Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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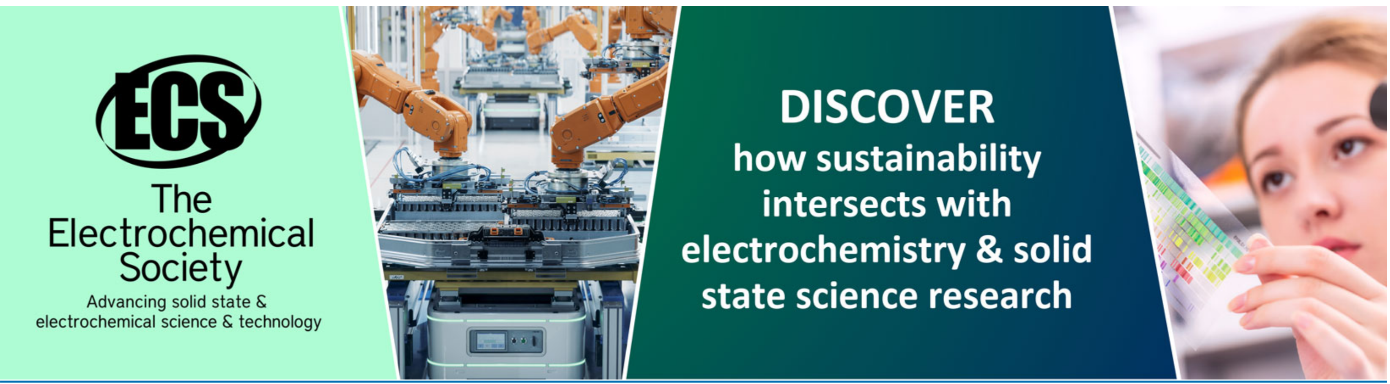
To cite this article: F Carlucci and W Tiano 2021 *J. Phys.: Conf. Ser.* **2069** 012160



Journal of Physics: Conference Series **2069** (2021) 012160 doi:10.1088/1742-6596/2069/1/012160

Acoustic design and optimization of an organic architecture, a cross disciplinary design of an open-space airport case study

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Abstract. Architectural innovation, both at morphological and technological scale, have increased the importance of new methodologies and tools for the building performance analysis. New organic shapes have decreased the reliability of traditional specialistic knowledge, highlighting the importance of new methodologies to manage complex models and analyse the indoor comfort. The aim of this paper is to present a case study of the acoustic design of an organic open-space airport, realized integrating architectural and acoustic concepts in the design workflow. The building, characterized by a curvilinear plan, a wavy suspended ceiling, and a tilted façade, behave as a single tall, large volume containing different small low-height closed service boxes. This architectural approach leads to a mixture of functions in the same large volume with a resulting complex problem of acoustic optimization. To that end, different studies have been conducted from the protection from external noise to the optimization of the reverberation time, and to the design of the speakers. Considering the geometric complexity, different tools and a particular methodology have been used to properly model the building and to optimize the use and the placement of acoustic absorbing materials.

1. Introduction

Air transportation is a crucial sector for human development and, despite different exogenous shocks such as, September 11 [1] or more recent COVID-19 crisis [2], it can be considered a constantly growing sector [3]. In China, for example, the air passengers have risen from 268 million in 2010 to 392 million in 2014 [4]. Similar trends can be identified in Europe where, in 2019, an increase of 3.8% of passengers has been registered compared with 2018 [5]. These trends highlight the importance of airport terminal design and construction and are increasing the attention on airport Indoor Environmental Quality (IEQ). Many studies have been conducted to understand the IEQ perception of the passengers. These surveys have shown that poor indoor air quality and noisy airport are the main causes of complaints. In particular, regarding acoustic comfort, the main source of dissatisfaction is the internal noise rather than external planes' noise [6].

These results confirm the great importance of a proper acoustic design of an airport terminal, a building typology that can be considered particularly complex due to its dimensions, to the high number of users, and to its open-space structure. In addition to this intrinsic complexity, new architectural innovations are increasing the complexity of these buildings through the implementation of new "organic" shapes. While the first definition of organic shapes was introduced last century, the fully development of these concepts came with the spread of computers and new parametric tools [7]. Indeed, thanks to the implementation of new algorithmic tools in the design process, nature-inspired shapes are rapidly growing their diffusion. Architecture is now focusing its attention toward more smooth, twisting, organic lines [8] and clear examples of this paradigm shift can be found in the most famous contemporary architectures. This new approach to architectural design has highlighted the need of new analysis tools for thermal, structural, and acoustic analyses. As the complexity of these new volumes decreases the reliability of traditional specialistic tools and knowledge, new methodologies are required to manage these models.

Considering the strong relationship between organic architecture and CAD modelling, a brief overview of the different types of geometric construction is needed to fully understand the workflow adopted for this case study. Two main modelling technique can be adopted in a CAD software: Non-Uniform Rational B-Spline (NURBS) and meshes. The former allows to describe accurately and in a compact way shapes (curves, surface or solids) thanks to the use of mathematically defined curves characterized by their order, weighted control points and knot vectors [9,10]. The latter is defined as a collection of vertices connected sequentially in simple surfaces called faces. Each face is bounded by a certain number of straight edges; the number of the edges defines the mesh type (triangle, quadrilateral) while the sequence of the vertexes define the mesh topology [11,12].

Organic shapes are usually generated with NURBs surfaces and solids as they are particularly appreciated in architectural workflow thanks to their accuracy and ease of use. Nevertheless, it is difficult to use these models in specialistic building physics software and a series of modifications and simplifications are needed. The aim of this paper is to present a case study of the acoustic design of an organic open-space airport, realized integrating architectural and acoustic concepts in the design workflow. The intrinsic complexity of the case study highlights the importance of a multidisciplinary and multi-tools approach in the realization of a reliable and easily-manageable model to describe the behaviour of these new shapes with the aim to find the balance between acoustic and architectural needs.

2. Methodology

2.1 Case study description

One of the main features that have driven the definition of the methodological approach for this case study is undoubtedly the model geometry. Indeed, the case study considered is characterized by a highly complex curvilinear plan with a variable height outward-tilted façade. The greatest element of complexity of the building is the wavy ceiling that defines a single open space volume with many open space areas with variable heights – ranging from 6 to 14 metres – and different uses. This great open space volume has no floor-to-ceiling walls but only a series of single-height (5 metres) or double height (10 metres) isolated closed “boxes” containing all the airport services (toilets, kitchens, etc.).

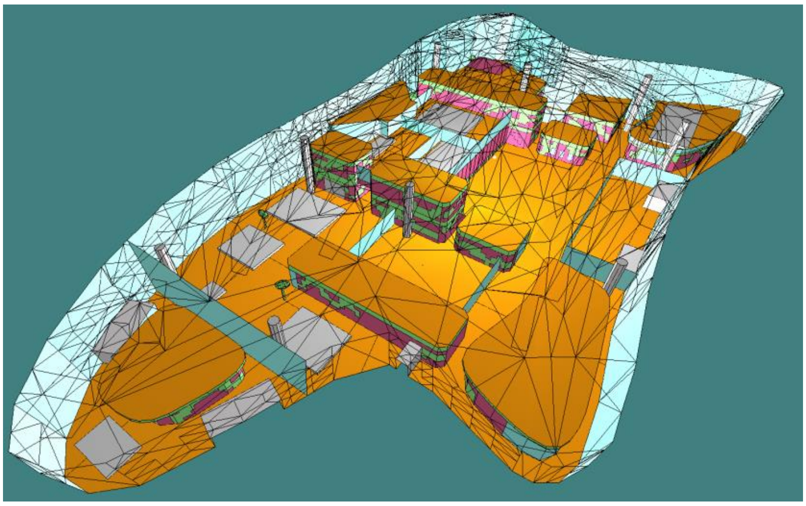

Figure 1. View of the model realized in CATT-Acoustic.

This architectural approach leads to a mixture of functions – from restaurants and rest areas to vip lounge – in a single volume with a subsequent mixture of privacy requirements and acoustic goals. In addition to this geometrical and functional complexity, many curvilinear lighting areas can be identified on the ceiling and on the walls, adding both a material and geometric surfaces diversification as specified in following paragraphs.

2.2 Geometric and acoustic modelling: software, approach, and analyses

To analyse the acoustic behaviour of the case study, the CATT-Acoustic software [13] has been selected thanks to its reliability. This software is based on the Randomized Tail-corrected Cone-tracing (RTC-II), which is an algorithm that combines the best features of the Image Source Model (ISM), Cone-tracing and Ray-tracing. While on the one hand this software allows a reliable acoustic modelling, on the other hand does not have a user-friendly interface for geometric modelling but relies on free-format hierarchic text files. To that end, considering the intrinsic complexity of the case study, a multi-tool approach has been considered to obtain a proper model to run the analyses in CATT-Acoustic.

Therefore, starting from the architectural 3D-model, a series of transformations and parametrizations have been adopted to obtain an acoustic reliable model without losing geometric and material definition. These transformations are particularly important considering that the acoustic of the airport has been studied running the simulation in the whole building simultaneously because of its intrinsic open-space nature. Therefore, considering the dimension of the building, the complex shape, the high number of geometric details, the high number of sources and receivers, and the computational demand of a detailed acoustic analysis it is fundamental to find the right balance between geometric reliability and model complexity.

The first important step of this procedure is to transform the original NURBS model in a simpler mesh model considering the discretization drawbacks and the consequent reliability requirements [14]. To that end, Rhinoceros [15] has been used and different transformations have been considered in order to contemporaneously reduce the number of meshes without losing relevant geometric information. A simple Grasshopper [16] algorithm has been developed to manage these transformations and to find the most suitable compromise between the architectural adherence and computational demand of a complex and too detailed model. Moreover, the Grasshopper algorithm has been used to control the coordinate system to easily choose and change the sources and receivers obtaining quickly valid coordinates to be directly implemented in the CATT-Acoustic. The main advantage of using a Grasshopper algorithm is to have an easy control on the parameters interested in the modelling activities such as the mesh simplification and the positioning of sources and receivers in the model. In this way, parametrizing the problem, it is easy and quick to compare different options and to change the model during the design development.

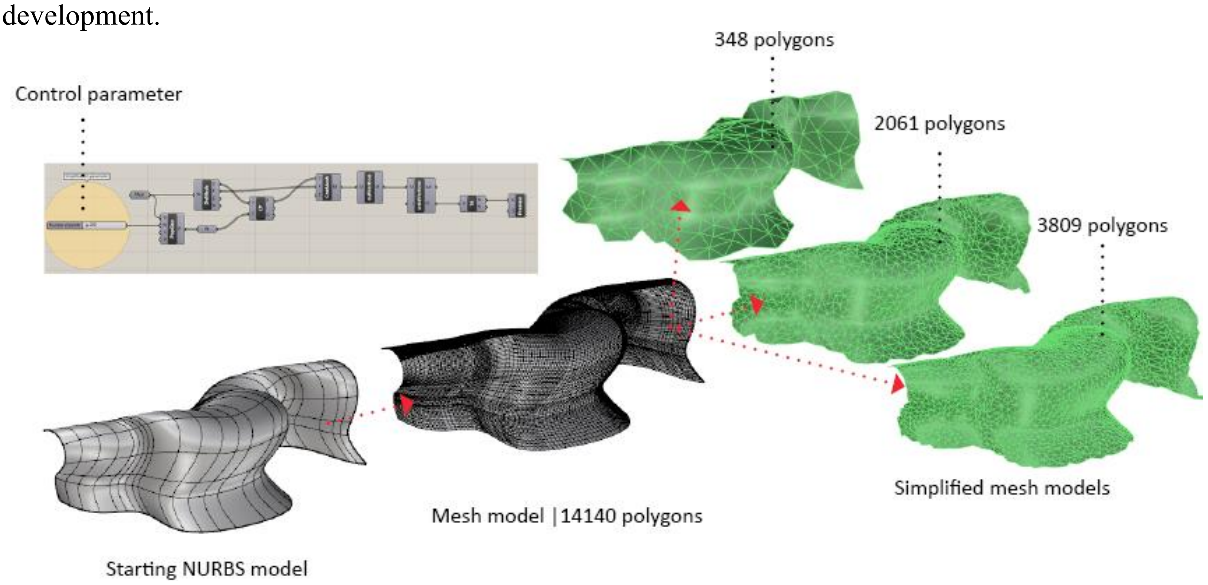

Figure 2. Schematic structure on a sample surface of the mesh simplification algorithm adopted.

Once the model has been considered properly simplified, a Sketchup model has been exported from Rhinoceros to assign specific materials to internal surfaces. The choice of using Sketchup relies on its capability to easily assign and change surfaces properties and on the availability of plugins capable of transform the model in the CATT-Acoustic compliant free format text files. In this case the SU2CATT plugin has been used to convert the mesh-based 3D model from Sketchup to the CATT-Acoustic "geo" format. Then, importing the model in CATT-Acoustic, all the acoustic details can be added from the simulation settings to the absorption coefficients, up to the sources' and receivers' coordinates obtained from the Grasshopper algorithm.

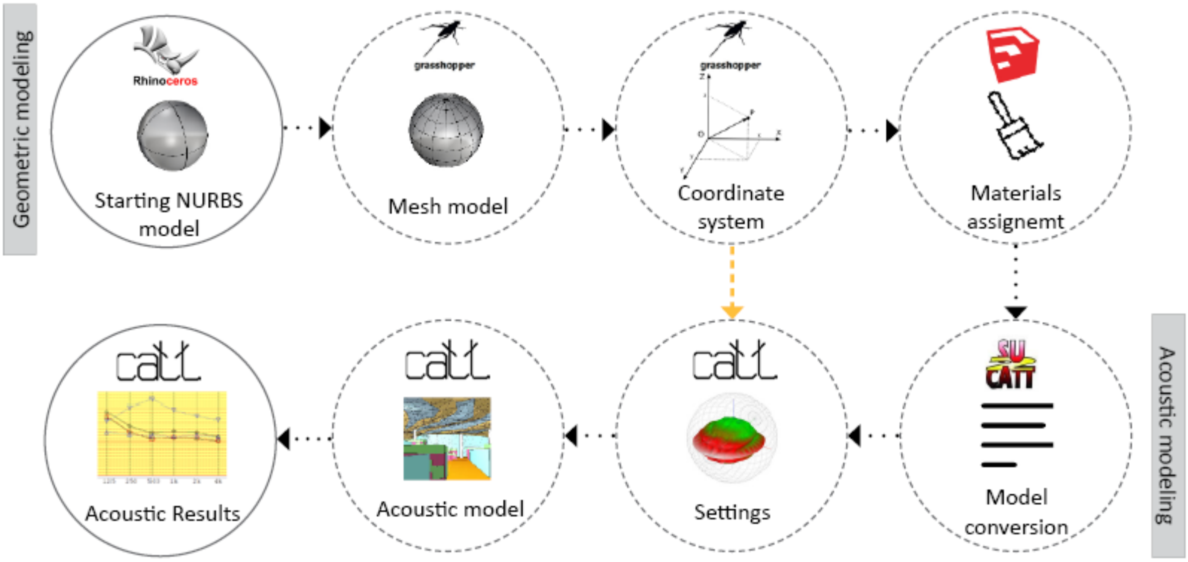

Figure 3. Schematic structure of the modelling approach adopted.

Considering the approach proposed, two main analyses have been conducted. Firstly, a set of analyses have been conducted to define the best absorbing materials and the best surface definition to reduce the reverberation time within the most exposed areas. Moreover, an intelligibility analysis of the main hall has been conducted through the positioning of loudspeakers and the evaluation of the Speech Transmission Index (STI) and of the Sound Pressure Level (SPL).

2.3 Cross disciplinary approach

The approach described has allowed to easily transform a complex organic-shaped architectural model in a simpler but reliable acoustic model. Thanks to this approach, the surface definition and the material differentiation has been easily decided in accordance with both architectural and acoustic needs. Firstly, the original architectural model has been analysed to identify surfaces and areas considered fundamental to improve the indoor comfort. Within these areas, architectural evaluations have been made to minimize the presence of lights and other reflective surfaces maximizing the sound-absorbing materials. These cross-disciplinary evaluations have been made in different steps, tuning the acoustic and architectural requirements throughout the whole design process. The modelling approach adopted has allowed, depending on the type of the architectural changes, to act in each of the different step of the structure shown in figure 3 starting from simple adjustments of the absorbing properties directly in CATT-Acoustic, to small geometric modifications in Sketchup, up to greater changes in the Rhinoceros model. Within this cross-disciplinary approach we have evaluated the minimum absorbing area and its distribution to reach a good acoustic comfort without compromising the architectural concept.

2.4 Acoustic surface integration, strategy definition, and material characterization

The main strategy is to add absorbing surfaces inside the airport defining a wall metal finishing that can host both lightings and acoustic panels. This metal cladding covers opaque area of box and all the main ceiling. A schematic sketch of lighting and acoustic interaction is shown below; aluminium sheet can be perforated either in lighting and absorbing area and the material provided behind it makes the surface working as an absorbing or lighting components.

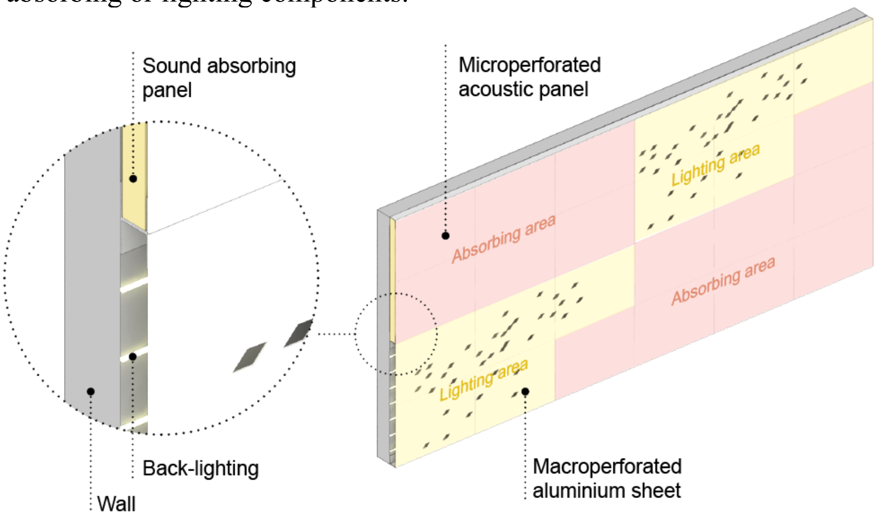

Figure 4. Sample box elevation and schematic view of acoustic and lighting surface interaction.

Lighting area is realized with holes spatially distributed in stripes and bands and is extended from wall to ceiling. Acoustic area insists on microperforated metallic sheet with an insulating panel on the back; in particular, two different micro-perforations have been considered as described in the in table below.

Table 1. Geometric characterization of the absorbing materials considered.

Finishing	Hole diameter [mm]	Distance between holes [mm]	Holes pattern [-]	Free area [%]
Wall area	0.3	3.0	Rhomboid	2.2%
Ceiling area	1.5	2.0	Rhomboid	22.0%

The surface distribution and a sample of the surface characterization are reported in the picture below and the corresponding materials and absorption coefficients are summarized in table 2.

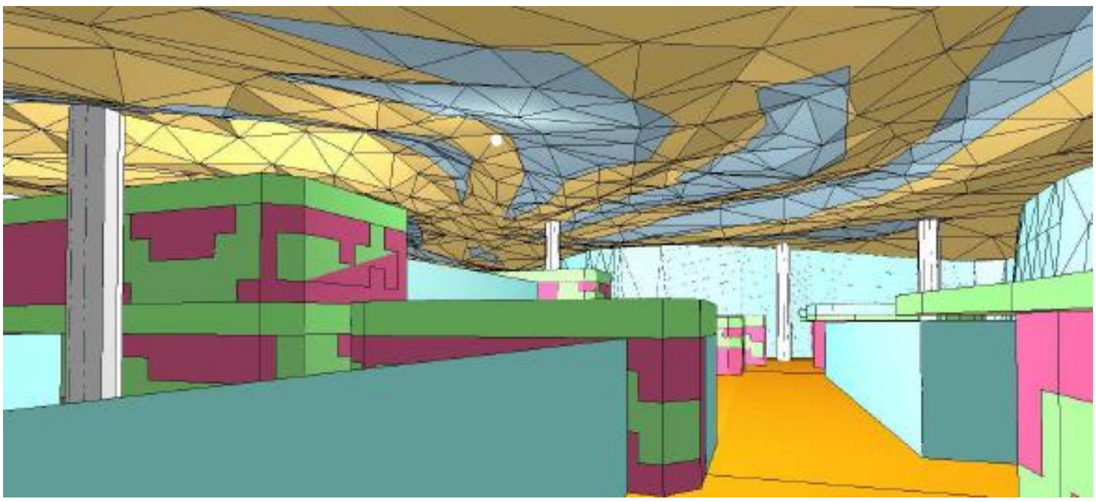

Figure 5. Internal view of the model in CATT-Acoustic with sound absorbing characteristics.

Table 2. Acoustic characterization of the materials considered.

Building components	Model colour	Absorption coefficients [a] [-]					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Floor	Orange	0.01	0.01	0.01	0.01	0.02	0.02
Glazed surfaces	Sky blue	0.18	0.06	0.04	0.03	0.02	0.02
Metal cladding	Green	0.25	0.15	0.05	0.05	0.10	0.10
Wall perforated metal cladding (absorbing area)	Purple	0.50	0.70	0.80	0.75	0.70	0.50
Ceiling perforated metal cladding (absorbing area)	Yellow	0.50	0.80	0.95	0.95	0.95	0.95
Ceiling lighting area with lateral microperforated surface	Grey	0.45	0.66	0.76	0.76	0.77	0.77

[a] Absorption data are taken from commercial products tested in laboratory (UNI EN ISO 354)

2.5 Theoretical background and targets

To evaluate the acoustical behaviour, two main parameters – briefly described below – have been considered to understand the reverberation and the intelligibility of the airport.

The first parameter analysed is the Speech Transmission Index (STI) proposed by Houtgast [21] that helps to understand the speech intelligibility of the airport, which is considered of fundamental importance for this building type. Houtgast focused the attention on the modulation transfer function (MTF) that describes the way in which the transient behaviour of the room changes the original signal. The final STI parameter is obtained starting from this function and converting all the octave bands and all the modulation frequencies in one single parameter considering both the mutual masking effect of adjacent bands and the signal-to-noise ratio. The resulting STI parameter ranges from 0 to 1 and covers different behaviours from a bad ($0<STI<0.3$) to an excellent intelligibility ($0.75<STI<1$). Codes and application standards typically recommend a minimum STI of 0.45 or 0.50 for Public announcements; suggesting a value of 0.60 or higher where non-native language listeners and hearing impairment are present [19], very common for airport users.

The second parameter, the reverberation time T_{60}, is defined as the time needed after the source shut-off to reduce the sound pressure level of 60 dB [20]. To avoid influences of the direct sound and early reflections it is evaluated excluding the first 5 dB of the decay, from -5 to -65 dB. Starting from this definition, other two parameters – T_{15} and T_{30} – have been adopted to describe the first part of the decay curve and to ease the on-site measurements considering respectively -5 and -20 dB, and -5 and -35 dB. As requirements for reverberation time in airport terminal spaces we will use different target for airport areas. Optimal reverberation values should be below 2 s [21], preferably between 1,1 and 1,5 s at least at speech frequencies (500 and 1000 Hz octave bands) an should be provided to achieve the minimum STI target [19]. The reverberation targets considered for each area that need reverberation control is reported in table 3.

We have also investigated the Public Announcement (PA) spatial placement to verify that intelligibility is fair in each airport terminal area. One of the main issues is to cover the large volume of the wide halls with a signal, intelligible and powerful while closed spaces – security check, office, meeting room etc. – can be equipped with classical systems that can achieve good intelligibility results. After the reverberation adjustments made in previous analyses, we have investigated in the main hall the PA systems and positioning to reach STI values higher than 0.50 with at least 70 dB(A) SPL in every airport area with passengers.

Table 3. Reverberation time targets.

Area	Surface [m^2]	Height [m]	Volume [m^3]	Optimal RT $_{(500\text{-}1000Hz)}$ [s]
Business lounge	332	6.1	2025	1.1
VIP lounge	343	11.5	3945	1.5
Restaurant - Business	202	6.1	1230	1.1
Restaurant - Landside	343	6.1	2090	1.1
Priority pass bar	164	6.1	1000	1.1
Baggage claim area	791	11.5	9095	1.5
Registration area / Infopoint	1413	11.5	16250	1.5
Departure hall	1046	11.5	12030	1.5
Pre-flight inspection area	356	11.5	4095	1.5

Results and discussion

Thanks to the abovementioned approach, quantitative analyses have been conducted to understand the acoustic behaviour of the airport. The results show that reverberation time is always lower than 2 s, considered as the minimum threshold for a fair intelligibility. A comparison with reference limits shows that reverberation is lower than 1.5 s in almost every space at 500 and 1000 Hz; this is a good result for this type of volume with no separation between different areas and ceiling higher than 10 meters. Higher values can be found in areas with lack of acoustic panels on walls, replaced by glass surfaces; however, even in these spaces, a good reverberation control is assured thanks to the high absorbance of the ceiling.

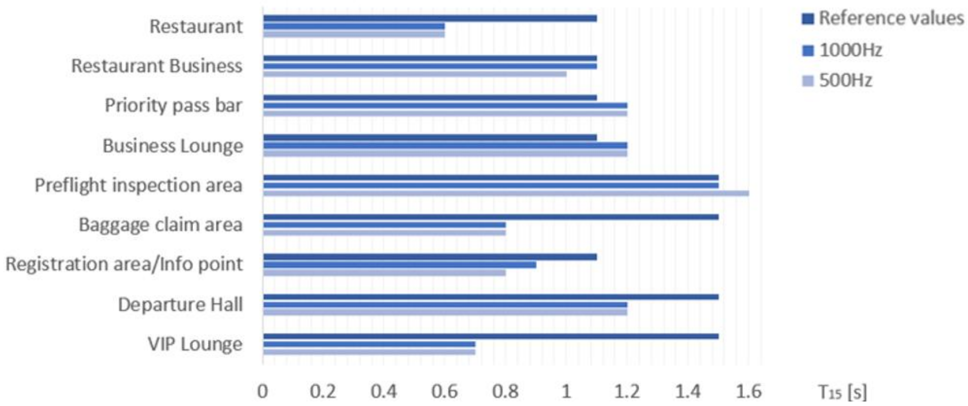

Figure 6. Reverberation time results for each terminal area.

Then, specific analyses for column loudspeakers have been performed to assure intelligibility in every open space of the main hall. We have made a preliminary definition of speakers model and positioning considering acoustic column with modular system, EN 54-24 certified. From this preliminary definition, we have changed number and position to obtain STI > 0.50 and SPL above 70 dB(A) in each area.

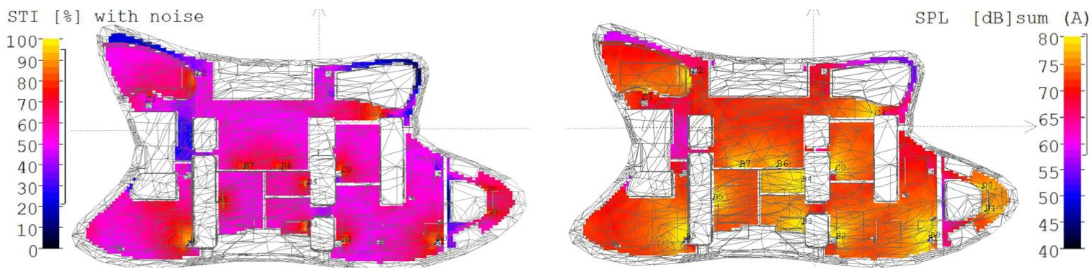

Figure 7. Maps of the STI (left) and Sound Pressure Level (right) in the final acoustic model.

Conclusions

The study conducted represents a way to approach an acoustic modelling problem in a complex organic open-space architecture. As the use of different software in this case is strictly necessary, the methodology adopted significantly helps the modelling activities and the interdisciplinary cooperation. Reaching the synthesis between architectural and acoustical needs can be highly challenging in organic complex spaces; nevertheless, the approach proposed has eased the information exchanges and has reduced as much as possible the modelling activities obtaining, at the same time, a particularly reliable acoustic model. From our point of view, obtaining the same reliability and modelling easiness with the free-format hierarchic text files of CATT-Acoustic or with traditional modelling activities is extremely difficult with this complex organic shapes. Moreover, this approach has allowed, during the design phases, to change the model in very few simple steps. Finally, the analyses conducted and the results obtained have confirmed that – with the correct multidisciplinary approach – it is possible to find the right balance between architectural and acoustical needs also in an extremely complex organic space.

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