VIRTUAL ACOUSTICS OF THE ROMAN THEATRE OF REGINA TURDULORUM

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ABSTRACT

Plinius ascribes the town of Regina (Casas de Reina, Badajoz) to the old region of *Beturia* under the rule of the district of *Corduba*. Its Roman theatre is almost perfect according to the canon rules and has been kept in an excellent state, both in its tiers and in its stage. In this work, the theatre is studied by means of acoustic simulation, which responds to the classical schema: *cavea*, *orchestra*, *scenae*, and a capacity of up to 1,000 spectators. Throughout this paper, an analysis is performed on the creation, adjustment, and validation process of the 3D model of the theatre for the simulation of its sound field, which is based on the experimental measurement of reverberation time. Once validated, the initial model is modified in order to assess the acoustic impact of various proposed interventions.

RESUMEN

Plinio adscribe la ciudad de Regina (Casas de Reina, Badajoz) a la antigua región de la *Beturia* bajo la autoridad del convento jurídico de *Corduba*. Su teatro es casi canónico y se conserva en excelente estado, tanto en gradas como en el frente escénico. En este trabajo el teatro se estudia mediante simulación acústica el cual responde al esquema clásico: *cavea*, *orchestra*, *scenae*, y un aforo de hasta 1000 espectadores. A lo largo de la comunicación se analiza el proceso de creación, ajuste y validación del modelo 3D del teatro para la simulación de su campo sonoro, apoyado en los ensayos experimentales del tiempo de reverberación. Una vez validado, el modelo inicial se ha modificado con objeto de evaluar el impacto acústico de varias intervenciones propuestas.

INTRODUCTION

Greek and Roman theatres are the only monuments of classical antiquity that, in some cases, serve the purpose for which they were originally designed: as places to perform theatrical performances. These public buildings were of major importance in the Greek and Roman eras.

Although most of these constructions are located in the Mediterranean area, they were built in the major cities of the ancient world not only in Europe, but also in the Middle East, North Africa and beyond. On an east-west axis, they extend from Alexandria of Oxo (today Ai Khanum, Afghanistan), on the threshold of the Indian subcontinent, to Lisbon, and, on a north-south axis, from the Roman colonies in England to Ptolemais in southern Egypt [1].

To date, 744 structures of ancient theatres have been identified and documented (Figure 1), of which 194 correspond to Greek theatres, while 425 theatres and 46 odeons belong to the Roman era; of the remaining 76, their precise Greek or Roman origins remain unknown. These theatres comprise a simple structure consisting of a large void where spectators sat (*cavea*), an intermediate zone where the action took place (*orchestra*), and the stage area (*scena*). In all probability, these buildings provide the first examples of how architectural acoustics themselves can sustain and improve oral and even musical communication in places of major capacity, thereby allowing a perfect reproduction of the dialogues for more than 10,000 spectators [2].

Figure 1. Theatres in Antiquity in Europe and north of Africa.
(*Ancient Theatre Archive. http://www.whitman.edu/theatre/theatretour/home.htm).*

Ever since Vitrubio [3] in the 2nd century BC, there have been numerous studies on the acoustics of both Greek and Roman classical theatres. It should be noted that the Greek theatre of Epidaurus (Greece) and the Roman theatre of Aspendos (Turkey) have been the focus of the majority of these studies. The techniques employed range from a basic interpretation of the sound propagation made by Vitrubio, to the modern computer techniques that, by means of acoustic simulation, model these theatres. In this context, the ERATO project [4] should be highlighted, which was financed by the European Union and lasted three years. One of the objectives of this project was to investigate the acoustics of outdoor theatres and odeons. To this end, virtual reconstructions were carried out using computer models of these spaces, which remained faithful to the archaeological information available thereof. In addition, this project implemented auralisations of a number of theatres by using musical instruments and musical pieces of the time. The aim pursued was none other than the development of conservation and restoration of architectural heritage that takes into account its acoustic characteristics.

Along the lines of the study developed on the acoustics of the Roman theatre of Italica [5], the 3D acoustic model has been created in this work, using the software CATT-Acoustic v9.0c, of the Roman theatre of the archaeological complex of Regina, municipality of Casas de Reina (Badajoz, Spain). The model has been adjusted based on the measurements made in situ of the reverberation time, and the influence of the dispersion coefficients of its surfaces are analysed for its validation.

THE CITY OF REGINA

Baeturia was a large territory located in the southwest of the Iberian Peninsula, and accurately defined by Pliny in his Natural History [6] as "the territory between the rivers Baetis (Guadalquivir) and Anas (Guadiana)". In this territory, two parts were known, one occupied by the Celts (Baeturia Celticorum) and another by the Turdili people (Baeturia Turdulorum). Located in the western zone, the Baeturia Celticorum bordered Lusitania and judicially depended on the conventus hispalensis. Baeturia Turdulorum, bordering both Lusitania and Tarraconense, judicially depended on the *conventus cordubensis.* In this territory, Plinio [7] includes six cities defined as "oppida non ignobilia" (populations that are still notable), one of which is Regina.

Regina is mentioned in Roman times in the itinerary of Antonino as "mansio" of the road that linked Emerita Augusta and Astigi (Figure 2).This provided one more way to reach Hispalis or Corduba [8], and this route (via X of Antonino) indirectly connected the capital of Lusitania with the capital of Betica. The city of Regina is located about 2 km east of the town of Casas de Reina and lies within its municipal area, in the current southern countryside of the province of Badajoz.

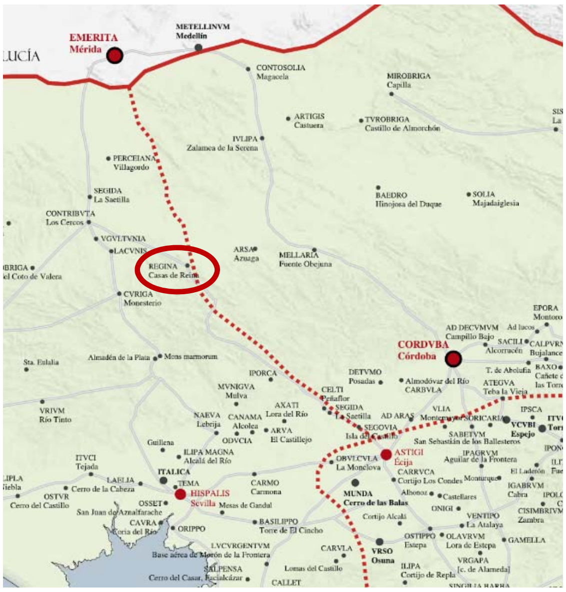

Figure 2. Network of ancient roads around Regina. (Atlas of the History of the Territory of Andalusia, Atlas of Andalusia, Institute of Cartography of Andalusia, Junta de Andalucía).

THE ROMAN THEATRE OF REGINA

The archaeological site of Regina, called "Los Paredones" by the locals, has been under investigation since 1978 [9], during which time its theatre, the main preserved monument, has been discovered. Work carried out has enabled the recovery of an exemplary building of the Hispano-Roman architecture of the second half of the 1st century AD, in a good state of conservation.

The theatre is the most emblematic building of ancient Regina (Figure 3). It is located at the north-western end of the city [9], on a gentle slope on which a good part of its cavea rests. It has a northeast orientation. The construction is made entirely of lime and stone mortar, *opus caementicium*, and the face of the whole work of *opus incertum*. Its cavea is composed of ten rows of sandstone seats, of which the first three, part of the fourth and some areas of the fifth row are preserved (Figure 4). The first step forms a kerb as a footrest. The grandstand is divided into four *cune*i (wedges) by three staircases. The total capacity of the cavea could be eight hundred spectators. In the high area there would probably have been a wooden stand or the space could simply have been crowned by a portico. Altogether, the *cavea* offers a total diameter of 53 m. The orchestra presents an almost semicircular floor of 16.40 m in diameter. The *proscaenium*, made of *opus incertum*, has a thickness of 1.17 m and an average height of one metre. The p*ulpitum* is 45 m long and 6 m wide. The stage consisted of a wooden platform supported by pillars symmetrically distributed at the base of the *hyposcaenium*. *The scaenae frons,* 39.40 m long, has a base, also in *opus incertum*, on which the columns supporting the entablature are arranged. In the wall of the *scaena*, three vaults open by which the actors entered.

Figure 3. Excavations in the campaign of 1980. (*J.M. Álvarez Martínez. Proceedings of Symposium: El Teatro Romano en la Hispania Romana. El Teatro de Regina. (1982)).*

Figure 4. State of the *cavea* before its rehabilitation.

The theatre of Regina, according to the data provided in its excavations [9], was abandoned from the middle of the fourth century AD. As for its date of construction, both for the structure of the building and for certain constructional details, it can be located in the Julio-Claudia era, in the time of Claudio-Nero, in the second half of the first century AD [9].

Figure 5. Current status during the performance of acoustic measurements.

In December 2013, a rehabilitation project was carried out on the stands (Figure 5), whereby they were reconstructed with a metal structure upon which a polyester sheet was placed that reproduced the shape and roughness of the stone. The theatre is currently in use, and the performances of the Regina Theatre Festival have been held for many years, the 11th edition in August 2015, in collaboration with the International Classical Theatre Festival of Merida.

EXPERIMENTAL METHOD

Measurements were carried out on the theatre without the presence of any public (Figure 5). The environmental conditions were monitored by measuring temperature (18º to 20ºC) and the relative humidity (50% to 60%), and the recommendations of the ISO [10] were followed. Although the wind speed was not monitored, the slight intermittent gusts were an inconvenience when recording impulse responses (IR).

The process of generation of the frequency exponential sweep signal to excite the theatre, and the acquisition and the analysis of IRs were carried out with the Dirac 5 programme through the Edirol UA-101 sound card. The signal generated was emitted by the AVM DO-12 dodecahedral source with a B & K 2734 power amplifier, for three positions of the source located at 1.50 m above the floor of the *proscaenium* (2) and in the *orchestra* (1). These signals were recorded at 18 reception points (Figure 6), distributed across the *cavea* (11), the *proedria* of the orchestra (5), and the *proscaenium* (2). The monaural IRs were collected using an Audio-Technica AT4050/CM5 multipattern microphone (omnidirectional and figure-of-eight) connected to a 4-channel Sound Field SMP200 polarization source. The binaural IRs were obtained with a Head Acoustics HMS III torso simulator (Code 1323) and the B&K-2829 micro-polarization source. In all cases, the microphone was placed 1.20 m from the ground.

ACOUSTIC MODEL AND SIMULATION

The acoustic simulation was carried out using the CATT-Acoustic v9.0c programme [11], based on geometric acoustic algorithms. The model was built using the available graphic documentation and the data collected in situ. For the geometric survey, a three-dimensional model was generated by the SketchUp programme, and finally exported to CATT-Acoustic through the SU2CATT v 1.3 plugin.

Results were obtained with the calculation engine TUCT v1.0h (The Universal Cone Tracer), which calculates the acoustic parameters from energy (E) and/or B-format and binaural impulse responses (h) based on the evaluation of sound pressure. Specifically, algorithm 2 has been chosen. The geometrical model, consisting of 1,588 plans, has dimensions of 62.7 x 40.7 m^2 in plan view and a height of 9.40 m, which would enclose a volume of 13,000 m^3 (under the imaginary plane that rests on its vertical limits), with a total surface of 6,307 m^2 (Figure 6a).

In order to adapt the acoustic conditions of the simulation to those of the real situation, the model has undergone an iterative tuning process in which the absorption and dispersion coefficients of the least known materials are adjusted. The process is concluded when the simulated reverberation times, spatially averaged in each octave band, differ by no more than 1 JND (5%)

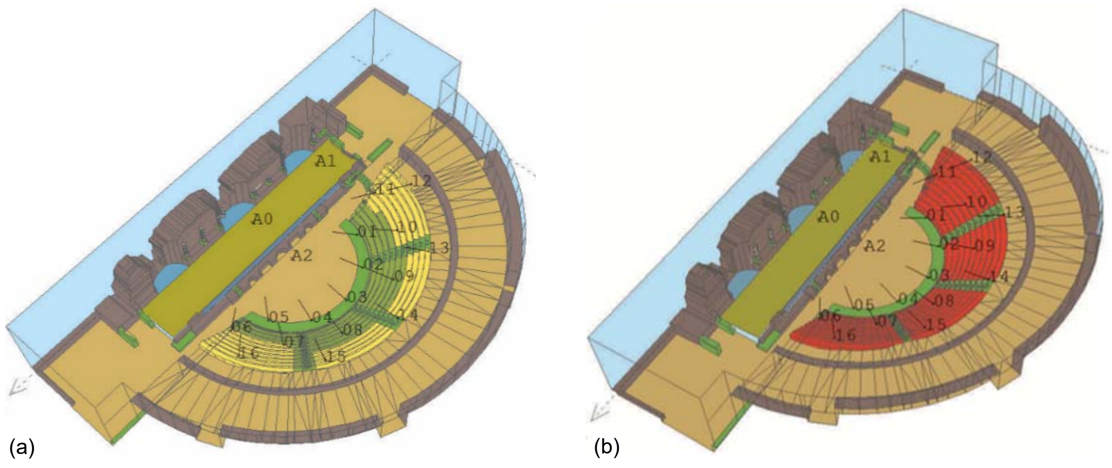

Figure 6. Computer model of the theatre: (a) in its current status; (b) idem under the hypothesis of occupancy.

from the corresponding values measured in situ. In this case, the calibration process has been especially complex, since it is an open space, the absorption of the upper closure plane dominates the rest of the surfaces and therefore the adjustment of the absorption coefficients fails to produce appreciable effects on the behaviour of the sound field. On the other hand, the geometry of the theatre, especially the *cavea,* assumes that the dispersion coefficients are significant for all the octave bands. Precisely the adjustment of these dispersion coefficients has provided the key to finally achieve the calibration of the model. To finish adjusting these values, full simulations were launched with 500,000 rays and an echogram duration of 1,400 ms, superior to the reverberation time measured in situ, and the algorithm 2 of TUCT was used.

Table 1. Areas, absorption (upper row) and dispersion (lower row) coefficients in octave bands of the materials for the simulation.

Surface, [reference]	Area (m^2)	Area (%)	Colour (Fig. 6)	Absorption and dispersion coefficients					
				125	250	500	1k	2k	4k
Void	3136.8	49.7		0.99 0.01	0.99 0.01	0.99 0.01	0.99 0.01	0.99 0.01	0.99 0.01
Land, [12]	1108.8	17.6		0.15 0.20	0.35 0.25	0.40 0.30	0.50 0.40	0.55 0.50	0.80 0.60
Opus Caementicium, [13]	1000.4	15.9		0.08 0.55	0.08 0.58	0.14 0.60	0.16 0.60	0.18 0.62	0.25 0.56
Polyester tier, [12]	261.3	4.1		0.25 0.55	0.23 0.58	0.16 0.62	0.12 0.62	0.11 0.60	0.10 0.56
Stone stairs, [14]	257.0	4.1		0.02 0.55	0.03 0.58	0.03 0.60	0.03 0.60	0.04 0.62	0.07 0.56
Wooden platform, [14]	192.7	3.1		0.10 0.35	0.07 0.35	0.07 0.40	0.07 0.40	0.07 0.50	0.06 0.40
Cavea stone, [14]	188.2	3.0		0.02 0.55	0.03 0.58	0.03 0.62	0.03 0.62	0.04 0.60	0.07 0.56
Mortar, [14]	93.2	1.5		0.01 0.55	0.01 0.58	0.01 0.60	0.02 0.60	0.02 0.62	0.05 0.56
Stage metal grille, [13]	29.1	0.5		0.08 0.55	0.08 0.58	0.14 0.60	0.16 0.60	0.18 0.62	0.25 0.56
Marble columns, [14]	26.5	0.4		0.01 0.35	0.01 0.35	0.01 0.45	0.02 0.40	0.02 0.45	0.02 0.50
Metal grille [12]	13.1	0.2		0.60 0.01	0.60 0.01	0.60 0.01	0.60 0.01	0.60 0.01	0.60 0.01
Seated audience, [14]	449.5	7.1		0.24 0.30	0.40 0.40	0.78 0.50	0.98 0.60	0.96 0.70	0.87 0.70

Table 1 shows the absorption and dispersion coefficients finally assigned to the surfaces, the associated colours in Figure 6, and the bibliographic references used.

In the simulations carried out in the reconstruction hypothesis of the *cavea* with the same existing stony material, the type of polyester material in the stands is not considered. In the case of full capacity, the surfaces "polyester tiers" and "*cavea* stone" change to " audience seating".

Table 2 shows the results of the calibration process for spatially averaged T_{30} values for source A0 (Figure 6a) centred on the *proscaenium*. It can be seen that for all octave bands, the differences obtained between the measured and simulated values are lower than 5%, that is, lower than 1 JND.

Table 2. Results of the calibration. Values of T_{30} (s), spatially averaged for A0, in octave bands.

Frequency (Hz)	125	250	500	1000	2000	4000
Simulated values	0.69	0.66	0.64	0.64	0.63	0.56
In-situ measured values	0.71	0.66	0.63	0.62	0.64	0.58
Difference (%)	-2%	0%	1%	2%	-1%	-2%

ANALYSIS AS A WHOLE

Figure 7 shows the spectral behaviour of the differences between the measured and simulated, spatially averaged values corresponding to the temporal, energy and binaural acoustic parameters. In order to make the differences for the different parameters comparable, they have been expressed in terms of their respective JND and the same vertical scale has been assigned to all four graphs.

We can observe that these differences, for all the parameters, are maintained in the range of ± 1 JND for all frequencies (in many cases, even within the range of ± 0.5 JND), except for the $IACC_E$, which presents more notable variations (between 1.5 and 2 JNDs) for the bands between 2000 and 4000 Hz, and C_{80} in the 125 and 250 Hz bands (between 1.5 and 2.3 JNDs).

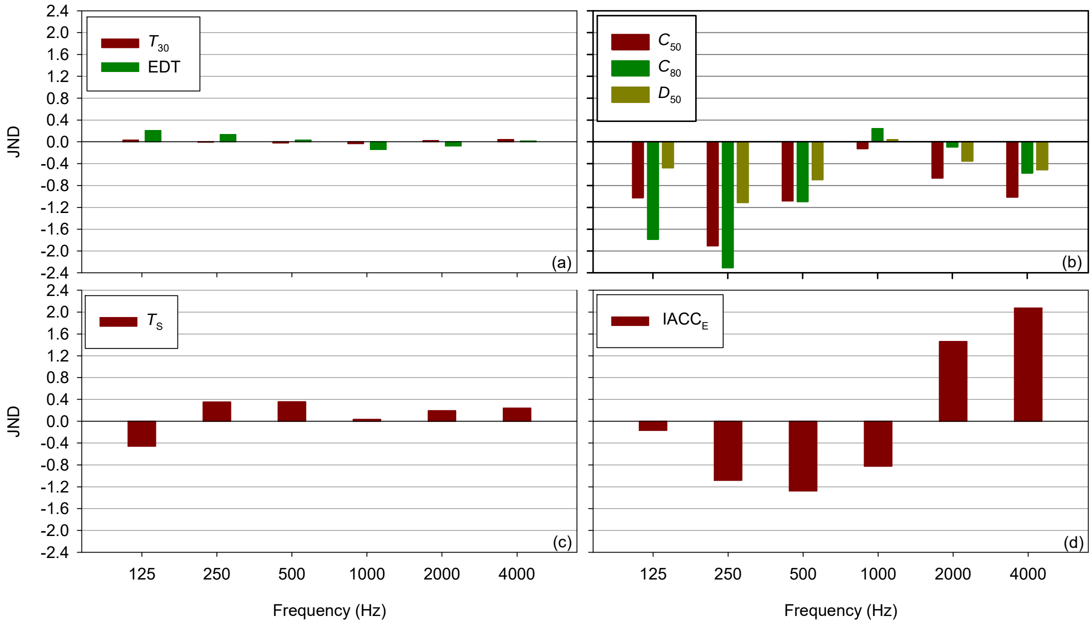

Figure 7. Spectral behaviour of the differences between the spatial average of the measured and simulated values of acoustic parameters: (a) T_{30} and EDT; (b) C_{50}, C_{80}, and D_{50}; (c) T_S and (d) $IACC_E$.

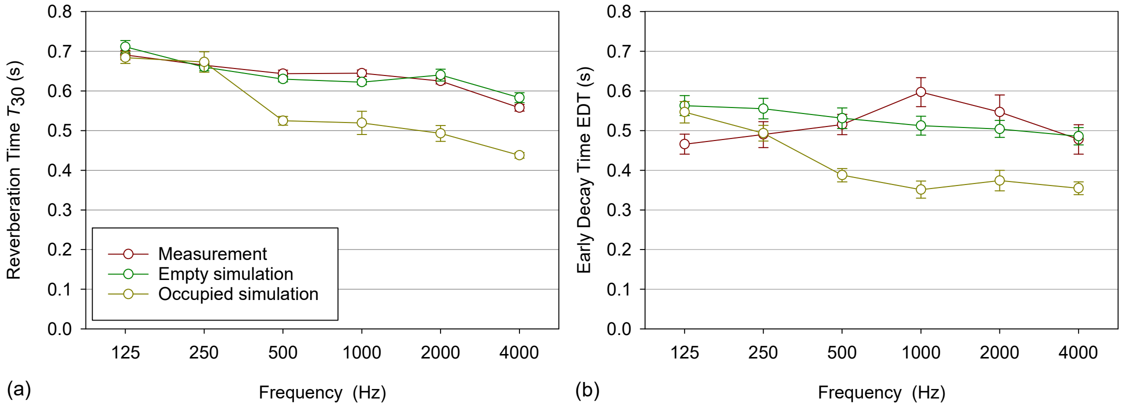

Figure 8. Spectral behaviour, spatially averaged, of measured values, and simulated values with the empty theatre, and with 100% occupancy: (a) for T_{30} parameter, and (b) for EDT parameter. Vertical bars value the spatial dispersion through the standard error.

STUDY OF OCCUPATION OF THE *CAVEA*

Figure 8 shows the spectral values of the reverberation parameters (T_{30} and EDT) spatially averaged, both measured and simulated, and for the situations of an empty theatre (Figure 6a) and at full capacity (Figure 6b). The measured and simulated T_{30} values are very similar under the empty theatre scenario (it must be taken into account that this is the parameter used to calibrate the model). The simulated EDT values reach their greatest difference in the frequencies of 125 Hz and 1000 Hz, which is practically the same in 500 Hz and 4000 Hz, although the difference always remains below 0.21 JND. The effect of the occupation of the tiers is evident as a notable decrease in both parameters, especially at medium and high frequencies.

STUDY OF THE RECONSTRUCTION OF THE TIERS IN STONE

An analysis has been carried out on the effect that the reconstruction of part of the tiers of the *cavea* (with polyester material) produces on the acoustic parameters. By taking advantage of the model developed for the simulation, we worked on the hypothesis of an intervention that used the same type of stone as the rest of the stands. From the geometric point of view, there is no change in the surfaces studied; in order to describe the new model, it suffices to change the coefficients that describe the acoustic properties of the materials (Table 2).

Figure 9 shows the spectral behaviour, spatially averaged, of the simulated values of the reverberation time T_{30} with the reconstruction of the grandstands in polyester and the hypothesis of said seating in stone. The result of the simulation shows that its effect is insignificant. We can see that both curves practically overlap in all octave bands, whereby the biggest difference is slightly less than 6% in the 250 Hz band, which is only 1 JND.

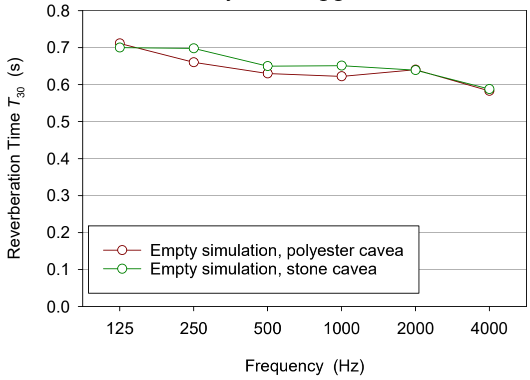

Figure 9. Spectral behaviour, spatially averaged, of T_{30} simulated values with polyester and stone *cavea*.

CONCLUSIONS

In this work, we have presented and discussed the process of making and adjusting a 3D model to simulate the acoustic field in the Roman theatre of the Archaeological complex of Regina Turdulorum in Casas de Reina (Badajoz). The model has been validated from the reverberation time values measured in situ, which has meant adjusting the dispersion coefficients of the surfaces of the model, since, for a plane with maximum absorption, the adjustments of the absorption coefficients fail to produce appreciable effects on the values of the parameters. The effect of the rehabilitation of part of the grandstand in polyester material and the influence of the presence of the public on the *cavea* on the acoustic parameters have been discussed. The detailed analysis of the point-to-point differences, the use of the model generated in the evaluation of further configurations (past or present) and of possible future interventions, both from the parametric and sensorial point of view through auralisations, constitute aspects to be investigated in the future.

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