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PRACTICAL NOISE IMMISSION MODELING FOR CONCERTS IN STADIUMS: SANTIAGO BERNABÉU - REAL MADRID (SPAIN)

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ABSTRACT

The recent controversy surrounding the cancellation of future concerts at the Santiago Bernabéu Stadium, affecting approximately 250,000 attendees, many of whom came to Madrid from other cities, has generated intense debate. Neighbors in the area claim that "it is a sports stadium, not a space for musical events", and express their complaints regarding the noise generated at these events. With the firm belief that it is possible to address residents' concerns about the development of noise-producing activities in a city, new regulations have been introduced to correct deficiencies in these activities [1]. This project evaluates the impact of these recreational activities on the quality of life of nearby residents and determines whether they follow legally established noise levels. To accomplish this, data collected from in situ measurements will form the basis for simulating the noise affecting residents, verifying the model's accuracy, and suggesting potential solutions.

Keywords: *noise immission, noise modeling, concerts, stadiums*

1. INTRODUCTION

On December 14, 1947, the Santiago Bernabéu Stadium was officially opened with a friendly soccer match as the new Real Madrid Stadium. Today, almost 80 years later, Real Madrid´s president Florentino Pérez claims that "We are in the final phase of meeting the great challenge that Real Madrid set itself five years ago: that the Bernabéu stands as a universal avant-garde icon and an architectural emblem of Madrid. It is the most iconic stadium in world football" [2]. Addressing the impact of the stadium's latest renovations.

In addition to providing a new aesthetic, the renovation also increased the stadium's capacity to 80,000 people and opened the door to new events such as recurring concerts. In 2024 alone, the stadium held more than 15 major concerts, each drawing around 65,000 attendees [3], the maximum allowed for these events. However, it is important to remember that Bernabéu is located in Chamartín District, a predominantly residential area, which is also an environmentally protected zone [4]. These events disturb the lives of local residents because noise affects their well-being and causes significant annoyance.

In the past, sound systems engineering for musical events focused on sound quality in the audience. There has been an increase in these events in stadiums along with complaints from nearby residential neighbors. Some novel and recent methodologies have contributed to addressing this major concern, linking complex loudspeaker systems to outdoor environmental propagation and working with detailed data of sound systems, stadiums, and surroundings for open-air events, as in [5, 6]. The current prediction tools do not provide right-away models to fill this gap. Environmental classical noise sources, such as road and train radiation, which are decorrelated, are significantly different from those of sound systems, which

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are coherent and highly directional acoustic sources [6]. There is a significant need to plan the environmental impact of these modern scenarios and reach the expected immision noise levels that comply with local regulations [6, 7].

However, some stadiums can be considered semi-closed rooms. Hence, the walls of the stadium do not behave as acoustic barriers, as in open-air events, and there is remarkable acoustic leakage through the walls. Real Madrid's stadium is located in a dwelling area and brings environmental conflict with its dwellers. This leads to a significant lack of relevant data regarding sound systems and building of insights.

This study proposes a practical methodology for modeling noise immision for concerts in semi-closed stadiums with sparse data and moderate resources but with accurate field measurements performed at the neighbors' façades.

The remainder of this paper is organized as follows: Section 2 explains the materials and methods, Section 3 discusses the results, Section 4 suggests mitigation solutions, and Section 5 presents the conclusions.

2. MATERIALS AND METHODS

This paper proposes a practical methodology that can contribute to predicting and finding solutions to highly complex problems. We work on a particular case: Real Madrid's stadium. However, the same approach can be applied to similar stadiums and musical events. Sparse data are a major drawback in these cases because it is common to encounter conflicts with victinity residential buildings and even non-compliant noise radiation according to local regulations. Hence, obtaining insights from stadiums such as loudspeaker setups and construction plans is rare. Our approach consists of the following steps.

1. **Field noise measurements**. We used noise measurements at keypoints/receivers to assess the scenario and obtain valuable data for modeling.

2. **Noise immision modeling**. We modeled the scenario using public data from the stadium and its surroundings, along with sound acoustical assumptions.

3. **Validation of the model**. We made measurements and modeling meet ends and provided a tool to evaluate current and future scenarios.

4. **Analysis of results**. We provided stakeholders with solutions to consider a range of challenges.

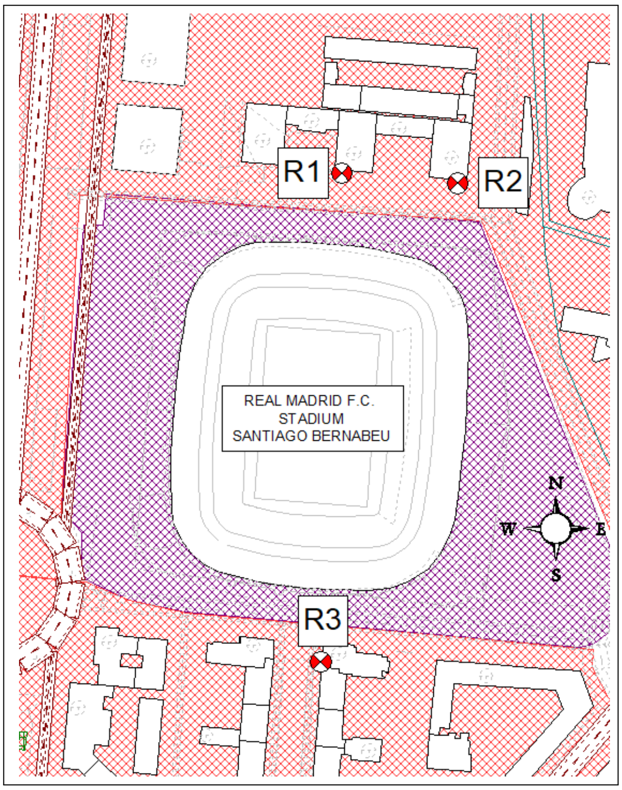

Figure 1. Location of the three receivers situated on the northern and southern sides of the stadium and the areas' land use (The red being residential and purple being recreational).

2.1 Field noise measurements

A noise monitoring campaign was conducted in the outdoor environment on 20th July 2024, the day when Karol G's concert took place. Measurements were taken every 5 s, including the indices required by RD1367/2007 [8] and the local law [1] (L_{Aeq}, L_{Ceq}, L_{AIeq}, and the spectrum in one-third octaves from 20 Hz to 10 kHz). The recordings covered the periods before, during, and after the concerts, allowing for the analysis of noise from activity (music) and noise without activity (no music).

Measurements were performed using 01 dB sound level meters, type SOLO, Class 1 equipped with third-octave filters compliant with the IEC 61672-1 Class 1

Figure 2. View of the microphone on the façade from a house in the vicinity of the stadium.

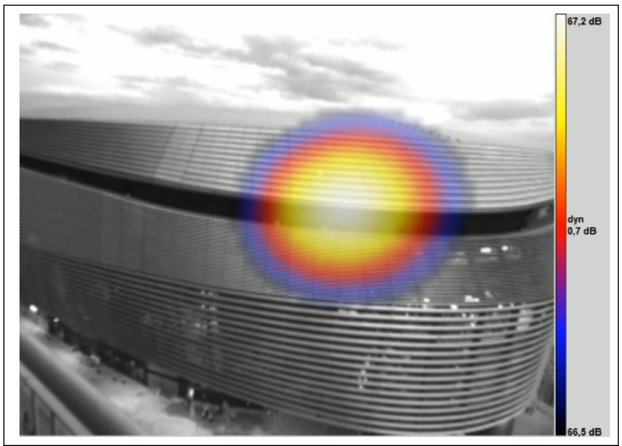

Figure 3. Visualization of the noise radiated from the stadium with an acoustic camera (Soundcam 2 Cae Systems).

standard [9]. A Rion NC74 sound calibrator that meets the IEC 60942 Class 1 standard [10] was used before and after the measurement campaign. All measuring instruments, including sound level meters and acoustic calibrators, have type approval and periodic verification in accordance with the Spanish law (ITC 155/2020 order) [11]. The measurements were performed simultaneously in multiple homes surrounding the Santiago Bernabéu Stadium.

For each sound level meter, the measurement microphone was placed outdoors, 2 m from the façade, using a telescopic pole and microphone extension cable. This positioning minimized the sound reflected by the façade. Each unit was located in one apartment; therefore, we were able to obtain the variability of sound levels at different heights from the street floor. The exact location is not detailed enough to maintain confidentiality and to comply with the Data Protection Act. Fig. 1 shows the locations of all receivers, that is, measurement points, from the stadium; the upper receivers R1 and R2 are on the northern side of the stadium and receiver R3 is located on the southern side.

2.2 Noise inmission modeling

The acoustic modeling was performed with Cadna A (Version 2025, DatakustiK), one of the leading softwares for calculation, presentation, assessment and prediction of environmental noise. Some software configurations worth highlighting: CNOSSOS-EU [12] is the propagation model for estimating L_{Aeq} for the moments of maximum noise impact according to the required limits. The stadium noise was modeled using horizontal surface sources for the ceiling and vertical surface sources for façades. These sources had different assigned values for the northern, southern, eastern, and western sides, and their values were specifically adjusted to those measured with sound level meters. The sound powers of these surface sources were adjusted in the frequency domain at the receivers.

We also incorporated traffic data assigned to each of the surrounding roads, setting up their average daily traffic densities (MDTD). The evaluation of traffic noise is based on the ambient noise scenario in the vicinity of buildings when there are no concerts, thus observing a large difference in levels between the two scenarios: 1) when only traffic noise was present, and 2) when there was only concert music.

Table 1. Model's Validation comparing the measurements results with the prediction value obtained by the model, L_{Aeq} dBA.

	Measurements L_{Aeq} dBA	Model L_{Aeq} dBA	Deviation (dBA)
R1	80	78,2	-1,8
R2	77,6	77,5	-0,1
R3	72,3	72,4	-0,1

2.3 Validation of the model

The validation consisted of comparing the prediction of the outdoor propagation model with the measurements using the same source and evaluation points. The sound levels of the noise sources involved in the model were conveniently adjusted to fit the measurements. Eventually, the deviations between both L_{Aeq} values were adequate to provide a valuable predictive model (less than 2 dBA), as shown in Tab. 1, thus validating the model. In Fig. 4 and Fig. 5, we observe the spectrum on both the north and south sides of the stadium.

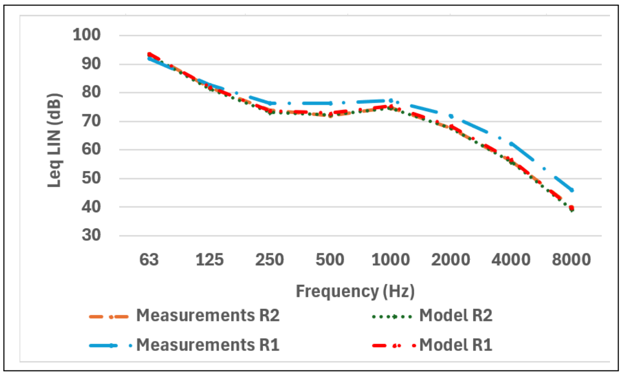

Figure 4. Spectra of measured and simulated levels in the northern side (Reveiver R1 and R2).

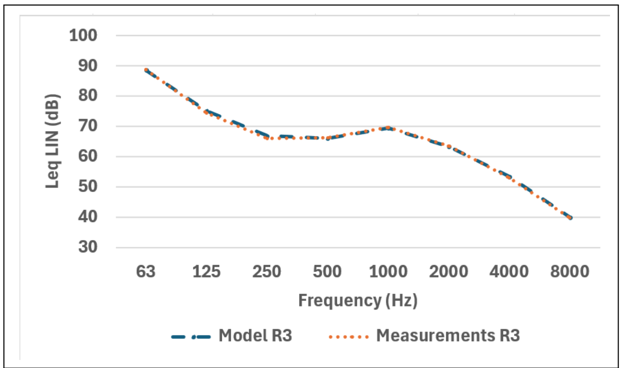

Figure 5. Spectra of measured and simulated levels in the southern side (Receiver R3).

During this project, we faced certain limitations, including a lack of access to the stadium or its construction plans, which restricted our ability to study sound propagation inside and near façade openings where sound leaks. The modeling was performed using surface sources with three validation receivers placed at different heights.

3. RESULTS

To assess compliance with noise regulations during the concert, land use in this area must be considered. Most of the study area is considered residential by the Madrid City Council, except for the area where the stadium is located, which is considered recreational and has its own limits. Fig. 1 shows the purple area, which is the recreational zone, and the red area, which is the residential zone. Since 1997, the stadium's surroundings have been declared an environmental protection area by the Madrid City Council, meaning that the limits should be restricted to 5 dB more than the rest of the acoustic areas [4]. This indicates that it is a noise-sensitive area owing to the amount of activities currently taking place and is considered a noise-saturated area.

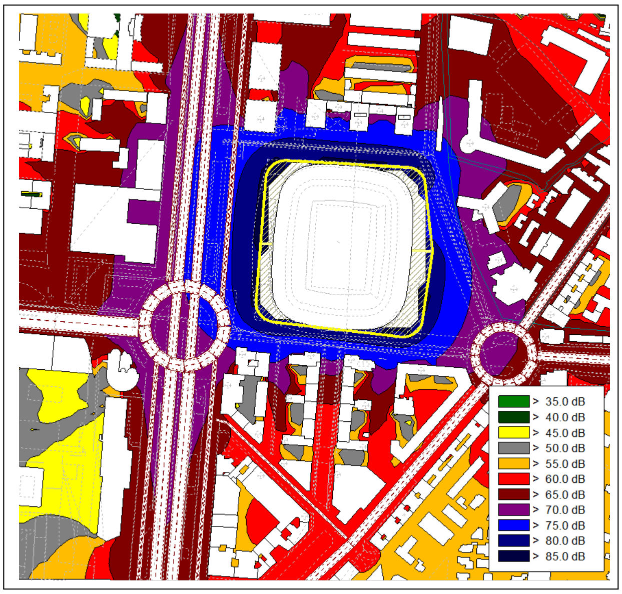

Figure 6. Global horizontal noise map of the area, including traffic and concert noise at 21 m height.

After simulating the noise map of the area shown in Fig. 6 shows how the problem impacts the whole neighborhood, not just the ones closest to the source, putting everyone at risk. Noise limits are exceeded in residential areas, at least within a 500-meter radius of the stadium center in the evening, and at night, they are exceeded at distances greater than 1 km. The "front line" buildings surrounding the stadium are receiving more than 70 dBA or 75 dBA, as seen in purple and blue on the map in Fig. 7. The area shown in red has noise levels higher than 60 dBA, which is the majority of the area whose levels exceed the legal limits established by law.

The simulated value is $L_{Aeq,5s}$, but we must consider 6 dB extra, owing to tonal and low-frequency components (there were no impulsivity components) in accordance with Article 15 of the Madrid ordinance [1], for the evaluation of $L_{Aeq,5s}$, which becomes $L_{Keq,5s}$. This can be observed in Tab. 2, as well as the extent to which the noise levels were exceeded at the receiver points compared with the limits in the evening and at night, when the concert took place. As can be observed, none of the points complies with regulations.It is worth mentioning that the current legislation establishes maximum noise emission limits because it is scientifically proven that exceeding these levels directly affects the health of people exposed to these noises.

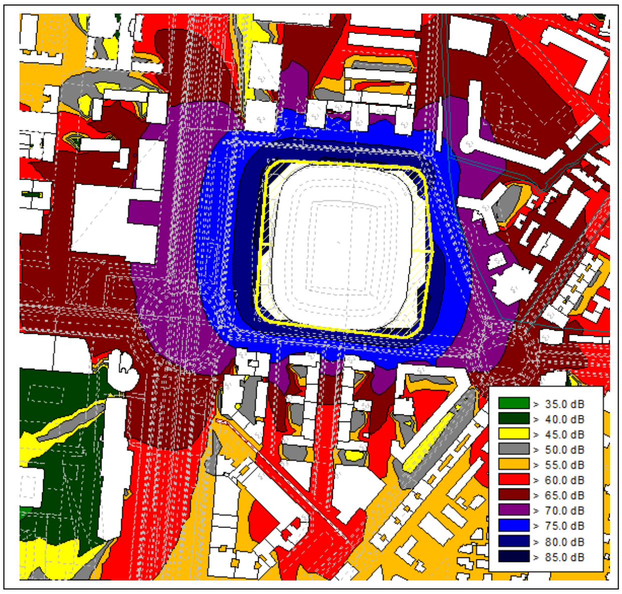

Figure 7. Horizontal noise map: ONLY concert noise at 21 m height.

In addition to modeling the concert, a simulation was conducted only in the area on concert days, considering the traffic of nearby streets. The streets surrounding the stadium, Rafael Salgado and Padre Damian Streets, and Concha Espina Avenue are not simulated, as traffic suffers a cut off during concerts. However, large avenues, such as Paseo de la Castellana, have constant traffic that contributes to global noise levels. As mentioned previously, we simulated roads in the area setting in Cadna A,

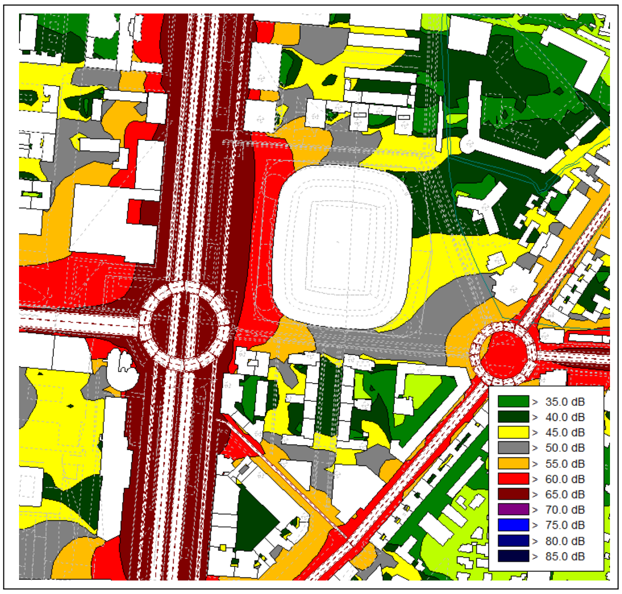

Figure 8. Horizontal noise map: ONLY traffic noise at 21 m height.

each with its traffic limit and MDTD capacity, to obtain the sound levels produced by them. As a result, we observed that Fig. 7 and Fig. 8, where we can clearly see a difference in the noise levels in the area.

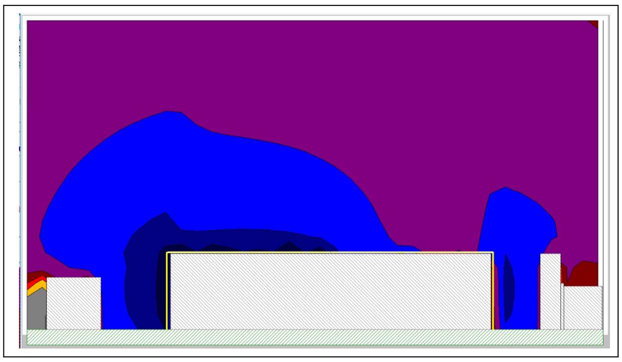

Figure 9. Vertical noise map during the concert.

In Fig. 7 we can observe how the front row of buildings functions as a barrier, reducing the noise observed in the vertical noise map in Fig. 9, which is a longitudinal cut along the z-axis perpendicular to the floor that crosses the stadium from North to South. Noise propagation from the middle of the stadium is shown in the middle of Fig. 9, towards the residential buildings located North and South

Table 2. Comparison of measured levels with legally authorized limits and the degree to which they were exceeded, both in the evening and at night.

Receiver	Measurements L_{KAeq} (dBA)	Limits Evening/Night (dBA)	Exceedance (Evening, dBA)	Exceedance (Night, dBA)	Compliant?
R1	80 + 6 = 86	55 / 45	31	41	No
R2	77,6 + 6 = 84	55 / 45	29	39	No
R3	72,3 + 6 = 78	55 / 45	23	33	No

(right and left sides of the figure). In Fig. 9 we observe that most of the acoustic energy is radiated by the vertical façades and roof of the stadium.

Although we do not know the exact speaker configuration at the concert, we do know that the stage was located near the southern side, facing North. Hence, northern sound sources are more powerful than southern ones. Furthermore, the ”front line” buildings act as acoustic barriers for more distant buildings, as shown in Fig. 9 we can see the gray area behind the building on the right, showing lower noise levels. However, horizontal maps have shown that noise from the stadium spreads through the streets perpendicular to the stadium, affecting most of the neighborhood.

In Fig. 8, just modeling with traffic noise, there are many more green areas, indicating noise levels of approximately 35 dBA; however, we can also observe yellow, gray, and orange areas, indicating meaningful noise levels between 45 dBA and 55 dBA. Tab. 3 shows a comparison of the sound levels reaching receivers R1, R2, and R3, modeling concert, and traffic, separately. With no concert, the receivers do not exceed the limits, whereas when simulating a concert, traffic noise barely affects the level received by the receivers.

Table 3. Comparison of traffic noise and concert sound pressure levels, L_{Aeq} dBA, during the concert by the prediction software.

	R1 L_{Aeq} dBA	R2 L_{Aeq} dBA	R3 L_{Aeq} dBA
Concert	78,2	77,5	72,4
Traffic	52,8	45,3	43,1

4. NOISE MITIGATION PROPOSAL

Looking at Fig. 4 and Fig. 5, we can observe that the problem is focused on low frequencies. The 63 Hz and 125 Hz bands have the highest levels, whereas the 8 kHz band has the lowest levels. Low-frequency noise causes vibrations that can cause discomfort among neighbors, thereby increasing their perception of noise (window vibrations).

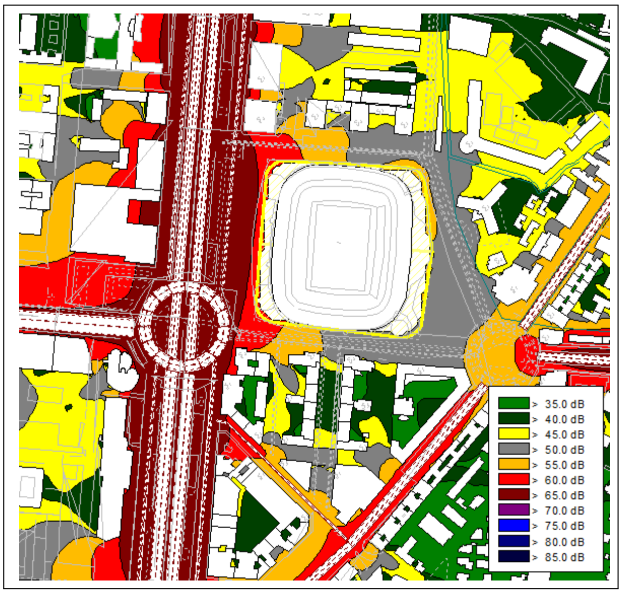

Figure 10. Noise map including corrective measures on the façades of the stadium and roof at 21 m height.

To lower the sound level of the show was first considered. In another concert (Aventura), after months of complaints from neighbors about noise, a test was conducted during the event. It was found that this could not solve the problem; it only frustrated the attendees, who claimed that ”they could not hear the music properly.” Therefore, it is necessary to provide solutions that reduce the noise

Table 4. Levels at the receivers after the proposed mitigation solutions and its compliance in the evening and at night.

	L_{Aeq} dBA	Evening Compliance	Night Compliance
R1	54,6	Yes	No
R2	51,8	Yes	No
R3	45,8	Yes	No

level approximately by about 30-40 dBA. After modeling several mitigation options, Fig. 10 shows the results of the simulation of an adequate solution. By acting homogeneously on the façades of the stadium, we obtained a decrease of 30 dBA, setting-up 30 dB transmission losses on the vertical surface sources. The same procedure was used on the roof, but the sound power was lowered 10 dB, setting-up 10 dB transmission losses on the horizontal surface sources.

In Tab. 4, the levels obtained at the receivers after applying the aforementioned modifications can be observed. As shown, these levels manage to comply with legal limits in the evening; however, at night, they are still noncompliant. Since it may be difficult to further increase façades' attenuation to comply with the more restrictive nighttime limits, we suggest considering modifying the schedule of the next stadium concerts that will take place during the evening hours.

5. CONCLUSION

In short, the noise levels generated by concerts in the stadium exceed what is permitted and healthy, and it is not a situation that can be sustained. A series of on-site measurements were taken at Karol G's concert, allowing for the creation and validation of a model in which the measurements and predictions match. Noise limits are exceeded in residential areas, at within a 500-meter radius of the stadium center in the evening and even more at night. As a problem that affects both the well-being and the inconvenience in the daily lives of the residents of the area, an improvement in the insulation of façades of the stadium by approximately 30 dB and the consideration of a new concert schedule are proposed to avoid exceeding these levels. This model can be used to directly incorporate the attenuation values obtained from façades and immediately obtain the expected emission values from nearby homes.

We encountered several limitations in accessing detailed information on the stadium's structure, which would be interesting to have more in order to create a simulation that better fits the existing openings and façade, as well as the sound insulation characteristics of the roof. It would also be useful to obtain the information necessary to simulate the transmission of the electroacoustic system during a concert, to consider the diffraction of linear arrays, and to gain a better understanding of how sound is transmitted from the inside of the stadium to the outdoor environment.

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