Seat Sublime: A Recommendation System to Accommodate User Preference in Concert Hall Seating Selection

Jeremy Rothman Salesin

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Tomás Méndez Echenagucia

Robert Peña

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ABSTRACT

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Jeremy Rothman Salesin

Chair of the Supervisory Committee:

Tomás Méndez Echenagucia

Department of Architecture

Most research on the "performance" of concert halls focuses on the acoustical performance of the hall. The 3382 ISO standard for performance spaces identifies certain key acoustical metrics for the hall, which are generally calculated as averages for the entire hall. Designers of the hall must also accommodate requirements to provide a certain number of seats, to provide better audience sight lines and seating closer to the stage, and to surround the hall with the many amenities required of modern halls. The result will always represent to some degree a set of compromises, yielding a diversity of different experiences depending on where one is seated in the hall. The "average" measure of performance space acoustics based on the 3382 ISO standard thus ends up not describing the musical concert-going experience for the individual attendee, and even if it did describe the acoustical experience, does not in any way capture the total experience of attending a concert in the hall. There is currently no standard or system that addresses all these factors together, yet research shows that the emotional experience of attending a concert

may be derived at least as much from the visual aspects of the performance as the acoustical aspects.

This research suggests that the design of concert halls, their ongoing management, and the concertgoer experience could be improved if the acoustical, visual, and physical seating experiences in the hall were matched to the individual concertgoer's preferences. This research further identifies and demonstrates the parameters that might govern such a system. The recommendation system proposed could be used in the design, management, and sale of tickets for concert halls to provide recommendations depending on the identified preferences of constituents, the known characteristics of the hall, and even the music to be performed in a particular concert. In any case, understanding that the concert experience is a combination of many factors, and that the seats in the hall can be selected to deliver a different experience based on the preferences of the concertgoer, could help foster a more holistic, conversation about concert hall design.

TABLE OF CONTENTS

1. INTRODUCTION 1
   - 1.1. OVERVIEW 1
   - 1.2. PROJECT RATIONALE – IS INDIVIDUAL SEAT VARIATION A "BUG" OR A "FEATURE" OF CONCERT HALLS? 3
   - 1.3. THESIS OVERVIEW 4
   - 1.4. AUDIENCE MEMBERS – WHO ARE THE AUDIENCE MEMBERS AND WHY DO THEY ATTEND A LIVE MUSIC PERFORMANCE? 5
   - 1.5. HUMAN HEARING 7
   - 1.6. RECORDED MUSIC VS. LIVE MUSIC – RELATIVE SOUND QUALITY 9
2. LITERATURE REVIEW 13
   - 2.1. CONCERT HALL DESIGN 13
     - 2.1.1. Historical Background 13
     - 2.1.2. Listener Acoustical Preferences Diverge 16
     - 2.1.3. Prior Concert Hall Seating Recommendation Systems 18
     - 2.1.4. Impact of Visual Input on the Emotional Experience of Live Music 19
     - 2.1.5. Why Build a New Concert Hall? 20
     - 2.1.6. The Rise of the "Vineyard" Style Hall 22
     - 2.1.7. Acoustical Differentiation of Vineyard Versus Shoebox Concert Halls 24
     - 2.1.8. Other Preferences (accommodation for physical differences, stairs, seats, aisles, proximity to restrooms, coat check, exits, price) 25
   - 2.2. RECOMMENDER SYSTEMS 26
   - 2.3. CONSTRAINED OPTIMIZATION 29
3. METHODOLOGY 30
   - 3.1. GOALS AND OBJECTIVES 30
   - 3.2. DESIGN METHODS AND TOOLS 32
     - 3.2.1. Visual and Physical Pipeline 35
     - 3.2.2. Acoustical Pipeline 37
     - 3.2.3. Benchmarking Acoustical Seating Data 40
     - 3.2.4. Scoring and Visualization Pipeline 41
   - 3.3. LIMITS OF THE INVESTIGATION 44
4. FINDINGS 44
   - 4.1. SYSTEM OUTPUT 45
   - 4.2. SPECIFIC EXAMPLES BASED ON SURVEY DATA 51
   - 4.3. VISUAL SIGHT LINES 55

5. CONCLUSIONS AND RECOMMENDATIONS 59

5.1. DESIGN PROCESS ENHANCEMENTS 59
5.2. IMPROVING MANAGEMENT OF THE HALL 59
5.3. ASSISTING PERFORMING ARTS ORGANIZATIONS 60
5.4. IMPROVING THE CONCERT EXPERIENCE 61
5.5. FUTURE WORK 62

ENDNOTES 64

BIBLIOGRAPHY 77

APPENDIX 1: SURVEY QUESTIONNAIRE 82

APPENDIX 2: MUSIIKKITALO SEATING PLANS 83

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LIST OF FIGURES

Figure 1: Hearing Level by Median Age 8

Figure 2: Sample Rates 10

Figure 3: Table of Concert Hall Openings 21

Figure 4: Concept Drawing and Seating Plan for Berlin Philharmonie. 23

Figure 5: Overall System Flow 32

Figure 6: Survey Questions 33

Figure 7: Overall System Processing Flow 34

Figure 8: Musiikkitalo Rhino Model 35

Figure 9: Musiikkitalo Model with sight line obstructions and seat characteristics 36

Figure 10: Seat Characteristic Generation Flow 37

Figure 11: Musiikkitalo model in Treble Technologies Tool 38

Figure 12: Comparison of Lokki versus Treble Acoustical Results 40

Figure 13: Example of Overall Seat Score Display 42

Figure 14: Closeup of Seat Scores Shown on Model 43

Figure 15: Grasshopper Seat Picker Controls 43

Figure 16: Color Scale 45

Figure 17: Acoustical Preference Seat Scores (ECVR weighting) 46

Figure 18: Visual Seat Scores Only (Soloist's Face) 47

Figure 19: Combined Acoustical and Visual Scores (equal weighting) 48

Figure 20: Distance to Bar Scores 48

Figure 21: Acoustical, Physical, and Visual Scores Combined (equal weighting) 49

Figure 22: Acoustical, Physical, and Visual Scores Combined (weighting in that order) 50

Figure 23: "Josh" Seat Preference Map 51

Figure 24: "Josh" Top 100 Seat Scores 52

Figure 25: "Alex" Seat Recommendation Map 53

Figure 26: "Alex" No Balcony Preference Seat Recommendation Map 54

Figure 27: "Kate" Seat Recommendation Map 54

Figure 28: "Dianne" Seat Recommendation Map 56

Figure 29: Number of “Head” Obstructions in Musiikkitalo. 57

Figure 30: Vienna Musikverein Main Floor “Head” Obstructions. 57

Figure 31: Vienna Musikverein Venue Seating Plan Identifying Obstructed Views. 58

1. INTRODUCTION

1.1. Overview

> "The best adventure, for an architect, is to build a concert hall. Perhaps it is even nicer for a luthier to build a violin; but it is (with all the differences in size and use) very similar activities. After all, it's always about building tools to make music and listen to music. It is the sound that commands, it is the sound box that must know how to vibrate with its frequencies and energy."
> – Renzo Piano[1]

Architects surely love to design concert halls, but the undertaking of bringing those designs to fruition is immensely expensive and politically fraught, so why do cities build concert halls? Fundamentally, concert halls are a driver of civic pride, urban renewal, musician training for the next generation, and ultimately tax dollars gleaned from tourism and entertainment in the cities in which they are built. To most effectively serve their function, concert halls must attract the finest musicians, high quality soloists and conductors, concertgoers and tourists. To accomplish this, it is helpful if the hall is both a visual icon and a hall renowned for high quality acoustics, and one in which musicians want to perform and attendees enjoy the experience.

How should an architect go about designing a hall that meets these goals? The designer tries to keep in mind multiple key factors that influence the user experience in the hall (where user is primarily defined as the concertgoer, but also includes the musicians and conductors) – acoustical, visual, and physical (the amenities of the hall and its seating). But this paper acknowledges and argues that even if all these factors are taken into account, there will always be variations in the experience based on different seats selected within the hall, and therefore a system that reveals to the designer and the concertgoer the difference between those experiences would maximize concertgoers' satisfaction with the experience in the concert hall.

Most research on the "performance" of concert halls focuses on the acoustical performance. The 3382-1 ISO standard for performance spaces identifies certain key acoustical metrics for the hall, which are generally calculated as averages for the entire hall.[2] Commentators have offered additional methods for assessing acoustical performance in different locations in the hall,[3] but these methods have not been widely adopted. Meanwhile, additional demands are made on the designers of halls to accommodate a certain number of seats, to provide better audience and musician sight lines and seating closer to the stage, and to surround the hall with the many amenities that are required of modern halls. Conductors may insert their preferences as well.[4] The result can be a compromise of architectural and acoustical requirements, yielding a diversity of different experiences depending on where one is seated in the hall.

The "average" measure of a performance space based on the 3382-1 ISO standard thus ends up not describing the musical concert-going experience for the individual attendee, and even if it did describe the acoustical experience, does not in any way capture the total experience of attending a concert in the hall. There is currently no standard or system that addresses all these factors together, yet the concertgoer experience could be improved if the acoustical, visual, and physical experience in the hall were matched to the individual concertgoer's preferences. This thesis examines the parameters that might govern such a recommendation system and proposes a system that could be used in concert halls to provide customized seating recommendations to patrons depending on the characteristics of the hall and the music to be performed in a particular concert.

1.2. Project Rationale – Is Individual Seat Variation a "Bug" or a "Feature" of Concert Halls?

Today the variation of concert experience between different seats in a hall is treated as a 'bug.'[5] That is to say, as in computer programming, if seats vary from the average calculated for the hall, the variation is not an intended consequence of the design. The ISO standard identifies hall averages and assumes that even though the experience may differ at different locations in the hall, the average can describe the suitability of the experience in the hall for all attendees.[6] This approach has been criticized by various commentators whose work will be discussed in more detail below.[7] But even if the average did describe the actual experience in all seats in the hall in all material acoustical respects, the individual concertgoer's acoustical preferences may differ, as will their reasons for attending the concert and therefore their evaluation of the ideal seating location based on other factors such as sight lines and proximity to amenities. The ISO standard uses spatial averages to describe the concert halls, and averages listener preferences to describe "ideal" acoustic conditions. Thus, the experience of the individual in the hall may vary from the "ideal" for that individual and in this sense can be seen as a 'bug' in the hall – delivering a less-than-ideal experience for that concertgoer. If a system existed to fully inform concertgoers of the experience they would receive based on the seat they select, the variation between seat experiences could be turned into a 'feature,' rather than being a 'bug' in the design.

1.3. Thesis Overview

This thesis proposes a theoretical framework for a recommendation system that could identify appropriate seat locations for a concertgoer based on known characteristics of the venue and known (or self-proffered) preferences of the individual concertgoer. The reward for using such a system would be enhanced user satisfaction of concertgoers attending a performance at a venue. In addition, if concertgoer satisfaction with the venue is increased by sitting in a location that best matches concertgoer preferences, concertgoers may be more inclined to return to the venue, and the venue and performers may thus be able to sell more tickets and also sell seats that otherwise might not be viewed as desirable in the absence of knowledge of the true benefits and drawbacks of those seats. The system may also allow more informed pricing of seats based on popularity of seats as identified through use of the recommendation system. In the future, this system could be implemented as a Software as a Service (SaaS) offering to ticket selling services, concert hall operators, or performing arts organizations utilizing venues, allowing them to better connect with and understand their customers and meet their needs. Designers would benefit from the availability of such a system in order to test the variations between seats during the design process, and review alternative designs with their clients, illustrating the impact of various design choices.

This thesis will first address some preliminary matters as underpinnings to the detailed discussion – why do humans still care to attend live musical performances when so much recorded music is available at their fingertips, and so much technology exists to deliver that music directly to their ears? If the motivations for attending live performance can be better understood, the system proposed here can be tuned to help deliver that experience. Section 2 below reviews relevant literature, finding that there is abundant reason to conclude that concertgoer preferences diverge acoustically, and that visual factors are also key to emotional engagement in a performance. Section 2 also touches on relevant concepts in concert hall design, recommender systems and constrained optimization problems. Section 3 explains the methodology used in constructing the Seat Sublime system proposed in this research, and findings from use of the system with actual surveyed concertgoer preferences are discussed in section 4. Finally, the conclusions and recommendations are presented in section 5.

In short, people attend live music because it connects with audiences in ways – both emotional and acoustical – that recorded music cannot. Architectural designers benefit from keeping this in mind as they consider designs for concert halls.

1.4. Audience Members – Who Are the Audience Members and Why Do They Attend a Live Music Performance?

Attending live musical performances lowers stress hormones,[8] contributes to positive mental feelings,[9] reduces the audience's stress more as compared with listening to recorded performance,[10] and is associated with "superior attention and temporal entrainment."[11] Further, a survey of 20,000 concertgoers ranging in age from 13 to 65 surveyed across 11 countries found that music rated ahead of hometown, politics, race, or religion in defining respondents most as a person.[12] "[R]espondents reported feeling less emotionally intense while streaming music (-27%) or while playing video games (-31%). And respondents reported that they were 10% more likely to value live music over sex."[13]

While these statistics are gathered from attendees of other forms of live music beyond symphonic concerts, there is also research specifically on classical music attendees. This research, discussed further below, also indicates that the emotional experience of combining the visual with the acoustical – in being able to see the performer – as much as doubles the emotional experience of hearing the music in classical music performances.[14]

"Data from opinion polls [in Germany] suggests that the proportion of [classical music] concertgoers in the overall population amounts to roughly 28 per cent. In the course of a year some 44 per cent of the population will attend at least one event with (primarily) classical music, meaning opera, classical concerts, organ and choral recitals, musicals, dance and ballet."[15] A 2023 survey found that out of 2,000 people surveyed by the Royal Philharmonic Orchestra in the UK, 84 percent of people were interested in experiencing an orchestral concert, up from 79 percent of the population surveyed in 2018.[16]

"Roughly 10 percent to 15 percent of Americans have what might be termed a close or moderately close relationship with classical music, and again as many have weaker ties."[17] While this is a small subset of the overall concert-going population, they are often driving attendance of a larger group:

> "Indeed, the study paints a picture of a largely invisible "shadow audience" for most orchestras — people who've attended concerts but who did not buy their ticket and may not have participated in the

> purchase decision process. Results … indicate that, on average, 40 percent of those who've ever attended a concert by their local orchestra did not (and have never) purchased a ticket."[18]

This finding has important implications for the determination of what constitutes the ideal experience in the concert hall – if attendees are not there entirely for the music, but rather for the social experience, might they be less attuned to the acoustics of the hall and more interested in the visual pageantry, social aspects of attendance, and other amenities of the hall besides the musical experience in and of itself? This difference in motivation for attendance likely has implications for seat selection in the hall relevant to this thesis.

1.5. Human Hearing

The means by which humans hear is also relevant to this analysis because humans are more sensitive to sounds at certain frequencies, and more apt to lose the ability to hear higher frequencies as they age. The physical process of human hearing has been well summarized as follows:

> We can hear, without damage, a ratio of sound intensities of about 1:1000 000 000 000. The quietest whisper we can hear is a billionth of the intensity of the sound of a jet aircraft taking off heard at close range. In engineering terms you could say human audition is equivalent to a true 20-bit system – 16 times better than the signal processing inside a compact disc player! Interestingly, the tiniest sound we can hear occurs when our eardrums move less than the diameter of a single atom of hydrogen.[19]

For the purposes of music listening, human hearing is theoretically capable of hearing the range of 20Hz-20,000Hz that is generally relevant to the frequencies (and their associated harmonics) generated by typical symphonic instruments and choral music.[20] It is important to note, however, that human hearing typically deteriorates with age as shown in Figure 1.[21] Thus, the average concertgoer over 60 years of age will likely have mild hearing loss above frequencies of approximately 6000 Hz, which will increase to moderate hearing loss at the age of 70 and moderately severe hearing loss above these frequencies by the age of 80. While this level of frequency loss may not interfere with the ability to hear the fundamental tones of orchestral instruments, it will interfere with the ability to hear the harmonics of these tones, and thus to experience the fullness of sound available.[22]

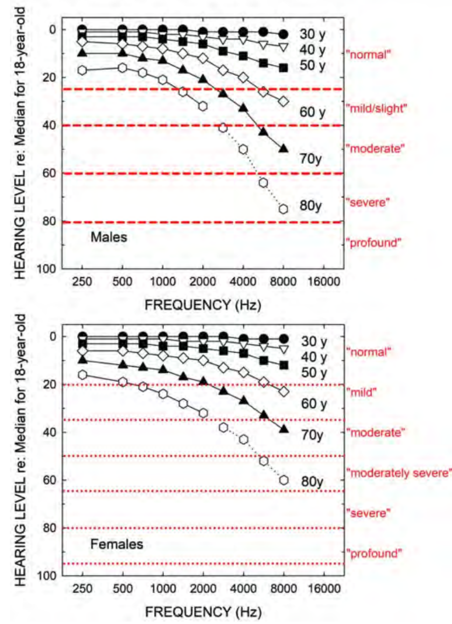

Figure 1: Hearing Level by Median Age

Classical music concertgoers in the United States tend to be an older crowd, with one study commissioned by 15 orchestras in 2002 finding half of subscribers were 65 or older, and even in 2019, 62% of the New York Philharmonic's audience was 55 or older.[23] So it is not unreasonable to assume that the average concertgoer is not fully experiencing the higher-level harmonics of sound in the hall in which they attend a concert, regardless of whether the hall's acoustics are delivering those frequencies to the concertgoers' ears.

In addition, it is important to note research demonstrating that "reflections from the side are amplified more than those from above, in particular at high frequencies based on the shape of the human head."[24] This characteristic of human hearing is highly relevant to concert hall design, as the placement of side walls and their proximity to seats in the hall will have an outsized impact on the perceived acoustics of the hall.

Finally, it is possible that variations in preferences for clarity versus loudness, versus other acoustical characteristics of music, may be the result of where the sound processing for different aspects of music and speech take place in the human brain. As Ando and Singh discuss in a paper from 1995,[25] right hemisphere brain processing is considered to control IACC (interaural cross correlation)[26] and average listening level. Left brain activity is largely associated with processing time delay gap and reverberation. Ando and Singh propose that different people will process these signals differently depending on personal brain factors.[27] The results may influence individual preference for seating location in a concert hall based on the characteristics of the acoustics at different seating locations. If this is true, then it may be impossible to "please all of the people all of the time,"[28] and thus a system that identifies the differing characteristics of different seats may be necessary to best suit the preferences of different concertgoers.

1.6. Recorded Music vs. Live Music – Relative Sound Quality

Another key preliminary question is the frame of reference for sound quality available to the average concertgoer when listening to music in other contexts as compared to the live concert experience. Listening to recorded classical music in a quiet environment utilizing a sound system capable of delivering CD-level sampling quality can provide a frequency and dynamic range similar to that in a concert hall. But while this is theoretically possible, the actual experience of listening to recorded music available to the average classical music listener in the course of their normal daily lives may be quite inferior to that available in a live musical performance. This is because the average listener is often listening using technology that limits the frequencies and dynamics of the recording, often in an environment that negatively impacts the ability to hear clearly as a result of surrounding noise.

"To reproduce a given frequency, the sample rate must be at least twice that frequency."[29] A table of sample rates and relative quality for various media is shown in Figure 2.[30]

Sample rate	Quality level	Frequency range
11,025 Hz	Poor AM radio (low-end multimedia)	0–5,512 Hz
22,050 Hz	Near FM radio (high-end multimedia)	0–11,025 Hz
32,000 Hz	Better than FM radio (standard broadcast rate)	0–16,000 Hz
44,100 Hz	CD	0–22,050 Hz
48,000 Hz	Standard DVD	0–24,000 Hz
96,000 Hz	Blu-ray DVD	0–48,000 Hz

Figure 2: Sample Rates

In surveys in the United States, it appears those that have an affinity for classical music often listen to it on the radio and by way of recordings in their automobiles and homes,[31] and "only half of those who express the very highest level of preference for attending classical music concerts actually attend, even infrequently."[32] As shown in Figure 2, the sample rate for FM radio is around 22,050 Hz, resulting in a frequency range of 0-11,025 Hz. CD quality audio provides a frequency range of approximately 0-22,050 Hz. Limited bit depth will also limit the potential amplitude range of the signal.[33] Intervening ambient noise from traffic while driving or in the home or office listening environment may also degrade or interfere with the quality of the audio experienced.

Another limiting factor on recorded music quality is introduced if the listener is using Bluetooth either in the connection from the source to the amplifier or from the amplifier to the output methodology (speakers, earbuds, or headphones). Even if the highest quality audio is used for the source, the Bluetooth transmission codec (which determines the audio encoding and decoding of the transmission) will dictate the bit rate, bit depth, and sampling rate of the audio. This may impact the audio quality available to the listener. The impact can be summarized as follows:

> "Even if you store the highest-quality files on your device, how they sound through your Bluetooth headphones depends in part on the transmission codec. In most cases, the bit rate is what holds back even the high-end codecs from reaching CD quality (16-bit; 44.1kHz; 1,411Kbps) or better. Higher-end audio codecs like LDAC can support up to 32-bit and 96kHz sound, but only about two-thirds the bit rate of CD quality at best (990Kbps), so you still lose data in the process."[34]

Frequency response of the output device (speaker, headphones, or earbuds) will also limit the frequencies that can be heard by the listener. The degradation of audio signal that results from compression, transmission, ambient noise, the codec used for playback, and the limitations of the output device may help explain why the acoustical experience of listening to live music is often so far superior to that of recorded music, even putting aside the visual and social factors associated with concert performance further discussed below.

To summarize, a concertgoer with average human hearing will benefit from a live music performance through increased emotional connection to the experience as a result of the visual and social aspects of attendance, as well as the superior acoustics that may be available in the concert hall, as compared to that which may be experienced through a recording of the performance. But in a recorded performance, a listener can adjust the volume, the bass and treble response, or even through the use of a more sophisticated equalizer, the volume of certain frequencies, as well as in sophisticated listening systems, the balance between speakers in front of, around, and behind the listener. These latter advantages of recorded performance could in essence be brought to the concert hall if a system existed to identify the differing acoustical characteristics between seats. Such a system is proposed in this thesis. But first, we review the literature on concert hall acoustics for insights that are important to determining which questions to ask the user in order to identify seating preferences that will make a meaningful difference in the experience of attending a concert in a hall.

2. LITERATURE REVIEW

2.1. Concert Hall Design

2.1.1. Historical Background

Concert halls today are designed first and foremost as a venue for performance of symphony orchestras, although their design may take into consideration the need to accommodate the performance of other types of musical and spoken performance. The definition of what makes for a "great" concert hall has largely centered on the acoustics of such a hall considered in the light of orchestral music, largely of the classical and romantic periods of composition, from roughly 1750-1820 and 1820-1920 respectively.[35] The study of such halls is relatively recent, arising in the last 100 years first in the work of Wallace Clement Sabine on room acoustics,[36] ascending through the work of Leo Beranek and his survey of concert halls beginning with the publication of his "Music, Acoustics, and Architecture" book in 1962,[37] and now the subject of detailed scientific measurement as typified in the work of Tapio Lokki, and his work at Aalto University in Finland.[38] It is useful to understand the synergies between the composition of classical music as it evolved from the 18th through the 20th centuries and the differentiation of architectural design centered on spaces for the performance of symphonic music. Each informed and enhanced the other as halls were designed with this specific use in mind, all with the goal of accommodating a growing audience with an appetite for experiencing live symphonic musical performance.

Compositions from the classical period (including the symphonies of Mozart and Beethoven) represent an evolution from the secular music of the Baroque period that preceded it.[39] While secular music of the Baroque period (roughly 1600-1750) emphasized a more intimate type of music experienced in smaller rectangular halls of 300-500 seats and reverberation times below 1.5 seconds, the classical period saw the development of a new musical direction emphasizing "fullness and depth … over … clarity and briskness."[40] The popularity of this new style of classical music drove the growth of audiences and in turn spurred the construction of larger concert halls specifically designed for concerts of these works, accommodating audience sizes of as many as 2400 people, with reverberation times in the range of 1.6-1.8 seconds.[41] These concert halls were well suited to the musical compositions of their time, and composers were also able to write music with the characteristics of these halls in mind, although some such as Beethoven wrote pieces of music that seemed to anticipate (or in the future at least would benefit from) the existence of halls with longer reverberation times.[42] Vienna's Musikverein (opened in 1870) and Amsterdam's Concertgebouw (opened in 1888) are still today often cited as the two most acoustically preferred halls for symphonic music.[43] Both of these halls are a classic "shoebox" configuration, which describes the proportions of the interior of these halls – essentially rectangular high boxes.[44]

This synergy and this configuration may have been the result of some serendipity in the building materials and methods available to architects of that time, as well as the preferences for decorative and social elements in the halls. For example, the available beams to span a roof were timber, and thus were limited to approximately 80 feet in length; the shoebox shape was required to make best use of these beams without intervening columns in the hall.[45] Walls were largely built of masonry or covered in plaster resulting in hard reflective surfaces on the side walls. At the same time, the aristocracy's social desire to be seen, shared by the growing middle class of the day, led to the incorporation of box seats in surrounding balconies above the orchestra (floor seating). The orchestra seating was filled more with the common people (or in some cases utilized for dancing by removing or covering the seats). The decorative style involved ornate ornamentation of all sizes on the surrounding walls and in large hanging chandeliers.[46] The combination of these elements provided for reflective surfaces on the side walls and from the balconies close to the listeners, many diffracting surfaces of different sizes, and a high ceiling with large internal volume relative to the footprint of the hall. The result was ultimately a reverberation time of 1.6-1.8 seconds with highly diffuse sound and clarity driven by the close sidewall reflections.[47]

The preferences for fullness of sound and blending of melody and underlying chords continued for roughly the next 100 years of the Romantic period (including such composers as Brahms, Tchaikovsky, and Debussy). As mentioned above, the gold standard halls for live symphonic performance from early in this time period include the Vienna hall with a reverberation time of 2 seconds (when the hall is occupied), and Amsterdam's Concertgebouw, also with a reverberation time of 2.0 seconds at mid-frequencies ("but as it is wider it emphasizes the early sound reflections less, therefore, the music played in it merges with less clarity and more fullness of tone").[48]

Given the renown of these types of shoebox halls constructed specifically for the performance of music and providing the fullness of tone desired by composers of some of the most popular music desired by audiences, one might expect that all concert halls built in their wake would follow the same basic architectural configuration. There are, however, reasons why these halls are not considered ideal for all audiences – in particular driven by the need to accommodate more seats and changes in the aesthetic and social preferences of concertgoers. There also appears to be a divergence in human preference for different acoustical experience in symphonic music, while the visual aspects of concert attendance have also taken on additional prominence. The research examining these developments is explored below.

2.1.2. Listener Acoustical Preferences Diverge

The acoustic performance of a hall will reflect the consequences of its architectural design and choice of materials as influenced by the acoustic consultant and other experts working on the project.[49] But ideal acoustics are subjective. This is true even among experts. For example, Minoru Nagata, founder of the world-renowned Nagata Acoustics (known for its work on Los Angeles' Disney Hall, Musiikkitalo in Helsinki, and DR Koncerthuset in Copenhagen, among many others), offered the opinion that the famous Vienna Musikverein provides too much sound volume for certain pieces of music ("too loud for Stravinsky") while "the sound of the Berlin [Philharmonie] hall enabled the audience to listen comfortably to relatively loud performances in a way not possible at the Musikvereinsaal."[50] Sometimes, the venue selected for a concert is so inappropriate to the subject matter that the audience simply walks out.[51]

Nagata emphasized clarity and room response in his designs, focusing on:

> "parameters relating to the subjective balance between clarity and reverberation;
> "parameters relating to the subjective impression of listening loudness;
> "parameters relating to the spatial impression."[52]

Meanwhile another expert on concert hall acoustics, Professor Tapio Lokki at Aalto University in Finland, finds that the sound in certain halls, although perhaps performing as intended by its acoustic designer, are not always to his personal taste.[53]

Studies have shown that audiences also have different preferences in the acoustical characteristics of the hall in which they attend a symphonic musical performance.

> "Many studies to date have identified that the individual acoustical preferences by listeners are heavily polarized. To some, excellent acoustics signifies a high articulation that allows the separation of the minutest of details, although the enveloping sensation is not strong. … In contrast, many expect to experience a brilliant and intimate sound with lots of dynamics, with strong bass and high frequencies."[54]

In addition, studies have demonstrated that the preference for the hall varies based upon the musical selection being performed and the location of the listener in the hall:

> "The main results show that listeners can be categorized into two different preference classes. Some listeners prefer clarity over reverberance and the others love strong, reverberant and wide sound. Interestingly, "late Romantic symphonic music" (Bruckner) is appreciated more in less reverberant halls while "Classical period symphonic music" (Beethoven) without dominating brass instruments benefits [from] louder and more reverberant halls. In addition, the preference order of the halls is quite different in different positions in the studied halls and timbre of the sound is an important factor for preference."[55]

Given the empirical evidence of differences in individual preference in different halls and different locations in a particular hall when listening to different musical selections, it is sensible to think that an informed audience would be a happier audience in terms of selecting their seating location based on the acoustical experience to be expected in a particular seat during a performance.

2.1.3. Prior Concert Hall Seating Recommendation Systems

In fact, there has been at least one attempt to create a system to allow ticket buyers to select seats in a concert hall based on a seat map generated to match their acoustical preferences, after having those preferences evaluated through A/B testing using music played back through different acoustical filters. Such a system was built for the Kirishima Concert Hall in Kagoshima, Japan, and reported on in the proceedings of the conference on music and concert hall acoustics 1995. Four acoustical factors were identified as key to the user preferences – the listening level, the initial time delay gap,[56] the reverberation time, and the interaural cross correlation.[57] The individual ticket buyer was tested for preferences on each of these factors independently, and then a seat map was generated for the user identifying the seats most likely to match their preferences[58] based on the calculation of acoustical properties for these four factors for each seat in the hall.[59] While this system acknowledges the inherent acoustical differences between seats in a concert hall and the importance of user preferences in selecting concert hall seating, it ignores the similar importance of visual and other preference factors in selecting seating in the hall, to maximize user satisfaction with the seat chosen.

2.1.4. Impact of Visual Input on the Emotional Experience of Live Music

Research indicates that "visual performance cues seem to be just as important as auditory performance cues in terms of the subjective emotional reaction of the observer."[60] And while this research was conducted with regard to classical music and is thus directly on point,[61] it is interesting to note that the same phenomenon has been identified in the movie-going experience, which is inherently perceived as visual-first, where the film writer and director George Lucas stated: "Sound is 50 percent of the movie going experience, and I've always believed audiences are moved and excited by what they hear in my movies at least as much as by what they see."[62] Thus, there is both empirical and anecdotal evidence of the importance of both the visual and the auditory to the overall emotional experience of attending a performance.

It is worth noting that from this author's experience, the vast majority of concert halls seats are priced highest for those located with the best sight lines to the stage, generally starting with the near and center orchestra and front row balcony (or "dress circle") seats. Seat prices seem to generally decrease in proportion to the degree to which seats are further off-center line or farther from the stage. This practice seems to inherently recognize that the visual characteristics of a seat are specific to that seat, but assumes that the acoustical experience is either exactly correlated with those same factors or is the same among all seats. Based on the results of the research discussed further below, either of these assumptions about the acoustical properties of each seat would be incorrect.

2.1.5. Why Build a New Concert Hall?

Construction of a new concert hall is an expensive and lengthy undertaking.[63] Yet they are being constructed at a remarkable pace in major cities around the world. Concert halls have opened in major cities around the world in the past 25 years at a rate averaging more than one per year, including the following: [64]

City	Country	Concert Hall Name	Year Open	Type	Capacity	Resident Orchestra	Architect(s)	Acoustician
Rome	Italy	Parco della Musica	2002	Vineyard	2800	Accademia Nazionale di Santa Cecilia	Renzo Piano	Jürgen Reinhold
Singapore	Singapore	Esplanade - Theatres on the Bay	2002	Surround	1600 (concert hall) 2000 (theatre)	Singapore Symphony Orchestra	Michael Wilford, DP Architects	Artec
Moscow	Russia	Moscow International House of Music	2003	Vineyard	1800	Russian National Orchestra	Antonio Citterio and Partners	ADA-AMC (a WSDG company)
Los Angeles	USA	Walt Disney Concert Hall	2003	Vineyard	2265	Los Angeles Philharmonic	Frank Gehry	Nagata Acoustics
Amsterdam	Netherlands	Muziekgebouw	2005	Shoebox (moveable walls)	725	Various Resident Orchestras	3XN	Peutz Consultants
Porto	Portugal	Casa da Música	2005	Shoebox	1300	Orquestra Nacional do Porto	Rem Koolhaas	Renz Van Luxemburg
Beijing	China	National Centre for the Performing Arts	2007	Shoebox	2000 (concert hall)	China National Symphony Orchestra	Paul Andreu	Not Identified
Copenhagen	Denmark	DR Koncerthuset	2009	Vineyard	1800	Danish National Symphony Orchestra	Jean Nouvel	Nagata Acoustics
Guangzhou	China	Guangzhou Opera House	2010	Vineyard	1804	Guangzhou Symphony Orchestra	Zaha Hadid	Marshall Day Acoustics
Montreal	Canada	Maison symphonique de Montréal	2011	Shoebox	2100	Orchestre symphonique de Montréal	Diamond Schmitt Architects	Sound Space Design
Helsinki	Finland	Musiikkitalo	2011	Vineyard	1700	Helsinki Philharmonic Orchestra	LPR Arkkitehdit	Nagata Acoustics
Miami	USA	New World Center	2011	Vineyard	756	New World Symphony	Frank Gehry	Nagata Acoustics
Reykjavik	Iceland	Harpa	2011	Shoebox	1800	Iceland Symphony Orchestra	Henning Larsen Architects	Artec
Shanghai	China	Shanghai Symphony Hall	2014	Vineyard	1200	Shanghai Symphony Orchestra	Arata Isozaki	Nagata Acoustics
Katowice	Poland	NOSPR Concert Hall	2014	Surround	1800	Polish National Radio Symphony Orchestra	Konior Studio	Nagata Acoustics

Paris	France	Philharmonie de Paris	2015	Vineyard	2400	Orchestre de Paris	Jean Nouvel	Marshall Day Acoustics Nagata Acoustics (personal consultant to Nouvel)
Budapest	Hungary	Béla Bartók National Concert Hall	2015	Shoebox	1700	Hungarian National Philharmonic Orchestra	Stefan Puskás and György Wagner	Russell Johnson
Seoul	South Korea	Lotte Concert Hall	2016	Vineyard	2036	Seoul Philharmonic Orchestra	Coop Himmelb(l)au	Nagata Acoustics
Hamburg	Germany	Elbphilharmonie	2017	Vineyard	2100	NDR Elbphilharmonie Orchestra	Herzog & de Meuron	Nagata Acoustics

Figure 3: Table of Concert Hall Openings

> "As concert halls have evolved into multipurpose destinations — complete with chic restaurants, bars and the inevitable education centers — local officials and business leaders have come to view them as a chance to revive a downtown or add luster to their city. Orchestra administrators see a draw for new audiences and a means of raising their group's profile. Music directors envision a platform to artistic greatness. Orchestra members hear wonderful new acoustics. The music-loving public looks forward to more and better concerts."[65]

This, despite the fact that "of all building types, they consistently seem to run … wildly beyond budget, are delivered so late and become so controversial. … From the saga of the Sydney Opera House (10 years late, 15 times over budget) to Los Angeles's Walt Disney Hall (16 years in the making) and Copenhagen's Koncerthuset (in 2007 the most expensive concert hall ever — almost destroying its client, Danish National Radio), the contemporary concert hall has become an architectural nightmare."[66] They are built by city after city, large and small,[67] seeking the revitalization, luster, and increased draw for citizens and tourists, as identified above.

2.1.6. The Rise of the "Vineyard" Style Hall

As mentioned above, many halls constructed since the mid-1960s are "vineyard" style in configuration. Why change the shape of the hall when the "shoebox" design was a time-tested shape for successful symphonic concert halls? First, as further discussed below, these shoebox shaped halls may not provide equivalent sight lines for all concertgoers as the size of halls increases.[68] Sight lines from the rear and sides of the hall may be obstructed by the distance from the stage and intervening audience-member heads due to lack of rise of the floor, as well as by supporting columns for the balconies, if any.[69] In addition, as the hall size increases in order to accommodate more audience seating, the loudness decreases at further distances, and reverberation time my exceed the ideal for the type of music being performed. Clarity may suffer as side walls and reflecting surfaces are further removed from seats located near the center of the orchestra. Seats below a deep balcony may be shadowed acoustically.[70] Altering the shape of the hall in order to accommodate more audience seating with improved sight lines may also result in failed experiments: fan shaped halls, for example, were found not to provide the desired side reflections into the audience for musical performances.[71]

In an effort to accommodate more seating while responding to the acoustical and visual sight line limitations of shoebox halls at larger sizes, and also responding to a changing society's desire for a more egalitarian seating arrangement in concert halls, a revolutionary design was pioneered by Hans Scharoun for the Berlin Philharmonic's new concert hall, opening in 1963. Scharoun's original concept drawing and the Philharmonie

Hall seating plan are shown below in Figure 4.[72]

Figure 4: Concept Drawing and Seating Plan for Berlin Philharmonie.

Herbert Von Karajan, the Berlin Philharmonic's world-famous conductor, was an advocate of this proposal, saying:

> "Of all the designs submitted, one seems to stand out above the others; which is founded on the principle that the performers should be in the middle .... This project seems fortunate on several grounds: the deployment of the walls certainly makes good sense acoustically, but the most impressive of all is the complete concentration of the listener on the musical event. I know of no existing hall in which the seating question is so well resolved as in this project."[73]

The resulting hall – Berlin Philharmonie – has been well-regarded since its opening (after some initial adjustments),[74] and many halls designed since have followed the vineyard style configuration.[75] But some have criticized this layout as being acoustically inferior to shoebox halls for symphonic music. The research on the acoustics of vineyard style halls versus shoebox halls is discussed next.

2.1.7. Acoustical Differentiation of Vineyard Versus Shoebox Concert Halls

Tapio Lokki is a professor at Aalto University in Finland. His research focuses on room acoustics with a particular interest in concert halls. He is a prolific author of scientific papers on this and related matters, and even a cursory search of his work yields many articles that may be of interest in illuminating the subject of concert hall design. He summarizes the acoustical peculiarities of vineyard style halls as follows:

> "In a modern concert hall, unobstructed sight lines and having the orchestra surrounded by the audience are often the leading design criteria. Acoustically, such [surround], arena, and vineyard-type halls usually offer high clarity. In contrast, they often have many shortcomings, such as lack of envelopment, openness, brilliance, warmth, and dynamics, in addition to practical challenges related to audience noises (coughing, rustling the printed program, etc.). Moreover, the seats on the side and behind the orchestra are prone to peculiar balance with the orchestra, or a rather inaudible soloist."[76]

Professor Lokki's research also confirms the different acoustical experience between different seats in a hall, and the polarization of individual acoustic impressions in a hall,[77] although he concludes that no one prefers "weak and distant sound."[78] Professor Lokki's work aptly summarizes the difficulty of identifying the "best" seat or even the most preferred hall: "[P]reference is highly individual, and on an overall level assessors are grouped into two preference classes. Moreover, the judgements vary between listening positions and for different music. This indicates that it is almost impossible to define which hall is the most preferred."[79]

While Professor Lokki's body of research certainly supports the conclusion that individual preferences for seating location will vary based on the music being performed, the characteristics of the hall, and the individual concertgoers' preferences, another commentator has been willing to state categorically that "the most favourable [sic] acoustic conditions among today's concert halls with capacity over 1800 listeners can be provided by vineyard configuration."[80] This seems an overly broad conclusion based on an assumption that "lateral reflection surfaces are brought closer to the listeners allow[ing] dividing the interior of the room into smaller, acoustic segments acting individually."[81] It is not clear that this assumption is accurate as to the existence of lateral reflecting walls operating in this fashion in all vineyard style halls. And this conclusion also assumes that there is one definition of "best" acoustics, which is inherently suspect given the other research on the appropriate acoustics for different musical compositions and individual acoustical preferences of listeners. Nevertheless, the impression that vineyard style halls provide a superior experience for concert halls larger than 1800 listeners appears to be borne out by the prevalence of this type of hall among large halls constructed in the past 20 years or more.[82]

2.1.8. Other Preferences (accommodation for physical differences, stairs, seats, aisles, proximity to restrooms, coat check, exits, price)

While not explicitly identified as a subject of scientific research, it is certainly the case that concertgoers have other seating preferences having to do with other aspects of the concert-going experience. Examples include a preference for being near the aisle so as to quickly access the lobby or exits or to avoid a claustrophobic experience in the center of a long row of seats, a preference for a seat closer to the rest rooms, or to the lobby bar at intermission, or a preference for a chair that is moveable as opposed to one that is fixed. Some concertgoers may have physical differences that also dictate certain seating within the hall – for example, those in wheelchairs, or those preferring not to have to navigate stairs. These will also dictate seating preferences in the hall and may, in some cases (such as the need to accommodate a wheelchair), trump the acoustical or visual preferences as a necessity that must be considered first in seat selection. All these types of preferences are referred to in this paper as "physical" seating preferences.

Price may also be a factor for concertgoers who want the best seat within a certain price range of seating. As noted above, price is often set for seats in a hall based on seats being on a visual centerline, and in many cases being within a few rows of the front of the balcony or mezzanine (often referred to as "dress circle"), or in the center orchestra seating. These seats may not be the best acoustically, however, especially if they are far from side-reflecting surfaces. Being able to specify and accommodate all of these seating preferences and identify the most ideal seating location for an individual from a combination of the acoustical, visual, physical, and price points of view would be the primary benefit of a seat recommendations system.

2.2. Recommender Systems

> "Recommender Systems (RSs) are software tools and techniques providing suggestions for items to be of use to a user. The suggestions relate to various decision-making processes, such as what items to buy, what music to listen to, or what online news to read."[83]

The system for seat recommendation proposed in this paper is inherently a recommender system. Similar to systems that recommend a streaming show to watch, a book to read, or a song that a listener might want to listen to next, the seat recommendation system would help a non-expert listener select a seat based on a set of preferences identified about or learned from the concertgoer. "Recommender systems emerged as an independent research area in the mid-1990s," and "have rapidly grown with the increasing overload of choices available on web sites."[84] They are now commonly accepted in daily use on sites such as Amazon and Netflix, where the data on which to base a recommendation can be derived from "various types of knowledge and data about users, the available items, and previous transactions stored in customized databases," as well as information derived from statistically similar users' preferences.[85]

It is important to note that recommender systems benefit both the user and the service provider.[86] For the service provider (or in the case of a concert hall, the venue or orchestra management), the recommendation service can increase user satisfaction by helping match the concertgoer with the seat most well-suited to a concertgoers' preferences. This can also increase sales if those concertgoers enjoy the experience more and choose to return more often. A recommendation system could also sell seats which might at first glance not appear to be in prime locations within the hall, if those seats happen to meet a particular concertgoer's preferences. For the user, the seat recommendation may simplify the seat selection process while also providing a better concert experience, and allow even a novice or first-time visitor to identify the best seat to suit his or her preferences.

Recommender systems today often utilize machine learning to filter large amounts of data and come to a recommendation,[87] generally utilizing one of three techniques:

- Collaborative Filtering, where the user's preferences can be compared to other users with similar preferences to derive a recommendation;
- Content-Based Filtering, where the user's preferences can be compared to specific item's characteristics to identify a recommendation; and
- Hybrid Systems, which make use of both collaborative and content-based preference information.[88]

But recommender systems, particularly those based on collaborative filtering, suffer from the so-called "cold start" problem: "to adapt to a user, the system needs to know what the user liked in the past. This is needed in content-based filtering to decide on items similar to the ones the user liked."[89] This problem could be avoided by asking users to explicitly rate items when they start to access the recommender system,[90] if the user is able to do so. The system proposed in this paper makes use of a concertgoer survey to collect a small set of data on which to base recommendations. It might be possible to generate better data once a seat recommendation system is in use if concertgoers would rate their seat after attending a concert (for example, on the ubiquitous five-star scale so often used in online ratings). With a sufficiently large data set, the recommendation system could apply machine learning to start to identify characteristics of user's profiles (demographics, age, gender, type of music liked, other concerts attended, response to prior surveys, and the venue and seat and rating provided by the concertgoer for those prior experiences) in order to derive a recommendation based on the ratings of that individual and similar concertgoers. It would be quite interesting to see if machine learning identified other characteristics and correlations that might unexpectedly be associated with certain seating preferences (left- or right-handedness, for example, which might indicate processing of sound elements in different hemispheres of the brain leading to different preferences in clarity versus expansiveness).

While machine learning thus holds great promise for the future once robust data sets exist of user ratings of the experience of engaging with different pieces of music in different seats in different concert halls, at the moment a recommendation system is likely to need to rely on explicit user feedback on preferences in order to provide recommendations.

2.3. Constrained Optimization

Constrained optimization is a form of applied mathematics that helps solve problems of allocation of limited resources. Constrained optimization systems use known attributes of constrained resources to allocate those resources based on identified criteria in complex problems. Constrained optimization differs from machine learning in that machine learning infers relationships or finds solutions by learning from large sets of data, while constrained optimization doesn't learn, but rather makes decisions based on known constraints such as customer preferences and limited inventory of available products, with the goal of making a recommendation that maximizes customer satisfaction.[91] "Both constrained optimization and machine learning seek to minimize an objective (or loss) function — constrained optimization searches within the bounds of all constraints for an optimal solution (minimum loss), whereas machine learning creates a mapping from its training data to the loss function that can then be extrapolated to new data."[92] Constrained optimization can thus at least initially be more helpful to the seat recommendation system than the machine learning applicable to typical recommender systems because it does not depend on learning from a large data set, and thus avoids the cold start problem. In the long run, the two techniques could work together to form a more robust recommender system that could better predict user preferences, but in the near-term constrained optimization would be more capable of recommending a seat in a concert hall (a limited resource when subdivided by all the visual, acoustic, and physical characteristics of that particular seat) to a concertgoer with a set of unique preferences. Creating a mathematical model to support the recommendations using constrained optimization theory is, however, beyond the scope of this paper (and the present capabilities of this author).

3. METHODOLOGY

3.1. Goals and Objectives

The literature thus establishes that:

- Acoustics, visual sight lines, and physical seat characteristics vary at different seats in a hall, even when the ISO standard for concert hall acoustics is followed (which calls for averaging results of acoustical measures across multiple locations in the hall).
- Concertgoers can perceive these differences in acoustics at different locations in the hall.

- The differences perceived and preferences will change based on the individual, the musical selection being performed, and the specific characteristics of the hall.
- Visual information is as important as acoustical information to the emotional experience at a musical performance.
- Concertgoers have different reasons for attending concerts and different needs while at the venue, and these purposes may be more social or physical than specifically related to the performance of the concert program.[93]

Thus, the primary goal of this research project is to create a recommender system that can take into account all of these varying preferences – acoustical preferences, sight lines, and physical amenities of seats in a concert hall – on an individual seat basis. This system could be used in at least four distinct ways:

1. Assisting in the design process to help visualize for designers and clients the likely results of their choices on the concertgoing experience.
2. Assisting in the management of the hall in planning performances and even managing the application of variable acoustic measures within the hall (for example, moveable curtains, sliding or rotating panels, or variable humidity), before and even during performances.
3. Assisting performing arts organizations in selling seats that will be most appropriate for concertgoers; and

4. Assisting concertgoers in selecting seats that best align with their preferences in the concert experience.

3.2. Design Methods and Tools

How should such a recommender system work? This thesis proposes the following: First, ask a series of questions to identify preferences in various aspects of seating; then ask the concertgoer to engage in A/B testing of different sound clips to isolate acoustic preferences; and finally propose a seating location that takes into account the identified preferences (and the musical works to be performed, if that information is also available). A diagram of the overall system is shown in Figure 5.

Figure 5: Overall System Flow

The questions should be organized so that they progressively narrow the possible seating locations as quickly as possible (and with the lowest number of questions possible) to reach a recommendation. The user may also be asked to rank the importance of visual, acoustical, and other seat characteristics.

A survey was created that limits the questions to one on physical seat characteristics, one on visual characteristics, and two A/B listening sample questions. The A/B sound samples consist of an anechoic recording[94] of an orchestra playing an excerpt from Mahler's symphony no. 1, played back as if the listener is sitting in different sections of the Musiikkitalo concert hall – specifically, the first pair consists of one sample in section 1P (front of stage, relatively centered in the orchestra section of seating), and one in section 2E (located in the balcony behind stage left); the other A/B pair is simulating section 1D (stage right on the side), and 1L (stage left, in front of the stage. These pairs were chosen as the first tests a significant difference in sound level versus reverb; the second pair tests variation in clarity. The location from which the acoustical samples are derived is not revealed to the user. The physical and visual survey questions are shown in Figure 6 and Appendix 1: Survey Questionnaire.[95]

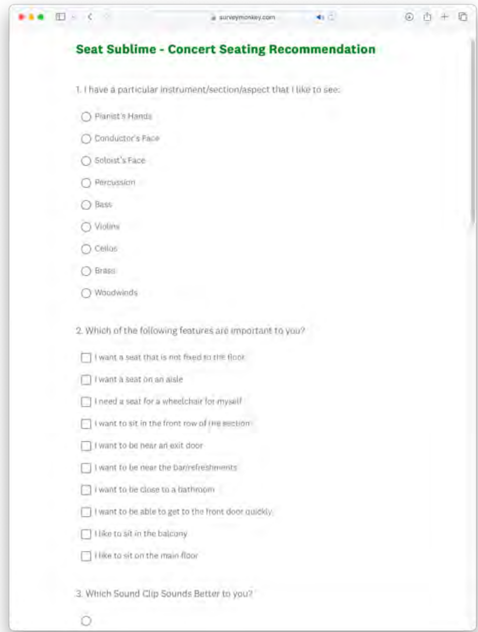

Figure 6: Survey Questions

The overall flow of the system, and the tools applicable to each step are shown in Figure 7.

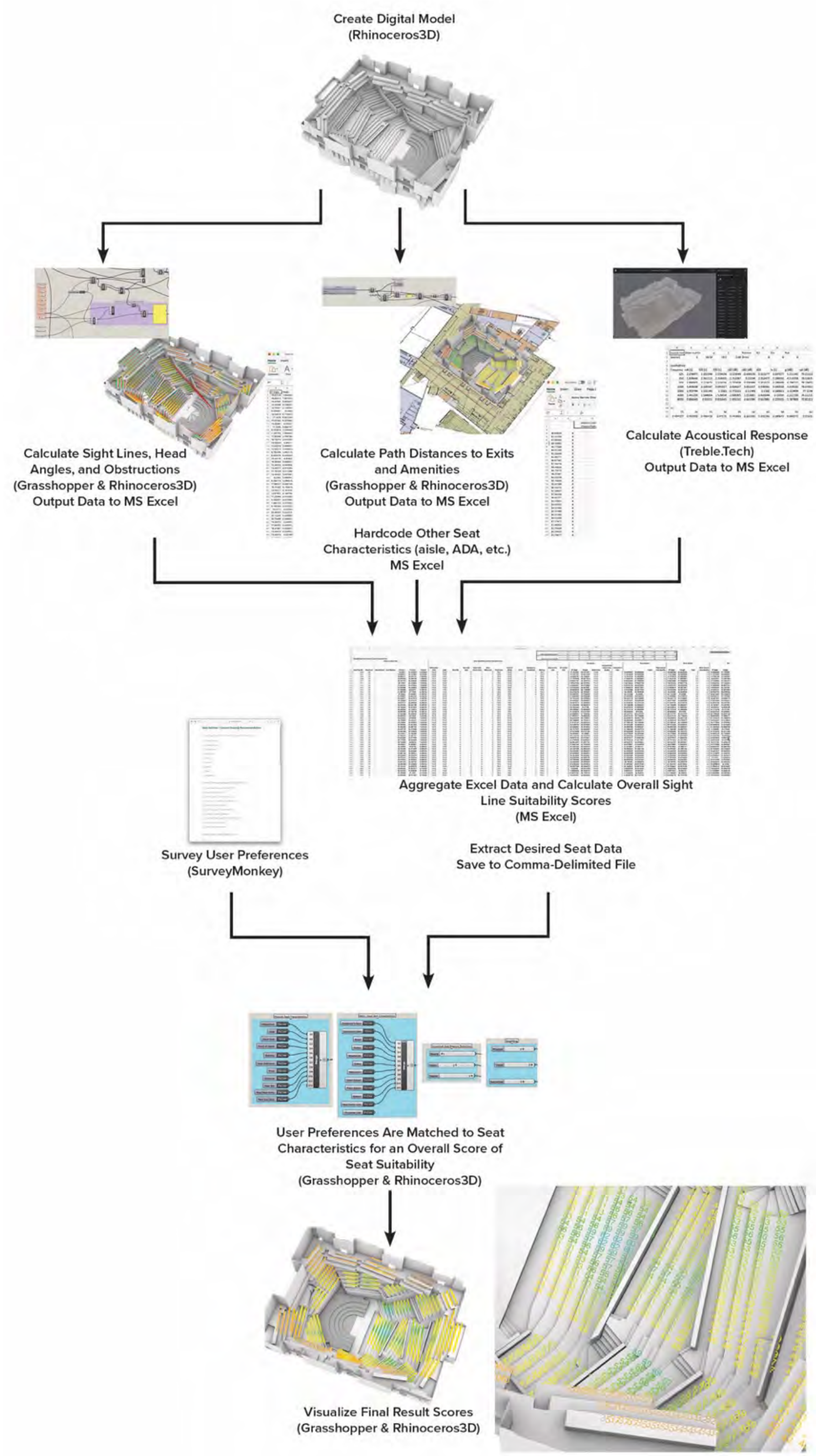

Figure 7: Overall System Processing Flow

3.2.1. Visual and Physical Pipeline

The visual and physical pipelines for determining seat characteristics start with a digital model of the venue created using the commonly available modeling software Rhinoceros 3D from Robert McNeel & Associates (referred to hereafter as "Rhino").[96] An aerial view into the model is shown in Figure 8. (The model also includes doors, ceiling, and the suspended reflector among other features that have been removed for ease of illustration.)

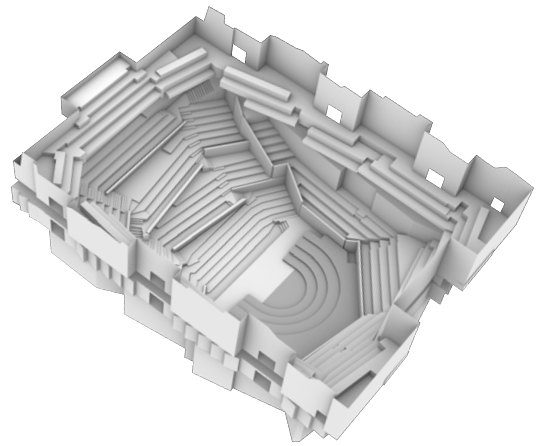
Figure 8: Musiikkitalo Rhino Model

The model was analyzed using the Grasshopper visual programming environment offered as part of Rhino. The Grasshopper scripts take the location of each seat, calculate a placement for the concertgoer's head (assumed to be 1 meter above the seat surface), and looks at the view path to a particular point on the stage which designates the location of the conductor as well as various instrument sections and the likely location of a soloist. The Grasshopper script identifies the XY and Z angles of the concertgoer's head based on the angular difference between the baseline normal to the front of that particular seat and the direction the head would have to be angled in order to be looking directly at the chosen point on the stage. The script can also determine whether a concertgoer's view is obstructed by any other object in the hall (such as a wall, or the floor surface of the balcony), and the definition of "obstruction" can be adjusted to assume an obstruction exists if a wall or other surface is within a chosen distance of the actual obstruction. This allows the system to take into account partial obstructions of view, where an entire instrument section may not be viewable from a particular seat. A visualization of these capabilities is shown in Figure 9. The Grasshopper script can also determine partial obstructions based on the heads of the concertgoers seated in rows in front of a given seat (as will be further discussed below).

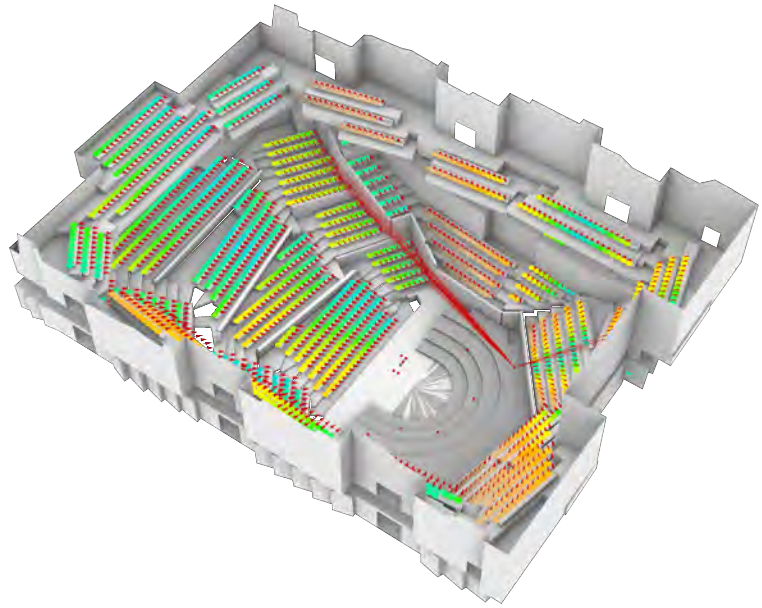

Figure 9: Musiikkitalo Model with sight line obstructions and seat characteristics

Separate Grasshopper scripts calculate characteristics such as path lengths to the exit doors, main concert hall entry, bar at each level, and bathrooms. Other physical characteristics of particular seats, such as whether they are on an aisle, whether they are wheelchair accessible seats, and certain other features are identified by reference to plan drawings of the hall, and hard-coded into spreadsheets as true and false values.

Once all of this visual and physical seat characteristic data has been generated, it is output to Microsoft Excel spreadsheets. Individual spreadsheets are generated for the view to each stage point, which points include the conductor, instrumental or vocal soloist (along with the information about the direction the soloist is facing), piano soloist (along with information on the direction the piano soloist is facing), and the following instrumental sections (based on typical American orchestral seating plans): percussion, basses, cellos, violins, violas, brass, and woodwinds. Head angles and distances from seats to various amenity points are graded on a scale of 0-10 based on where the score or distance falls compared to all other seats in the hall. The overall flow is shown in Figure 10.

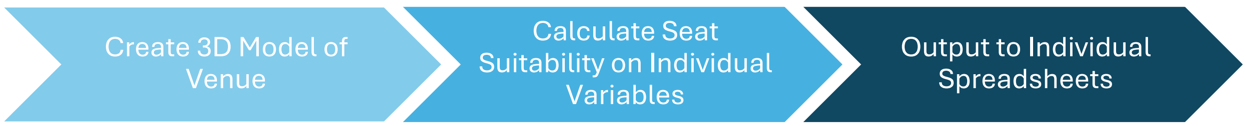

Figure 10: Seat Characteristic Generation Flow

The spreadsheet data is assembled along with acoustical data into a single spreadsheet documenting all the calculated characteristics for each seat, which is fed back into a different script for display of seat suitability once matched to a concertgoer's preferences as further described below.

3.2.2. Acoustical Pipeline

The acoustical pipeline for calculating individual seat characteristics starts with the same Rhino model, which is then imported into an online room acoustic simulation tool provided by Treble Technologies, a company based in Reykjavik, Iceland.[97] The Treble online tool allows the various layers in the model to be assigned materials with acoustical properties to match those used in the hall. The user can choose from a library of materials already provided in the tool, or create new materials customized for properties including absorption, reflection, and scattering coefficients by frequency band. Because the layers in the Rhino model in this case separate walls and floors at each level, doors, ceiling, overhead reflector, seats, glass elements, seating, stage, and other surfaces, each of these elements can be assigned different materials as may be desired to accurately depict the material properties in the hall. For purposes of this study materials were selected from the Treble standard library of materials in order to emulate conditions in the hall and attempt to match the overall reverberation time identified by Nagata Acoustics for the hall.

In addition, ideally the model would be "watertight" – meaning that all outer surfaces meet such that during acoustical simulation rays cannot exit the model. With a watertight model, the Treble tool can simulate the sound propagation in the room using two different simulation methods:

- Wave-based, which is based on a "discontinuous Galerkin finite element method"; and
- Geometric-based, which is "based on a combination of the image source method for early reflection modeling and the ray-tracing method for late reverb modeling."[98]

The Treble tool is, however, capable of analyzing acoustical response without a watertight model using only geometric-based solving. This is the method used for generating acoustical data from the Treble tool for this paper.

Once the materials are assigned to the model, the next step in the Treble tool is

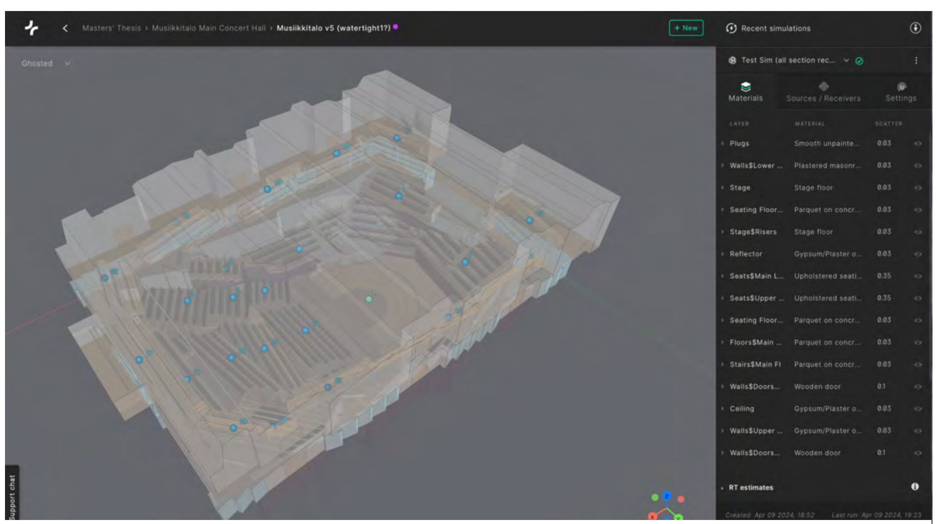

Figure 11: Musiikkitalo model in Treble Technologies Tool

to place sources and receivers in the model. As will be further discussed below, for analysis of Musiikkitalo's acoustical properties using the Treble tool, three different simulations were run:

1. A point receiver was placed in all seating sections and a single source was placed on the stage at the location of the conductor's podium (shown in Figure 11).
2. A point receiver was placed in all seating sections and 10 sources were placed on the stage in locations approximating the location of various sections of a symphony orchestra.
3. A point receiver was placed in seating locations replicating those tested in the Tapio Lokki paper reporting on the acoustics of the Musiikkitalo main concert hall.[99]

Data was obtained from the Treble tool for each receiver in seven frequency bands (centering on 125 Hz to 8000 Hz) for the following acoustical measures: edt, t20, t30, c50, c80, d50, g, and spl. This data was downloaded from Treble as a spreadsheet for analysis with other seat characteristic data.[100] For purposes of this paper's seat recommendation tool, the data from the first simulation identified above for the 500-1000 Hz frequency bands was averaged, and the t30 data was utilized to approximate reverb, c80 was used to approximate clarity, and g was used to gauge loudness.[101] The data from simulation 3 was used to compare the Treble tool's data with the acoustical parameters measured in the Lokki paper, for benchmarking purposes as further discussed below. In addition, envelopment was estimated based on actual measured data taken by Tapio Lokki in the hall, as this data was not available from the Treble simulation.

3.2.3. Benchmarking Acoustical Seating Data

Professor Tapio Lokki measured acoustical characteristics of the Musiikkitalo main concert hall and reported those findings in several articles.[102] He was also very generous in supplying more granular details of those measurements to support the work on the analysis in this paper. Based on the data supplied by Prof. Lokki, it was possible to benchmark the acoustical measurements obtained from the Treble Technology simulation against the actual results obtained from the measurements taken in the hall by Prof. Lokki. A comparison of results is shown in Figure 12.

Difference Between Lokki and Treble Results

Frequency	edt [s]	t20 [s]	t30 [s]	c50 [dB]	c80 [dB]	d50	g [dB]
125	0.143173023	0.096522256	0.198810795	-0.878057135	-0.97047683	-0.041291987	-2.24887081
250	0.332731092	0.00730576	0.018017599	-0.130737527	-0.294485768	-0.018423512	0.565727428
500	0.356529683	0.320465155	0.308810922	2.466205964	1.263921727	0.128549086	-0.121850386
1000	0.354972172	0.272462501	0.253045818	1.416698693	0.643632335	0.071393691	-4.017744729
2000	0.206462086	0.201541451	0.161778148	2.57925918	1.65108628	0.130305944	-5.853438993
4000	0.03530224	0.086674772	0.161202519	3.015303411	1.990858491	0.155808308	-5.260069125
8000	0.023986415	0.141059738	0.200440685	3.360794217	2.742757802	0.164454059	-3.951001971

% Difference

Frequency	edt [s]	t20 [s]	t30 [s]	c50 [dB]	c80 [dB]	d50	g [dB]
125	5.9%	4.0%	8.2%	20.0%	61.8%	-15.2%	-75.8%
250	15.0%	0.3%	0.8%	4.5%	406.5%	-5.5%	11.1%
500	15.9%	13.2%	12.7%	-951.3%	86.5%	26.7%	-3.0%
1000	16.0%	11.5%	10.8%	-100.4%	91.3%	17.0%	-17639.6%
2000	10.3%	9.4%	7.6%	-1327.8%	92.4%	26.7%	231.4%
4000	2.4%	5.2%	9.5%	298.9%	56.2%	28.0%	173.1%
8000	2.6%	13.1%	17.8%	77.0%	37.0%	22.8%	76.9%

Average of 500-1000 Frequency Bands

	edt [s]	t20 [s]	t30 [s]	c50 [dB]	c80 [dB]	d50	g [dB]
Lokki:	2.230330793	2.406094758	2.384724477	-0.835330342	1.08292854	0.451249351	2.047821497
Treble:	1.874579866	2.10963093	2.103796107	-2.776782671	0.129151509	0.351277962	4.117619055
Diff Between A	0.355750928	0.296463828	0.28092837	1.941452329	0.953777031	0.099971388	-2.069797558
Difference %:	16.0%	12.3%	11.8%	-232.4%	88.1%	22.2%	-101.1%

Figure 12: Comparison of Lokki versus Treble Acoustical Results

Based on this data, it appears that the Treble results for reverb measures compare favorably with the Lokki data, varying by approximately 12% with regard to the 500-1000 Hz average for t20 and t30. Early decay time (edt) variation was 16% for the average of these bands, and d50 22%. The measures for clarity however were significantly different (varying 88% for c80 and 232% for c50), and G varied by 101%. The Treble data did not provide insight into envelopment measures, and therefore LJ and LEF from the Lokki data were used for the modeling supporting this paper.[103] There are many possible reasons for these variations. First, the model utilized to generate the Treble acoustical data was not watertight and thus only geometric solving was used to determine the acoustical properties.[104] In addition, the materials in the model may not have adequately replicated the actual materials in the hall, particularly in terms of diffusion coefficients. Further refinements of the model might allow these values to more closely align.

While the variations between the Treble and Lokki data are an interesting subject for further study, for purposes of the Seat Sublime recommendation system they are not significant as the data can still be used to show the different recommendations that might be derived based on matching stated concertgoer preferences to acoustical data, whether or not the available data in this case is perfectly accurate.

3.2.4. Scoring and Visualization Pipeline

As noted above, the data derived from the visual and physical seat characteristics is compiled along with the acoustical data into a single spreadsheet. That aggregating spreadsheet performs some additional calculations to average the XY and Z head angle results and take into account the obstruction results in order to provide visual seat characteristic ratings to each stage point graded on a scale of 0-10. Specifically, the system currently averages the XY and Z angles and assigns a score, but if the view from that seat to the target stage location is obstructed then the score is automatically reduced to 0. It is possible that a concertgoer might care more about the XY angle than the Z angle, and if so this formula could be adjusted to weight the average in that direction.

The aggregated and processed data is then output to a comma-delimited file that can be read back into a Grasshopper script. That Grasshopper script allows the user to apply a concertgoer's preferences as derived from the survey data, in order to output an overall matching score for each seat. The system permits the user to output all scores and show them on the model itself as seat scores, seat numbers, or colored dots. Figure 13 shows an example of this output for all seats in the Musiikkitalo hall.

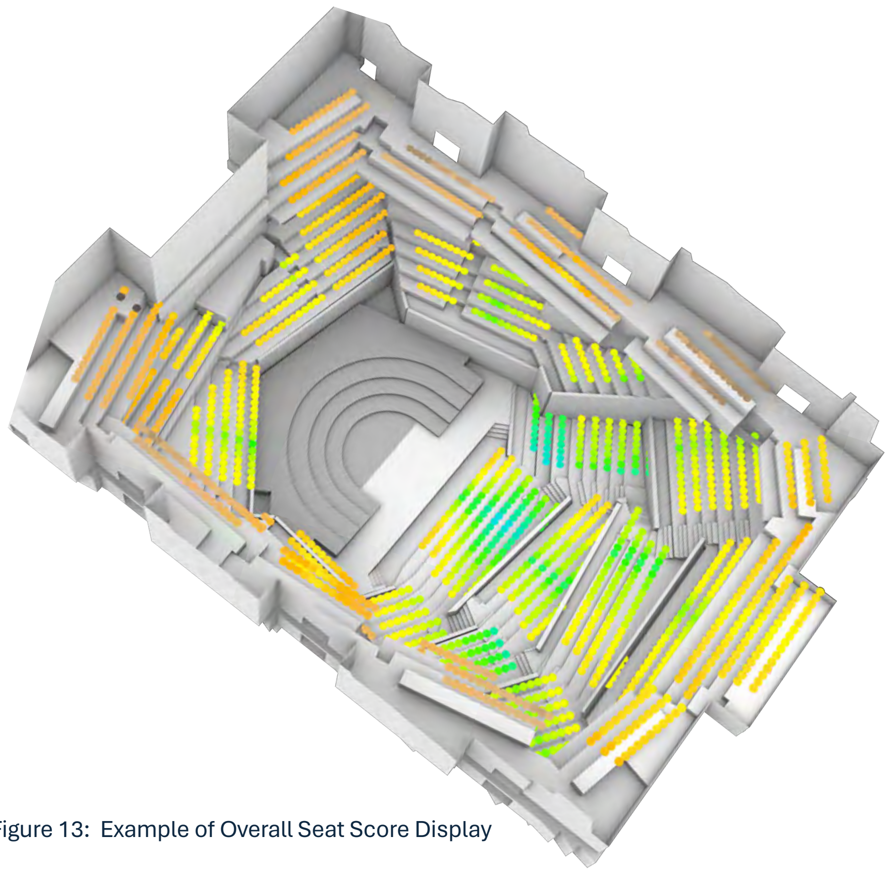

Figure 13: Example of Overall Seat Score Display

A closeup of seat scores is shown in Figure 14. The user can also choose to visualize only a chosen number of seats that best match the surveyed concertgoer's preferences as will be shown below.

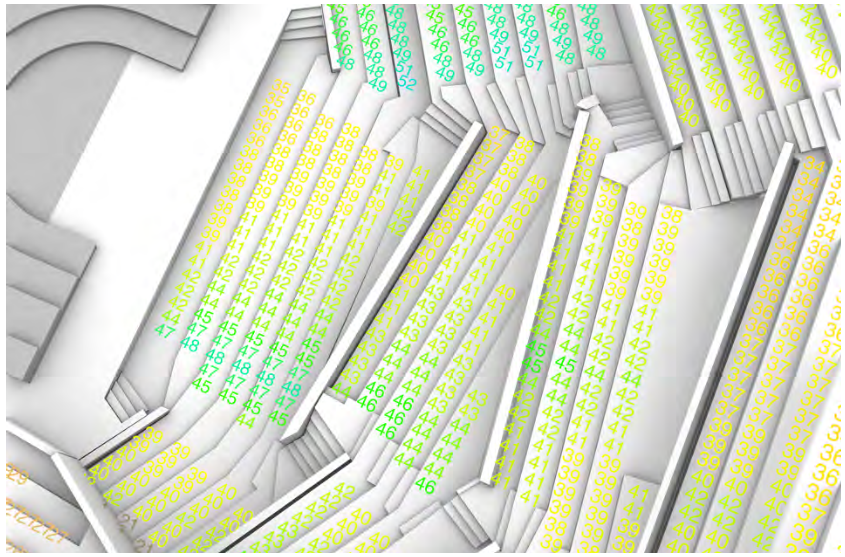

Figure 14: Closeup of Seat Scores Shown on Model

The user interface within the Grasshopper script for applying the concertgoer's preferences based on survey data is a simple interface of True/False selections and sliders that allow weighting of physical versus visual versus acoustical preferences. The interface also allows weighting of specific acoustical preferences among reverb, clarity, envelopment, and loudness. The Grasshopper controls are shown in Figure 15.

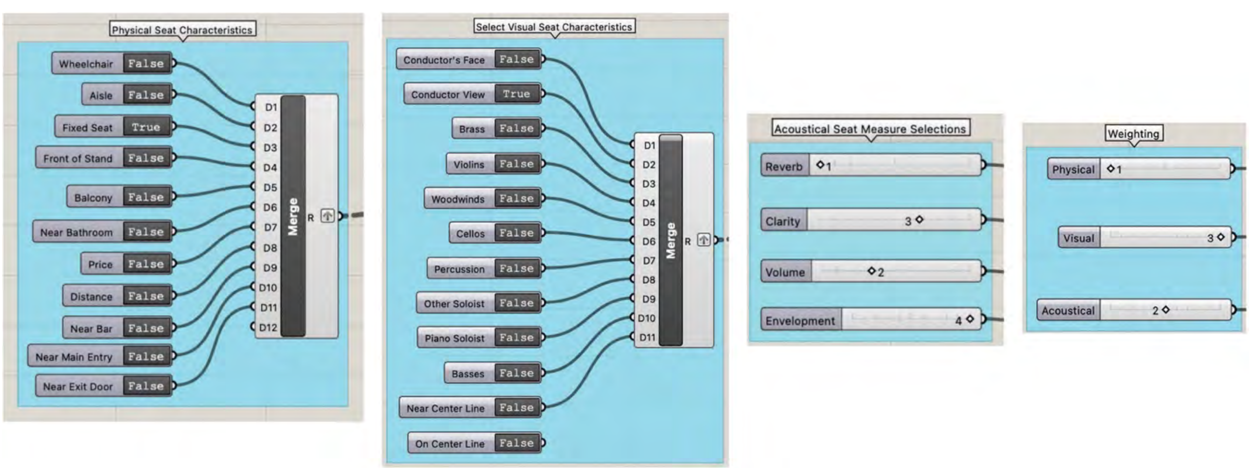

Figure 15: Grasshopper Seat Picker Controls

3.3. Limits of the Investigation

Several enhancements could improve the fidelity of the measurements. The acoustical measurements would be more precise if the model were made watertight, and even better if the actual original 3D model for the building's design were used to perform the calculation. In addition, materials chosen in the modeling and their specific acoustical characteristics could be further tuned, and as mentioned above, sound sources could be tuned to the characteristics of specific instrument sections. Surface receivers could also be used to measure acoustical parameters that might be more closely identified to each seat, as opposed to using a point receiver in each section and then assigning that data to all seats in that section. But even without these enhancements, the system is able to generate useful results for all of the purposes desired.

4. FINDINGS

The Seat Sublime system presented in this paper demonstrates that with knowledge of the characteristics of an individual seat in a hall, the "bug" – that the experience in the seats in the concert hall differ – can be turned into a "feature" to improve the experience of an individual concertgoer. The system can also positively impact the design process, the management of the hall, and the ability of performing arts organizations to sell tickets, as further discussed below. Some examples of the results of the system are discussed below.

4.1. System Output

Once all the acoustical, visual, and physical data is compiled into the master spreadsheet and output to a csv file, the system works in real time to display the suitability of seats in the hall based upon preferences stated by the user. The results of surveys are used to identify these concertgoer (or client or designer) preferences. The survey participant answers two questions about specific aspects of the performance they would like to see (such as the pianist's hands, the percussion section, the conductor's face, or other identified locations on stage), and the physical characteristics of seats (such as whether the seat is on an aisle, wheelchair accessible, in the balcony, near an exit, and similar physical factors). The acoustical character preferred by the concertgoer is identified based on A/B testing of different sound samples impacted by the acoustics of the hall. The survey is attached in Appendix 1: Survey Questionnaire.

Several examples of the Seat Sublime system in operation are discussed below. Note that the examples utilize a color scale where the highest scores (best matching seats) are shown in bright blue, with the scores declining through a spectrum of greens to yellow and orange and then into the browns, with the lowest scores shown in black. The color scheme for this scale can be adjusted to user preference. The scale is shown in Figure 16.

BEST WORST

Figure 16: Color Scale

As noted above, the Seat Sublime system combines scores based on acoustical, visual, and physical seat measures, weights them based on user input, and provides a final view of the score of each seat. This final score (typically between 0 and 60)[105] can be visualized as a color-coded numeric score, seat number, or dot (or any other character), depending on the user's visualization preference. Results can be shown for every seat in the hall or limited to only a certain number of seats scoring highest, again based on user preference. The scoring top and bottom scores can be defined in the grasshopper script to identify a specific chosen lower and upper threshold for "best" and "worst" seats or can be allowed to assign "best" and "worst" based on the highest and lowest score available in the venue resulting from the seat scores and the assigned weighting. All results shown in the accompanying figures are generated using the latter method of scoring.

To demonstrate how this works, the results can first be broken down and visualized at each stage in the process. We will start with an example where the surveyed preferences identify an acoustical preference weighted highest for envelopment, followed by clarity, then volume, and then

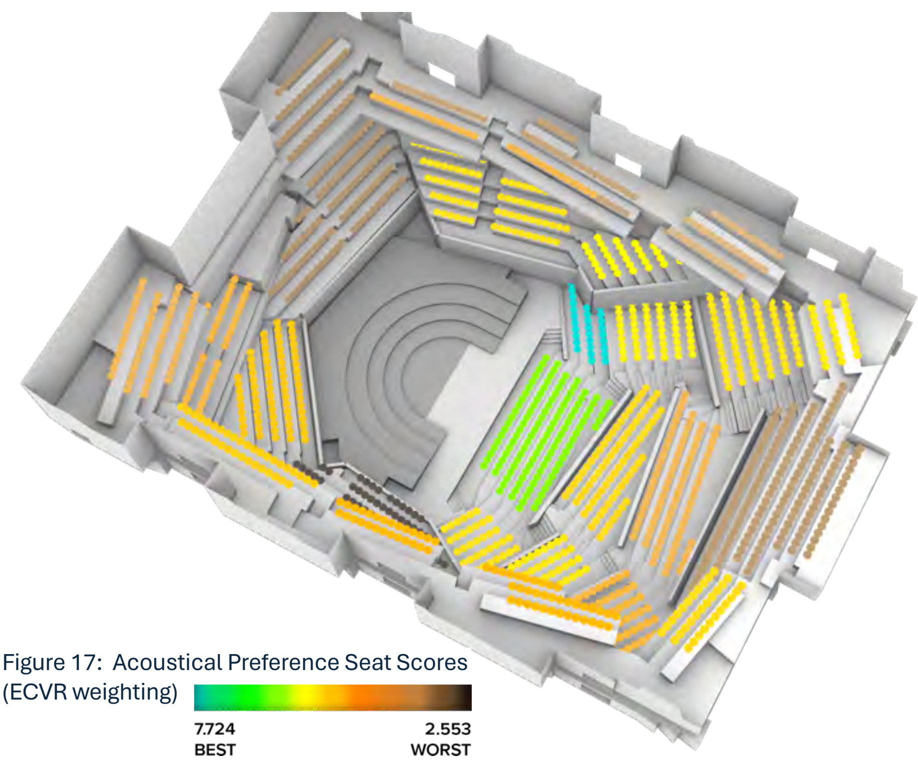

Figure 17: Acoustical Preference Seat Scores (ECVR weighting)

reverberation time at the lowest weighting. The resulting seat scores based only on acoustical preference are shown in Figure 17. Note that acoustical results in the current iteration of the system are available only by seating section because one point receiver was modeled in each seating section (for a total of 28 sections). As a result, all seats in a particular section show the same score.

A visual preferences for a good sight line to the (non-piano) soloist's face (which might be identified in a concertgoer's survey) results in the seat scores in the hall shown in Figure 18. This shows only the visual preference score of the seat alone.

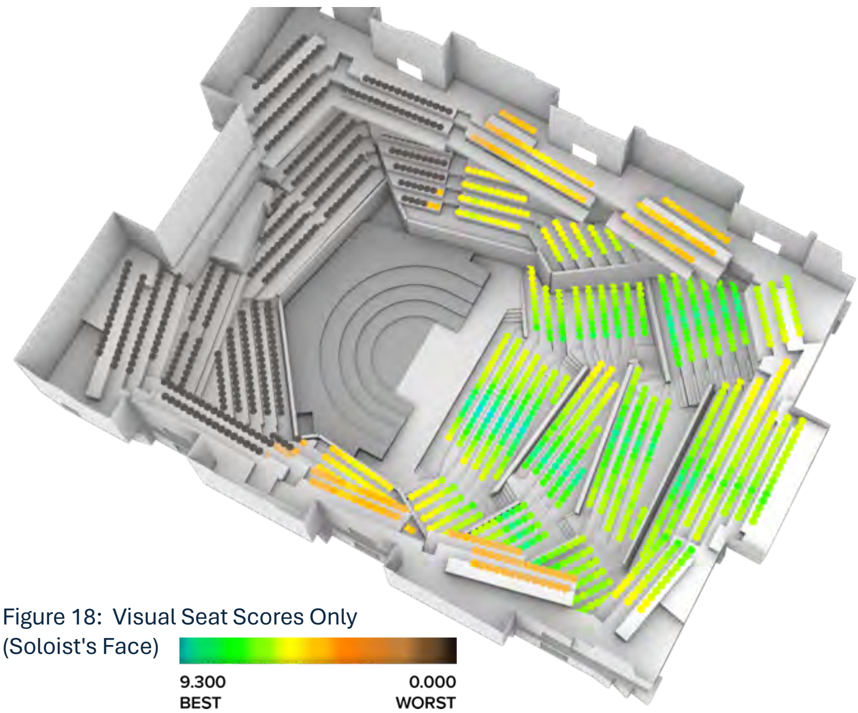

Figure 18: Visual Seat Scores Only (Soloist's Face)

The visual and acoustical scores can be combined. Using equal weighting between the acoustical and visual measures, these combined scores are shown in Figure 19.

These seat scores represent a compromise based on equal weighting of the two scores, with the best seats continuing to be low in front of the stage. Upper seats score less well than in the visual characteristic alone, since they do not score as well acoustically.

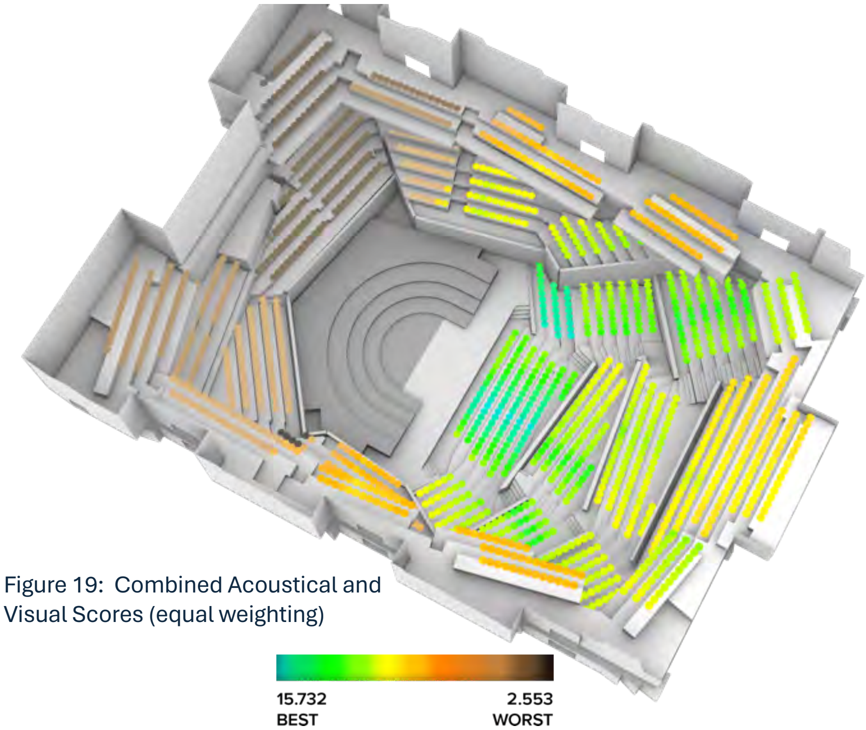

Figure 19: Combined Acoustical and Visual Scores (equal weighting)

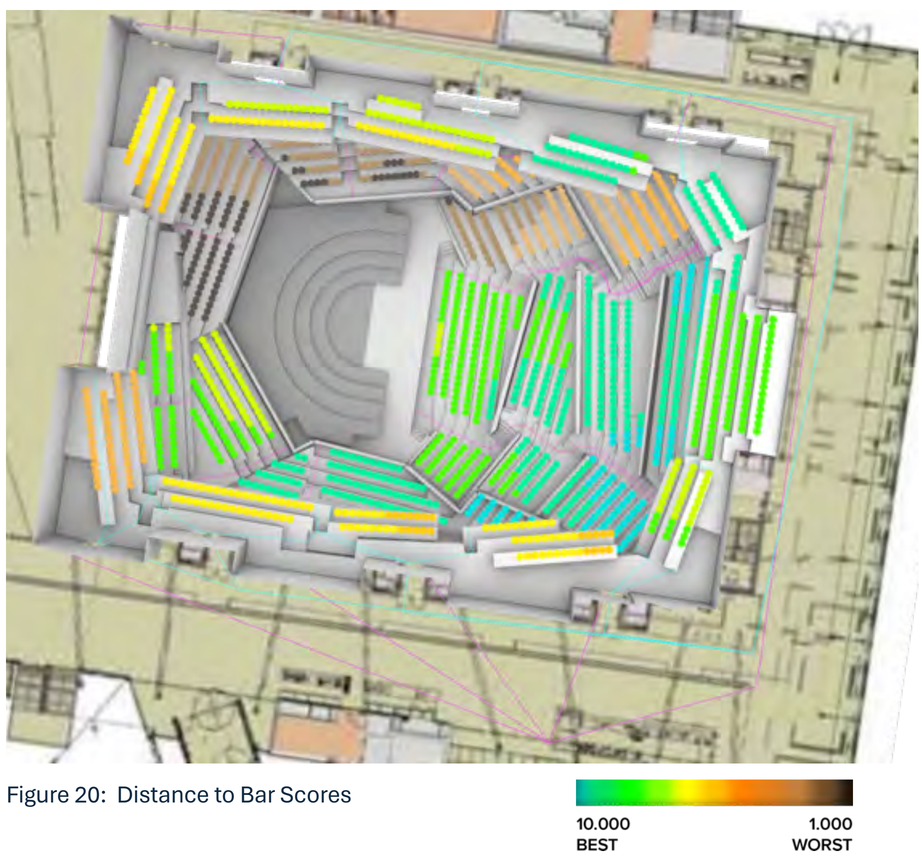

Figure 20: Distance to Bar Scores

The physical seating preference in this example might be for a seat that has a short distance to the bar at intermission. The seat scores for this preference alone are shown in Figure 20, which also shows the paths that would need to be followed to get to the bar, in magenta for the main floor and cyan for the balcony (the bar on the main floor is located at the bottom of the image, and the bar on the balcony level is located to the right in the image).

The acoustical, physical, and visual preferences can then be combined. The resulting seat scores based on an equal weighting are shown in Figure 21.

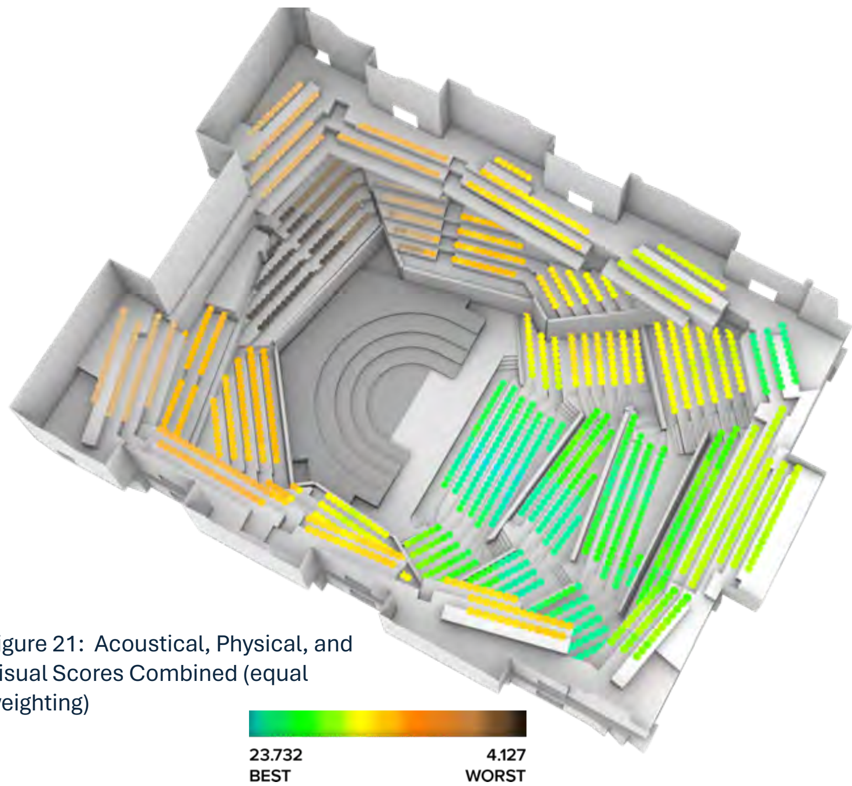

Figure 21: Acoustical, Physical, and Visual Scores Combined (equal weighting)

In the typical operation of the system, it is assumed that a weighting might be applied to the scores where certain parameters of seating preference are valued more highly than others. The weighted-score seat map is shown in Figure 22. In this example, acoustics are identified as most important, followed by physical as the second most important attribute, and then finally the visual component of the seat score as the least important preference. As can be seen from a comparison of Figure 21 and Figure 22, the weighted score favors seats that scored well for matching the acoustics desired, but are now moved closer to the exits nearest to the bar, with some remaining influence from the visual seat parameter. Thus, the overall

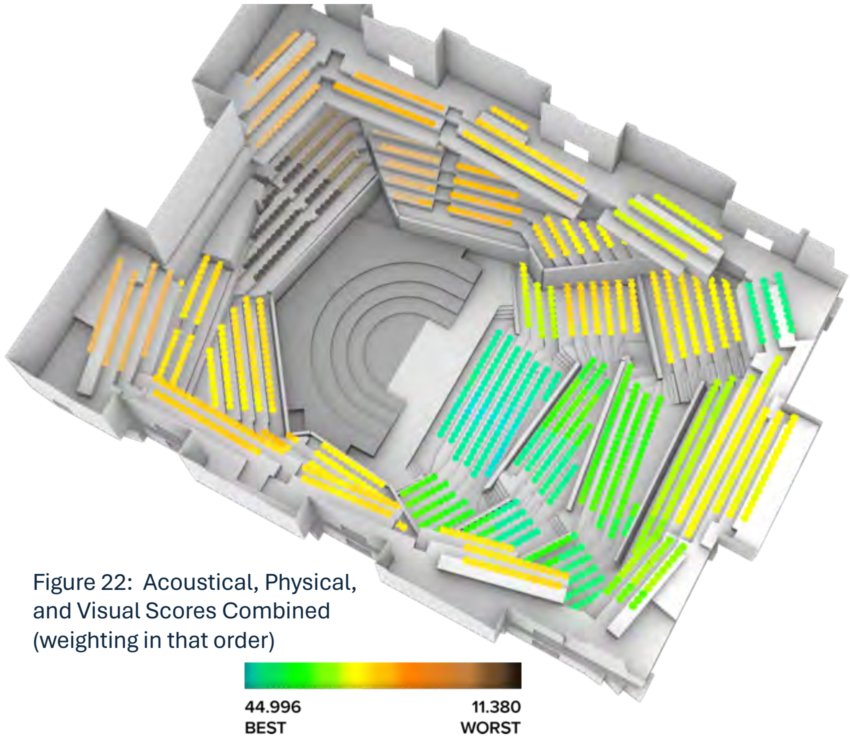

Figure 22: Acoustical, Physical, and Visual Scores Combined (weighting in that order)

recommendation has shifted towards the side of the hall closest to the exit to the bar, but still the highest scoring seats are low and generally centered. This example shows how the system combines scores in a fairly simple example where the results may be more intuitively obvious. The surveyed preferences are not always so simple, as in the three examples of actual surveyed user results discussed below.

4.2. Specific Examples Based on Survey Data

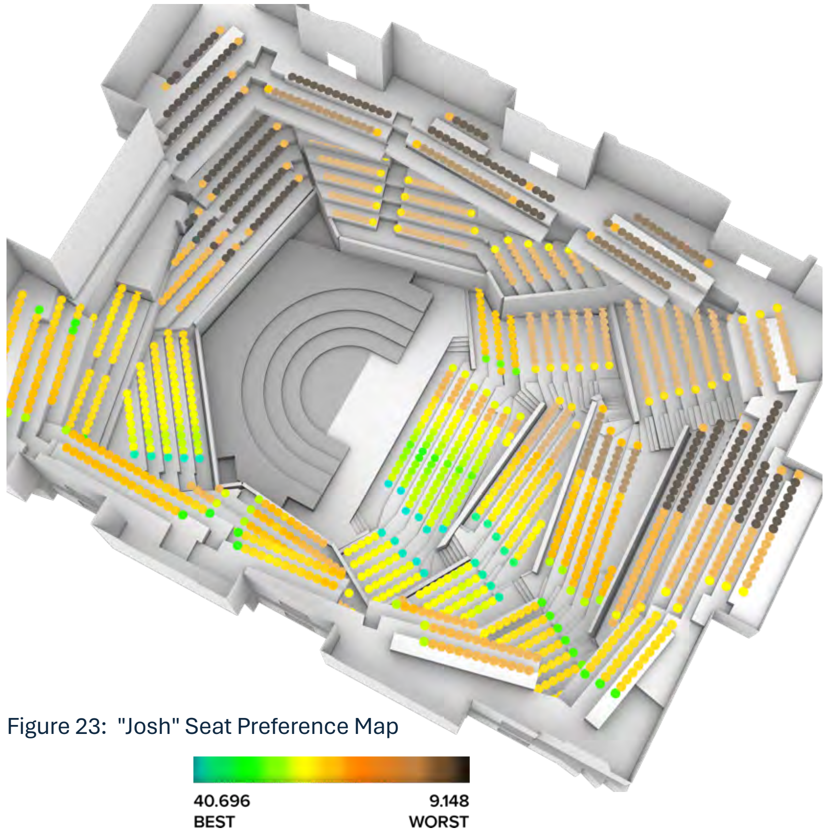

Figure 23: "Josh" Seat Preference Map

"Josh" – Based on the survey results, Josh wants to see the piano soloist's hands, prefers acoustics that are essentially higher in envelopment, volume, and clarity, as compared to reverb, and wants an aisle seat. For purposes of this analysis, ranking of acoustics was in the order of envelopment, clarity, volume, and reverb (ECVR), and overall weighting of preferences was acoustics first, then visual, and then physical (AVP). The resulting seat map is shown in Figure 23. This figure shows that seats surrounding stage right are preferred as these will have better view of the pianist's hands, and seats that are directly in front of the stage on this side have the most preferred acoustical profile. The aisle seats in this area are the highest scoring (shown in bright blue). It is interesting to note, however, that the seats behind stage right with good sight angles to the pianist's hands also score reasonably highly.

Figure 24 shows the actual scores generated by the Seat Sublime system for the top 100 seats in the hall based on Josh's stated preferences. As can be seen, given the weighting of acoustics first, then visual, then physical characteristics, most of the best fit seats are located in the lower sections of the hall in front of stage right, but there are seats that score highly in other locations, primarily due to their scoring well on the "aisle" preference, as well as the sight lines. These factors identify "good" seats matching Josh's overall preferences in many different sections, showing that the hall has many good seats available based on this set of preferences.

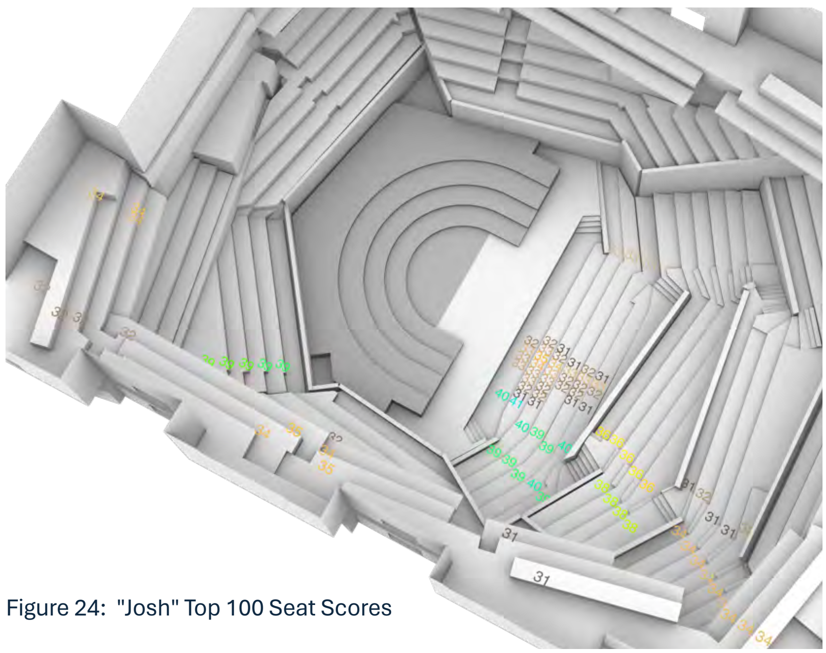

Figure 24: "Josh" Top 100 Seat Scores

A different set of preferences was submitted through the survey by "Alex." Her preferences include seeing a (non-piano) soloist's face, sitting in the balcony, and similar acoustical preferences to "Josh." The system weighting for her preferences was identified as first visual, then acoustical, and then physical seat characteristics (VAP). The resulting seat recommendation map for "Alex" is shown in Figure 25.

As might be expected with this set of preferences, the identified best fit seats are all located facing the front of the stage. Because of the stated preference for the balcony some seats high in the corners that might

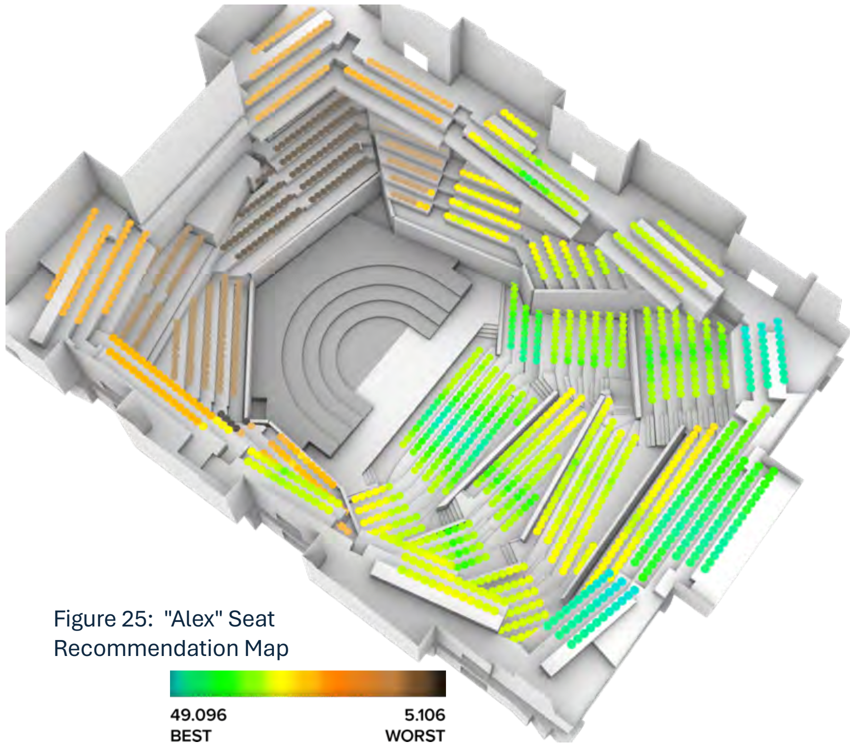

Figure 25: "Alex" Seat Recommendation Map

not score as well on acoustical measures as those down below result in a higher score. It is interesting to note the changes to the resulting seat recommendation map if the preference for balcony seating is removed, as shown in Figure 26.

That map shows lower scores in the balcony, and the best seat matches are now lower down in the hall, although there are still plenty of seats in different section available to fit this preference profile. It is possible the survey could be adjusted to ask concertgoers to rank their order of preference for the different measures, or to state certain requirements as absolute (for example, the preference for a wheelchair accessible seat).

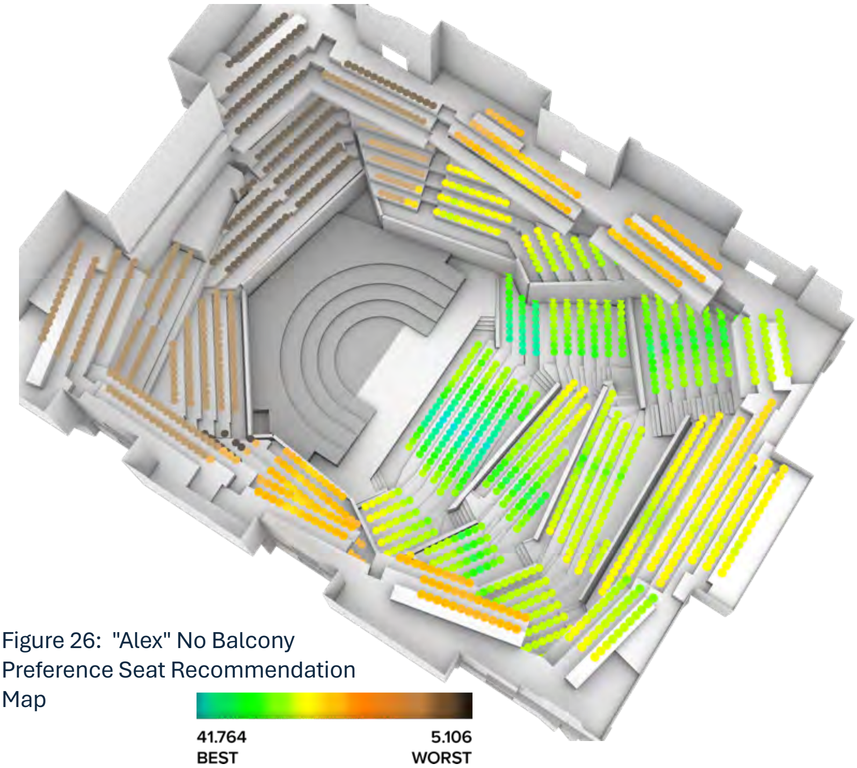

Figure 26: "Alex" No Balcony Preference Seat Recommendation Map

Another concertgoer ("Kate") identified a desire to see the percussion section, preferred an aisle seat, and showed similar acoustical preferences to

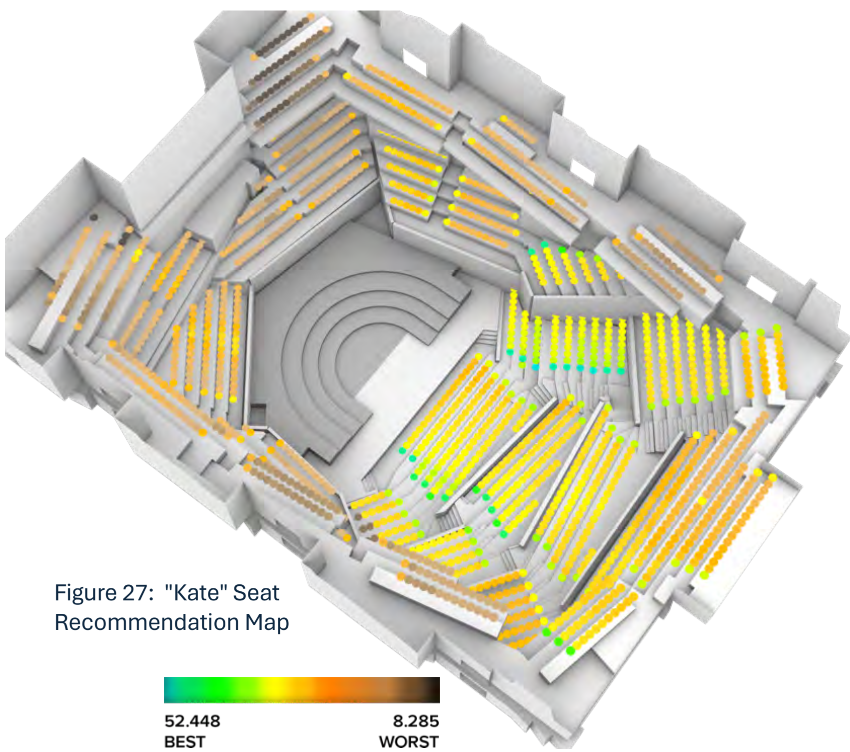

Figure 27: "Kate" Seat Recommendation Map

“Josh” (ECVR). Weighting was VAP. The resulting seat recommendation map is shown in Figure 27. The recommendations have shifted in this case to identify a cluster of best fit seats with a more direct sight line to the percussions section (assumed in this analysis to be located on the back riser of stage right per typical American practice). The more appropriate acoustics based on the surveyed listening profile were near the reflecting/diffusing walls located stage left, and seats on the aisle scored highly.

4.3. Visual Sight Lines

The analysis of visual sight lines takes into account identified obstructions such as walls or floors in the line of sight from a particular seat to a particular section of interest on the stage. And as mentioned previously, the definition of “obstruction” can be tuned in the model based on a radius around the line of sight so that the system can be tuned to identify an obstruction as any wall or floor surface that is within a certain distance from the lines of sight. The results shown here are generated assuming an obstruction exists if the sight line comes within 1.5 meters of the wall or floor surface. This is intended to take into account the fact that the points on stage are identified as points, but sections of the orchestra are actually spread out in groups. So if there is an obstruction within 1.5 meters of the sight line it is quite likely that part of the instrument section is not visible. This is a tunable parameter.

In general, it is also possible to identify seats with more or less obstructed views based not only on the wall and floor surfaces, but also based on the heads of the audience members in front of a seat. The option to state a

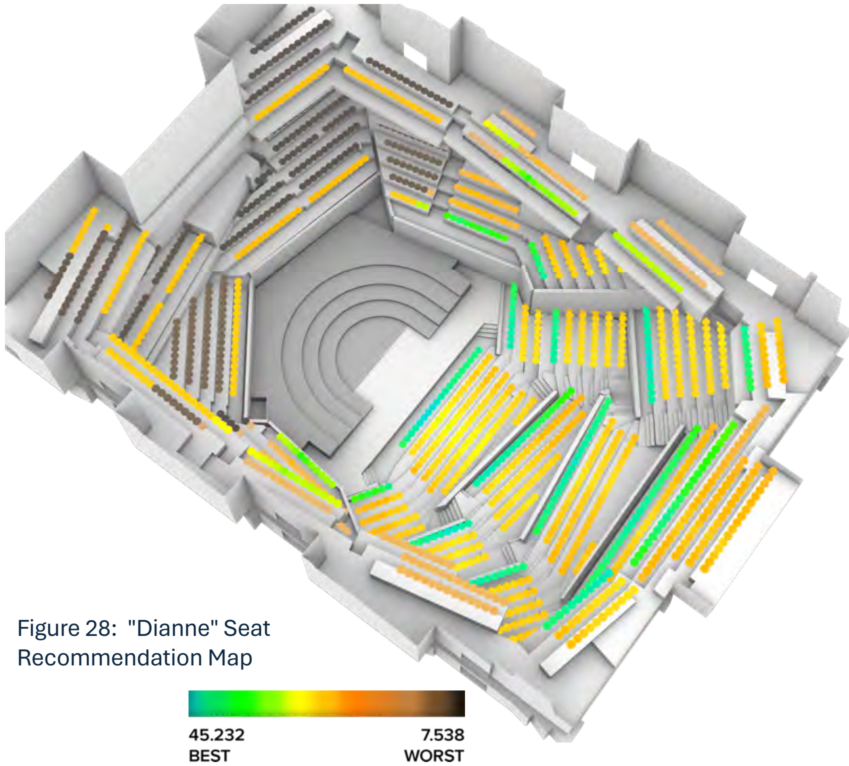

Figure 28: "Dianne" Seat Recommendation Map

preference for this was included in the survey only as a preference for sitting in the front of a seating section. An example of results for someone stating this preference can be seen in Figure 28. This concertgoer ("Dianne") also stated preferences to see the soloist's face and an RECV acoustical profile. Weighting was VPA.

But it can be assumed that the vast majority (if not all) concertgoers would prefer a seat where their view was not obstructed by the heads of the audience members seated in front of them. The system is therefore capable of identifying "head" obstructions for every seat in the hall. An example of this analysis based on the view to the conductor is shown in Figure 29. This shows the number of "heads"[106] that could be expected to be within 0.35 meters (or 14 inches) of the line of sight from any given seat in the Musiikkitalo hall. The maximum number is 6, but the vast majority of seats in the hall are in the range of 0-2 head obstructions.

It is interesting to note for comparison the results of this analysis when applied on the same basis to the seats on the main floor of the Vienna Musikverein, which is shown in Figure 30. The Musikverein – a hall renowned for its acoustics – has a largely flat orchestra-level seating floor, and the result is the likelihood of many more obstructed views for those sitting on the main floor. Using the same 14" radius as utilized in the Musiikkitalo example, the highest head obstruction count is 35, and most seats have more than 5. Side (parterre) seats behind the parterre first row are also significantly obstructed (and the analysis shown in Figure 30 does not even take into account the obstructions from the columns and walls in the hall).

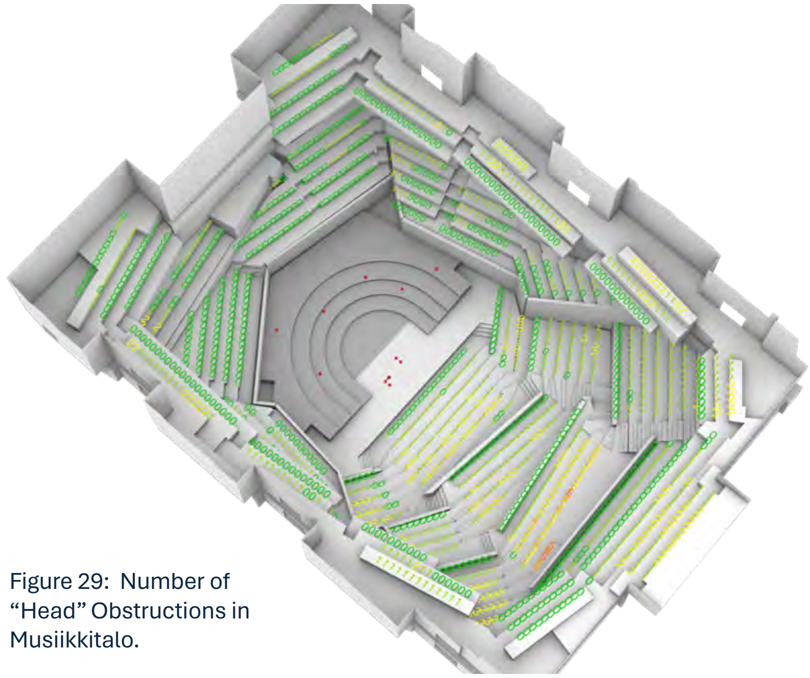

Figure 29: Number of "Head" Obstructions in Musiikkitalo.

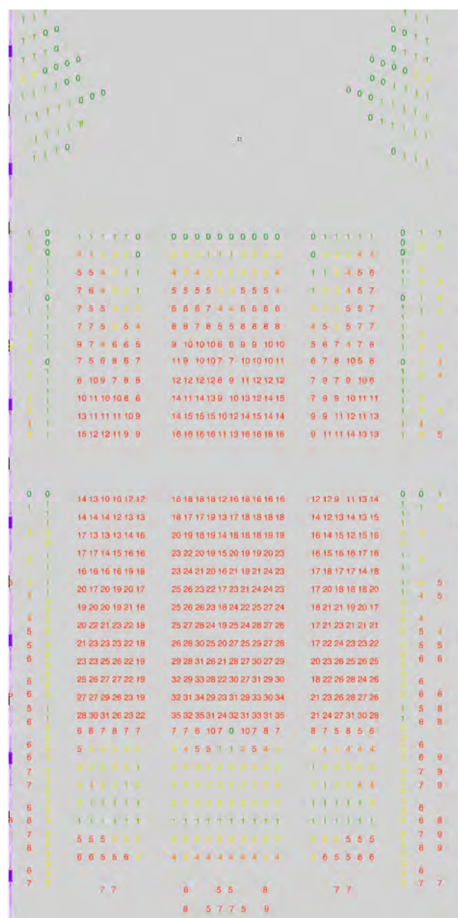

Figure 30: Vienna Musikverein Main Floor "Head" Obstructions.

The seating map provided by the Musikverein[107] (shown in Figure 31) identifies partially obstructed views for the parterre and stage corner seats (in red), but apparently does not consider (or disclose) the potential impact of the many rows of seating at floor level as a result of the lack of floor rise in the center of the hall. Having not experienced sitting in those seats for a concert, this author cannot comment on the experience of those sight lines. But it may be that the preference for vineyard style halls is in part attributable to the apparently far less obstructed views of the stage in a vineyard style hall than those in a traditional shoebox hall such as the Musikverein. This preference for better visual sight lines may be somewhat in tension with the identified acoustical differences between the two types of halls, where a vineyard style hall may not be preferred acoustically by many concertgoers. But the overall concert experience, as demonstrated in this paper, is a combination of acoustical, visual, and physical seat (and hall) characteristics, and there are seats in vineyard style halls that can fit virtually any set of desired parameters reasonably well.

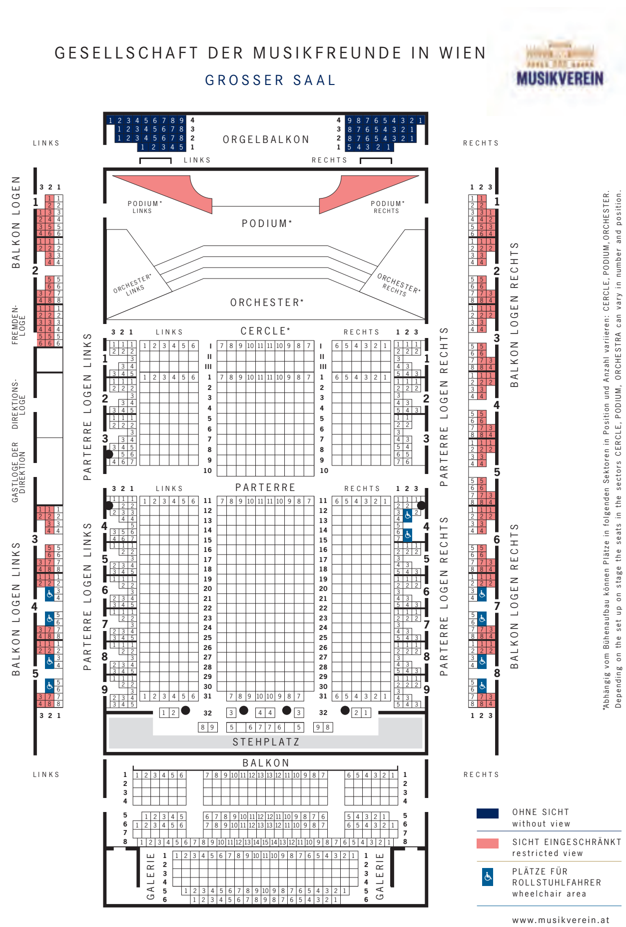

Figure 31: Vienna Musikverein Venue Seating Plan Identifying Obstructed Views.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Design Process Enhancements

How might the availability of the Seat Sublime system benefit designers of concert halls? To begin with, one could conduct surveys of potential audience members at the start of the design process, or survey stakeholders (conductors, musicians, venue managers, and others) to identify their preferences. These surveys would help inform the design and develop a common language between designers and clients. In addition, the discussion between client and architect could be enhanced with visualizations of the many differences in seating characteristics resulting from different design choices. The system is also useful for demonstrating that while not all seats are created equal, there are many definitions of the "best" seat in the hall. The system can show "best" as seen from many different concertgoer perspectives. The system might also help translate the many different words used (even when limiting the conversation to one language) to describe the conditions in the hall – acoustical, visual, and physical. Sometimes, a picture is truly worth a thousand words.

5.2. Improving Management of the Hall

The Seat Sublime system could also be useful in the management of the hall in planning performances and even managing the application of variable acoustic measures within the hall, before and during performances. When planning a performance, the deployment of different variable acoustic measures (such as curtains or sliding or rotating wall panels) could be tested in the model to determine the impact on the sound in different seating locations. If the variable acoustic measures can be deployed through "push-button" technology, the musical program might be expanded to accommodate different types of music requiring different variable acoustic measures at different times in the program or different locations in the hall. This could expand the repertoire available to be presented at any given performance.

5.3. Assisting Performing Arts Organizations

The Seat Sublime system could also be used to assist performing arts organizations in selling seats that will be most appropriate for concertgoers. Ideally a survey similar to that designed for this study would be available to potential ticket buyers. The program being presented for the selected concert would also be known, and thus the characteristics of the music – such as whether and what type of soloists will take part or the degree to which the concert will be loud or quiet, feature certain instrument sections, etc. – would also be known. The Seat Sublime system could then be tuned to generate a resulting seating chart that is specific to that concertgoers' preferences aligned with the music to be performed and offer appropriate seats for that concertgoer. This might allow a concertgoer to select different seats for different concerts based on the music to be performed. It could also sell seats in sections that might be deemed less preferable by a concertgoer based on the information normally available, which largely consists of a seating map for the hall with prices based on orientation of the seat on the center line of the hall and distance from the stage. The goal would be greater concertgoer satisfaction, engagement, and the sale of seats that might otherwise be deemed undesirable.

To the extent that concertgoers can also rate their seating experience (as has become ubiquitous in today's world) it might then be possible to use this feedback to tune the recommendations of the Seat Sublime system such that matching of stated preferences to seating locations can be improved. Ideally this will continuously improve the system, and ultimately the concertgoers' satisfaction with the concert experience, hopefully leading to increased "stickiness" of concertgoers, repeat attendance, and more ticket sales.

5.4. Improving the Concert Experience

Assisting concertgoers in selecting seats that best align with their preferences in the concert experience is ultimately going to benefit concertgoers by providing them with the experience they want to have at a concert. In addition to the benefits noted above for increasing repeat attendance, from a concertgoer's perspective it may also become possible to recommend not only what seat to sit in, but what concert hall to choose in order to experience a particular piece of music in a manner that is best in tune with the concertgoer's preferences. While this may only be of benefit to those with the ability to travel to see concerts in different halls, for connoisseurs it may be a significant enhancement of their concertgoing experience.

5.5. Future Work

While an implementation of the Seat Sublime system is proposed in this research, enhancements can be conceived that could provide superior results when additional data becomes available. To begin, the model used for acoustical simulation could be further tuned to match measured results, as discussed above. This would enhance confidence in the system as digital models are created for additional venues where such accurate and granular (by seating section or seat) actual acoustical measurements are not available.

Additional data would come in part from user ratings of the recommendations provided for the individual seat selections. User ratings would enable a feedback loop and future machine learning enhancement of the system. In addition, the system could be enhanced to predict which seats would be more desirable for a particular concertgoer based on more general information that might be publicly available or privately available with permission, and without as much input from the user. Examples might include demographic correlations, music stored on one's mobile device, other concerts attended, or other seats purchased at the same or similar venues and user ratings for these concerts, if available. The system could find correlations about user preference that may not even be known to the concertgoer, enhancing their experience at a particular venue, and resulting in the kind of concert hall experience that cities seek when they spend the time and money to build a new hall. This would further enhance the reputation of the venue, the orchestra, the musicians, and the conductors performing within the hall, and perhaps thereby also enhance the reputation of the hall's designers, and of the city itself as a cultural center.

Even without these enhancements, understanding that the concert experience is a combination of many factors, and that the seats in the hall can be selected to deliver a different experience based on the preferences of the concertgoer, and implementing a system that identifies these differences and makes them known turns the ‘bug’ of individual seat variability into a ‘feature’ of the concert hall, and can lead to a more holistic conversation about concert hall design.

ENDNOTES

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[1] Auditorium Parco della Musica website, History of the Auditorium (translated by Google Translate).

[2] Measurement of room acoustic parameters, Part 1: Performance Spaces, EN ISO 3382-1:2009.

[3] Lokki, Tapio & Pätynen, Jukka. (2019). *Architectural Features That Make Music Bloom in Concert Halls*. Acoustics. 1. 439-4. Lokki, Tapio & Pätynen, Jukka & Kuusinen, Antti & Tervo, Sakari. (2016). *Concert hall acoustics: Repertoire, listening position, and individual taste of the listeners influence the qualitative attributes and preferences*. *The Journal of the Acoustical Society of America*. 140. 551-562. 10.1121/1.4958686.

[4] Herbert Von Karajan, the world-famous conductor of the Berlin Philharmonic, was a key advocate of what is credited as the first "vineyard" style concert hall: the Philharmonie hall in Berlin, designed by Hans Scharoun. Osborne, Richard (1998). Herbert von Karajan: A Life in Music. Chatto & Windus. pp. 475. ISBN 1-55553-425-2. Schmid, Rebecca, A Hall that Invites the Audience Into the Music-Making. *The New York Times* (December 22, 2013). Available at https://www.nytimes.com/2013/12/23/arts/international/a-hall-that-invites-the-audience-into-the-music-making.html.

[5] "In engineering, a bug is a design defect in an engineered system that causes an undesired result." Wikipedia, entry for "Bug (engineering)." https://en.wikipedia.org/wiki/Bug_(engineering).

[6] "The results measured for the range of source and microphone positions can be combined either for separate identified areas or for the room as a whole to give spatial average values. This spatial averaging shall be achieved by arithmetic averaging of the reverberation times." Measurement of room acoustic parameters, Part 1: Performance Spaces, EN ISO 3382-1:2009 at 10.

[7] "[The ISO] standard has recently been criticized on many grounds: The algorithms to compute the parameters are imprecise, the applied frequency range is too narrow, and a single omnidirectional source is a poor representation of the dozens of sound sources present in a real orchestra. Moreover, the objectively measured parameters fail to describe the details of perceived acoustics." Lokki, Tapio, "Tasting music like wine: Sensory evaluation of concert halls." *Physics Today* 67 (1), 27-32 (2017), citing J. Bradley, *Appl. Acoust*. 72, 713 (2011); L. Kirkegaard, T. Gulsrud, *Acoust. Today* 7, 7 (2011).

[8] "[O]ur results suggest that attending a live performance leads to lower secretion of glucocorticoids and a reduced cortisol/cortisone ratio, indicating lowered biological

stress. These results are in line with 22 previous studies showing that listening to music in the controlled setting of either a laboratory or a hospital can reduce cortisol levels. However, this study has also extended previous results. Firstly, it showed that decreases are also found in the partner glucocorticoid cortisone, which demonstrates a wider glucocorticoid involvement. Secondly, this is the first time that such decreases have been found not only in tightly controlled laboratory settings but in the naturalistic setting of a public concert in a cultural space." Fancourt, Daisy and Aaron Williamon, "Attending a concert reduces glucocorticoids, progesterone and the cortisol/DHEA ratio," *Public Health*, Vol. 132, pp. 101-104 (2016) available at https://doi.org/10.1016/j.puhe.2015.12.005 and https://www.sciencedirect.com/science/article/pii/S0033350615004990.

[9] "Fortnightly gig attendance could extend life expectancy by NINE years; Wellbeing increased by 21% from just 20 minutes of gig time, compared to just 10% for yoga and only 7% for dog-walking." Fagan, Patrick and O2, "Science says gig-going can help you live longer and increases wellbeing," *Virgin Media* (March 27, 2018) available at https://news.virginmediao2.co.uk/archive/science-says-gig-going-can-help-you-live-longer-and-increases-wellbeing/.

[10] Shoda H, Adachi M, Umeda T, "How Live Performance Moves the Human Heart," *PLoS ONE* 11(4) (2016) available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4841601/pdf/pone.0154322.pdf.

[11] *Ibid*.

[12] Live Nation, "The Power of Live" survey (September 27, 2018), available at https://www.livenationentertainment.com/2018/09/global-study-reveals-why-live-music-is-one-of-the-most-powerful-human-experiences-and-the-ultimate-escape-from-digital-overload-21/.

[13] *Ibid*.

[14] See Section 2.1.4.

[15] Stampa, Benedict. "Concert Halls." Deutscher Mus|Krat (September 1, 2018, edited March 30, 2022). https://miz.org/en/articles/concert-halls, citing polls reviewed in Reuband, Karl-Heinz. Preferences and Publics. *MIZ deutches musikinformations zentrum* (February 1, 2019). https://miz.org/en/articles/preferences-and-publics.

[16] Classic FM. "A survey from one of the UK's top orchestras suggests the public's appetite for live orchestral performances has grown over the last five years." https://www.classicfm.com/music-news/survey-research-royal-philharmonic-orchestra/

[17] Classical Music Consumer Segmentation Study: How Americans Relate to Classical Music and Their Local Orchestras." Commissioned by 15 American Orchestras and the John S. and James L. Knight Foundation. https://www.esm.rochester.edu/iml/prjc/poly/wp-content/uploads/2012/04/2002_Classical_Music_Consumer_Report.pdf.

[18] *Id*. at 10.

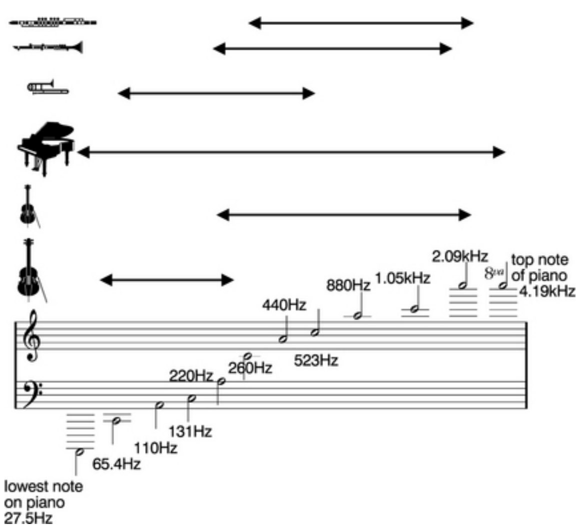
[19] Brice, Richard. "Good Vibrations – The Nature of Sound." *Music Engineering*, Ch. 2, p.12-40 (Newnes, 2001). "The fluctuation of air pressure created by sound waves is a change above and below normal atmospheric pressure. This is what the human ear responds to. The varying amount of air molecule pressure compressing and expanding is related to the apparent loudness arriving at the ear. The greater the pressure change, the louder the sound. … The threshold of pain is around 200 microbars. This wide amplitude range of sound is often referred to in decibels. Sound Pressure Level (dB SPL), relative to 0.0002 microbar (0dB SPL). 0dB SPL is the threshold of hearing and 120dB SPL is the threshold of pain. 1dB is about the smallest change in SPL that can be heard. A 3dB change is generally noticeable and a 6dB change is very noticeable. A 10dB SPL increase is perceived to be twice as loud." Sound Service (Oxford) Ltd. Website "Basic Studio Room Acoustics: Loudness." https://www.soundservice.co.uk/basic-room-acoustics.html#:~:text=The%20greater%20the%20pressure%20change%2C%20the%20louder%20the%20sound.

[20] Brice, *supra*.

[21]Humes, Larry. What is "Normal Hearing" for Older Adults and Can "Normal-hearing Older Adults" Benefit from Hearing Care Intervention? *The Hearing Review* (July 14, 2020). https://hearingreview.com/inside-hearing/research/what-is-normal-hearing-for-older-adults. See also ISO 7029:2017.

[22] Brice. "Remember that the frequency components of the sound produced by each of these instruments extends very much higher than the fundamental tone. Take for instance the highest note on a grand piano. Its fundamental is about 4.19 kHz but the fourth harmonic of this note, which is certainly seen to be present if the sound of this tone is analysed on a spectrum analyser, is well above 16 kHz." The fundamental tone frequencies for various orchestral instruments are summarized below:

Instrument	*Lower frequency limit (Hz)*	*Upper frequency limit (Hz)*
Choir	82**	880**
Piano	27.5	4190
Violin	196	2600
Viola	131	1050
Cello	65.4	780
Flute	260	2090
Piccolo	532	4190
Guitar (electric)	82.4	2090*
Guitar (bass)	41.2	220*



[23] Tommasini, Anthony. "Classical Music Attracts Older Audiences. Good." *The New York Times* (August 6, 2020). https://www.nytimes.com/2020/08/06/arts/music/classical-music-opera-older-audiences.html#:~:text=It's%20true%20that%20classical%20music,audience%20was%2055%20and%20older.

[24] Lokki, Tapio, "Tasting music like wine: Sensory evaluation of concert halls." *Physics Today* 67 (1), 27-32 (2017), citing [Bill Hartmann in PHYSICS TODAY, November 1999, page 24].

[25] Ando, Yoichi and Prabhat Kumar Singh, "Global subjective evaluations for design of sound fields and individual subjective preference for seat selection," in Ando, Yoichi and Dennis Noson editors, Music & Concert Hall Acoustics: *Conference Proceedings from MCHA 1995*, Academic Press (1997), pp. 30-38.

[26] The difference in signals received by a person's ears.

[27] Id., at 31.

[28] Quote attributed to Abraham Lincoln.

[29] Adobe.com. Digitizing Audio. https://helpx.adobe.com/si/audition/using/digitizing-audio.html.

[30] Table from Adobe.com. "Digitizing Audio." https://helpx.adobe.com/si/audition/using/digitizing-audio.html

[31] "The 1997 [US National Endowment for the Arts Survey of Public Participation in the Arts] indicates that 41 percent of Americans listen to classical music at least once each year on radio. Of Americans surveyed, 34 percent indicated that they have listened to classical music at least once a year on recordings." Dempster, Douglas. "Wither the Audience for Classical Music?" *Harmony*, No. 11 (October 2000).

[32] Classical Music Consumer Segmentation Study: How American Relate to Classical Music and Their Local Orchestras." Commissioned by 15 American Orchestras and the John S. and James L. Knight Foundation at 2.

[33] Adobe.com. Digitizing Audio. https://helpx.adobe.com/si/audition/using/digitizing-audio.html

[34] Gideon, Tim. "What are Bluetooth Codecs? A Guide to Everything from AAC to SBC." *PC Magazine* (updated August 7, 2023). https://www.pcmag.com/how-to/what-are-bluetooth-codecs-a-guide-to-everything-from-aac-to-sbc#

[35] Beranek, *Concert Halls and Opera Houses*, 10-11.

[36] Sabine "defined the reverberation time, which is still the most important characteristic currently in use for gauging the acoustical quality of a room, as number of seconds required for the intensity of the sound to drop from the starting level, by an amount of 60 dB (decibels). His formula is:

$$T = \frac{V}{A} \bullet\ 0.161 s\, m^{-1}$$

Where

T = the reverberation time
V = the room volume
A = the effective absorption area"

Wikipedia, Wallace Clement Sabine, https://en.wikipedia.org/wiki/Wallace_Clement_Sabine#:~:text=Wallace%20Clement%20S abine%20(June%2013,the%20world%20for%20its%20acoustics.&text=Richwood%2C%20Ohio%2C%20U.S.

A good discussion of Sabine's history and the start of room acoustics is also contained in the podcast "How to Design the Acoustics of a Concert Hall" (Makovsky, Paul. "How to Design the Acoustics of a Concert Hall." *Architect* (December 20, 2022). https://www.architectmagazine.com/practice/podcasts/podcast-how-to-design-the-acoustics-of-a-concert-hall_o.)

[37] Leo Beranek, a professor at MIT, wrote several early and highly regarded books in the field of acoustics. His first book on concert hall design, *Music, Acoustics, and Architecture*, was published in 1962 and is considered a classic in the field. A revised and expanded version was published in 1996 and again updated in 2004. The research method is scientific measurement of hall acoustic parameters along with extensive surveying of concertgoers including music critics, musicians, and conductors.

[38] See the papers authored by Tapio Lokki cited in this paper.

[39] For purposes of this discussion, religious music of the Baroque period, largely intended to be played in church and cathedral environments and in chapels of the wealthy or royal patrons is ignored in this discussion. While this genre of music led to further musical development, it was less influential in the design of the concert hall targeted to the performance of the symphony orchestra. Beranek at 10.

[40] *Id*.

[41] *Id*.

[42] *Id*. at 12.

[43] Heathcote, Edwin. "The problem with building concert halls." *Financial Times* (August 19, 2016).

[44] *Id*.

[45] Makovsky, interviewing Prof. Michael Ermann of Virginia Tech School of Architecture at 38'.

[46] Makovsky at 39'.

[47] Beranek at 11.

[48] Beranek at 12.

[49] "[T]he acoustics of a concert hall can be predicted to a considerable degree of accuracy on the basis of the architect's plans, and those plans can thus be tweaked as necessary to achieve the acoustics desired." Lokki, Tapio. "Concert hall acoustics – but on whose terms?" *Finnish Music Quarterly* (Columns) (March 31, 2019).

[50] Nagata, Minoru, "Design problems of concert hall acoustics", *J. Acoustic Soc. Jpn.,* Vol 10, No. 2, pp. 59-72 (1989).

[51] Dunworth, Liberty. "Beatles tribute concert at cathedral triggers audience walkout over 'wall of noise.'" *NME* (May 16, 2024). https://apple.news/A-Vy_s_A6QRmkNLoxQajKmg.

[52] Nagata, Minoru. "What We Have Learned from the Listening Experiences in Concert Halls—Physical Properties and Subjective Impressions of Five Concert Halls in Tokyo." *Applied Acoustics* 31, 29-45 (1990).

[53] Lokki, Tapio. "Concert hall acoustics – but on whose terms?" *Finnish Music Quarterly* (March 31, 2019).

[54] Pätynen, Jukka and Tapio Lokki, "The Acoustics of Vineyard Halls, is it so Great After all?" Acoustics Australia (2015) 43:33-39 at 38.

[55] Lokki, Tapio, Jukka Pätynen, Antti Kuusinen, Sakari Tervo, "Concert Hall Acoustics: Repertoire, listening position, and individual taste of the listeners influence the qualitative attributes and preferences." *J. Acoust. Soc. Am.* 140, 551-562 (2016) at 562.

[56] Other authors have discussed, and to some degree questioned, the initial time delay gap (ITDG) as a key acoustical measure. See Hyde, Jerald R. "Discussion Of The Relation Between Initial Time Delay Gap (ITDG) and Acoustical Intimacy: Leo Beranek's Final Thoughts On The Subject, Documented." *Proceedings of the Institute of Acoustics*, Vol. 38. Pt. 3. (2018).

[57] Sakurai, Masatsugu, Yuji Korenaga, and Yoichi Ando, "A sound simulation system for seat selection," in Ando, Yoichi and Dennis Noson editors, *Music & Concert Hall Acoustics: Conference Proceedings from MCHA 1995*, Academic Press (1997), pp. 51-59 at 54. This

concert hall had a special anechoic room set aside for testing ticket purchaser preferences as shown in the plan below.

These four factors are also discussed in another article from the proceedings: Ando, Yoichi and Prabhat Kumar Singh, "Global subjective evaluations for design of sound fields and individual subjective preference for seat selection," in Ando, Yoichi and Dennis Noson editors, *Music & Concert Hall Acoustics: Conference Proceedings from MCHA 1995*, Academic Press (1997), pp. 30-38.

58 Samples of two representative seat maps are provided in Sakurai, at figure 6.9:

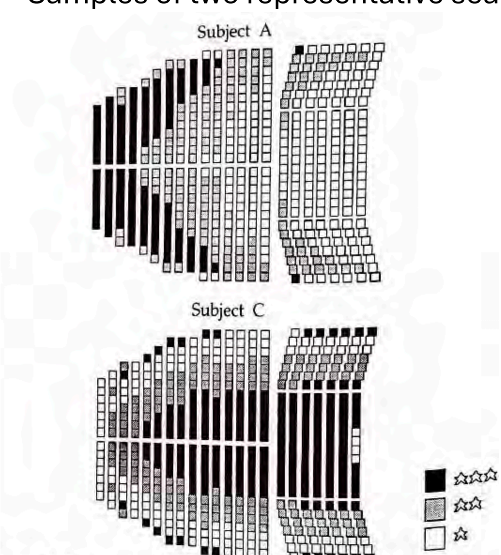


Fig. 6.9 The preference grades classified into three levels.

59 The method for calculation of the individual seat acoustical parameters is further discussed in Nakajima, Tatsumi, and Yoichi Ando, "Calculation and measurement of acoustic factors at each seat in the Kirishima International Concert Hall," in Ando, Yoichi

and Dennis Noson editors, *Music & Concert Hall Acoustics: Conference Proceedings from MCHA 1995*, Academic Press (1997), pp. 39-49.

[60] Vuoskoski, Jonna K., Marc R. Thompson, Charles Spence, Eric F. Clarke. "Interaction of Sight and Sound in the Perception and Experience of Musical Performance." *Music Perception*, Vol. 33, Issue 4 (April 2016) at 457. *See also* Vuoskoski, Jonna K. and Tuomas Eerola, "Extramusical information contributes to emotions induced by music." *Psychology of Music* 2015 43:2, 262-274.

[61] Vuiskoski (2015) at 265; Vuiskoski (2016) at 459.

[62] AZ Quotes: George Lucas. https://www.azquotes.com/quote/812678. *See also*, Gray, Tim. "Sound is 50% of the Movie, but Hollywood is Often Tone-Deaf." *Variety* (February 22, 2018). https://variety.com/2018/film/awards/sound-movie-blade-runner-get-out-phantom-thread-1202705398/, and the general description by George Lucas on the background for creating the THX sound system and certification found at https://www.youtube.com/watch?v=1RxI7Dqq1b8. I can also attest to having personally heard George Lucas state that sound was 50% of the experience, although in that context and speaking about THX's approach to sound certification in theaters, what I recall him saying was "they tell me sound is at least 50% of the experience." In any case, it appears from the available quotes online that he came to believe what he was being told.

The THX sound quality certification system has been installed in movie theaters, home audio devices, car stereos, computers, and many accessory devices since its debut in 1983, demonstrating the importance of sound to the content-consuming public. No discussion of THX would be complete without the Deep Note sound. https://www.thx.com/deepnote/.

[63] In addition to halls in Sydney, Los Angeles, and Copenhagen discussed by Heathcote in the text, Hamburg is a famous example (although subsequently lauded for having achieved many of its objectives for the city) – seven years late, completed by a cost as much as 10 times its original estimate (€77m versus more than €700m), and ultimately subject to a parliamentary inquiry investigation resulting in a report of 800 pages in length. Wainwright, Oliver. "'We thought it was going to destroy us' … Herzog and De Meuron's Hamburg Miracle." *The Guardian* (November 4, 2016).

[64] List assembled from ChatGPT Query results, February 21, 2024 and May 30, 2024, supplemented by information from the relevant concert hall, architect, and other websites.

[65] Wakin, Daniel J. "In Cities Across the United States, It's Raining Concert Halls." *The New York Times* (September 3, 2006).

[66] Heathcote, *supra*.

[67] Wakin mentions Nashville, Orange County, Toronto, Miami, Philadelphia, North Bethesda, Fort Worth, and Omaha.

[68] See discussion at section 4.3.

[69] *Id*.

[70] Everest, F. Alton and Ken C. Pohlmann. Master Handbook of Acoustics. Seventh Ed. McGraw Hill (2022) at 558.

[71] Makovsky at 41'.

[72] Schmid, Rebecca, A Hall that Invites the Audience Into the Music-Making. *The New York Times* (December 22, 2013). Available at https://www.nytimes.com/2013/12/23/arts/international/a-hall-that-invites-the-audience-into-the-music-making.html. Images from Berlin Philharmonic website. https://www.berliner-philharmoniker.de/en/.

[73] Osborne, Richard (1998). *Herbert von Karajan: A Life in Music.* Chatto & Windus. pp. 475. ISBN 1-55553-425-2.

[74] Schmid notes "The podium had to be rebuilt three times and a series of 10 acoustic sails hung from the ceiling before Karajan was satisfied."

[75] Heathcote, *supra*.

[76] Lokki, Tapio & Pätynen, Jukka. "Architectural Features That Make Music Bloom in Concert Halls." *Acoustics* 1. 439-449 (2019). While focusing his work on acoustics, Dr. Lokki acknowledges that other aspects of concert hall design are important to the concert-goer experience, noting: "For many, a concert is primarily a social event and the acoustics of the hall is only one part of the whole experience. The architects and acousticians need to pay attention in particular to flows of people and design of lobbies to enable socializing without problems. An example of unsuccessful design is the new Helsinki Music Centre where the locations of the cloakroom and restrooms are impractical. Moreover, flow of people is really slow taking almost five minutes for the last spectator to reach the lobby at intermission. Such logistic issues are really important, although this paper naturally concentrates in detail only [on] the acoustics of concert halls." Lokki, Tapio. Why is it so hard to design a concert hall with excellent acoustics? *Proceedings of ACOUSTICS 2016* (9-11 November 2016, Brisbane, Australia).

[77] Pätynen, Jukka and Tapio Lokki, "The Acoustics of Vineyard Halls, is it so Great After all?" *Acoustics Australia* (2015) 43:33-39.

[78] Lokki, Tapio, "Tasting music like wine: Sensory evaluation of concert halls." *Physics Today* 67 (1), 27-32 (2017).

[79] Lokki, Tapio, Jukka Pätynen, Antti Kuusinen, Sakari Tervo, "Concert Hall Acoustics: Repertoire, listening position, and individual taste of the listeners influence the qualitative attributes and preferences." *J. Acoust. Soc. Am.* 140, 551-562 (2016).

[80] Jablonska, Joanna. "Architectural Acoustics in Vineyard Configuration Concert Halls." *Journal of Architectural Engineering Technology* 7:2 (January 2018).

[81] *Id*.

[82] *See* table of concert halls in the text at note 64.

[83] Ricci, Francesca, Lior Rokach and Bracha Shapira. "Chapter 1: Introduction to Recommender Systems Handbook" in *Recommender Systems Handbook*. Springer Science+Business Media, LLC (2011) at 1.

[84] *Id*., at 3.

[85] *Id.,* at 2-3.

[86] *Id*., at 5.

[87] Maruti Techlabs. "Types of Recommendation Systems & Their Use Cases." *MLearning.ai* (August 16, 2021).

[88] *Id*.

[89] Masthoff, Judith. "Chapter 21 Group Recommender Systems: Combining Individual Models" in *Recommender Systems Handbook* at 695.

[90] *Id*.

[91] Liu, Chang. "Constrained Optimization: How to do More with Less." *Georgian* website. https://georgian.io/constrained-optimization-how-to-do-more-with-less/.

[92] Text message exchange with Kate Salesin, Ph.D. candidate in computer graphics at Dartmouth College (May 19, 2024).

[93] As noted above, nearly half of the audience may attend a concert at the invitation of someone else that bought the tickets, and therefore the guests may have preferences

different than the ticket buyer or be less engaged in the musical performance itself. While the ticket buyer could ask their guests to answer the recommender system questions in order to get a sense of the preferred seating location from the guests' point of view, it is more likely that the ticket purchaser will actually be the one selecting the seats based on his or her own preferences, and must thus be counted upon to influence their choices by what they know of their guests' preferences.

[94] These anechoic recordings are described in Pätynen, Jukka & Pulkki, Ville & Lokki, Tapio. (2008). "Anechoic Recording System for Symphony Orchestra." *Acta Acustica united with Acustica*. 94. 856-865. 10.3813/AAA.918104.

[95] Weblink to the survey is: https://www.surveymonkey.com/r/QT2T9HC.

[96] Rhinoceros 3D available at https://www.rhino3d.com. The model was created primarily through the use of two plan drawings and a section drawing available in Toyota, Yasuhisa, Motoo Komoda, Daniel Beckman, Marc Quiquerez, Erik Bergal, *Concert Halls by Nagata Acoustics: Thirty Years of Acoustical Design for Music Venues and Vineyard-Style Auditoria*, ASA Press (2020) at 85-86.

[97] https://www.treble.tech.

[98] See Treble documentation at https://docs.treble.tech/user-guide/simulations/simulation_settings.

[99] Lokki, Tapio, Sakari Tervo, Jukka Pätynen, and Antti Kuusinen. Musiikkitalon Ison Konserttisalin Akustiikka (Acoustics of the Music House's Large Concert Hall) (2013). https://users.aalto.fi/~ktlokki/Publs/musiikkitalo_akupaivat_2013.pdf.

[100] Other data available includes plots of EDC, Impulse Response, Frequency Response, and Spatial Decay. These plots were not used in calculating the characteristics of individual seats.

[101] This simulation might be improved by creation of custom sound sources that approximated the frequencies and directionality of the different instrument section. Time did not permit the creation of such sources, but this could be an addition to future work.

[102] Lokki, "Musiikkitalon Ison Konserttisalin Akustiikka," *supra*. Pätynen, "The Acoustics of Vineyard Halls, is it so Great After all?" *supra*.

[103] LEF and LJ were averaged across the 125-1000 Hz frequency bands as recommended in the ISO standard. Using the Lokki-sampled data for envelopment measures was also not ideal, however, as the Lokki data was not taken in every seating section, and was either used for multiple sections or interpolated between sections to assign these characteristics

to unmeasured sections, and thus may not be entirely accurate in certain seating areas. The Treble data was available for a receiver in each seating section of Musiikkitalo for all data available from Treble.

[104] While a watertight version of the model was created for testing, there were difficulties in importing this version of the model into the Treble system, rendering it unusable for use in the acoustical analysis.

[105] Scores within the acoustical category are a weighted average of the envelopment, clarity, volume, and reverb score resulting in a number that is between 0-10. The visual and physical categories are averages of the selected preferences scores within each category, theoretically also ranging from 0-10. The three overall categories are then weighted such that the category chosen as most important is multiplied by 3, the second most important category is multiplied by 2, and the least important category is multiplied by 1. The typical resulting score is thus theoretically between 0 and 60. The system is, however, capable of weighting categories equally or ignoring a category (by setting that importance to 0).

[106] In this example, the "head" used for the calculation is a point based on the center point of each seat, but this point could be expanded to take into account the larger dimensions of actual heads, if desired.

[107] Source: Musikverein website. https://www.musikverein.at/downloads/GS-Saalplan.pdf.

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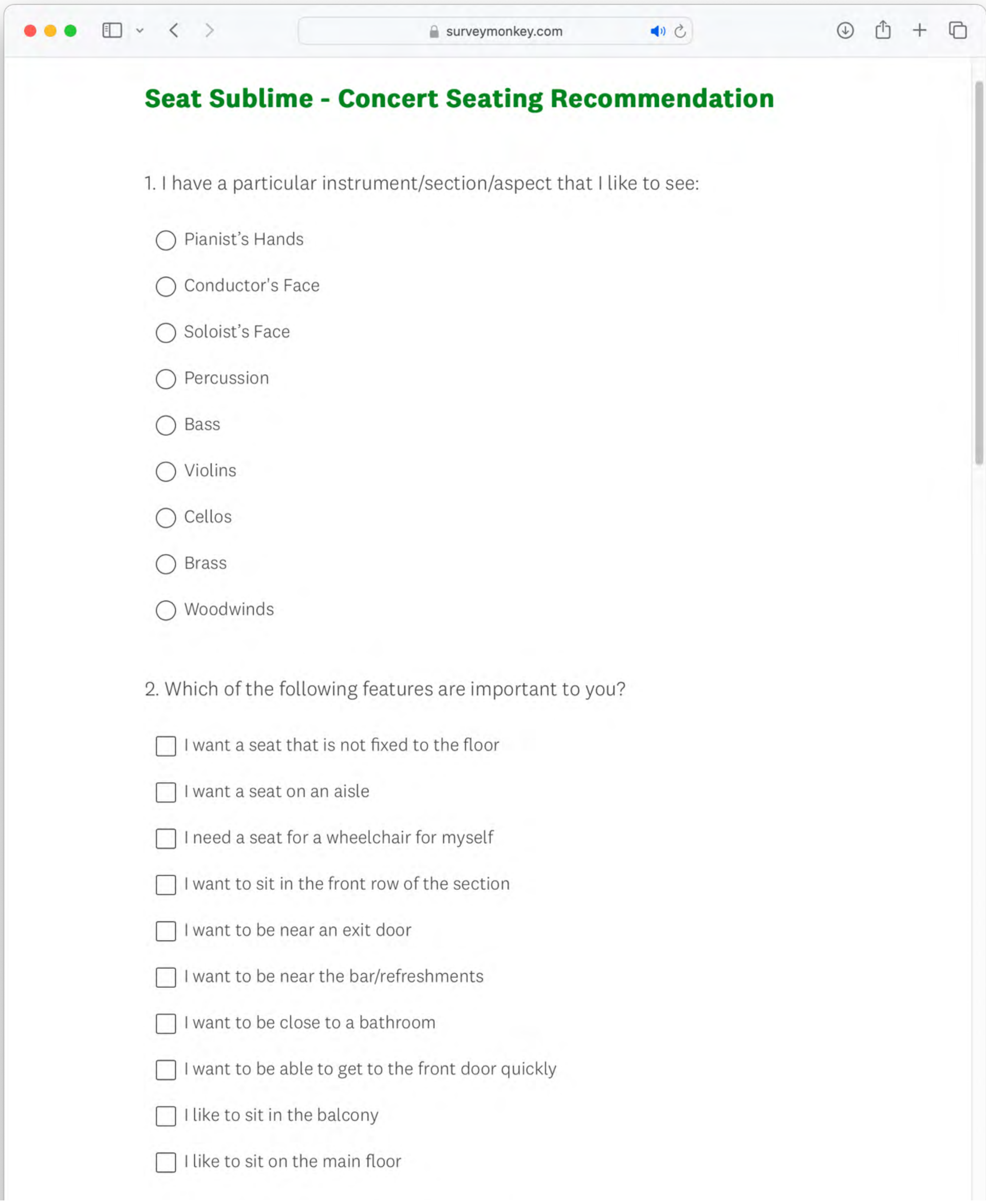
Appendix 1: Survey Questionnaire



surveymonkey.com

Seat Sublime - Concert Seating Recommendation

1. I have a particular instrument/section/aspect that I like to see:

- ◯ Pianist's Hands
- ◯ Conductor's Face
- ◯ Soloist's Face
- ◯ Percussion
- ◯ Bass
- ◯ Violins
- ◯ Cellos
- ◯ Brass
- ◯ Woodwinds

2. Which of the following features are important to you?

- ☐ I want a seat that is not fixed to the floor
- ☐ I want a seat on an aisle
- ☐ I need a seat for a wheelchair for myself
- ☐ I want to sit in the front row of the section
- ☐ I want to be near an exit door
- ☐ I want to be near the bar/refreshments
- ☐ I want to be close to a bathroom
- ☐ I want to be able to get to the front door quickly
- ☐ I like to sit in the balcony
- ☐ I like to sit on the main floor

Questions 3 and 4 were A/B audio choices.

Appendix 2: Musiikkitalo Seating Plans