Shape the Design with Sound Performance Prediction

A Case Study for Exploring the Impact of Early Sound Performance Prediction on Architectural Design

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Abstract. Acoustics is typically considered only late in developed design or even post occupancy, if at all, for specification of finishes and furnishing, and typically with a remedial mindset. In this paper, the role of sound performance as a design driver in increasing the speech privacy of a semi-enclosed meeting space in an open plan interior is studied. Sound performance prediction is applied as an imperative input to inform the meeting space design. The design is the second iteration in an evolving series of meeting spaces, and therefore has benefited from both subjective experiments and objective measurements performed with the first meeting space prototype. This study promotes a design method that offers a strong relationship between the digital simulation of sound performance and design development. By improving the speech privacy of a meeting space by means of purely form, geometry and design decisions, the significance of architecture in tuning the sound performance of a space is investigated.

Keywords: Sound Performance Prediction, Sound Simulation, Meeting Space, Architectural Design

1 Introduction

With the recent trend of using simulation techniques in processes of designing, acoustics has always received less attention from both designers and software developers in comparison to the other design parameters such as light and energy. One probable reason is the complexity of sound wave behavior and human sound perception.

Although there has been much improvement in acoustic simulation and computational techniques in recent decades [1], architects barely apply sound performance prediction as a design driver in the early stages, except for the design of concert halls and auditoriums. In the best scenario, sound performance is thought of as a self-contained aspect of a design, with no influence on the other design imperatives, and it is considered and analyzed only in the final phases of the design.

Often, the result of sound performance analysis doesn't cause a major modification in the final design and geometry but only serves as a representation of a promising output of a project. Even if the result is not encouraging, it simply implies that space needs further treatment after construction. This counters the purpose of prediction, which is to improve the acoustic performance of a room before it is built [2]. This is to say that architects approach acoustics in a remedial mode of practice after either the design completion or building construction [3].

This study integrates the acoustic analysis as a design driver in an architectural design process. The aim is to highlight the significance of sound performance prediction in the design progression, particularly in spaces that require sound considerations as fundamental to the use of space. Meeting rooms are one of those spaces that need specific acoustic considerations to provide an acceptable level of speech privacy and speech intelligibility. A semi-enclosed meeting room is selected as the design case study in this research to address the lack of speech privacy as one of the most prevalent complaints reported in the open plan interiors.

Moreover, the research investigates and develops a design method that offers a strong relationship between digital sound simulation and parametric design. It combines the results of the previous subjective analysis with simulation prediction to inform the geometry and shape the space. The project has benefited from the experimental studies conducted in the first prototype of a semi-enclosed meeting space and therefore subjective analysis was actively involved in the design process together with acoustic simulation techniques. This novel work-flow has enabled us to obtain feedback from subjective experiments, notably in regards to human auditory perception, when digital modelling has provided limit answers.

2 Project Background

The motivations for initial investigations were the field observation at Sagrada Familia Church in Barcelona when it was opened to the public in 2010. The very first human sound experience of the space was a diffused sound field, which was ascribed to the scattering effects of doubly curved hyperboloid cells in the nave walls [4]. Following the hypothesis, a 1:1 prototype of a hyperboloid wall was built and analyzed in SmartGeometry 2011 [4] to confirm the sound scattering attribute of the hyperboloid geometry.

With promising results obtained, the research extended further to investigate the impact of diffused sound fields on increasing the speech intelligibility of small spaces. A semi-enclosed meeting space composed of hyperboloid modules was designed, named FabPod and situated in an open plan office at the Design Hub, Royal Melbourne Institute of Technology (RMIT) University in Melbourne, Australia. The non-rectangular walls and highly articulated cells with hyperboloid geometry in FabPod aimed to achieve a less echoic, resonant space and consequently more speech intelligibility (Fig.1a) [5]. At this stage, the focus of the research was tuning the sound

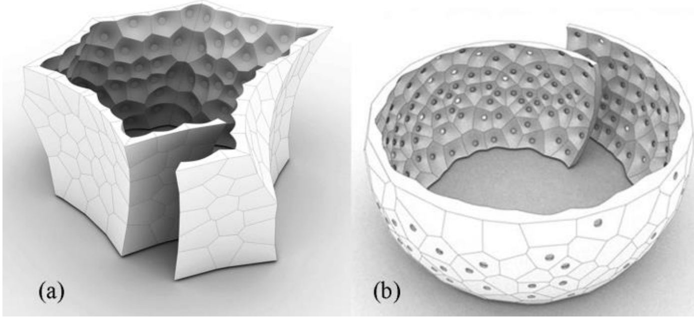

Fig. 1. (a) Meeting space final design, convex form. (b) proposed concave form

performance of the pod's interior through surface articulation. Underpinning the FabPod's overall geometry was the fabrication limitation and construction logic for having planar hyperboloid intersections. This could be achieved by intersecting various circles to produce a convex form that is aesthetically more preferred than a concave shape (Fig.1b).

Upon completion of the 1:1 prototype, further measurements and experiments were performed in the FabPod I to evaluate the pod's sound performance from both objective and subjective views. Improved speech intelligibility inside the meeting pod was confirmed with acoustical measurements [6], while in the preliminary speech privacy measurements, the FabPod I could not meet the criteria of a private space [7]. In addition to the measurement processes that conformed to international acoustic standards [8], two distinctive subjective experiments were performed adopting an architectural rather than engineering approach. The first subjective experiment aimed to verify the sound simulation prediction with the human auditory experience in the pod [9], while in the second subjective experiment the impact of sound diffusion field and improved speech intelligibility on speech privacy of the space was investigated.

A cross validation technique was applied during the first experiment with human participants to verify the results of the Odeon (Room Acoustic Software) simulations. That is, the field measurements performed during the experiment were compared with previous standard acoustical measurements. The consistency between the two objective measurements established reliable grounds for the architectural subjective setup and verified the human perceptions of privacy. Subsequently, simulation results were further congruent with human sound perception in the space, which provided a platform for predicting the sound performance of the second generation of the design, FabPod II, with sound simulation software, Odeon [9].

In the second subjective experiment, human sound experience substantiated the significance of sound field diffusion in tuning the acoustic environment, yet the improved speech intelligibility did not affect participants' vocal effort and consequently did not influence the speech privacy. This experiment included a thorough investigation of the speech intelligibility of the space and its relationship with human vocal effort and speech privacy, which is beyond the scope of this paper. But it is vital to mention that the experimental outcomes indicated that the direct sound is the primary sound energy that governs a face-to-face conversation in small meeting rooms; therefore, improving the speech intelligibility of a small space beyond a certain point, although perceivable by human ears, should not be the priority. This experimental finding altered the focus of the research in designing the second design iteration for the pod from increasing speech intelligibility to increasing speech privacy, and also from surface articulation design to the overall geometry of the space.

With the above research background, the FabPod II development as presented in this paper followed a series of already established design proposals to create an innovative design to fulfill fabrication process, sound performance, and architectural aesthetic requirements.

3 Sound Simulation

Physical modelling and scaled physical modelling was widely adopted and applied for more than 60 years before digital acoustic simulations provided a more powerful and time-saving alternative [10]. Developed digital modelling techniques for sound prediction provide an opportunity for architects to integrate the sound phenomenon considerations in the early stages of design. Yet, the validity of the results and the degree of consistency with human auditory perception is still in question. In addition, the limitations of such simulations should be recognized and acknowledged in the design process, as discussed below.

3.1 Simulation Technique

Acknowledging potential sources of errors such as Computer Aided Design (CAD) model approximation, material data and algorithmic details [11], for this case study the room acoustic software Odeon has been adopted as the software of choice. Odeon uses a hybrid room acoustical model which combines both ray tracing and image source methods and has limited practicality in simulating surface articulation. The validity of the software results and its consistency with the human auditory perception have already been verified by the subjective experiment and objective measurements performed by the authors in the first generation of the design [9].

Moreover, Insul, sound insulation performance predictive software has been used to determine the sound transmission reduction through the structure and material. Further details of the Insul simulations are beyond the scope of this paper, however, the data produced by this software was imported into Odeon to fully integrate the impact of both material and structure into the digital modelling prediction. This method has been developed to improve the simulation predictive results for FabPod II since the effect of transmission loss had not been considered in the initial simulations of FabPod I.

3.2 Simulation Parameters and Specifications

The research aimed to address speech privacy, one of the most common problems of open plan spaces. Therefore, the results of this study might be informative in general for all types of open plan offices. But, since this is practice-based research, context is therefore required. The first iteration of the pod is situated in an open plan working space in the RMIT Design Hub and the second prototype will be situated in the same building but on a different floor level. The office is 55 x 10 x 3.30 m high with three entirely glassed walls and one painted concrete wall. The acoustic specifications for all surfaces are illustrated in Table 1. For eliminating the impact of materials in simulations, all of the pod surfaces were assigned a 20% absorbent material.

Table 1. Absorption coefficient (α) of the open interior surfaces

Frequency (Hz)	*125*	*250*	*500*	*1000*	*2000*	*4000*	*8000*
Ceiling	0.30	1.00	1.00	1.00	1.00	0.97	0.97
Floor	0.00	0.05	0.05	0.10	0.05	0.00	0.00
Glass	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Wall	0.10	0.05	0.06	0.07	0.09	0.08	0.08

Interpreting the sound simulation outcome requires the selection of appropriate parameters. For many years the Reverberation Time (RT), regardless of the space characteristics, was the primary parameter for analyzing sound performance [12]. Since the initial part of the decay curve, that is significant for speech intelligibility, is not included in the RT, the human speech perception, therefore, cannot be fully represented in small spaces. Instead, a more recent parameter, the Speech Transmission Index (STI), has been developed to describe the quality and the amount of the speech understood in the space. The STI is a value between 0 and 1. Odeon calculates the STI by applying the indirect method in compliance with the international standards ISO 9921 and IEC 60268 [13].

The target of the design is to achieve minimum STI in the open working area while maintaining the required speech intelligibility in the pod, where more conversations and meetings are taking place. Less STI in the open office areas offers less speech comprehension, which delivers more speech privacy for occupants holding a meeting in the pod. In addition, more speech privacy brings less distraction and more productivity in the open office.

4 Architectural Design Development

The back and forth process between architecture and acoustics together with feedback obtained from the first prototype consequently shaped the composition of architectural design. In this section, following the interaction between sound interpretation and geometric rules, a continuous improvement in speech privacy of the open plan space can be noticed.

While acoustic simulations provide both visual and numeric results, for this paper, a grid colored map of STI has been selected as a preferable architectural method of presentation.

4.1 Geometric Investigations

Preliminary design for the second prototype simply followed the convex form derived from aesthetic preferences in the FabPod I but in two different iterations. Two overall enclosed surfaces were presented in the initial phase of the design. Both geometries stemmed from a funnel shape that has a smaller area in the plan relative to the ceiling with the walls gradually diverging towards the top.

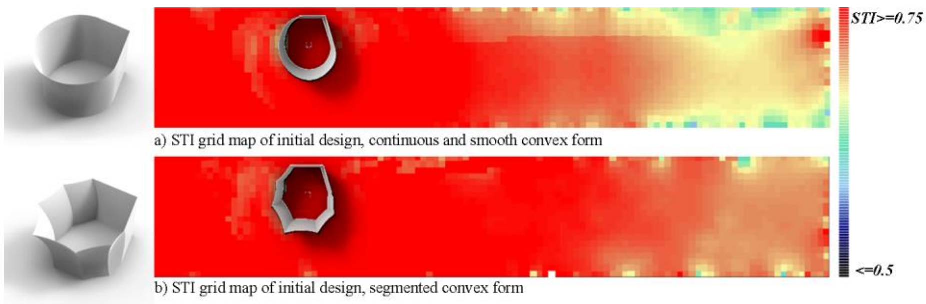

Fig. 2. Odeon simulation results for two iterations of convex geometry

The results of the simulation for the first two iterations are illustrated in Fig. 2. The STI grid map of the working area suggests that both geometries failed to provide a minimum privacy requirement of the space. A supplementary cumulative distribution graph shows that quite 100% of the working area has the STI above 0.6 which is the maximum threshold for providing poor speech privacy (Fig. 3). This can be explained through the nature of the funnel form which may assist the sound waves in propagating out from the pod and beginning to spread in the open interior in a shorter period of time.

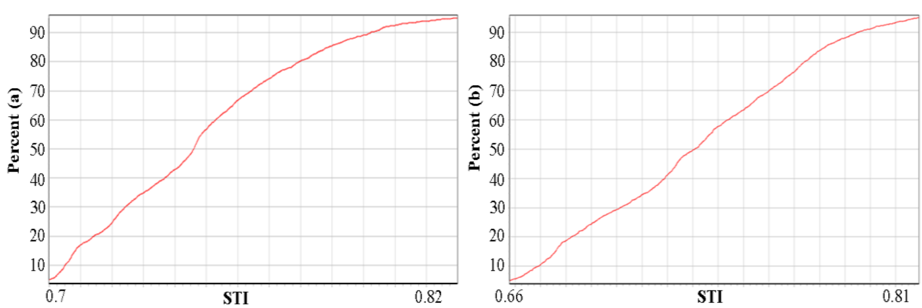

Fig. 3. Cumulative distribution graphs a) segmented convex pod, b) continuous convex pod

Although both forms with similar volume and curvature were almost unsuccessful in fulfilling the privacy requirement, it is clear from the Fig.2 that a convex form with a smooth and continuous structure performs better than the segmented shape with intersection lines. The negative curvatures inside the pod in these two iterations appear to be the most problematic cause of decreasing speech privacy. Therefore, the degree of the curvature might be one of the most important factors which highly influence the sound behavior in the space. The ratio of pod's top edge area to floor area seems to be another determinant factor.

At this stage of the design, it was hypothesized that the characteristics of the general structure, degree of the curvature and ratio of the top to floor area needed further investigation and consideration for feedback into the design.

In order to undertake a comparative analysis to study the three above-mentioned parameters of the hypothesis, a geometric system including intersecting spheres, smooth surfaces and boolean operations was established. With this system, both discrete and continuous forms can be generated using the same parameters in terms of size, curvature and composition (Fig. 4).

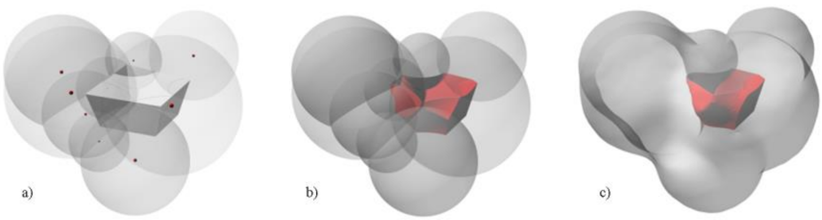

Fig. 4. Geometric system a) intersecting spheres, b) boolean operation, c) smoothing

First Set of Comparative Shapes: Diverging Shape and Curvature Degree

For investigating the impact of concave geometry and diverging form two identical geometries were developed. The forms consist of convex parts which clustered in a concave form. Therefore, the overall compositions read as a concave shape.

Comparing this set of geometry with the initial design highlights the advantage of diverging form over the converging structure (Fig. 5).

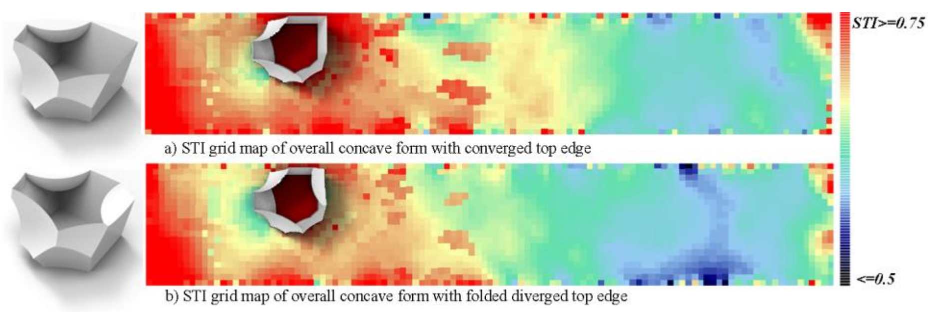

Fig. 5. Odeon simulation comparison, Set I

The only difference between the two pods in the comparison in Fig. 5 is the folding part on the ceiling edge which changes the pod's curvature. As illustrated in the STI simulation results, the slight alteration not only decreases the sound transmission to the immediate surroundings but also offers effective improvement at multiple locations across the whole office area. This modification provides STI below 0.6 for at least 20% of the working area, which is a 10% improvement relative to the other geometry.

Second Set of Comparative Shapes: Smoothing the Intersection Lines

In the process of refining the geometry in response to the sound performance, the intersection lines in the second form above (Fig. 6b) was converted to a smooth, continuous form to further investigate the effects of surface alteration.
As indicated in Fig. 6, the outcome is promising in terms of increasing speech privacy. One possible reason might be attributed to the increasing reflections inside the pod when the structure is more joined and unified. The extended reflections keep the sound energy inside the pod for a longer period of time and only releasing the energy into the open interior after significant sound energy decay.
The cumulative distribution function graph shows an improvement of 12% in the total area having the STI below 0.6, compared to the previous geometry.

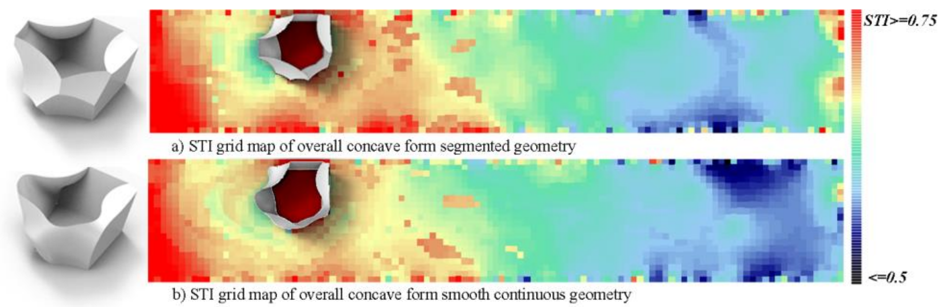

Fig. 6. Odeon simulation comparison, Set II

Third Set of Comparative Shapes: Reducing the Ratio of Ceiling to Floor Area

In this section, the first geometry from the first set of comparative shapes was simply flipped upside down to invert the ratio of the top edge to the floor area. Comparing the two simulations readily suggests a dramatic increase in speech privacy of the space (Fig. 7). The efficiency of the latter pod in terms of sound performance can be explained by having more control on the sound rays' paths, impeding sound propagation and reflecting sound waves back into the pod.

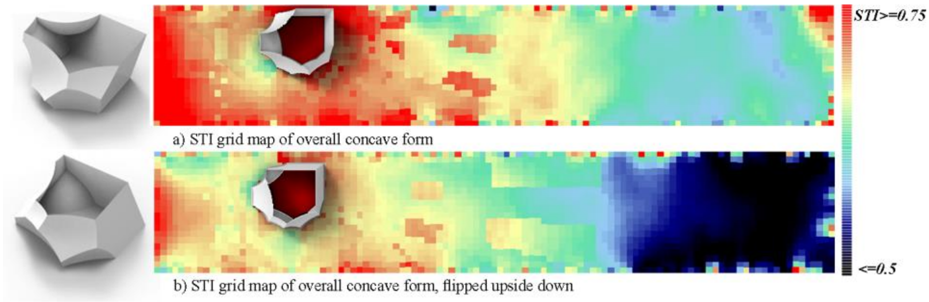

Fig. 7. Odeon simulation comparison, Set III

4.2 Tectonic System Development

A digital fabrication and construction system was developed in parallel with the sound performance exploration as one of the primary aspects of architectural design. The 3-way interaction between the architectural design, fabrication development and sound performance analysis provides the possibility of offering practicable geometries and structures. The feasibility of the workflow was verified by both digital and physical prototyping (Fig 8, 9). The digital prototype at this stage is an illustration of a balance between the sound performance, constructability and architectural design.

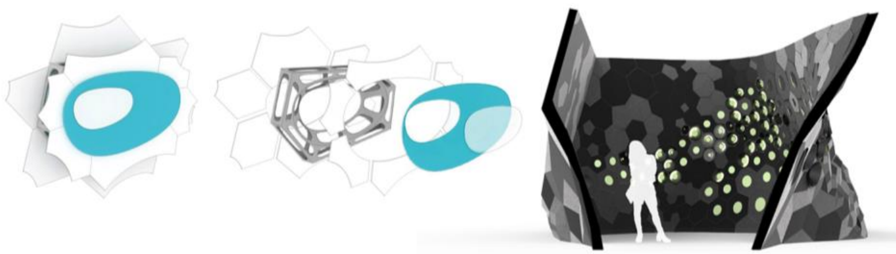

Fig. 8. Digital prototyping parallel to acoustic analysis

Fig. 9. Physical prototyping parallel to acoustic analysis

The construction system has been developed with a lightweight thin modular steel metal structure. Individual cells are custom cut in sheet metal and folded in a cellular arrangement for increasing structural strength and stacked together to provide the overall system framework that can be covered later with acoustic panels. This construction technique allows the system maximum flexibility, which can be readily adapted to various forms while maintaining the modularity for further extension and mass production in manufacture. Also, the system can be adapted to local conditions and fit into different project briefs. Furthermore, a thermal formed CNC (Computer Numeric Controlled) trimmed conoid is used to create aperture to provide light and visual connection between the internal and external spaces.

To develop the construction work-flow parallel to the design progress, several prototypes for modules were produced which ultimately had a great impact on the architectural design. One of the most influential constructed elements was the aperture.

It was decided to fit two apertures on a single conoid to cut down the material waste (Fig. 10). Also, for reducing the number of cells the operational volume of the robotic arms was maximized which directly affected the conoids' size.

As Fig. 10 illustrates, each of the two unique apertures in different sizes is calculated and mapped onto one standard thermal formed conoid. This fabrication process increased the size of the apertures dramatically and prompted larger steel modules (Fig. 11). As a result of fabrication constraints, the cell size limits the application of surface articulations and therefore calls for a new design composition with less geometric complexity.

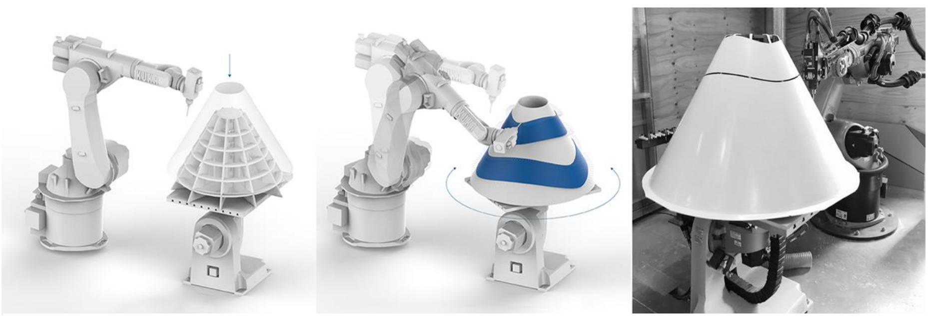

Fig. 10. Map two conoids on one large cone in the trimming process

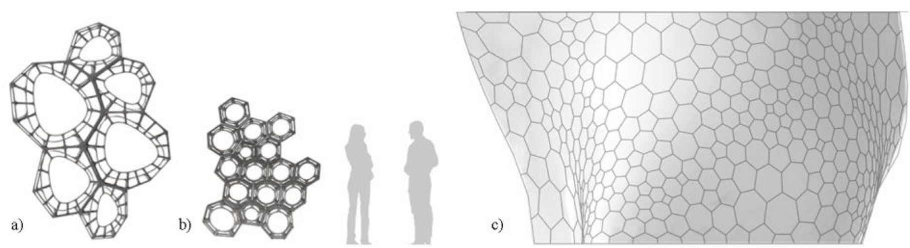

Fig. 11. Conoids size alterations, a) new cells, b) former cells, c) cells mapped on last iteration

4.3 Design Decisions: A Trade-Off Architectural Solution

Responding to both acoustic needs and fabrication constraints simultaneously requires a new parametric design that delivers a novel architectural solution to all the individual parameters.
For achieving the highest possible speech privacy whilst addressing the construction requirements, two primary design decisions were considered targeting a new formal composition:

- For facilitating the planarization, construction, and assembly process, a combination of both discrete and continuous geometry is suggested. Although the notion of continuity appeared to be one of the sound performance parameters, a compromise in the new design offers a better architectural solution.
- A double layer structure is proposed to address both acoustically well-performed interior concave surfaces and an aesthetically preferred exterior convex shape.

New Geometric System

In redesigning the geometry, a new method of intersecting tori rather than spheres has been adopted for three primary reasons:

- A torus has two internal and an external curvature. The radius of each curvature can be modified individually and therefore offers greater freedom in the design process and brings an inherent simplicity for construction. This includes an ease in assembling and dismantling when splitting the pod into separate tori.
- For achieving a geometry with the better sound performance the internal tube curvature can be adjusted while a gentle exterior curvature helps avoid potential construction problems. The double curvature of the torus is a particularly effective strategy for a double layer structure. It assists in providing enough flexibility to control the distance between the layers.
- Another advantage of the double curvature in the torus geometry over the sphere is the significant reduction in the unpleasant sound reflections at one focal point. This is specifically beneficial in improving the speech intelligibility of the space.

A double layer skin is developed with a grasshopper script with an exterior diverging structure and interior converging shape (Fig. 12).

The double skin geometry was simulated in Odeon to verify the sound performance of the system and to rank the iterations in order of improved speech privacy. It can be seen from Fig. 13. that the design process of iterations followed an upward trend in increasing the speech privacy. There is a dramatic improvement in the speech privacy of the open interior from the first initial design with 100% of the space having full speech intelligibility to the final iteration, where almost 55% of the space has STI below 0.6.

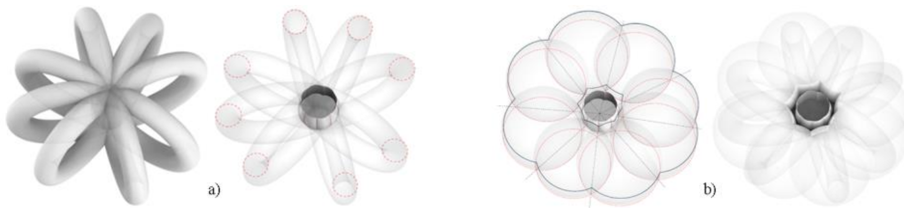

Fig. 12. a) Internal layer, intersecting tori, b) external layer, intersecting hemispheres

5 Conclusion

This study investigated the impact of architectural design in improving the sound performance of semi-enclosed subspaces within an open interior. Acoustics can be applied as a design driver at early stages of design and the interaction between auditory analysis and other design imperatives such as fabrication constraints can play an active role in shaping the architecture. In the design process of a semi-enclosed meeting space in an open layout interior, as a case study in this research, a speech privacy improvement of approximately 55% was achievable purely by the means of architectural geometry. This improvement can be further increased by applying acoustic solutions such as absorbent materials. Moreover, the results of this study might be informative generally in terms of geometric rules for semi-enclosures in open interiors to increase the speech privacy and therefore productivity.

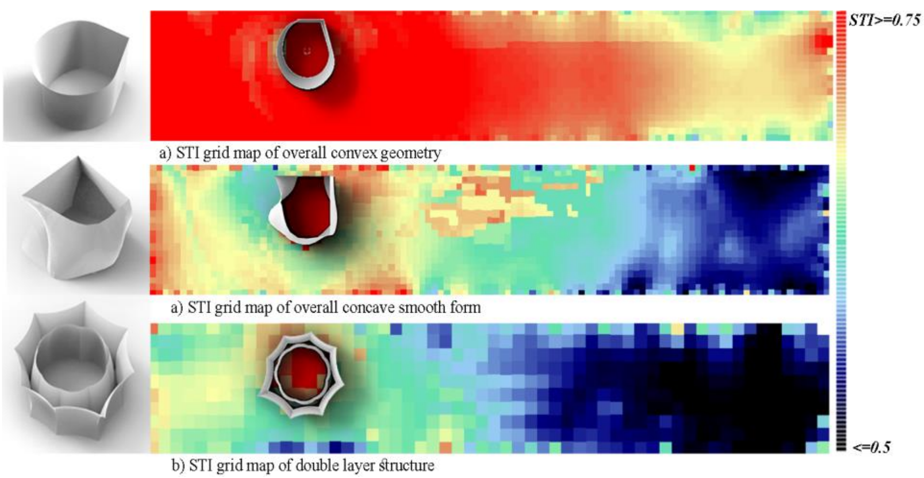

Fig. 13. Increased speech privacy in the design progression from top to bottom

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