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Title

PHYTO-REMEDIATION: A NATURE-BASED SOLUTION AGAINST POOR AIR QUALITY

By

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The Supervisory Committee certifies that this ***thesis*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF ARCHITECTURE

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PHYTO-REMEDIATION: A NATURE-BASED SOLUTION AGAINST POOR AIR QUALITY

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ABSTRACT

Wildfires, escalating in intensity each year, have plunged California into a crisis of indoor air quality, particularly during the wildfire season. This thesis dives into a potential solution: the use of exterior green walls as a respiratory system, employing phytoremediation. Phytoremediation harnesses the plant's natural ability to cleanse soil, water, and air of contaminants. The prevalence of heavy smoke, composed with particulate matter 2.5, from these increasingly fierce fires poses a significant health risk in California. This research advocates for a plant-based biological filtration system as a promising alternative to conventional methods.

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LIST OF ABBREVIATIONS

HVAC .....Heating, Venting, and Air Conditioning

IAQ .....Indoor Air Quality

AQI .....Air Quality Index

PM.....Particulate Matter

VOC .....Volatile Organic Compounds

NO2.....Nitrogen Dioxide

O3.....Ozone

SPRE.....Single Pass Removal Efficiency

CADR .....Clean Air Delivery Rate

1. INTRODUCTION

With the number of natural disasters vastly increasing, our earth and its inhabitants are exposed to many environmental changes. One of those changes includes poor air quality. In recent summers, temperatures have dramatically increased to record-high digits. These hotter temperatures have created drier conditions, allowing fires to spread faster and burn more intensely. In return, several major U.S. cities have experienced one of the worst air quality index (AQI) readings ever recorded. According to the New York City Community Air Survey and New York State Department of Environmental Conservation, New York City recorded its all-time high AQI reading on June 7th, 2023. Images of New York showed an orange sky hiding away its famous skyline. People on the streets were shown wearing masks and were told to remain indoors. Several other cities were experiencing the same symptoms brought by wind from wildfires in Canada. It is not just happening in California and in a world where, according to the Environmental Protection Agency (EPA), the average American spends 90% of their time indoors, it is time to think about what we can do to remediate our surrounding environments both indoors and outdoors. Will we supply the lungs of our buildings with more efficient HVAC systems only to increase energy use, or are there other design solutions that can remediate today's poor air quality?

1.1. Problem Statement

Our ambient air can be full of toxins that most of us are often unaware of. There are times when the indoor air in a building can be worse than the outdoor ambient air. As a result, the popularity of air diffusers and air purifiers have increased, not only in office spaces but also throughout many homes, hotels, schools, and many other indoor spaces. During the COVID-19 pandemic, hotels specifically have invested in state-of-the-art filtrations systems that are meant

to scrub the air traveler's breath. However, even though these systems can reduce the number of airborne particles it can increase the costs of HVAC systems in a building. Some experts including ASHRAE also seem to be skeptical, noting this technology is still emerging and lacks rigorous studies. In turn, shifting efforts towards studies that are nature-based including phytoremediation can demonstrate a growing effort within the architecture field.

1.1.1. Research Question(s)

To start thinking towards a nature-based solution and tackle air pollution in the ambient air, the research question being investigated throughout this research, "How can phytoremediation be integrated in architecture to remediate indoor air quality?", revolves around using specific plants to perform as the main filtration systems for buildings.

1.1.2. Proposed Outcomes

The proposed outcomes throughout this research entails the ability to showcase an alternative solution to combat indoor air pollution. A deep investigation through simulations and façade designs will be conducted towards hotels that can serve as clean air shelters and towards residential projects that can serve as homes and relief towards the housing crisis. In turn this research can raise an awareness towards new forms of ventilation requirements and alternatives. Another outcome entails being able to provide filtered air into the building by using the circulation air through a green wall. This active bio filter should meet all standards of air quality requirements. Further investigation of biofilters will serve as the basis to challenge how we think about HVAC systems. Rather than having a green wall simply serving as indoor landscaping, this research will push buildings to become resilient to the effects of natural disasters by planning and designing ecological systems in an equitable way.

1.2. Objective

The objective throughout this research identifies a growing issue concerning air quality and the aim to investigate and demonstrate its significance towards a potential solution.

1.2.1. Aim

Throughout this research, an alternative nature-based solution to today's conventional HVAC systems will be proposed by integrating the benefits of phytoremediation to combat poor indoor air quality in San Francisco, California. Not only will a nature-based solution be proposed but also be able to effectively replace the need of conventional filtration systems in its entirety.

1.2.2. Significance

The United Nations (UN) projects that 68% of the world's population will live in urban areas by 2050. That means two out of every three people will live in urban areas, highlighting the need for more sustainable solutions in major cities. Cities will continue to grow not only in the number of people but also in the number of buildings and natural disasters. By integrating nature-based solutions to the design of buildings, they can become resilient to such events while reducing energy consumption.

2. BACKGROUND

2.1. Background Overview

The following research entails the search for the role of phytoremediation in plants, a new wall system developed by SOM, and an investigation held in Australia for an exterior green panel. It was essential to focus the area of research regarding phytoremediation towards the focus on air and through the Phytoremediation Research the definition is further explored. Also, by looking at what research architectural firms, including SOM, are currently researching, one can see the current architectural technologies being explored in real life projects. Another area of focus for this research includes a study held in Australia which tests the efficiency of a green panel in an exterior setting, targeting Particular Matter 2.5 or often referred to as PM2.5. Together, this research will lay the foundation for the research being held throughout this thesis and aim to fill in any gaps found.

2.2. Literature Review

2.2.1. Previous Research

2.2.1.1. Phytoremediation Research

Although the prefix Phtyo- is relatively new, this five-letter prefix encompasses the main research point. Only truly established in the 1980s, phytotechnology was one of the first words widely used. Phytotechnology refers to a plant's ability to remediate contaminants and prevent them in the first place. However, this book uses it more towards the remediation of contaminants in soils. Only briefly touched upon, the topic of air arises during the middle of the book. The six contaminants classified by the U.S. EPA as air pollutants in the indoor environment are O3, CO, SO3, NO2, PM, and VOCs. Emphasizing why these contaminants are a danger is an estimate made by WHO, saying more than 1 million premature deaths can be attributed to urban air

pollution in developing alone. The term "sick building syndrome" also relates to poor indoor air quality as it causes fatigue, allergies, poor productivity, and headaches, among other symptoms. The U.S. EPA also ranks indoor air quality among the top five public health concerns, encouraging a plant-based biological filtration system as a promising alternative to conventional methods. Three examples are referenced in this book. The first is "vine walls," consisting of climbing vines planted at the base or top of the wall. The second is "living walls," where the entire plant is integrated into the vertical growing system, including the root system. The third is called "biofilter walls," which differ by having water or air flow contact with a plant's root zone for remediation. During plant selection, it is thought that one must pay close attention to the actual plant. However, since most of the degradation occurs in the root biology of the plant, other factors should be noticed, like aesthetics and the plants' ability to live in a vertical environment. Therefore, providing more plant species diversity can likely increase degradation rates.

2.2.1.2. Wall System Research

Designed by a collaboration between Rensselaer Polytechnic Institute and Skidmore, Owings & Merril, this active phytoremediation wall system works with a building's existing HVAC system to improve indoor air quality. This modular wall system comprises pods containing hydroponic plants with exposed roots, increasing the air-cleaning capacity by 200 to 300 percent. The wall system is specifically designed to allow air to flow directly over the root system, which allows the rhizomes on the root to digest VOCs and PM. A four-module system in an apartment would have the impact of 800 to 1200 house plants. A prototype was first developed in an emergency response center in New York, designed by the local office of SOM.

Figure 1. Active Phytoremediation Wall System

This system shows the importance of the active role within the wall. Comparing this with Bill Wolverton's BioHome, where a different approach was used, a passive system. Without the active system that allows and directs air into a plant's root system, remediation efficiency would be minute. Another significant contrast is the use of hydroponic plants vs. common indoor house plants as living air purifiers. Although I can see why it might be ideal to use hydroponic plants, I intend to begin my research with plants native to North America. While having 50 houseplants in-house to purify indoor air quality passively might be okay, this approach would not be ideal in a commercial setting with thousands of square feet. However, this was just the beginning of the research, which started in the late 1960's.

2.2.1.3. Exterior Wall Panel Research

During the 2019 – 2020 summer in Australia, the "Black Summer" wildfires led to concern over the health effects of exposure to wildfire emissions. The term "Black Summer" was used to describe the intensity of exposure to the effects of wildfire events. To reduce the exposure, five green wall panels were installed in an outdoor setting with plants native to

Australia and the ability to remediate air pollution, including NO2, O3, and PM2.5. For 14 days, ambient and filtered air streams were monitored to measure the SPRE of each pollutant. This research specifically targeted how plants could improve outdoor air during a wildfire season.

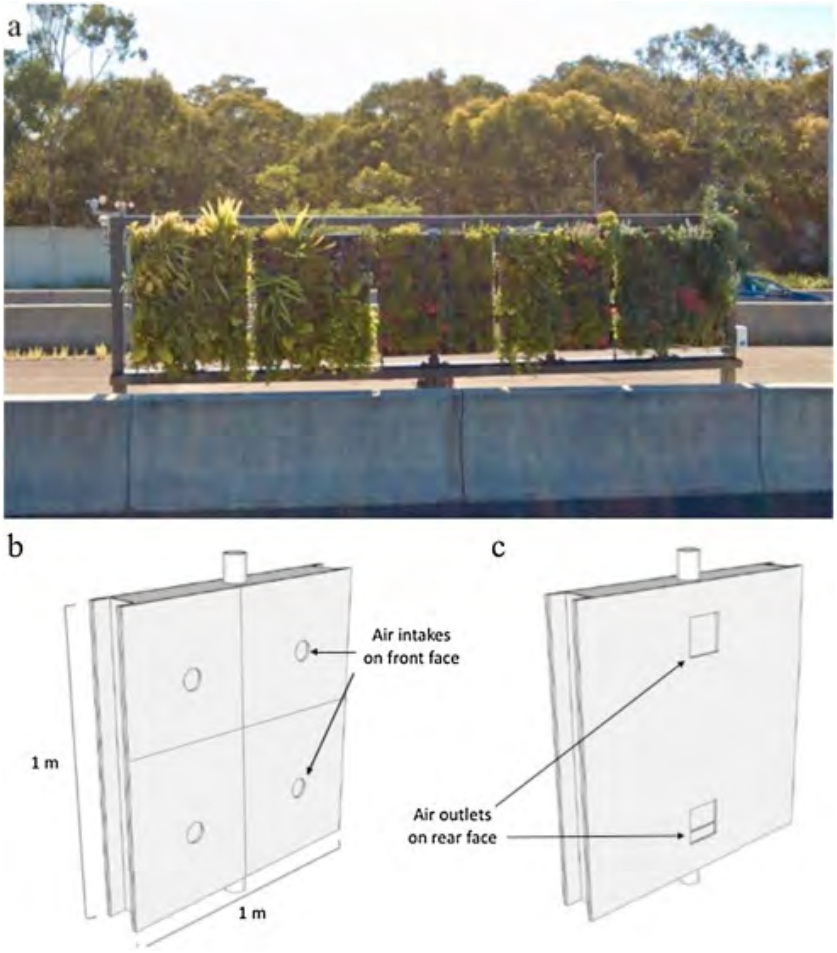

Figure 2. Exterior Green wall panel

After the research, it was shown how this experiment only showed positive results for O3. The results of NO2 and PM2.5 were considered negative because the removal rate was considerably less when compared to O3. However, other variables might have influenced the filtration efficiency. Since these green walls were located outside and exposed to rain, the plant's moisture level varied throughout the trial period. It is also possible that ambient temperature and

humidity may have led to variations in SPREs throughout the trail. This shows how the use of green walls in indoor settings may be more appropriate as the protection provided by a building depends on the type of construction and the degree of infiltration of outdoor air.

2.2.2. Gap Identification

Although there are current investigations being undertaken, much of the past research often focuses on the remediation of volatile organic compounds or VOC's. As seen in the panel being used from SOM, interior green panels are primary chosen to scrub the indoor air. Also, with the limited small-scale trials held in Australia after the black summer, there still lies an opportunity for exploration towards a large-scale investigation.

2.3. Project Type

The project type for this project includes a hotel typology with a focus on wellness. After reading various reviews on Google one of the main benefits of a good hotel is cleanliness and soundproof walls. Through this thesis there will be an emphasis on the cleanliness of indoor air quality.

2.4. Project Issues

Much of the research is currently being investigated in Australia and even so much of the research being conducted is relatively new. The metrics are different and because this is an emerging technology much of the sizing will be a minimum requirement and further investigation will need to be held in order to test the efficiency of biofilters in an architectural project.

3. METHODOLOGY

3.1. Approach

Throughout this research much of the data collected will focus on two areas, the first being the collection of plants and the other being the collection of historical data regarding air quality index (AQI) and indoor air quality (IAQ). With the collection of data, a simulation model developed through Anylogic will be used to further understand the role of phytoremediation in an architectural project.

3.1.1. Data Collection

3.1.1.1. Selection of plants

A plant's ability to remediate VOC, CO2, and PM2.5 will determine the selection of plants. Based on the studies from Irga P.J. (2017) and Matheson S. (2023), plants will be selected from the proven remediation record, either in a laboratory setting or in situ. Investigations will include past data to determine the single pass removal efficiency (SPRE).

3.1.1.2. Collection of historical data

To find the clean air delivery rate (CADR) of each pollutant, determining the AQI measurement of a chosen city will be conducted by examining a series of maps and data from AirNow, which shows the average and extremes of AQI readings. 4CAir Collection of past data on indoor air quality (IAQ): After the AQI is collected, data from PurpleAir will be used to collect the readings of indoor air pollutants. For this research report, the study from Liang Y. (2021) will provide various readings from PurpleAir, specifically from San Francisco, California, regarding indoor air quality (IAQ).

Due to this emerging topic, limited research that describes the CADR for specific plants is available. CADR = SPRE x biofilter airflow rate. For example, as discussed in the trials from Australia, Pettit, T. (2020), during the "Black Summer," there was an average SPRE of 24.84% for PM2.5 using a volumetric flow rate of 884.8 m3/h.

3.1.1.3. Inputting data and validation of measurements to develop design simulations.

To truly understand the benefits of integrating phytoremediation with a building's HVAC system, a simulation will be created using Anylogic. In this simulation, a standard HVAC system with the help of a biofilter will demonstrate full clean air ventilation. Further explained in the research results, a flow rate is needed to initialize a simulation model in Anylogic. Figure 1 shows different infiltration rates that can be entered as a flow rate to test different scenarios and infiltration rates of a typical building in San Francisco. An infiltration rate of 18% will be used throughout this research investigation. This 18% is the lowest infiltration rate in Figure 1.

3.1.2. Analysis

3.1.2.1. Anylogic Software

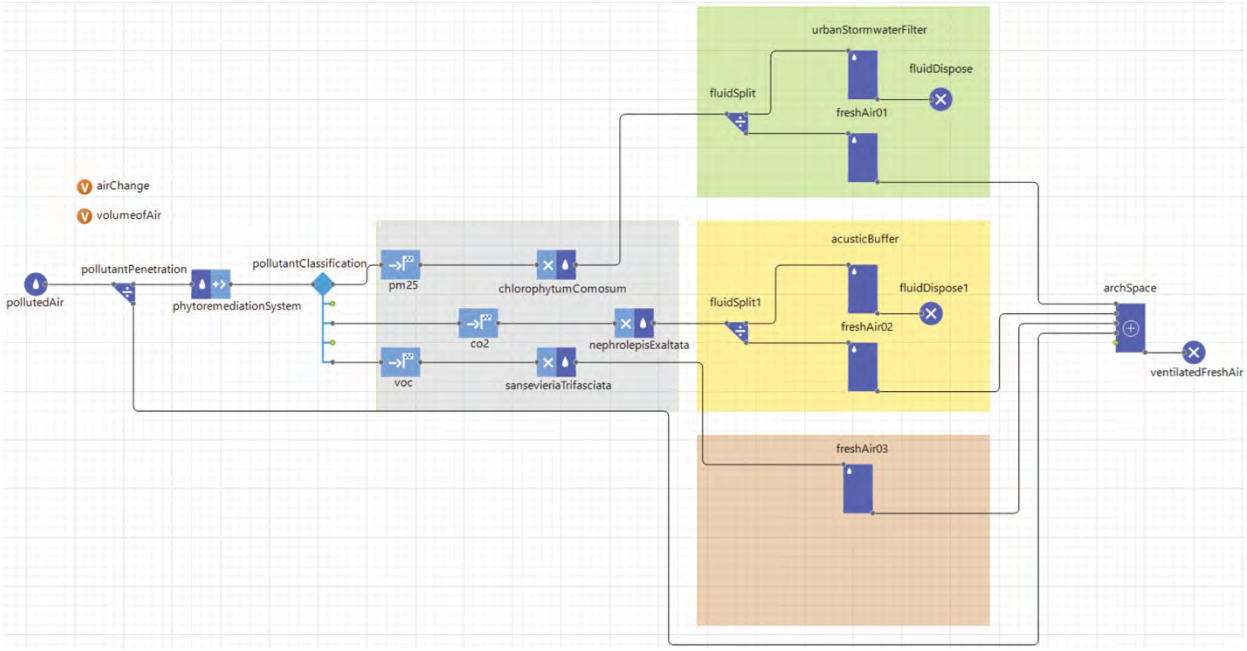

Figure 3. Anylogic Simulation Model

Anylogic is a leading simulation modeling software that allows professionals from across various industries to gain a deeper understanding of complex systems and processes. A user can choose from six different types of libraries, including process modeling, pedestrian, road traffic, rail, fluid, and material handling. This research report will mainly use components from the fluid library. The fluid library will allow the simulation to have various characteristics of flows, such as rate and throughput, which is an essential part of the desired standalone biofilter. In addition to the fluid library, some components of the process modeling library were used. Some limitations of this software include a sole one-way flow and the under supply of accurate representation of some components in a biofilter.

3.1.2.2. Development of simulation model

To develop the simulation model in Anylogic, it was essential to enter a flow rate at the start of the simulation. The units in Anylogic for the flow rate were decided to be entered as cubic meters per second. For this reason, the volume of air was entered as cubic meters at the beginning of the simulation model using the fluid-source block named polluted air.

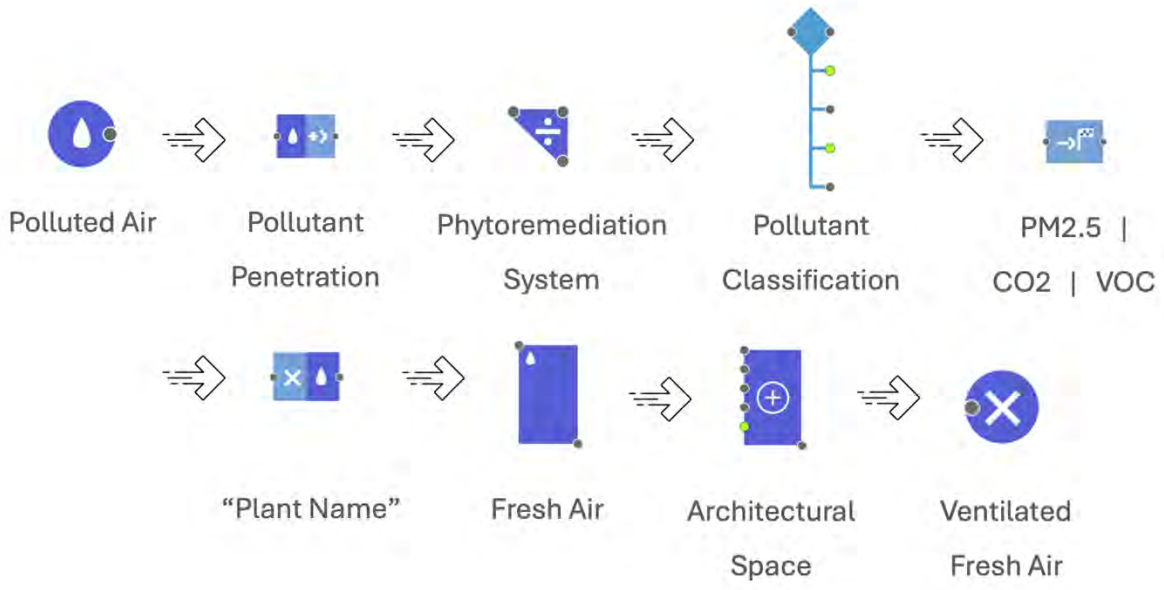

Figure 4. Anylogic Fluid Components

As the simulation progressed, the fluid-split block was used from the fluid library to represent the separation of air infiltration named pollutant penetration. This block allows users to separate the flow rate by entering the desired fractions. To determine an accurate infiltration rate, data from Liang, Y. (2021) was used to determine that about 18% of polluted air is what enters a typical building, which means that in the usage of conventional HVAC systems and filters, about 82% gets effectively filtered. These percentages were taken from California studies, focusing on the Bay Area, as this will be the area of study for a potential building that could solely use an active green wall filter for indoor air quality monitoring.

Assuming 18% of polluted air enters a building, the polluted air continues through the fluid-to-agent block. This block, named the phytoremediation system, is where the phytoremediation system process begins.

The polluted air is then separated even further into three different pollutants. These pollutants include particulate matter (PM2.5), carbon dioxide (CO2), and volatile organic compounds (VOC). The select-output-five block, labeled as pollutant classification, has five outputs that can make five different distinctions. For this simulation model, three outputs were used out of the five to represent each pollutant.

Moving forward through the model, the move-to block represents each pollutant and advances towards the agent-to-fluid block. Labeled as PM2.5, CO2, and VOC.

For each pollutant, there is an agent-to-fluid block. Each agent-to-fluid block is then associated with a specific plant that has demonstrated the efficiency to remediate its according pollutant. Chlorophytum Comosum can remediate PM2.5, Nephrolepis Exaltata to CO2, and Sansevieria Trifasciata to VOC.

As the polluted air goes through the simulation, it can do more than transform into fresh air. After leaving the agent-to-fluid block, the fluid gets diverted by another fluid-split block. This step shows the other benefits of an active green wall. From the review paper of the Matheson, S. (2023) study, the other benefits include the performance of acting as an acoustic buffer and urban stormwater filter. These benefits then go through a tank block, representing all the benefits of a biofilter.

Towards the end of the simulation model, the fluid-dispose block is introduced. For some tanks, such as the urban stormwater filter and the sound buffer tank, a fluid-dispose block is

shown to demonstrate the effect. As for the remediated fresh air, it ends in the designated architectural space, which represents a building.

At the end of the simulation model, all the fresh air finally reaches the architectural space. The mix-tank block is assumed to reach an entire filtered space, firstly by an effective HVAC filter and secondly by integrating a biofilter. At the very last step, the last block is another fluid-dispose. This last block shows the ventilated fresh air and concludes the simulation model.

3.1.2.3. Sizing of Biofilter

A metric used to indicate the effectiveness of the biofilter in an in-situ application is the air cleaner effectiveness. Irga, P. J. (2017) This tells us the capacity of the biofilter to serve as a standalone ventilation system for the main spaces of a hotel. Four air changes per hour will be used to size the biofilter to serve as a standalone ventilation system for all scenarios. Based on the calculation of Irga, P. J. 2017 the biofilter in its most effective operational setting would require 0.1872 modules per m3 to supply a ventilation equivalent of 4 air changes per hour. Assuming all this for each space that will form part of the program, the volume of spaces in a hotel and apartment building will be used to estimate the biofilter size required to replace mechanical ventilation fully.

3.1.3. Conclusion

Although several studies have been conducted to analyze the effectiveness of a biofilter, in situ studies on a large-scale trial still need to be conducted. Additionally, only a few tests are being conducted for indoor spaces. Green walls have been previously used in buildings to treat urban stormwater or act as an acoustic buffer. However, only a few have been used to tackle the emergence of particulate matter in the urban ambient air. Many indoor biofilters have

been shown to “scrub” the air but have only focused on VOCs. Biophilic design has also been primarily associated with green walls as it has been shown to have a substantial psychological impact on the inhabitants of urban areas.

3.2. Project Location (larger scale)

The project location for this project is situated in the state of California, U.S. Usually split between two regions, Southern California, and Norther California, much of the state has a Mediterranean climate. Summer temperature in Los Angeles and San Francisco both are the coolest compared to the interior of the state making it an ideal destination for many travelers. However, California has experienced poor outdoor air quality especially during wildfire season. According to the California Air Resources Board (CARB), PM2.5 contributes to 5,400 premature deaths due to cardiopulmonary causes per year, in addition to 2.800 hospitalizations for cardiovascular and respiratory diseases and 6,700 emergency room visits for asthma each year.

Figure 5. Site Map

3.3. Project Location (smaller scale)

Focusing on the city of San Francisco and specifically in the neighborhood of Nob Hill the site can be found in between Union Square and Chinatown. Much of the surrounding area is residential with town homes and apartment buildings, small local business can also be found including nails salons and laundry mats. Valuable views can be seen from the area as well including the Coit Tower and Alcatraz Island to the North, the Transamerica Pyramid building to the East, and the Golden Gate Bridge to the Northwest. Upon initial investigation it was noted of a similar project typology in the same site. Project review meetings (PRV) were opened in May of 2007 for new construction of a mixed-use building of 30 units with a green hotel, senior housing, and retail. Although closed in that same year it was used as assurance of the potential a project like this can have on the site.

3.4. Specific Site

The specific location of the proposed site for this project lies on the corner of Clay St and Powel St. The site entails the combination of five lots, combining lot one through five as shown in Figure 6, the first lot counts with 3,000 square feet, lot number two with 9,543 square feet, lot number three with 1,232 square feet, lot four with 1,120 square feet, and lot five with 1,458 square feet for a total of 16,353 square feet.

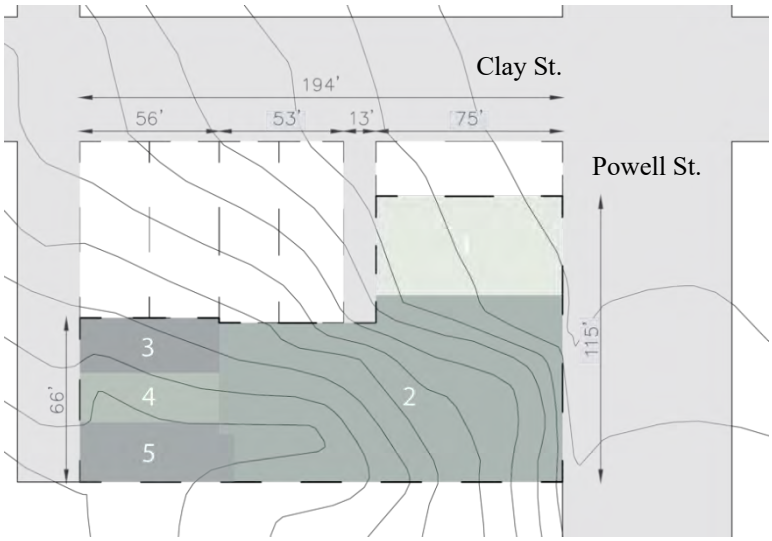

Figure 6. Lot Map

Currently San Francisco is classified into 14 different districts and public use. Referring to Figure 7, lot one and two are classified under the residential-commercial combined district as RC-4 High Density. Lot three, four, and five are classifies under the residential, mixed (houses & apartments) district as RM-3 Medium Density. The residential-commercial district is intended to protect, conserve, and enhance the surrounding areas with structures that provide residential uses while having neighborhood-serving commercial uses. Commercial uses are usually in or below the ground story that can provide the needs of nearby residents yet not generate excessive vehicular traffic. Structures in RM-3 District are primarily apartment buildings of 10 units or more. Most of these districts are close to downtown and vary in size, many buildings exceed 40 feet in height.

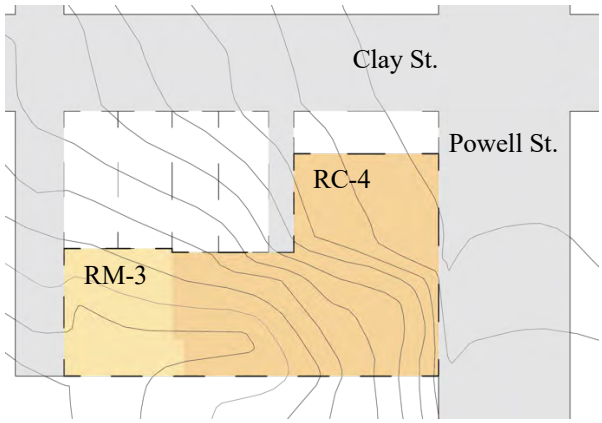

Figure 7. Zoning Map

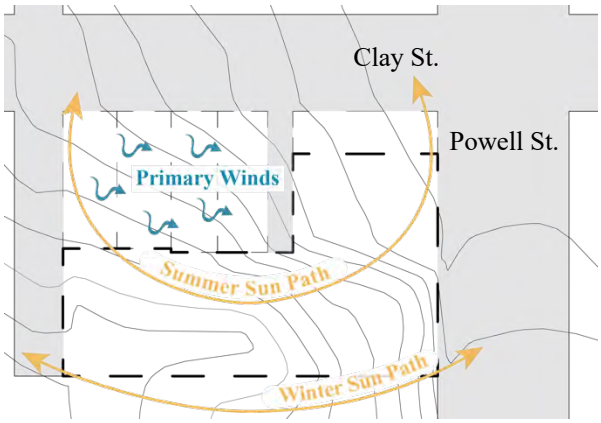

Figure 8. Sun Path & Wind Direction

3.5. Precedents / Case Studies

3.5.1. Torre Sevilla

Figure 9. Torre Sevilla

Torre Sevilla, designed by Pelli Clarke & Partners, is a mixed-used tower that stretches 37 stories high a forms part of a vibrant development in the historic city of Sevilla, Spain. It has

transformed the site into a lively destination for shopping and dining, formed by a dramatic split podium around the base of the tower it creates a pedestrian-only walkway with shops and cafes. At the north end, the street widens into a plaza where pedestrians can enjoy fountains and the smell of the city's iconic orange trees. A unique design in the façade of this building includes a sun-shading program focusing on the importance of the sun path and the hot temperatures of the city. Each fin is carefully integrated in a calibrated system according to the angle and intensity of the sun. Other sustainable features include a grey-water recycling system and a fresh air intake system.

Figure 10. Split Podium

The influence that Torre Sevilla had towards the thesis project includes the integration of a pedestrian promenade and the development of a fin design along the façade of the building. By

having a split podium design a large individual building becomes two, with one serving primarily as residential and the other serving as a hotel. Through the integration of a pedestrian promenade, especially having tenants that can be opened 24/7, it can create commercial space to serve the community of Nob Hill including convenient stores and pharmacies. Regarding the façade design, the focus that this firm has put towards a passive approach has led the development of a passive approach to create fins along the pedestrian walkway in this project. In this case the fins will provide a sense of direction for the primary winds that can bring in the air toward the location of the biofilter and serve as a unique aesthetic towards the design.

3.5.2. 1 De Haro

Figure 11. 1 De Haro

1 De Haro is San Francisco's first cross-laminated timber (CLT) building and California's first multi-story, fully mass timber building. Designed by Perkins&Will, this building provides a mix of office and light industrial space that makes it both sustainable and

marketable. This four-story building is made up of a concrete podium and CLT which makes this structure lighter, quicker to construct, and more beautiful than a steel or concrete building. As a façade the designer has chosen to wrap the building with a glass curtain wall which allows the beauty of the exposed CLT to be observed from the outside. Due to San Francisco's soil the thought of having a massive concrete structure led a deep investigation to compare the cost of CLT vs. concrete. CLT not only proved to have a lighter structure but also a faster construction frame as well.

Figure 12. CLT Structure

Since 1 De Haro is also located in San Francisco it was easily proven that a similar approach would be followed to choose CLT as the main structural design. With a concrete podium also shown to be a good base for 1 De Haro, again it was easy to stick with this base design for both the residential tower and hotel tower. Although on this occasion much of the

CLT is left exposed to show off the beauty of wood, it will be hard to have the same approach in both a residential application and hotel application. The best hotels are bound to well sound proofed walls and most residents living in apartments would say that not being able to hear noises from neighbors is a major benefit.

3.6. Detailed Space Program

Through the objective of providing fresh air to a new kind of green hotel, much of the program for the hotel tower will include typical rooms for the upper floors and typical studio, one-bedroom, and two-bedroom apartments. Complying with the zoning and height regulation the hotel tower will sit on the northeast corner and have the main entrance be on the east elevation. On the other hand, the apartment building will sit on the southwest corner and have the main entrance on the west side. RC-4 allows for structures to have a building height of 105’-0” while RM-3 allows for structures to have a building height of 85’-0”. Therefore, working under these guidelines and assuming a typical ceiling height for both the apartment tower and hotel tower of 9’-0” the estimated number of floors for the apartment building would be 5 stories and 8 stories for the hotel building.

4. RESULTS AND CONCLUSIONS

4.1. Final Project Description

This section will break downs the various characteristics of the proposed project for a hotel building and apartments building in San Francisco, California. Ultimately going back to answering the main question of, “How can phytoremediation be integrated in architecture to remediate indoor air quality?” other components that came into question were, “What will a biofilter look like on a building?” and “How will it work?”.

4.1.1. Floor Plan Grid

As stated in the precedents a CLT structure with a concrete podium will lay out the design for the structure. In using CLT, a grid was developed with large spans reaching 30’-0” and smaller spans reaching 20’-0”. Thanks to the strength of CLT and its capabilities to span large distances very few columns can be noticed in the interior of the building.

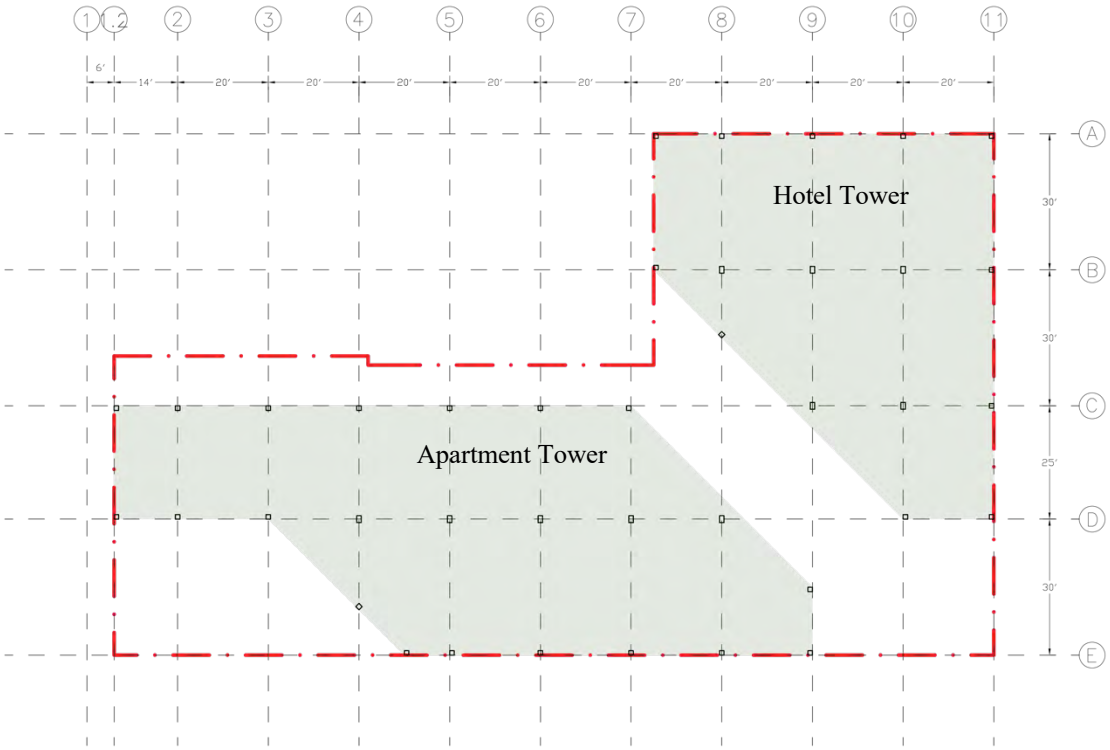

Figure 13. Floor Plan Grid

4.1.2. Pedestrian Circulation and Foundation Design

With great influence form Torre Sevilla, a pedestrian promenade was developed and because of the seismic activity in San Francisco the foundation counts with a raft foundation and base isolators. The pedestrian promenade was used to separate each building typology but also creates the opportunity to have shops along the walkway.

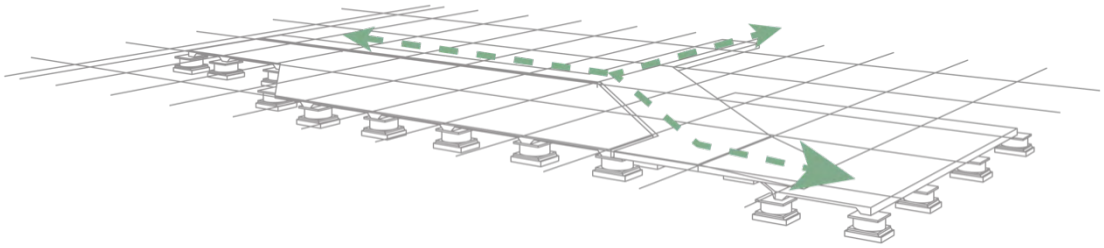

Figure 14. Foundation Design

4.1.3. Structure and Fins Design

As part of the goal to provide a holistic design solution, Cross Laminated Timber or CLT was structurally used to showcase sustainable design and durability. The integration of CLT and bio filters was used in aim to show a holistic design not only one that prioritizes structural integrity but also embodies a commitment to sustainability. The residential building to the west has a total of eight floors. Floors two through eight are made from CLT and a concrete podium is situated on the ground floor. The hotel sits on the east side, again with a concrete podium for the ground floor and Floors two through eight counts with a CLT Structure.

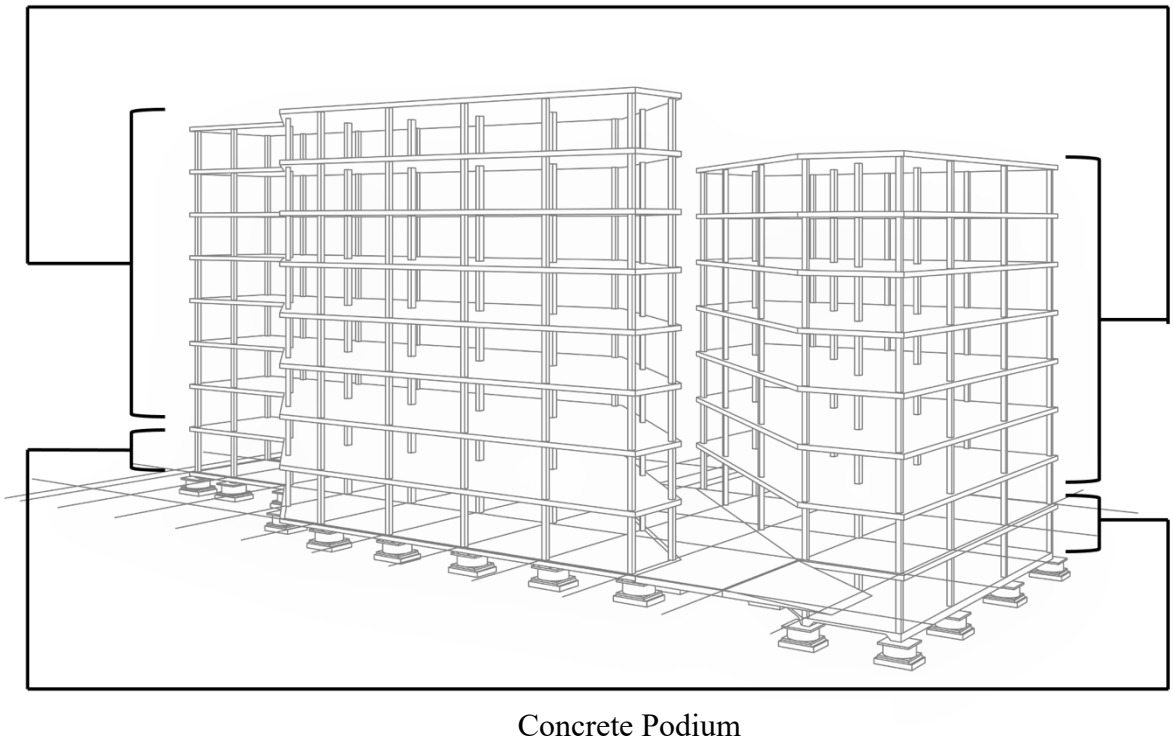

Figure 15. Structure Design

To give the wind some kind of direction and bring in the air towards the sides in between the buildings. A series of fins were developed. Much of the design for these fins came from looking at a human lung which in turn is what these biofilters do. Provide fresh air and serve as a lung for both buildings. These fins vary in size and extend outwards in various lengths with a maximum length of four feet. Different options for the fin design were considered through the design development phase. On one occasion the possibility of adding fins that pivot was considered. However, with a dynamic system that pivots according to various wind directions the energy use would increase. In turn, a more passive design approach was taken and have the fins be static in motion. These fins would be made of CLT with a prefinished coating to address the withering of wood due to water and salt.

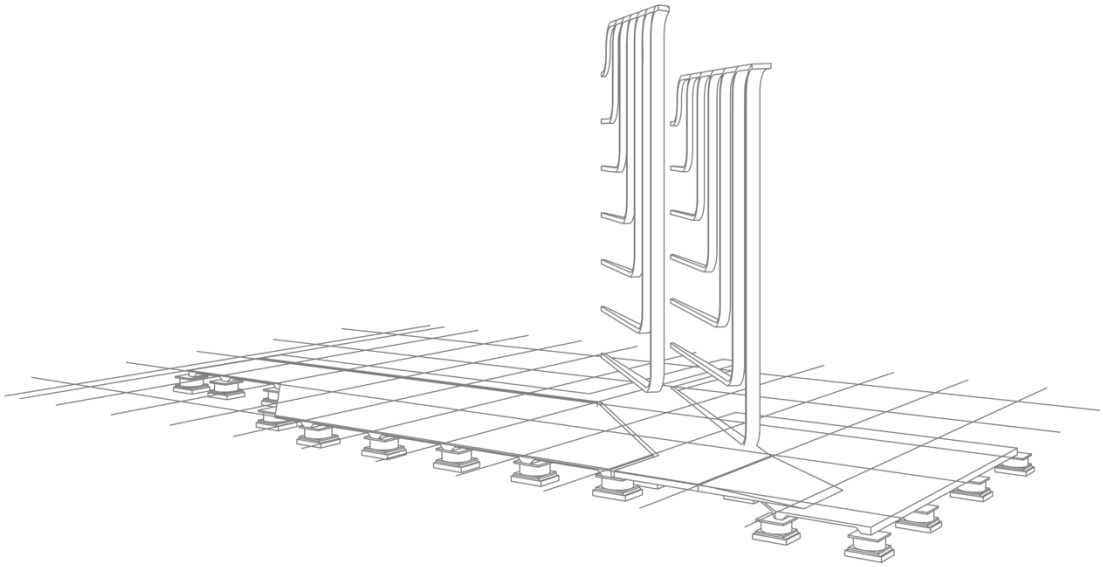

Figure 16. Fin Design

4.1.4. Final Floor Plans

The final floor plans for each building vary according to each of their building typology. The residential building counts with studio, one-bedroom, and two-bedroom options. An important feature of these apartments is that each one will count on both a washer and dryer as the laundry mat across the street recently closed. On the ground floor, senior housing will be prioritized to provide a more seamless experience to access public spaces including the pedestrian promenade. Towards the outside and along the walkway on the northeast side commercial tenant space will be available. In allowing only two spaces along the walkway will provide the necessary needs for residents and not have empty shops. The sizes for these spaces are 1400 sq ft and 1300 sq ft. These smaller spaces can serve for small businesses that might want to start small and later expand into larger spaces if success is seen. This has been a rising option for many in San Francisco as many are weary about future success.

Figure 17. Floor Plan

The layout for the hotel tower is typical with standard rooms with one and two bed options, a deluxe one bed option is also available. All rooms allow for one king bed and rooms with two beds allow for a second queen bed. It was important to keep the room relatively the same in size to allow for a simple and easy way to estimate the sizing need for each room. On the ground floor the main spaces include a lobby, a vestibule, seating area for breakfast, a meeting room, restroom, storage space and kitchen space. Much of the main floor will be limited to windows which is why a smaller floor plate will be used. The hallways throughout the hotel are measured at six feet and a mechanical room is situated on each floor to allow for the biofilters to work efficiently.

Figure 18. Floor Plan Square Footage

4.1.5. Biofilter Location

As mentioned before the primary winds come from the northwest, therefore it became easily evident that the most suitable location for the biofilters reside along the north side of the residential building and in between both buildings. This also helped with a privacy issue if instead glass were put on both sides in between both buildings people would be looking at each other from each side.

Figure 19. Biofilter Locations

4.1.6. Façade Grid

The envelope design is composed of a grid with measurements of 18” in width and 10’ in height which is a standard size for fiber cement boards specifically from the Nichiha brand. Again, to eliminate material waste and use standard sizing this would allow for faster construction time frames and less material waste. As for the green panel sizing, this allows for panels to measure at a minimum of 36” in width and 10’ in height which aligns with the facade grid, because much of the calculations are assumed to be set at a minimum the façade design grid would allow for panels to be changed from fiber cement boards to green panels if needed. The proposals also feature a rhythmic pattern in the facade which reflect the direction of the flow of the primary winds in San Francisco. In turn, each window was strategically placed in alignment with the floor plan development. Each window measures 36” in width and 72” in height that

again fits within the facade grid. The windows also have the option to be operable in times when the exterior ambient air is not polluted, allowing for natural ventilation.

4.2. Biofilter Sizing & Design

The next step then involved having to calculate the size of the biofilter. The first step was to calculate the square footage of each space and then find the volume as well. Summing up the square footage for the apartment building, a total of 28,862 sq ft was calculated and summing up the square footage for the hotel building a total of 21,287 sq ft was calculated. Taking a closer look at the calculations needed, it was necessary to calculate the volume of each space. In this case using 9'-0" as the ceiling height. A metric used to indicate the effectiveness of the biofilter in an in-situ application is the air cleaner effectiveness. Irga, P. J. (2017) This tells us the capacity of the biofilter to serve as a standalone ventilation system for the main spaces of the hotel building and apartment building.

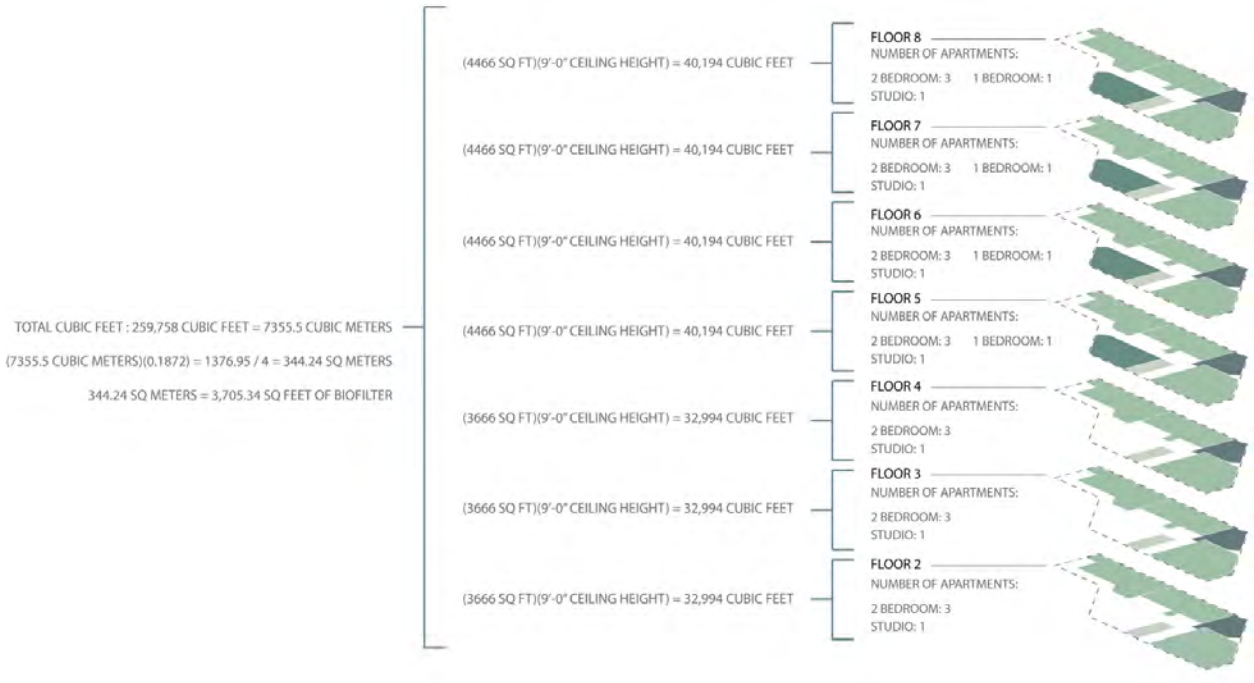

Figure 20. Apartment Calculations

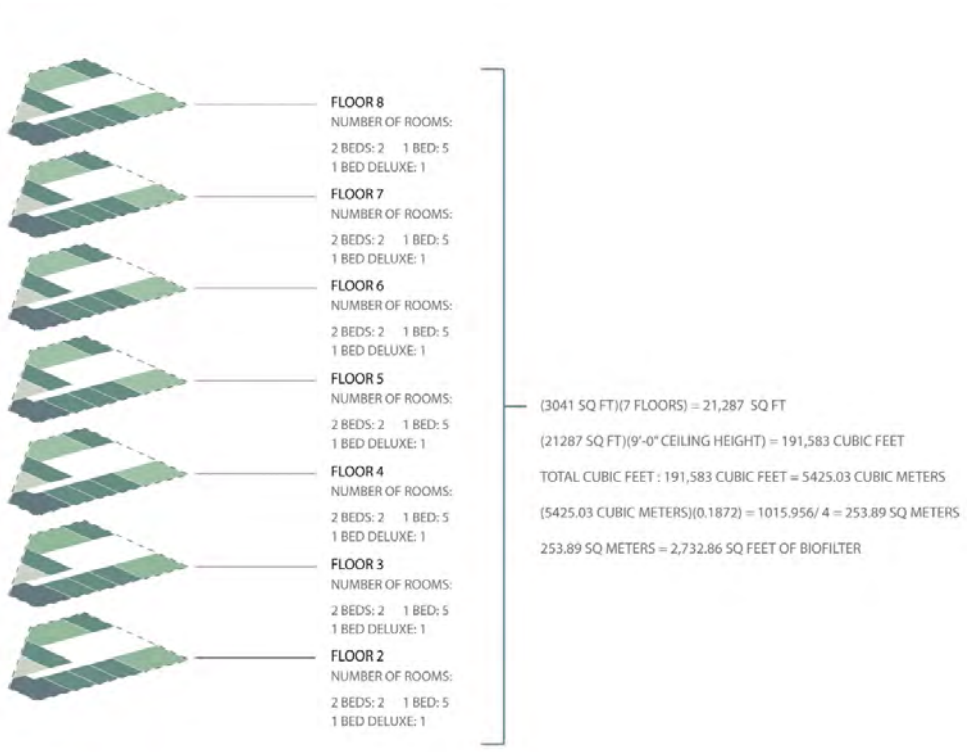

Figure 21. Hotel Calculations

Based on the calculation of Irga, P. J. (2017) the biofilter in its most effective operational setting would require 0.1872 modules per m3 to supply a ventilation equivalent of 4 air changes per hour. Therefore, bringing in that factor of 0.1872 to calculate the square footage of the biofilter needed was essential toward the calculations. The results then by using the total volume and the factor of 0.1872 gave the requirements of 3,705 square feet needed for the apartment building and 2,732.86 square feet needed for the hotel. The final design exceeded the requirements and 4,690 square feet biofilter was provided to the apartment building and 3,888 square feet of biofilter was provided.

4.3. Project Design and Documentation

4.3.1. Final Boards

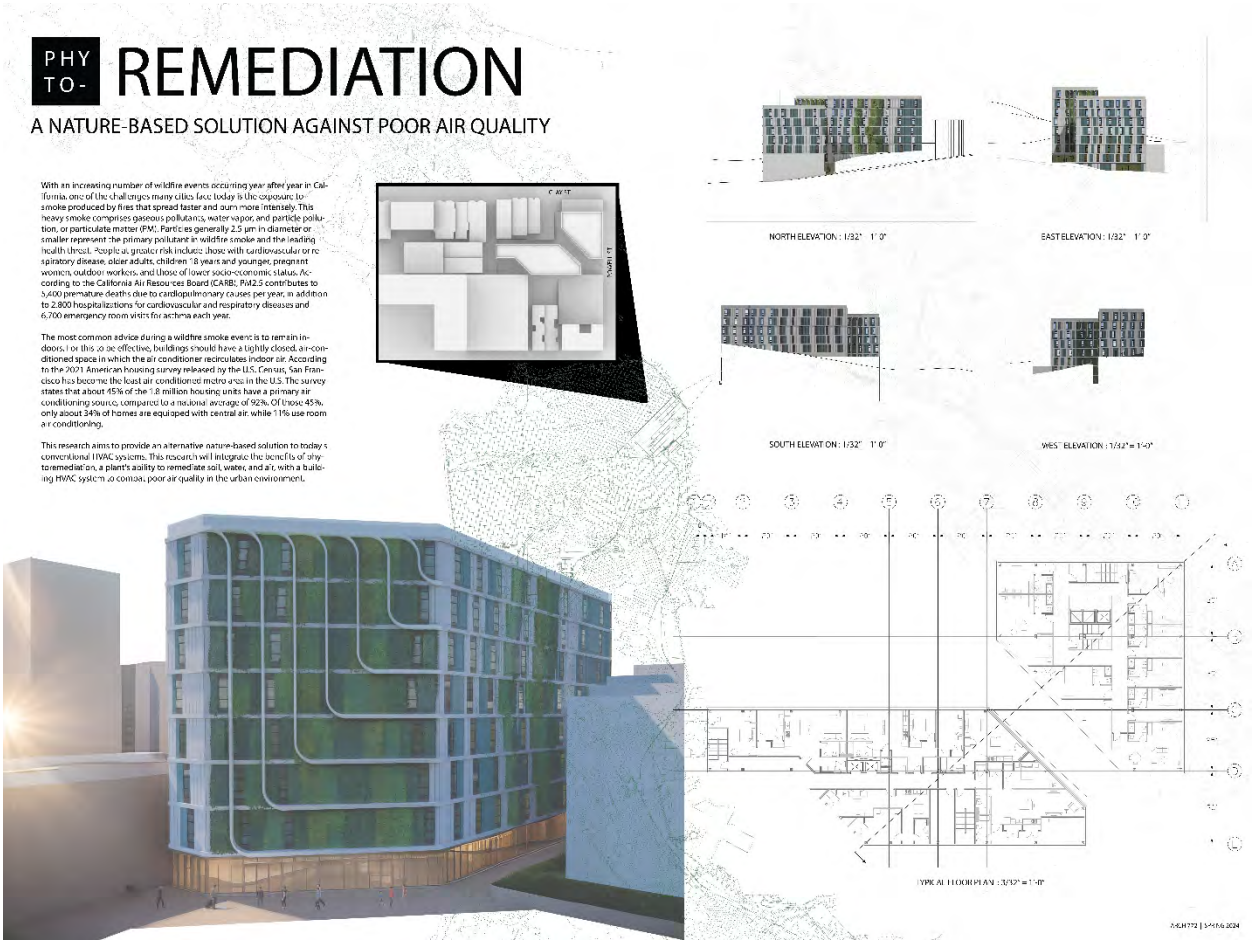

Figure 22. Final Board 01

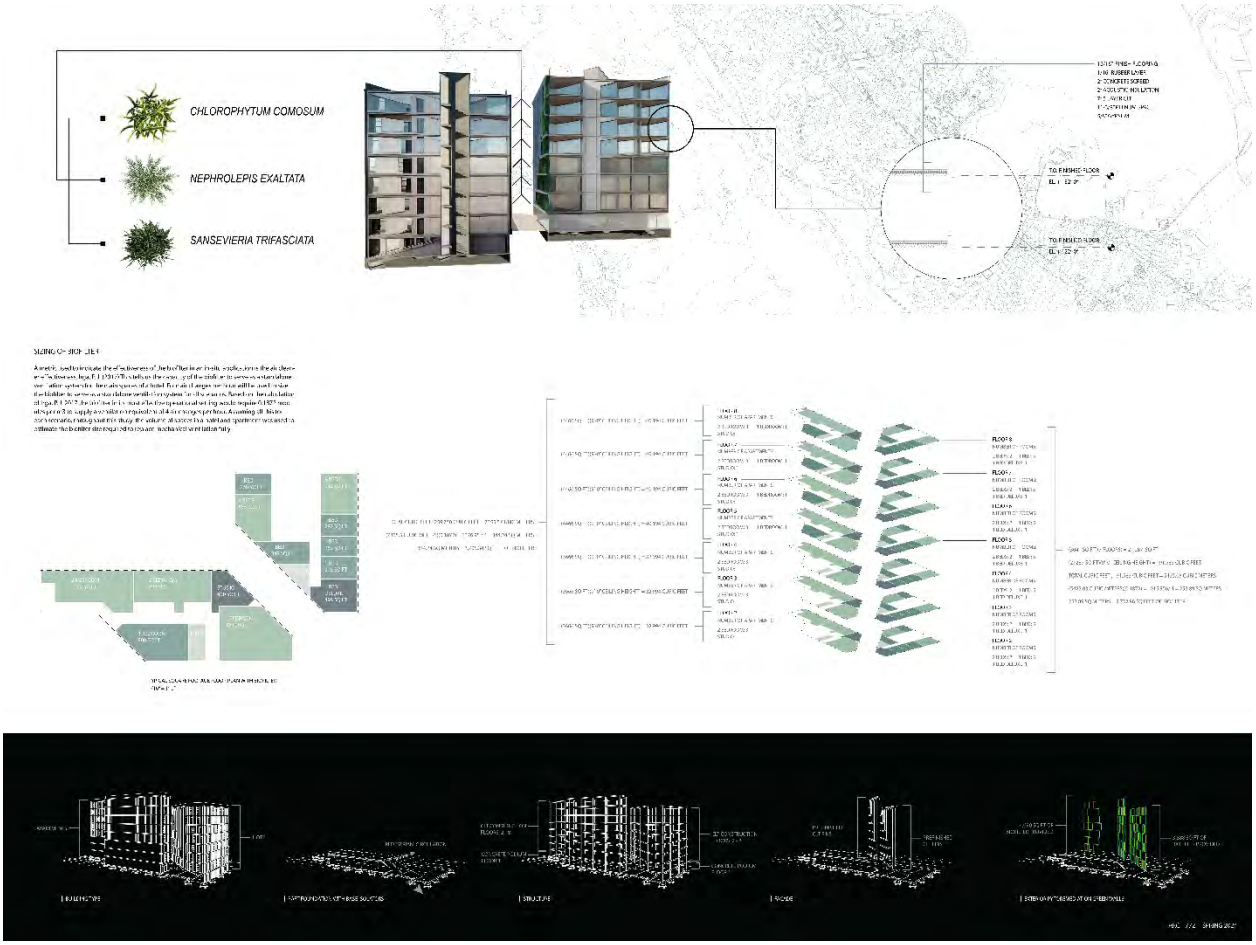

Figure 23. Final Board 02

4.3.2. Supplemental Materials

Also, as part of the project design and documentation, two videos were including as supplemental materials. The First video titled, “Exterior Views”, are meant to showcase both buildings on the site. It’s current surrounding are also visible showing Alcatraz Island, Coit Tower, and the Transamerica Pyramid. The second video titled, “Pedestrian Promenade”, is meant to showcase a pedestrian’s experience as they are walking through the space and noticing important elements of the design project including an apartment entrance, the senior housing entrance, and a second hotel entrance.

4.4. Conclusions

Although much of the research regarding biofilters and relatively new and there is a strong belief in these biofilters that should be considered for future construction. Several studies have been conducted to analyze the effectiveness of a biofilter, however large-scale trials still need to be conducted. Green walls have been previously used in buildings to treat urban stormwater or act as an acoustic buffer. However, only a few have been used to tackle the emergence of particulate matter in the urban ambient air. Many indoor biofilters have been shown to "scrub" the air but have mostly focused on VOCs. Also, biophilic design has been primarily associated with green walls as it has been shown to have a substantial psychological impact on the inhabitants of urban areas. Much of the research out there aided in estimating the sizing but more research needs to be conducted to truly measure the effectiveness of these filters.

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