

Architectural Façade Retrofitting of an Educational Building to Reduce Traffic-Induced Noise Load

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Abstract Noise pollution is a phenomenon that affects many large cities and is caused by several factors, one of which is traffic noise due to the high population density in urban areas. This paper aims to investigate three retrofitting techniques to reduce traffic-induced noise on the main façade of the architectural department building at Cairo University. Initial physical measurements recorded a minimum noise level of 63.9 dB(A), exceeding World Health Organization (WHO) standards. The first technique explores geometry manipulation by altering the inclination angles (5° and 15°) of the façade protrusions. The second technique evaluates two sound-absorbing cladding materials: green wall systems and coarse concrete tiling. The third technique combines the two approaches, applying the cladding materials to the optimized angles. Using I-Simpa as a computational simulation tool, the sound pressure levels (SPL) resulting from each technique were analyzed. The results indicate that the base case scenario with a 0.75-meter protrusion achieved an average SPL reduction of 1.7 dB(A) with a green wall and 2.4 dB(A) with coarse concrete. However, implementing a combination of techniques—including increased protrusion, inclination, and surface treatment—proved more effective, achieving a maximum SPL reduction of 2.8 dB(A) from the highest recorded level. This study demonstrates the potential of integrated retrofitting strategies to address urban noise pollution effectively.

Keywords Façade Retrofitting, Façade Cladding, Computational Simulation, I-Simpa, Absorbing Materials,

Sound Pressure Level

1. Introduction

Noise reduction in densely populated urban areas is an important challenge due to building proximity, high population density, and frequent noise sources such as transportation, manufacturing processes, and human interactions. To effectively combat noise in such scenarios, an integration of urban planning, architectural design, and the use of noise-reducing materials and technologies is required. Some of the key elements for reducing noise in congested areas are vegetation and green infrastructure, street and paving design, traffic management, and, most crucially, building façade design [1], [2], [3].

Geometrical manipulation as a façade retrofitting technique has been a part of this field of study for many decades. Façade geometry manipulation involves the strategic use of building elements such as balconies, parapets, and claddings to control sound reflection, transmission, and absorption. Research on façade shapes and acoustic treatments has demonstrated that manipulating these features can significantly reduce noise levels, particularly in areas like street canyons, where sound reflections from buildings amplify environmental noise [1], [3].

This study focuses on retrofitting strategies for Cairo

University's architecture department building, which is heavily impacted by traffic noise. The study investigates three approaches: geometric modification, usage of sound-absorbing materials, and a combination of the two approaches. The objective is to find the most effective technique for minimizing noise transmission and improving acoustic comfort throughout educational buildings—a setting that is frequently overlooked in noise mitigation research.

2. Literature Review

Several studies have highlighted that adjusting the design of façades protrusions, especially balconies, can effectively reduce noise load in addition to control noise transmission from the urban space to the indoor environments [1], [4], [5], [6], [7]. While closed or semi-closed balconies are a common feature in residential buildings, they are not as common in educational buildings. As a result, façade protrusions in educational settings can take various forms depending on the design, which also influences sound behaviour. Adjusting the upper and lower profiles of the facade protrusions and experimenting with different angles of inclination is a common method. These adjustments obstruct sound waves from urban spaces, thereby reducing noise transmission to indoor space [1], [5], [7], [8], [9].

In a study by Niesten [9], ray-tracing simulations using CATT Acoustics were used to evaluate the acoustic impact of different façade designs in an urban area. Three façade designs were tested: sound-absorbing, sound-reflecting (upward), and a combination of both. These designs aimed to reduce sound levels in a courtyard area in Delft, the Netherlands. The results showed a reduction of 9.3 dB(A) using sound-reflecting technique, though this raised concerns about increased noise in other areas due to sound diffraction. The combined design offered a more balanced solution, achieving reductions of up to 6.7 dB(A), making it more practical for real-world applications.

Different absorbing materials have been assessed as façade cladding to enhance acoustic conditions and decrease noise-induced loads. Additionally, permeable tiles composed of recycled glass—a waterproof, stone-like material—have been investigated. While absorbing materials are beneficial in improving acoustic conditions, studies demonstrate that combining geometrical manipulation with absorbing materials as external cladding yields better results.

Studies have investigated different façade shapes and acoustic claddings to explore their impact on noise reduction in urban environments, particularly in street canyons where buildings line both sides of the street. Noise pollution, including leisure noise from nightlife areas, is a growing issue in densely populated cities. Research demonstrates that building façade design can significantly improve urban acoustic comfort through

Performance-Based Design (PBD). Balconies, for example, produce a noise-reducing shielding effect, with deeper balconies (1.5 m) resulting in up to 1 dB(A) noise reduction. The deeper the openings, the less noise is transmitted through the windows. Integrating absorbent materials with boosted balcony forms improves performance even further, as increased absorption effectiveness leads to superior noise reduction. However, no specific materials were selected for cladding in these studies. Significantly, façade design adjustments have been demonstrated to be more effective in reducing noise than substituting street surfaces with sound-absorbing pavement, highlighting the importance of early architectural planning in noise mitigation [1].

Green walls have also been investigated as a façade cladding alternative, offering benefits for both thermal mass and urban environments. In addition to their aesthetic value, green walls serve as effective acoustic absorbers, reducing sound pressure levels by 5-8 dB(A) [10], [11], [12]. A study by Carlucci [11] demonstrated the environmental benefits of modular living green walls in a semi-arid Mediterranean climate, showing reductions in air temperature by up to 8 °C, increases in relative humidity by 6.6%, and reductions in sound pressure by up to 5.1 dB(A).

A study conducted by Van Renterghem [12] shows that the sound pressure level reduction achieved by green walls is dependent on their design and placement. The effect of covering half of a façade with green walls resulted in a 3-4 dB(A) reduction, however, only covering the first 0.5 m of the façade yielded a 1-3 dB(A) reduction. Lower-floor placements provided better sound absorption, emphasizing the significance of location and coverage area. While modular green walls are a prominent technique, Azkorra highlighted limitations that must be addressed during early design stages, such as structural systems, connections to the façade, aggregation processes, and maintenance [10]. Furthermore, the absorption effectiveness of green walls varies depending on the structural system, materials, and plant species.

Beyond green walls, researchers have investigated modifying conventional building materials like concrete to enhance their acoustic properties [13], [14], [15]. There are different types of concrete cladding, and each behaves differently based on the dense of the mixture, through defining the size, and type of the aggregates, as lightweight concrete mixtures act as a good sound absorber due to the loss of noise energy [14], [16]. A study by Calleri [13] investigates how different façade materials affect the acoustic characteristics of a small urban square and listeners' perception of space wideness, using three different absorbing materials which are coarse concrete, plain painted block work and green walls. The results demonstrated that the absorption coefficient of facades and listener location have a substantial impact on perceived space width, although the scattering coefficient did not perform. This confirms using absorbent materials could have a positive impact on the urban environment,

especially in areas with high noise levels.

Acoustic software tools are widely used in architectural and environmental acoustics to simulate, measure, and analyze sound behaviour in built environments. These tools help predict noise levels, design noise control solutions, and evaluate acoustic performance in urban and indoor settings. Specialized software can simulate room acoustics, outdoor environments, or both, enabling designers to test and refine design options to meet acoustic comfort requirements efficiently [17], [18]. Various design solutions can potentially be examined and modified using simulation to fulfill acoustic comfort criteria, decrease noise pollution, and improve sound quality while remaining cost-effective and time-efficient. Computational models simulate sound propagation, reflection, and absorption, predicting reverberation times, speech intelligibility, and sound pressure levels. This allows designers to evaluate how different materials and geometries affect acoustics [17], [18], [19].

This paper investigates three façade retrofitting techniques to reduce traffic-induced noise at Cairo University's architectural department building. By modifying the main façade design, the study aims to identify the optimal configuration for reducing noise loads measured at eight different windows. The research explores modern, widely used façade cladding materials to assess their acoustic performance, demonstrating that aesthetics and functionality can coexist in building acoustics. Focusing on an educational building as a case study highlights the importance of acoustic comfort in such environments, which often receive less attention than residential buildings in noise mitigation research, despite their sensitivity to noise pollution.

2.1. Research Methodology

Façade retrofitting of educational buildings has become an inevitable approach to maintaining buildings' resilience in the face of various types of environmental pollution. Noise pollution caused by traffic noise is one of the major factors influencing the acoustic comfort in educational buildings, as these buildings hold lots of mental and physical activities, therefore they are considered a very sensitive environment to the outdoor noise. Addressing this issue is critical to ensuring a conducive learning environment.

This research explores three retrofitting techniques. The first technique involves geometry manipulation, which modifies the length and angle of inclination of existing façade protrusions. The second technique compares two different sound-absorbing materials as façade cladding options. The third technique combines the two approaches by adjusting the angle of inclination while applying sound-absorbing materials to achieve optimal noise reduction.

This research methodology is structured into several sections, as depicted in Figure 1. The first section involves

a literature review, analyzing previous scientific work conducted on similar cases, including approaches, methods, findings, and results. This is followed by a comparison of different acoustic simulation tools, with a focus on introducing I-Simpa, the software used in this study to predict sound properties. The third section describes the case study, which focuses on Cairo University's architectural building. This building is a part of a complex exposed to heavy traffic, especially during school days. Key factors such as site layout, façade design, and noise sources are analyzed to understand the context and challenges. The fourth section outlines the research method, which is divided into two parts. First, physical measurements are conducted at selected windows on the façade during three different times on a busy school day to identify peak noise hours. Second, a 3D digital model is created, and the acoustic conditions are calibrated using I-Simpa based on the field measurements. The software is then used to predict sound pressure levels after modifying the lower and upper façade protrusions and testing different cladding materials with varying absorption coefficients. The goal is to identify the optimal solution for improving acoustic conditions and reducing the noise-induced load on the façade. The fifth discusses the results, comparing the effectiveness of different façade treatments and highlighting the best-performing solutions. Finally, the sixth section presents the conclusion, proposing a list of recommendations for similar buildings and discussing the limitations of the study.

2.2. Software Applications

Acoustic simulation tools have become a widely adopted method for calculating and predicting the acoustical conditions of both existing and upcoming architectural projects due to their accuracy, feasibility, and time-saving capabilities [17], [18].

Several acoustic software tools are capable of delivering accurate or near-accurate results, though they vary in features, applications, and availability. Some are particularly suitable for façade acoustical simulations, as they cover a wide range of acoustic properties [17], [18]. However, one major challenge for users is the availability of these tools. Many are commercial software with high subscription fees and lack educational licenses, while others offer demo or free trial versions without full features, making their results unreliable for research purposes.

Additionally, many available software tools are specialized in room acoustics and cannot be used for urban environment simulations. Despite this, some studies have addressed this issue by identifying software tools that are either free or offer educational licenses and are capable of handling both room acoustics and urban environments [17], [18].

A selection of well-known simulation tools used for façade design is presented in Table 1. Cadna A, CATT-Acoustics, and Odeon are standalone commercial

software tools, though they provide free trial licenses with limited features. On the other hand, Pachyderm Acoustics is a free, open-source plugin for Rhinoceros and Grasshopper, covering most fields except sound insulation.

Finally, I-Simpa is a standalone software with a free license available. While each of these tools covers several different fields, they all include environmental noise simulation capabilities.

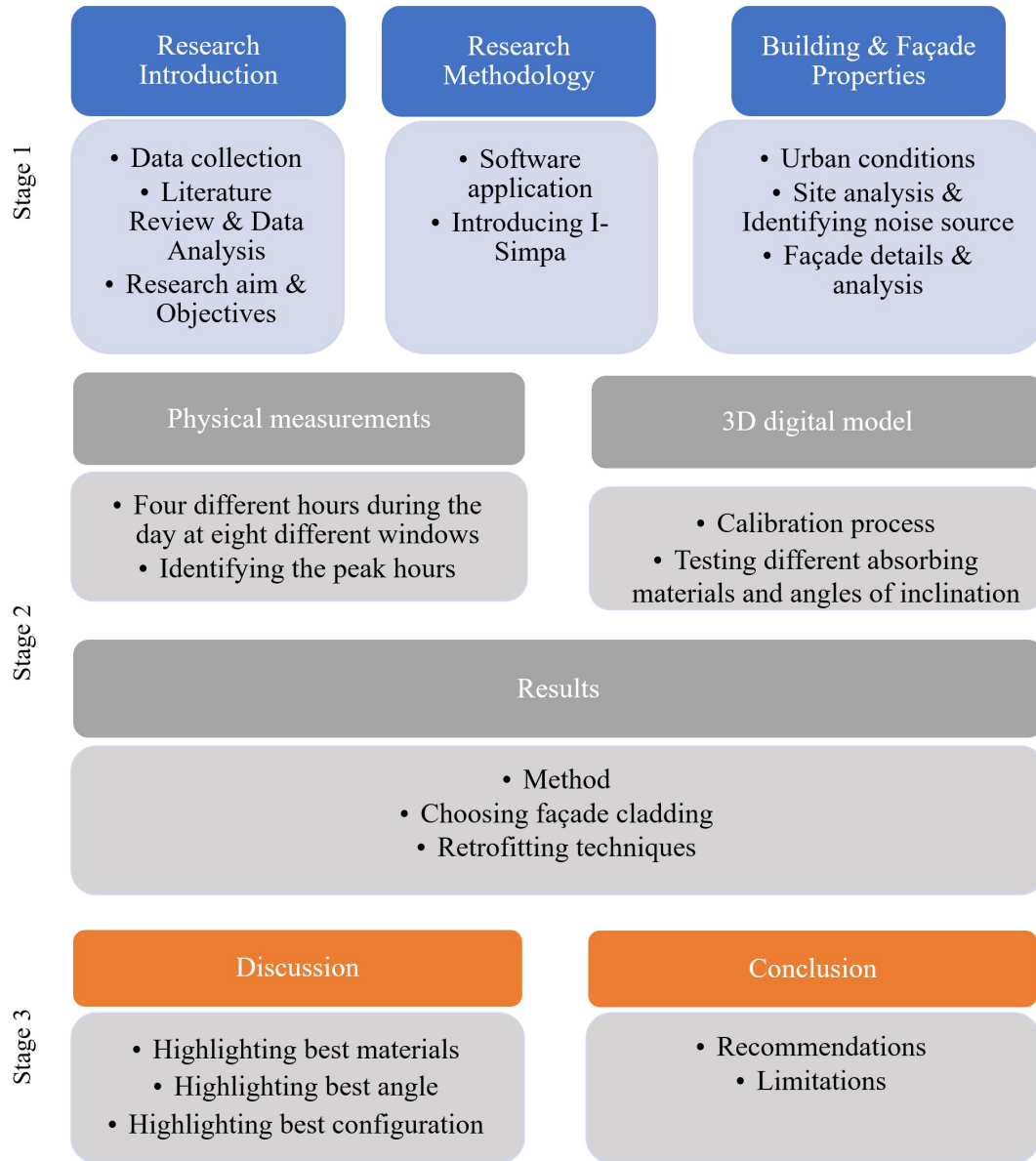


Figure 1. A flow chart for research methodology

Table 1. Various acoustical software programs for assessing both room and facade acoustics [17], [18]

Name	Type	Availability	Field				
			EV	SI	NM	AU	3D
CadnaA	Geometric	Commercial	■	■	■	■	■
CATT-Acoustics	Geometric	Commercial	■	■	■	■	■
Odeon	Geometric	Commercial	■	■	■	■	■
I-Simpa	Geometric	Free	■	■	■	■	■
Pachyderm Acoustics	Geometric	Free	■	■	■	■	■

2.2.1. Introducing I-Simpa

I-Simpa is the selected acoustic simulation tool to dedicate the SPL for all the research scenarios. It is a noise simulation software with a graphical user interface, designed as a free, open-source computational tool for simulating sound properties in virtual 3D models. This software enables architects and engineers to simulate sound behaviour in both indoor spaces and open outdoor environments. Its 3D visualizations provide valuable insights into how sound interacts with architectural elements such as walls, floors, and ceilings [19].

To perform simulations, users must define the absorption efficiency of materials, the characteristics of noise sources, and the placement of receivers in terms of location, orientation, and directivity. Environmental factors such as temperature and humidity must also be considered. I-Simpa is specifically designed to host numerical codes for simulating sound propagation in three-dimensional domains. Originally developed as a research tool, it is applicable to room acoustics, building acoustics, and environmental acoustics. The software supports energetic ray tracing models, reverberation theory, and sound particle tracing [19].

I-Simpa is equipped with key features, including TCR (based on the classical theory of reverberation) and SPSS (a sound particle tracing code) [19]. The software covers three main fields: Environmental Modeling (EV), Noise Mapping (NM), and 3D Geometry Manipulation (3D), as illustrated before in Table 1 [17]. These capabilities make I-Simpa a versatile and powerful tool for acoustic simulations in both architectural and environmental contexts.

I-Simpa has the potential to produce accurate results; however, its reliability depends on several factors, including the complexity of the geometry, the input parameters, and the specific acoustic conditions being modeled.

- **For simple geometries**, I-Simpa generally provides reliable results, particularly when simulating sound propagation using ray-tracing and sound-particle tracing methods.
- **For complex environments**, accuracy may decline due to challenges in modeling sound diffraction, reflections, and absorption in highly irregular spaces.

- **Empirical comparisons** indicate that while I-Simpa can closely align with real-world measurements, discrepancies may arise, especially in highly reflective or non-standard environments [19].

2.3. Case Study Description

The case study focuses on the architecture department building at Cairo University, an educational building located on the university's campus in Giza, Egypt. The campus is situated in a congested area near several landmarks, experiencing peak traffic during weekdays. The surrounding urban area has undergone significant changes, including the expansion of streets to accommodate increasing traffic, the addition of bus stops, and ongoing construction activities. These factors contribute to elevated noise levels, particularly from the nearby six-lane, two-way main street, which serves as the primary noise source.

The building itself is a seven-storey height, consisting of a ground floor and six upper floors. It is surrounded by four other buildings on each side, with small green nodes scattered across the campus. However, these green spaces are insufficient to create an effective sound buffer against the noise from the main street, as cleared in Figure 2. The building's façades are composed of rigid modules of openings separated by vertical and horizontal protrusions, none of which include specialized acoustic treatments. Additionally, the façade is externally coated with plain paint, as shown in Figure 3.

The window is divided into two parts, as depicted in Figure 4, which shows the window's cross-section, while Figure 5 presents a 3D view of the windows. The upper section consists of single-layered glass within a metal frame, serving as the primary source of natural light and ventilation. The lower section features metal strips and horizontal reinforced concrete (RC) protrusions with a depth of 0.75-meter. Figure 3 illustrates the selected mid-floor (the highlighted yellow floor), chosen to minimize measurement bias by ensuring it is neither too close nor too far from the street-level noise source. Finally, Figure 6 displays the complete floor plan, emphasizing the examined façade facing the highest levels of noise pollution.

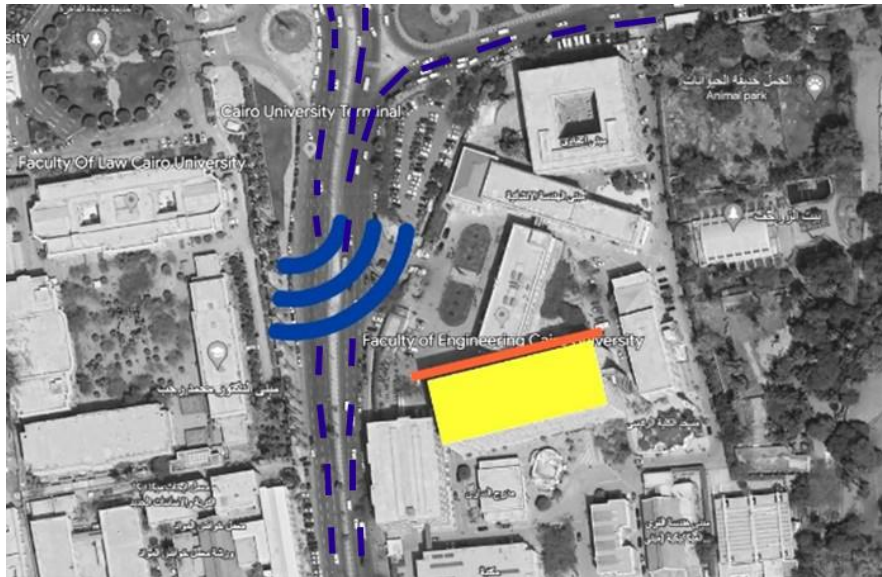


Figure 2. A satellite image of the campus layout highlights the building and identifies the noise source originating from the adjacent street



Figure 3. A real-life image of the building's façade is provided, with the third floor highlighted as the focused floor plan for the investigation

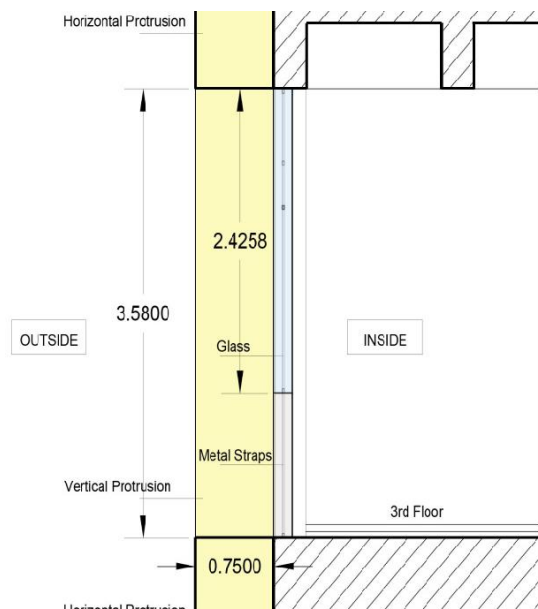


Figure 4. A detailed wall section at the windows is provided, with the protrusions highlighted in yellow

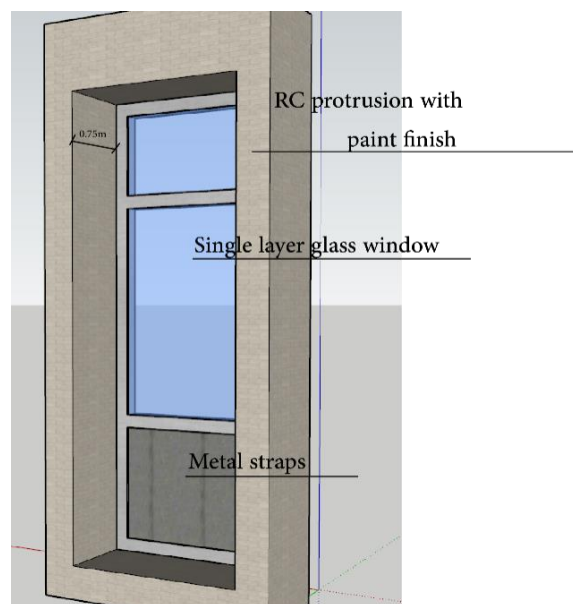


Figure 5. A 3D of a single unit on the façade, showing the existing façade design and materials

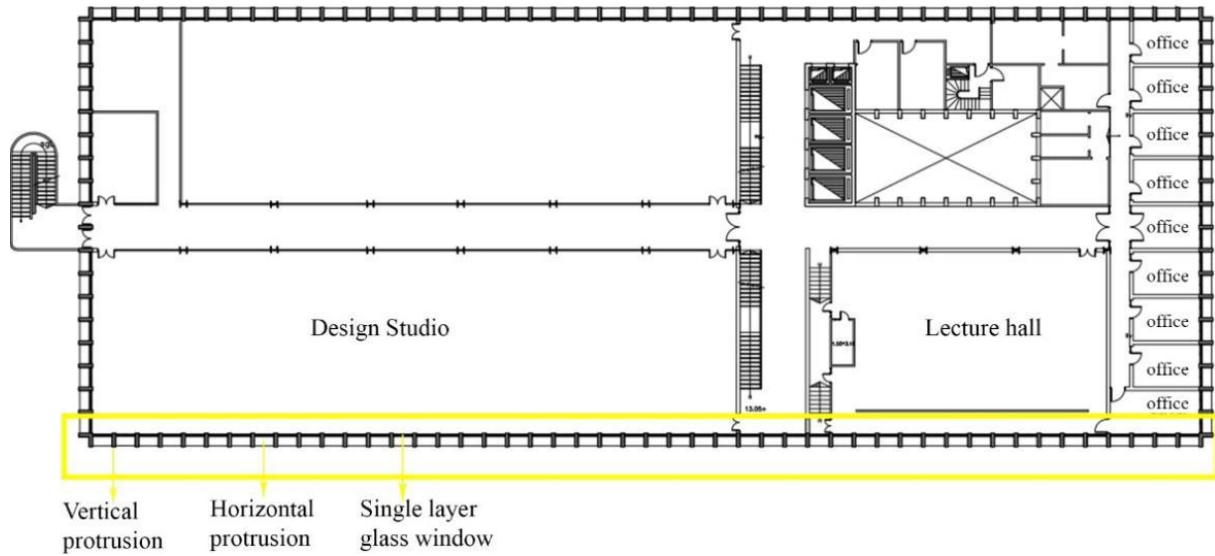


Figure 6. Architectural floor plan for the typical floor, which corresponds to the 3rd floor

3. Result

3.1. Overview

This research focuses on geometry manipulation techniques by modifying the deep horizontal protrusions, which will function as noise barriers. Different slab profiles will be tested using two inclination angles: 5-degree, and 15-degree. The vertical protrusions will remain unchanged to preserve the amount of natural light entering the space, while the horizontal protrusions will not be enclosed by handrails to maintain the main design concept of the façade. To achieve optimal results, it is essential to incorporate sound-absorbing materials, as geometry manipulation alone is not highly effective. Absorbing materials were chosen over scattering materials to avoid creating additional sound wave reflections, which could negatively impact the urban environment, especially in areas where buildings face each other [13].

Several absorbing materials have been proposed, modified, and widely used as façade cladding. These include natural materials, such as green walls, chemically engineered materials like concrete, and recycled materials made from glass or fibers [9], [10], [12], [13], [16], [20].

In this study, two absorbing materials were selected: green walls and coarse concrete tiles, as shown sampling in Figures 7 and 8. These materials were chosen due to their widespread use in modern architecture and their additional environmental benefits. The selection of two distinct materials—one natural and passive, the other chemically engineered—aims to investigate and compare their effectiveness in providing a better acoustic environment inside the building by reducing the noise load on the façade.



Figure 7. An example of green wall cladding is provided, showcasing its application as a natural sound-absorbing material for façades



Figure 8. An example of concrete tiles with wide pores is provided, showcasing their application as a sound-absorbing material for façades

The presence of vegetation on façades, or in other words, green walls, is a common sight—whether intentionally designed or occurring naturally as climbing plants grow on building exteriors. Over the last few decades, green walls have become a popular approach in modern building design. This trend is driven by the numerous environmental benefits of vegetation, such as controlling solar radiation and reducing heat transmission into indoor spaces. Additionally, numerous studies have demonstrated that vegetation and green walls serve as effective

sound-absorbing materials, helping to reduce sound transmission from outdoor to indoor environments [9], [10], [13], [16], [20].

Designed green wall systems have enabled architects to effectively manage the natural elements of vegetation, addressing concerns such as irrigation, water drainage, and future plant growth without compromising the building's structural integrity or the comfort of its occupants. Due to the wide range of designs available, each green wall system features a specific sub-structure that not only supports the vegetation but also acts as an additional sound barrier. The acoustic effectiveness of these systems varies depending on the length and depth of the sub-structure [9], [10], [13], [16], [20].

On the other hand, chemically produced materials such as concrete have been a popular façade cladding choice for architects, particularly in modern architecture, due to their minimalistic yet visually striking appearance. However, concrete is generally not considered environmentally friendly, whether during its production or recycling phases. The acoustic performance of concrete varies depending on its surface texture. Smooth or slightly rough concrete façades tend to reflect sound waves, acting as a reflective medium. In contrast, coarse concrete surfaces function as sound-absorbing materials due to the random air pockets within the concrete, which trap sound waves and reduce their transmission [13], [16].

Additionally, concrete can serve as an effective sound absorber and insulator when mixed with other materials that enhance its noise reduction coefficient. Although concrete is typically preferred for indoor sound control applications, it has also demonstrated promising results in outdoor settings [13].

3.2. Physical Measurements

According to the World Health Organization (WHO) 2018 guidelines, noise levels in educational buildings should not exceed 30 to 35 dB in classrooms to ensure speech intelligibility and effective information extraction [21].

As highlighted in previous studies, middle floors are often more responsive to façade modifications and treatments than lower floors, particularly because lower floors typically feature more façade openings [1], [13]. As a result, physical measurements of the existing Sound Pressure Level (SPL) were conducted on the third floor, which serves as the intermediate floor, as explained earlier in Section 3.

For the physical measurement stage, readings were collected mid-week on a typical school day when traffic density is higher compared to weekends. Measurements were taken with the windows open, which is their usual

state. Data were recorded at four different times during the school day: 10 am, 12 pm, 2 PM, and 4 PM. A TENMARS Sound Level Meter TM-103, with a tolerance of ± 1 dB(A), was used for this purpose, as shown in Figure 9. Figure 10 depicts all the measurements recorded at eight windows across the façade—four in the design studio (on the left side of the plan) and four in the lecture hall (on the right side of the plan). The readings identified 12 PM as the peak hour, with the highest recorded reading at 66.6 dB(A) and the lowest at 63.9 dB(A). The device was placed 60 cm away from the façade, following methods outlined in current literature.



Figure 9. Portable sound meter device

3.3. Validation and Calibration Process

The 3D virtual model was developed as a simulation in which the model is simplified as much as possible by removing extraneous geometrical aspects that have no effect on the simulation results. This reduction in complexity not only decreases the model's file size but also reduces simulation runtime. Additionally, merging and connecting surfaces with identical materials can minimize potential errors during the importing process. These steps are illustrated in Figure 11. This approach also streamlines the data identification process once the model is imported into the simulation software, resulting in a more efficient workflow. I-Simpa provides integrated tools for 3D model correction and approximation, significantly simplifying façade geometry.

The model was imported and organized into five groups using I-Simpa, as simply demonstrated and highlighted in Figure 12. The model is divided into four groups, representing the four fundamental materials: conventional brick, glass, metal, and asphalt. Additionally, there is a fifth group that symbolizes the envelope or box in which the simulation will take place. This envelope has an absorption coefficient of zero for air, creating a closed atmosphere suitable for outdoor simulations.

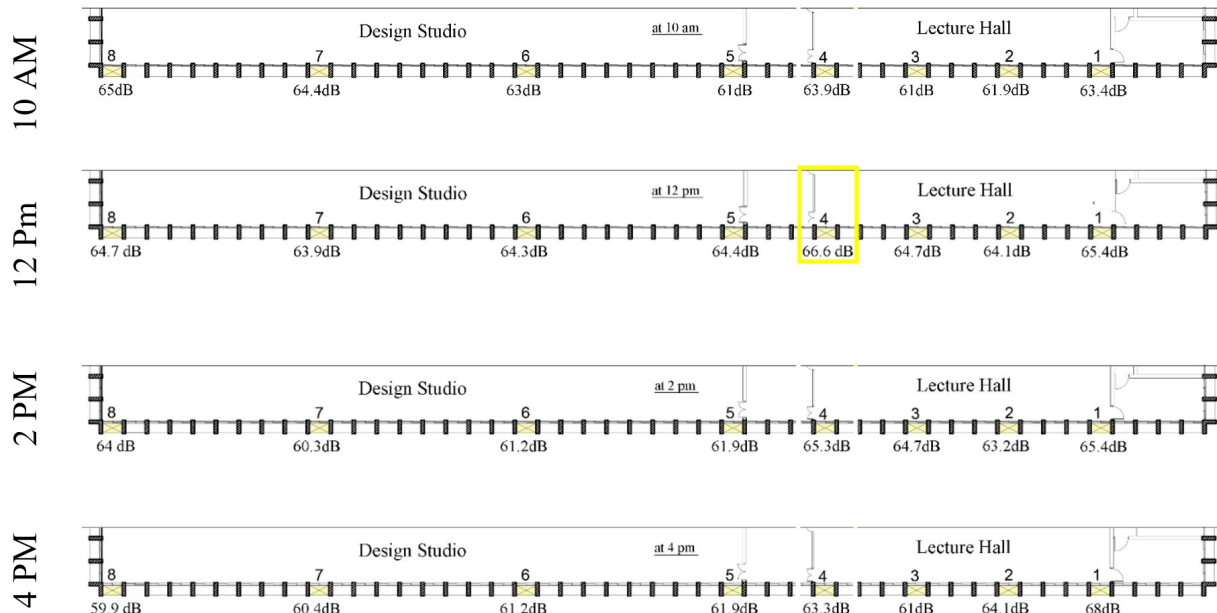


Figure 10. Partial plans depict the readings obtained from eight selected windows at four different times

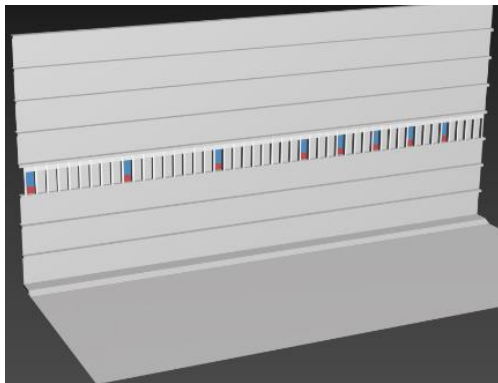


Figure 11. The façade was simplified before being imported into I-Simpa

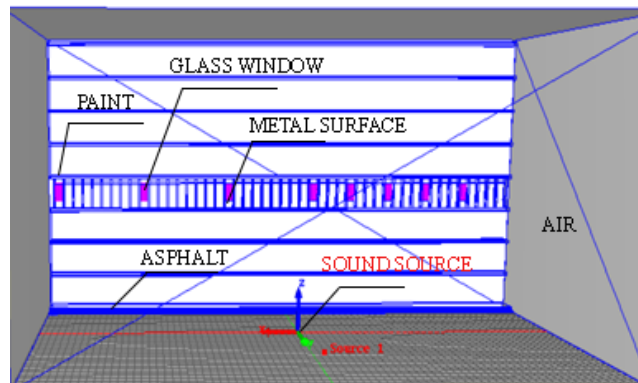


Figure 12. The element selection to add the actual existing materials of the façade

The original building materials used for calibration were added under **Project Data > Materials > Users**, where new materials were created. Each material was manually assigned specific absorption coefficients across different frequencies, based on the data provided in Table (2). Additionally, I-Simpa also allows users to add custom material data by importing text files into the project database.

After positioning the receivers (labeled from Receivers 1 to 8 as green spots) on the selected windows—corresponding to the locations where physical measurements were taken—the sound source was added to the project database. Figure 13 shows the sound source, marked with a red spot, with a sound power level of 82.4 dB(A). The source was positioned 10 meters away from the center of the façade.

To ensure successful calibration, a comparison was made between the physical measurements and the

simulated results. The differences between the two are detailed in Table 3. The comparison was conducted using linear regression analysis and root mean square error (RMSE), yielding a correlation of 87%.

3.4. Simulation Output

3.4.1. The Implementation of Absorbing Materials

The first retrofitting approach involves using absorbing materials as an alternative cladding instead of normal paint. Two different cladding materials were selected and tested based on previous literature: green walls [13] as an example of passive treatment, and coarse concrete [13] as an example of a commonly used building material. Their absorption coefficients, shown in Table 4, were added to the project database. This retrofitting approach was tested by changing only the material of the protrusions around the windows.

Table 2. The imported values of the materials' absorption coefficients used in the calibration process [9]

Frequencies	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000HZ
Standard façade Brick	0.03	0.03	0.03	0.04	0.05	0.07
Glass Ordinary Window	0.35	0.25	0.18	0.12	0.07	0.04
Road Standard Asphalt	0.02	0.03	0.03	0.03	0.03	0.02
Metal Straps	0.05	0.1	0.1	0.1	0.07	0.02

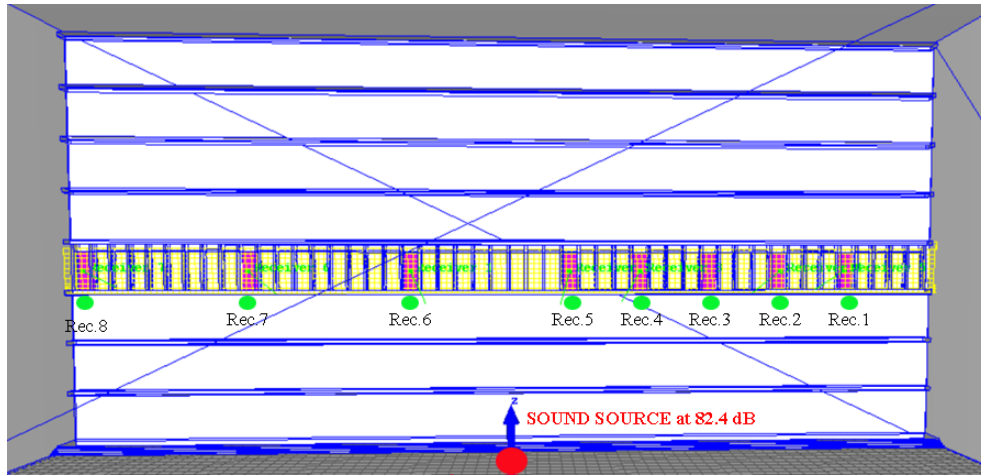


Figure 13. The eight sound receivers were placed on the selected windows, with the sound source placed adequately for measurement

Table 3. Difference in readings between the physical measurements and the calibration (simulated) results

Receivers	Rec.8	Rec.7	Rec.6	Rec.5	Rec.4	Rec.3	Rec.2	Rec.1
Physical Measurements in dB(A)	64.7	63.9	64.3	64.4	66.6	64.7	64.1	65.4
Simulated Measurements in dB(A)	64	64.1	64.3	64.6	66.7	64.5	63.5	63
Difference in dB(A)	0.7	-0.2	0	-0.2	0.1	0.2	0.6	2.4

Table 4. The absorption coefficient of the two selected materials [9], [13]

Frequencies	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000 HZ
Green Wall	0.85	0.85	0.76	0.68	0.68	0.66
Coarse Concrete	0.36	0.44	0.31	0.29	0.39	0.25

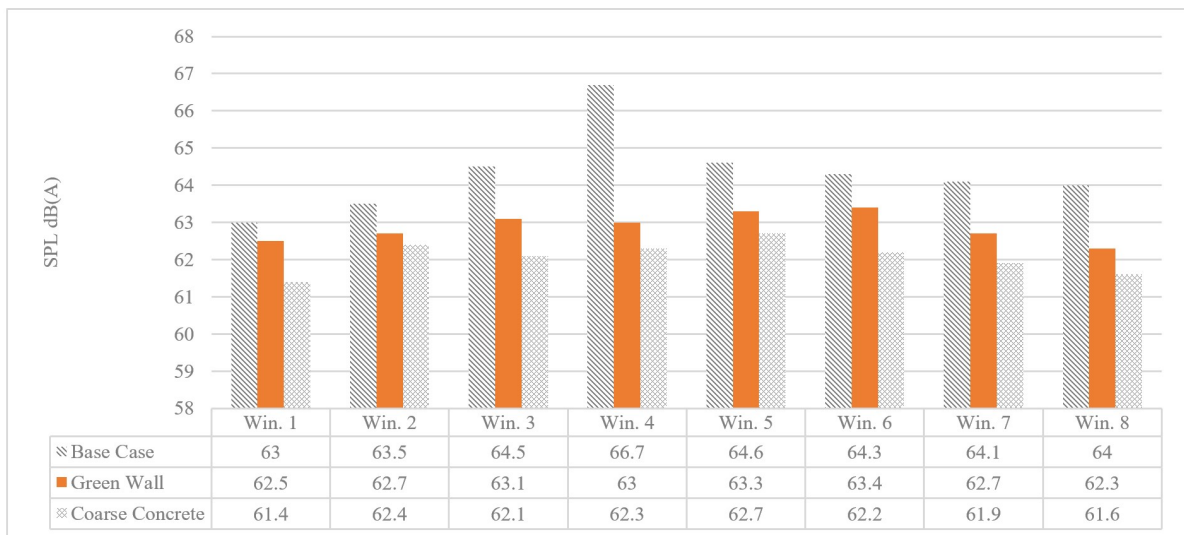


Figure 14. Comparison of only absorbing materials on the protrusion (during the initial scenario)

When comparing the base case results with the application of green walls as façade cladding, a slight reduction in sound pressure levels was observed, ranging from 0.5 to 1.7 dB(A), except at window no. 4, where the noise level decreased by 3.7 dB(A). In contrast, coarse concrete demonstrated superior noise reduction performance, with reductions ranging from 1.1 to 2.4 dB(A), and a notable decrease of 4.4 dB(A) at window no. 4. These results are illustrated in detail in Figure 14. Consequently, coarse concrete was found to be more effective in mitigating noise compared to green walls when used as façade cladding.

3.4.2. The Manipulation of Façade Geometry

The second technique is the retrofitting approach, which involves manipulating the geometry of the façade, as shown in Figure 15, as representing the base case scenario. This is achieved by extending both the upper and lower façade protrusions from 0.75 m to 0.90 m canopy (as shown in the highlighted yellow parts), increasing the depth of the protrusions—a method previously tested by Badino [1]. In addition, the angles of inclination of the upper and lower protrusions were adjusted with two distinct angles assessed: 5, and 15-degrees, as shown in Figures 16, and 17 [1], [5], [8].

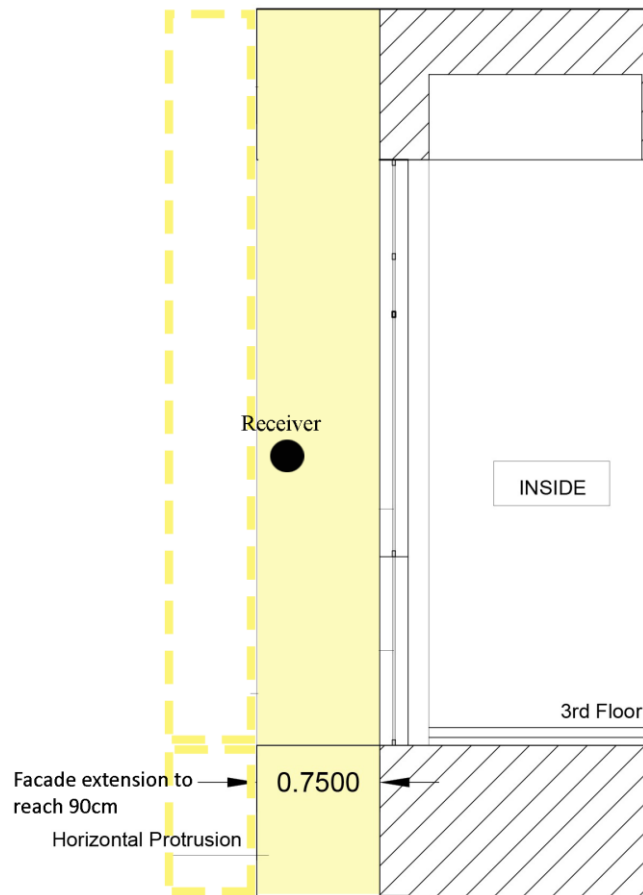


Figure 15. The horizontal RC protrusions were extended by 0.15-meter, increasing their depth from 0.75 to 0.9 meters

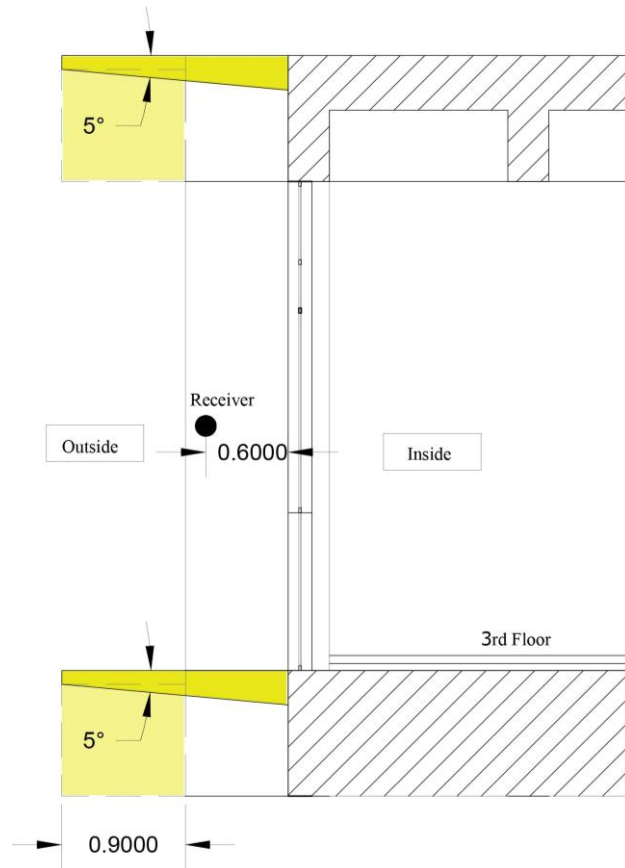


Figure 16. The same feature shown in Figure 16 was applied, along with a 5-degree inclination of the vertical protrusions

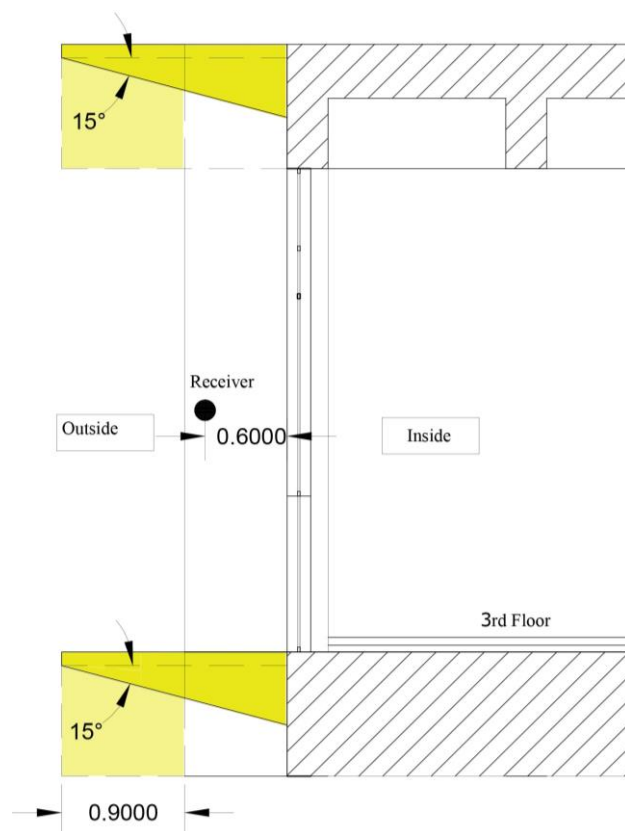


Figure 17. The same feature shown in Figure 16 was applied, along with a 15-degree inclination of the vertical protrusions

When both scenarios are compared, the initial protrusion of 0.75-meter is compared to 0.15-meter extensions, resulting in a total of 0.90-meter. As shown in Figure 18, the data reveal that SPL increased for all windows adhering to the extension, with only the exception of window no.4, which decreased. The increase in SPL ranges from 0.4 to 1.6 dB(A), whereas at window no.4, the value dropped by 1.3 dB(A). This phenomenon results from the trapping of sound waves and increased reflections, which increases the SPL.

The third technique combines two approaches: protrusion inclination and surface material cladding. Figure 19 presents the results of six scenarios, incorporating a 0.9-meter protrusion (after extension) with surface inclinations of 5 and 15-degrees, along with cladding treatments using a green wall and coarse concrete. The findings indicate that greater inclination yields more favorable outcomes compared to the original base case, with sound pressure level (SPL) reductions ranging from 1.4 to 2.8 dB(A).

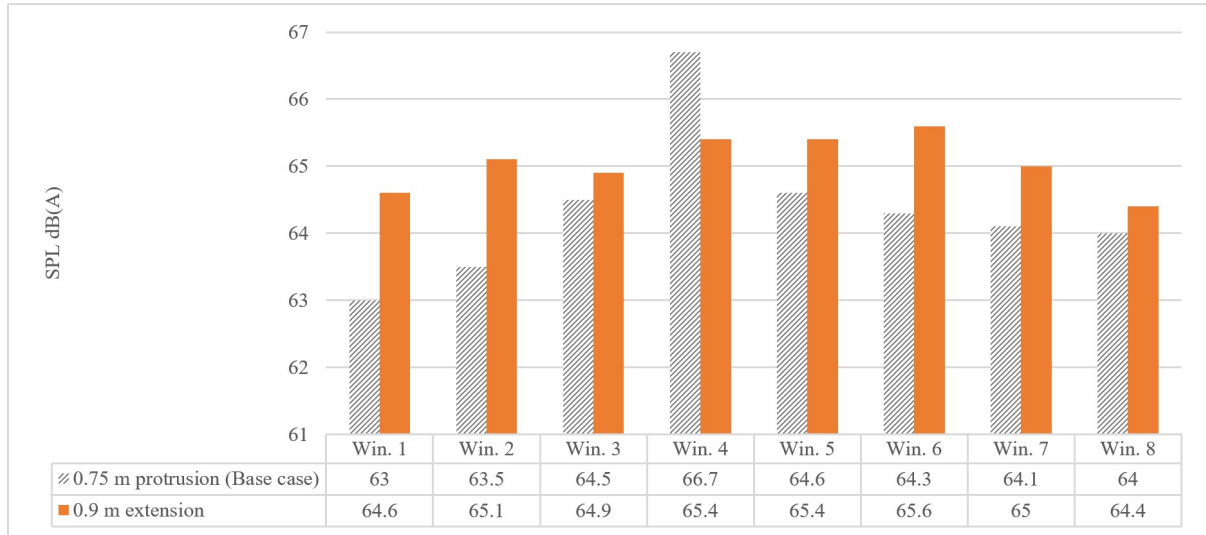


Figure 18. Comparison Between the Initial 0.75-Meter Horizontal Protrusion and the Extended 0.9-Meter Protrusion

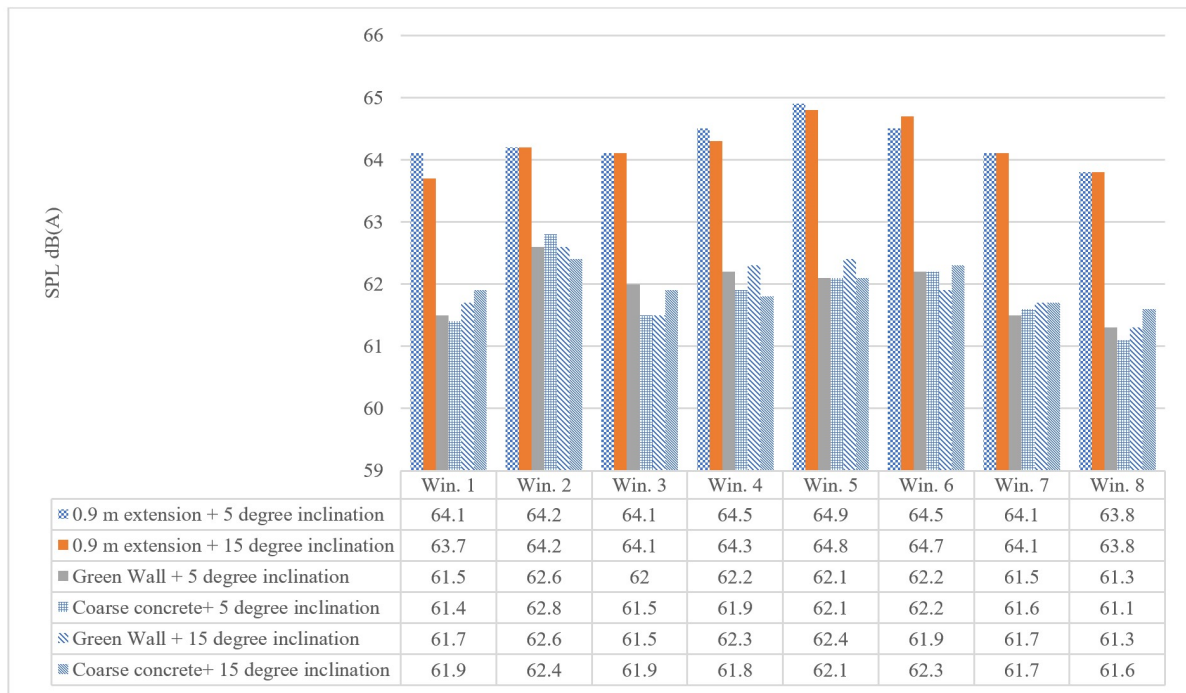


Figure 19. Comparison Between 5- & 15-degrees Inclinations for the Horizontal Protrusion while using Different Material Cladding

Extending the initial 0.75-meter protrusion by 0.15-meter contributed to less favorable results than the original condition, with an SPL increase ranging from 0.4 to 1.6 dB(A). Despite this increase, Figure 19 demonstrates that treatments are more successful at reducing SPL. When comparing the horizontal 0.90-meter protrusion (zero-degree inclination) to the 5-degree inclination, the results show a significant SPL reduction of 0.5 to 1.1 dB(A). Similarly, the 15-degree inclination shows a similar pattern, with decreases ranging from 0.6 to 1.1 dB (A).

When comparing the first two scenarios—5-degree and 15-degree inclinations with a 0.9-meter protrusion—the results indicate that the 15-degree inclination achieves a greater SPL reduction at specific windows: 0.4 dB(A) at window no. 1, 0.2 dB(A) at window no. 4, and 0.1 dB(A) at window no. 5. Both inclinations yield the same reduction values at windows no. 2, 3, 7, and 8. However, at window no. 6, the 5-degree inclination demonstrates a superior SPL reduction of 0.2 dB(A).

When applying green wall treatment as a cladding surface material to the base case scenario with a 5-degree inclination, the results indicate a significant reduction in SPL across all windows, ranging from 1.6 to 2.8 dB(A). Similarly, coarse concrete demonstrates a comparable performance to green walls, with reductions ranging from 1.4 to 2.8 dB(A). When analyzing the 15-degree inclination using the same approach, SPL reductions range from 1.6 to 2.8 dB(A) for green walls and from 1.8 to 2.7 dB(A) for coarse concrete. Figure 19 provides a detailed breakdown of these reduction values.

4. Conclusions

The investigation of three distinct façade retrofitting techniques revealed an impact on noise load; however, none of them surpassed the WHO-recommended 45 decibel threshold. This outcome can be attributed to several factors: first, each window responded uniquely to the retrofitting techniques due to its specific location and the varying number of soundwaves encountered; second, the protrusions' shallow depth of 0.9-meter proved insufficient for effective noise attenuation.

When the green wall is implemented as a cladding surface material with no inclination to 0.75-meter protrusion, the results' corresponding reduction values vary from 0.5 to 1.7 dB(A), with the notable exception of window no. 4, which is 3.7 dB(A). While coarse concrete reduced SPL more effectively than green walls, with values ranging from 1.1 to 2.4 dB(A), window no.4 reduced SPL by 4.4 dB(A). The results demonstrate how coarse concrete is more effective for SPL reduction than green wall at 0.75-meter in depth. However, when the two depths of 0.75-meter and 0.9-meter are compared, it exhibits less successful in SPL reduction; the greater the depth, the more noise it makes. This is due to the accumulation and trapping of sound waves, which results in additional

reflections, causing the sound pressure to intensify. The sound level increases by 0.4 to 1.6 decibels (A).

Using absorbent materials as a retrofitting approach resulted in better results than the original scenario for both inclinations of 5 and 15 degrees, with a maximum SPL decrease of 2.8 dB(A). All reducing values are consistent with earlier research in the same range [1], [3], [4], [12].

5. Recommendations

Retrofitting existing façades to mitigate noise has emerged as a realistic option for keeping buildings functional. However, implementing retrofitting measures post-construction provides challenges, as there is limited flexibility for modifications and innovative enhancements. Furthermore, solutions introduced at later stages often prove less effective in fully addressing the targeted acoustic issues. As a result, prioritizing acoustical comfort from the project's inception is critical to ensuring long-term advantages for building occupants.

Architects and acoustic specialists should emphasize to clients that achieving optimal façade solutions and meeting current requirements do not guarantee the avoidance of future challenges. Rather, the focus should be on enhancing overall performance and proactively considering the building's future interactions with various criteria and evolving conditions, especially in the context of potential urban development.

Façade openings are pivotal in shaping a building's interaction and response to its urban surroundings, acting as gateways that transmit environmental elements into indoor spaces. For buildings situated in high-traffic areas, several factors such as the size, shape, and glazing type of openings—must be carefully considered in design. However, budget constraints on some projects call for innovative solutions. Architects and acoustic specialists can explore design treatments that either employ unique geometries, enabling buildings to self-shield and control noise levels at openings, or integrate sound-absorbing materials seamlessly into the building's original design concept.

Absorbing materials significantly improve sound behaviour and reduce indoor noise transmission without impacting the outdoor environment, unlike scattering or reflecting materials. This makes them an ideal choice for buildings within complexes or those directly facing other buildings, as they effectively control noise without creating additional reflections or disturbances.

Absorbing materials come in various types, shapes, and compositions. For solid materials, acoustic performance is influenced by density, porosity, and surface texture: denser particles tend to reflect sound, while materials with larger pores provide better sound absorption. Examples include certain natural stones and porous concrete, which are affordable, readily available, and durable with minimal maintenance. These materials are particularly effective in

budget-conscious projects, where they can be seamlessly integrated into façade designs for optimal acoustic results.

Green walls as façade cladding not only enhance a building's aesthetics but also provide environmental benefits. However, incorporating green walls requires early planning, as they depend on a specialized sub-structure and specific installation techniques, which can also serve as acoustic barriers. Therefore, it's essential to coordinate and carefully study both the building's main structural system and the green wall sub-structure to align with the architectural façade design. While all green walls require high maintenance to preserve plant vitality and design integrity, some applications demand advanced irrigation and drainage systems, potentially adding to project costs.

Vegetation serves as an effective noise barrier, so maximizing the building's exposure to grass, shrubs, and trees is beneficial. Soil absorbs urban noise to some extent, while dense tree arrangements can significantly block sound propagation, acting as a natural barrier to sound waves. Although trees may not fully block low-frequency sounds like traffic noise, they help diminish mid to high-frequency noise through scattering and absorption, enhancing acoustic comfort in urban settings.

Façade protrusions play a vital role in noise screening, with their size, shape, and depth directly influencing their effectiveness. Deeper protrusions are generally more effective at reducing sound transmission, but the angle of inclination must be carefully planned to avoid reflecting sound waves back onto the building surface. However, these strategies can also limit natural light penetration, necessitating integration with other solutions, like using sound-absorbing materials, to balance acoustic control with lighting needs.

Geometry manipulation in façade design has shown significant potential for enhancing acoustic comfort by enabling configurations that reduce noise load on façades and limit indoor noise transmission, either by redirecting or absorbing sound waves. Achieving optimal acoustic performance requires testing various designs and scenarios to find the most effective configuration. For this approach to be feasible, increased accessibility to acoustic software tools is essential. Encouraging researchers and practitioners to contribute to the development of open-source software can help broaden access and promote real-world testing. This accessibility allows architects and designers to quickly assess the acoustic performance of different façade designs, streamlining coordination between architectural vision and the detailed acoustic input from consultants or engineers during the concept phase.

6. Limitations

When implementing geometrical retrofitting solutions, maintaining the amount of natural light entering space was a concern. Therefore, it was necessary to keep the vertical

protrusions in their original form. To avoid reducing natural light, the depth of the protrusions was limited to 0.9-meter, even though previous studies suggested that a depth of 1.5-meter might have yielded better results [1].

Measurements were conducted with the windows open, as they typically remain in this state due to the building's reliance on passive and natural ventilation as its primary ventilation strategy. Although this approach does not control noise transmission into the indoor space, it could be considered in future studies.

When modeling the façade using external software, there is a risk of losing data and modeled elements during the import stage. Therefore, the model needs to be as simple as possible. It should also be tested and debugged before transferring, ensuring all surfaces are closed and joined. Encouraging developers to add a modeling feature to the simulation software would provide more accurate results. Alternatively, creating plug-ins to link simulation software with other modeling tools would save time during the simulation and modification process, preventing data loss.

Using I-Simpa as a Simulation tool as it is more efficient for simple geometries to achieve optimal results. Although it allows for flexible input of materials' absorption coefficient data, either manually or through text files, the visualization of the model still needs improvement. Currently, imported models are displayed in a very basic manner, leaving room for refinement.

During the virtual simulation, reflections from surrounding buildings, other physical elements, and traffic noise were treated as a single entity to simplify the process. Additionally, wind speed was not considered in the simulation.

Acoustic simulation is an essential tool for predicting sound behaviour in buildings, but it faces several technical, environmental, and design-related challenges. Accurate modeling must address complex geometries, material properties, and real-world environmental conditions. Architects need to carefully balance acoustic performance with other project constraints such as aesthetics, cost, and functionality.

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