THE DESIGN OF THE SNFCC OPERA THEATRE AUDITORIUM AND A REFLECTION OF THE RECIPROCAL INFLUENCE BETWEEN OPERA THEATRE AND CONCERT HALL DESIGN

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1 INTRODUCTION

Opened in 2017, the new Stavros Niarchos Foundation Cultural Center (SNFCC) is one of the largest cultural projects recently realized in Europe. The vast and ambitious development is a cornerstone of continued urban renewal and regeneration, as well as a progressive 21st Century investment in cultural infrastructure for Greece to share knowledge, culture, and the presentation of the performing arts. Its success is in many ways a symbol of the revitalization of the country after its period of crisis, playing a major role in the economic, cultural and sociological development of Athens, and of the country.

Led by Renzo Piano Building Workshop Architects, the project features a building set within a new 200,000m^2 park which contains the National Library and National Opera House. The Opera House is the new home for the Greek National Opera and Ballet with a 1,400-seat opera theatre, a 480-seat alternative stage, and a full suite of opera, chorus, orchestra, musician and dance's rehearsal and practice rooms. The occupied spaces are set inside an artificial hill, built to elevate, and provide views to the Aegean Sea to the South, and to the Acropolis to the North, and project visitors at the intersection of the exceptional history of these sites. The public park, which covers the building, provides a sense of informality and ownership to the surrounding community, families, and visitors. Visitors are invited to wander through the Mediterranean vegetation before entering the facility to attend an event, visit the library, sail on the canal, take a dance lesson, or enjoy the architecture.

The first article[1] published about the project in the acoustics community discusses the initial concept for the design of the opera house, at the inception of the project. The second article[2] presents the final acoustical performances of the performance spaces once completed, and the range of formal/informal, indoor/outdoor performance venue environments.

In this article, we invite the readers into the journey of the making of the opera theatre, highlighting the influences and ideas for its design following five generations of designers at Arup, and the inspirations and benchmarks in relation to Greek Culture. We follow with a summary of the final acoustical performances of the opera theatre and compare them with a range of other relevant opera houses and concert halls. Throughout the article, we point out how in recent history concert hall design has influenced the design of opera houses, and from the observations of the performance of the SNFCC opera theatre, ask the question if features of opera house design could help with future concert hall designs. We highlight particularly how the musical and immersive characteristics of the theatre are supportive of both the opera and the symphonic sounds, and how these features can be transposed to the design of new venues. As closing a section, we provide project examples implementing this approach, ranging from the adaptative re-use of existing spaces, reconfigurable opera/symphonic venues, to surround concert halls.

2 OPERA HOUSE DESIGN, AN ARUP LEGACY

2.1 Early Period (1953-1980)

The advent of Arup as a firm since its creation in 1946, is intricately linked with the accomplishment of the Sydney Opera House. Solving the construction challenge of the giant pre-cast concrete shells envisioned by Architect Jørn Utzon, Ove Arup imagined a structural system of rectilinear steel elements, derived from a regular sphere, allowing re-usable molds to fabricate the concrete ribs that support the shells and components that could be fabricated off site, and put together as a kit of parts. This kicked-off a tradition for innovative opera house design at Arup. Core to the project design and delivery of the project ambition, Ove implemented a mindset for multi-disciplinary collaboration – a novel approach at the time – supported by robust engineering, to enable imaginative architecture that can carry the ambitions of a nation, thus reconnecting with a long tradition of emblematic opera house buildings, (Versailles, Garnier, Semperoper, Staatsoper, etc).

In 1963, the firm eventually created its own architectural design practice, Arup Associates, integrating architecture and engineering. The lead partner, Derek Sugden, Arup's first acoustician, and structural engineer by training, built-up the first portfolio of concert hall and opera house projects. If Ove could be seen as carrying the philosophical framework of the practice, Derek brought the humanistic and sensorial aspects, and applied his enjoyment of music and opera to the making of joyful and warm buildings. He often said: "The sound is as important to me as the surface. Our ears define the nature of space". Some of Derek's most representative music spaces and approach to materials include the design of Snape Maltings Concert Hall in collaboration with composer Benjamin Britten, the renovation of the Buxton Opera House, Covent Garden Royal Opera House, and the Glasgow Theatre Royal. In 1994, he collaborated with Michael Hopkins and Partners, (now Hopkins Architects), to design the new Glyndebourne Opera House - a notable milestone, along with the Plymouth Civic Theatre, as it signifies a turning point in opera house design, where the focus of design was more to create an intimate opera space to the scale of human voice, rather than an oversized auditorium with compromised acoustical qualities, which had been a trend in the middle of the century to popularize the genre.

2.1.1 New Avenues for Acoustical Design (1980-2000)

In 1980, following several decades of work in the field of acoustics, Arup Acoustics was officially launched[3] by Derek Segden and recently appointed partner Richard Cowell, joining from Sound Research Laboratories (SRL). Together they gave shape and grew the dedicated acoustical practice globally. Richard was both an architect and acoustician by education and training, who bridged the humanist design of Derek with contemporary acoustical research. Richard was always keen on exploring new avenues for design, and he introduced at Arup Acoustics this desire to expand beyond the status-quo. For the Plymouth Civic Theatre (1982), he was responsible for including sound reinforcement under deep balconies, a ceiling which can be lowered, an orchestra enclosure formed from structural fabric stretched on screens, an inflatable overhear reflector, and a 90-channel assisted resonance system, (building on the work he had developed previously with Peter Parkin and Henry Humphreys[15]). He later worked on the refurbishment of the Brighton Dome using the Carmen active reverberation system, the London Royal Opera House, and the English National Opera. In 1993, Richard Cowell helped young architect Zaha Hadid to develop the design of her competition winning scheme for Cardiff Bay Opera House.

Digital as well as physical scale modeling tools significantly grew during the 1980's and 1990's, when Raf Orlowski first joined Arup Acoustics. Raf greatly expanded Arup Acoustics digital and scale modeling capabilities, particularly at more challenging scales (1:50), which were applied to the Glyndebourne and subsequently, Oslo, and Copenhagen opera houses, various concert halls, and large-scale transportation projects. This led to the first auralization experimentations conducted by Raj Patel and Neill Woodger in the mid 1990's.

2.1.2 A Modern Opera House Archetype (1995-2010)

Each period of the practice merged in the late 90's with Rob Harris, who celebrated the lyric character of opera house design. Following from his collaboration with Derek Sudgen on the Glyndebourne Opera House, Rob led the design of the Oslo and Copenhagen opera houses[4]. Both are designed as major platforms for international touring opera performances, with fully equipped staging systems, complete set of practice and rehearsal rooms, and maker shops. Resembling small cities, with hundreds of people transiting through the facility every day, they became international benchmarks for new opera theatre design.

Both houses are designed with a moderate seat-count[5,6] expanding from the Glyndebourne opera house precedent, and incorporate features from concert hall design that would enhance the musical and symphonic qualities of mid-19th century opera house archetypes, often characterized with deep orchestra pits and cavernous audience balconies.

In Copenhagen and Oslo:

- The floor plans follow a horse-shoe shape at the rear, with straight balconies on the side, and forestage walls resembling a shoe-box for sound projection and lateral sound
- The walls are made of heavy timber construction for tonal quality, and preserve the bass for dramatic effects, while older opera houses tended to have lighter walls[9]
- The pit is fully open to the auditorium to liberate the full symphonic sound of the orchestra
- A large orchestra reflector covers the pit for ensemble support, as in a concert hall
- Motorized acoustical curtains, generally used in concert halls, can be deployed along the walls of the balcony to reduce reverberance and adapt acoustics to different musical styles or opera repertoire
- Oslo opera house is designed with a 2.0 second occupied reverberation time, following the goals set from the client to favor the post-romantic repertoire, similar to a symphony hall
- Balcony fronts are shaped to project sound towards the audience balconies, and prevent from echoes from sound systems

The completion of these projects was followed by the design of the Wexford National Opera House[7], which will continue the trend towards smaller and more intimate opera theatre auditorium, and the Wales Millennium Centre in Cardiff, which will progress the integration of adjustable acoustics to accommodate amplified music within an opera theatre.

2.1.3 Designing Through Listening (2010-now)

Advancements in computer processor and modelling technics, and internal investment funds culminated in the late 1990's with the creation of the Arup SoundLab, pioneered in New York by Alban Bassuet, Neill Woodger and Raj Patel. While designing new spaces would typically require traveling to several venues to identify benchmarks, ambisonic outputs from computer models, or Soundfield recordings were used in the SoundLab to compare real and virtual spaces. Paired with parametric design and hundreds of design iterations, auditoria projects are progressed and optimized through listening tests with design teams and clients, to better designate design goals, and fine-tune design outputs prior to construction.

Modern technology was also used to study the lesser-known acoustical features of old halls that proved to be successful over multiple centuries, including a selection of renowned baroque opera houses[9], which were part of the 150 historical European spaces tested for the Constellation Research[8]. The research highlighted the role of materials, proscenium geometries, scale and wall shaping in the acoustical achievements of these halls both for opera and music, and became influential in subsequent Arup opera house designs, including the Wexford Opera House, and ultimately the opera house of the Stavros Niarchos Foundation Cultural Center.

3 OPERA THEATER AUDITORIUM ACOUSTICAL DESIGN

Our team began the design of the new opera house for SNFCC by contrasting Arup opera house designs with the architect's vision for the whole project, historical Greek precedents, and the present local Greek culture. The brief asked for the first purpose-built state-of-the-art opera house in the country able to present touring international productions. The design would have to be innovative, inviting, warm, intimate, flexible allow different opera repertoires and amplified music events, designed through listening, and grounded in Greek history.

As detailed in previous publications, the team led reviews of Greek music historical context, and acoustical measurements in venues currently used in Greece by the Greek National Opera (Olympia Theater, Megaron Alexandra Trianti, Epidaurus and Herodium amphitheaters). The inspirations for the overall shape and geometry of the auditorium gravitated towards a design that would bring together the acoustical features of some of the most renowned opera theatres to give Greece the opera house that it never had, and pay tribute to the significant contribution of Greek ancient culture to opera and the science of theatre design.

Building on Oslo and Copenhagen, the design aimed to maximize attributes such as intimacy, symphonic reverberance, singing clarity, envelopment, and tonal quality. The design moved towards the Semperoper and Teatro Colon, both recognized internationally as having the preferred acoustics for opera[11]. Both precedents bring together a smaller number of rows per balcony (two to three), limited balcony overhangs, and large openings between the balcony and the main auditorium to acoustically engage the main drum of the auditorium with the volumes of the balconies into a unified acoustical volume, and provide early reflections from the balcony walls, often occluded by deeper balconies. Open and shallow balconies along a circular plan shape were in fact the common features of 19th century German opera houses[12], inspired by Greek ancient theaters, such as the Schauspielhaus (1821), Carlsruhe, Munchen, Hamburg and Mainz opera houses. These precedents served as the basis for Semperoper and its acoustical achievement, and as inspirations for our design, which closed the loop between Greek's ancient theaters and the new opera house for SNFCC.

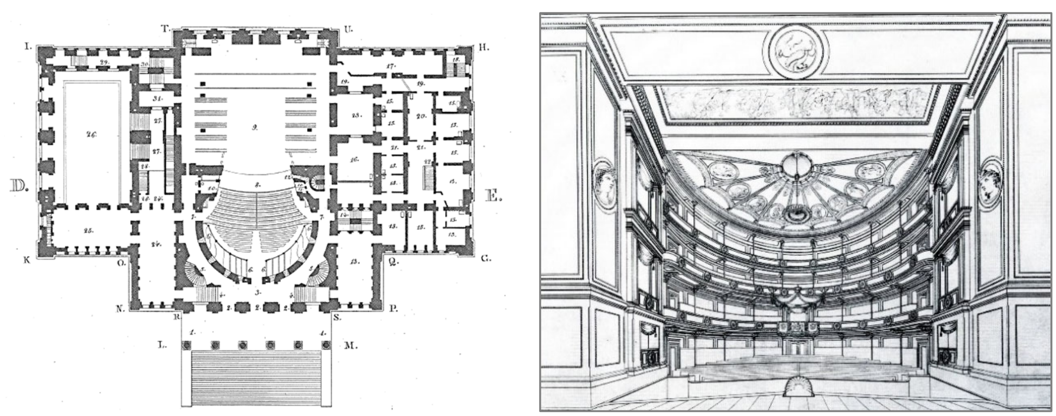

Figure 1: Floor plan and perspective view of the Berlin Schauspielhaus, Karl Friedrich Schinkel (1821)

To distribute sound reflections within the balconies, and prevent focusing, the team took inspiration from an acoustical survey of the Epidaurus amphitheatre, and particularly from the repetition of the stone stepping combined with the shallow seating rake, which creates a sense of reverberance, as well as envelopment and proximity. We used a similar repetition pattern along the walls and under-balcony surfaces. Small corners provide local early reflections, while convex scallops distribute sound towards the rear behind the audience's heads, as a "sliding" acoustical effect along the perimeter of the auditorium. The return of sound from all the wall shaping can also be felt on stage for singing support, as it can be experienced at the center of Epidaurus' performer area.

Noise regulations in orchestra pits, and a desire to improve the musical sound of the orchestra in opera theatres have resulted in eliminating stage overhangs, and in pushing the orchestra further into the auditorium. While useful to reduce sound levels in the pit, this move can impact the balance between singers and orchestra in the auditorium - which can grow up to 110 musicians for some larger post-romantic compositions - and for the orchestra to occupy more than half of the audience's field of view to the stage, with the risk of un-balancing the set-design spectacle. In SNFCC, the opera house is designed with 4 orchestra pit lifts, and a 2.5m stage overhang, laid with acoustical ceiling panels. The pit can then incrementally grow towards the audience depending on the size of the orchestra while maintaining the musicians close to the proscenium line, avoiding un-necessary empty pit spaces, and with some of the orchestra loudness controlled by the stage overhang and acoustical panels.

Taken from baroque theaters, which used deep proscenium frames to create perspective effects and voice projection[9], the proscenium and forestage areas at SNFCC are connected into gradual frames projecting singing voices into the auditorium, and helping with ensemble support.

To reinforce the symphonic and dramatic orchestra sound, the walls are constructed with multiple layers of timber tightly bonded and glued together to achieve $100kg/m^2$ surface density to preserve the bass, as in a modern symphony hall. The high-quality finish and challenging construction of the wall panels was realized by local Greek contractor Epexyl Architectural Interior Fit-out, using parametric, cut-to-shape, and vacuum pressed MDF boards.

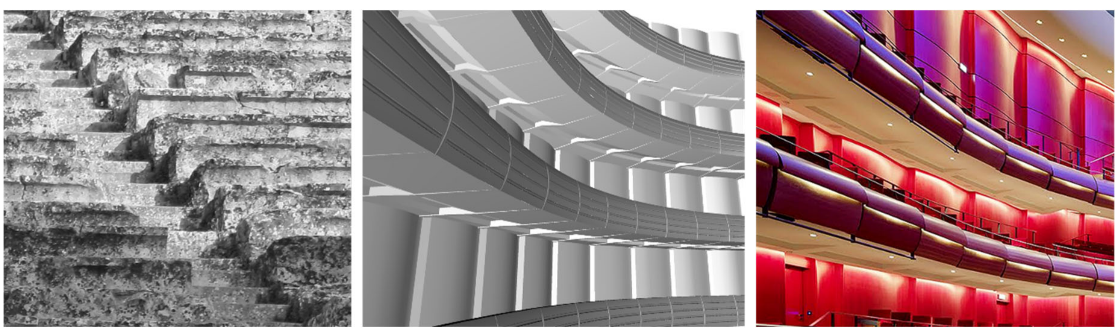

Figure 2: Steps at Epidaurus used as inspiration for the wall and under-balcony shaping at SNFCC – close-up view of the steps, acoustical model of the walls, and final construction.

Figure 3: View to the front and the rear of the opera house at SNFCC[13]

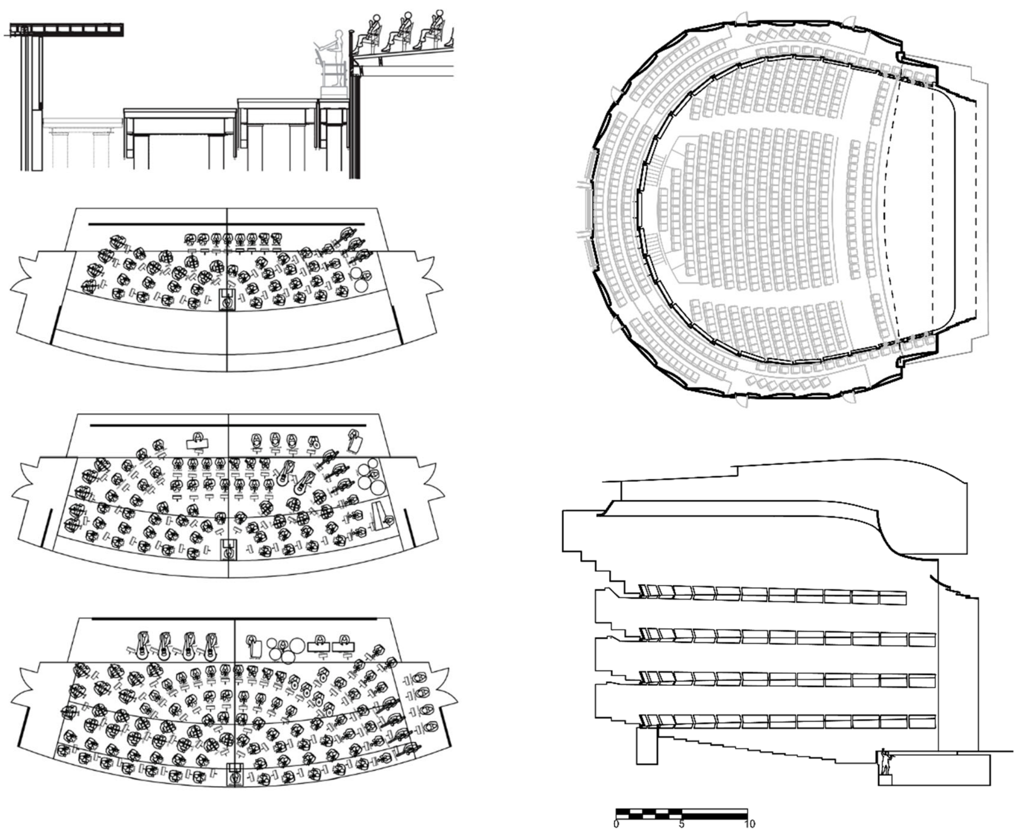

Figure 4: Pit lift configuration examples to maintain the orchestra close to the proscenium line. Plan and section of the opera house to the right.

4 BENCHMARKS COMPARISON

The team conducted acoustical measurements in the finished spaces, and the complete results were published at the 2018 Institute of Acoustics Conference in Hamburg, Germany[2].

In this section, we summarize the final acoustical performance of the opera theatre, and compare the results with a selection of both opera houses and concert halls often used as benchmarks for new designs. An objective is to contrast the differences with other opera theatres and to propose desirable target ranges for traditional proscenium-type grand opera. The second is to contrast the sound aesthetics between opera theatres with different concert hall typologies to observe potential overlaps, since concert hall design has grown its influence into the design of opera houses. Acoustical performances are presented in terms of objective and subjective metrics, and spatial energy distribution.

4.1.1 Objective and Subjective Parameters

The table below summarizes the commonly used objective acoustical parameters used to describe acoustics for opera.

	Targets	SNFCC	OSL	COP	SEM	MET
RT	1.40s – 2.00s	1.80s	2.10s	1.40s	1.70s	1.15
$RT_{w/Ac.\ Curtains}$		1.30s	1.50s			
EDT/RT_{stage}	85% – 100%	90%	85%	70%	98%	97%
EDT/RT_{pit}	85% - 100%	92%	89%	82%		
G_{mid}	0.0dB - 3.0dB	2.2dB	0.0dB	0.7dB	2.7dB	0.4dB
G_{diff}	0.0dB - 2.0dB	0.4dB	-1.2dB	-2.3dB	1.0dB	-1.3dB
BR	1.0 - 1.25	1.10	1.10	1.21	1.23	1.0
$D50_{stage}$	45% - 65%	51%	50%	62%	50%	58%
$C80_{pit}$	-3.5dB - 0.0dB	-2.1dB	-2.0dB	2.1dB	-3.0dB	0.45dB ±3.2dB
ITD	15ms – 25ms	17ms				23ms
$1\text{-}IACC_{early}$	0.60 – 0.75	0.64	0.60		0.72	0.62

Table 1: Proposed target ranges of excellence for traditional proscenium-type grand opera, and measured occupied performances for SNFCC, Oslo, Copenhagen, Semperoper, and the New York Metropolitan opera houses. Parameters (including ITD) are averaged across stalls and balconies. D50 values assume a 10% increase due to human voice directivity.

The measured acoustical performances in SNFCC successfully align with the target values taken from Semperoper. A higher envelopment is measured in Semperoper, which could be a consequence of the shallower balconies being more acoustically engaged than in other theaters, (2 rows per balcony in Semperoper, instead of 3 in SNFCC), and additional wall shaping and ornamentation along the balcony fronts and walls.

There is a wide range of reverberation times when comparing all the venues. Reverberation time in the MET is lower due to its large seating capacity. To fit the larger audience, the walls and the ceiling are pushed further away from the audience and the singers, which impact the singing/orchestra balance and intimacy indexes. In the MET, the shorter reverberation time of the main opera house drum is compensated by the high running reverberance created by the acoustics within the larger and more open balconies. This is a design alternative for high seat-count theaters (> 2,500), which aims to create localized reverberation within each seating section - a trend in mid-century American halls, (e.g. Carnegie Hall Radio City Hall).
As a recommended target range for reverberation time, we will focus on moderate seat-count typologies (1,200 < seat count < 2,200). We use Copenhagen as the lowest recommended reverberation time limit, and Oslo as the upper one, which was specifically designed to accommodate Wagner operas and long dramatic reverberations.

The recommended target range for the loudness index ranges from 0 to 3dB. Loudness values below the MET (<0dB) could result in difficulty in hearing the singers. Higher loudness values could result in overpowering orchestra sound, particularly for the large post-romantic orchestra forces. The ideal loudness difference between the stage and the pit in the auditorium is one of the most difficult criteria to achieve. It is influenced by the globality of the acoustical design. Too high (> 2dB), the orchestra sound could be perceived as being suppressed in comparison to singing voices, as if located under a deep overhang; too low (<0dB), the orchestra could overpower singing voices.

A bass ratio above 1.25, whilst desirable for symphonic music could lead to excessive bass in relation to singing voices.

For singing clarity, all the venues converge towards an optimum value of 50%. We propose an ideal target range between 45% to 65%, with the upper limit as measured in Copenhagen, which could sound overly direct and frontal above that limit.

Subjective parameter diagrams below are shown as overlays with the proposed objective parameter target ranges, and comparison with the SNFCC opera house (dark grey curve).

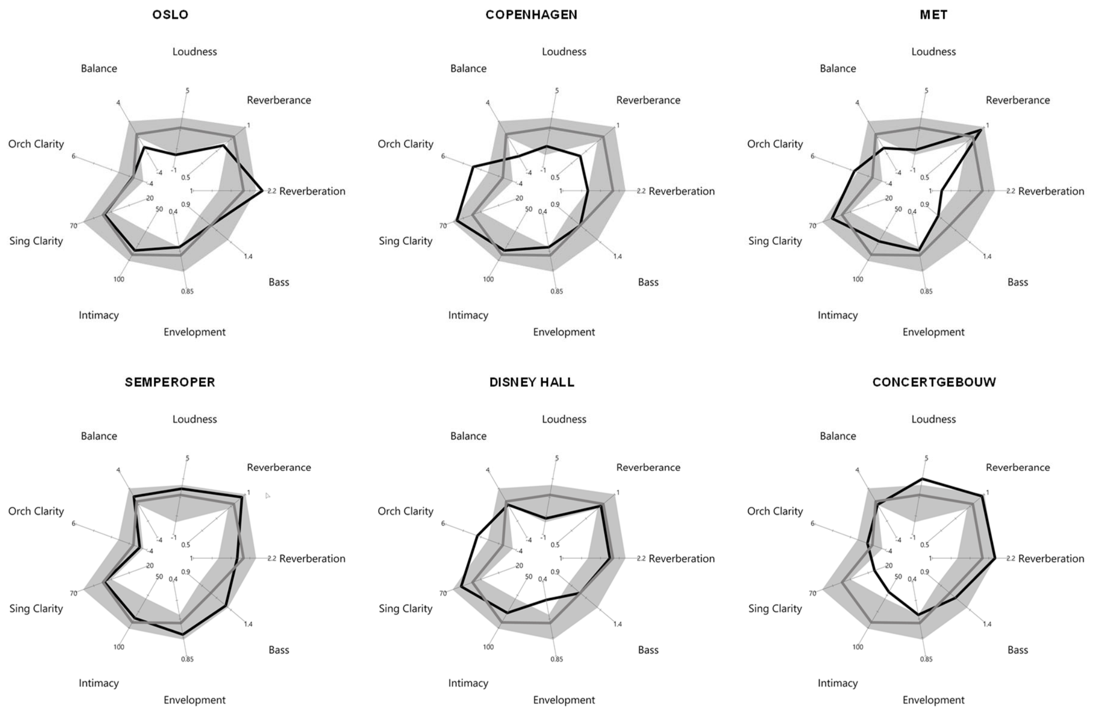

Figure 5: Mapping of subjective parameters. Grey area: optimum ranges for traditional proscenium grand opera. Grey curve: SNFCC.

The diagrams aim to give a visual representation of the sound aesthetic of each hall: Oslo as a dramatic reverberant venue, Copenhagen as clear and intimate venue, the MET as a clear, live, and frontal experience, and Semperoper, which appears as an ideally balanced opera house auditorium's acoustics. There are of course important variations around these trends between different seating sections, but these results encapsulate the acoustical nature of the spaces generally well.

It is interesting to observe the performance of Disney and Concertgebouw overlaid with the opera house target ranges. The Concertgebouw is well outside the desired target range for singing clarity, intimacy and envelopment, but relatively on target for the other parameters. A vineyard hall such as Disney Hall better fits the desired opera house target ranges, due to its higher clarity - not surprisingly since a surround hall naturally brings the audience around and closer to the stage as in an opera house. We further discussed these results in the final sections.

4.1.2 Spatial Distribution

The spatial energy distribution is calculated from Soundfield microphone measurements conducted by Arup. The acoustic intensity is then added within spatial segments[10], by separating the lateral and on-axis energies, and summing the acoustic intensity within 5 vertical segments. This results in 20 lateral segments, (10 front-lateral, 10 rear-lateral), and 10 on-axis segments, (5 rear and 5 frontal).

Spatial distribution diagrams for representative positions in the stalls are shown below.

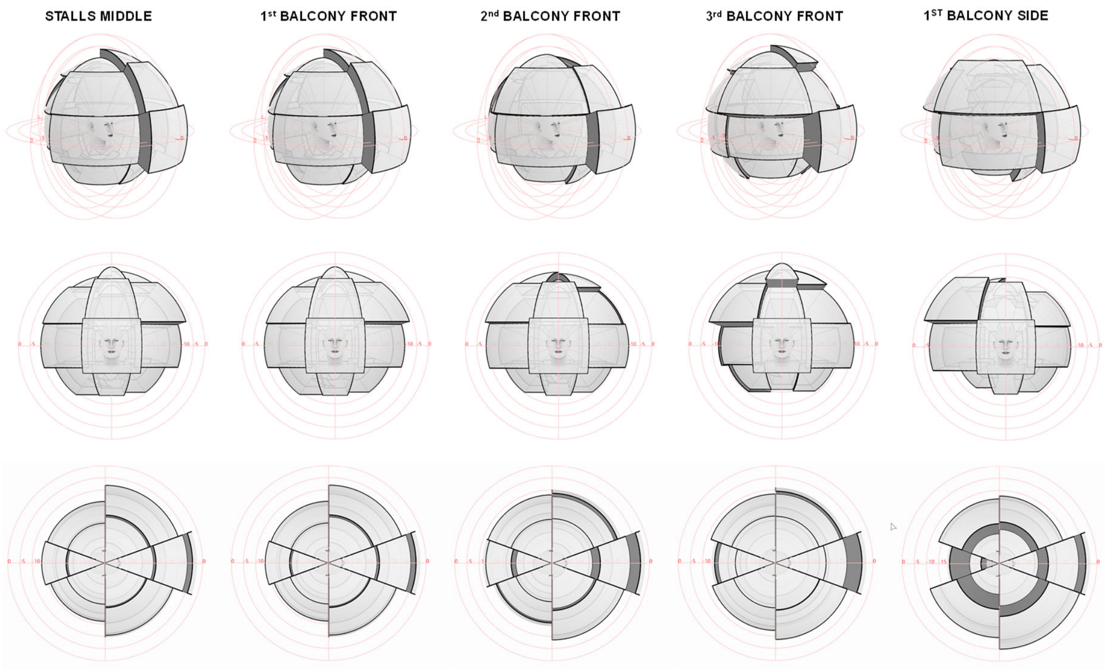

Figure 6: Spatial energy distribution at representative locations in SNFCC

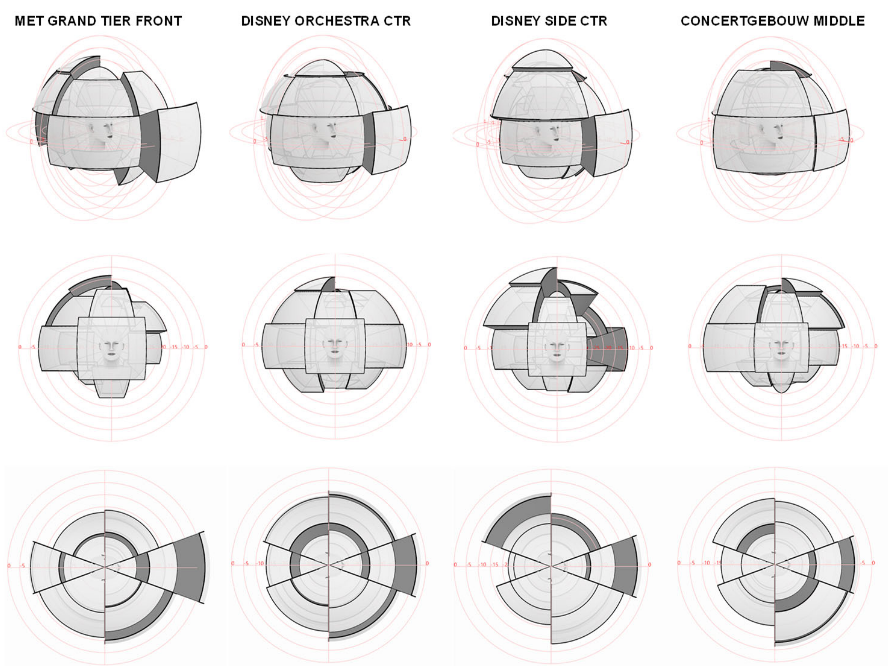

Figure 7: Spatial energy distribution for a selection of positions in the Metropolitan Opera, Disney Hall, and the Concertgebouw

We note that the spatial energy distribution in the various sections of SNFCC are evenly distributed, with lateral energy coming from both sides and the rear, including for a position in the middle of the side balcony section. The frontal energy rises by approximately 5dB above the rest, which helps for the impression of clarity. These results indicate a very immersive acoustical experience, and demonstrate the effect of the shallow balconies and wall shaping being acoustically engaged with the main drum of the opera theatre auditorium. The spatial distribution even shares similarities with the response measured in the middle of the Concertgebouw, (lower direct contribution there).

The direct sound is stronger in the MET, as indicated by the singing clarity value. There is a notable amount of energy coming from the rear, which demonstrates the effect the acoustical build-up within the MET Grand Tier section. The response is more lopsided, due to the width of the balcony and distance attenuation.

Interestingly, the spatial distributions in SNFCC share similarities with some of the orchestra sections in Disney Hall, but seating positions to the side of the stage in Disney Hall show lopsided responses due to the un-even geometries that surround them. A consequence comes to mind: to improve the richness of surround halls, sound reflecting and diffusing surfaces could be more deliberately laid out around blocks of audiences surrounding the stage, to replicate the effect of shallow balconies of the opera theatre.

5 FUTURE DESIGN – IMMERSIVE VENUES

Comparing opera theatres with concert halls, as shown above, yields a question, if concert halls are influencing the design of opera theatres, could the design of opera theatres influence the design of new concert halls? There is a very clear trend for vineyard concert halls, which aim to bring the audience closer to the performers, concentrating the focus of the audience and performers together into a visually exciting architectural environment. However, their acoustics are often questioned due to a lack of richness compared to the more elongated concert halls naturally promoting lateral sound and quicker reflections. As it can be seen on the above diagrams, the opera house naturally promotes intimacy and envelopment. The best ones, such as Semperoper and Teatro Colon achieve this result by surrounding the audience with sound using shallow balconies - while noting that Semperoper is more often used for symphony than traditional opera. Therefore, could vineyard or large concert halls be improved by breaking down seating banks into smaller groups, and introducing acoustical surfaces within the auditorium? And could the convergence of the concert hall and opera house archetypes serve as a model for new immersive spaces?

This is a question that our team continues to explore in past and recent projects. For example, concert halls have often used the same outer envelope to promote reverberation and early reflections. By divorcing the two acoustical effects, an outer shell can be responsible for reverberation, while a carefully crafted inner acoustical shell, like the shallow balconies of an opera house, could create early reflections for intimacy, clarity, and envelopment, as schematically indicated below. Such an approach can also open new design avenues for immersive lighting and sound systems.

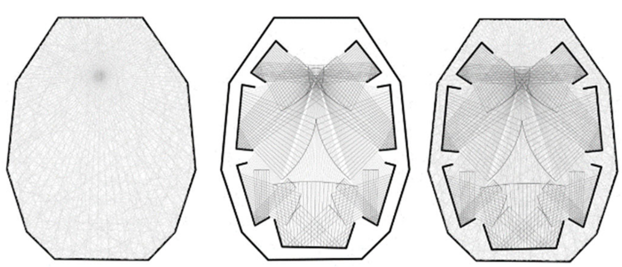

Figure 8: Inner / outer shell venue concept converging opera house and concert hall designs

An early experimentation of this concept can be found in the Bridgewater Hall in Manchester, from the work of Derek Sugden and Rob Harris[4] in the early 1990's, which breaks-up the audience into vineyard blocks with reflecting surfaces detached from the outer envelope of the hall. A more recent precedent is our original design for the new Brown University Performing Art Center, used for symphonic music, opera, and dance, using audience towers set inside a larger volume surrounding the audience with immersive technology.

Building a new concert hall or an opera house can be financially out-of-reach for some organizations. We are also exploring the design of lightweight and low-cost acoustical shells that can be deployed inside warehouses or industrial spaces, taking advantage of the overlap of both acoustical effects.

Figure 9: Left - Deployable acoustical shell inside an industrial space (Waterfire Arts Center, Providence, Rhode Island), Middle – Surround venue scheme for the Sinfonia Varsovia concert hall competition (SO-IL Architects), Right – Concept for the new Brown University reconfigurable venue space, and immersive sound system (opening 2023)

Immersive venues are a modern trend for new concert halls, opera theatres, lyric and drama theaters, xR performance spaces, and art installations[14]. The role of technology continues to grow in contemporary productions, and younger audiences are expecting to become participants in a field of experiences, rather than be a distant spectator under a deep balcony. A potential avenue for design offered in this study is to consider architectural acoustics as part of the phenomenology of audience immersion, one that can satisfy the acoustical requirements of multiple music genres, while allowing early on in the design process real-estate for technology.

Opera has always been a manifestation of the convergence of music, storytelling, and contemporary technology – from painted sceneries, to flown scenery sets, video projection, singing robots, and VR effects – and the authenticity of natural acoustics still has an important role to play. Combined with adjustable acoustics, distributed immersive and spatial sound systems, immersive architecture, and a range of formal and informal experiences, we hope that SNFCC can serve as a model for new designs that continue to bring audiences together to celebrate live performance.

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