Acoustic Spatial Design Methodology and its Application in Health Environments

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Abstract:

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Hospital design too often overlooks the need for acoustic tempering; as a result, patients experience longer recovery times and hospital staff experience high rates of hypertension, leading to excessive turnover and greater health risks among those brave enough to shoulder the burden of overseeing recovery [1]. Through proper acoustic intent, hospitals can become spaces of genuine peace for those who are healing as well as for the people who spend most of their lives in these environments. Through the implementation of simulation techniques employed by acoustic designers, the architectural community can benefit by understanding the sonic impacts of design decisions in real time and ensure their proposals lie within acceptable noise levels, mitigating the negative impacts of unwelcome sound within healing environments. As hospitals exist as a typology in which the condition of its occupants is a primary concern, the results of this research seek

to maintain the established societal function and pave the way for future research into acoustic specification of other architectural typologies. Through this work, it is determined that through the use of glass doors and application of acoustic plasters on patient ward walls in lieu of gypsum board, the hospital can better address the acoustic comfort of its inhabitants.

Foreword

This work would not be possible without the assistance of many people who have been instrumental in its making. Without the ever-present support of my family, John Blanchard, Holly Higgins, and Jack Blanchard, my partner, Niki Peters, and our dog Hazel, I would not have made it through to the point I find myself now. This work began in an effort to understand the world just a little more and try to help the people who need as much support as possible. In the wake of the COVID-19 pandemic, patients and hospital staff entered into a realm of constant survival and restless efforts to save lives, often to the detriment of individual needs. It became clear to me that, though I initially wanted to focus this research on schools, offices, and hospitals, the hospital should become the focus of the work and the patient ward especially became a point of careful consideration. With discerning guidance from my thesis committee, Tomás Méndez Echenagucia and Heather Burpee, this work stands as a realization of my passion for the intersection between architecture, acoustics, and design technology to better inform the architectural design process. It is my hope that healthcare designers and, indeed, all spatial designers understand the importance of auscultation as a tool for realizing a comprehensive spatial aesthetic and that the depth and understanding of space achieved through acoustic simulation is given the weight it deserves.

Additional thanks to Doctor Jessica Woan of the Seattle V.A., Christopher Sims of ARUP, Peter Dodds of Facebook, Bill Stewart of SSA Acoustics, Michael Ward, Ryan Mullenix, and Ryan Hullinger of NBBJ, PJ Bauser of Mahlum, and Scott Crawford of LMN Architects for their assistance throughout the development of this work. These individuals took the time to speak with a graduate student who knows little of the intricate process of healthcare design and acoustic specification - their expertise has been very much appreciated.

Let this research stand as a representation of the beauty of curiosity.

Contents

Chapter 1

Theoretical Framework

1.1 Architectural Theoretical Development

This thesis is developed from the position that musicianship is an equally valid influence on architectural practice as any other. In this mode of thought, one is able to apply musical perspectives to acoustically tune a building for a specific purpose, conducting the circulation and movement of sound through space for the improved spatial experience of all occupants and better fulfilling the societal role required of the typology. The basis of this school of thought is established in phenomenology, notably the weight afforded to the way human senses interact with the space in which they occupy. In focusing on one mode of perception, many spaces experience failings in the comprehensive way users experience space, leaving too many noisy restaurants, stressful offices, distracted students, and restless patients. The occupational noise present within the environment can often go unnoticed as users of the space can habituate to noise without mitigating the body's instinctual response [1]. When exposed to regular noise, the body initiates a "fight or flight" mechanism that triggers neuroendocrine and vascular alterations via synaptic links in the reticular formation and mesencephalon or through emotional and cognitive perception of noise by cortical and subcortical structures. For the layman, noise is harmful to the body as it wears us down throughout the day and increases blood pressure, causing hypertension and disrupting sleep for those attempting to recover in this space meant for healing. Noise also produces a psychosomatic response, furthering the perception that hospitals are stressful environments. The disruption of communication worsens the ability of hospital staff to perform their delicate work as medical errors are more likely to occur in noisy environments [2] [1].

1.1.1 Auscultation and Psychoacoustics

Much like the human body, a building's health can be examined through acoustic monitoring. This method, known as auscultation, has been utilized by health professionals since Hippocrates first described the practice [3]. Through understanding of the sounds present in the body and knowing what a healthy body should sound like, one is able to gather clues about potential solutions to remedy the cause of irregularity within the acoustic space. Many nurses use this practice to monitor wards, making judgements based on distinction between normal and abnormal sounds. This may be due to the ability of the human ear to perceive a greater capacity of captured information than the directional capabilities associated with sight [3]. This is a double-edged sword, however, as many patients experience an unnerving sense of constant surveillance akin to Foucault's panopticon. Foucault recognized hospitals, like disciplinary institutions, are spaces in which power is directed towards the control and organization of people as well as their behavior; patients must be sorted, categorized, and spatially arranged in accordance with the nature and description of their complaint [3]. Further, due to the hierarchy associated with the typology between observers and the observed, patients become complicit in their own subjugation to expedite their recovery [3]. This established hierarchy is reinforced through the limited control the user has of their sensory environment; giving patients a modicum of control over how much sound is permeating their restorative space would transform the perception of hierarchy in the space. As it stands now, patients remark that they are unable to forget the presence of authority or the other acoustic indicators of being in a hospital, further solidifying the stark contrast between their home environment and the sterile ward [3]. From their perspective, the first thing a patient loses is privacy, then dignity, then sanity [3]. Sounds are proven to play a key role in this process, infiltrating and pervading the physical and mental spaces and ultimately dissolving the boundaries of private and public space. This thesis asserts that it is the control and tuning of this pervasive force that allows the creation of private recovery space within the hospital typology; private space is needed by both hospital staff and patients to escape the panoptic nature of the space and focus on restoration and recuperation in an incredibly stressful environment. Based upon the way that sensitive information is shared between medical professionals, patients actively become aware of one another's maladies [3]. There is a pressing need for behavioral change among hospital staff which can be reinforced through their workspace. With the allowance of private discussion space, hospital wards are free to become spaces of accurate auscultation. Though the practice of auscultation is steadily being replaced by computerized visualization, the instrumentation used still requires quiet to operate accurately, indicating a change is needed not only to preserve doctor-patient confidentiality but to also ensure accuracy of computational auscultation [3]. It is noted that four areas of medicine are particularly auditory in nature: general practice, pediatrics, respiratory medicine, and cardiology [3]. Of these four wards, the general patient ward will be the particular focus of this thesis and will be handled with expressed sensitivity to reinforce its acoustic spatial needs.

1.1.2 Acoustic Ecology

The art and science of acoustic ecology will be another mode of conceptual analysis for this thesis due to the specific lens it affords the spatial designer. Acoustic ecology is the study of sound in an environment ; if one is to design a hospital's spatial arrangement through the lens of an orchestral conductor, one must be aware of the time and place pivotal sounds are emitted as well as what role those sounds play in the larger scope of their environment [4]. As based on R. Murray Schafer's concept of soundscape ecology, the understanding of sound within its environment provides indications of the physical responses or behavioral characteristics of those living within that environment [4]. To fine tune the spatial experience of hospital staff and patients, one can view each sound source present within the typology as an instrument in a symphony orchestra with the potential to drastically alter a user's perception of the space as a whole. Metaphorically, each instrument in this symphony has its part to play but must be shown when to express itself and when to allow another voice to come forward. In doing so, what was once a cacophony can become a melodic spatial experience, in harmony with the spatial users and other sound sources present. A further specification of acoustic ecology is the Acoustic Niche Hypothesis, founded through sonic measurements of natural environments in which many different creatures cohabitate. It is observed that each creature occupies its own sonic niche in the frequency spectrum, adding to the chorus of natural voices that combine to create a unique sonic fingerprint of a habitat [4]. In observing the acoustic spectrum of the same location over a period of years, one is able to monitor the overall health of the habitat and observe if any species are no longer present in the soundscape. In joining the perspective of an acoustician with the practice of architecture, one should design with respect for the ear and voice, implement sound symbolism awareness beside functional signaling, establish rhythms and tempi of the natural soundscape, and implement balancing mechanisms to account for any outlying noises [5]. To follow established principles to integrate an accumulated architectural design education and the fundamental principles of acoustic design, this thesis will proceed through mastering the psychophysiology of hearing, exhibit gained knowledge of sound propagation, demonstrate the specific requirements of disparate architectural spaces, and iterate design to achieve established restorative sound levels [5]. Much of the acoustic research currently performed in the built environment is concerned with either workplace or scholastic spaces, indicating a need in the research community for additional experimentation to be performed on heath environments.

Though hospitals are determined to be essential institutions by both architectural and structural building codes, the acoustic consideration simply is not prioritized, leading to the issues present within the typology today. If the contemporary society seeks to show respect to its hospital staff for their continual sacrifice, it is the belief of this research that the hospital environment itself needs to be optimized for the health and wellbeing of all its occupants. For too long, the impact of unwelcome sound has been an invisible detriment to health, lingering throughout the built environment regardless of the intent of tranquility for designed space. Environments focused on healing can fulfill their societal role at a higher degree with proper acoustic consideration; ecological serenity in designed space is needed now more than ever.

1.2 Literature Review

It is important to consider existing frameworks of study and understanding into the way acoustics impacts architectural design as well as ways that acoustic simulation tools are currently being used. Work conducted by the Universtiy of Washington's Integrated Design Lab serves as a foundational overview of the acoustic issues considered by this research but the summaries presented offer causes and solutions that need to be explored further to determine root causes of acoustic issues in the environment [6]. The studies undertaken by Dzhambov et al. proves vital to the foundational nature of this research, proving that there is both a lack of examination into the acoustic comfort of hospital staff and the issues they encounter within their daily life. This source indicates the need for acoustic tempering of hospital space for the betterment of nurses but does not provide architectural solutions nor place the blame on the design of the space itself [1]. This is also true of the thesis work conducted by Peter Dodds though much more of the cognitive effects of prolonged noise exposure are discussed in depth [7]. Tom Rice's book on the work of auscultation within healthcare environments as well as documentation of patient experiences within the patient ward broadens the perspective of this research to understand the Western cultural bias toward visual representation and visual realization but does not address an architectural solution to the problems presented within nor provide a methodology to improve the restorative capability of hospital space [3]. Reports from Bernard Krause's work on the Niche Hypothesis and Aki Pasoulas' work on acoustic ecology further the concept of a sonic spatial environment filled with life but does not address the built environment [4, 8]. This topic is addressed by Alessia Milo but is centered on architectural design education, being removed from the healthcare environment. Milo's work also does not demonstrate how architectural acoustics may be simulated or designed within an iterative process [5]. This is covered, however, by Birdja et al., Danny Boglev et al., Kelly Doyle et al., and Samuel Clarke in an examination of how to design healing spaces for the critically ill as well as methods on how to reach acoustic design goals [9, 10, 11, 12]. Studies into the existing layout and soundscape of the hospital serve to provide viable data of recorded spaces but only the work conducted by Busch-Vishniac et al. give sufficient information into the location of recording equipment, level of occupation of the patient room, and a full spectrum of sound recordings across center octave frequency bands such that the calibration model created has sufficient measurable parameters to determine its effectiveness as an acoustic model [13, 14, 15, 16, 17, 18, 19, 20, 21, 22]. The economic rationale for improved acoustic consideration is discussed most in-depth by Blair Sadler et al., but is also extensively researched by Roger Ulrich in several papers integrated into this work as well as demonstrated through the product development of several corporations [23, 24, 25, 26, 27, 28]. Foundational understanding of acoustic theory, simulation, representation, qualification, and quantification also lies within the scope of this work, indicating a need for continuous reference of Vorlander's textbook on auralization as well as procedures of using acoustic simulation software as it is the opinion of this work that these concepts are not sufficiently integrated into the typical architectural education path within the United States [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48]. More than anything, there seems to be a lack of acoustic understanding in the process of architectural design and yet still so many aspects of acoustics that have yet to be fully integrated into the building design process. This work seeks to delve into the integration of acoustics and architecture to better serve end users of designed space and mitigate harmful effects of noise when possible.

1.3 Acoustics and the Hospital

According to research compiled by the University of Washington's Integrated Design Lab, there is a direct correlation between sleep disturbance in patients with schizophrenia and medication compliance, noting that "patients with more disturbed sleep are likely to suffer more severe symptoms and be less medication compliant" [6]. The compiled research also notes that insomnia can be an indicator of an acute schizophrenic episode, indicating that limitation of noise transmission through treatment spaces may minimize schizophrenic episodes in mental health wards. Improving acoustics, however, is shown to contribute to decreased strain on staff, facilitating an environment where the capacity for patient care is heightened. Low noise levels have also been connected to a reduced perception on workplace demands, increasing workplace social support. In mitigation of noise, patients and staff are proven to achieve a higher level of occupational quality and the spaces in which they occupy have the opportunity to better fulfill their societal role, freeing the healing body from environmental pressures and strain [1] [15].

Age	Nurses (N, Percentage)	Hypertension (N, Percentage)
<30	29, 30.21	4, 13.79
31-40	31, 32.29	0, 0.00
41-50	28, 29.17	5, 17.86
51-60	6, 6.25	4, 66.67
>60	2, 2.08	2, 100.00

Age	Nurses (N, Percentage)	Hypertension (N, Percentage)

Table 1.1: A Qualitative Assessment of Nurses and Their Reported Rates of Hypertension as a Result of Their Work Environment

Table 1.1 illustrates the self-reported rate of hypertension at one hospital that, when paired with the tasks they perform throughout their day and how long they have been working at that specific hospital, demonstrate nurses newest to their environment and working in the same location throughout the day report higher rates of hypertension [1]. This indicates a need for hospitals to have a better consideration of the acoustic strain the environment has on its inhabitants in both the short term and the long term. It is also important to acknowledge the overwhelming abundance of noise in existing hospital spaces. As demonstrated in *Noise Levels in Johns Hopkins Hospital*, hospitals are becoming noisier each year and have become a place where there is no escape from the constant cacophony of alarms and conversation [16] [13]. These results are demonstrated below in Figure 1.1 and it should be noted that results for nighttime noise indicate the same increasing level of noise over time [16] [20]. Effects of noise stress on the body has myriad negative effects, among which are delayed cognitive development in children, psychological triggers for individuals with post-traumatic stress disorder, a lower threshold for noise resulting in sleep disturbance, increased heart rate, changes in the immune system, anxiety, mood shifts, elevation of cortisol production, hypertension, myocardial infarction, vasoconstriction, elevated blood pressure, and elevated adrenaline levels [1] [16] [27].

This information is also best understood qualitatively; as demonstrated on a webpage developed by the Federal Aviation Administration, the information above indicates that hospitals are currently about as loud as a vacuum [29]. This is best demonstrated as an infographic:

Approaching phenomenology with a focus on acoustic perception of space, one is able to open a new branch of design centered around

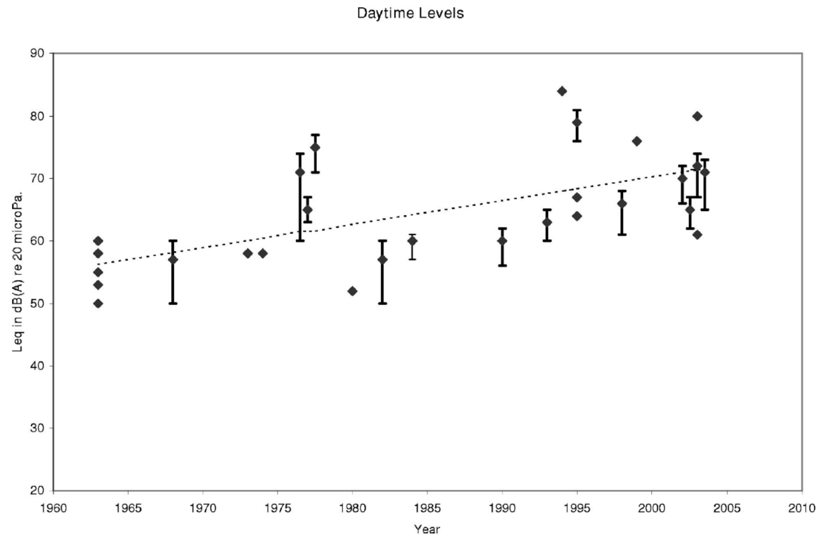

Figure 1.1: A Depiction of the Rising Levels of Daytime Noise in Hospitals Over the Past Sixty Years [16]

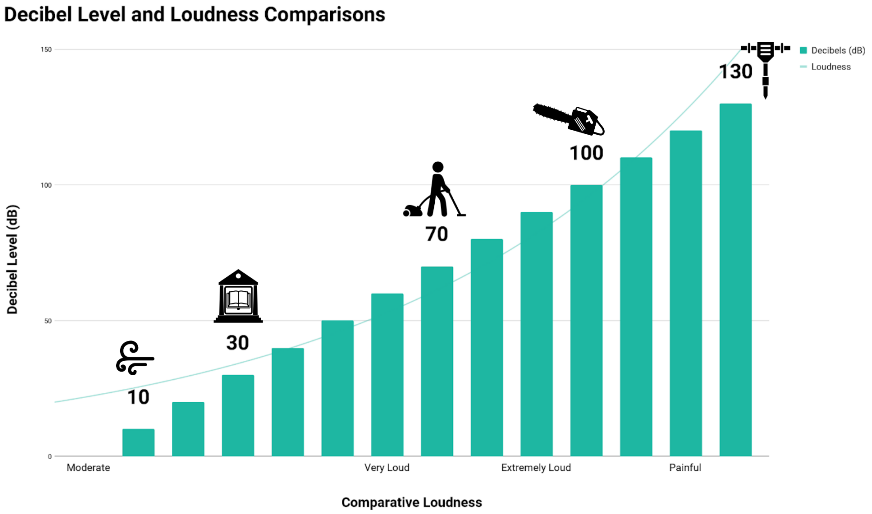

Figure 1.2: A Graph Demonstrating Respective Loudness as Compared to Decibel Levels

harmonious dwelling. Western schools of thought are primarily visual in nature; the "anthropology of the senses" as described by David Howes in the 1980s and 1990s notes that "sensory perception is a cultural as well as a physical act," [3] otherwise stated that the senses are not only mechanistic receptors of information but are also mediators of social value. The priority given to visual aesthetic has created myriad spaces deemed appealing for any combination of reasons; this thesis posits that acoustic design priority will usher in a new conceptualization of spatial experience with new possibilities for inhabitants to live, work, learn, and recover in peace.

1.3.1 Acoustic Concepts

The acoustic concepts explored by this research necessitate an overview of acoustic behavior in space. Sound exists as pressure waves in a material. The loudness of sound, known as its sound pressure level (SPL), is measured in decibels (dB) which are on a logarithmic scale. For reference, 45 decibels is about as loud as the constant humming noise from a refrigerator. Sound pressure waves are characterized by the number of times a material's particles are compressed by their acoustic energy per second, known as wave frequency. High frequency sound waves have shorter wavelengths and vice versa. The human ear is tuned to frequencies from 20 Hz to 20,000 Hz so it can detect a large spectrum of sound waves. It should be noted, however, that certain frequencies affect the ear differently and some pitches sound more intense [30]. The acoustic ray tracing used in this research builds upon the knowledge that for any sound source created within an enclosure, a near-infinite number of sound particles travel with energy outwards in all directions. To run the acoustic diffusion equation model used by this research, one needs to know the average distance a particle can move in a space without colliding with another particle. To find this, one needs to know the geometry of the space, its surfaces, and how the sound energy behaves when colliding with a surface. In examining three kinds of collision conditions, it is possible to determine the average length at which one particle collides with another. This concept will be explored more in section 2.6. The acoustic diffusion equation modeled in this study determines how sound travels through spaces from a known source of noise. Knowing sound from that source will travel in every direction outward, the acoustic diffusion equation is able to model how that sound bounces all around that space and through walls given the materials' ability to absorb and transmit sound particles across a wide range of energy. This model can also depict the path of travel for individual sound particles. The equation used for this model is dependent upon some constants such as the speed of sound in air and the acoustic energy density, which are both dependent upon the medium in which the sound travels. For this study, the only medium used to fill space is air. Ultimately, the more loud the sound that arrives at the patient's ear in their bed, the more disruptive the sound will be on sleep or maintaining focus in the hospital. The last acoustic concept explored in this study is a pressure acoustic model for each individual room being simulated to understand the way low frequency sounds, such as vibrations from air conditioning, travel through each space. This model also allows for an interpretation of where sounds within a room will be amplified and therefore where the patient's bed should be placed to reduce the stacking of low frequency noises that would disrupt sleep. The higher or lower the pressure in one part of a room, the louder a sound will seem to someone hearing that sound.

1.3.2 Acoustic Formulae

As for the mathematical side of acoustics, there are two key equations to be familiar with: the Sabine equation (1.1) and the Norris-Eyring equation (1.2).

$$RT_{60} = \frac{0.049V}{S\bar{\alpha}} \tag{1.1}$$

where, RT_{60} is the time in seconds required for a sound to decay 60 dB, V is the volume of the room, S is the boundary surface area, $\bar{\alpha}$ is the average absorption coefficient, or the summation of all boundary surface areas multiplied by their respective absorption as a percentage of the sound being absorbed into a material with respect to the initial amount of sound energy. For true absorption values in excess of 0.63, the Sabine equation can give resultant α values in excess of 1.0. The Norris-Eyring equation 1.2 gives $\bar{\alpha}$ values from 1.0 to 0 for true absorption values when calculated from actual RT_{60} measurements. [34]

$$RT_{60} = \frac{0.049V}{[-Sln(1-\bar{\alpha})]} \tag{1.2}$$

From these two equations, one is able to compute the resultant reverberation of sound in an enclosed space. For rooms coupled close together, however, additional specific equations are needed.

1.4 Questions Being Asked

This work is positing the question of what the hospital patient ward *should* sound like. Within the scope of research, this question will be addressed through answering smaller questions: is there any one patient ward layout that results in a quieter environment for patients and staff? What kinds of materials should be used in patient wards to create a more quiet space for work and recovery? How much material change is needed to achiteve the desired acoustic environment? How little change can be made in the patient ward to achieve a more positive healing environment for patients and staff? To answer these questions, this research will employ an acoustic model and test multiple parameters of acoustic spatial design to better understand the intricacies of the environment and better understand the acoustic principles at play when designing architectural space.

Chapter 2

Methodology

2.1 Rationale

To exemplify the benefits of acoustic priority in aesthetic realization, this thesis will examine and improve upon the soundscape of a hospital through layout optimization and material choice for low decibel levels. Curiously enough, hospital sound is most often measured in terms of objective sound level, potentially due to the fact that the sonic environment is typically defined as a subjective and personal experience [13]. The lack of stimuli within hospital settings has a particular effect on patients, supporting the value in understanding the noises present within the soundscape [13]. The results of a study conducted to determine common stressors on a patient's acoustic environment determined that the most noticeable element of the hospital soundscape is conversation recorded at an average of 69 decibels [13]. The hospital staff should not be asked to operate their lives in hushed tones so the solution to creating a more hospitable acoustic environment should not lie in altering staff behavior. Instead, the environment itself should be designed around these environmental stressors being present regardless of the placement of the patient rooms or the location of the nurse station on each floor. Given this, deepening an understanding of perceptive subjectivity will be necessary for this research as patients will pick up on conversational noise easily so the solution lies in reducing the time it takes for unwelcome sound to dissipate. It should be noted that quietness of hospital environments is consistently one of the worst rated Hospital Consumer Assessment of Healthcare Providers and Systems (HCAHPS) categories reported yet little research exists linking measured acoustics with these HCAHPS surveys due to financial implications [14] [49]. This leads to an indication that any hospital space designed under the purview of this research should be designed to satisfy both qualitative and quantitative baselines and methodology should be established to measure both acoustic aspects of simulated space. Hospitals are often regarded as loud environments by their inhabitants [14]. In a study of the decibel levels of several different floor plans, every floor plan observed failed to achieve occupied speech intelligibility index ratings of "good" with all floor plans receiving either "marginal" or "poor" grades [14]. Patients clearly desire quieter spaces but hospitals that implement "Quiet Time" were ultimately found to have little to no change in recorded decibel levels, indicating a need for systemic change within the typology [14]. This study also indicates a need for implementation of design features such as material choice, door usage, overall layout, and private versus semi-private rooms that impact patient perception of acoustic space to improve satisfaction [14]. To ensure comprehensive solution generation, this thesis will compile a survey of acoustic reflectivity among materials typically installed in hospitals and propose a list of approved materials such as acoustic curtains [14] and high-performing ceiling tiles [25] for architectural implementation, proving the application of such materials will improve the sonic environment. Materials and processes observed to improve the perceived acoustic environment will also be considered [9]. These material absorptive qualities will then be weighed against the noises emitted in the space by human speech in the hospital as recorded throughout the day [17]. The outcome of this experimentation will then be compiled into a guideline for designing future health environments.

2.2 Evaluation Criteria

To determine the success of any given floor plan iteration, this research will employ methodology outlined in chapter three of *Integrating Evidence-Based Design: Practicing the Healthcare Design Process.* In this chapter, a procedure is outlined to first outline goals and generate a hypothesis for a healthcare environment, create annotated floor plans outlining the application of gathered research, and check outcomes of each iteration based on whether or not guiding principles and design guidelines were used continually throughout the schematic design phase. Other considerations for each design proposal is how flexible the space is to consider long-term growth of the hospital or service expansions, the overall environment of care, and the potential reduction of operating rooms or bed capacity [12]. From there, observations about each layout will be recorded and commented on for strengths and weaknesses while still giving special attention to the acoustic behavior of the resultant layout. A threshold of approximately 45 dBA in the patient room is to be noted specifically as a noise threshold at which patients' sleep is disturbed [20]. It should be noted throughout this research that staff behavior is a significant contribution to the noise present within the environment so the potential implementation of behavioral design measures should also be under consideration. Specific staff behaviors to be reinforced by the environment are speaking in a low voice, holding discussions during rounds in a separate room, taking care in handling trays and metallic objects, turning off electronic devices that emit noise or disabling noise-making features, and an overall awareness of the harmful effects of noise on recovery and efficiency [20].

2.3 Methodological Considerations

One potential solution in decreasing the noise present in hospitals is to isolate the noisy environments from the recovery environments; if the noise is going to exist within the space regardless, there may be an opportunity to change the way floor plans are arranged to ensure acoustic separation. To do so, this study will employ methods of parametric design as demonstrated in Dr. Thomas Scelo's Integration of Acoustics in Parametric Architectural Design. This methodology involves assigning an acoustic value to each element of a typical hospital floor plan and, through iteration and fine-tuning, create an acoustically optimized floor plan that guarantees a healthier soundscape for occupant health and wellbeing [40]. This study will also apply methodology outlined in Alessia Milo's The Acoustic Designer: Joining Soundscape and Architectural Acoustics in Architectural Design Education as a design guide, following procedural guidelines to integrate acoustic design into spatial development. Specifically, the methodology of linking the relationship of acoustic ecology to architectural design through understanding the relationship of sounds with life and society to develop principles to be carried forward throughout the research process [5]. This guide also outlines the process of implementing fundamental practices such as a "soundwalk," or designed gradual sonic experience associated with circulation, to generate creativity, stimulate research, and finalize sonic narratives. Through this process, a designer instills listening and soundmaking practices upon spatial inhabitants to allow for reflection on one's spatial relationship to the sounds existing within space, thereby characterizing the soundscape [5]. Given the conceptual nature of this thesis project, the soundwalking methodology will be employed through a simulated or conceptual experience [39].

2.4 Architectural Methodology

The physical relationship between spaces will be under primary consideration in this work. To prioritize occupant comfort, this study will employ design recommendations put forth by experts in health design, observing the evidence based design approaches outlined by Roger Ulrich, Wolfgang Sunder, Erica Ryherd, and Kerstin Persson Waye among others. As per the recommendations set forth and specifically noting the acoustic performance of the resultant geometries, this study will employ the following standards: employment of sound-absorbing ceiling tiles, prioritize design of single-patient rooms, removal or reduction of loud noise sources, alteration of occupant behavior to reinforce acoustic sensitivity, inclusion of walls that extend fully to the ceiling, provision of decentralized nursing stations, ensure patient access to daylight, feature views to nature, and installation of hygienic high performance sound-absorbing materials on floors and walls [2] [27]. Through the application of evidence based design recommendations in healthcare settings, this study aims to implement measures used to decrease patient pulse amplitudes, decrease incidence of rehospitalization, prevent impairment of task performance among staff, curb overexertion due to noise fatigue, mitigate the overlapping of sounds causing staff to raise their voices, heighten compliance with the Health Information Portability and Accountability Act (HIPAA), and increase overall patient satisfaction [2]. Further, as the iterative design process allows, furniture within the patient room will be considered. For this, evidence based design research will be employed and build upon studies conducted that demonstrate higher patient satisfaction when the patient bed is placed furthest from the room's entry, oriented such that caregivers will always approach the patient from their right side. The patient room will be located midway down the corridors, approximately thirty-six to seventy feet away from a centralized nursing station, allowing for spatial and acoustic separation from noisier programmatic elements on the floor plan [19]. Zoning criteria and health design standards must also be adhered to, ensuring patients have appropriate space on either side of their bed for hospital staff or loved ones to gather. Further consideration is needed of necessary staff fittings such as a small workplace and washbasin to ensure the design proposal coincides with contemporary design standards for the typology [21].

2.5 Acoustic Methodology

For the purposes of this research, concert halls will be considered as a model of architecture that requires specific acoustic methodological intervention. The software and strategies used to acoustically examine designed space fall under the purview of this research and will therefore be examined thoroughly to determine the most effective way to model the propagation of sound throughout virtual space. To create a designed acoustic environment, one must employ various computational methods to simulate architectural space, iterating form to prioritize low reverberation times that ultimately improve disparate aspects of sound quality. Due to the richness of research provided in acoustic spatial design, one can employ methods such as seeking tailored early sound reflections through establishing a direct inverse relationship between the time delay and the geometry of the space [40]. Further approaches are proposed in optimization algorithms using probability to represent all uncertainty within the model, multi-objective genetic algorithms [38], and integration of a Maya script [40], though it should be acknowledged that many of these procedures require further research to implement their concepts successfully into the research proposed and few of these papers directly relate to hospital spaces. It is the hope of this research that developing a baseline knowledge of acoustic practices will assist in the development of hospital soundscapes specifically tailored to reduce propagation of unwelcome sounds into patient rooms or other spaces of healing and focus. It is also possible for architects to consider other fields in practical development. This research will also examine one specific aspect of biology, the acoustic niche hypothesis, in conceptual design. Bernard Krause notes that “there is a symphony of natural sounds where each creature voice performs as an integral part of an animal orchestra… experienced composers know that in order to achieve an unimpeded resonance the sound of each instrument must have its own unique voice and place in the spectrum of events being orchestrated” [4]. This mode of thought, when applied to architectural design, will prove instrumental for this research as even the geometric layout must be handled with the delicacy of a musical composition. In envisioning the self as composer and the program elements as instrument voices, sound will prove a foundational aspect of design. As the intent of this research is to prioritize acoustic impact of design decisions, this mentality will carry the architectural concept forward and potentially serve as a model for future typological examinations.

2.6 Mean Free Path and Ray Tracing

Before regarding the primary equation used for this study, the acoustic diffusion equation, this study must acknowledge a key parameter in its computation: the mean free path. To understand the interaction of particle travel in enclosed space, one must employ the mean free path equation to determine the average distance traveled by particles between two successive collisions. In homogenous, rectilinear rooms, the mean free path equation is as follows:

$$\lambda = \frac{4 * V}{S} \tag{2.1}$$

where V is the volume of a given room and S is the surface area of its walls. For more irregular rooms, however, such as the long hospital corridors studied by this research, a more complex computation is involved in which the constant for rectilinear rooms, 4, is replaced:

$$\lambda(x) = \int_0^\infty p_{nc}(x, l) dl \tag{2.2}$$

where formula 2.2 includes the probability of traveling a distance, l, without colliding with another particle [32]. It is important to emphasize that a larger mean free path value results in a louder resultant space, indicating the importance of this metric in simulation and determination of the resultant occupational quality of a space's inhabitants. Through this computation, the acoustic diffusion equation model generated may compute its results based upon specific room geometries given. As demonstrated in section 2.9, the model used for this study has the capability to run a ray tracing model alongside the acoustic diffusion equation and thus is capable of generating a graph that illustrates the mean free path as generated in a diffuse scattering, ideally diffuse, and mixed reflection wall condition. These three states are dependent upon the specific material used on the face of each surface in a volume. From this graph, the user of the model is able to see mean free path values and choose one to use and populate data for the acoustic diffusion equation model.

2.7 The Acoustic Diffusion Equation

The Acoustic Diffusion Equation, hereafter referred to as ADE, is based on the analogy between sound energy density and a density of sound particles traveling at the speed of light, c along straight lines. As noted in Escolano et. al., [47]

> “Through this method, the acoustics of enclosed spaces may be modeled so long as those spaces feature diffusely reflecting surfaces. This equation is a function of position r, and time, t, defined on a domain, V. It satisfies a second order partial differential equation with mixed boundary conditions,
>
> $$\frac{\delta w(r,t)}{\delta t} - \mathrm{D\bar{V}}^2 w(\mathrm{r,t}) + cmw(r,t) = P(t)\delta(r - r_s) \quad (2.3)$$
>
> in V,
>
> $$-D\frac{\delta w(r,t)}{\delta n} = Acw(r,t) \quad (2.4)$$
>
> on dV.”

Equation 2.3 is the inhomogeneous diffusion equation, where $\bar{V}^2$ is the Laplace operator (or differential operator given by the divergence of the gradient of a function on Euclidean space), $D{=}\lambda\ c/3$ is the diffusion coefficient, w is the acoustic energy density, r is the position of the particle, t is time, and c is the speed of sound in the given medium. Equation 2.4 is an expression of the boundary conditions that model the local effects on the sound field of differing degrees of absorption, α, on surfaces.

2.7.1 Limitations of the Acoustic Diffusion Equation

This model is best used in determining sound propagation in late reverberation times (RT) but also approximately one mean-free time prior to the time at which mixing occurs [36]. Additionally, the model is utilized best when illustrating the acoustic detail of coupled rooms, in particular the transition phenomena occurring at the coupling aperture [35]. A key limitation is that the ADE is most accurate when dealing with absorption coefficients less than 0.45 [47] but this may potentially be mitigated by implementing the Eyring formula [45]. In layman's terms, this formula describes the way sound travels through adjoining walls to determine how a noise generated in one room affects the acoustic space of an adjacent room.

2.8 Summary of Key Variables Being Observed

The most important variables being observed through this research pertain to the materials specified in the patient ward, the shape of the patient ward, the acoustic performance of boundaries that separate spaces, and the sound sources' location and intensity within designed space. The α, or absorption coefficient, is representative of a material's ability to absorb or reflect sound energy across the spectrum of frequencies. The sound transmission loss, or STL, indicates the amount of sound energy lost as sound travels between spaces and through materials. The space's volume is dependent upon the amount of space present within each room that sound can travel in. The surface area, then, is the area of each boundary enclosing a volume. It should be noted that two spaces can have the same volume but each boundary enclosing that volume can have wildly different surface areas. The frequency of sound is represented in specific octave bands for the scope of this study: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. These key frequencies are typical for acoustic measurement and, in studying these specific frequencies, materials studied may be assigned values respective to their absorptive capabilities across a wide spectrum of sound energy. It should be noted that all sounds emitted exist with energy across a full spectrum of frequencies to some capacity but most sounds audible to the human ear and emitted within a patient ward predominantly feature intensities in one or more of the given octave bands. The final parameter, the mean free path or λ, is dependent upon the volume of the space studied and is not automatically generated by COMSOL. This value must be determined by a user as an average of sound particle behavior conditions and is therefore a variable input by the user of COMSOL, subject to human error. The graph shown in Figure 2.1 demonstrates the wide range of values given after computing the mean free path in an irregular geometry; in this instance, a value of 4.45 is chosen as it represents a reasonable worst-case scenario.

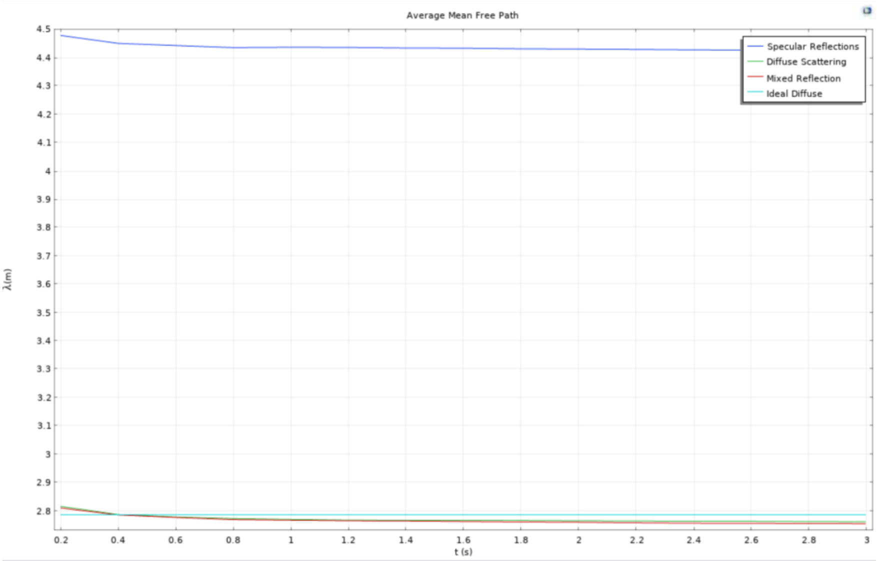

Figure 2.1: Average Mean Free Path in the Weinberg 5C Corridor

Variable	Label	Units
α	Absorption Coefficient	%
STL	Sound Transmission Loss	dB

Variable	Label	Units
V	Volume	m^3
SA	Surface Area	m^2
f	Frequency	Hz
λ	Mean Free Path	m

Table 2.1: Variables Observed Within the Scope of Research

2.9 Acoustic Diffusion Model

This research will employ COMSOL Multiphysics 5.6, hereafter referred to as COMSOL, which is a multiphysics software with a robust acoustic interface that has the capability to model the propagation of sound in digitally modeled space. This digital model will be created from replicating patient ward floor plans in Rhinoceros 7, a digital modeling software commonly used for architectural design, and will demonstrate the correlation between spatial form and occupational quality. In implementation of COMSOL's Acoustic Diffusion Equation Model, one is able to visualize the diffusion of sound as well as generate acoustic ray tracing in virtual space from a user-generated three-dimensional model. This software will assist throughout the development of this research in understanding the quantitative impact of design changes in a typical hospital patient ward as well as provide estimations on the acoustic quality of those spaces [33]. Ray tracing is highlighted specifically as a method in which noise propagation can be understood; the simulation of every vector emanating from a point source of unwelcome sound will highlight the surfaces and pathways that must be specifically considered. Through visualization, a designer can sculpt an acoustic ecology as a preliminary architectural tool and use resultant data to determine the success of a given spatial arrangement. It is through this methodology that this study seeks to design a hospital with acoustic quality as a primary quantitative design driver. As per the recommendation of Valaeu et. al., the first phase of design will utilize the diffusion model and the second phase will use ray tracing to give more detailed and accurate results [42]. By utilizing the analytical potential of COMSOL, iterative design may be also used to optimize resultant floor plan layouts of hospital spaces given inputs of typical decibel levels for disparate noise sources and the composition of wall cavities. Through analyzing the propagation of noise, this research will determine the time delay and energy level with respect to the direct sound, energy levels with respect to the reverberant field, angle of arrival to the listener, and frequency dependence of reflection energy as a function of the reflecting surface dimensions. Given the location of patients in their rooms and the source of known noises that would disturb sleep, this research will further iterate hospital layouts to minimize nighttime disturbances in patient rooms, effectively preventing sleep loss due to noise propagation, decreasing environmental stressors in the recovery process. In doing so, a model will be generated that demonstrates an ideal spatial arrangement for recuperation in health environments and create a guideline for future development of health environments.

2.9.1 Calibration of the Acoustic Diffusion Model

A key aspect of the use of a model to generate meaningful results is its calibration. For this, results from *Noise Levels in Johns Hopkins Hospital* and *Quieting Weinberg 5C: A Case Study in Hospital Noise Control* will be employed to assign materials, establish linkages, populate data for noise sources, and track resultant noise levels in specific spaces to determine if the digital model used can produce results recorded by professionals in an existing patient ward [16] [15]. Some key findings from these studies illustrate noise levels for specific rooms throughout the ward as well as noise levels throughout the day as recorded without any behavioral change to normal hospital operation and recorded with a Larson-Davis system 824 that uploaded results to a computer for analysis [16].

In Figure 2.2, one is able to see the range of noise levels recorded with respect to spaces in the ward, ranging anywhere from 52 dB(A) to 70 dB(A) depending upon their location and the specific activities

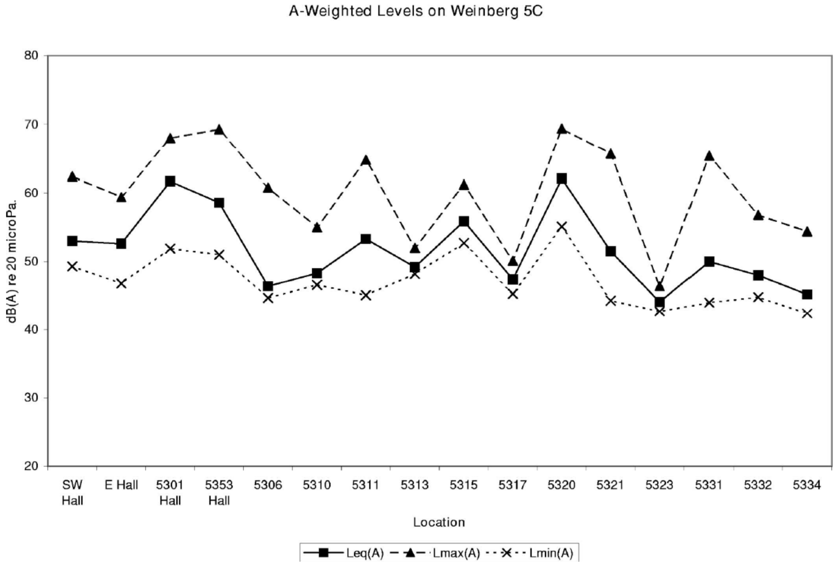

Figure 2.2: Noise Levels Per Room in Johns Hopkins Weinberg 5C Patient Ward

taking place in the ward. This data is used to give a range of acceptable results coming out of the COMSOL model and determine if all material assignments used throughout the model or sound sources given are sufficiently close to the recorded scenario or if adjustments need to be made to set a baseline condition for other geometric configurations.

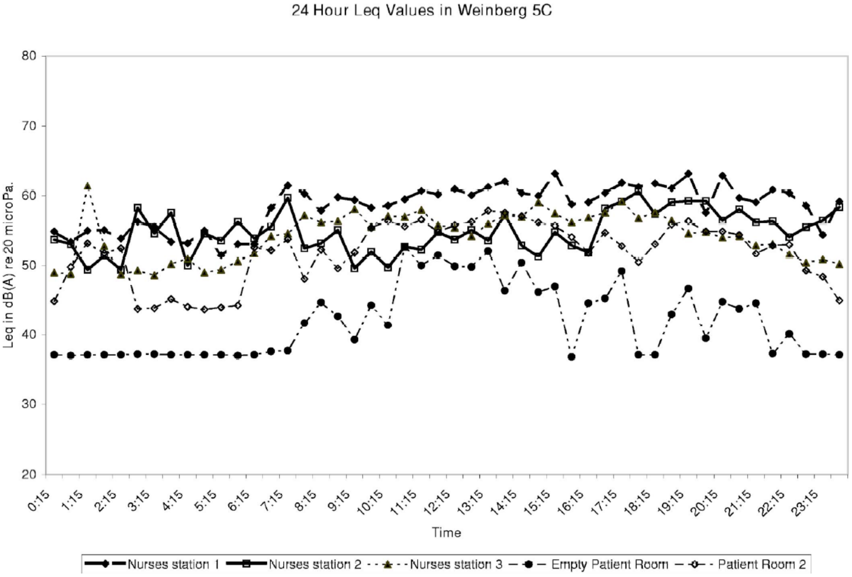

Figure 2.3: Noise Levels Per Hour at Five Locations in Johns Hopkins Weinberg 5C Patient Ward

In Figure 2.3, the range of sound present in the patient ward throughout the span of a full day is shown, indicating the variability of noises present throughout the ward and further indicating why many patients find it difficult to maintain a normal sleep schedule while recovering. The variability of noises, especially at nighttime, is a known disruptor of peaceful sleep and while this research will not address the depth and complexity of this issue in full, it broadens the range of sound data at specific locations in the model for calibration.

In tandem with the previous set of data corresponding to specific locations in the ward, this data creates a much more complete picture of the impact normal hospital operations have on the noise levels present even in an empty room, allowing for this research to examine patient rooms without internal noise stressors. Again, the calibration of the model will be based on ensuring the model results and inputs match the recorded data shown.

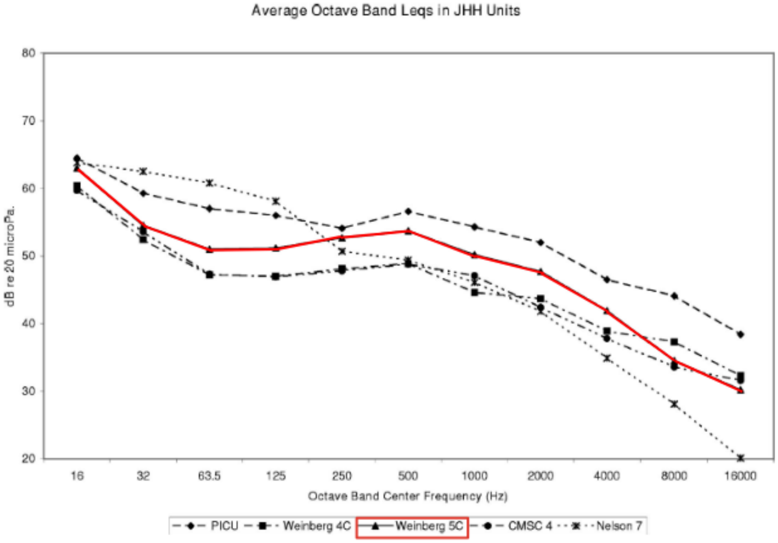

Figure 2.4: An Indication of the Spectrum of Sound at Specific Octave Band Frequencies in Weinberg 5C

In Figure 2.4, one can see an average spectrum of sound across octave band center frequencies in Weinberg 5C. This data is important as an input for the sources of noise present within the ward as sound is comprised of energy with differing levels respective to each frequency band. Each material assigned within the model has differing capabilities to reflect and absorb sound across the frequency spectrum so having this data as a component to each sound source is vital to the depth of understanding how that sound behaves in the space.

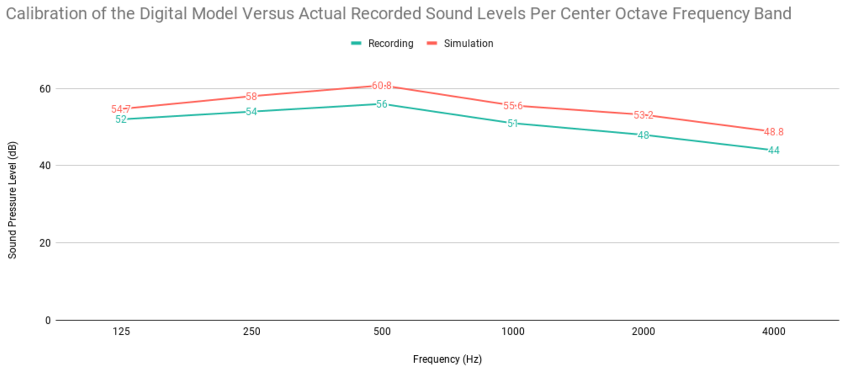

Figure 2.5: The Resultant Calibration Curve in Comparing the Recorded Data in Weinberg 5C and the Digital Model's Resultant Sound Pressure Levels

In Figure 2.5, the difference between the recorded sound pressure levels in Weinberg 5C and the simulated sound pressure levels present at the centralized nurses' station in the simulation is shown. Due to the fact that the simulation data is taken from a point at which six sound sources are all making noise equivalent to the recorded sound pressure levels taken from Weinberg 5C, it is determined that the model is close enough to the actual recorded acoustic condition and therefore testing may take place with the model generated.

With the floor plan shown in Figure 2.6, the model may be constructed to include patient rooms and their respective distances to a centralized nurses' station. With this in mind, the walls are constructed along their centerline and a node representing the patient's head is placed in its appropriate location. Due to the need for simplification between the constructed space and the way COMSOL separates spaces, only six patient rooms and one nurses' station was modeled for this calibration model in an effort to increase malleability of

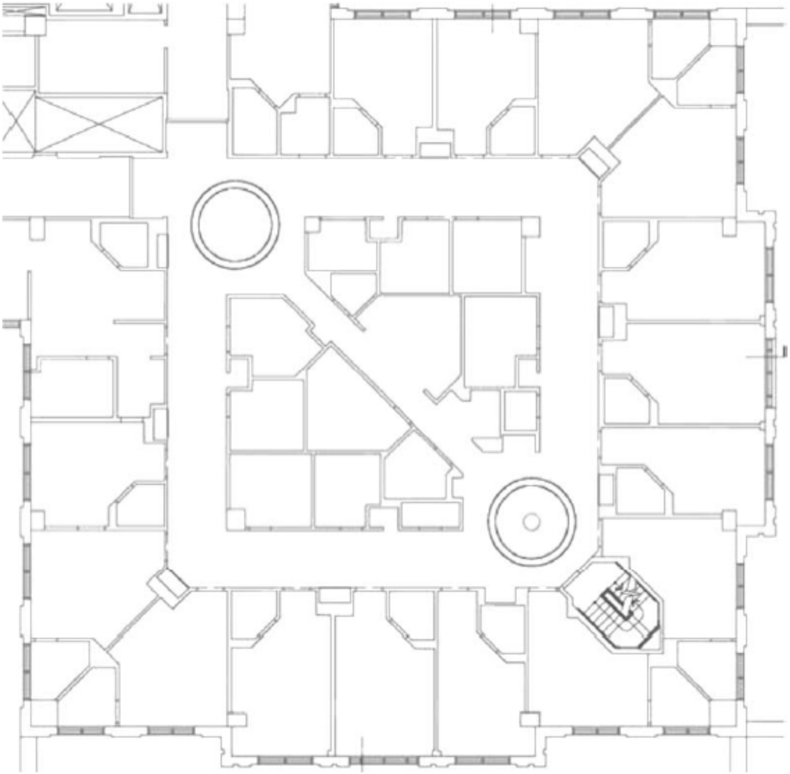

Figure 2.6: The Floor Plan Given for the Weinberg 5C Patient Ward in *Quieting Weinberg 5C: A Case Study in Hospital Noise Control*

the model's parameters. In addition, this first model tested serves a learning model in the scope of this research as later models will be more complex and build out further from the methods used to create this model and understand the specificity of COMSOL's computation methods.

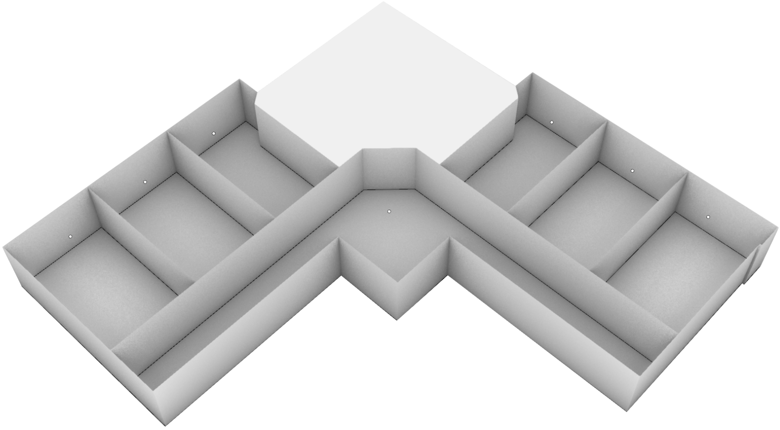

Figure 2.7: The Resultant Model in Rhinoceros 7 to be Imported into COMSOL

Figure 2.7 is the resultant model constructed from the floor plan in Figure 2.6. Any spatial adjacency must have duplicate surfaces present for COMSOL to indicate a separation between spaces where sound transmission loss (STL) values may be indicated as per guidelines set forth in the Facilities Guidelines Institute (FGI) 2018 or dependent upon the material specified. Though boundaries and geometries may be drawn directly in COMSOL, modeling patient wards in Rhinoceros 7 with the method shown is more intuitive and can be more specific and precise depending upon the changes made to the original floor plan.

2.10 Specific Products to be Used

Occupants of the hospital typology are currently suffering from sleep disturbance, high blood pressure, poor and psychological health, resulting in slow recovery rates and high staff turnover rates [11]. Acoustics are difficult to control in hospitals as a result of the openness of the plan as well as the need for infection control and sterility for all surface finishes, often resulting in the use of hard materials that reflect sound [11]. Modifying the acoustics of these spaces, then, relies on installation of washable sound absorbing ceiling and wall panels, with hygienic-grade options becoming more available [11] , such as the Ecophon Hygiene Advance Wall [24] and luxury vinyl floor tile (VLT) [50]. Ultimately, however, a key step in acoustic treatment of hospital space is reliant upon the initial design phases, indicating a need for noise-sensitive areas to be specifically considered for spatial isolation from excessive noise generators within the hospital environment. While there is a need for noise-sensitive spatial reasoning to be applied to layout design, there is not yet an example of a successful hospital floor plan or the implications of that layout. This thesis argues that a hospital floor plan properly designed with acoustic intent will improve the health of its occupants and ensure the typology stays true to its societal function.

2.11 Data Used in the Acoustic Diffusion Equation Model

The calibration of the acoustic model is the first major consideration of this research. To this end, data from several studies regarding hospitals will be fed into COMSOL to ensure the model is producing results within a small margin of error to actual conditions. The complexity of acoustic simulation requires fine attention to detail in both modeling the patient rooms and running the simulations that generate visualizations of noise propagation. For the sake of the site of the model, it shall be assumed that the hospital is located sufficiently far away from any highways or flight paths in order to have more finite control over the sounds existing within the building. For each surface present in the model, a full spectrum of absorption coefficients is needed for each octave band. For this, correspondence with Michael Ward from NBBJ's Seattle office regarding typical sound transmission class (STC) wall assemblies is cross-referenced with Table 1.2-6 from the FGI 2018. A higher STC value indicates a material will be more effective in damping sound traveling from one room to another.

As per the industry standard, three wall cavities will be implemented in this research. The first of these walls is STC 35 walls, comprised of one layer of 5/8" gypsum board full height, 4" steel studs at 16" on center full height with fiberglass batt insulation, and another layer of 5/8" gypsum board 6" above the ceiling. The second wall type is STC 45 walls, containing the same assembly as the STC 35 wall but including one layer of 5/8" gypsum board full height in-between the 4" steel studs and the gypsum board 6" above the ceiling. The third wall is STC 55, including one layer of 5/8" gypsum board 6" above the ceiling before the first layer of 5/8" gypsum board full height. These three wall types are then assembled in the model as surfaces placed at the centerline of walls on a floor plan placed as a background bitmap in Rhinoceros 7. From there, the model is exported as a STEP file (.stp) and imported into COMSOL for analysis. The absorptive spectra of each wall is found based on referencing the annex from Michael Vorländer's *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms, and Acoustic Virtual Reality.* This annex provides the random-incidence absorption coefficients, α, for a wide variety of materials and assemblies, allowing for each specific wall assembly to have a resultant absorption spectra in COMSOL. Additional wall types and absorption spectra are to be found in specific product brochures and will be used to match specific STC values as accurately as possible [28].

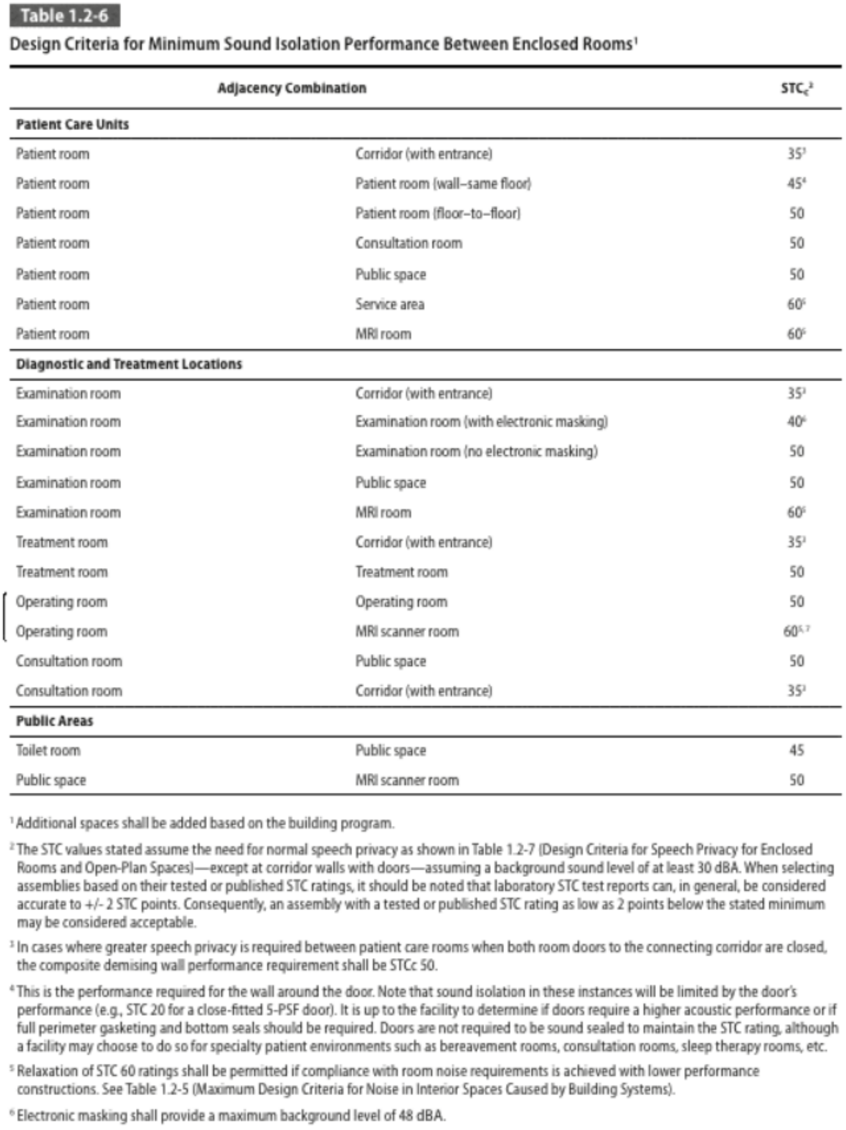

Table 1.2-6

Design Criteria for Minimum Sound Isolation Performance Between Enclosed Rooms[1]

Adjacency Combination		**STC_c**[2]
Patient Care Units		
Patient room	Corridor (with entrance)	35[3]
Patient room	Patient room (wall–same floor)	45[4]
Patient room	Patient room (floor–to–floor)	50
Patient room	Consultation room	50
Patient room	Public space	50
Patient room	Service area	60[5]
Patient room	MRI room	60[5]
Diagnostic and Treatment Locations		
Examination room	Corridor (with entrance)	35[3]
Examination room	Examination room (with electronic masking)	40[6]
Examination room	Examination room (no electronic masking)	50
Examination room	Public space	50
Examination room	MRI room	60[5]
Treatment room	Corridor (with entrance)	35[3]
Treatment room	Treatment room	50
Operating room	Operating room	50
Operating room	MRI scanner room	60[5,7]
Consultation room	Public space	50
Consultation room	Corridor (with entrance)	35[3]
Public Areas		
Toilet room	Public space	45
Public space	MRI scanner room	50

[1] Additional spaces shall be added based on the building program.

[2] The STC values stated assume the need for normal speech privacy as shown in Table 1.2-7 (Design Criteria for Speech Privacy for Enclosed Rooms and Open-Plan Spaces)—except at corridor walls with doors—assuming a background sound level of at least 30 dBA. When selecting assemblies based on their tested or published STC ratings, it should be noted that laboratory STC test reports can, in general, be considered accurate to +/- 2 STC points. Consequently, an assembly with a tested or published STC rating as low as 2 points below the stated minimum may be considered acceptable.

[3] In cases where greater speech privacy is required between patient care rooms when both room doors to the connecting corridor are closed, the composite demising wall performance requirement shall be STCc 50.

[4] This is the performance required for the wall around the door. Note that sound isolation in these instances will be limited by the door's performance (e.g., STC 20 for a close-fitted 5-PSF door). It is up to the facility to determine if doors require a higher acoustic performance or if full perimeter gasketing and bottom seals should be required. Doors are not required to be sound sealed to maintain the STC rating, although a facility may choose to do so for specialty patient environments such as bereavement rooms, consultation rooms, sleep therapy rooms, etc.

[5] Relaxation of STC 60 ratings shall be permitted if compliance with room noise requirements is achieved with lower performance constructions. See Table 1.2-5 (Maximum Design Criteria for Noise in Interior Spaces Caused by Building Systems).

[6] Electronic masking shall provide a maximum background level of 48 dBA.

Figure 2.8: FGI 2018 Table 1.2-6: Design Criteria for Minimum Sound Isolation Performance Between Enclosed Rooms

2.12 Calibration Model Results

After following the guidelines to create the model and bring it into COMSOL, the behavior of sound within the space is simulated. To ensure the accuracy of initial trials, all doors within the model have been left open to mirror a real condition within the ward, ensuring nurses working at their centralized nursing station have visual access to patients. With five nurses working at this station all speaking at once, the sound levels were deemed to be accurate to the recorded sound values in Weinberg 5C as depicted in Figure 2.2 for the hallway spaces. From this, the acoustic diffusion equation results in this spread for the sound pressure levels at 500 Hz:

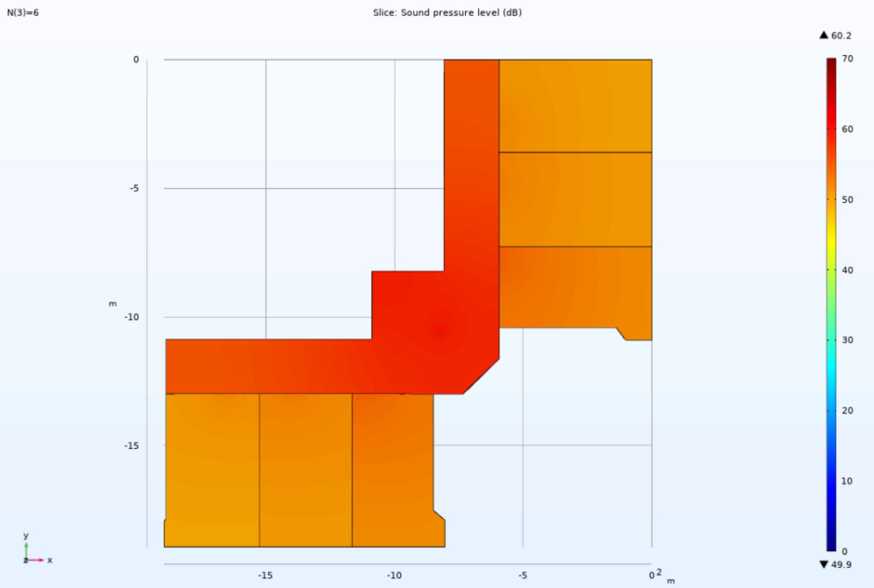

Figure 2.9: The Sound Pressure Levels in Weinberg 5C With Doors Left Open at 500 Hz

For all spaces shown within the model, the maximum sound level is 60.2 dB and the lowest sound level is 49.9 dB for this octave band.

These results demonstrate the worst-case scenario within the ward with the absolute minimum sound level within the ward being 38.9 dB at 125 Hz. Given the recorded data shown in Figures 2.2 and 2.3, these sound levels lie within the expected range. From this point onward, the material assignments and conditions in the ward will serve as a default case and any further alterations to the material assignments or types of boundary separations will be considered as a changed condition.

2.13 The Schroeder Frequency

To fully comprehend the spaces studied in the scope of this research, the model used will generate information regarding the Schroeder Frequency. The Schroeder Frequency is the frequency at which a room switches from a low frequency region dominated by separate modes and a high frequency region dominated by a much more dense modal overlap with statistical properties [30]. Essentially, this frequency is a key turning point for each individual room studied at which the sounds moving within it are either resonating at frequencies under the Schroeder Frequency or reflecting at frequencies above the Schroeder Frequency. This difference between resonant spaces and reflective spaces ultimately has a large impact on the way sound moves and how people within that space hear. Though it is not a primary point of focus for spatial iteration, it provides a useful point of data for a comprehensive understanding of the spatial behavior. The Schroeder Frequency is shown in Section 1.3.2 as Equation 1.1.

2.14 Layout Iterations Studied

Due to the time constraint of this research, specific hospital floor plans must be chosen and studied to gain an understanding of the significance of layout distribution on the resultant acoustic quality of space. For this, the calibration model discussed in 2.9.1 as well as two other layout arrangements of patient wards will be studied to provide statistically significant points of data for all materials, geometries, and assemblies studied. As the information for the calibration model has been provided previously, this section will focus on the two other patient ward plans covered by this study. In an effort to be as thorough as possible in the analysis of hospital spaces, the floor plans used for study are based heavily upon as yet unbuilt hospitals designed by leading healthcare design firms, building upon the experience and resources these firms have to generate informed, highly functional healing spaces. Though these plans are pushing the standards of contemporary healthcare design, this research seeks to further iterate these designs for their acoustic quality. The first of these plans, hereafter referred to as Hospital 2 or H2, features a long corridor with decentralized nurses' stations and patient rooms that face each other while allowing for the individual rooms to have full access to exterior views. The patient room geometry includes a small individual restroom and a change in the typical rectilinear patient room as it shifts into a more abstract tessellation. Due to this, the H2 ward is expected to have a different acoustic behavior as compared to the calibration model's spatial distribution.

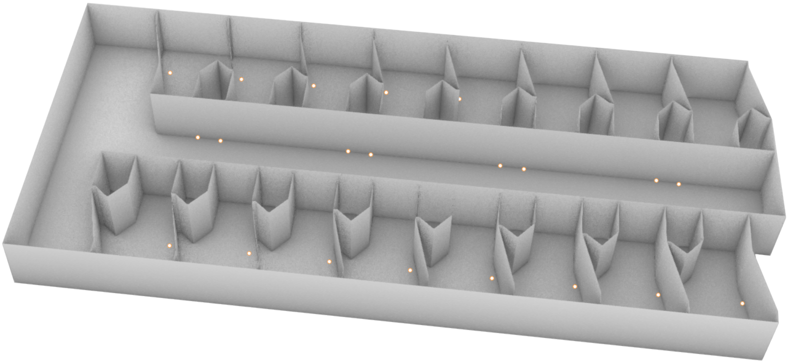

Figure 2.10: A Model of Hospital 2

The final hospital studied by this research, hereafter referred to as Hospital 3 or H3, also features decentralized nurses' stations but does not have patient rooms facing one another. Between H2 and H3, there are sixteen patient rooms but arranged very differently - it should be noted that H3 has a larger corridor volume (the corridor in H2 is 1192.818 cubic meters while the corridor in H3 is 1340.495 cubic meters) and both H2 and H3 include much more designed space than the calibration model. This results in a wider array of spatial attributes to be studied under the scope of this research and can generate a sensitivity response to what aspects of space contribute most to the resultant occupant experience.

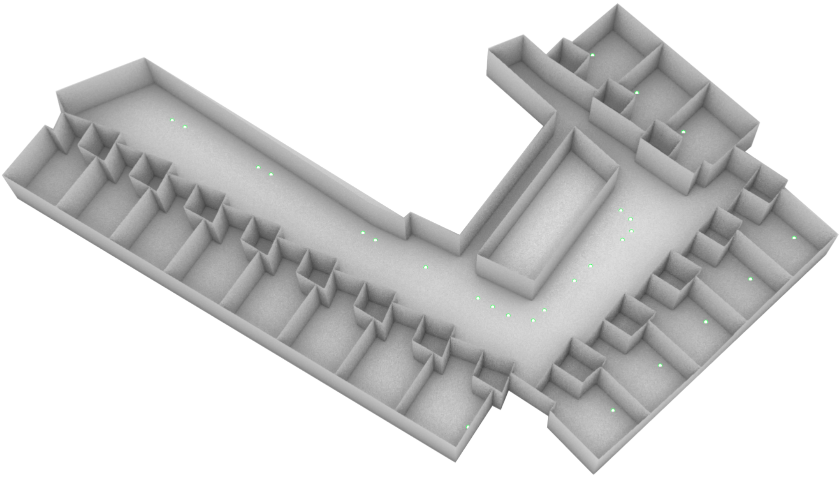

Figure 2.11: A Model of Hospital 3

Though this research will certainly benefit from further layout studies, the three iterations described demonstrate contemporary configurations of hospitals as assembled by preeminent design teams in the field of healthcare and also represent the changes that have taken place in the field over more than fifty years, demonstrating the industry shift from centralized nursing stations to decentralized nursing stations, allowing this research to demonstrate the acoustic spatial changes resulting from this shift in two different settings. If there is ultimately a large acoustic difference in the behavior between one spatial configuration and another, this research seeks to demonstrate such a difference and utilize this information to recommend spatial configurations in future designed spaces.

2.15 Geometric Iterations Studied

Beyond the spatial iterations discussed in Section 2.14, further specific geometries will be iterated upon through this research to determine if any one geometric configuration produces an improved acoustic environment for the patient or hospital staff. These geometric iterations introduce minor spatial changes into established layouts, looking first at H2 as the calibration model's programmatic layout represents a built preexisting state and this research seeks to be implemented to demonstrate the need for change in as yet unbuilt patient wards. If this iteration process demonstrates a need for a geometric change, it is the opinion of this study that the results would be more useful when demonstrated for a space that exists in a readily changeable state. Given the default H2 geometric spatial forms as the first geometric iteration, the first geometric change from the patient ward depicted in Figure 2.10 is a change in the shape and form of the walls and windows of the patient ward to make the space more curvilinear and, optimistically, alter the way sound travels such that the sound particles converge and dampen one another's energy within pockets of space in the corridor. Hereafter, this geometric iteration for H2 will be referred to as Concave Walls. The concavity of the space is in reference to the experience of an individual walking through the corridor.

The third geometric iteration for H2 is a change in the amount of ceiling surface area in the corridor and patient room while maintaining the amount of floor area. To do this, the walls of the corridor are angled in an effort to direct sound particles toward the ceiling of the

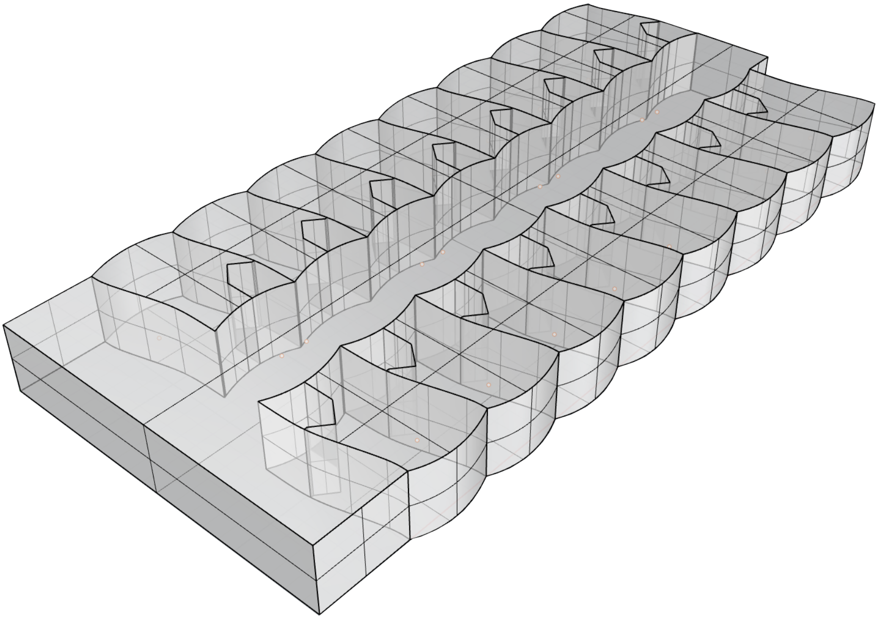

Figure 2.12: A 3D Perspective of the Concave Wall Geometric Iteration for H2

corridor, known to be a highly malleable surface in hospital construction such that more absorptive materials may be placed on the ceiling as compared to floors, doors, windows, and walls [27] [25] [26]. The resultant spatial form is highly unconventional and unlikely to ever be constructed regardless of the acoustic simulation results; angular walls in a healthcare setting would prove difficult to keep hygienic and would prove very difficult to build and operate due to the specificity of its form and departure from conventional modularity. Still, this research deems it important to test to what degree the amount of ceiling surface area impacts the acoustic behavior in the space where speech noise is generated. Hereafter this geometric iteration in H2 will be referred to as Max Ceiling.

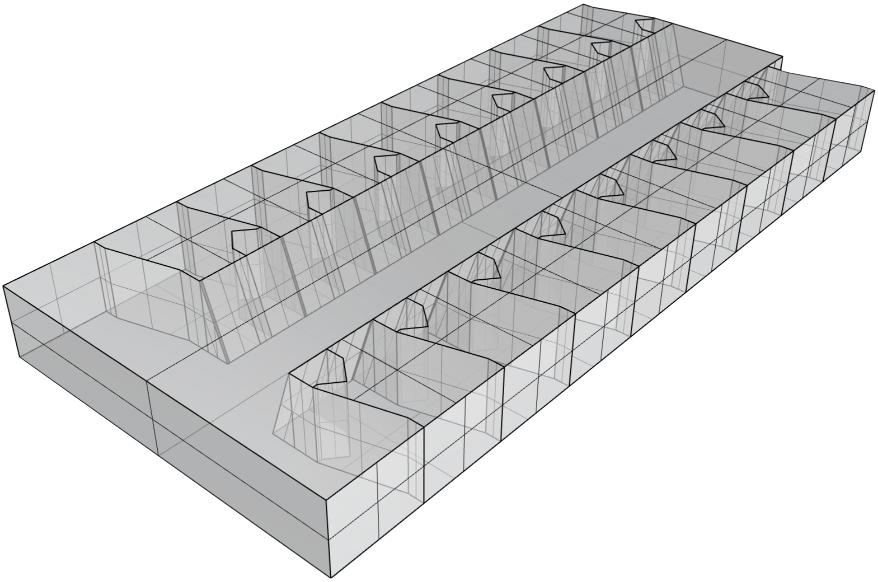

Figure 2.13: A 3D Perspective of the Max Ceiling Geometric Iteration for H2

The final geometric iteration for H2 is built upon the same conceptual spatial driver as Concave Walls in that both are an effort to redirect the way sound particles reflect off of walls in the corridor but this iteration, hereafter referred to as Sawtooth, is a more jagged and angular approach. Sawtooth is considered to be the most realistically applicable geometric iteration as compared to the other two changes from the default geometric condition as there are no curved surfaces and all walls are perpendicular to the floor. It should be noted, however, that the Sawtooth plan would be difficult to navigate in an emergency situation and may prove to feel unwelcoming to those experiencing the space due to the number of harsh corners in the corridor.

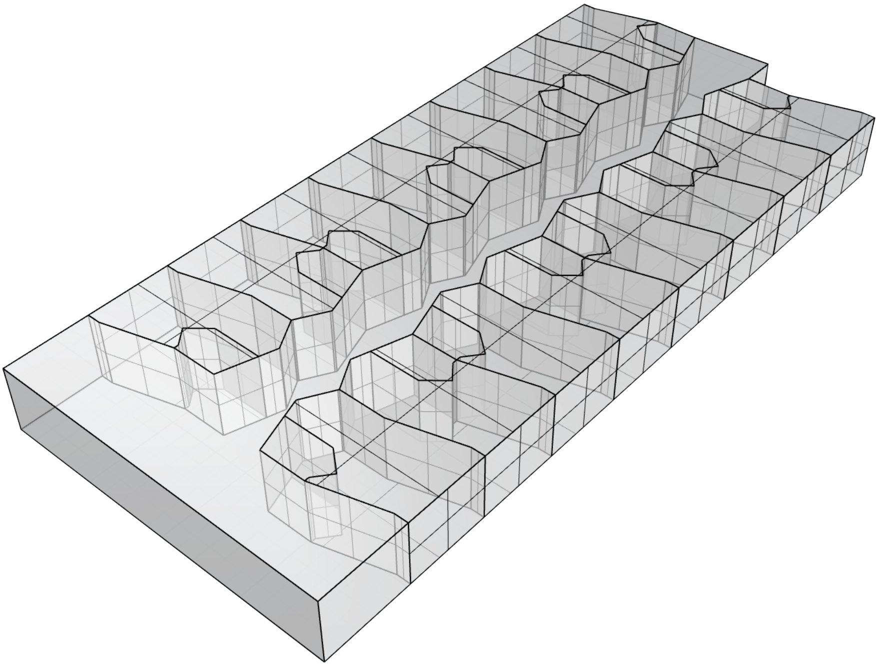

Figure 2.14: A 3D Perspective of the Sawtooth Geometric Iteration for H2

As of this point in the research, further geometric iterations may be considered in H2 and H3 if the results prove demonstrably promising; if any geometric iteration does not improve the acoustic condition for patients and staff by more than 10 dB for any octave band frequency within the scope of this research, no further geometric iterations will be considered and the bulk of testing conducted will be shifted to focus on material iterations.

2.16 Material Iterations Studied

To further understand the acoustic behavior of the patient ward, this research will employ a material iteration approach and seek to determine if any one material makes a dramatic improvement to the acoustics of the patient ward while still being reasonably priced. For this, each spatial configuration will be studied in its default geometric configuration with the same material assignments assigned to respective surfaces as the configuration model. It should be noted that for material iteration studies, all doors will remain open and further studies will iterate upon a closed door scenario. The list of materials studied for each surface are as follows: For walls, the default finishing material is 1/2” painted gypsum board nailed to 2x4s at 16” on center and other materials studied are a plasterboard on frame with 13 mm boards including a 10 cm cavity filled with mineral wool, a 40 mm acoustic plaster, a 40 cm cavity microperforated absorber, and a hybrid absorber-diffuser named a BAD panel that is mounted on 2.5 cm fiberglass.

For the ceilings, the default material condition is a plasterboard ceiling on battens with air space above on a 0.5” grid. Other materials studied are a perforated gypsum board 27 mm thick hung 300 mm from the ceiling, a fiber absorber on a perforated sheet metal cartridge, a 4 cm cavity microperforated absorber, a hybrid absorber-diffuser (again, the BAD panel mounted on 2.5 cm fiberglass), and a geometric surface comprised of trapezoidal boxes typically found in acoustic studios.

For the doors, the default condition is to have the door open as this is a behavioral condition commonly found in older hospitals. The materials studied in this iteration are solutions ranging from a closed

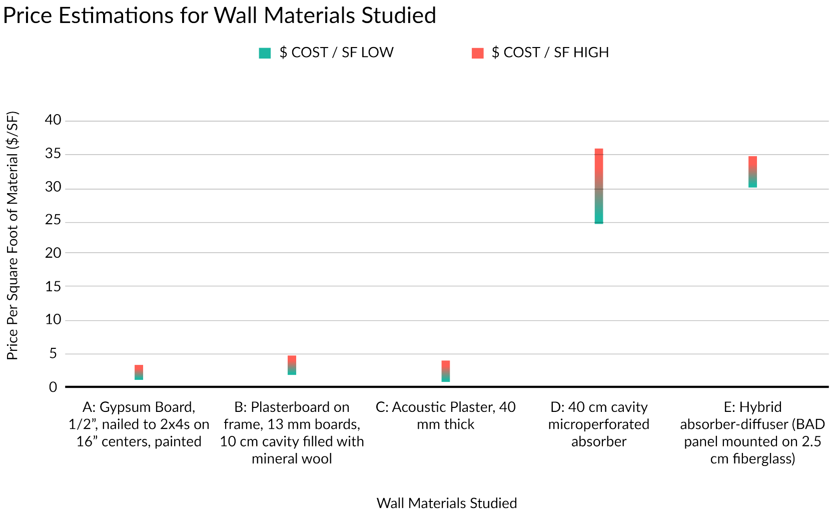

Figure 2.15: A Price Estimation of Each Wall Material Studied

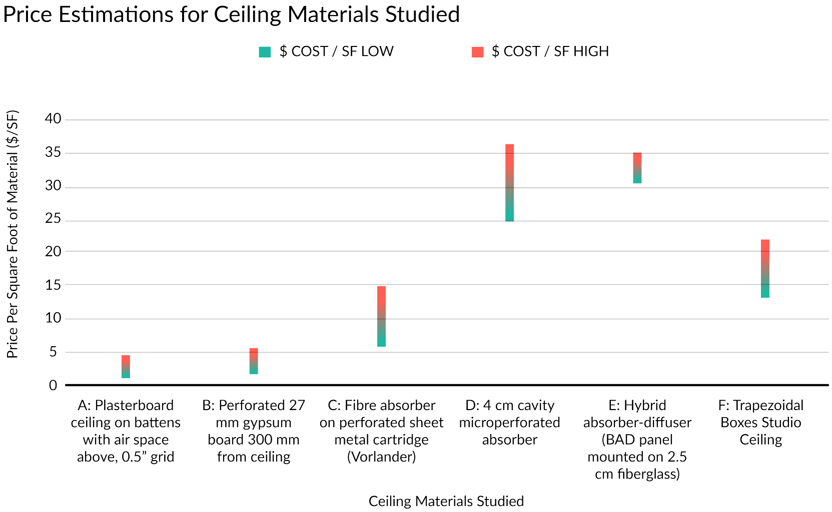

Figure 2.16: A Price Estimation of Each Ceiling Material Studied

wooden door, a closed hollow wooden door, and a glass door modeled as a pane of glass greater than 4 mm thick.

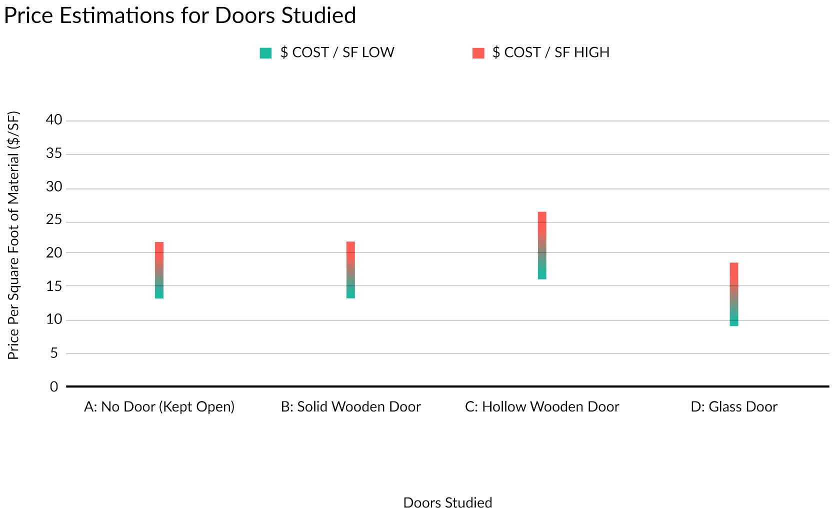

Figure 2.17: A Price Estimation of Each Door Studied

Materials chosen for study in this research are chosen as a spectrum of typical finishings in hospital construction as well as hygienic and high-performing acoustic materials meant to reflect a spectrum of possibilities for each surface though by no means are the materials chosen a comprehensive demonstration of available products. All material data and information are taken from either acoustic textbooks [30] [31] or from specific manufacturers of acoustic materials [28] and government websites to source pricing estimations [51] on a simplified range of low, middle, and high as compared to other finishing materials for that surface. The material iterations will also explore wall compositions to determine if any one spatial separator, whether it be between the patient room and another patient room or the patient room and the corridor, is a primary determinant of resultant acoustic comfort. For this, each spatial separator will be modeled as an STC 55 wall, indicating a high-performing wall capable of decreasing decibel levels from one space to another by roughly 55 decibels. This iterative approach will determine if resources in hospital construction would be best spent in improving the damping capabilities of wall cavities or if those resources should be focused on finishing materials.

2.16.1 Creation of a Data Matrix

From the data gathered from material iterations, a data matrix may be created to house all relevant information generated by COMSOL. Further, a delta matrix may also be generated to determine the difference between iteration results and better determine if any one material, any one geometry, or any one spatial distribution results in an improved acoustic condition for the patient or for hospital staff. For this, two spatial points are of particular interest in each model generated: the point at which the patient lays their head in their bed and one of the points from which human speech is generated, or a nurses' station. These two points are of interest as they are representative of the patient experience of space and the hospital staff experience of space respectively. To find the acoustic data at these two points, they are given to COMSOL as points as which data shall be extracted and then that data is input manually into the matrix from the exported text document. From this, the delta matrix subtracts a surface's material change from its original condition and is averaged among the two lowest, two middle, and two highest center frequency bands studied by the acoustic diffusion equation model. These averages will determine the best performing material for low frequency, middle frequency, and high frequency sounds.

2.16.2 Percentage Material Iterations

The last round of material iterations will focus on the amount of material added to a surface to increase its absorptive capabilities, again focusing the results of this research on where resources should be focused to best improve the acoustic condition of the space. For this, the first model imported into COMSOL features a 2 m by 2 m surface placed above each nurses' station, a band of wall 0.01 m away from the wall surface and approximately 1/3 of its height, and a portion of each door approximately 20 percent of its width and 80 percent of its height to be modeled as glass instead of a solid door. Further studies increase these material percentages until each respective surface's full area is comprised of a more absorptive material. These iterations seek to determine if the change from any surface's default material in these locations and at these dimensions to the highest-performing material observed in the material iteration process result in a dramatically improved condition. Further, this process can create a metric demonstrating the effectiveness of altering a given percentage of each surface studied by this research, likely indicating a metric of effectiveness per percentage of material changed. For healthcare designers, this tool should prove useful in finding where and how resources may be spent to best improve acoustic comfort for patients and staff given a fixed amount of resources to spend on acoustic control.

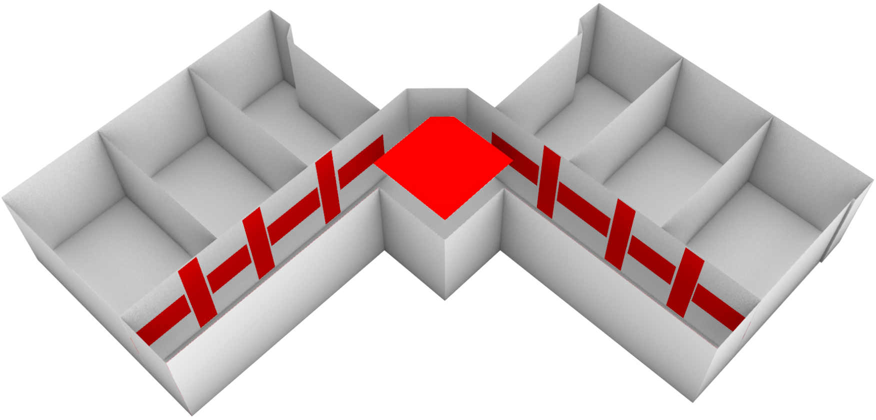

Figure 2.18: A Model Illustrating the Percent Material Change of Surface Area in H1

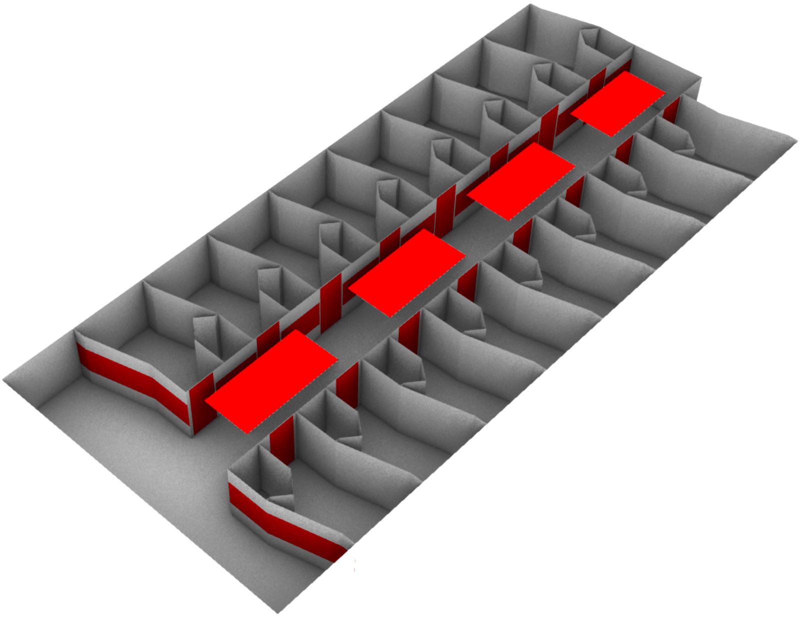

Figure 2.19: A Model Illustrating the Percent Material Change of Surface Area in H2

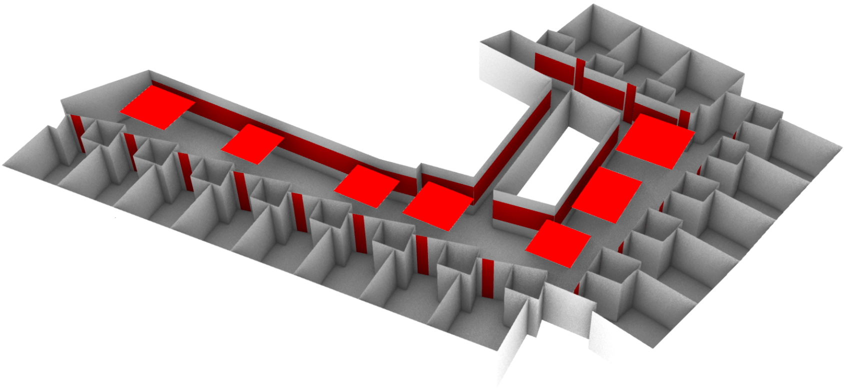

Figure 2.20: A Model Illustrating the Percent Material Change of Surface Area in H1

2.17 Acoustic Pressure Studies

To run the acoustic model generated by COMSOL, a mesh must be specified to approximate all surfaces in digital space. The creation of this mesh is of particular importance for studies involving acoustic pressure as the minimum mesh size must be as follows:

$$\frac{c_0}{f_MAX}/6 \tag{2.5}$$

Where c_0 is the speed of sound in air, taken as 343.2 m/s, f_{MAX} is the largest frequency studied, taken to be 4000 Hz. This same equation is used for the maximum mesh size but replaces the 6 constant with a 5. This specific sizing of the mesh ensures COMSOL runs an accurate estimation of the behavior of acoustic pressure within digitally modeled space [33]. Once generated, this model is capable of demonstrating a full spectrum of sound pressure levels across a wide frequency spectrum and illustrate the relationship between spatial geometry and phenomenological spatial properties such as disparate levels of loudness for various frequencies of sound as perceived by the patient in their bed. This information serves to deepen the architectural understanding of designed space and demonstrate the impact of patient room geometry upon its resultant acoustic behavior and the patient's perception of sounds within that space.

2.18 Assumptions Made and Definition of the Scope of Research

Due to the time frame of this research, several assumptions must be made to limit the scope of this research. It should be noted that patient monitoring devices are regularly considered the largest source of noise and sleep disruption within the hospital [20] [9] [14] [22]. It is not, however, the role of the architect to specify patient monitoring devices. Instead, this research asserts that what can be controlled by the architect within the hospital is the way human speech travels within space given that monitoring devices may very well become digitized or wearable within the next decade but hospitals will consistently be filled with people; noise from those people will consistently be a source of disruption [13] [22]. Given the immense architectural scope of the hospital, this research will specify and examine just one patient ward within the hospital to be able to fully understand and control the acoustic environment within the time allotted. Further, it is shown that specifying individual patient rooms rather than shared rooms results in an expedited recovery process [27] [26] [14]. Though there are existing solutions for patients recovering in open plan hospital wards [37] [7] [11], many changes that need to take place to improve the acoustics of the patient ward are foundational and need to be introduced as early as possible in the architectural design process to have the greatest effect on the final outcome [27]. From this standpoint, this research will examine geometric configurations, material assignments, and resultant behavioral conditions (such as leaving an opaque door open or leaving a glass door closed to maintain visual access to the patient from the nurses' station) to examine the acoustic condition of the patient ward. That being said, materials used on the floors of patient wards need to be a clean, hard surface for ease of operation and sterilization. Due to this, material iterations will focus on ceilings, walls, and doors. This research should also acknowledge the large impact furniture has on the acoustic behavior of patient rooms but, due to time constraints, this research will iterate upon empty patient rooms [18]. Though furniture geometries and the materials used to assemble that furniture changes the way sound behaves in an enclosed space, the furniture is ultimately movable whereas the walls and materials assigned to the final geometries of patient wards are fixed and therefore under scrutiny by this research. Additional design goals will maintain the patient's access to natural light and visual access to green space wherever possible to correspond with existing best practice methods of healthcare design [19].

2.18.1 Decisions Made to Simplify the Design Conditions

The site for this project will be such that the patient ward is over 1,000 feet from the nearest highway, over 7,000 feet in slant distance away from any aircraft flight track, and over 1,500 feet from the nearest rail line. The outdoor day-night average sound level is less than 65 decibels (dBA) and the minimum exterior shell composite sound transmission rating is 35. The windows in patient rooms will not be operable to ensure a fixed condition at wall openings. The minimum sound transmission class (STC) rating of any wall within the designed space is 35.

2.19 Criteria for Success

As the patient ward is demonstrably simulating a real-world condition, several key focus points will be observed with interest moving forward: the location of each patient's head in their bed as well as the corridor where hospital staff spend their work day. The sound pressure levels at these points of interest will be recorded after each change in the material choice or geometry of the patient ward and directly compared against the default condition to determine if the changes made from the default condition indicate an improved acoustic environment for patients, hospital staff, or both. Ideally, any reduction in decibel levels being carried through the corridor from a source of noise will result in a lower sound pressure level at the patient's head. To be clear, this research is not advocating for absolute silence in the patient ward - the absence of negative sound does not necessarily create a positive environment [13]. This research is asserting a higher standard of acoustic consideration within the patient ward and pushing forth an environment designed for the sleep health of each patient and the occupational health of hospital staff; any design recommendations put forth by this research will quantitatively demonstrate a reduction in the propagation of noise within the hospital environment through spatial configuration, geometry, and material changes. It must be stated, however, that many of the acoustic changes necessary for reduction of sound pressure levels in the hospital are behavioral [20]. Though architecture can certainly alter behavior through design, education of hospital staff on the effects of noise is considered to instigate the most meaningful changes in the acoustic environment [9].

2.20 Sources of Error

There are many possible sources of error throughout this process, namely the input of any data by a human hand. As I am by no means an acoustician or intimately familiar with acoustic concepts or testing methods, much of the process that has been laid out and iterated upon is due to my own inexperience with the subject matter or the softwares used to study or understand the hospital environment. I am also not an expert in healthcare design; any recommendations put forth by this research should be taken with the knowledge that the healthcare environment, and even the patient ward specifically, is far too complex for any one study to comprehensively tackle and understand in the time period allotted to this research. Though this research does not declare any conflicts of interest or biases, there are likely unknown biases that have been undertaken during the process of this thesis. Further, this research was conducted under the guidance of two experts in their fields but there are always opportunities for miscommunication or questions that should have been asked but were not. There is also the opportunity for error during multiple stages of model creation which ultimately impact the results generated by COMSOL. From nearly-invisible gaps in the digital model to inaccurate estimations on the Mean Free Path values that should be input for each modeled space, the creation of the model itself provides plenty of opportunity for error.

Chapter 3

Results and Discussion

3.1 Acknowledgement of Negative Results

As data taken from the COMSOL model indicates, negative numbers are a possible output from the model used. It should be noted at this point that negative numbers are not an impossibility; energy that does not pass through a given spatial separation could cause a pressure differential between two sides of a surface for multiple center octave band frequencies. This indicates that the sound received by a receiver on the other side of that surface would feel more ”dead” with the absence of those frequency bands but a sound could still be heard.

3.2 Ray Tracing and Mean Free Path

First, the results from ray tracing studies conducted within COMSOL to determine the mean free path values used as inputs for the acoustic diffusion equation. Again, these results are a representation of several different kinds of release conditions for sound particles as they collide with boundary surfaces within the model and the final mean free path value used as an input is typically a worse-case value depicted on the graph. The higher the mean free path value, the noisier the space becomes due to the relationships demonstrated in Equations 2.1, 2.3, and 2.4.

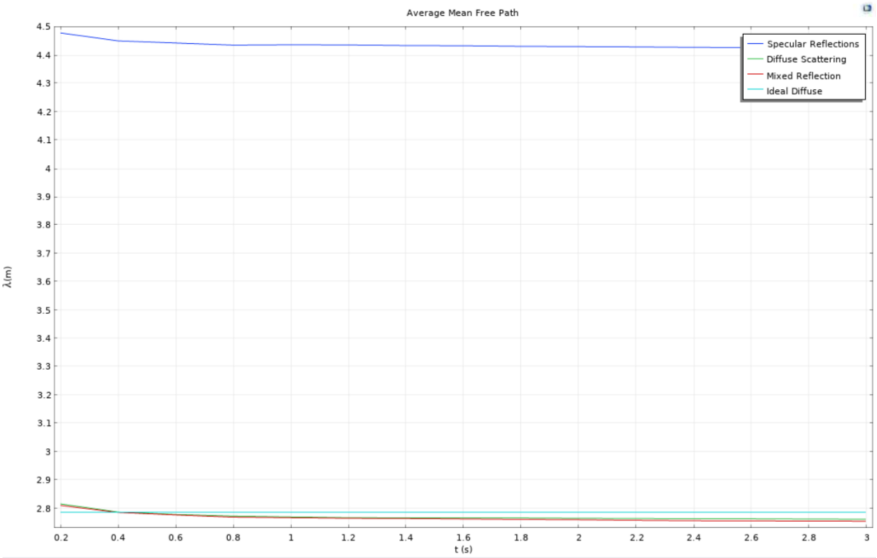

Figure 3.1: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in H1

The chosen value used for the mean free path in the corridor of H1 is 4.45 while the value used for patient rooms is taken to be the value used for regular, rectangular spaces as shown in Equation 2.1.

The chosen value used for the mean free path in the corridor of H2 is 4.27 and the value used for the patient room is 2.77. These vary, however, in each geometric iteration studied in Hospital 2:

The geometric iterations exemplify best how the alteration of volume and surface area can change the acoustic behavior of space. Purely through a change of the corridor shape, the mean free path value can vary in value and range across time. Given how resultant computations rely upon this metric, this research predicts that there will be a dramatic difference in resultant decibel levels present

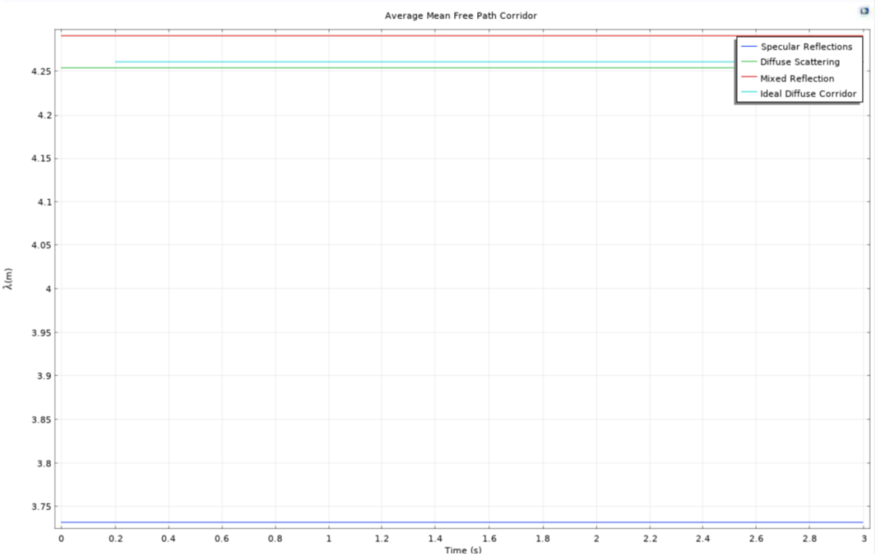

Figure 3.2: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in H2

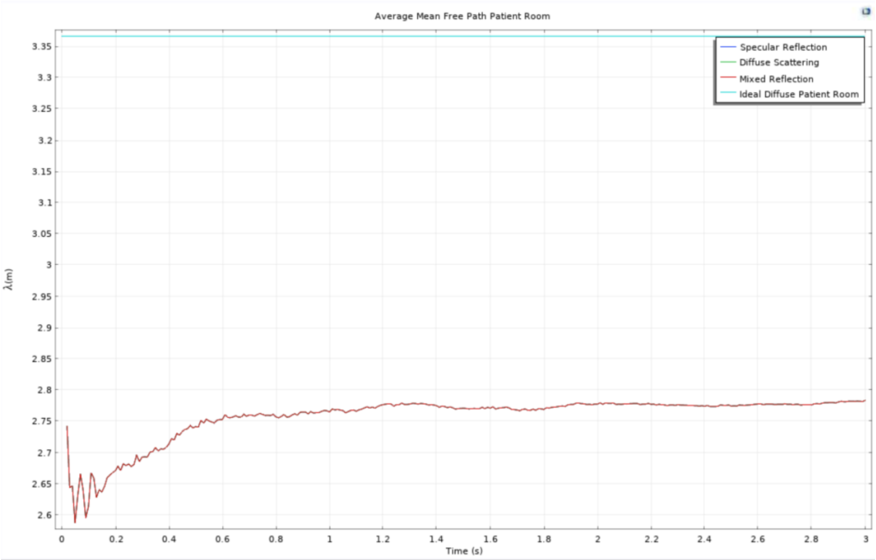

Figure 3.3: A Graph Depicting the Results of the Mean Free Path Computation for the Patient Room in H2

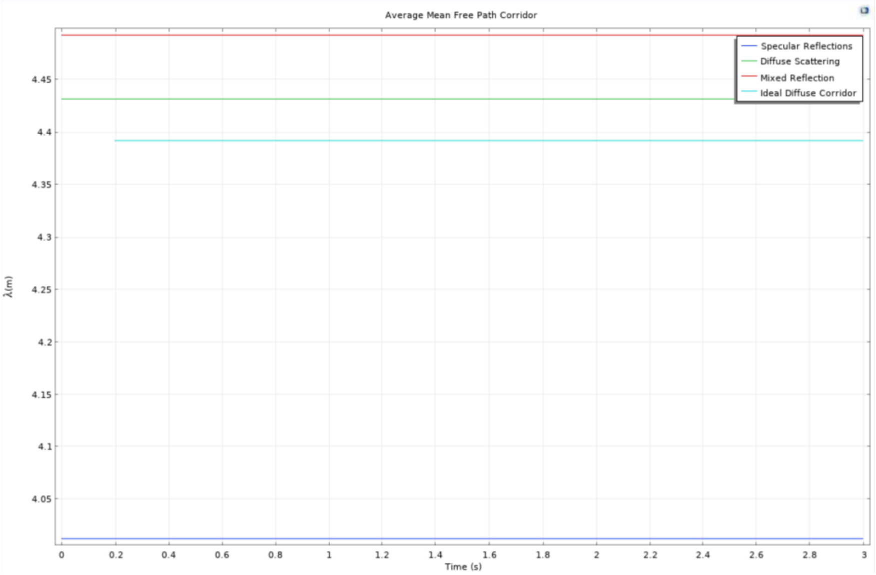

Figure 3.4: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in the Concave Wall Geometric Iteration of H2

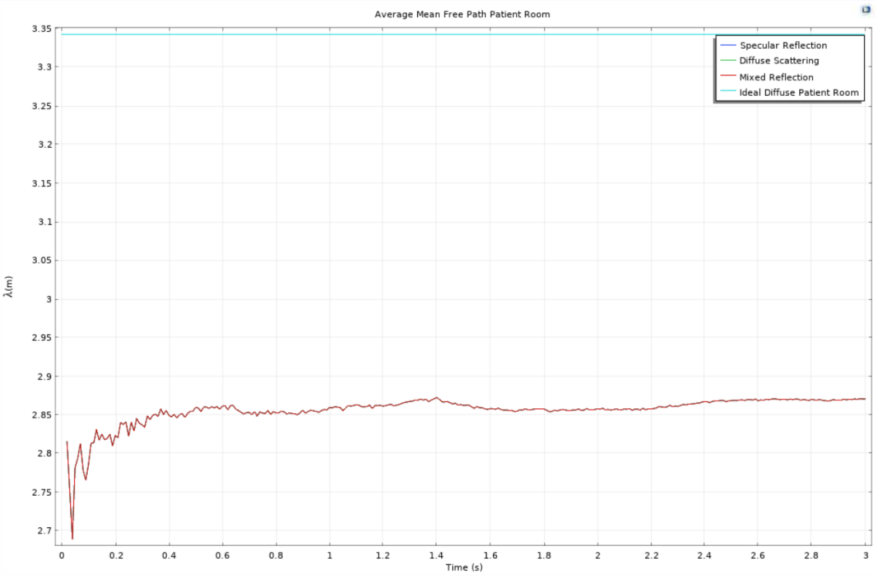

Figure 3.5: A Graph Depicting the Results of the Mean Free Path Computation for the Patient Room in the Concave Wall Geometric Iteration of H2

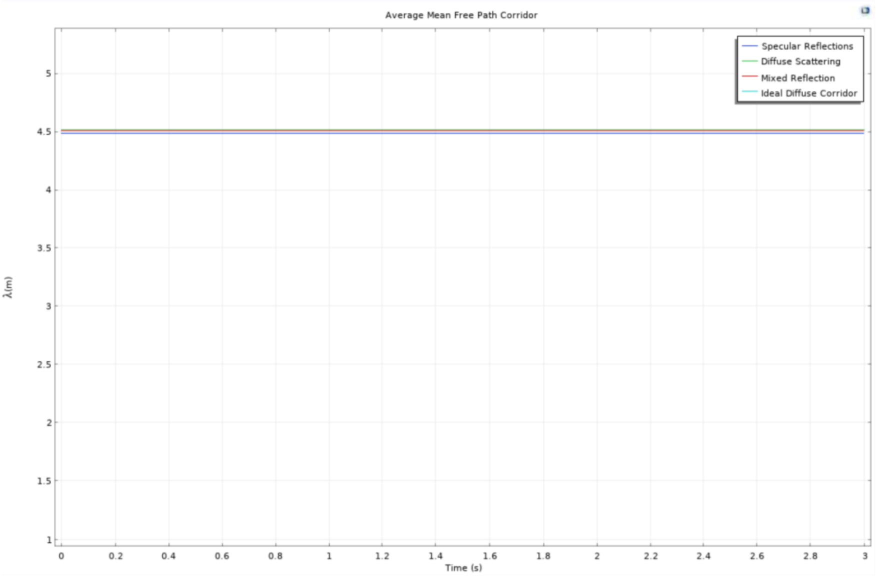

Figure 3.6: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in the Max Ceiling Geometric Iteration of H2

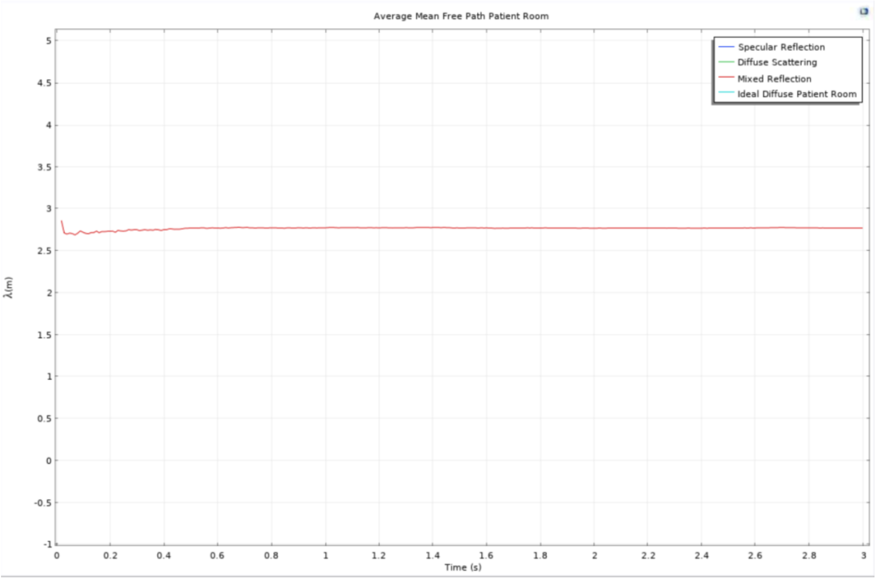

Figure 3.7: A Graph Depicting the Results of the Mean Free Path Computation for the Patient Room in the Max Ceiling Geometric Iteration of H2

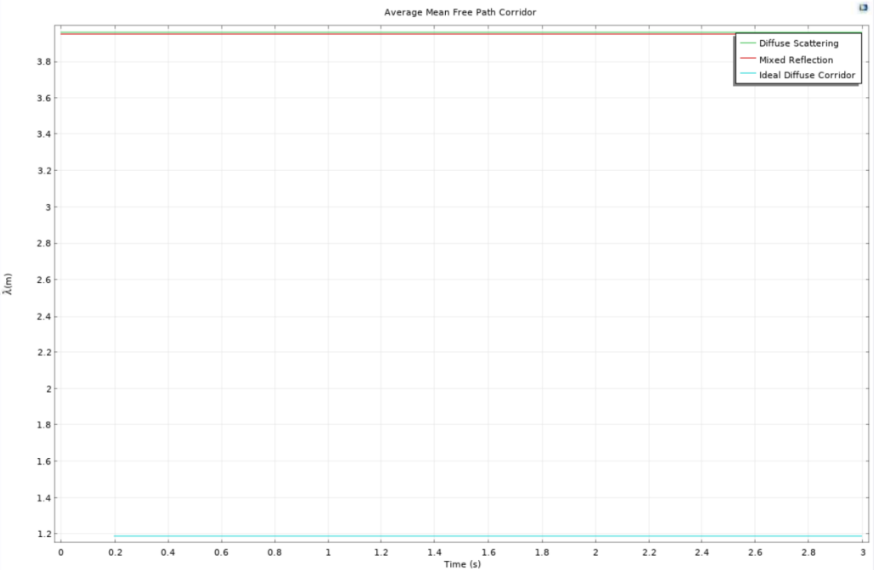

Figure 3.8: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in the Sawtooth Geometric Iteration of H2

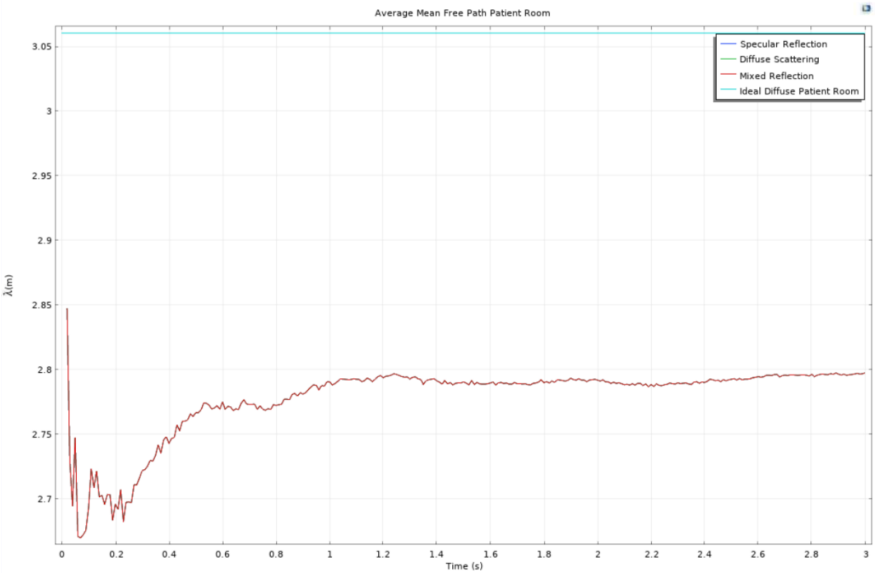

Figure 3.9: A Graph Depicting the Results of the Mean Free Path Computation for the Patient Room in the Max Ceiling Geometric Iteration of H2

in the corridor of Hospital 2 between each simulation given default material assignments. As for the patient rooms, the behavior of the mean free path value seems to be slightly more straightforward with release conditions coinciding to one plot. This leaves less room for user interpretation between release conditions though the value still changes between each geometric iteration and often these values are separate from ideally diffuse conditions. Next is the mean free path for Hospital 3.

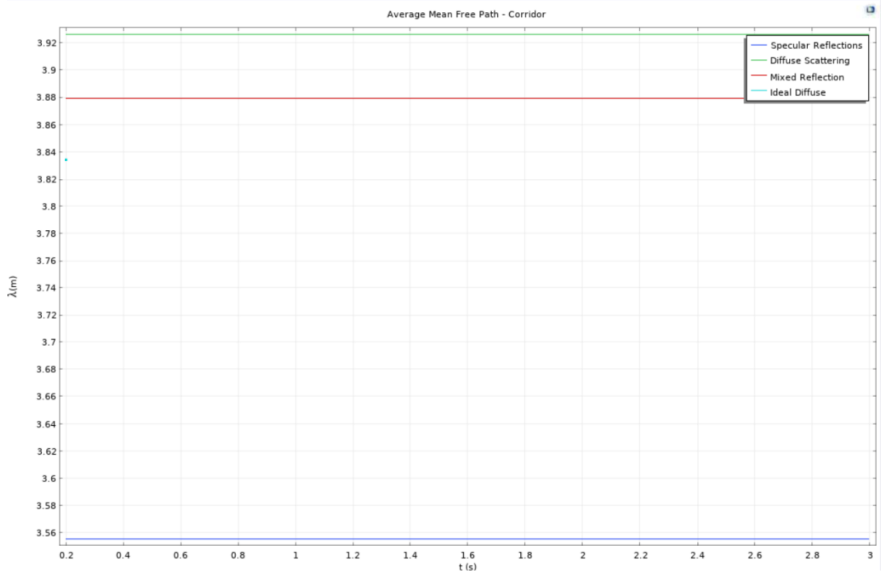

Figure 3.10: A Graph Depicting the Results of the Mean Free Path Computation for the Corridor in H3

The chosen value used for the mean free path in the corridor of H3 is 3.80 and the value used for the patient room is 2.64. So overall the highest mean free path value is in the corridor of the Max Ceiling geometric iteration of Hospital 2 and the lowest value is in the irregularly shaped patient room in H1. Though it is known and widely accepted outside of this research, this data indicates that even

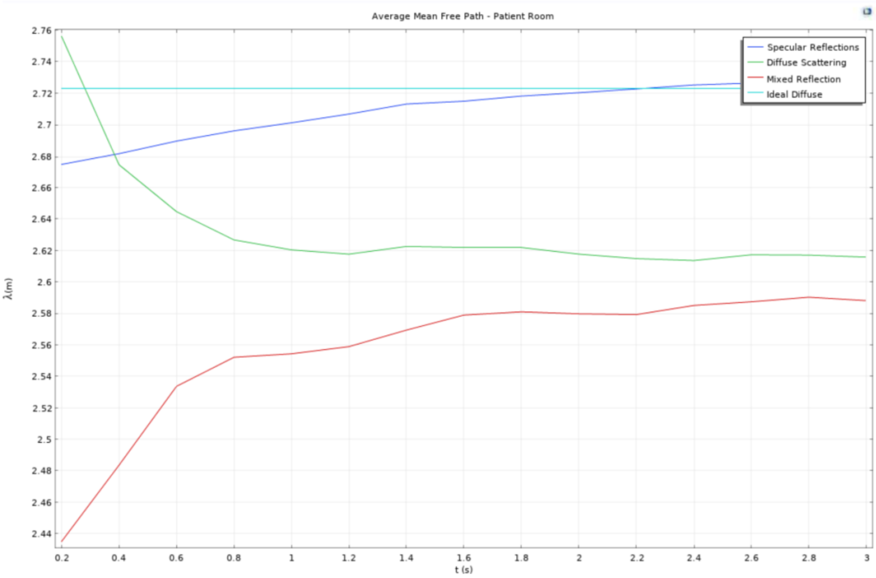

Figure 3.11: A Graph Depicting the Results of the Mean Free Path Computation for the Patient Room in H3

the smallest change in room shape results in a dramatically different spatial behavior of sound. The final chosen values for mean free path in each space is shown below.

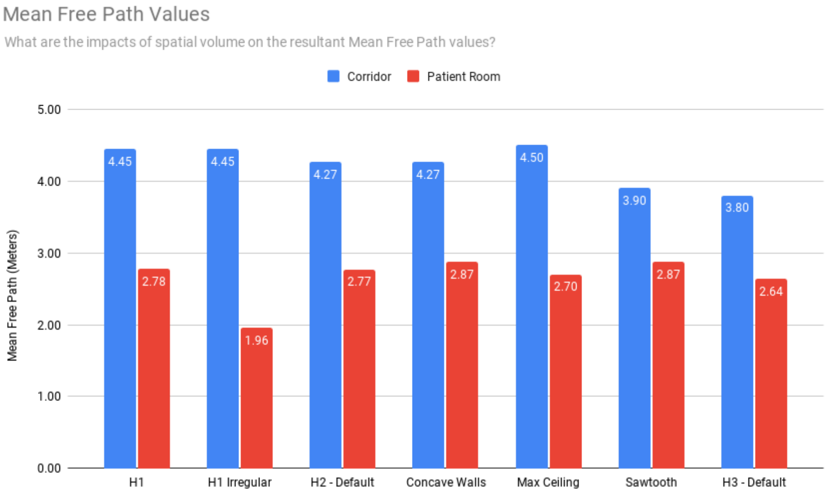

Figure 3.12: A Graph Depicting the Chosen Mean Free Path Values in All Spaces Studied

This leads to the initial assumption that the irregularly shaped patient room in Hospital 1 will inherently be the quietest space studied given a condition of default material assignments.

3.3 Acoustic Diffusion Equation Results

The results coming from the acoustic diffusion equation testing are some of the most important of this study. From the acoustic diffusion equation model for each space being tested, the hypothesis established in Section 3.2 regarding the assumption that the irregularly shaped patient room in Hospital 1 will be the quietest space can be put to the test. Further, if there is any one layout, geometry, or material that results in a quieter space for patients and hospital staff, the upcoming results will demonstrate that information. Additionally, if there is any one layout, geometry, or material that results in a quieter space on its own, the implication from the data is that desired acoustic change may be met by first implementing that respective layout, geometry, or material in future spatial designs.

3.3.1 Results from Layout Iteration Studies

Between Hospital 1, Hospital 2, and Hospital 3, the quietest space will have the lowest decibel level given a default material assignment on all surfaces. Something to be observed in these findings is the absorptivity of each space. The absorptivity is the denominator of the Sabine Equation, Equation 1.1, demonstrating that the quietest space has a more effective volume to surface area ratio. These studies are asking if there is any one patient ward layout that results in a quieter stay for patients and a less noisy place to work for hospital staff. First, the results from the location of a nurses' station in each space:

From these results, it already seems that Hospital 2 has a quieter corridor than the other layouts by about five to ten decibels consistently. The qualitative difference would be going from a corridor that sounds like a dishwasher to a corridor that sounds closer to moderate rainfall. This leads to a further finding that the corridor in Hospital 2 is more geometrically absorptive than the other two layouts so there is a way to design space that results in a quieter experience for its occupants. Another result may be that the decentralized nursing stations featured in Hospital 2 and Hospital 3 result in a quieter space than Hospital 1 but further study into the acoustic effect of specifying centralized nursing stations may be needed. Next, the resultant patient experience between the three layouts studied:

Here the results are even more pronounced - Hospital 2 results in a quieter patient experience. Whether this is due to the fact that Hospital 2 has a quieter corridor and therefore a quieter patient room

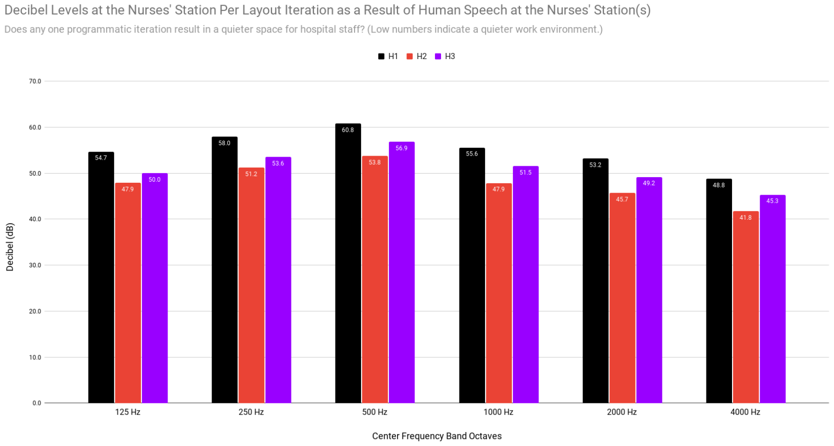

Figure 3.13: Decibel Levels at the Nurses' Station Per Layout Iteration

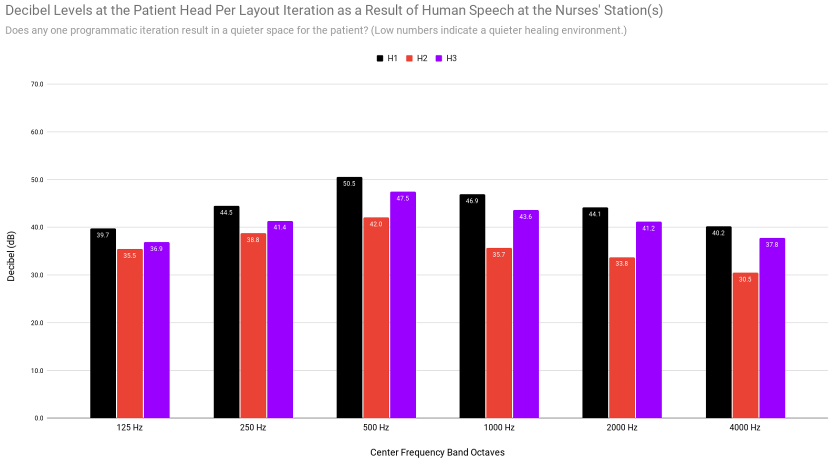

Figure 3.14: Decibel Levels at the Patient Head Per Layout Iteration

or if the form of the patient room in Hospital 2 inherently creates a quieter experience for the patient or a mix of both is unclear from the data. Regardless, the corridor shape and patient room of Hospital 2 is the quietest layout iteration between both points in space examined. Therefore, there is one hospital layout that results in a quieter space: the layout of Hospital 2.

3.3.2 Results from Geometric Iteration Studies

From the results in the previous section, the geometric studies undertaken are an attempt to improve upon what is already proven to be the optimal layout configuration for acoustic comfort between the three patient wards observed in this research. In Hospital 2, it is the initial belief of this research that small changes to the geometric form of the ward can result in a quieter environment. Again, the three geometric changes to Hospital 2 are changing its corridor and patient room walls to be curved instead of rectilinear or straight (Concave Walls), changing those same walls to be angled out to maximize the ceiling surface area in the corridor (Max Ceiling), and changing those walls to be more jagged throughout the corridor (Sawtooth). These plots are delta plots that indicate the resultant change from a default condition, the default layout of the Hospital 2 ward, to a changed condition: each respective geometric change. First, the results at the nurses' station in the corridor:

From this information, it appears that there is no one geometric iteration that makes a significant enough difference to warrant the necessary changes to standardized construction methods associated with each geometric iteration. At most, altering the default geometric layout of Hospital 2 results in a positive change of about half a decibel in the corridor. This indicates that, unless the data from the patient head is significantly different, the default layout of Hospital 2 should remain the recommended architectural spatial configuration among all layout and geometric iterations observed by this research.

As it turns out, there is still no dramatic change in decibel levels at the patient head, indicating that if further acoustic change is

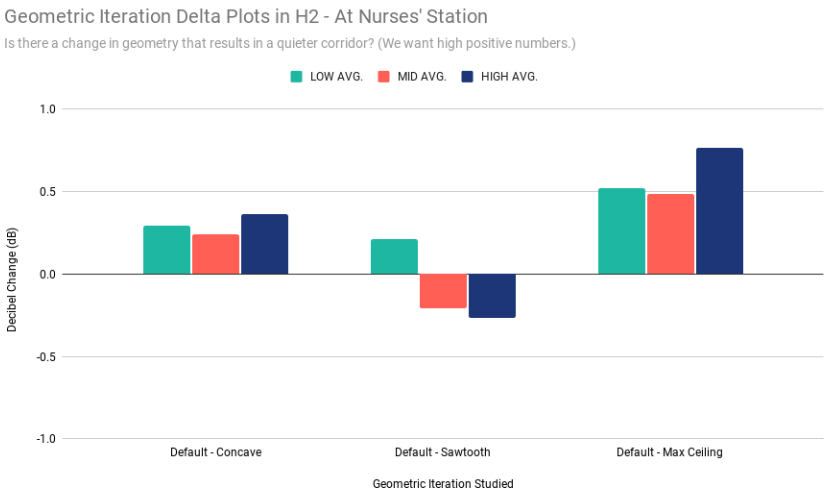

Figure 3.15: A Delta Plot of the Resultant Decibel Change Between the Default Layout of Hospital 2 and Each Geometric Iteration at the Nurses' Station

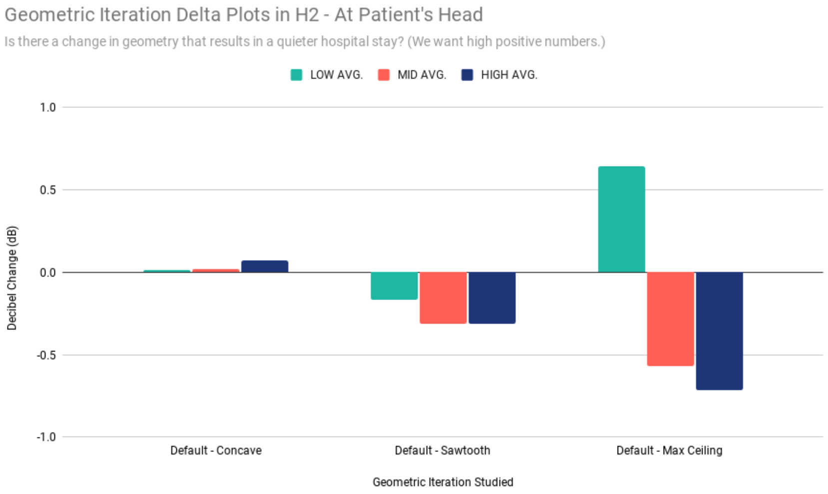

Figure 3.16: A Delta Plot of the Resultant Decibel Change Between the Default Layout of Hospital 2 and Each Geometric Iteration at the Patient Head

needed within Hospital 2, that acoustic change will likely not come as a result of geometric changes to the layout. This gives the finding that the desired acoustic change in the patient ward will stem from material changes or changes to the acoustic absorption coefficients in the denominator of Sabine's Equation (Equation 1.1) - changing total absorption in a space is more likely achieved through material change than through changes to surface area as the spatial configuration of healthcare settings is highly regimented in the United States. Additionally, the only way to change the denominator of Sabine's Equation without changing the numerator is through altering the absorption coefficient of respective surfaces.

3.3.3 Results from Wall Cavity Iteration Studies

To see how material change impacts resultant acoustic spatial behavior, the first round of results will demonstrate how altering wall cavity material composition, or wall assembly sound transmission class (STC), impacts the resultant patient and staff experience of the patient ward. Again, these are changes from a default condition in which the spatial boundaries between the patient room and the corridor are an STC 35 wall, the spatial boundary between patient rooms is an STC 45 wall, and the minimum STC otherwise is 35. It should be maintained that a higher STC indicates a higher ability for the wall cavity to absorb and not transmit sound energy through itself. These studies were undertaken with default material assignments on all surfaces in each space as well as closed doors between the patient room and the corridor. The y-axis of these plots are kept at a fixed range across all material iteration studies so that the results may be compared at a glance - an ideal iteration will feature a change of approximately 20 to 30 decibels, indicating the qualitative change from a running dishwasher in the corridor to the quiet hum of a refrigerator or the moderate rainfall in the patient room to a quiet library.

From these plots, it is clear that the change in wall cavity composition does not bring the acoustic behavior of the patient ward closer to the desired acoustic change of 20 to 30 decibels. From the model

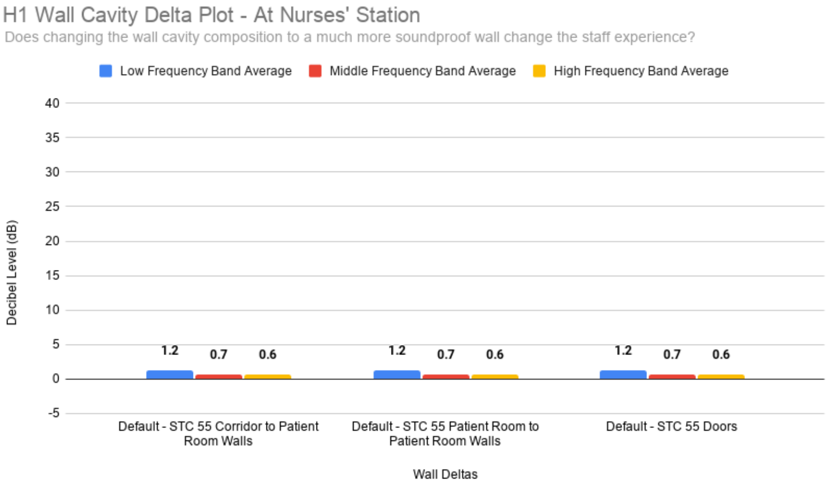

Figure 3.17: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Nurses' Station in Hospital 1

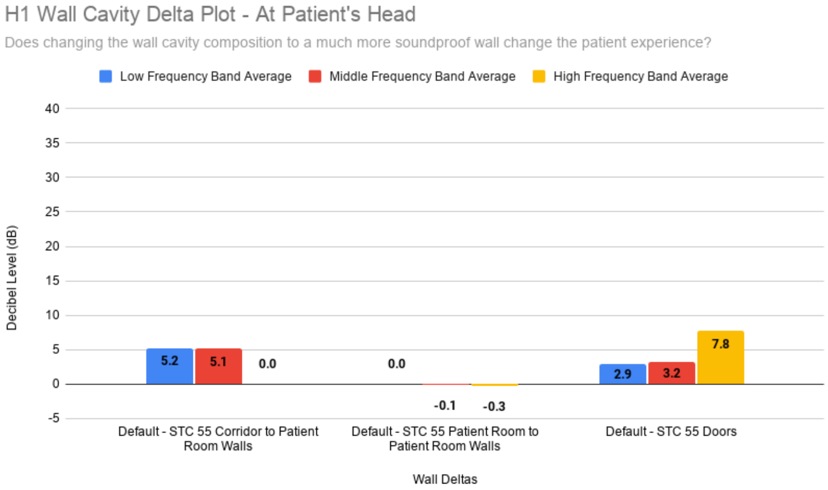

Figure 3.18: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Patient Head in Hospital 1

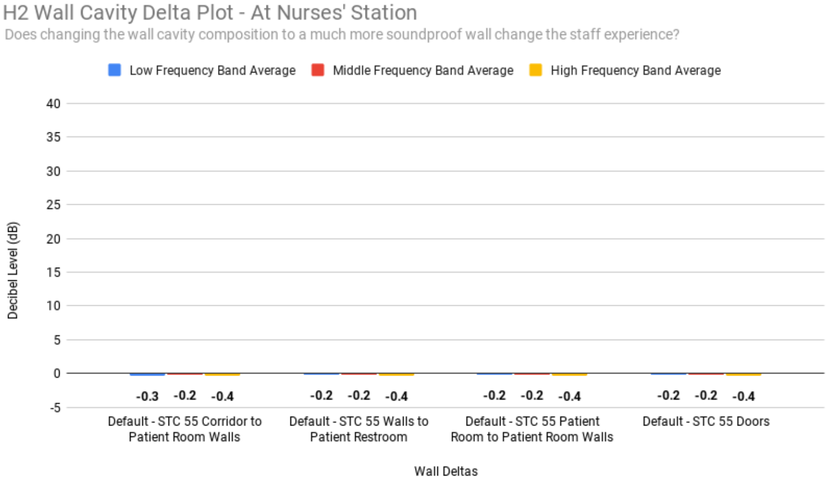

Figure 3.19: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Nurses' Station in Hospital 2

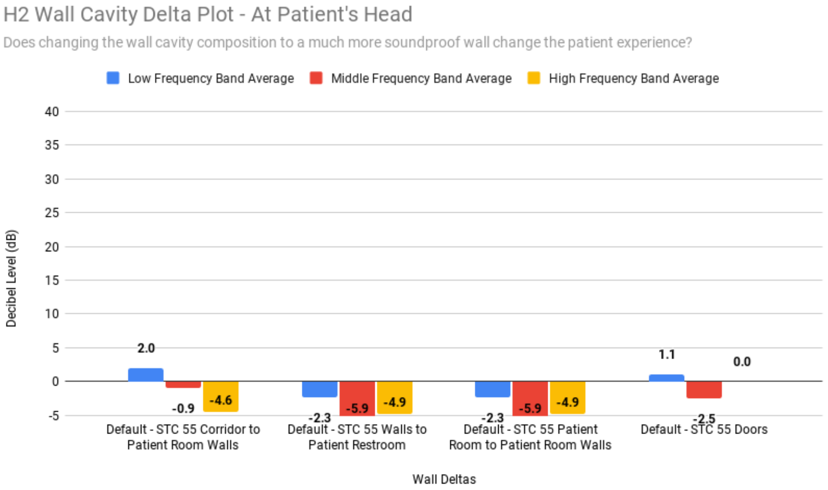

Figure 3.20: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Patient Head in Hospital 2

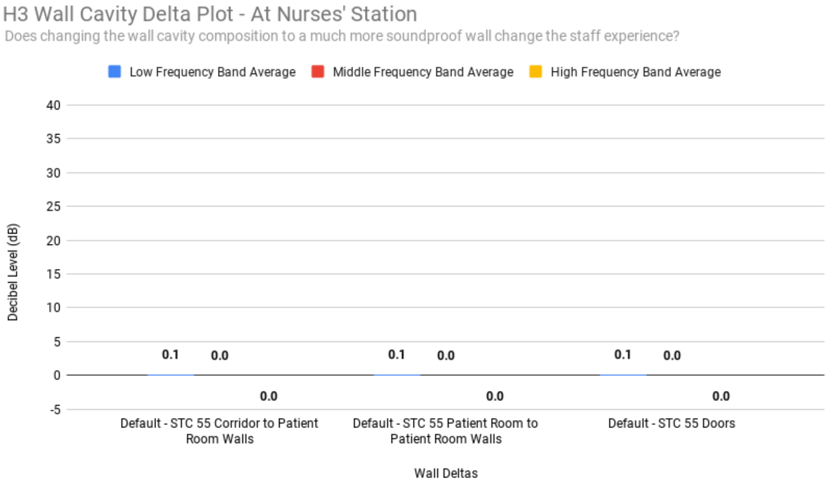

Figure 3.21: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Nurses' Station in Hospital 3

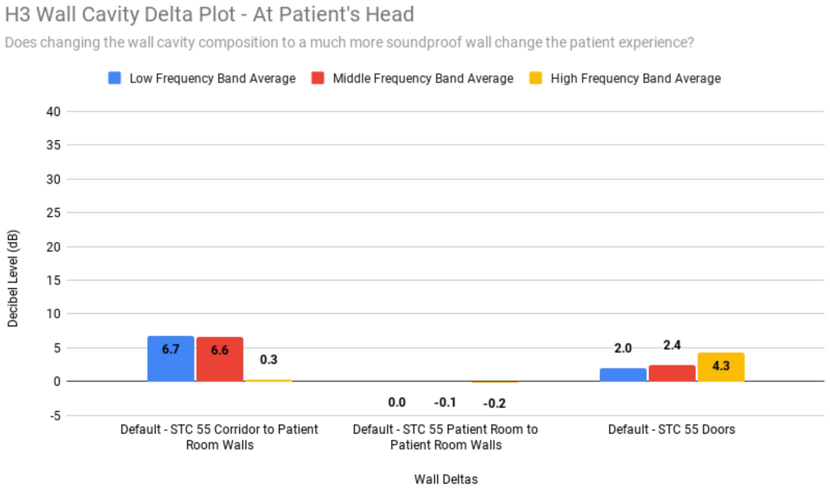

Figure 3.22: A Delta Plot of the Resultant Decibel Change Between the Default Wall Assembly Specification and Higher Performing Wall Assemblies at the Patient Head in Hospital 3

used, then, it appears that the wall cavity is not the place to invest resources if a larger acoustic change is desired.

3.3.4 Results from Wall Surface Iteration Studies

Now to address material change on specific surfaces within the model in each layout studied. In these studies, the default material is a 1/2" thick gypsum board and the doors between the corridor and the patient room are kept open to simulate the behavioral condition discussed in Section 2.18 of Chapter 1. On the wall, it appears that there are materials that make significant change in the resultant acoustic behavior when used as a finishing material:

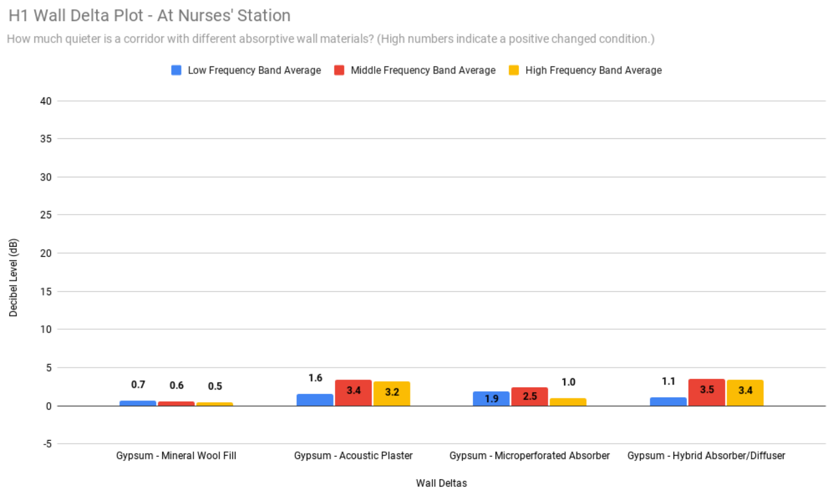

Figure 3.23: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Nurses' Station in Hospital 1

From this information, it becomes clear that the patient experience is greatly improved through the use of an acoustic plaster or

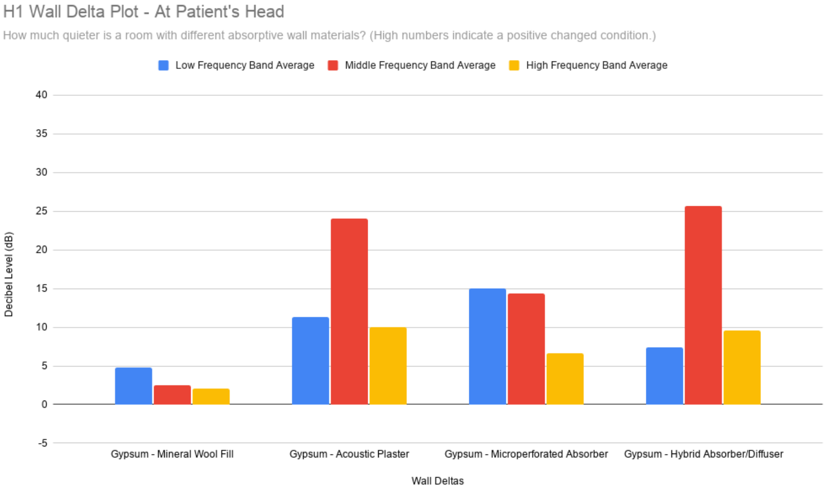

Figure 3.24: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Patient Head in Hospital 1

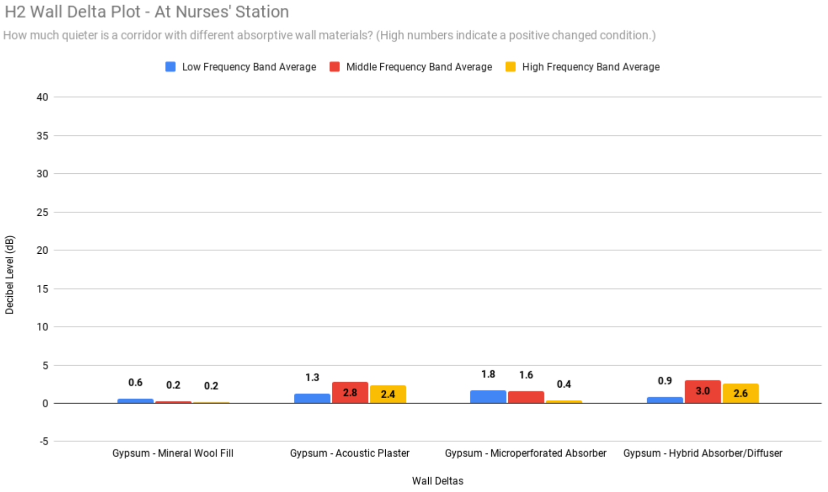

Figure 3.25: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Nurses' Station in Hospital 2

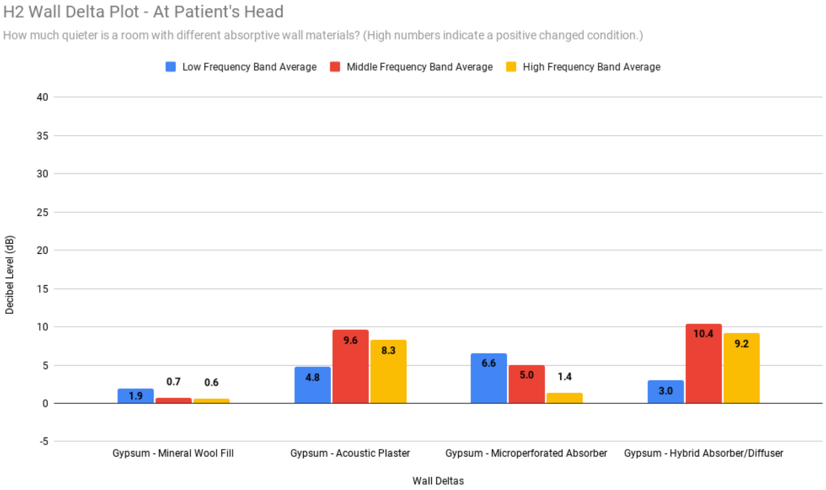

Figure 3.26: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Patient Head in Hospital 2

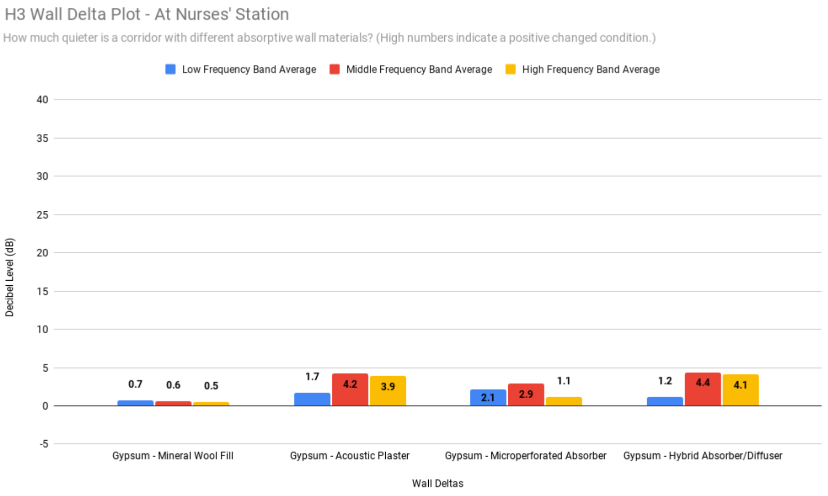

Figure 3.27: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Nurses' Station in Hospital 3

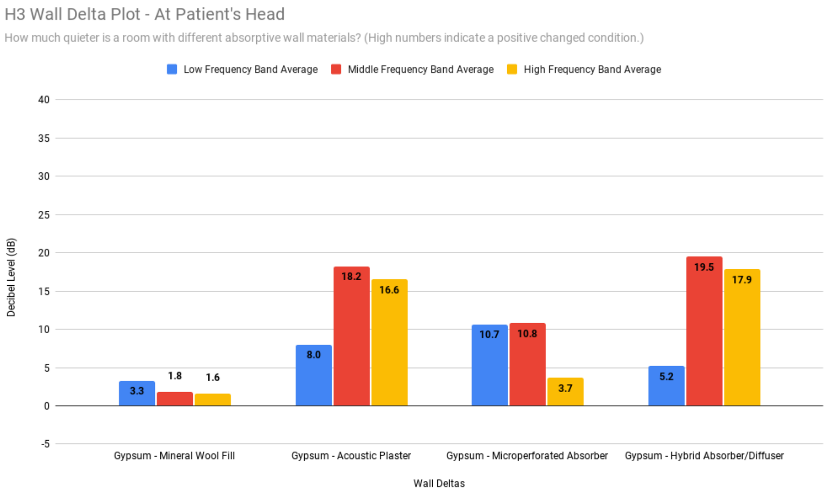

Figure 3.28: A Delta Plot of the Resultant Decibel Change Between the Default Wall Material and Each Wall Material Studied at the Patient Head in Hospital 3

the hybrid absorber/diffuser on the walls of the patient ward. It should be noted, however, that the comparative price between those two materials is great as exemplified in Figure 2.15. For this reason, this resarch recommends the use of a 40 mm acoustic plaster in place of 1/2" gypsum board throughout the patient ward for the resultant acoustic benefit to the patient when using the acoustic plaster and the comparative cost between the two alternatives. It should be noted, though, that the hospital staff do not experience this benefit when the acoustic plaster is specified; acoustic changes in the corridor may stem from the use of a different material or from a separate kind of study regarding behavioral changes of people working in the corridor. Research into this is provided in *Better Sleep Experience for the Critically Ill: A Comprehensive Strategy for Designing Hospital Soundscapes* [9] as well as the conclusions of *Evaluating Hospital Soundscapes to Improve Patient Experience* [14]. Still, the other surfaces examined in this study must be observed to determine if the ceiling truly is the first place to invest limited resources when looking to improve patient ward acoustics.

3.3.5 Results from Ceiling Surface Iteration Studies

Similar to the wall surface testing, the default material assigned to the ceiling is a plasterboard tile and doors between the corridor and the patient room are once again kept open. As it turns out, the ceiling material iterations do not produce similar results to the wall surface material iterations:

From these results, it is demonstrated that a change in ceiling material does not result in as significant of change in the patient's acoustic experience as compared to the change in wall surface material but a more absorptive ceiling material does reduce decibel levels more effectively in the corridor of the patient ward than a change in wall surface material. As the results in this data is relatively comparable, it is the recommendation of this research that if a ceiling material change is desired, changing the ceiling material should come down to an economic difference. In this research and among the materials

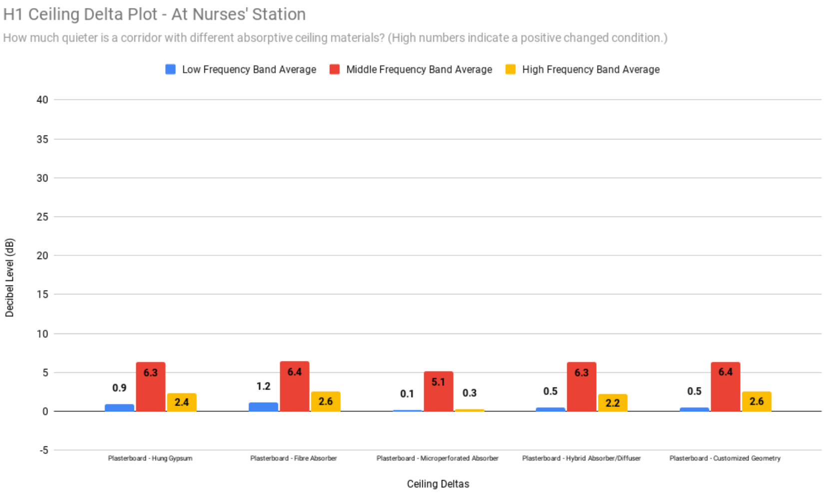

Figure 3.29: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Nurses' Station in Hospital 1

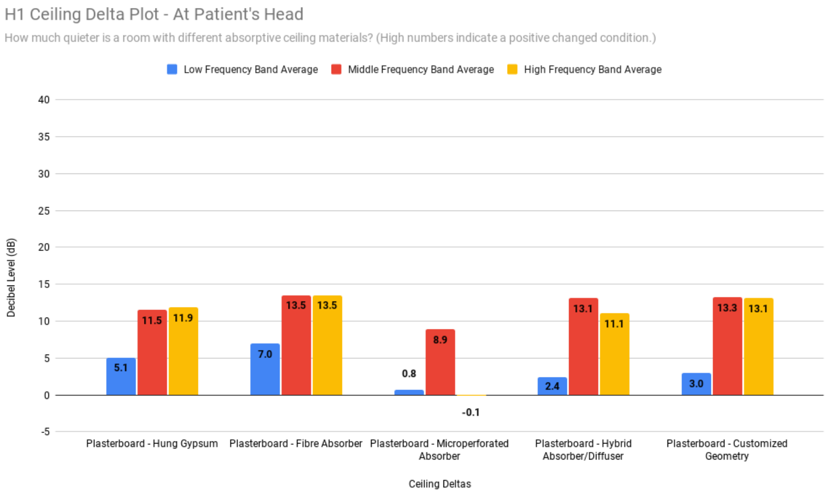

Figure 3.30: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Patient Head in Hospital 1

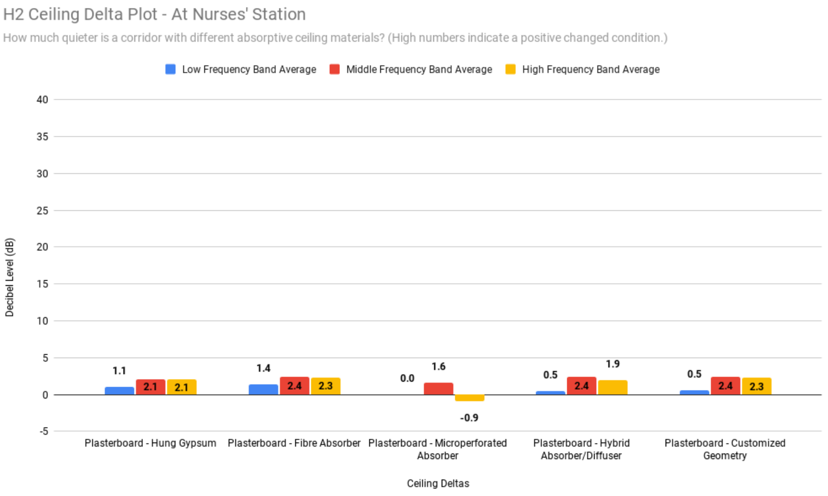

Figure 3.31: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Nurses' Station in Hospital 2

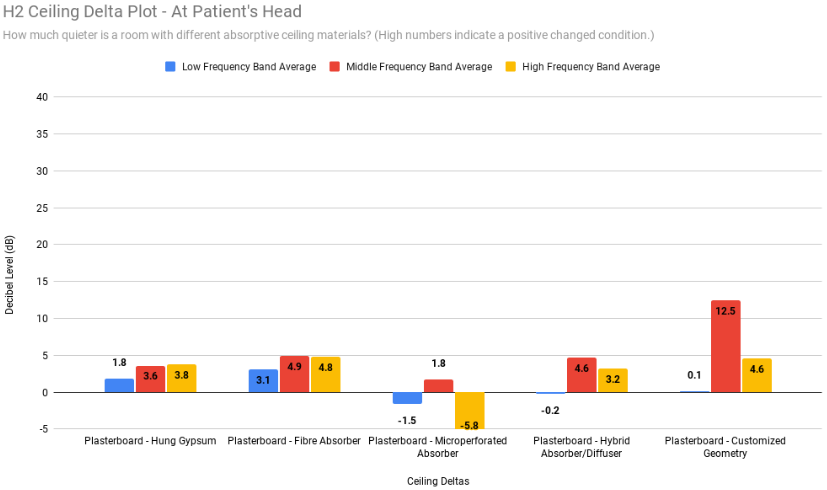

Figure 3.32: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Patient Head in Hospital 2

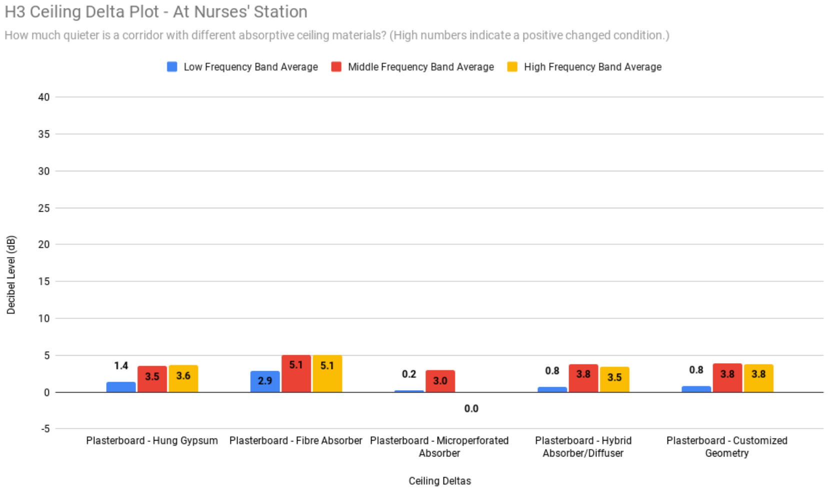

Figure 3.33: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Nurses' Station in Hospital 3

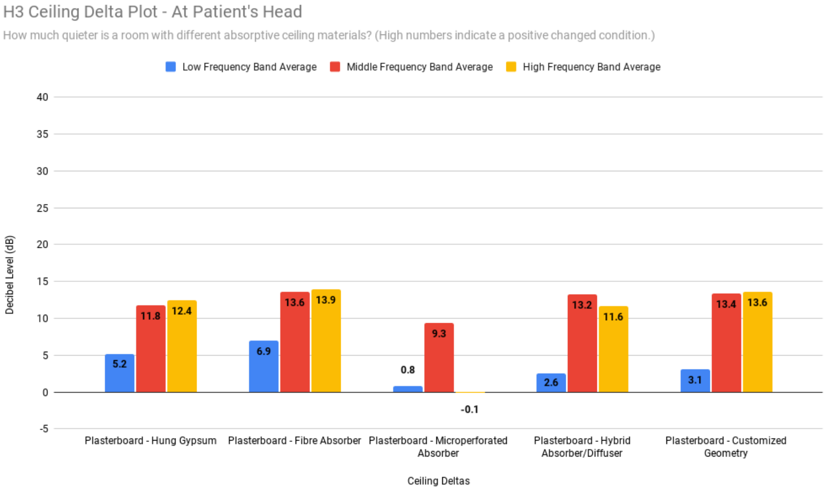

Figure 3.34: A Delta Plot of the Resultant Decibel Change Between the Default Ceiling Material and Each Ceiling Material Studied at the Patient Head in Hospital 3

studied, the least expensive material studied is the hung perforated gypsum ceiling. From the data shown, it can be demonstrated that between changing wall surface materials or ceiling materials, the first place to invest resources meant for improving the acoustic environment of the patient ward should be the wall surface. Up next are the results from the door iteration studies.

3.3.6 Results from Door Iteration Studies

Changing the door material in patient wards is going to be a key demonstration in depicting the impact of specifying an opaque door or a transparent door on the patient's acoustic comfort. Keeping in mind that hospital staff can be known to keep doors open when visual access to the patient from the nurses' station is desired, the results coming from the use of a closed glass door are of particular importance:

Some very important (and likely predictable) results are coming from these rounds of testing. The finding that the corridor becomes slightly louder (a negative delta plot result) is to be expected as closing the door to the patient room provides another surface in the corridor for sound particles to bounce off of where they would otherwise diffuse into the patient room. As for the patient experience, however, it is found that closing the door between the patient room and the corridor results in a significantly more quiet healing environment. Qualitatively, these results indicate a change from hearing moderate rainfall constantly to healing in an acoustic environment similar to a quiet library. This difference is massive and, through the model used by this study, indicates the possibility of achieving the desired acoustic outcome. Looking at the results, it seems that the glass door performs about as well as the solid wooden door and the hollow wooden door so it is the recommendation of this research that glass doors be specified in patient wards to ensure the visual access between hospital staff and patients is maintained while still providing the patient a desired level of acoustic privacy. Further studies into alternate solutions in providing patients visual and acoustic privacy

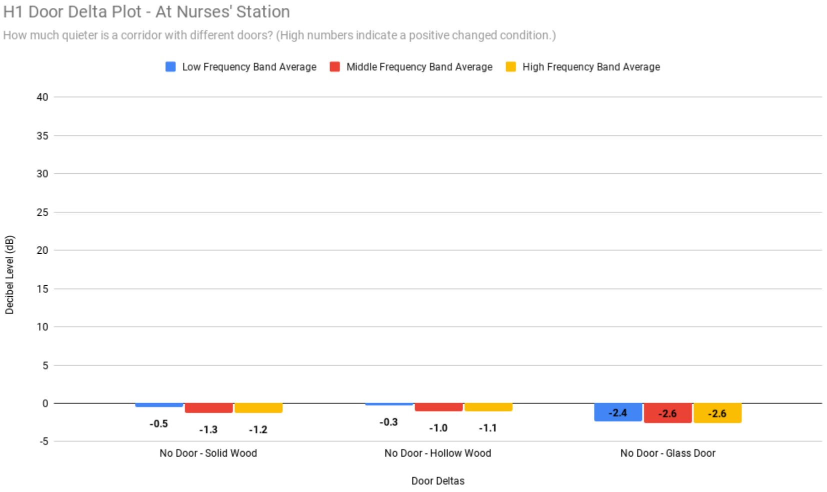

Figure 3.35: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Nurses' Station in Hospital 1

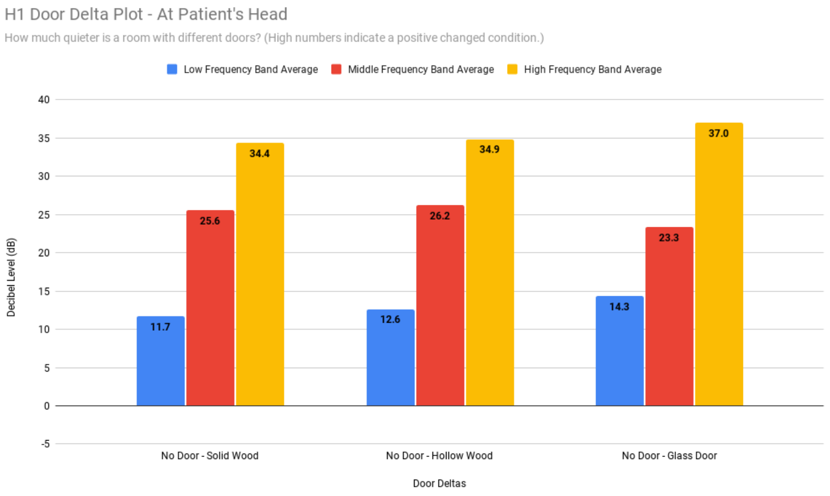

Figure 3.36: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Patient Head in Hospital 1

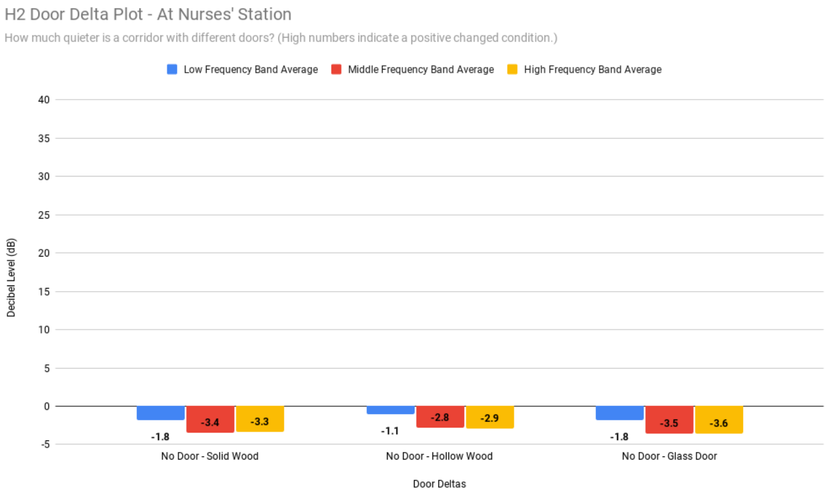

Figure 3.37: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Nurses' Station in Hospital 2

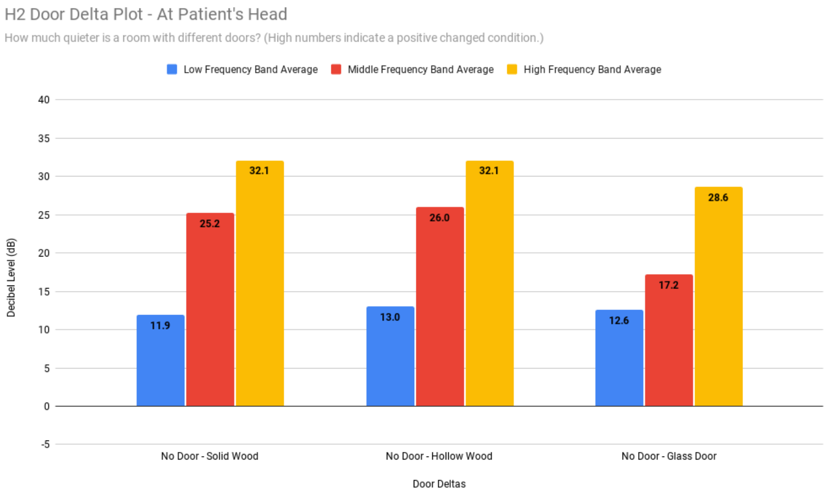

Figure 3.38: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Patient Head in Hospital 2

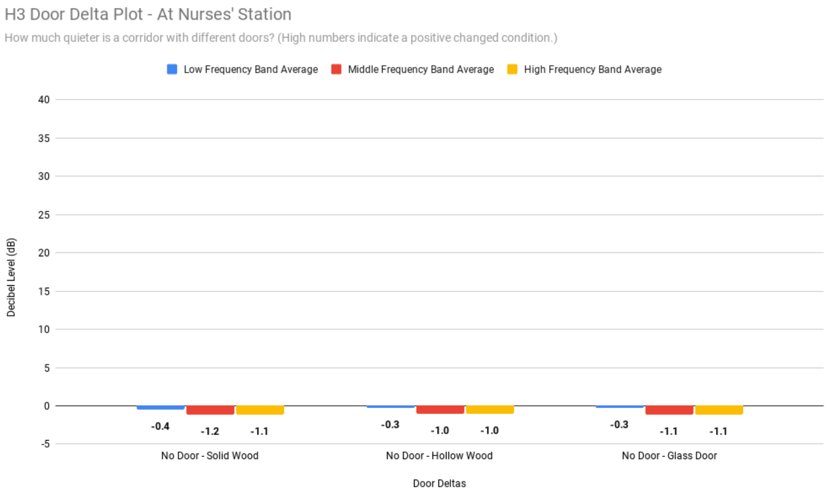

Figure 3.39: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Nurses' Station in Hospital 3

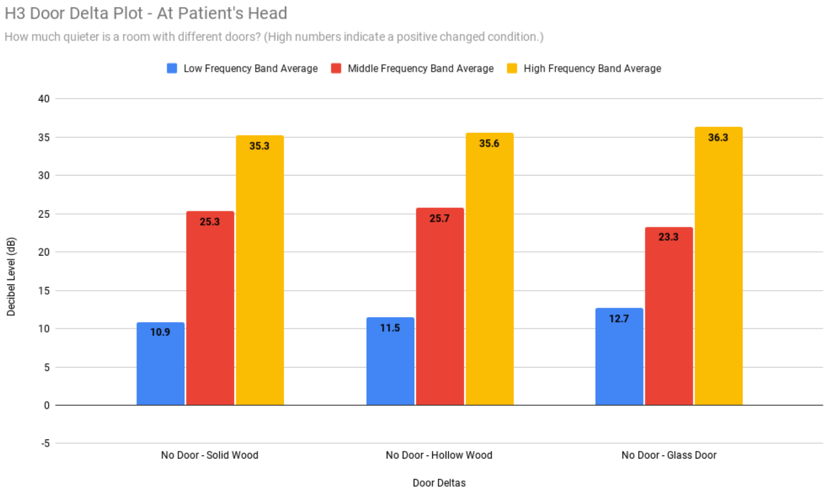

Figure 3.40: A Delta Plot of the Resultant Decibel Change Between Keeping Doors Open and Closing Them at the Patient Head in Hospital 3

is recommended by this research as technological advancements may allow for various methods in maintaining this desired visual access while ensuring the patient ward does not become a panopticon; patient perception of their healing environment is another key health factor to consider in the design process [3].

3.3.7 Results from Percent Material Change Iteration Studies

Given the results of the previous sections, it is important to now consider how much material change is going to result in the desired acoustic outcomes in the patient ward. This testing is asking how little material change is needed in the corridor to ensure the patient ward functions as best as possible for the acoustic health of its occupants. To first answer these questions, material iterations were undertaken in which portions of the surfaces in the corridor of each layout studied were covered by another material as described in Section 2.16.2 in Chapter 2. In the initial round of testing, a portion of the corridor wall is changed from the default material, 1/2" gypsum board, to the 40 mm acoustic plaster as it was found to be the highest-performing and most cost-effective material in the previous rounds of testing. The doors between patient rooms and corridors are also closed in this model.

From this data, with each point representing a separate test and respective percent coverage of the wall in the corridor with the trendline indicating the overall effectiveness of gradual material change - the steeper the line of best fit, the more effective the material is in covering a portion of surface area. In this idealized model, it is shown that there seems to be no rate of diminishing marginal returns from increasing the amount of absorptive material covering the wall surface. Up next is the same type of testing for the absorptive ceiling material found to be most cost-effective for its performance in the previous rounds of testing: the hung perforated gypsum ceiling.

As it turns out, the ceiling data looks very similar to the wall data. Again, there is no point of diminishing marginal returns in this

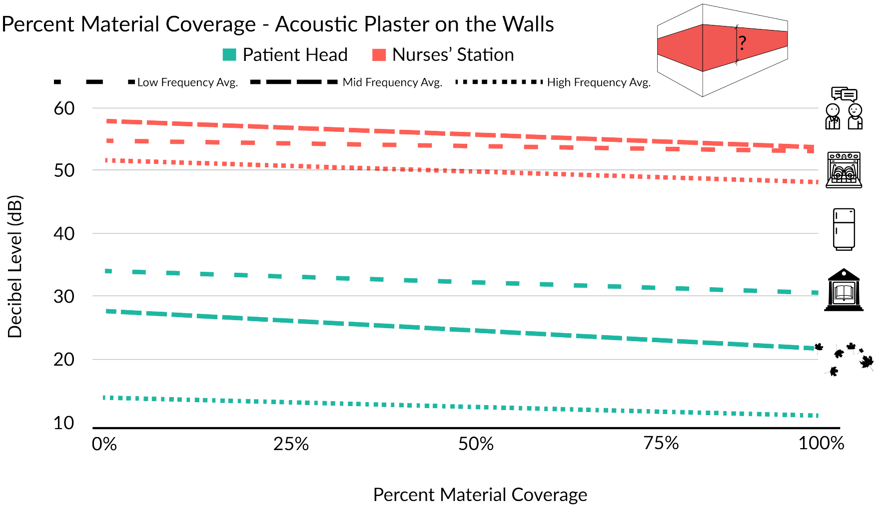

Figure 3.41: A Depiction of the Resultant Decibel Reduction at the Nurses' Stations and Patient Heads in Each Layout Studied as the Wall Becomes More Absorptive

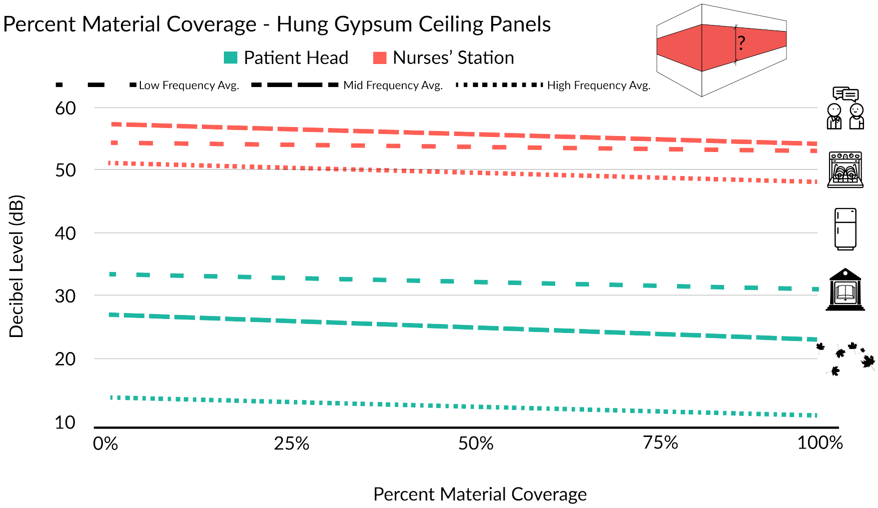

Figure 3.42: A Depiction of the Resultant Decibel Reduction at the Nurses' Stations and Patient Heads in Each Layout Studied as the Ceiling Becomes More Absorptive

idealized model, indicating that the more total coverage of the ceiling with an absorptive material, the quieter the space becomes. Though it is difficult to tell, the line of best fit from Figure 3.41 is more steep, indicating that covering a portion of the wall with an absorptive material is a more effective acoustic choice than covering a portion of the ceiling with an acoustic material when doors are closed in the patient ward. Still, both graphs illustrate something else: once doors are closed in the patient ward, it seems that the maximum amount of acoustic change that can be found for the patient and hospital staff is about five decibels regardless of how much absorptive material is used on the walls or ceiling. This indicates more than the other rounds of testing that the first, most absolutely key decision in the acoustic healthcare design process is the specification of glass doors in the patient ward as it ensures the acoustic privacy of the patient. To reduce the noise level in the corridor, studies outside of material specification may prove to be more beneficial. Next, the results from altering the amount of glass present on the doors separating the patient room and the corridor:

This study demonstrates that replacing the amount of wood on the doors to patient rooms with glass results in a noisier space for both patients and hospital staff. This is predictable as this testing is replacing wood with glass - glass is a more hard, reflective material than wood. Using more glass than wood on a door inherently will make the door surface more reflective. It is likely than there is an optimal amount of glass to be used on these doors that allow hospital staff to maintain visual access to the patient while still keeping as much absorptive material on the door as possible. In the last round of testing, the decibel levels as a result of a combined gradual increase of absorptive walls, absorptive ceilings, and glass on doors is observed:

As is expected, there seems to be no point at which increasing the absorptivity of the space as a whole results in a louder space for patients or hospital staff. It is surprising, however, that even in increasing the total coverage of absorptive materials to 100 percent does result in a significantly quieter space; truly the biggest acoustic change that can be made in the patient ward is ensuring doors are

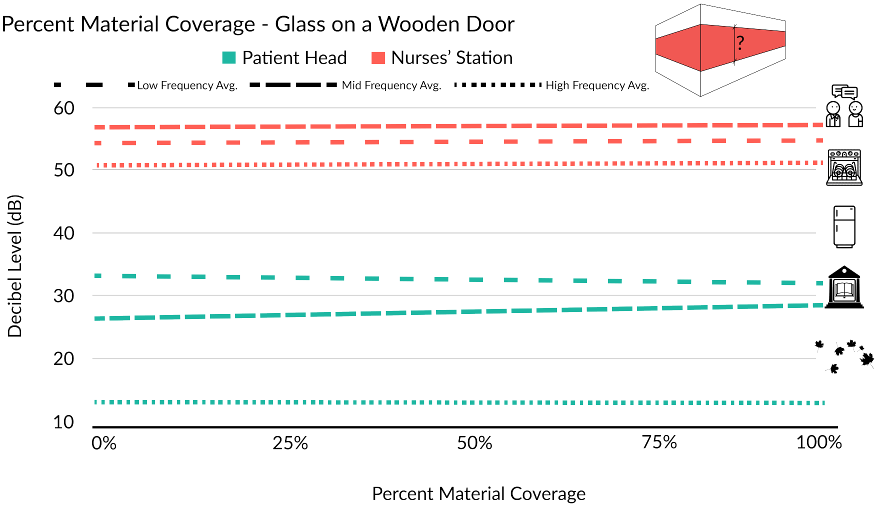

Figure 3.43: A Depiction of the Resultant Decibel Reduction at the Nurses' Stations and Patient Heads in Each Layout Studied as More Glass is Used on the Doors to Patient Rooms

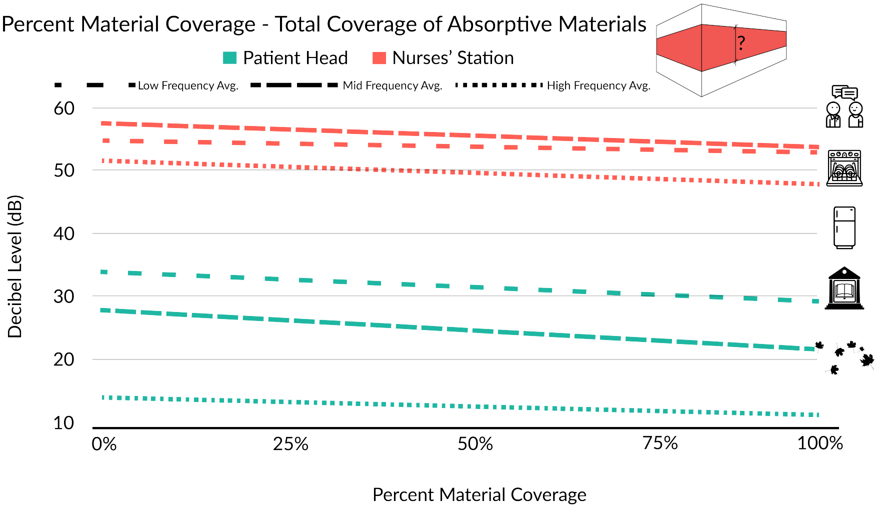

Figure 3.44: A Depiction of the Resultant Decibel Reduction at the Nurses' Stations and Patient Heads in Each Layout Studied as Walls and Ceilings Become More Absorptive and More Glass is Present on the Doors to Patient Rooms

closed between patient rooms and the corridor when designing for the human voice stemming from nurses' stations in the corridor. From that point onward, it seems that the application of 40 mm acoustic plaster on wall surfaces instead of gypsum board throughout the ward will result in a quieter space. Though changing ceiling surface materials will also result in a quieter corridor, the patient experience is not impacted as heavily as when wall surfaces are changed to the acoustic plaster. As a final look at the material effectiveness studies, below is information regarding their respective prices from low to high as well as information regarding the impact of changing all surfaces to their most absorptive iteration:

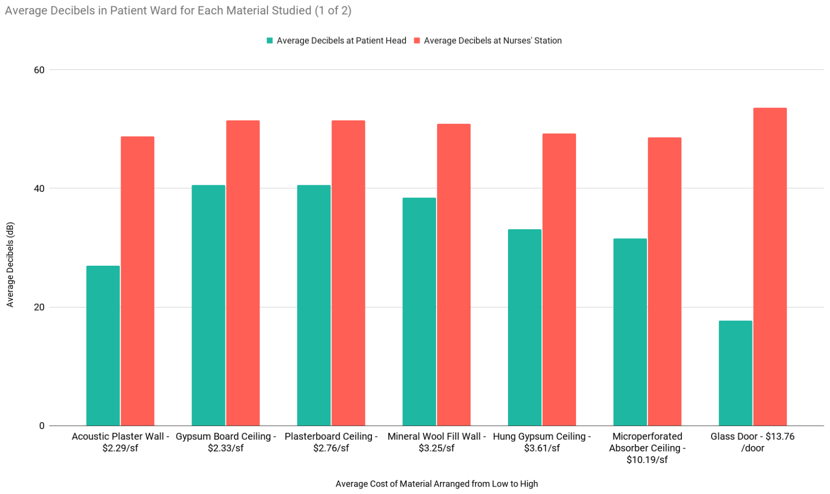

Figure 3.45: An Average of Decibel Levels from Each Layout Studied When Each Material is Applied on All of its Respective Surface as Compared to its Price (1 of 2)

These results are placed to order the materials from overall price, low to high, based on an average of each material's low and high price estimate.

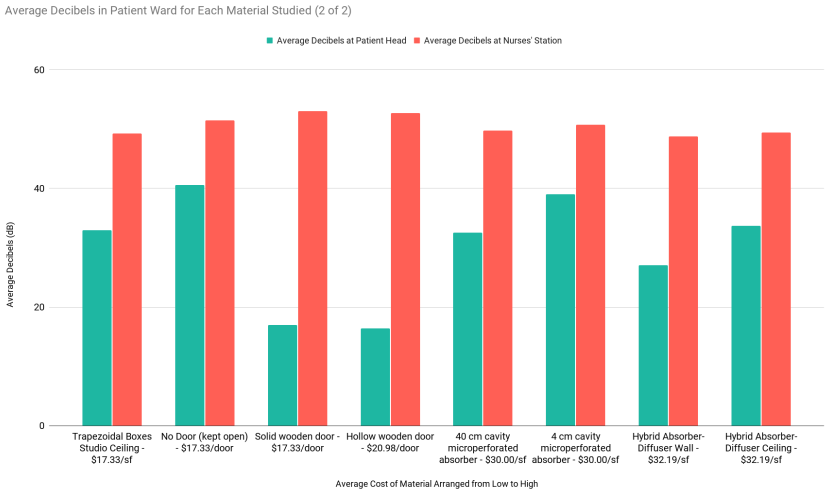

Figure 3.46: An Average of Decibel Levels from Each Layout Studied When Each Material is Applied on All of its Respective Surface as Compared to its Price (2 of 2)

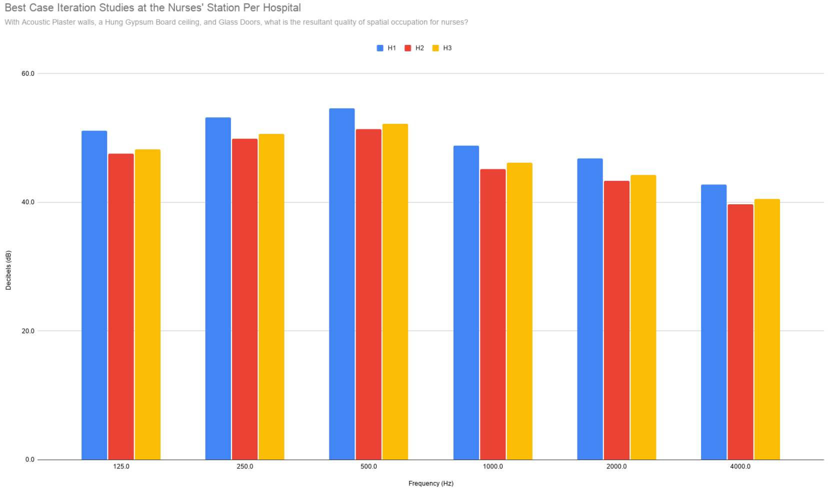

Figure 3.47: A Depiction of the Resultant Decibel Levels in Each Layout Iteration Studied at the Nurses' Station When All Highest-Performing Materials are Used

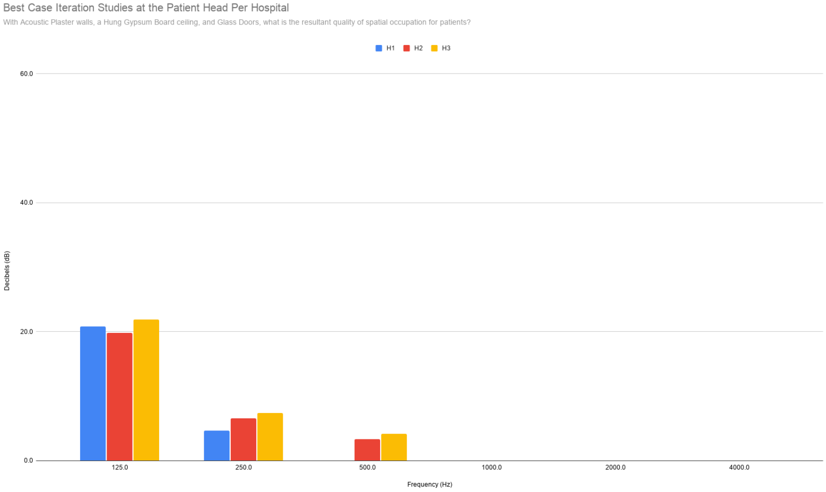

Figure 3.48: A Depiction of the Resultant Decibel Levels in Each Layout Iteration Studied at the Patient Head When All Highest-Performing Materials are Used

These results demonstrate that the use of the highest-performing acoustic materials on all surfaces create a corridor that is not significantly quieter than the base condition but creates a patient room that is very acoustically dead. This space would be unnerving for the patient to occupy as sounds would be fully absorbed by the surface materials in some frequencies and any reflected sounds would appear empty or incomplete. Though this is an interesting acoustic phenomenon, the patient's healing environment should be restorative and allow hospital staff to operate to the best of their ability.

3.4 Sound Pressure Testing Results

This section deals with the results coming from the finite element acoustic method for pressure acoustics simulations. These results indicate the pressure distribution in each patient room studied as a factor of the patient room geometry and the resultant distribution of perceptual loudness of sound frequencies. Essentially, this data depicts resonant frequencies that are created as a result of spatial geometry and the impact the acoustics of the room has upon the patient's experience of their healing environment. If there is a low frequency that appears to have a high resultant sound pressure level, this indicates that air handling systems or other mechanical systems that emit low frequency sounds should be studied to ensure their noises are not amplified for the patient. Below are the pressure acoustic testing results for each patient room studied:

Already between these two graphs, one can tell the difference a small change in the shape of a room makes in determining the resultant sound pressure levels at a point in space. Continuing on with the other spaces studied:

This data collected onto one graph illustrates the resultant spread of patient experiences across all patient room iterations studied:

And that same graph in terms of absolute value is as follows:

From this information, it initially appears that Hospital 2's default configuration results in a much more loud space across all frequency bands studied but this may be due to an error in testing or an error

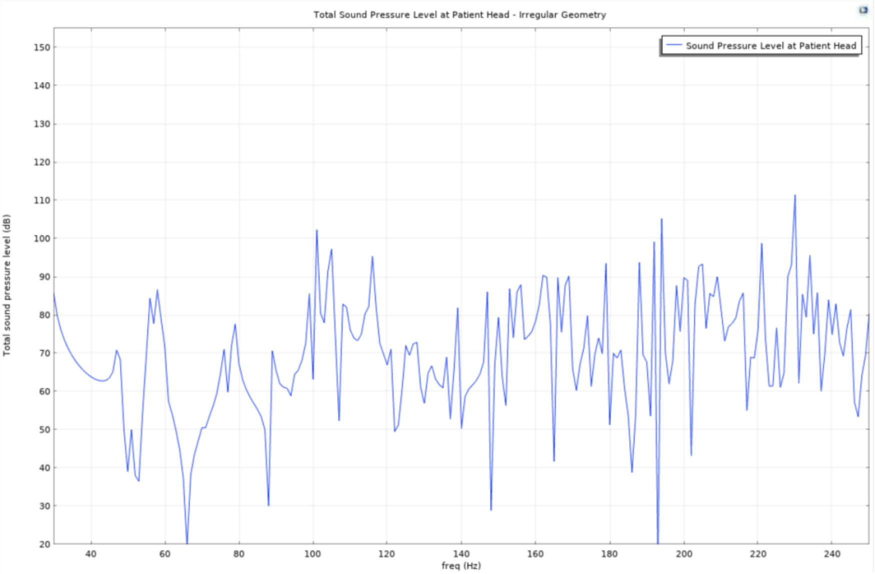

Figure 3.49: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Irregular Room in Hospital 1

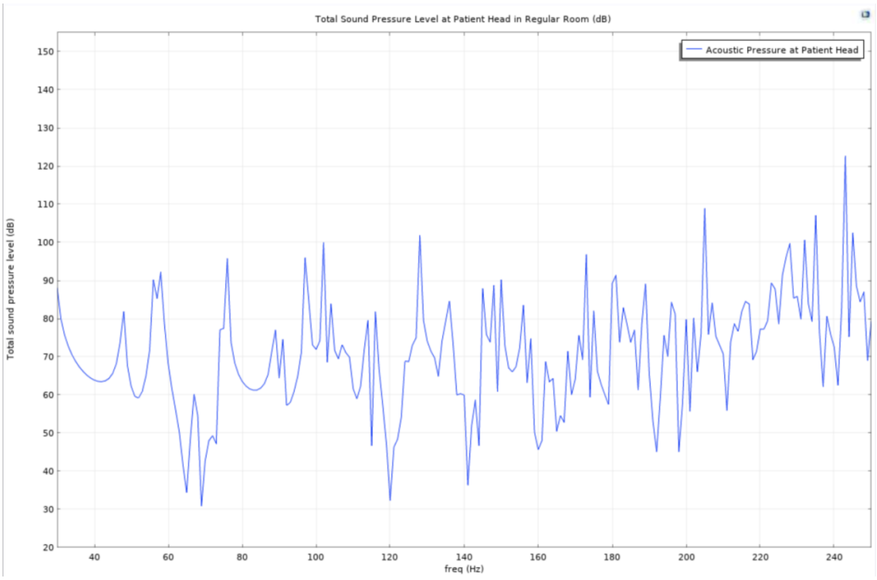

Figure 3.50: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Rectilinear Room in Hospital 1

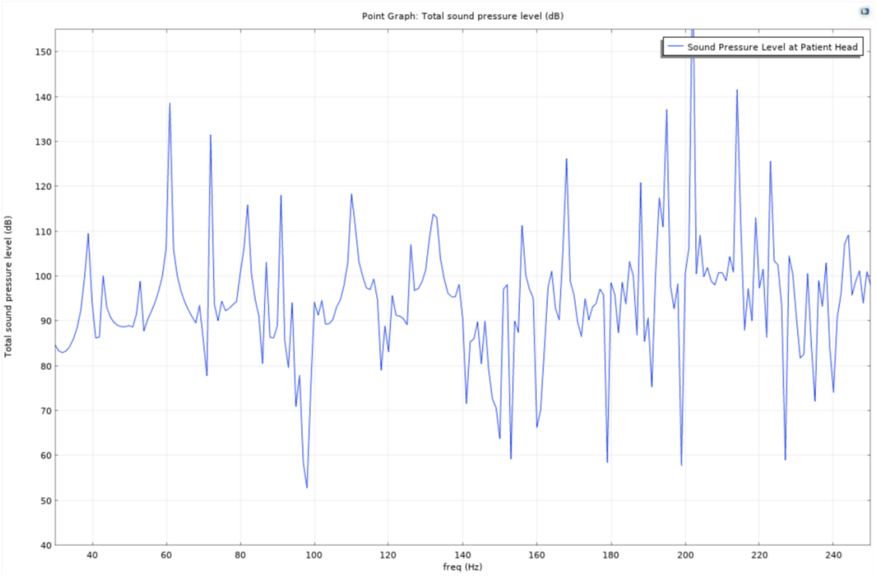

Figure 3.51: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Default Patient Room Configuration in Hospital 2

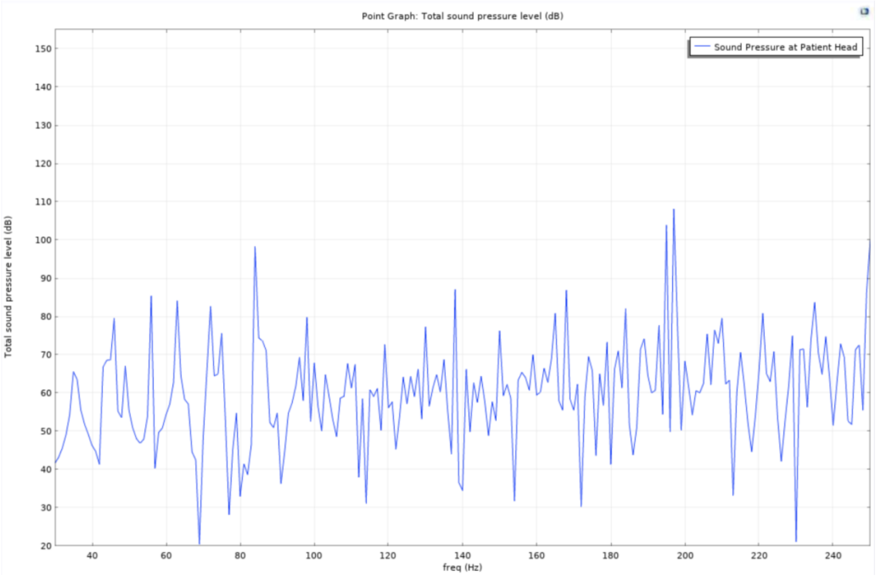

Figure 3.52: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Concave Walls Patient Room Configuration in Hospital 2

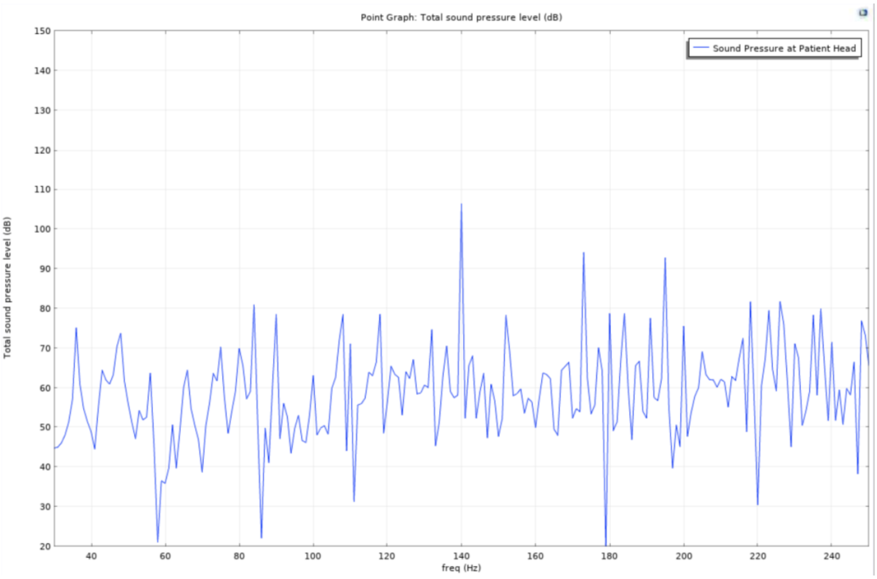

Figure 3.53: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Max Ceiling Patient Room Configuration in Hospital 2

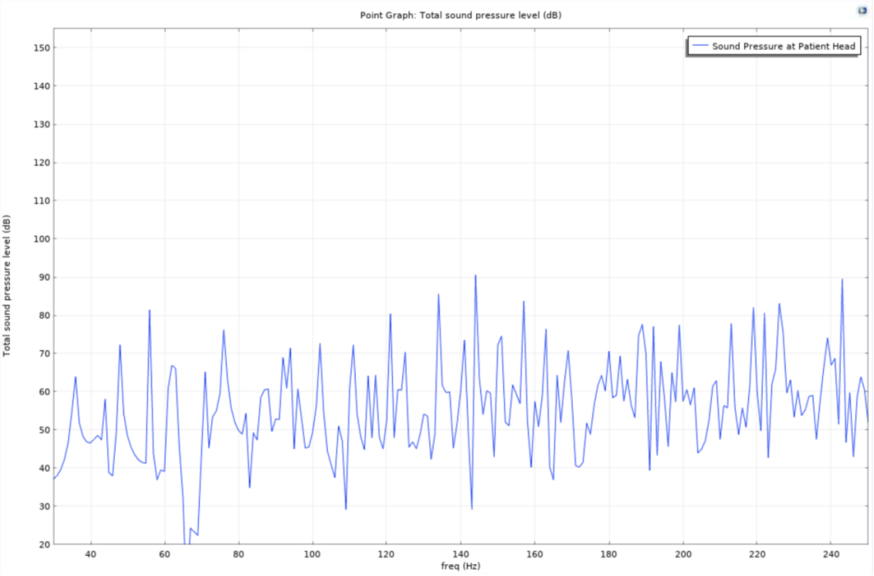

Figure 3.54: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in the Sawtooth Patient Room Configuration in Hospital 2

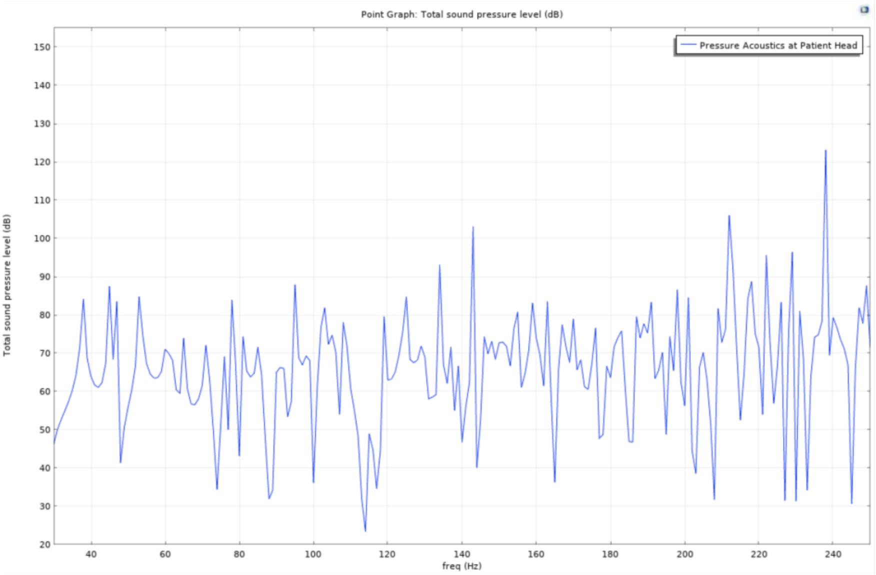

Figure 3.55: The Spread of Frequency Versus Sound Pressure Level at the Patient Head in Hospital 3

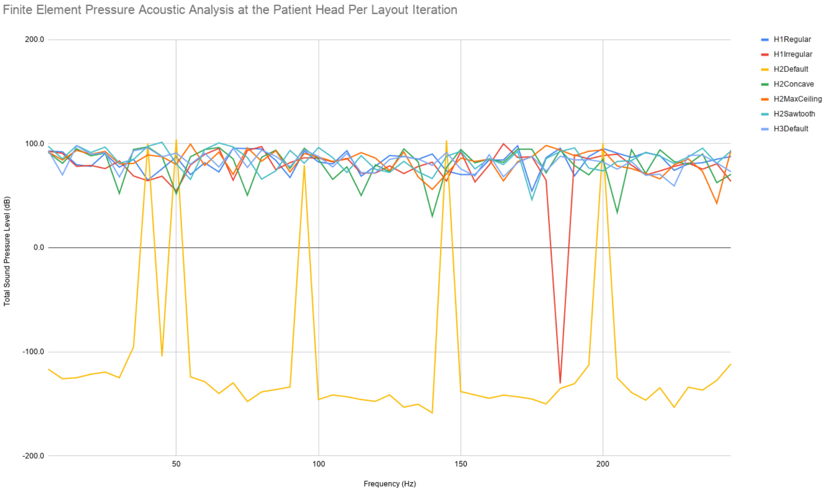

Figure 3.56: Finite Element Pressure Acoustic Analysis at the PatientHead Per Layout Iteration

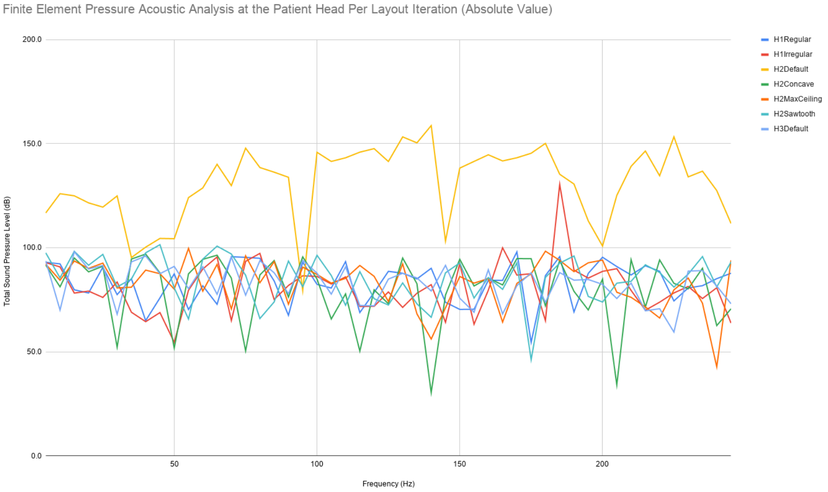

Figure 3.57: Finite Element Pressure Acoustic Analysis at the PatientHead Per Layout Iteration - Absolute Values

present in the meshing of the model. On top of that, it seems that the Concave Walls configuration of Hospital 2 may result in an overall quieter space purely from the way sound pressure is distributed in the space. Further study is likely needed to understand the implications of these results and determine if any recommendations may be put forth in the relationship between the spatial form of the patient room and sound pressure distribution. Ultimately, there is still a great amount of information that can be gathered through this method of testing that can inform the way patient rooms impact the resultant acoustic experience and healing process.

Chapter 4

Conclusions and Future Research

4.1 Conclusions

Sound is an inescapable aspect of built space; to work without consideration for the effect room form has upon its inhabitants is a failure of the built environment when the people inhabiting that space have little to no choice in the matter and need that space to be as welcoming as possible. This research began with a frustration in the way that abundant noise in the built environment impedes the intended use of architectural spaces. There are many key decisions to be made throughout the design process - so many that, when faced with consultations from structural engineers, mechanical engineers, landscape architects, and acousticians, oftentimes priorities must be shifted such that some recommended best practices fall through the cracks or only minimum requirements are met. This research has demonstrated that, through an understanding of the way acousticians design patient wards and set forth their recommendations, the acoustic intent of spatial occupation may serve to reinforce the societal function of the typology and add to the argument being set forth to the client on material use, spatial layout, and geometric form. As architects, it is the duty of the design team to work with the client and put forth the most realized idea of the building being developed; this building must serve society to the best of its ability and fulfil its function for at least the next fifty years into the future. Through understanding why acoustics matters and how its principles may be applied to better serve society, the architect can ensure their designs represent the culmination of their team's ability to understand how space functions as a physical object and present that understanding to their client. It has been proven in this thesis that hospitals are becoming noisier each year and that this overabundance of noise is a detriment to both patients and hospital staff in the patient ward. In understanding the acoustic principles employed by consultants in the building design process, these detrimental qualities of space may be avoided and alternatives may be explored that better answer the question of how the patient ward should function. Through the use of simulation tools such as COMSOL Multiphysics 5.6, an understanding of key acoustic equations such as Sabine's Equation, and a curiosity for how interdisciplinary practice can inform architectural design, a greater respect and appreciation for acoustic design methods can develop and strengthen the conversations held in the construction process. In this research alone, it has been demonstrated that the use of acoustic tools in the spatial design process lead to several interesting findings: the impact of keeping doors open in the patient ward, for starters, has an immensely detrimental impact upon the quality of the patient's sonic environment. If the patient is to recover in peace while hospital staff maintain visual access to the patient from the nurses' station, the model used in this research demonstrates that glass doors should be implemented instead of opaque doors. There is also likely an ideal amount of glass on the surface of the door that allows for visual access to the patient while still keeping the surface of the door as acoustically absorptive as possible. From that point onward, further acoustic recommendations set forth through the use of this research model are to use acoustic plaster instead of gypsum board throughout the patient ward wherever possible to set forth a higher mode of acoustic performance in the patient ward. Beyond that, study into the overall absorption of ward spaces will demonstrate a correlation between surface area, volume, and material absorption to inform the way that spatial design impacts the resultant acoustic behavior of space. Using this method to iterate layout and geometric form will be a key vein of future research. Further findings from this study indicate the way sound pressure levels are also impacted by spatial form yet further study into these relationships is necessary to understand the depth of these relationships and if any specific recommendations may be put forth in the context of the patient ward. More than anything, this process and its results demonstrate that this type of model and mode of simulations can assist designers in understanding the relationship between material combinations, layouts, geometric forms, and boundary compositions to better reach desired acoustic outcomes.

4.2 Future Research

From the findings of this study, recommendations into future avenues of research have also arisen. For starters, it should be stated that any efforts to replicate the results found with the model used would be greatly appreciated; the field of hospital acoustics is limited in its reach and application within the built environment so any additional research should stand as a value to the community as a whole. From that point onward, studies into other hospital wards can serve the typology as a whole in understanding the way spatial form impacts the healing process. Psychoacoustic analysis would also be beneficial and would serve as an added bonus to the research provided by this study. Though the research of this thesis has been primarily quantitative, much of the built environment operates within the realm of qualitative understanding and research into the way patients and hospital staff perceive their space could serve as an added impetus for change within the typology. The use of alternative simulation tools could also be a benefit to the findings of this research, demonstrating the strength or weakness of the findings shown within this thesis and likely disseminating knowledge of the tools available for use within the realm of spatial design. Beyond that, further layout, geometric, and material iterations outside those explored within the scope of this research can only bolster the understanding of the sonic behavior of the patient ward or other simulated spaces to better inform healthcare design practices and practices outside healthcare design as well. Lastly, any efforts to bring the idealized condition of the model presented in this research to a more realistic condition, whether through further specification of acoustic sources, spatial boundaries, material absorption spectra, etc. can serve as a benefit to the understanding of the way sound behaves in real space. It is the belief of this research that any effort to promote interdisciplinary thinking within the built environment and elsewhere is sure to be a benefit, furthering understanding between individuals and bringing the goals of society as a whole closer to fruition.

Appendix A

Appendix

A.1 Schroeder Frequency Graphs

A.2 Absorption Coefficients for Each Material Studied

A.3 Sound Transmission Class Values for Each Cavity Studied

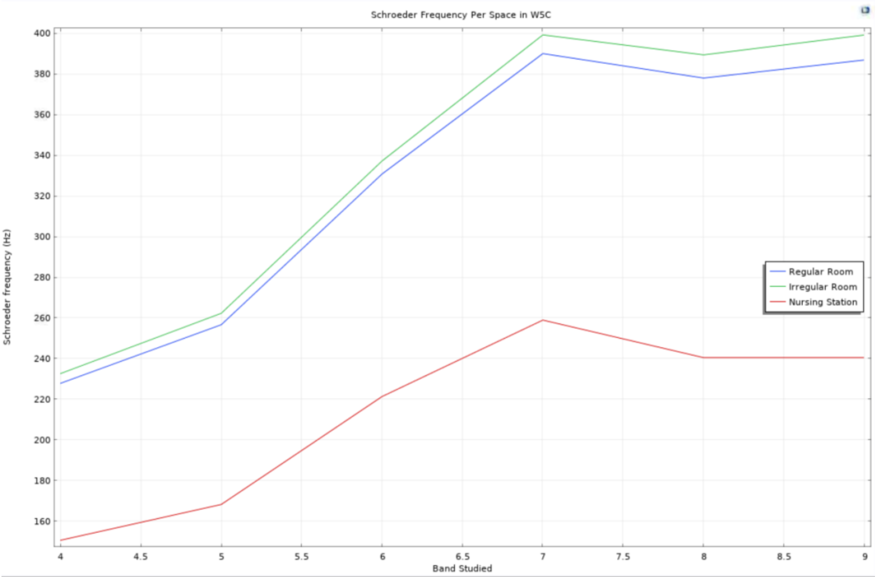

Figure A.1: A Demonstration of the Schroeder Frequencies Observed in the Corridor, Regular Room, and Irregular Room in H1 Per Center Octave Frequency Band Studied

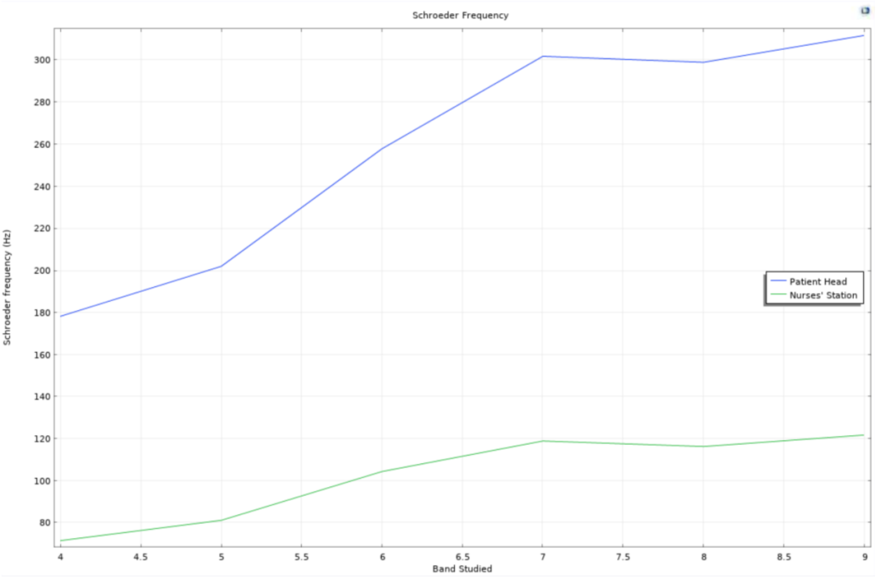

Figure A.2: A Demonstration of the Schroeder Frequencies Observed in the Corridor and Patient Room in the Default Layout of H2 Per Center Octave Frequency Band Studied

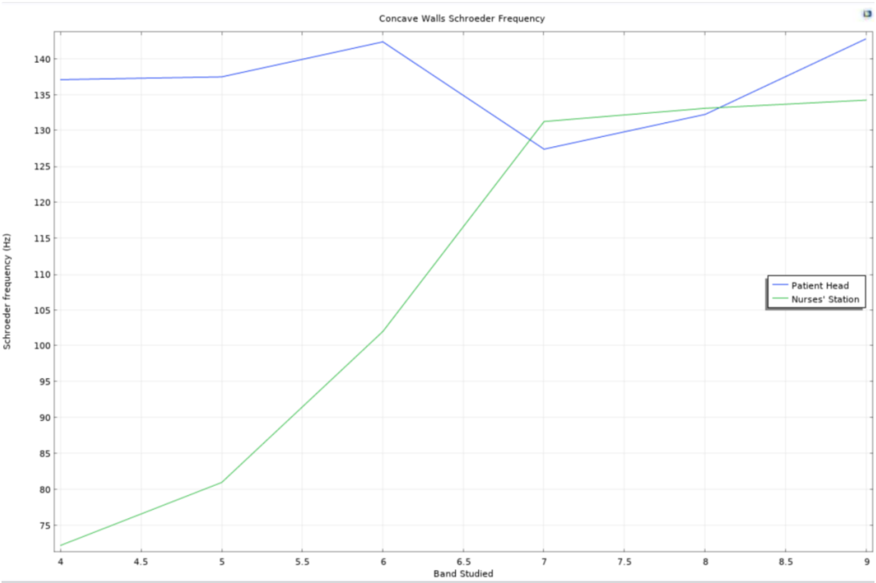

Figure A.3: A Demonstration of the Schroeder Frequencies Observed in the Corridor and Patient Room in the Concave Walls Layout of H2 Per Center Octave Frequency Band Studied

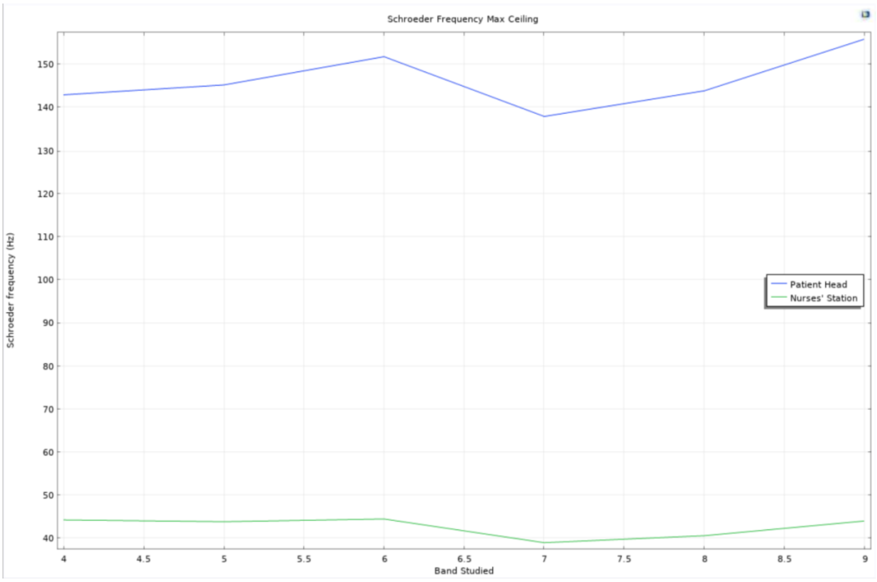

Figure A.4: A Demonstration of the Schroeder Frequencies Observed in the Corridor and Patient Room in the Max Ceiling Layout of H2 Per Center Octave Frequency Band Studied

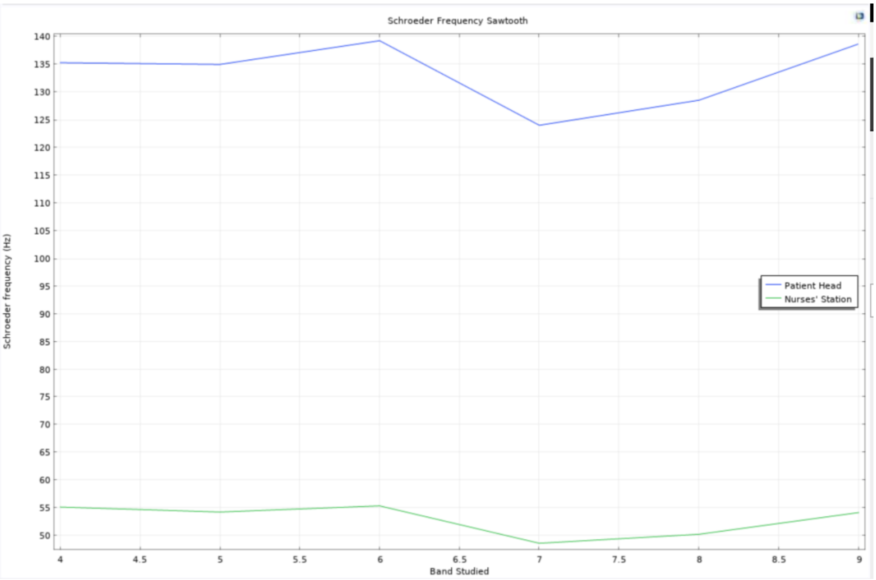

Figure A.5: A Demonstration of the Schroeder Frequencies Observed in the Corridor and Patient Room in the Sawtooth Layout of H2 Per Center Octave Frequency Band Studied

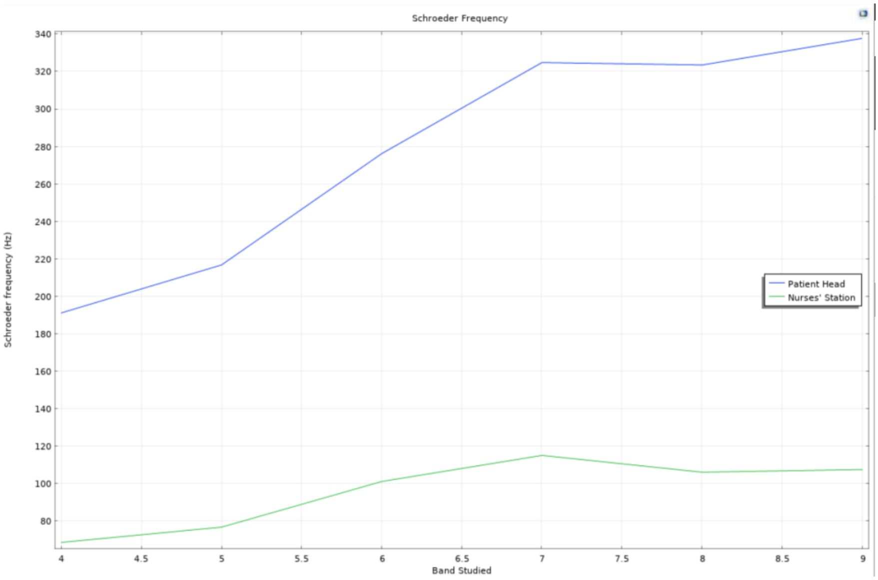

Figure A.6: A Demonstration of the Schroeder Frequencies Observed in the Corridor and Patient Room in H3 Per Center Octave Frequency Band Studied

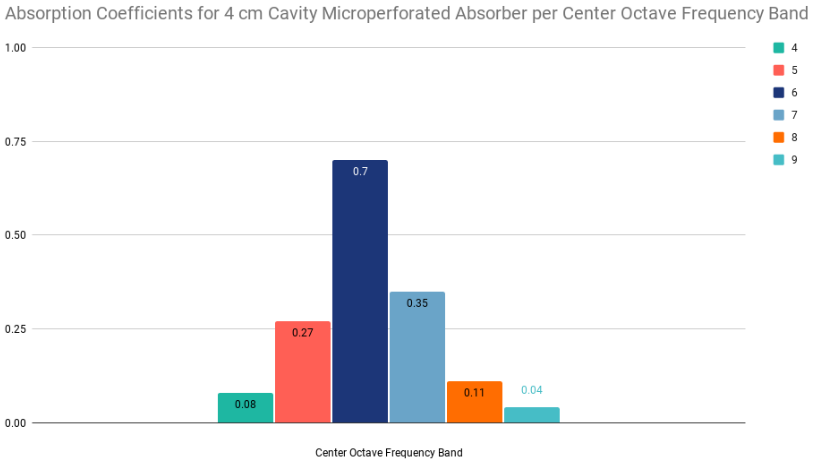

Figure A.7: Absorption Coefficient Values for the 4 cm Cavity Microperforated Absorber Across Center Octave Frequency Bands

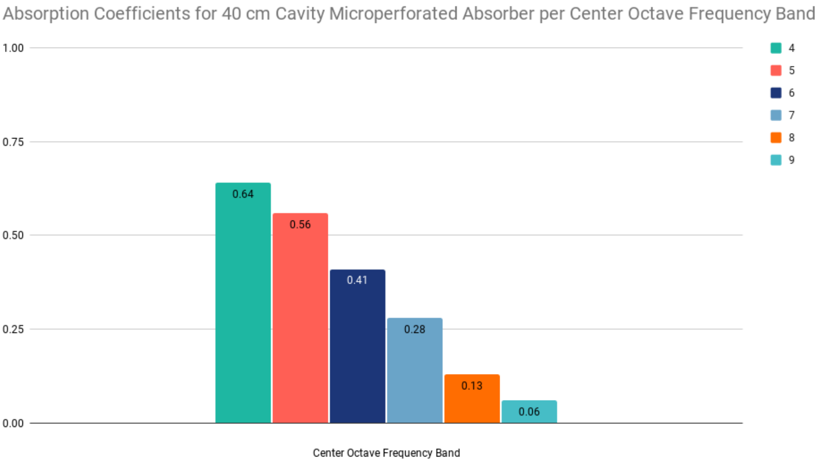

Figure A.8: Absorption Coefficient Values for the 40 cm Cavity Microperforated Absorber Across Center Octave Frequency Bands

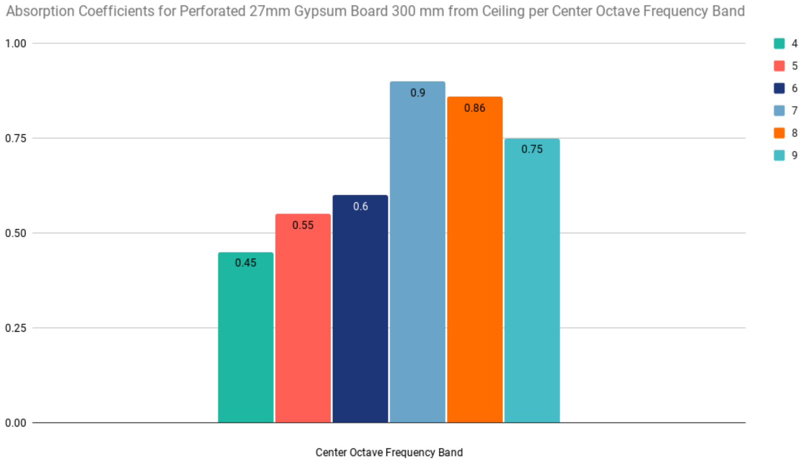

Figure A.9: Absorption Coefficient Values for the Perforated Gypsum Board Hung 300 mm from the Ceiling Across Center Octave Frequency Bands

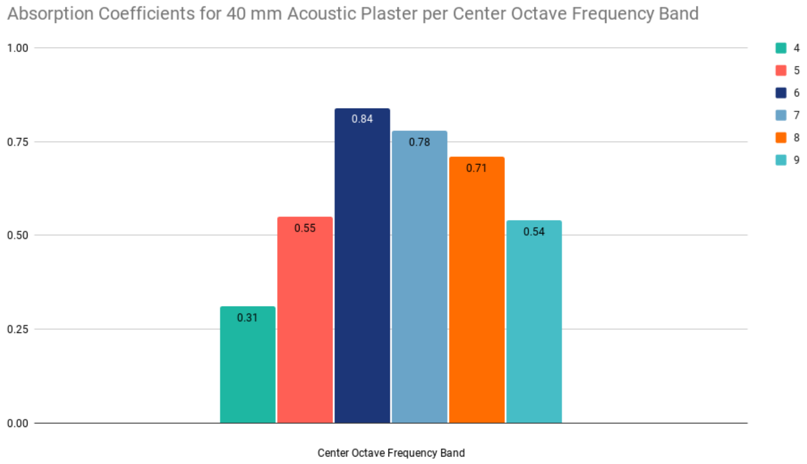

Figure A.10: Absorption Coefficient Values for the 40mm Thick Acoustic Plaster Across Center Octave Frequency Bands

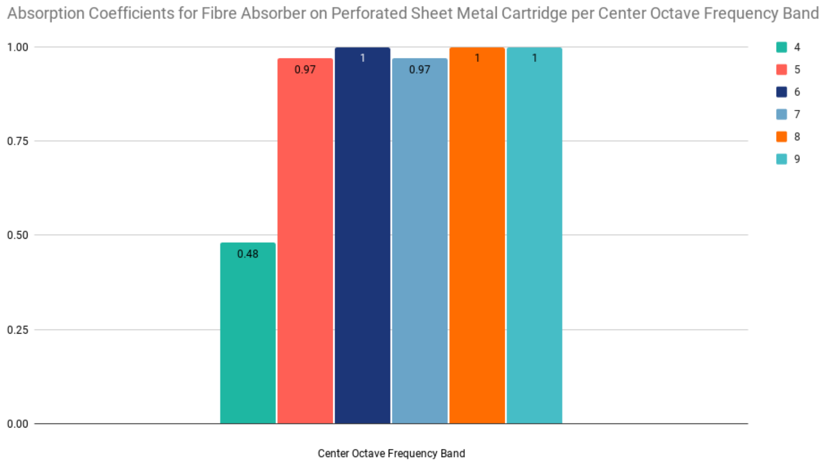

Figure A.11: Absorption Coefficient Values for the Fibre Absorber on a Perforated Sheet Metal Cartridge Across Center Octave Frequency Bands

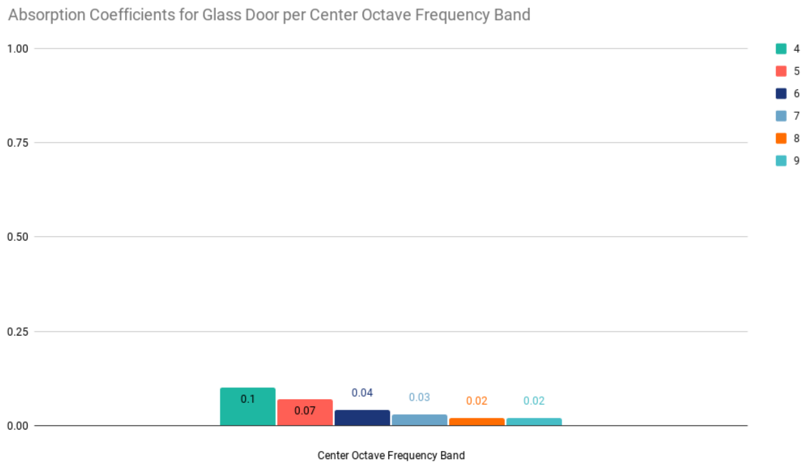

Figure A.12: Absorption Coefficient Values for the Glass Door Across Center Octave Frequency Bands

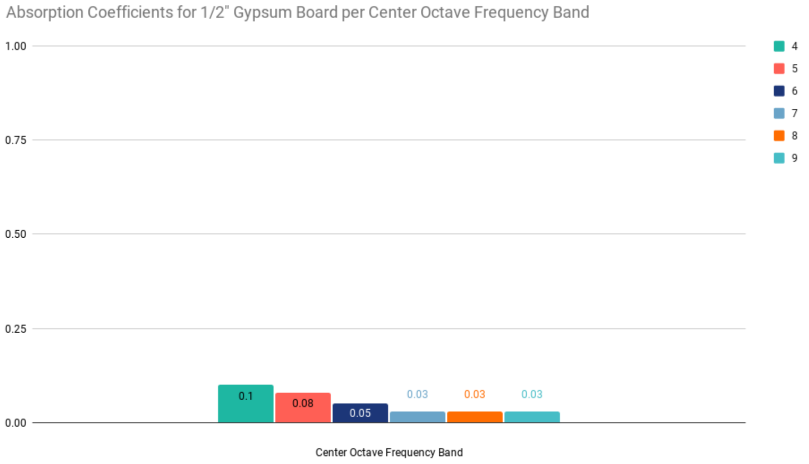

Figure A.13: Absorption Coefficient Values for the 1/2” Gypsum Board Nailed to 2x4s on 116” Centers Across Center Octave Frequency Bands

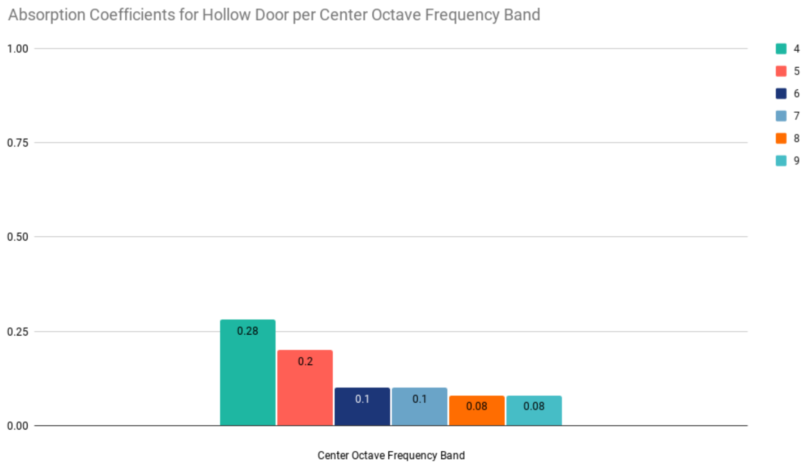

Figure A.14: Absorption Coefficient Values for the Hollow Door Across Center Octave Frequency Bands

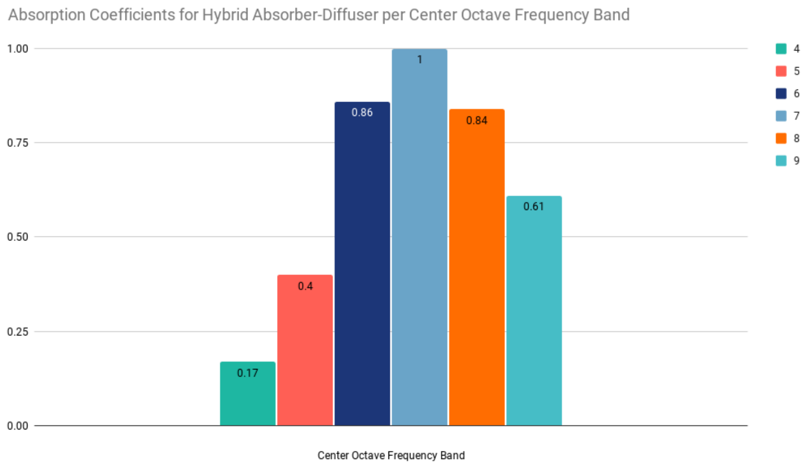

Figure A.15: Absorption Coefficient Values for the Hybrid Absorber Diffuser Across Center Octave Frequency Bands

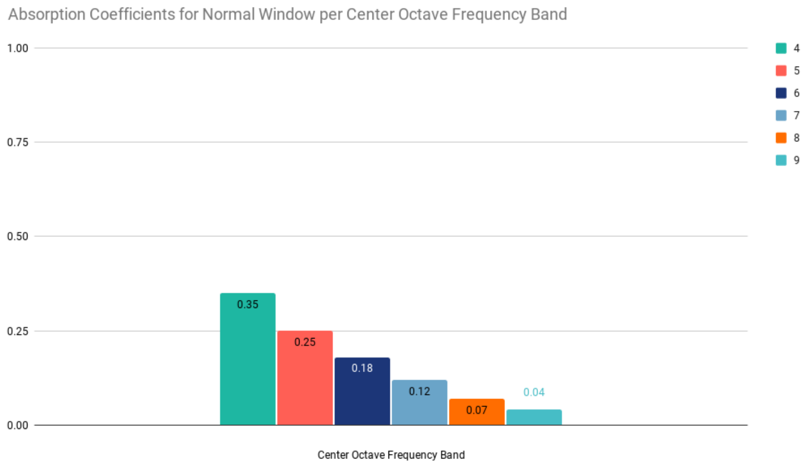

Figure A.16: Absorption Coefficient Values for a Normal Window Across Center Octave Frequency Bands

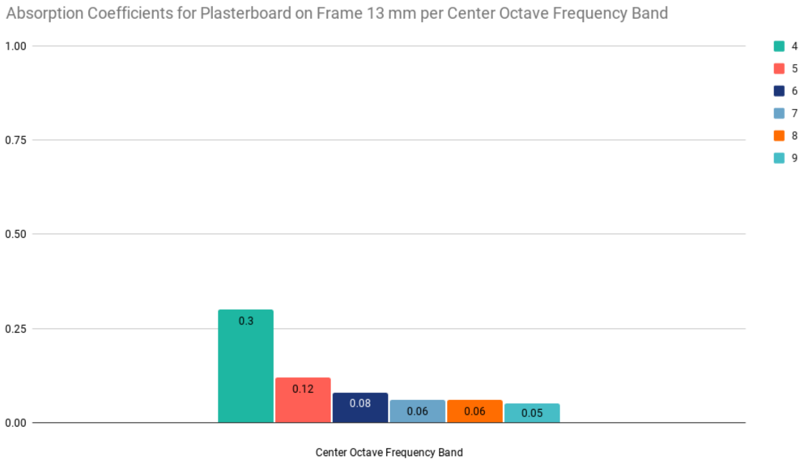

Figure A.17: Absorption Coefficient Values for the Plasterboard on Frame With 13 mm Boards and a 10cm Cavity Filled with Mineral Wool Across Center Octave Frequency Bands

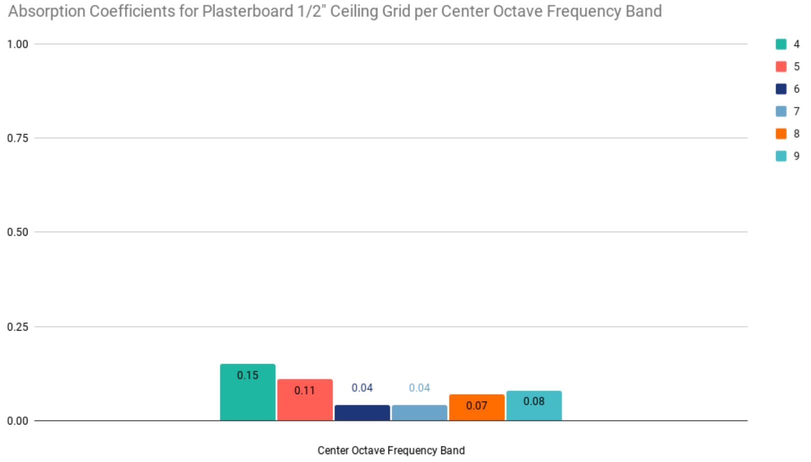

Figure A.18: Absorption Coefficient Values for a Plasterboard Ceiling on Battens with an Air Space Above on a 1/2” Grid Across Center Octave Frequency Bands

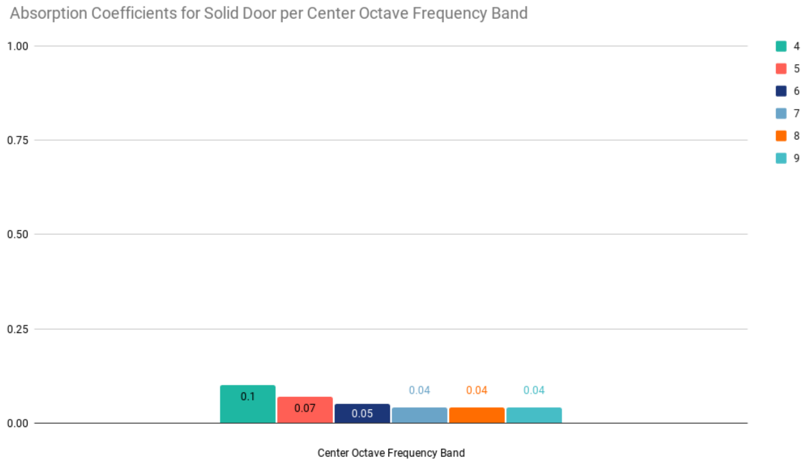

Figure A.19: Absorption Coefficient Values for a Solid Door Across Center Octave Frequency Bands

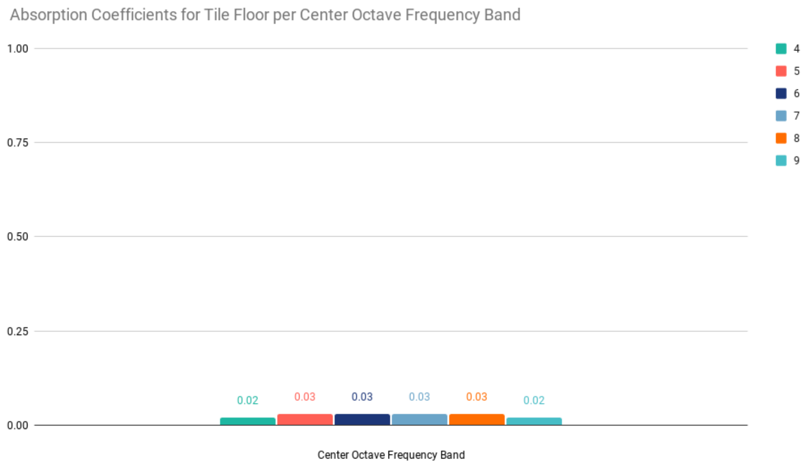

Figure A.20: Absorption Coefficient Values for the Tile Floor Across Center Octave Frequency Bands

Figure A.21: Absorption Coefficient Values for the Trapezoidal Box Custom Studio Ceiling Across Center Octave Frequency Bands

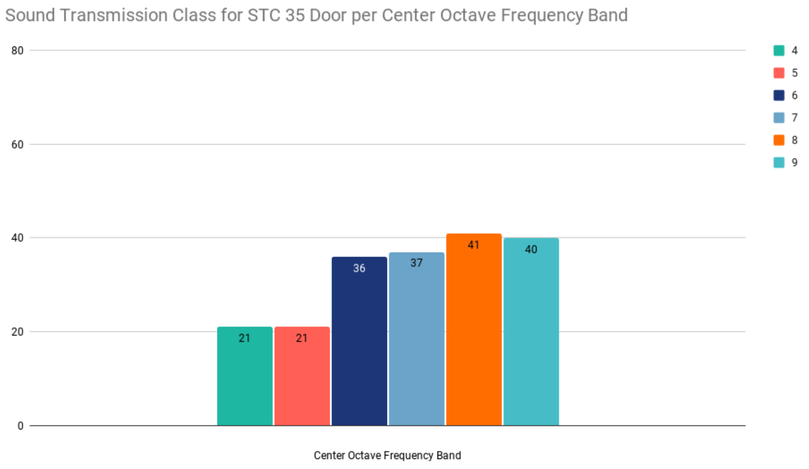

Figure A.22: Sound Transmission Class Values for a Solid Door Across Center Octave Frequency Bands

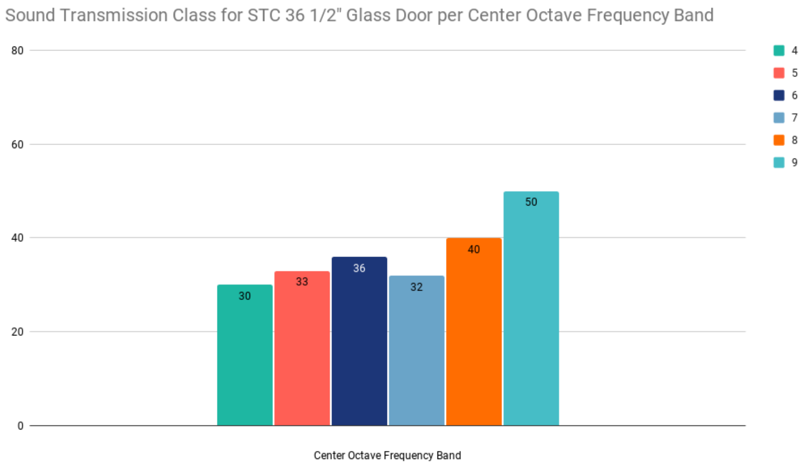

Figure A.23: Sound Transmission Class Values for a Glass Door Across Center Octave Frequency Bands

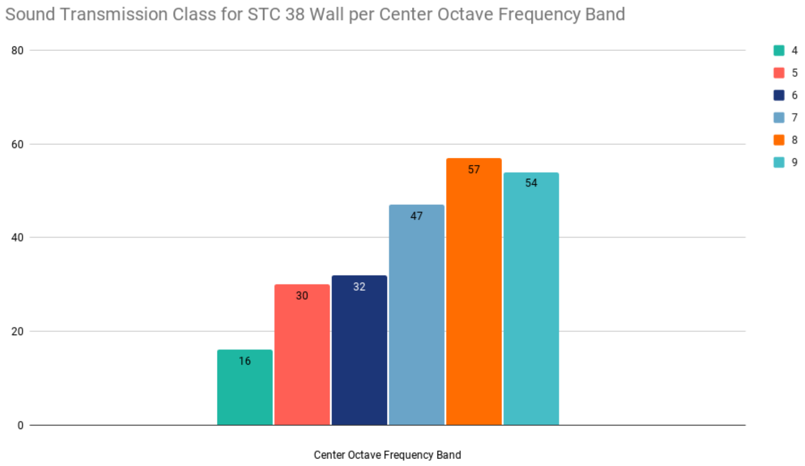

Figure A.24: Sound Transmission Class Values for an STC 38 Wall Across Center Octave Frequency Bands

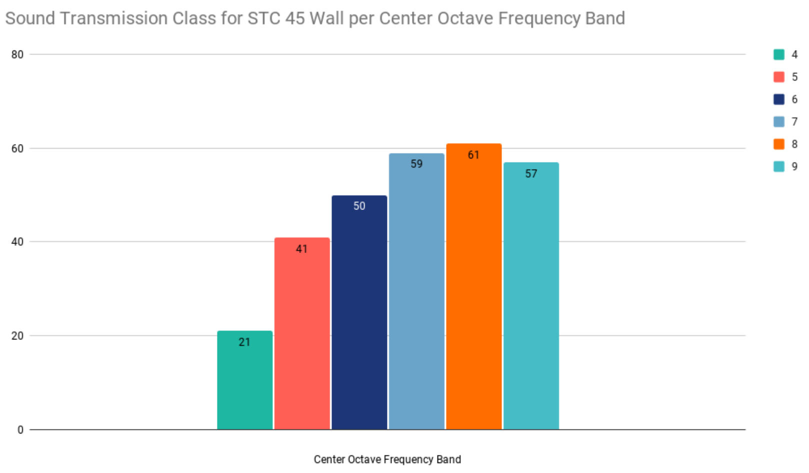

Figure A.25: Sound Transmission Class Values for an STC 45 Wall Across Center Octave Frequency Bands

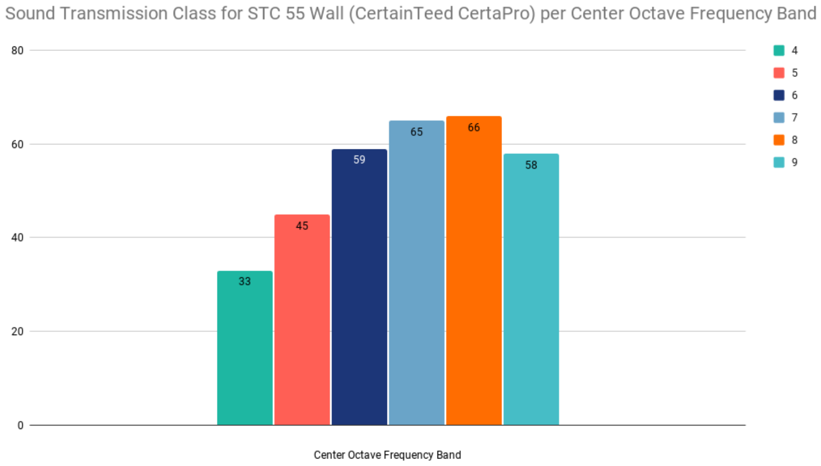

Figure A.26: Sound Transmission Class Values for an STC 55 Wall Across Center Octave Frequency Bands

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