Noise Directive [12] defines it as "unwanted or harmful outdoor sound created by human activities". Therefore, albeit the majority of studies and of legislations focuses mainly on noise from transports and industrial activities, the noise due to nightlife ("movida") can also be considered as one of the causes of environmental noise pollution. This is especially true for central areas of cities that combine residential buildings with high concentration of clubs and pubs, where nightlife noise causes tensions between clubs owners, dwellers and inhabitants [13], who experience health and economic impacts [14].
Moreover, in central city areas, where realizations of new buildings or renovations of existing ones

have to fit into the compact historical urban fabric [15], the noise pollution is likely to be exacerbated by the so-called canyon effect [16,17]. Continuous building fronts along narrow streets reflect the sound multiple times, hence increasing the sound pressure level within the urban environment.

This phenomenon can however be reduced by careful design of building shapes and materials, as demonstrated by previous studies (see, among others, [18 - 20]). Architects and urban planners can therefore play a crucial role in the present and future management of environmental noise pollution, as also recognized by the European Commission [21]. However, despite this internationally acknowledged connection between building design and outdoor noise mitigation, the latter is still not properly included among the drivers of a typical architectural design process. Acoustic issues are typically assessed at the final design stages, when technological details are defined in order to meet law requirements in term of protection of indoor environments form external noises [22]. In this way, the acoustic quality of outdoor spaces, both private and public, is not taken into account, limiting the possibility of future inhabitants to enjoy quiet spaces.

Scientific research has been assessing the problem of outdoor noise mitigation through architectural design in recent years, focusing on the effects of urban spaces proportions [23, 24] façade geometries [18, 25] and acoustic properties of materials and elements [20, 26], with particular attention to green walls and roofs [19, 27]. However, most of the research has since now focused on experimental investigation of specific technical solutions, dealing with simplified ideal situations, while the integration of the problem in the building design process, in all of its empirical complexity, remains highly understudied.

Integration of acoustics requirements within the initial stages of the design process has been assessed in recent years for the design of spaces with specific indoor acoustic requirements. The possibilities offered by performance-based design (PBD) have been investigated in the design of both the overall architectural shape [28, 29] and minor elements such as acoustic panels [30]. In PBD, the combination of simulation tools and parametric design environments allow designers to evaluate different scenarios and modify the proposals according to the performance they want to maximize [31]. In parametric modelling tools, the characteristics of the model are defined by parameters set by the designer. The variations of such parameters generate the different designs that are evaluated through the simulation tool [31,32], allowing for the automatized assessment of a great number of different alternatives. Moreover, this approach allows the designer to define which characteristics of the model can be changed in order to pursue the chosen performance and which ones need to be unvaried due to other necessities, hence integrating the acoustic performance with other aspects of the complex building design process.

In this research, the use of PBD is employed in the design of building façades in order to minimize the outdoor sound pressure level in a narrow urban street. In particular, it is applied in the choice of façade materials of a contemporary building inserted in a parcel of an historical neighbourhood, in which night-time noise levels due to recreational activities are high and exacerbated by the compact urban layout. The effects of façades geometry variations and of sound absorbing asphalt applied to the street surface are also evaluated Preliminary design guidelines are then given. The work aims to be a step forward in the connection of the acoustic and the architectural aspects through a tool that is intended as a support for architects in the preliminary phase of a project.

2. Methodology

The case study selected for the research is a building located in via Saluzzo, in the nineteenth-century neighbourhood of San Salvario, in the city of Turin (Piedmont, IT). The building, a complete renovation of a multilevel car park realized between 2006 and 2010, has a plastered concrete façade with insertion of glass balconies and loggias. The actual façade is therefore characterized by flat, highly reflective surfaces. Figure 1 shows a picture of the façade of the building, retrieved from the designers' website [33].

A 3D model of a portion of the street in which the building is inserted has been created using Rhinoceros (V. 5). Only the building façades have been modelled in order to limit the calculation load. The street is 11 m wide and a portion of 80 m length has been considered for the study. The façade of the case-study building has been modelled on the basis of the project drawings provided by the designers, while the façades of the surrounding historical buildings have been derived from straightened pictures obtained with RDF software developed by IUAV university [34]. Figure 2 shows an aerial and an internal view of the model, in which the case-study building is marked in blue and red.

Figure 1. Picture of the case-study building façade.

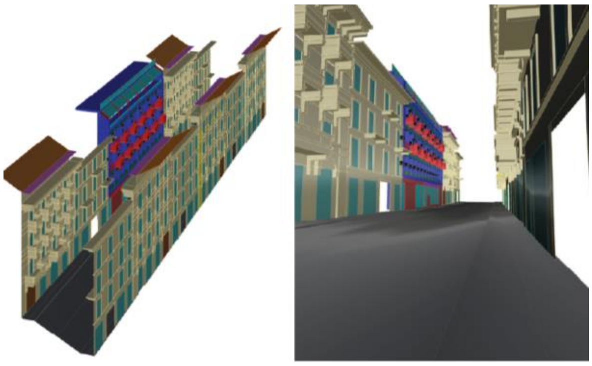

Figure 2. Views of the 3D model realized for the study.

The use of different layers in the model has been studied on the basis of future changes that are foreseen during the optimization phase. Therefore, besides setting layers with respect to the different materials that are found in the case-study building and in the surrounding ones, a specific layer has been assigned to each part of the case-study building façade for which different materials will be tested during the simulations.

The PBD method has then been implemented through the parametric design environment of Grasshopper and the open source simulation tool Pachyderm Acoustical Simulations. Grasshopper is a graphical algorithm editor integrated in Rhinoceros, which enables to generate parametric models of complex geometries through mathematical functions that are set by the designer through the use of ready-made components. Pachyderm Acoustical Simulations is a geometrical acoustics simulation plug-in that works within both the Rhinoceros and the Grasshopper environment.

When running acoustical simulations in Grasshopper environment, both versions of Pachyderm (For Rhinoceros and for Grasshopper) work together. Acoustical properties of the different layers (absorption and scattering coefficients) as well as sources and receivers positions are set in Rhinoceros environment and will be then recalled in Grasshopper algorithm.

All the layers of the Rhinoceros model are recalled in the Grasshopper environment using Human plug-in. Geometries and material properties associated to each layer in Rhinoceros are recalled and re-associated in Grasshopper through specific components (a complete explanation of the procedure is reported in [35]). Through this association, the room parameters for the acoustic simulations are set. Sources and receivers are recalled from Rhinoceros environment through Pachyderm for Grasshopper and, together with room parameters and calculation parameters such as number of rays, cut-off time and reflection order, are used as input components for the acoustic simulations. Impulse responses are recorded in each microphone position and acoustic parameters (reverberation time and sound pressure level in this case) are evaluated.

1.1. Model calibration

The model has been calibrated by fitting the simulation results of the current state with in-situ measurements of reverberation time (RT) and sound pressure level (SPL). Since the aim of the study was to define a procedure that could be implemented by a designer with basic acoustic knowledge, without the use of professional tools for acoustic measurements, a smartphone (Miezu M3s) with specific open-source apps was used as a receiver while a set of balloons was used as a source for RT measurements [36].

RT measurements have been conducted using the app APM Tool Light by Suono & Vita [37]. Receivers have been placed in positions were pedestrians are likely to pass, at a height of 1.60 m above the ground, hence simulating the average position of the ears of a standing listener. Sources have been placed in order to simulate the position of both vehicle engines (center of the road, 0.50 m

from the ground) and chatting people (side of the street, 1.60 m from the ground), as both kind of sources are likely to be found in the area. Figure 3 shows a picture of the measurements setup as well as the sources and receivers positions.
The algorithm has been set in order to replicate the source-receiver combinations used in in-situ measurements through the use of cherry-picker components that allow picking a specific receiver from the data trees of receivers that is associated to each source. It then calculates RT values for all the combinations, to be compared with the RT values derived from in-situ measurements.
The sound absorption and scattering coefficients of the materials used in the model have been inferred from existing literature. Variation within 5% of the value of each coefficient have been applied in order to reach a good consistency between simulated and measured reverberation time.

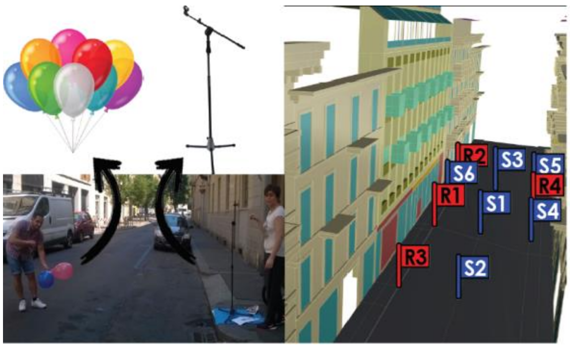

Figure 3. Reverberation time measurement setup and sources and receivers positions.

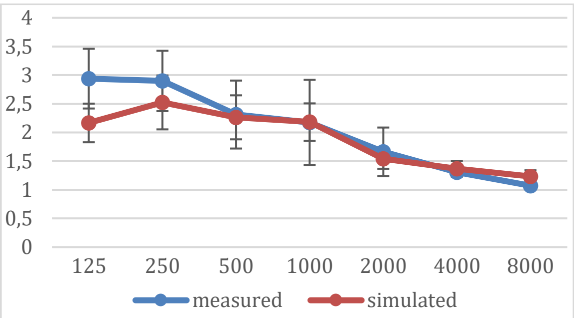

Figure 4. Measured and simulated T_{20} values.

Figure 4 shows a comparison between measured and simulated T_{20} values. Simulated and measured values show a good consistency between 250 Hz and 4000 Hz (Figure 4),
SPL in-situ measurements have been performed with OpeNoise app from ARPA Piemonte [38]. The tool has been calibrated in anechoic chamber of Politecnico di Torino, using a sound source 4205 by Brüel & Kjær and a sound level meter NTI XL2 with M2230 microphone (Class 1) as a benchmark. Meaurements have been taken during a Saturday night (data..), when the noise levels in the street are expected to be particularly high and the sound source is more localized (group of people chatting loudly outside of a pub in front of the building). The receivers have been placed at 1.60 m from the ground in four different positions (2 in the street, 1 on a balcony and 1 inside a loggia), as shown in Figure 5. 20 minutes recordings, with 2 minutes interval savings, have been conducted in each position.
The Simulations have then been conducted by placing in the model four receivers, replicating the position of in-situ ones, and an omnidirectional sound source with a chatting noise power spectrum, simulating the position of the group of chatting people that can be found in the real situation (1.60 m from the ground and 1.50 m from the opposite building front). The sound source power has been adjusted until a good consistency between the simulated and the measured SPL values for all four receivers (Figure 5) has been reached.

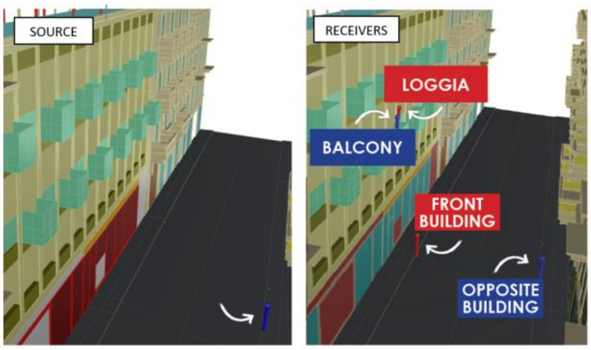

Figure 5. SPL measurements: source and receivers positions.

1.2. Facade alternatives simulations

After the model calibration, a new version of the algorithm has been created, in order to automatically change materials applied to selected parts of the façade and test different possible solutions based on the criteria of maximizing the reduction of the outdoor sound pressure level.
Five different layers were elected for possible materials changes, i.e. the ceilings and the floors of the loggias, the parapets of loggias and balconies, the floors of the balconies and the plaster of the whole façade. For each layer, 4 to 6 possible materials have been identified through an in-deep the research among materials available

on the market. These choices have been based on specific criteria, that is, (1) the materials are appropriate for outdoor use and (2) availability of information about their acoustic properties such as sound absorption and scattering coefficients. The chosen materials have been added in the layer list of Rhinoceros and can therefore be recalled in Grasshopper.

Table 1 shows a scheme with all the materials that have been chosen for each layer, together with their acoustic properties.

A grid of 36 receivers has been placed on the balconies and loggias of the building façade, as shown in Figure 6, simulating the position of standing listeners. The sound source, as located and characterized in SPL model calibration, has been used for all the following simulations. The algorithm has been set in order to provide mean and standard deviation values of the A-weighted SPL resulting for all receivers.

The automation has been ran through Galapagos, a native component of Grasshopper that uses an evolutionary-based algorithmic solver. Galapagos will change materials associated to each layer (genome) in order to minimize the average SPL obtained from all receivers (fitness). In this way, all the 3600 possible material combinations have been tested in order to find the best possible solution. Materials marked in light blue in Table 1 are the ones which have been selected by the optimization.

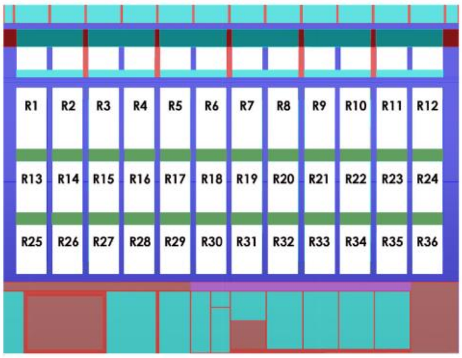

Figure 6. Grid of receivers used for simulations.

Finally, in order to have a preliminary evaluation of further possible solutions, in a second phase of the work the effects of sound absorbing asphalt and ground floor materials has been tested through manual modifications of the model. Modifications of the geometry have also been realized, as shown in Figure 8, and their influence on SPL has been evaluated.

Table 1. Chosen materials and their absorption (α_w) and scattering (s) coefficients. The scattering coefficient are average values for 500 Hz and 1000 Hz octave bands. Materials marked in light blue are the ones selected as output of the optimization. This configuration of materials will be marked as M1 in the result section (Table 2).

Facade	**Plaster**	**Rough plaster**	**Acoustic plaster I**	**Acoustic plaster II**	**Glass granules panels**	
	$\alpha_w = 0.05$ s = 0.02	$\alpha_w = 0.05$ s = 0.45	$\alpha_w = 0.65$ s = 0.02	$\alpha_w = 0.35$ s = 0.02	$\alpha_w = 0.90$ s = 0.02	
Parapets	**Glass**	**Aluminium panels I**	**Aluminium panels II**	**Wood I**	**Wood II**	**Wood III**
	$\alpha_w = 0.10$ s = 0.02	$\alpha_w = 0.60$ s = 0.02	$\alpha_w = 0.70$ s = 0.02	$\alpha_w = 0.10$ s = 0.02	$\alpha_w = 0.20$ s = 0.02	$\alpha_w = 0.25$ s = 0.67
Balconies floor	**Glass**	**Wood**	**Panel fabric finish I**	**Panel fabric finish II**		
	$\alpha_w = 0.10$ s = 0.01	$\alpha_w = 0.20$ s = 0.01	$\alpha_w = 0.60$ s = 0.01	$\alpha_w = 0.90$ s = 0.01		
Loggias floor	**Concrete**	**Wood I**	**Wood II**	**Wood III**	**Plastic/vinil**	
	$\alpha_w = 0.05$ s = 0.01	$\alpha_w = 0.10$ s = 0.01	$\alpha_w = 0.15$ s = 0.01	$\alpha_w = 0.15$ s = 0.01	$\alpha_w = 0.05$ s = 0.01	
Loggias ceiling	**Plaster**	**Rough plaster**	**Quash**	**Aluminium panels I**	**Fiberglass panels**	**Glass granules panels**
	$\alpha_w = 0.05$ s = 0.01	$\alpha_w = 0.05$ s = 0.45	$\alpha_w = 0.60$ s = 0.01	$\alpha_w = 0.60$ s = 0.01	$\alpha_w = 0.70$ s = 0.01	$\alpha_w = 0.90$ s = 0.01

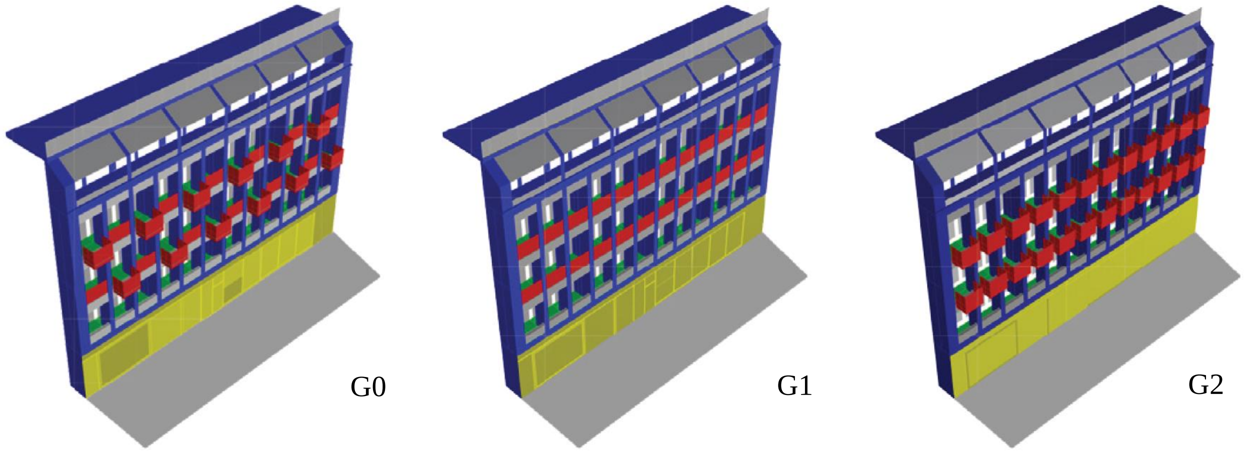

Figure 7. Modifications of the façade geometry: G0, real building façade; G1, all projecting balconies are eliminated; G2, the projecting balconies are located on the whole façade.

3. Results and discussions

Results of the automated simulations showed that the intervention on façade materials above the ground level (see Figure 6), when the geometry of the façade is kept unvaried, leads to a maximum reduction of 1.2 dB of the average SPL calculated for the receivers on the building façade.
Figure 8 shows the SPL reduction obtained for each receiver and averagely at each floor. The benefit derived from materials variations tends to increase for higher levels, even if with differences that are below the JND of 1 dB. Indeed the average SPL value reduction for the receivers on the third floor is 1.4 dB, compared to 1.2 dB for the second floor receivers and 1.1 dB for the first floor receivers.

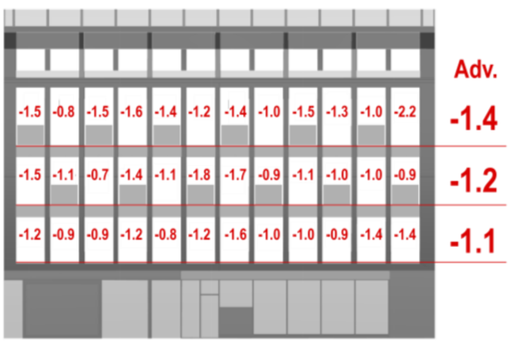

Figure 8. SPL reduction due to material modification for each receiver position. The numbers on the right side of the figure report the average SPL value for each floor.

Table 2 show the average SPL for all the façade layouts obtained by materials optimization, asphalt and ground floor material manual modification and geometry variations (Figure 7).

Table 2. Average SPL for the whole façade in all the tested scenario. For all the façade geometries (G0,G1,G2), three choices of facades materias have been tested: real building materials (M0), materials resulting from the optimization (M1) and additional modification of asphalt and ground floor (M2). The number marked in red correspond to the SPL for the real building (G0-M0).

Geometry	Materials	Average SPL [dB (A)]
G0	M0 – real building	46.9
	M1 –optimization	45.7
	M2 – additional modification of asphalt and façade ground floor	45.6
G1	M0	45.4
	M1	44.9
	M2	44.8
G2	M0	43.4
	M1	42.3
	M2	42.3

As can be seen from the Table, the influence of sound absorbing material on the ground floor and of sound absorbing asphalt are not substantial for receivers placed above the ground level, hence at the levels where building inhabitants are situated. Indeed, such solution resulted in a reduction of the average SPL value of 0.1 dB with respect to the solution obtained through the automated façade materials optimization. Geometry variations proved to have a more significant effect on SPL mitigation, since geometry G2 provided a SPL reduction with respect to the actual building geometry of 3.5 dB with no material variations (M0) and of 3.4 dB when the materials obtained from the optimization are applied to the façade (M1).

4. Conclusions

The present work focuses on the possibility of integrating outdoor noise mitigation within the architectural project, since the preliminary design stages.

In particular, performance-based design has been used in order to optimize the façade materials in order to maximize the reduction of the sound pressure level perceived by receivers set on balconies and loggias of a building. The study has been conducted through CAD software Rhinoceros, Grasshopper parametric design tool and Pachyderm Acoustic Simulations plug-in.

The automation allowed to test 3600 different material combinations, among a database of materials selected by the authors from existing literature and market research. Therefore, the use of performance based design greatly expanded the number of design options that can be evaluated.

Outcomes of the automatized materials optimization and of the following manual modification of the model can be summarized in the following points, which can constitute preliminary guidelines for designers:

- through the modification of façade materials an average SPL mitigation of 1.2 dB can be reached for the case-study building;
- the use of sound absorbing asphalt and of sound absorbing materials at the ground floor of the building has a negligible benefit for inhabitants living in the building;
- modification in the façade geometry have a greater influence on noise mitigation with respect to materials modification alone. In particular, the presence of a higher number of balconies can help to protect inhabitants from noise generated in the street.

The present study must be considered as a first attempt to integrate noise mitigation since the first phases of the design through the use of performance-based design. The tested procedure is intended as a support for designers in order to achieve some preliminary decisions and to better integrate acoustic aspects into the design process, going beyond the current practice.

Moreover, the study contributed to expand the knowledge on possible solutions that can be applied for noise mitigation and on the SPL reduction that each solution can provide. Similar studies can therefore contribute to the creation of guidelines that can help designers integrating solutions for outdoor mitigation in architectural projects.

Further developments of the work are envisioned. In particular, an enhancement of the algorithm is necessary in order to allow for automatized geometry variations of the façade and for the evaluation of the effects of both geometry and materials simultaneously.

Other possible improvements of the study are the testing of other case studies and other façade solutions as well as multi-parameter optimization conducted through Grasshopper solvers.

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