Correlation Between Attentiveness and Natural Light in a Library

A Major Qualifying Project Submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE

in Partial Fulfilment of the Requirements for the degree of Bachelor of Science

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Abstract

The conditions someone is in can affect the quality of work that they do. This project investigates whether there is a correlation between different amounts of natural light in a room and the attentiveness of a person in that room. We designed a Library to test for this correlation due to the number of different spaces a library can have. The design work covered the interior layout, structural design, and exterior site layout. The Personal Emotional Augmented Controlled Environment (PEACE) project also includes the design of a structural frame. With this knowledge, new considerations can be made when designing work and study spaces so that these spaces can help people work more efficiently.

Authorship

Dominick Timpanaro worked on case studies, site analysis, traffic study, conceptual designs, architectural design, landscape, code research, interior design, structural design, and Revit model. Fangyi Liu worked on the Revit model, the structural design of the building, and the structural frame for the PEACE project.

Acknowledgements

We would like to acknowledge and thank Professor Leonard Albano and Professor Soroush Farzin for their support and contributions to our research, as well as Karen Coghlan for their help with citations and sources on the paper. Also, we would like to thank Karris Krueger, Danforth Kenerson, and Rajul Deelip Raka for their contributions in D-term, 2022, and Esrom Negash for his contribution on this project during summer 2022.

Capstone Design Statement

Worcester Polytechnic Institute requires its students to complete a Capstone Design Requirement for their major. It requires the students to highlight what they have learned from their major. The work on this project is the work needed to fulfill the Architectural Engineering Capstone Design Requirement. The software programs Autodesk Revit, Microsoft Word, and Microsoft Excel were used for the design and organization of the architectural design of the project. The structural work was done using loads from the IBC and strength values for structural steel from the AISC *Manual of Steel Construction, 15th edition*. The structural design and analysis were done in RISA-3D and Excel spreadsheet. The structural work included using the NDS for wood members and the available literature for the supporting aluminum structure. A cost estimate for a prototype of the PEACE project was prepared based on the materials brought and used, and it was completed in an Excel spreadsheet.

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1. Introduction

Finding a place to get work done is a struggle for some students. For some people the environment around them can cause them to lose focus on the task or tasks they are trying to accomplish. There are many factors that can lead to a space not being suitable for a person, but these factors vary from person to person. We look to see how natural light plays a part in making a space a “good” or “bad” influence on a person's attentiveness.

According to Edwards, L, & Torcellini, a Daystar article, “Benefits of Natural Daylighting” (1998), states that there is increased student and teacher attendance, increased achievement rates, reduced fatigue factors, improved student health, and enhancement of general development. Furthermore, natural lighting eliminates noise and flickering from electric light sources and provides the best quality of light available in classrooms, gymnasiums, and corridors. Other research has shown that students in windowless classrooms are more hostile, hesitant, and maladjusted. Also, students in windowless classrooms tend to be less interested in their work and complain more. (Edwards, L, & Torcellini, p17)

This project focuses on how natural light can affect a person's attentiveness when trying to get work done. A library was designed to provide a context for investigating this research, which made the most sense due to a library having various rooms with various purposes/uses. With the knowledge found here we look to see how study/workspaces can be made so that students and other people can work at their most efficient levels.

2. Background

This section discusses general information on attentiveness and the effect of natural light on building occupants. This background information will be helpful for readers to understand the concept of this project.

2.1. Attentiveness

According to the dictionary provided by the APA (American Psychological Association) attentiveness is described in the following two ways: the state of being alert and actively paying attention, and the quality of actively attending to the needs of others. Factors that can influence someone's attention are described as external and internal. Examples of external factors are the size and intensity of a various stimuli, the color or contrast of a stimuli, and the emotional burden caused by a stimulus. Internal factors are how interested a person is in a stimulus, any emotions they have towards a stimulus, effort required by the task, a person's organic state and their train of thought.

2.2. Literature Review of the Effects of Natural Light on Building Occupants

As input to this project, the authors reviewed data and knowledge that covers many aspects of natural light and occupants. Throughout the review the type of occupancy changes (i.e., factory workers and students). The excerpts that follow provided insight into a vast range of things to consider when dealing with natural light in our building space.

The work of Franta and Anstead (1994) discusses the color of the light and how daylight compares to other sources of light. Daylight provides a better lighting environment than cool white or energy-efficient fluorescent electrical light sources because “daylight…most closely matches the visual response that, through evolution, humans have come to compare with all other light” (Franta and Anstead 1994). Most humans prefer a daylit environment because sunlight consists of a balanced spectrum of color, with its energy peaking slightly in the blue-green area of the visible spectrum (Liberman 1991) (Edwards, L, & Torcellini, p3)

According to Edwards, L, & Torcellini, A person's psychological state can be affected by daylight. Humans are affected both psychologically and physiologically by the different spectrums provided by the various types of light. These effects are the less quantifiable and easily overlooked benefits of daylighting. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. One of the important psychological aspects of daylighting is meeting a need for contact with the outside living environment (Robbins 1986).

Those are just two examples of how light can affect a person; other examples would include glare from the light, lack of light, and intensity of the light.

3. Architectural Design

The purpose of this project is to explore the relationship between human attentiveness and natural light in a built space. The space is in the top level of a designed library proposed on Highland Street in Worcester, Mass. The top of the library is a relatively quiet and private space, and the space will be built in one of the rooms. This chapter introduces the case studies of famous libraries and details the architectural design of the proposed library on Highland Street.

3.1. Introduction

Since Highland Street is surrounded by elementary schools, high schools and a college, a public library located on Highland Street would support students in academic achievement, reading and group working, as well as community activities. With the idea of making spaces that we could test for the correlation between natural lighting and attentiveness, a library made the most sense. This is seen in the case studies discussed below in section 3.2 because libraries come in many shapes, sizes and uses, the idea when making the building was to have different spaces unique to their own purpose.

3.2. Case Studies

Four libraries were researched to prepare to design the library. The libraries were selected for their use of natural light and the area around them, their interior layouts, and their exterior layout.

3.2.1. Clifton Park Public Library

Located in Upstate New York, the Clifton Park Public was chosen for its use of different-sized windows (see Figure 1 and 2). The building flows with light from the assortment of windows throughout the multi-floor space. The floor layout was also looked on for inspiration, due to the flow from the first to second floor. The second-floor features spaces for cooperative work, solo work, meeting spaces and has a large area for children. This children's area consists of their collection of children's books, as well as areas that a child could find comfortable for reading, and computers loaded with educational games.

Figure 1. Exterior Front View of The Clifton Park Public Library, Picture from WCGS

Figure 2. Interior view of the Clifton Park Public Library, "Clifton Park Halfmoon Public Library" by David Lee King is marked with CC BY-NC-SA 2.0

3.2.2. Central Library in Copley Square

This library was chosen for inspiration due to its floor layout. As seen in Figures 3 and 4, the library features many types of unique spaces, such as offices, reading spaces, café spaces, research rooms, and meeting rooms. For inspiration and guidance in this project's design, the floor layout of the Central Library was looked at. Specifically looking at the layout of the different sections of literature all in the same room.

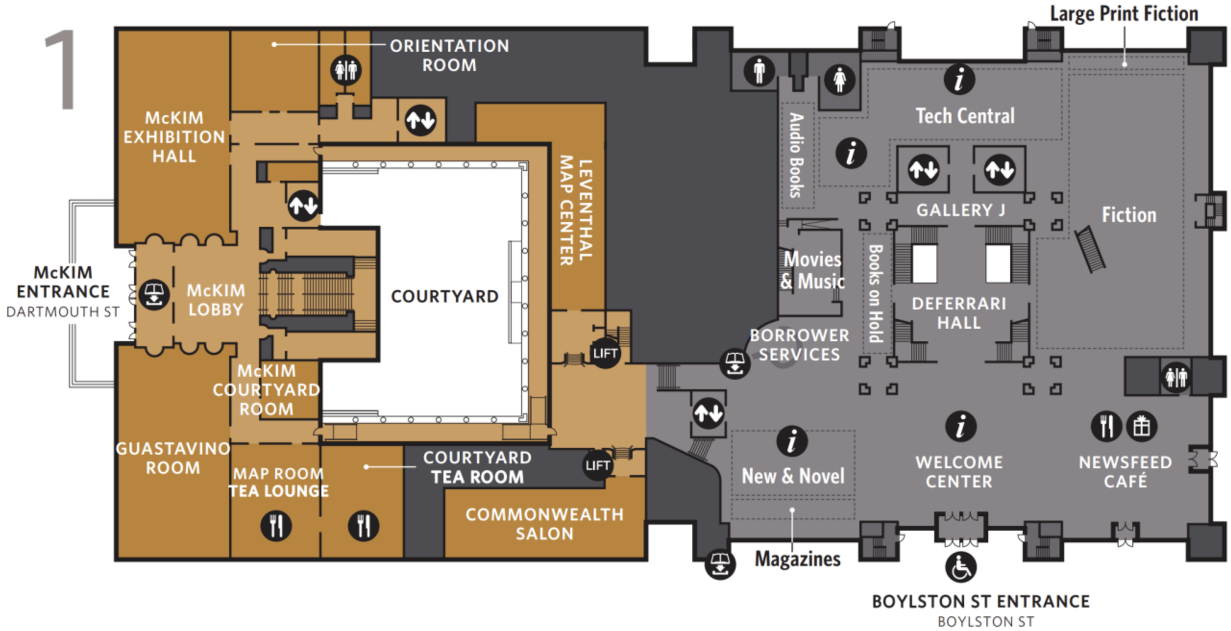

Figure 3. Floor Plan for Central Library

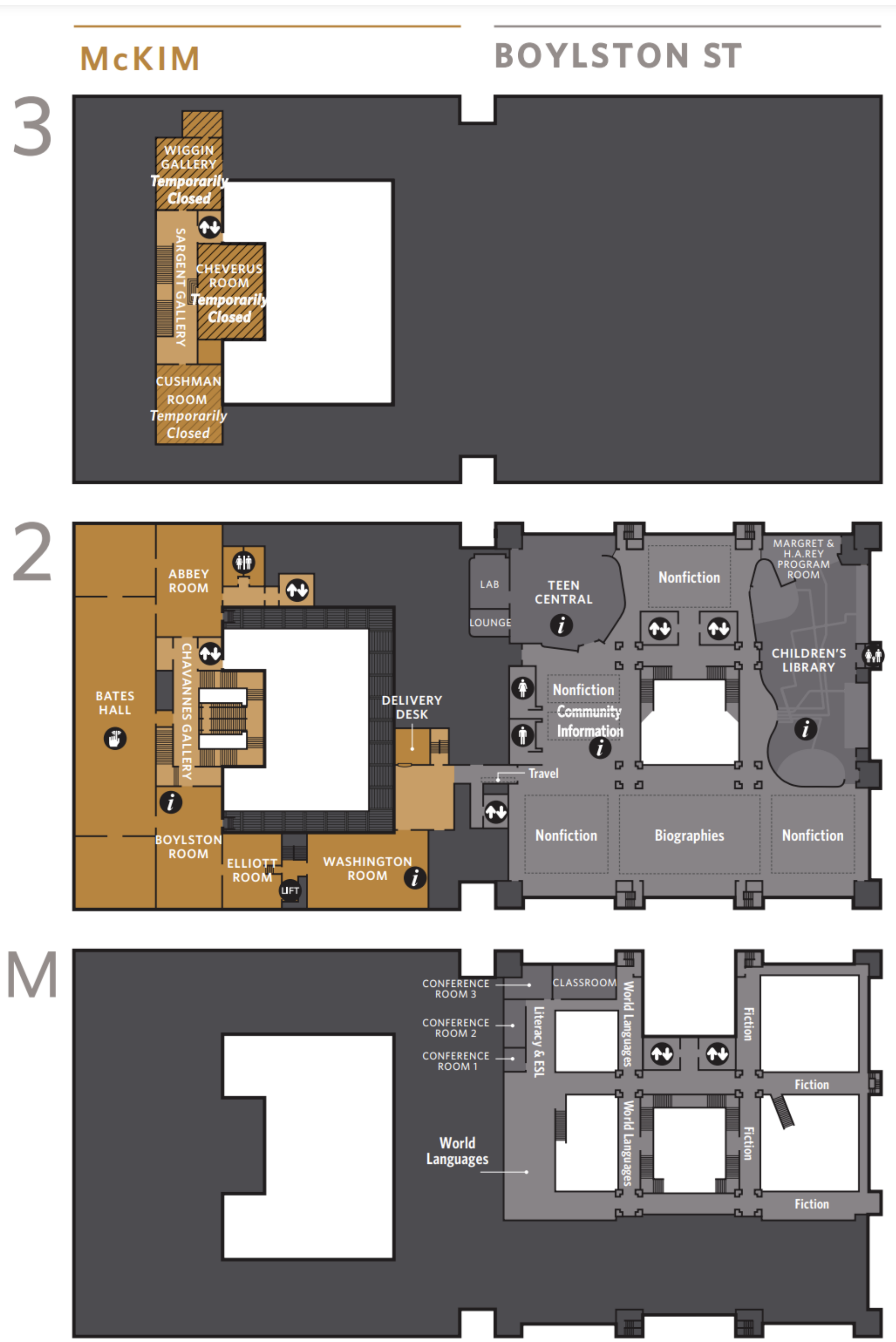

Figure 4. Floor Plans for Central Library

3.2.3. Geisel Library

The Geisel Library is the main library building for the University of California, San Diego, and it was designed by William Pereira. It opened in 1970 and had renovations done in 1993. The library was constructed in a way that its arches and other features resemble hands holding a stack of books (Figure 5). The initial design was made with the intention of renovating the space, which was done in 1993. The Geisel Library was researched to be used as an example of a reinforced concrete structure. The interior layout was also investigated for guidance for this project's design (Figure 6). The library also features landscaping known as The Snake Path, a path that winds through an assortment of gardens.

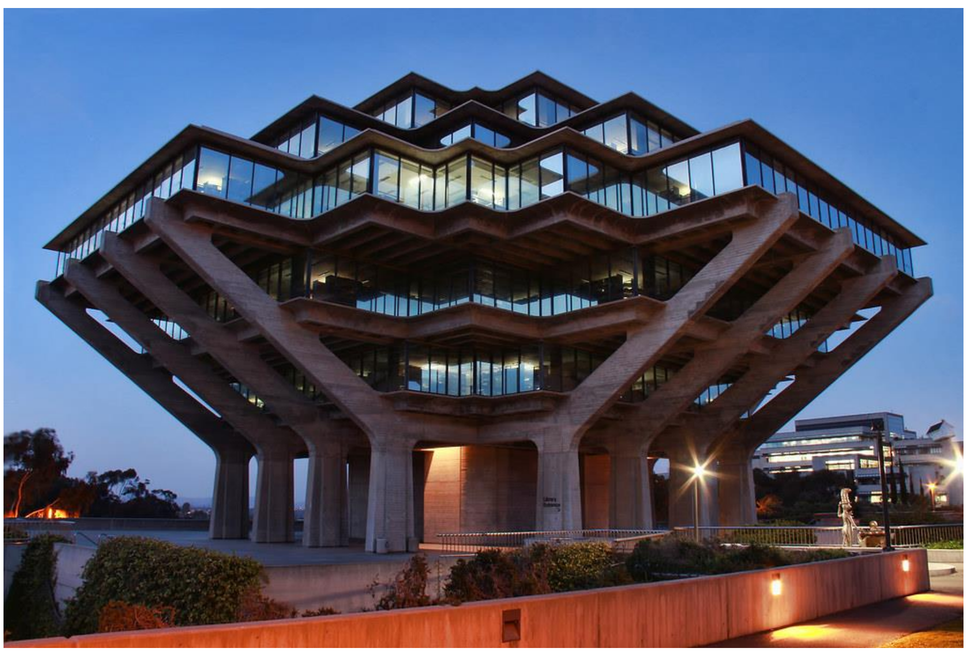

Figure 5. Exterior View "Night View of The Geisel Library, University of California San Diego" by o palsson is marked with CC BY 2.0.

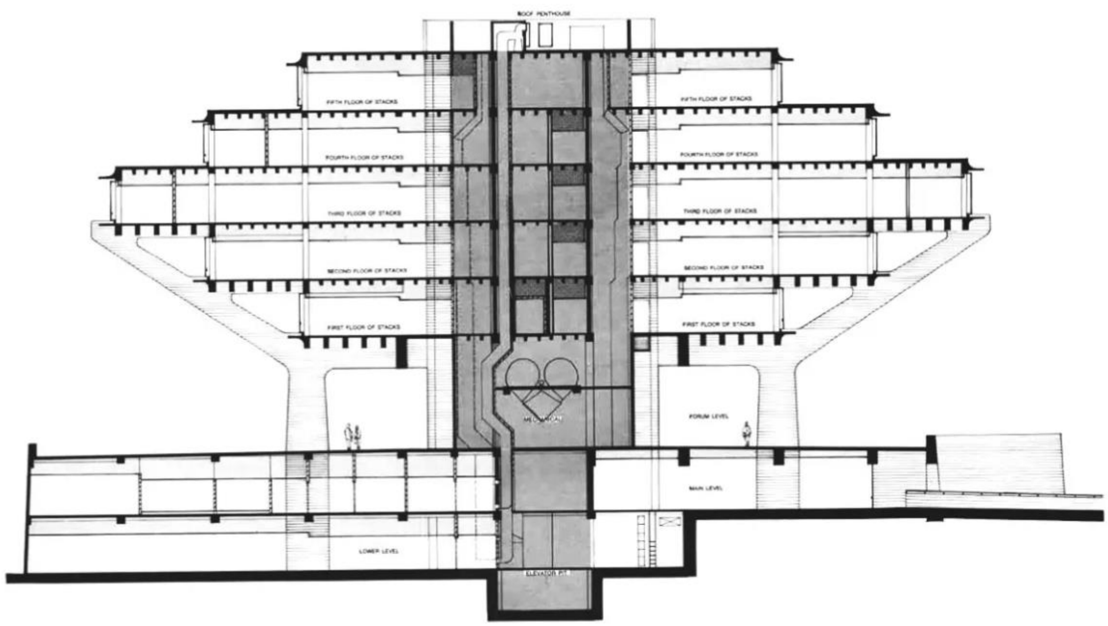

Figure 6. Section View of Geisel Library, ArchDaily

3.2.4. Stuttgart City Library

The Stuttgart City Library (Figure 7 and 8) is a large square building with a block façade around its exterior shell. The central aspect of the library, called the heart, is the true location of the library space. The interior is based off the Pantheon. The space is open in every direction on the inside and features a multi-floor gallery space. The books are located on the exterior of the heart area, which is an interesting way to organize the space and was considered during the design of this project.

Figure 7. Exterior View of The Stuttgart City Library, "Cube" by timtom.ch is marked with CC BY-NC-SA 2.0.

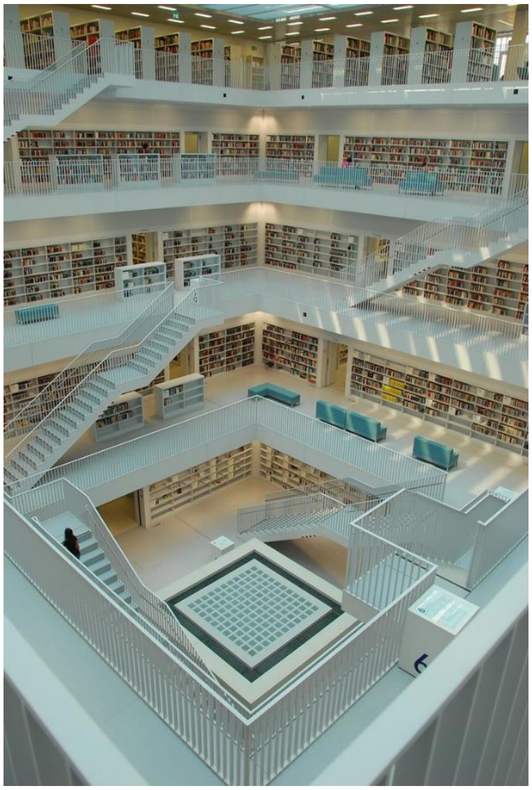

Figure 8. Interior View of the Stuttgart City Library, "Stuttgart Library Interior" by bobarcpics is marked with CC BY 2.0.

3.2.5. Summary of Case Studies

The four libraries highlighted above were researched to give ideas on how to design the proposed library. These designs varied from one another, setting the table to make the library in a way that fits with the surrounding community.

3.3. Site Analysis

This section will introduce the site analysis on Highland Street. Site analysis is an essential factor in the design process because it ensures the building makes the best use of the resources like natural light and views on the site.

3.3.1. Traffic

Traffic in the area is not bad for a city, and the noise level in the area goes up typically when the number of vehicles on the road increases. But the noise of traffic is not too distracting or loud for those in the building. The scale used in the accompanying figure was derived from Google's traffic option on Google Maps - the red circle indicates the point of measurement (Figure 9). The scale takes these colors and converts them into quantitative descriptors of traffic.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
9:00 AM	1	2	2	2	2	2	1
12:00 PM	2	2	2	2	2	2	2
3:00 PM	2	1.5	2	2	2	2	2
6:00 PM	2	2	2	2	2	2	2

Rank	Meaning (Fast meaning less traffic)
1	Fast
2	Kind of Fast
3	Kind of Slow
4	Slow

Figure 9. Traffic Ratings and Explanation

3.3.2. Transportation and The Surrounding Area

This location is right in the middle of a few schools and a college, giving people in the surrounding area a place to do work. There are numerous bus stops on Highland Street, and sidewalks all around the area. There is not much space for off-street parking.

Figure 10: Screenshot of Google Maps Showing the Sidewalks and Bus Stops

3.3.3. Classification

The site is located at 101 Highland Street, Worcester, MA 01609. It was chosen due to its access to Highland Street, large local community of residents and students, and for its access to public transportation. According to Worcester's website for zoning, this plot of land falls under the distinction of BL1 which allows libraries. Worcester is in Massachusetts, in the Northeast of the United States, where it can rain and or snow depending on the time of the year.

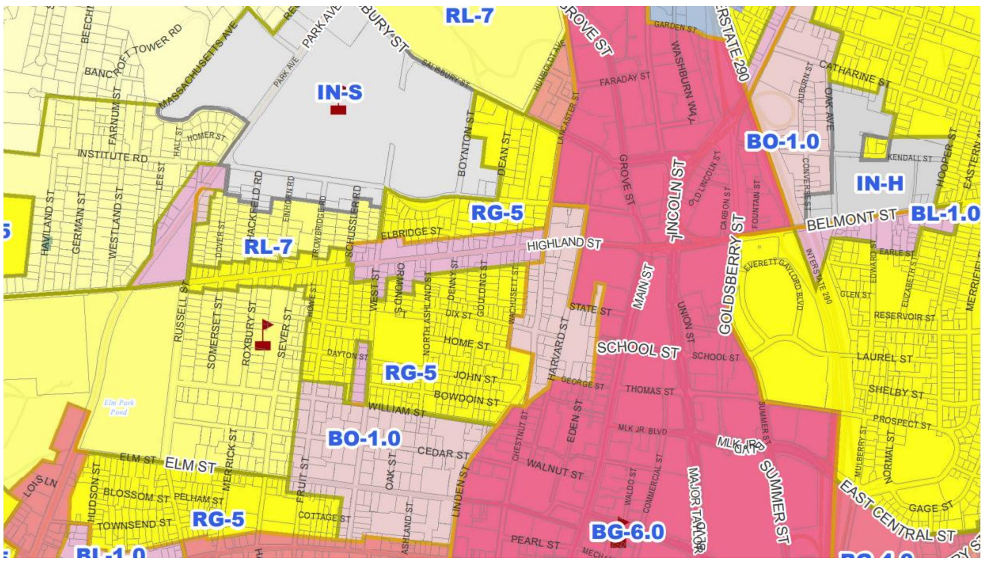

Figure 11. A Map for Zoning, The Blue dot shows the location of the site, Zoning ordinance & map | city of Worcester, ma. (n.d.)

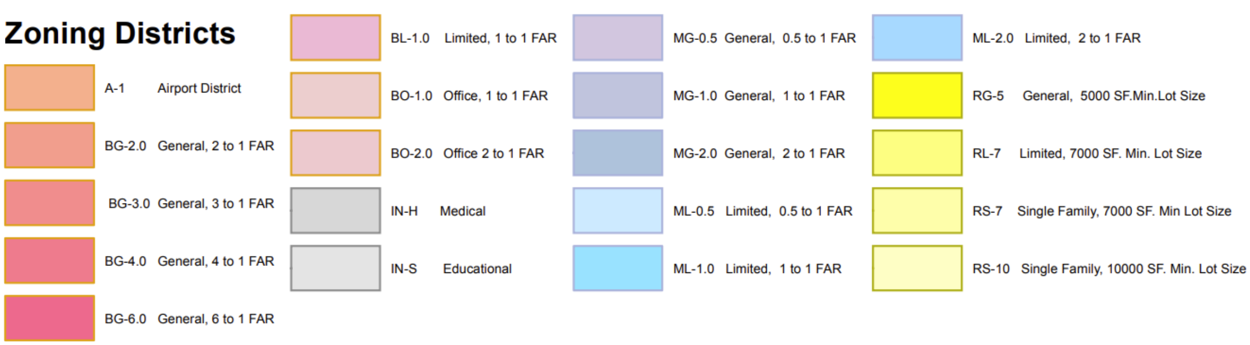

Figure 12. Key for Zoning Distinctions Map, Zoning ordinance & map | city of Worcester, ma. (n.d.)

3.3.5. Parking Spot and Set Back

Due to this distinction and the zoning laws of the area, the maximum floor area is restricted to 15,000 square feet. According to the same source, the overall setbacks required for the site are 10 feet to the sides of the lot and 20 feet for the rear. The metric used for determining the required amount of parking was one spot for every 350sq ft of floor space (see Figure 14, which is excerpted from the Worcester Zoning Ordinance) using that ratio resulted in the need for 29 to 31 regular spaces and two accessible spaces (Figure 15).

Figure 13. Google Maps screen shot with annotation

TABLE 4.4 - OFF-STREET ACESSORY PARKING REQUIREMENTS

USE	PRIMARY SPACES	
RESIDENTIAL	**Number per Measurement Unit**	
Single, two or three family dwelling	2	Dwelling unit
Multi-family dwelling	2	Dwelling unit
Group Residence	0.25	Bed
Lodging House	0.5	Bed
Housing for elderly (subsidized)	1	Dwelling unit
Dormitory	0.33	Dwelling unit
Continuing Care Retirement Community	1	Dwelling unit
CCRC Associated Medical Facilities	0.5	Bed
Temporary Shelter	0.1	Bed
All other Residential, including Hotel & Motel	1	Bedroom
Limited Residential Hospice House	0.5	Per bed, plus (1) per employee living on the premises
GENERAL	**Number per Measurement Unit**	
Nursing, Convalescent Home/Facility	0.33	Bed
Hospital		
In-Patient	1	Bed
Out-patient	3	Treatment room/space
Clinic	4	Treatment room/space
Educational Institution	10	Classroom, plus residential above
Places of Assembly (non-profit or profit)	0.25	Person accommodated
Day care center/Adult Day Care Center	1	Teacher or staff person
Library, museum, recreation/service facility	1	350 sf. Gross floor area
Club, lodge, other (non-profit and profit)	2.5	350 sf. Gross floor area
Health club (profit)	1	350 sf. Gross floor area
Heliport	1	350 sf. Gross floor area

Figure 14. Table 4.4, Building & zoning | city of Worcester, ma. (n.d.)

HANDICAPPED PARKING REGULATIONS
Combining the More Stringent Regulations of the Americans with Disabilities Act and the Massachusetts Architectural Access Board

All parking lots for customers or visitors (with the exception of valet parking), should have accessible spaces for vehicles with proper identification. Parking lots for employees (built or altered as of 1/26/92) must also have accessible spaces. If an employee with a disability needs such accommodation in an older parking lot, s/he should request it of the employer.

Parking Space Size:
Accessible spaces should be at least 8 feet wide, with level access aisles not less than 5 feet wide. Two accessible spaces may share a common aisle.

Location:
These spaces should be in a level location providing the shortest safe, accessible route of travel to an accessible entrance. With more than one accessible entrance, the spaces should be located near each accessible entrance. Sidewalks at such spaces should have curb cuts at each access aisle, so a person is not required to enter the stream of traffic to get to a sidewalk.

Parking Space Number:

Total Spaces	Required Accessible Spaces (521 CMR and ADA)
1-4 (ADA Only)	1 spaces without signage
5-14 (ADA Only)	1 space
15-25	1 space
26-50	2 spaces
51-75	3 spaces
76-100	4 spaces
101-150	5 spaces
151-200	6 spaces
201-300	7 spaces
301-400	8 spaces
401-500	9 spaces
501-1000	2% of total
1001 and Over	20, plus 1 for each 100, or fraction thereof, over 1000

Figure 15. ADA Handicap Parking Spot Guide, mass.gov

3.4. Overall Design

This section discusses the overall architecture design of the library including the program, site plan, and floor plans.

3.4.1. Program

Table 1 summarizes the space programming for the library and the total square footage. The library has three levels, and each level has a bathroom and stairs. The first level is designed as a public space. There is more space, an open reading area, and office space for collaboration. The second level has more space for bookshelves and storage. The third level has Tech suites and conference rooms for people who like self-study.

Table 1. Programs of the Library

Space	*SUG*	*Gross Area*	*Quantity*	*TOTAL SQFT*
Conference	19x13	247	2	494
Tech Suit	11x12	132	4	528
Cubby Spaces	5.6x5	28	8	224
Storage Space	6x8 6x10	48 60	1 each	108
Office	10x13	150	2	300
Bathroom	8.6x11	94.6	6	567.6
Computer space	3.6x4	14.4	8	115.2
Total				2336.8

3.4.2. Overall Architectural Design

The library's center is a 20ftx30ft rectangle, with two 10x20ft rectangles (wings) embedded in the street-facing side with a 45-degree twist. A small balcony extends from the second-floor façade for visitors to have a street view and a place to rest.

3.4.3. Site Plan

The back and east side of the building are the parking lot. The walking path is along the front of the building and plants are west and front side.

3.4.4. Floor Plans

The preliminary concepts for the floor plans were all sketched by hand and can be found in Appendix A. We took a screen shot of the floor layout and added it to a PowerPoint presentation -- there were three identical slides containing an open layout of the building. The PowerPoint presentation was then formatted to fit all the slides on one sheet of paper and printed.

The first floor was designed to house the library's many books, a café-like space, and rooms/storage for library staff (Figure 16). It is also home to a computer area with several computers to be used by those visiting the library. The checkout area has an exterior window slot for people returning books. The blue dots represent the planned location of the columns for the building frame. The interior column spacing was set to balance the desire for flexibility with economical girder sizes for resisting gravity loads (Figure 17 and 18).

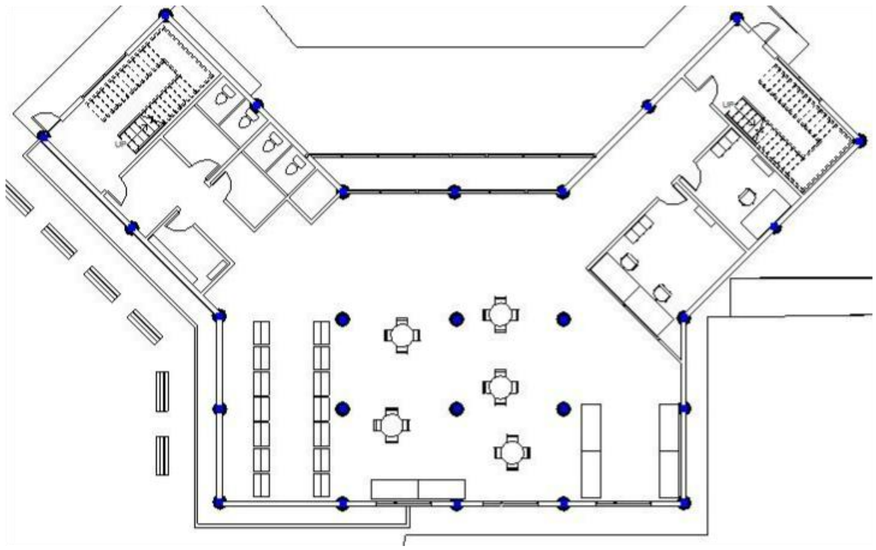

Figure 16.1st Floor Plan

Figure 17. 1st Floor View 1

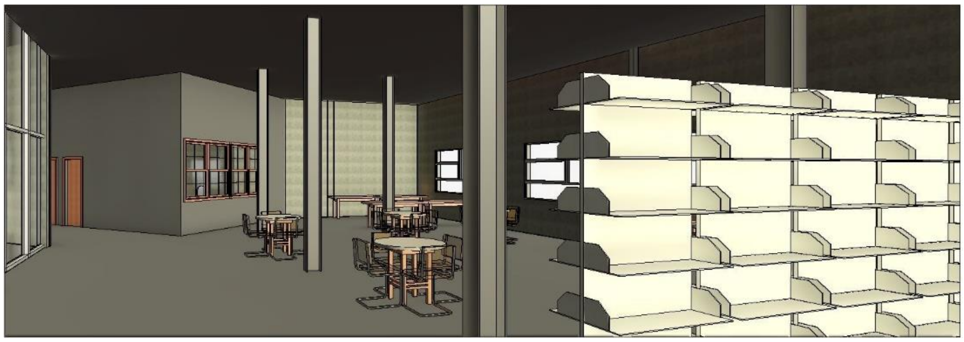

Figure 18. 1st Floor View 2

The second floor features more bookshelves and spaces for people to read and or do other activities (Figure 19). One of these areas will house a large semi-circular couch (Figure 20). Following the outline of the couch there is a table with stools for people to work on. Scattered around the area there will be different forms of seating that can be moved around to fit the changing uses for the space (Figure 21).

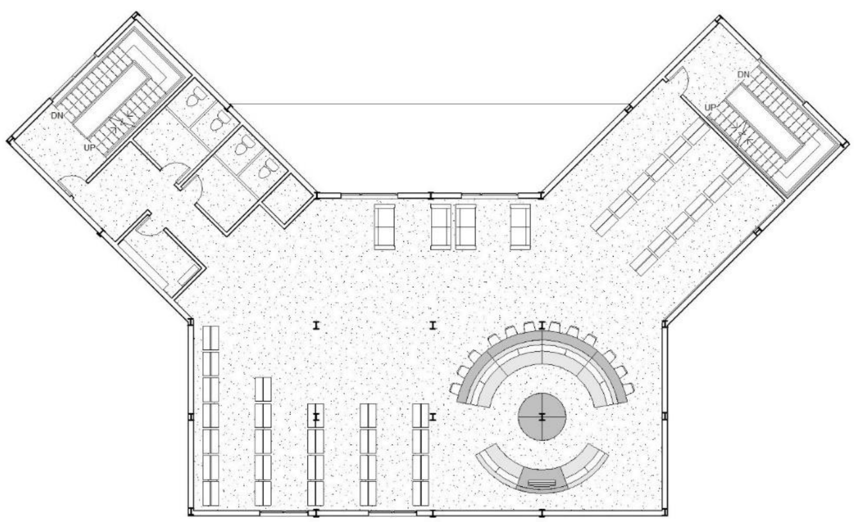

Figure 19.2nd Floor Plan

Figure 20. 2nd Floor View 1

Figure 21. 2nd Floor View 2

The third floor is the working floor where people come to do work; it features several tech suites designed for up to four people, as well as two large conference rooms (Figures 22, 23, and 24). These rooms were set up to allow the users to control the space, allowing them to adjust how much natural light is let in. See Appendix B for preliminary sketches of the tech suites and conference rooms. Renderings are shown in Figures 25 and 26. The third floor includes tables set up to allow a more casual place to work as well as cubby spaces for people to complete their individual work.

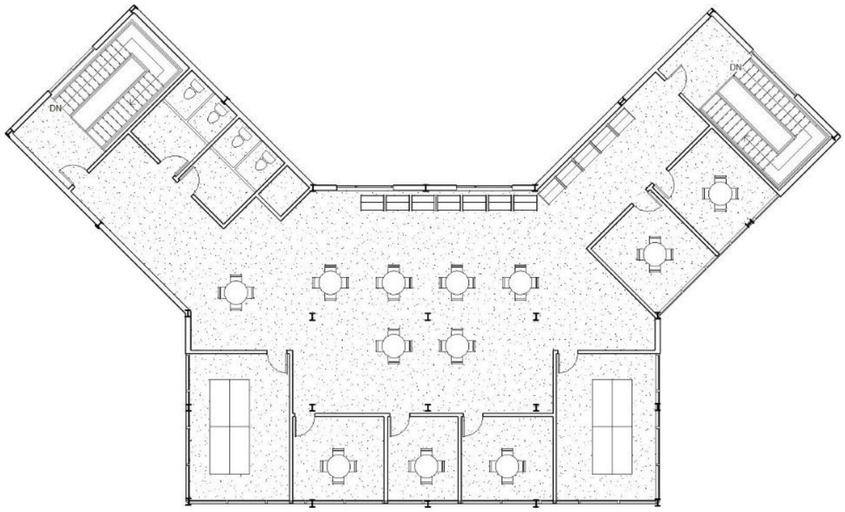

Figure 22. 3rd Floor Plan

Figure 23. 3rd Floor View 1

Figure 24. 3rd Floor View 2

Figure 25. Tech Suite

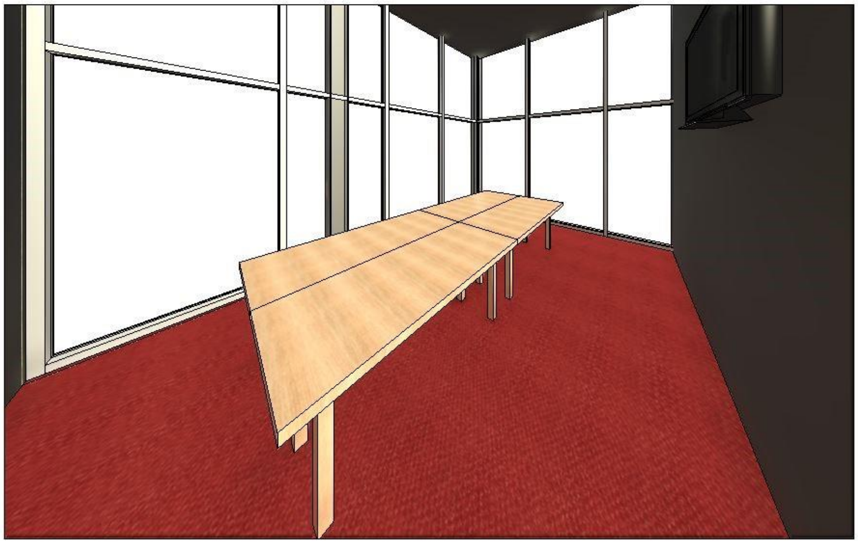

Figure 26. Conference Room

3.5. Landscape

When the weather is nice there is an area outside the library for people to gather and use. The landscape features flower boxes around the building, a walking path, park style benches, picnic tables, and a pond. This area will be surrounded by a line of bushes forming a wall that blocks the space from the sidewalk and the road. Putting life in the pond would depends on how storm water runs off in the area. The green rectangle is the area where the pond would go; the true shape of the pond would be left up to a skilled pond builder.

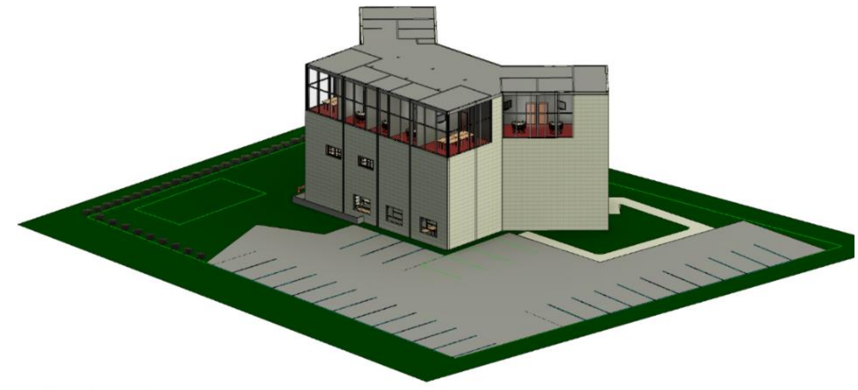

Figure 27. Exterior Rendering of the Library and Site

3.6. PEACE

With the development of technology, the functions of urban libraries are gradually changing. Modern libraries are developing in the direction of diversification and integration to meet the various needs of the public and increase users' participation. Modern libraries retain the functions of traditional libraries; however, public and private space to study, read, conduct research, collaborate, and communicate have been added to the description of a modern library. A public library should include:

- Public reading spaces
- Working space
- Media and technology center
- Quiet working space
- Room for staff members

When the library has multiple floors, architects tend to have the public space and collaboration space on the entrance and lower levels and a quiet area in the upper levels to provide a relatively insulated space for people to work and study.

Similarly, the proposed Highland St. library adopts similar ideas. On the first floor, public space includes bookshelves, a reception desk, an electronic workstation, and a cafe. The second level is a combination of quiet and public space where the public space could be used as a group work section or a reading section. The third level is for people who need and want to be in a quiet space. Tech suits are a space for a small group of people to collaborate or self-study. The public reading and working space can be used as a multipurpose space and provides flexibility in the use of space.

One room is also used to create a Personal Emotional Augmented Controlled Environment (PEACE) space. It consists of three walls and a ceiling, and each of them is constructed from 3.34'x3.34' triangular panels. Each division and top is connected to a beam and column (hanging from the ceiling) and move independently. The room has controlled ambient light intensity, color, sound, and scents projected by a projector. When people walk into this room, they could put a ubiquitous EEG headset on to record their data like heart rate and skin conductance. Meanwhile, they could set up the configuration of the PEACE to induce different feelings and emotions. The detailed information for the PEACE prototype is in Chapter 5 section 3.

4. Library Structural Design

4.1. Introduction

The purpose of a building structure is to resist the lateral and gravity load for its inherent stability and to protect the occupants and interior construction from environmental effects. The structure of the building must take into consideration that the building will be home to people and books, so it must be able to handle the appropriate design loads, as defined in the *Massachusetts State Building Code*. Due to the location of the site, the local building code also requires the consideration of snow loads.

4.2. Layout

We first had to choose how each floor was going to be supported. The first-floor level relies on a slab-on-grade to support the dead and live loads. The second-floor level relies on a grid of beams and girders to support a concrete slab on a metal deck. See Figure 28 below for the layout of the supporting beams and girders on the second floor (the numbers pertain to the members and load calculations presented in Table 2). Blue, yellow, and green lines represent beams while red lines represent girders. This layout was chosen because it provided the best balance between clear span distances and member sizes. Table 1 has the load calculations based on floor areas, and these were used for the member load calculations in Table 2. Table 2 presents calculations of loads and bending moments for the different spans of girders and beams.

4.3. Calculations and Member Sizes

After designing a few conceptual layouts, we decided to go with the one we chose due to the spacing working the best for the floor layout and for the flow of the building. We used a spreadsheet to organize our data and run the calculations.

After calculating the loads, the *AISC Steel Construction Manual, 15th edition* was used to determine the required size of the structural steel beams, girders, and columns based on the philosophy of Load and Resistance Factor Design (LRFD). When selecting the member sizes, a decision had to be made between having many different sized members or specifying sizes that worked for most situations, which would promote consistency throughout the systems. We decided to limit the number of different sized members throughout the system as a strategy for improving constructability.

The beam size chosen was W16x89, and this member size will support all loads for any span beam span. The girder sizes are W18x130, and this member size will support the loads put on the girders for all spans in the building.

We also used the *AISC Steel Construction Manual, 15th edition* for the column sizing. Based on the building being forty-five feet tall and the magnitude of the maximum column design loads throughout the building, we decided to go with W12x87 for our columns, providing the necessary support for the floors and roof of the building.

Table 2. Distributed load of the structure

	Distributed Load (psf)
Floor	
Dead Load	75
Live Load	150
Roof	
Dead Load	75
Live Load	20
Snow Load	50
Deck load	16

Table 3. Load Combination

BEAMS & GIRDERS

	Load Combination			
FLOOR	1.2D+1.6L	1.2(75)+1.6(150) =	330	psf
ROOF	1.2D+1.6S	1.2(75)+1.6(50) =	170	psf
COLUMN				
	Load combination			
COLUMN	1.2D+1.6L+0.5S	1.2(75+75+75) +1.6(150+150) +0.5*50 =	775	psf

Table 4. Load on each beam and columns calculated by tributary area

Area(ft2)	*Load (lb)*	*Load (kips)*
48	37200	37.2
90	69750	69.75
84	65100	65.1
96	74400	74.4
180	139500	139.5
168	130200	130.2
209	161975	161.975
221	171275	171.275
196	151900	151.9
223	172825	172.825
112	86800	86.8
184	142600	142.6
92	71300	71.3

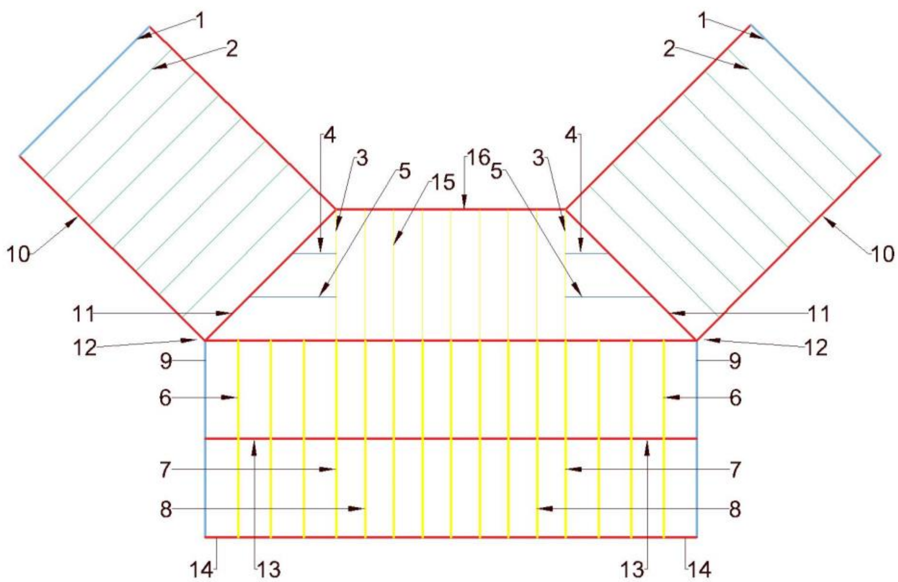

Figure 28. Location and Numerical Identification of Beams and Girders

Table 5. Beam and Girder Load Calculations

Floor Beams	*Area(ft2)*	*Load(kips)*	*Roof Beams*	*Area(ft2)*	*Load (kips)*
Bottom side	24	7.92	Bottom side	24	4.08
Bottom 4' mid(12')	48	15.84	Bottom 4' mid(12')	48	8.16
3.5'&4' (12')	45	14.85	3.5'&4' (12')	45	7.65
Bottom 3.5'(12')	42	13.86	Bottom 3.5'(12')	42	7.14
Top 3.5'(16')	56	18.48	Top 3.5'(16')	56	9.52
Top side	114	37.62	Top side	114	19.38
Wing side	46	15.18	Wing side	46	7.82
Wing middle	92	30.36	Wing middle	92	15.64
Triangle short	35.1	11.583	Triangle short	35.1	5.967
Triangle long	91.6	30.228	Triangle long	91.6	15.572

Table 6. Load on beam and floor girders

Floor Girders	*Area (ft2)*	*Load (kips)*	*Roof Girders*	*Area (ft2)*	*Load (kips)*
Bottom	360	118.8	Bottom	360	61.2
Middle	720	237.6	Middle	720	122.4
Top lower	536	176.88	Top lower	536	91.12
Top	176	58.08	Top	176	29.92
Wing lower	544	179.52	Wing lower	544	92.48
Wing two side	184	60.72	Wing two side	184	31.28

5. PEACE

5.1. Introduction

The purpose of PEACE is to create an immersive space with movable panels and conduct an experiment within the modular VR environment to explore the relationship between natural light and attentiveness. The PEACE space required a connection system to form the triangular panels into walls and ceilings. The connection needed flexibility, allowing adjacent panels to move independently, and it had to be scalable to create the desired enclosure for experimenting and collecting different data in a modular VR environment afterward.

5.2. Introduction to the Case Studies

Case studies were selected in a book called “Interactive Architecture – Adaptive World.” We choose four categories, catalyze, communicate, evolve, and mediate, and each category has three to four cases architecture. The idea was to use the concepts and skills to translate ideas into architectural form.

5.2.1. Catalyze

Catalyze means to bring about and inspire. In architecture, we should design a platform for the future, not the future itself—the catalyst for things that were never intended to. The first project is the EPIPHYTE CHAMBER. It is envisioned as an archipelago of interconnected halo-like masses that mimic human sensation through subtle, coordinated movements (Figure 29). An inflatable plant that grows without soil since local interactions between individual modules can lead to the emergence of global behavior. The EPIPHYTE CHAMBER is a sculptural work that explores artificial intelligence techniques through artificial intelligence, digital structures, and interactive technologies to create a biomimetic growing environment. An interwoven design of thousands of lightweight components and an elaborate canopy breathe and whisper in harmony. The fauna contains chemical metabolism that moves in slow reaction to people's reaction.

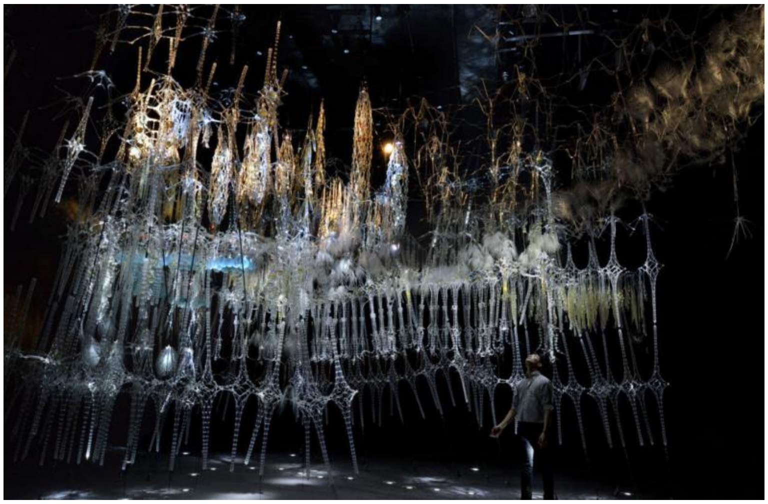

Figure 29. Epiphyte Chamber

The entire space resembles a womb, an interactive system that includes embedded machine intelligence that triggers the action of breathing, embracing, and swallowing through audience interaction (Figure 30 and 31). Technologies for interaction include touch, multitouch, gesture, and cognitive control.

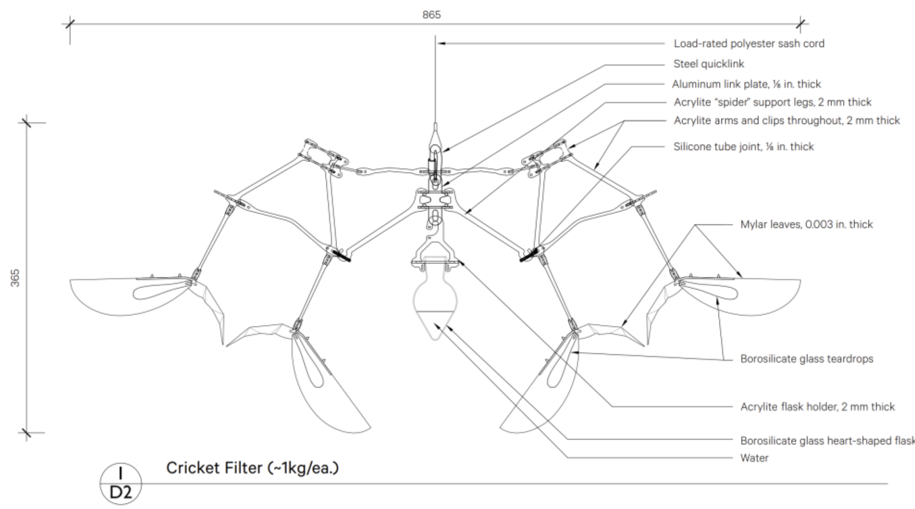

Figure 30. Architectural drawings of the complexity of the ecosystem 1

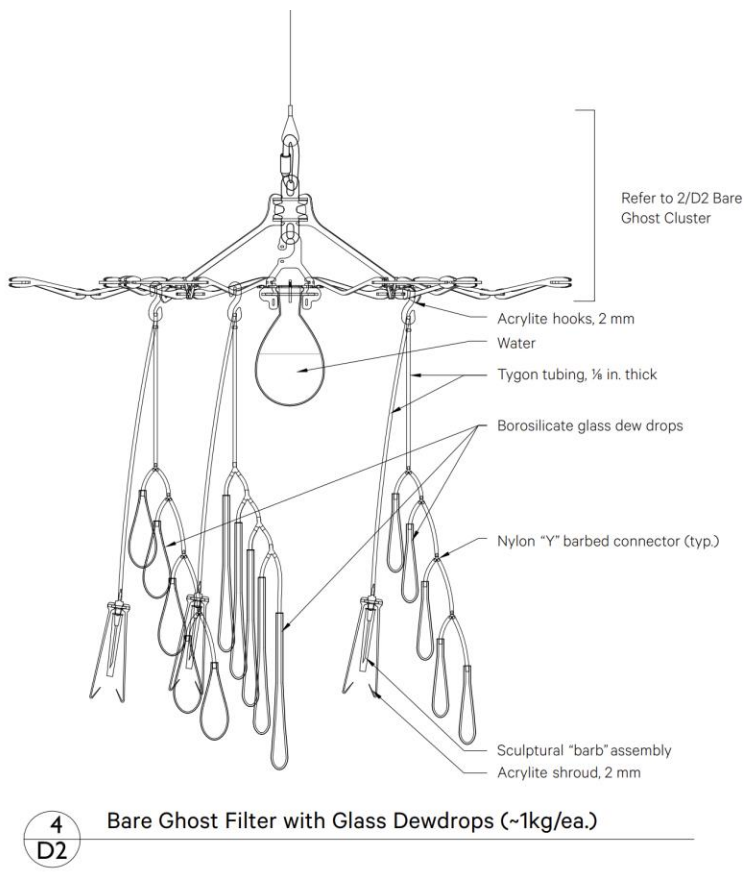

Figure 31. Architectural drawings of the complexity of the ecosystem 2

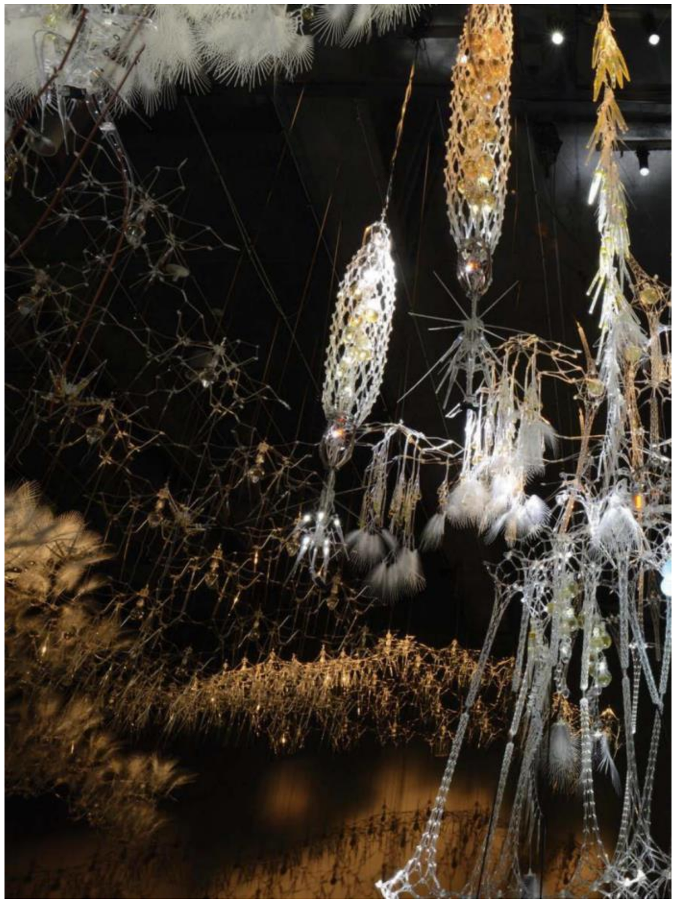

Figure 32. View of Epiphyte Chamber

The second project is “Conventions of Controls,” a project to promote gestural movement as a form of control of architectural elements. The prototype consisted of a three-sided room with no ceiling, and the walls contained three motorized windows and a door that were independently controlled. The wall also had a window that could rotate open or closed along the x-axis and a single partition wall that could move forward and backward on the y-axis (Figure 33). A Microsoft Kinect sensor was used to track the gestures of test subjects at the beginning, but the more recent projects utilize a Leap Motion instead (Fox, 2016). Three key strategies in building the structure were gestures, physical movement, and scale. The conclusion of this study states that gestural movement is the best-suited form of control of interactive architecture and building elements, not touch, speech, or cognitive control (Figure 34 and 35).

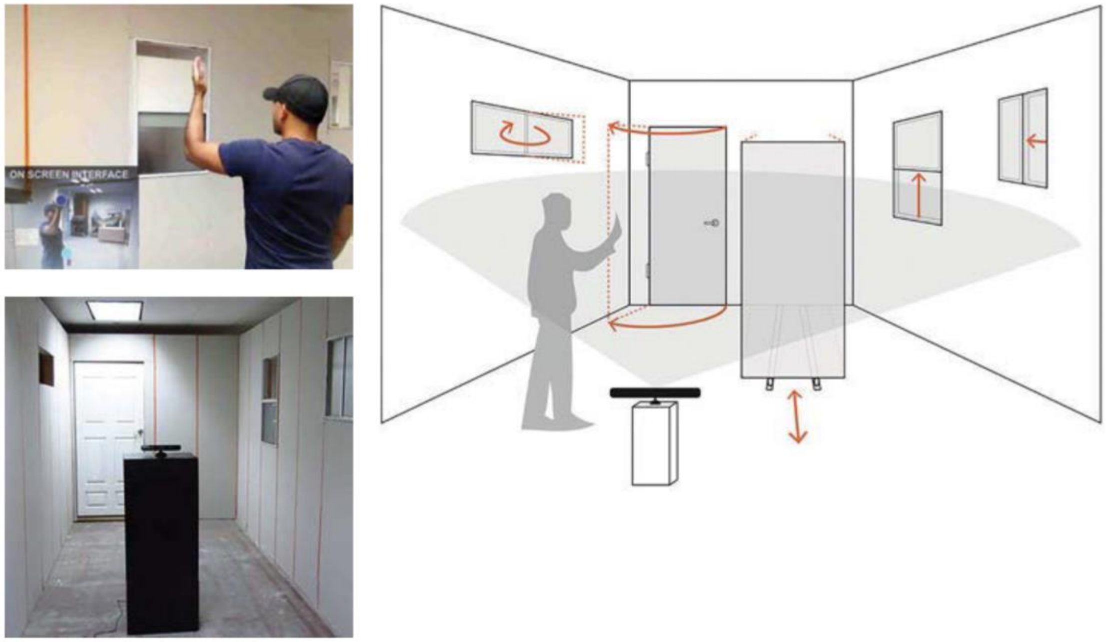

Figure 33. Constructed test cell for gestural control

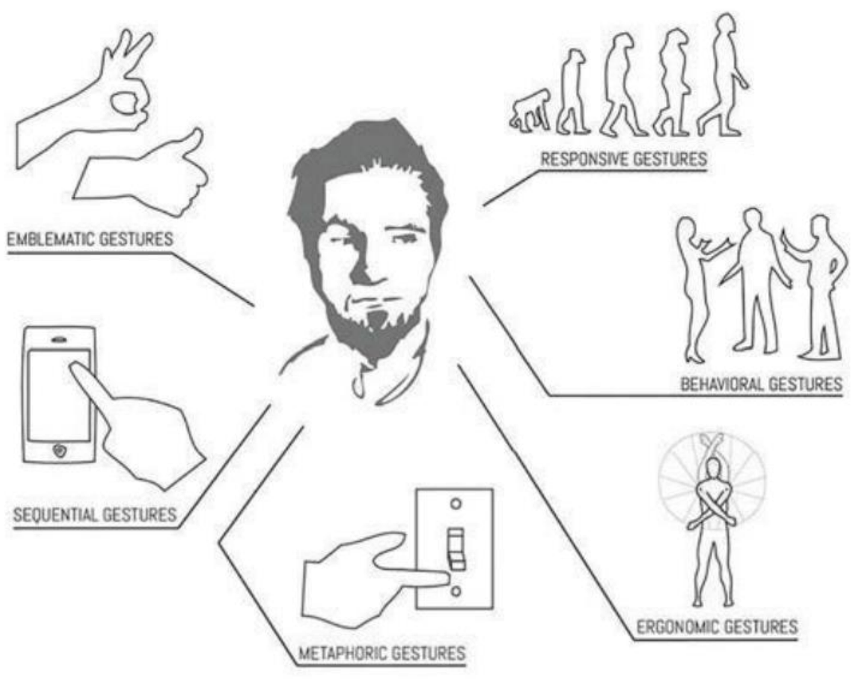

Figure 34. Diagram of the origins of intuitive gestural languages

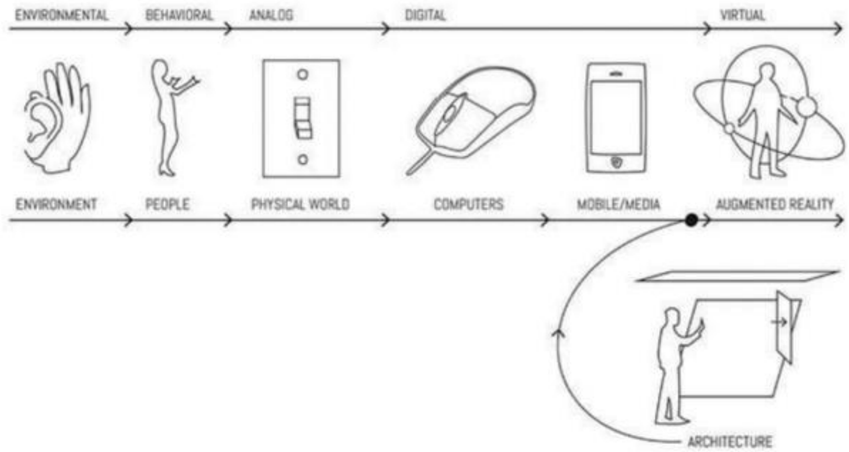

Figure 35. Diagram of the of gestural language

The third project is Alloplastic Architecture, an adaptive tensegrity structure that responds to human movement (Figure 36). This project was Behnaz Farahi's master's thesis at the University of Southern California School of Architecture in 2013. Architecture is the study and representation of the static. However, the city's architecture must embrace movement because the classical model of static, essentially timeless forms and structures is no longer adequate. Using Microsoft Kinect and Leap Motion, an interpretive dancer can dance around the structure as it responds to her movement. The central focus of this type of project is the relationship between material behavior, form, and interactive control systems.

Figure 36. In Alloplastic Architecture, a performance artist dances with the structure, which reacts to her presence without any actual physical contact

The living breathing wall is an interactive kinetic wall (Figure 37). It focuses on the relationship between material, form, and interactive control systems. The wall consists of a wooden frame box attached to the kinetic components and covered by fabric (Figure 38). The Kinect was installed on the top of the frame to detect the motion. It explores how simple elements in our surroundings can change their physical configuration as we interact with them.

Figure 37. Interactions with The Living, Breathing Wall

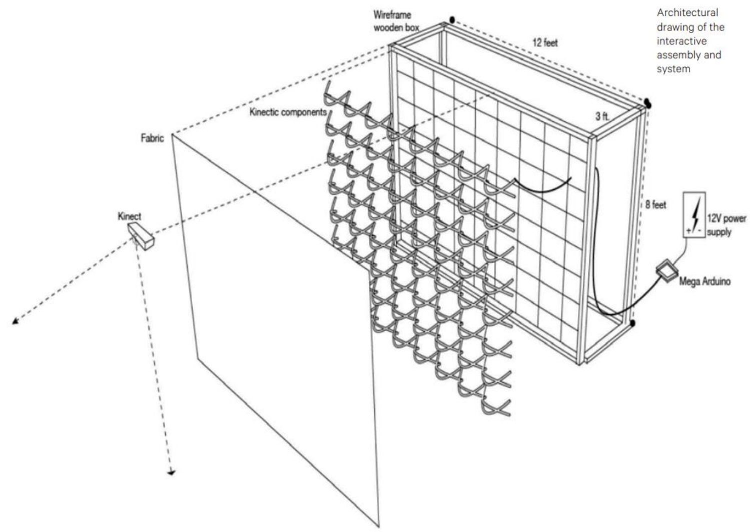

Figure 38. Architectural drawing of the interactive assembly and system

5.2.2. Communicate

In this book, the concept of communicate means buildings are no longer innate objects. They can tell stories and interact with their inhabitants. There is a correlation between sound and creativity: Silence helps people focus, but ambient noise helps with creativity. Each of the following pieces transforms its surroundings to create this sense of "space" and convey a message.

The first case is LIGHTSWARM (Figure 39). It was installed in the lobby of the Yerba Buena Center for the Arts in San Francisco. LIGHTSWARM was installed in a one-foot-deep area behind the exterior curtain wall. It was created to shade the interior of the lobby and make an interactive interface for the public. The curtain wall reacts to sound (inside and out) by vibrating. This is picked up through a large installed sensor array. This data is then passed into the lights in the form of variable color and brightness (Figure 40).

Figure 39. LIGHTSWARM

Figure 40. Views of interactive change over time

The second case is PLINTHOS. It was made for the ID10 Interior Design Show in Greece. The material used was brick, as it is rudimentary (Figure 41). MAB architecture firm wanted to add transparency to the brick. Therefore, bricks were laid on their side to expose the usually hidden holes. The glossy black mirror on the ceiling created a more prominent space illusion.

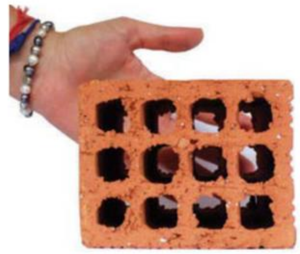

Figure 41. Concept image of brick translucency

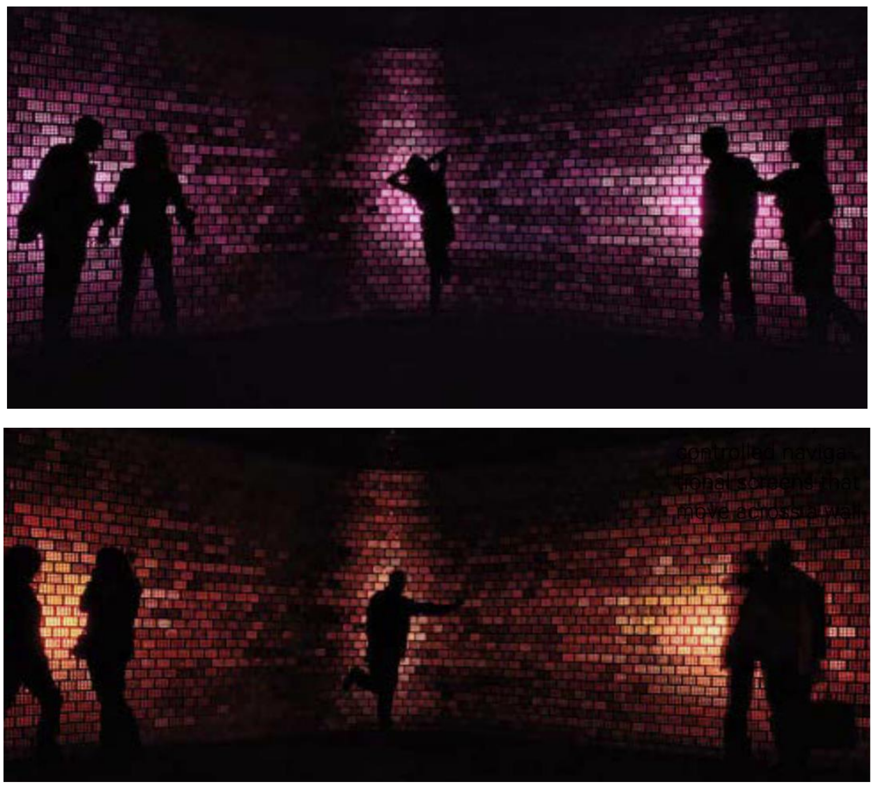

Figure 42. Views of interactive lighting variations

A white paper was present behind the brick wall to provide a reflective surface for the lights (Figure 43). Lights shining onto this make the light you see on the side here. It was run by a computer that would recognize patterns in the lights.

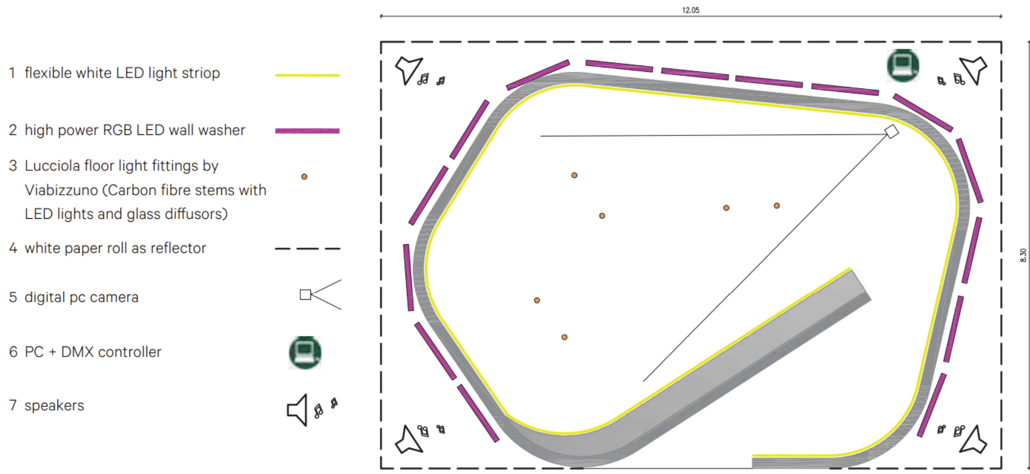

Figure 43. Diagram of interactive systems

The third case is the BALLS! (Figure 44). It is in Arup's Headquarters lobby. It is made from forty-two suspended balls in a 6x7 foot grid, and all the balls can raise and lower in a 6-story atrium. Bridging the gap between human and building interaction, Balls! can represent all sorts of data about the building to its inhabitants. Both passive and active interactions with the balls can be achieved. Tapping on a railing, volume level, and time of day are all ways it can be affected daily. The balls can also be changed for special events (Figure 45).

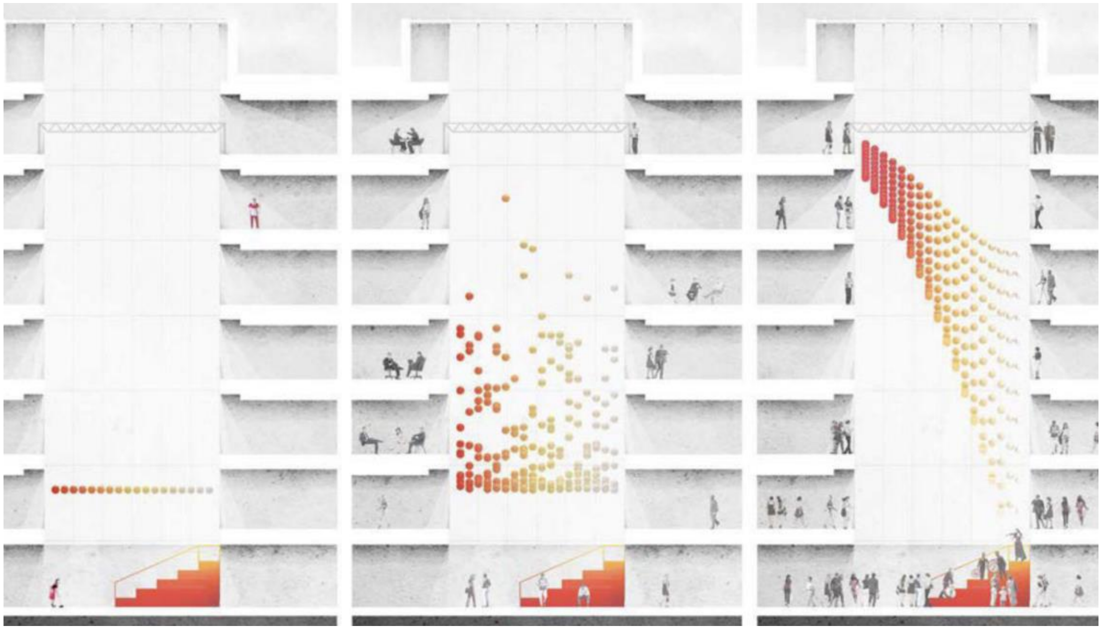

Figure 44. Architectural drawing of BALLS!

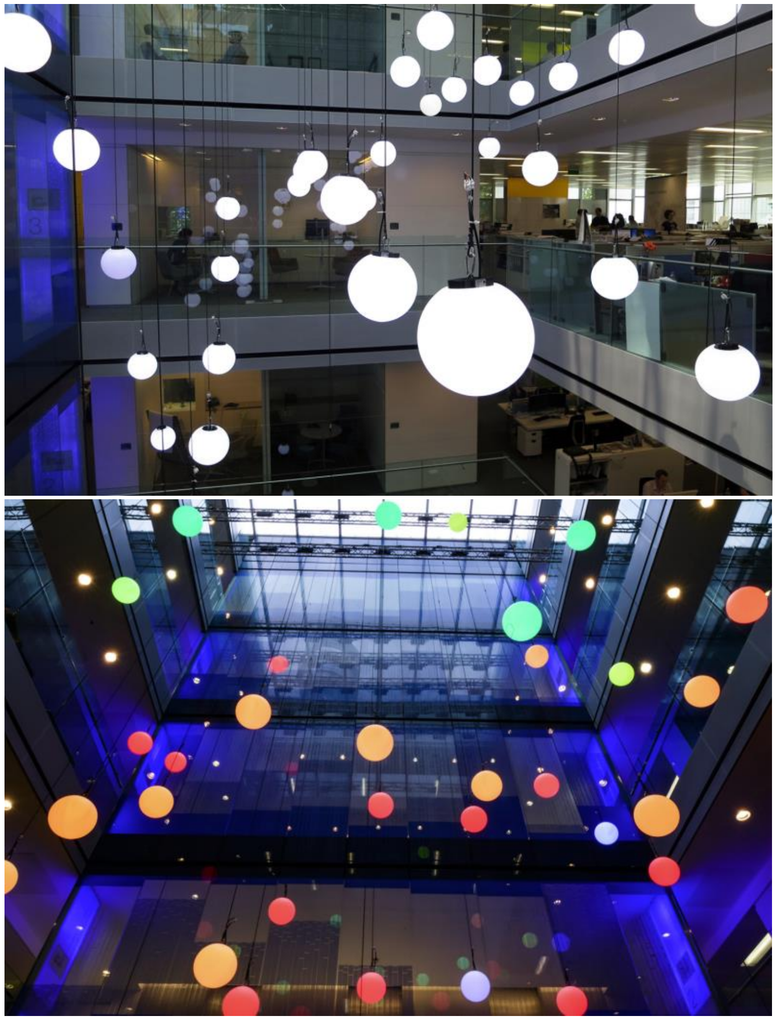

Figure 45. Views of the overall environment installed in the atrium of Arup's office building

The last case is MEGAFACES. It is a large-scale kinetic-volumetric LED display, and it was created for and won an architecture competition in partnership with the Olympics (Figure 46). The designers wanted to make an emotional connection with subscribers, the Russian public, and the Olympics' audience and to make a building that could take the appearance of those visiting. There were eleven thousand actuators moving spheres in and out of the plane, and each sphere contains an RGB LED lamp and can move up to 8 feet. A computer program calculates the best angle and distance to show the face on the screen (Figure 47).

Figure 46. View of installation in the context of the public plaza

Figure 47. Views of facade showing resolution from a distance

5.2.3. Evolve

Evolve means produced by natural evolutionary processes. In this chapter, the projects aim to achieve the symbiotic behavior and metabolic balance found in nature. There are two types of innovative materials. One changes in one or more of its properties (chemical, electrical, magnetic, or thermal) in response to change in external stimuli. The second transforms energy from one form into another. These materials exhibit photovoltaic, thermoelectric, piezoelectric, photoluminescent, and electro-restrictive behavior.

The first project is HYGROSCOPE + HYGROSKIN. The project explores a new responsive architecture model based on a combination of the inherent behavior of materials and computational morphology (Figure 48). The climate-sensitive building form is built on the dimensional instability of the wood with its moisture content. Hanging in a hygro-adjustable glass case, the model opens and closes according to changing climates without requiring technical equipment or energy. Simple fluctuations in relative humidity trigger silent changes in the internal motion of materials. The physical structure is the machine.

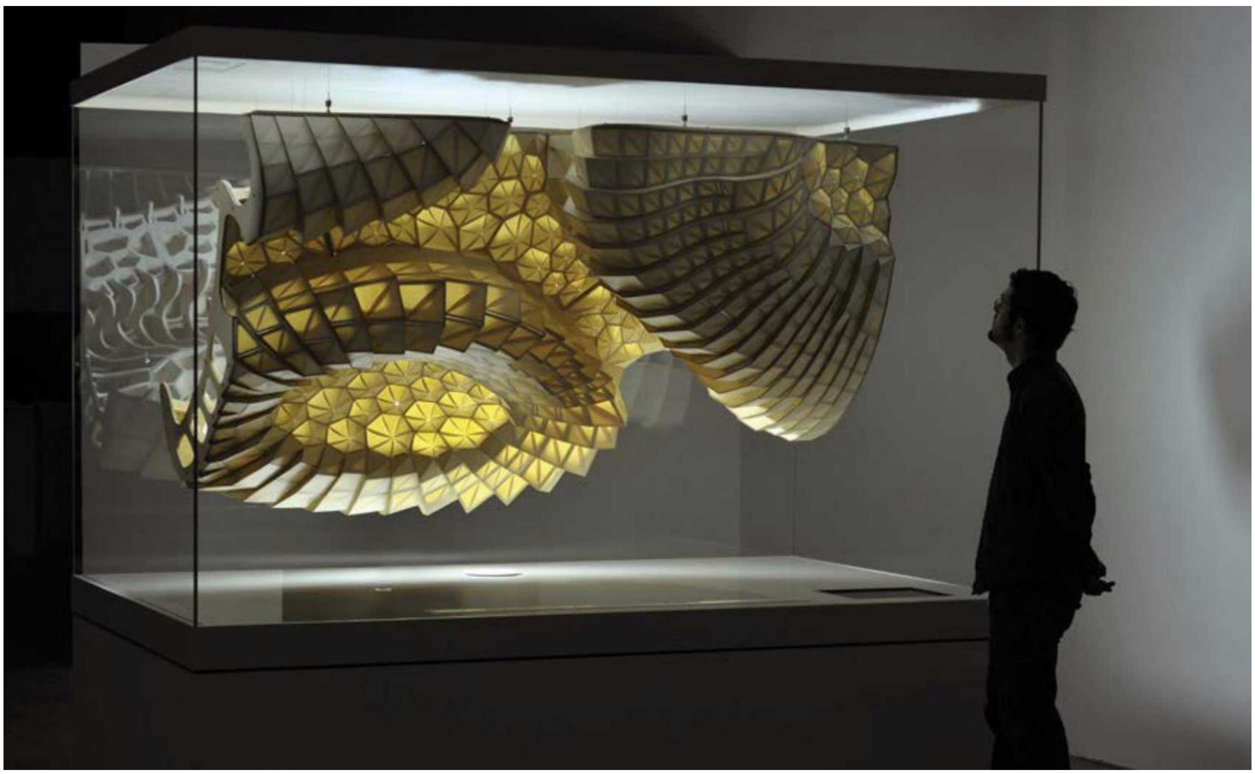

Figure 48. The Hygroscope installation as a permanent exhibit at the Centre Pompidou in Paris

The second project is BLOOM. This project acts as a sun tracking instrument indexing time and temperature, with a shape alluding to a woman's Victorian-era under garment (Figure 49). BLOOM stitches together material experimentation, structural innovation, and computational form and pattern making into an environmentally responsive form. It is made primarily out of a smart thermobimetal (a sheet metal that curls when heated) the form's responsive surface shades and ventilates specific areas of the shell as the sun heats up its surface. It also has the aid of complex digital software, as the surface is made up of approximately 14,000 laser cut pieces.

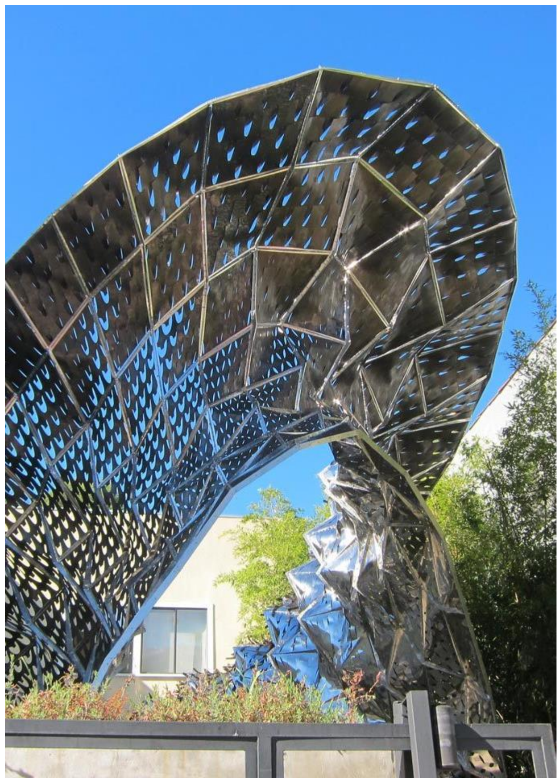

Figure 49. View of Bloom

The third project is SHAPESHIFT. SHAPESHIFT investigated the potential of electroactive polymers (EAP) to create a dynamic spatial intervention. EAPs are polymer-based actuators that convert electrical energy into dynamics and change their shape accordingly (Figure 50). In the field of "active materials", EAP is distinguished by its high deformability, high response rate, low density, and improved resilience. Each element consists of a thin elastic film that is attached to an acrylic frame and sandwiched between two compliance electrodes. This is achieved by coating both sides of the film with conductive powder and insulating them with liquid silicon. When a high DC voltage of the order of several kilovolts is applied, charges move from one electrode to the other, and the film is compressed along its thickness, resulting in planar expansion. Once activated, the EAP becomes thinner, and its surface area increases.

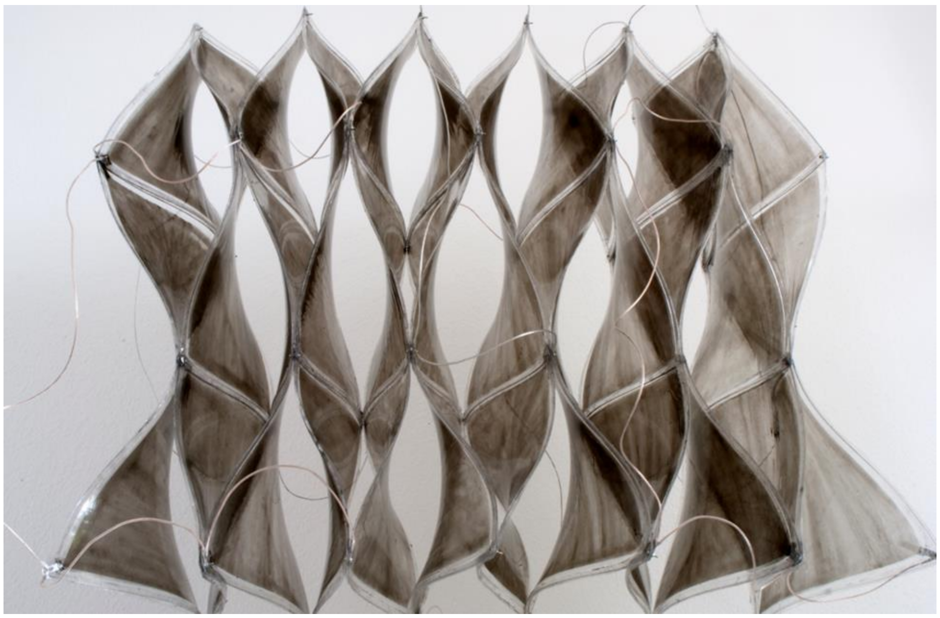

Figure 50. SHAPESHIFT

5.2.4. Mediate

Mediate means refers to the people within a building and the exterior environment, both of which are in a state of constant flux. The first case is shading system for the Al Babar Tower.

Due to the special hot climate of the UAE desert, most modern buildings use tinted glass, however, it has a large amount of energy consumption, lack of natural light intake, and blocked views. The architects from Aedas found inspiration from the traditional element of mashirabiya (Figure 51), a wooden grille that is used to block the sun and create privacy.

Figure 51. Traditional mashrabiya shading screen

The mashrabiya and shading system were combined according to the sun's trajectory, allowing for lower energy consumption and better views and light inside. The architects and engineers found a geometric parametric description of the movable panels on the facade in order to simulate their operation under sunlight and the variation of the angle of incidence with the different days of the year. Depending on the time of day, more than a thousand movable elements that respond to the position of the sun decorate the tower's façade (Figure 52).

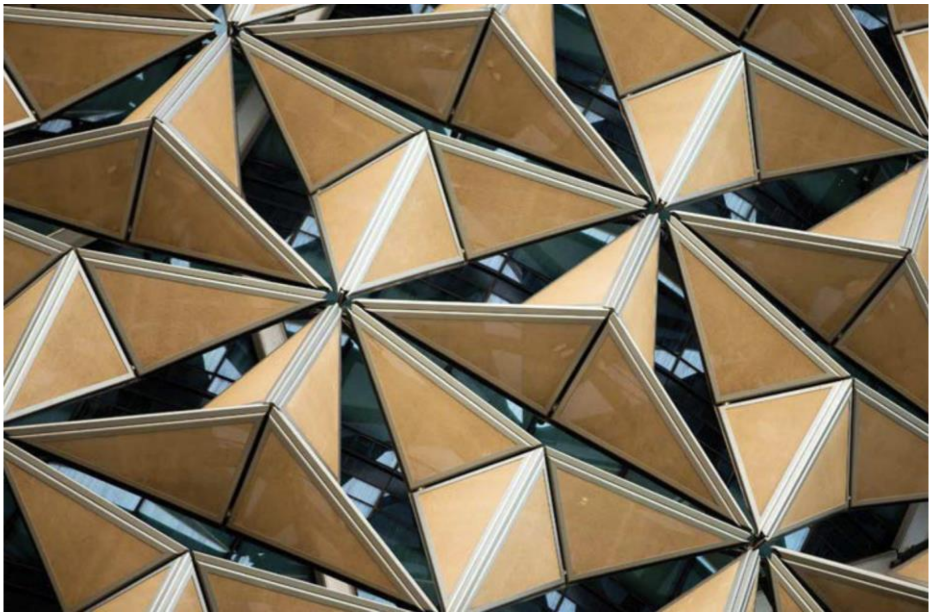

Figure 52. Detail of the mashrabiya units

Composed of a dynamic and light-sensitive sunshade, the shade system covers the light-receiving side of the building, leaving the north side untouched by excessive sunlight, while balancing natural light and energy conservation. The new computer-controlled shading wall can be used in the frame of each unit on the two-meter-long building facade. All triangles are coated with microscopic glass fibers and programmed to respond to the movement of the sun, thereby reducing solar gain and glare (Figure 53).

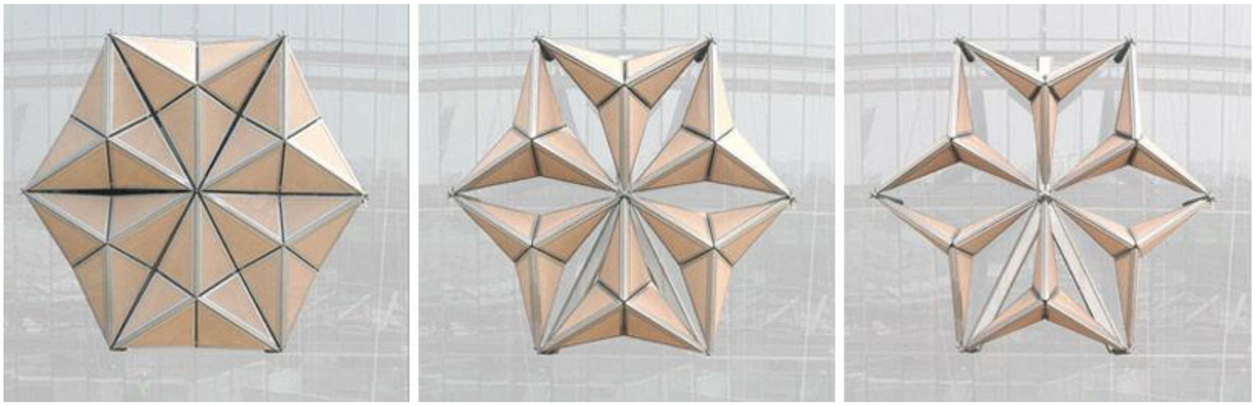

Figure 53. Mashrabiya units at unfold, midfold, and maximum-fold positions

The second case is KFW WESTARKADE TOWER, which is an office building located in Frankfurt, Germany. It's a prototypical ecological building with double-layered, wind-pressurized façade (Figure 54). The KFW WESTARKADE TOWER is world's first high-rise office building that can run on less than 100kwh/m2 of primary energy per year. This 15-story extension to the KFW banking group's headquarters was designed by the saurbrush Hutton.

Figure 54. KFW WESTARKADE TOWER

The TOWER's airfoil shape and circling cavity made the most prevailing winds for natural ventilation. The unique double-layered wind pressurized facade offers very high insulation values. The flaps on the outer layer maintain an even air pressure within the double façade (Figure 55). Consequently, the windows on the inner layer can be opened individually without undesired heat losses or draft. The facade is entirely clad in a saw tooth skin of angled glazing. Each window is separated by a slender colored panel alternately fixed and pivoting.

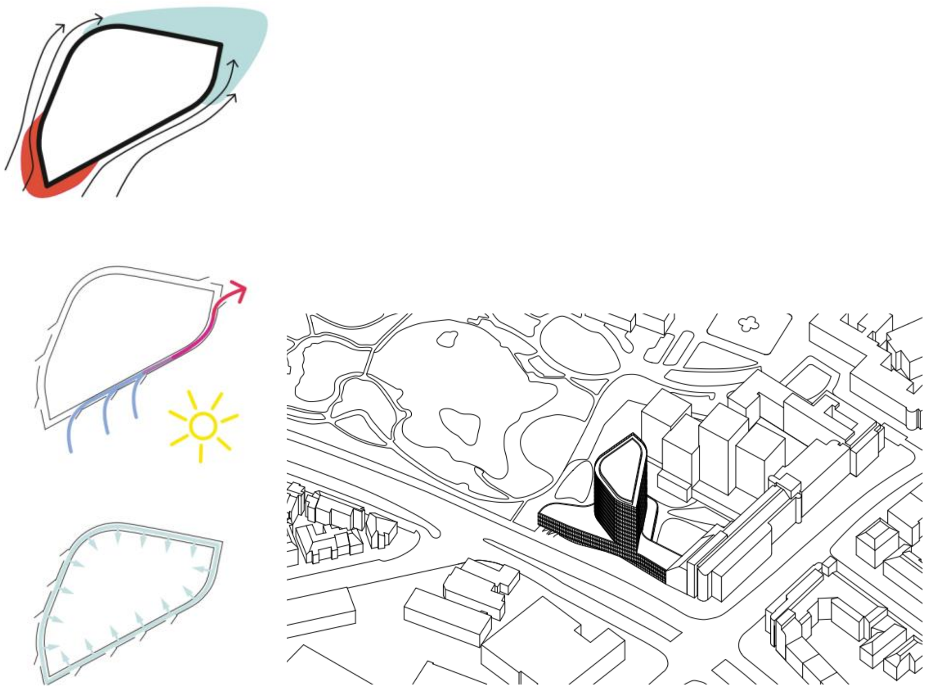

Figure 55. Performative qualities of the "pressure ring" in plan on the left and the right is isometric drawing of tower and urban context

The third case is Eco29 -- it was a wedding hall, and it is also the largest dynamic event space in Israel. It aims to rapidly accommodate a variety of layouts and scenarios inherent to the context of a wedding ceremony. The architect chose to use a mechanized wall and ceiling, cladding the entire space with a moveable fabric. They chose to use four ways to stretch the fabric, with a series of vertical and horizontal ribs. Each rib has seven motors, five on itself and two on the floor. The two ends of the system would be fixed and mounted to rolled steel tubing. The fabric was connected by a knot held by a sphere (Figure 56).

Figure 56. Exterior and interior views of the kinetic space

The last one is smart highway. This is an inclusive project developed by artist Dan, which aimed to create smart roads by using light energy and road signs. The electric priority is a charging lane that could charge the electric cars while driving. Interactive light is controlled by sensors; it will turn on when the traffic approaches (Figure 57). Dynamic paint is the marking that lights up and becomes transparent depending on the temperatures. Dynamic lines that can adjust continuous lines and dotted lines. Last one is wind light (Figure 58). Glowing lines absorb energy during the day and glow in the night. The wind generated by the passing cars will be collected by small windmills along the road, generating energy and then using this energy to light the lamps in the windmills. Therefore, the road contours become visible (Figure 59).

Figure 57. Electric priority (left) and interactive light (right)

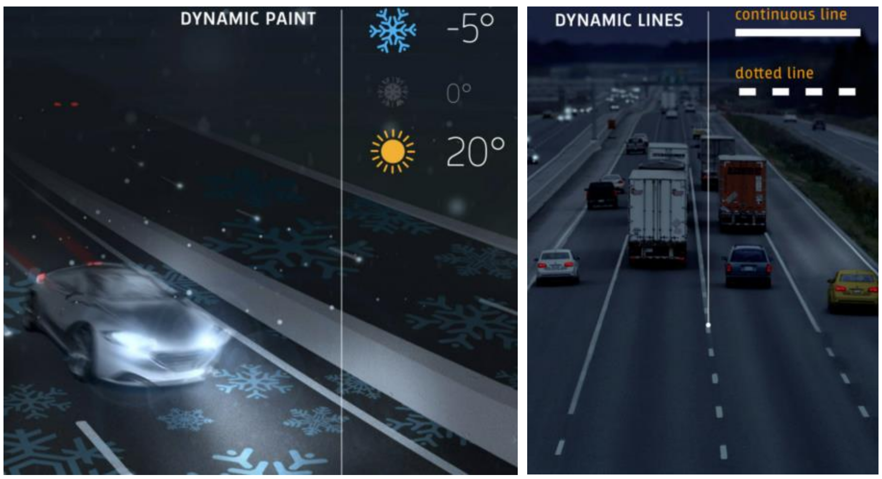

Figure 58. Dynamic paint (left) and dynamic lines (right)

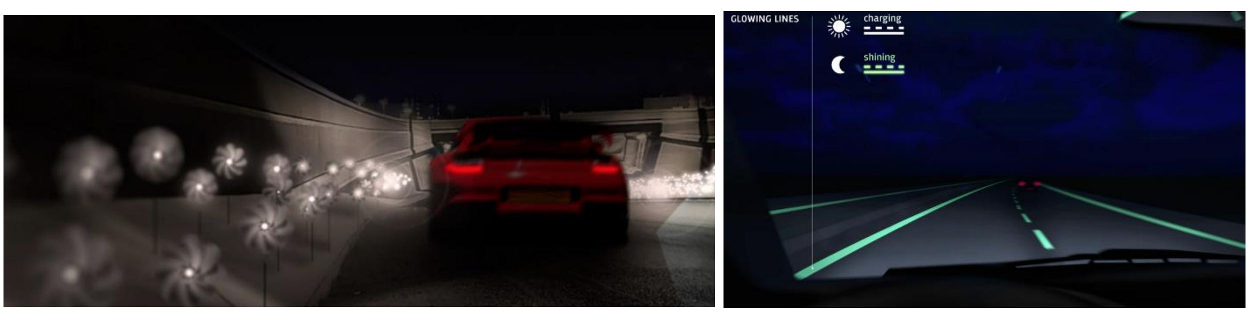

Figure 59. Figure 58. Wind light (left) and glowing lines (right)

5.2.5. Summary

Interactive architecture is more of kinetic architecture in which there is an integration of modern electronic technology and programming with the concept of architecture. Like the human body, architecture has a brain, sensory nerves, and autonomous action response, which can intelligently feel the needs of people, detect changes in the surrounding environment, and make active responses and changes according to the environmental and climatic conditions.

5.3. Overall Design

After the case studies, we started to design the PEACE space. Initially, we planned to use triangular panels covered with fabric to compose each wall and the ceiling surface. PEACE will place this space in a selected room at WPI. We connected the triangular panels at each corner, or vertex, to create an articulated wall and ceiling system. Specifically, portions of the wall will move back and forth independent of one another, and portions of the ceiling panel will move up and down, independent of one another. Servomotors can be installed within the walls and ceiling to provide their movements.

5.3.1. Floor Plan

The PEACE space consists of walls along three sides and one ceiling. These three elements will be covered by fabric. The fourth side of the space will be open and used as an entrance. The initial dimensions for a typical rectangular wall is 20 ft long by 8 ft tall. The ceiling is 20 ft by 20 ft square.

5.3.2 Investigation of Prototypes for the Wall and Ceiling Panels

In the beginning, we (one of the authors, Fangyi Liu) worked with a team of students to explore the construction of a prototype for the PEACE space, using paper and cardboard to explore the construction of the prototype. The initial prototype was to cut the paper into small right triangles, including 3 inches by 4 inches, 4 inches by 5 inches, and 3 in by 5 in, and use two to form a rectangle. Tape was used to connect the paper triangles at each corner; however, this first prototype did not provide the flexibility required for the movement of the wall.

Thin, one-inch thickness wood panels and laser cutters were used to construct triangular building elements for the second prototype. Also tested were two ways to use the triangular elements to form the wall. One way is using equilateral triangles to build the central part of the wall, and then using the half-panel on two sides to develop a rigid side. The other approach is like the first prototype: using a set of right triangles to create a small rectangle and then connecting these pieces to form one part of the wall. We used laser cutters to cut the one-inch thickness wood panel into 5-inch and 3.3-inch side length equilateral triangles. The 5-inch triangle could consist of two-panel rows (Figure 60). The 3.3-inch triangle is made with three rows. (Figure 61) We also made one 3 by 4-inch right triangle that consists of three rows (Figure 62). Tape was used to connect the triangles on the back of the wall. It was found that pushing on one intersection or vertex, the wall made with 3.3-inch side length equilateral triangles provided the best movement.

Figure 60. Wall made with 5-inch side length equilateral triangle

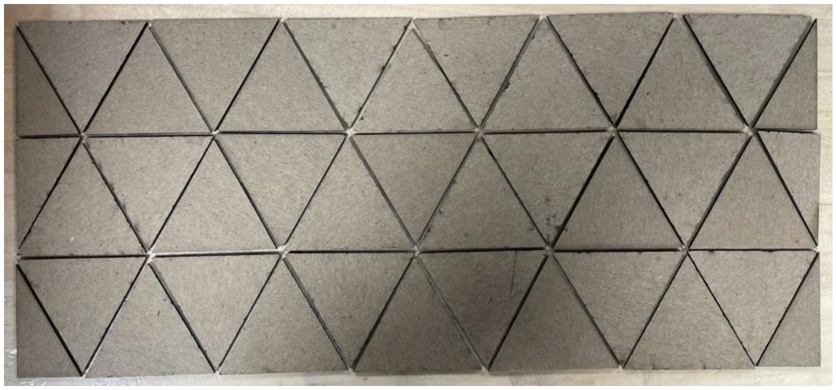

Figure 61. Wall made by 3.3-inch side length equilateral triangle

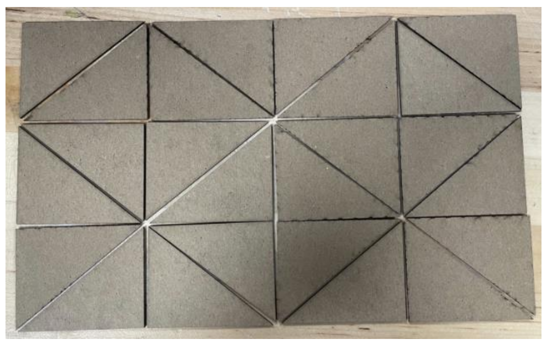

Figure 62. Wall made by 3 in by 4 in right triangle

5.3.3. Wall and Ceiling Panel Construction

We listed two choices of framing materials, one being wood members and the other being aluminum rods. First, the ends of three one-foot lengths of wood were mitered at a 45-degree angle. Two holes were drilled in the middle of each member, and wire was used to link three members together into a triangle. The wire provided more stability in case the glue doesn't have enough strength. The oblique sections were joined with a glue gun to form a triangular panel. After that, a piece of fabric was cut somewhat larger than the overall dimensions of the triangular panel so that the fabric completely wrapped around the edges of the panel. The fabric was glued to the wood members.

For a second alternative, one-foot lengths of aluminum wire were connected to form a triangle. The connection at each vertex was created using a one-inch-long rubber hose. Although this approach was quite lightweight, there was no way to cover the panel with fabric. Therefore, the decision was made to use 0.75 in x 1.5 in wood members to construct the triangular panels.

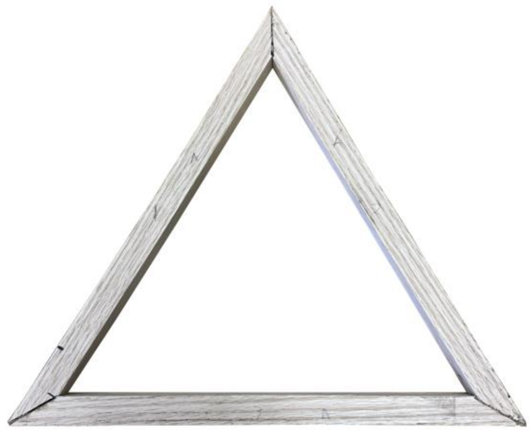

Figure 63. 1-foot-long wood stick connected by glue

The final side length for each equilateral triangle panel is 2.5 feet. The material used for panel framing is poplar, which is a lightweight hardwood that is easy to work with. The cross-section of each piece of poplar is 0.7 inches by 1.5 inches. We used a saw to cut the wood at the middle of the horizontal cross-section at 45 degrees, and the cross-section is a right trapezoid. The lateral leg faces the outside because it gives more flexibility to move back and forth when connecting two panels. On each piece of wood, a 60-degree angle was cut in opposite directions at each end, roughly half the thickness of the 0.5-foot length was ground off at each end.

Figure 64. The way of panel frame cut

Therefore, we could attach the end of the wood stick and stick them together to form an equilateral triangle panel. After that, we inserted a 1/4 in. x 20 mm type D zinc insert nut screw in the hole to connect it with the connector. IA staple gun was then used to attach the fabric on the back side of the panel.

Figure 65. Vertex connections

Figure 66. One piece of panel

5.3.4. 3D Printed Connections

As mentioned above, the wall and ceiling panels relate to each other, but the adjacent panels need to move independently and be scalable to create the desired enclosure. The maximum dimension of one wall is 19 ft by 9 ft. Therefore, the panel connections for the

PEACE were produced with a 3D printer because we could easily design and change the connections.

The connection between each panel is a cylindrical shell with six inner spheres that can rotate along the middle shell. The inner sphere has a hollow center that we could place the 1/4 in.-20 x 1-1/2 in. round head machine screw to mechanically fasten the connection to the panel vertex. The inner sphere could move at least 360 degrees.

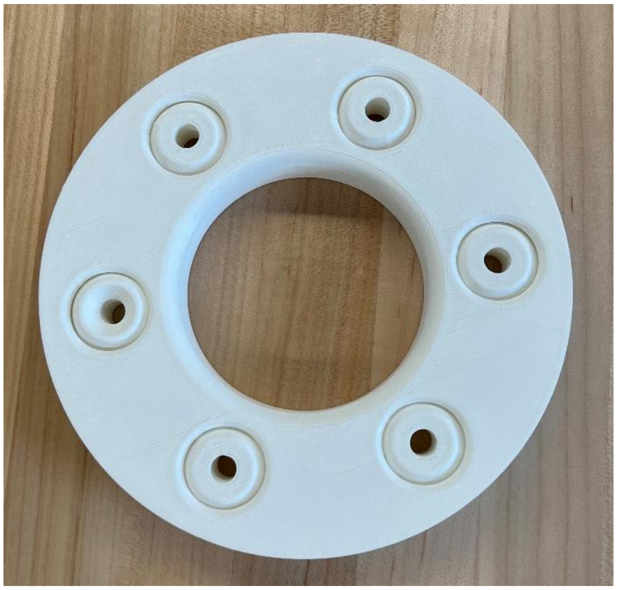

Figure 67. Panel connections

The connection between wall and beam is like the panel connections. Using a half hallow and printed the other half part connect with a screw so that it could be connect with the beam (see Figure 66).

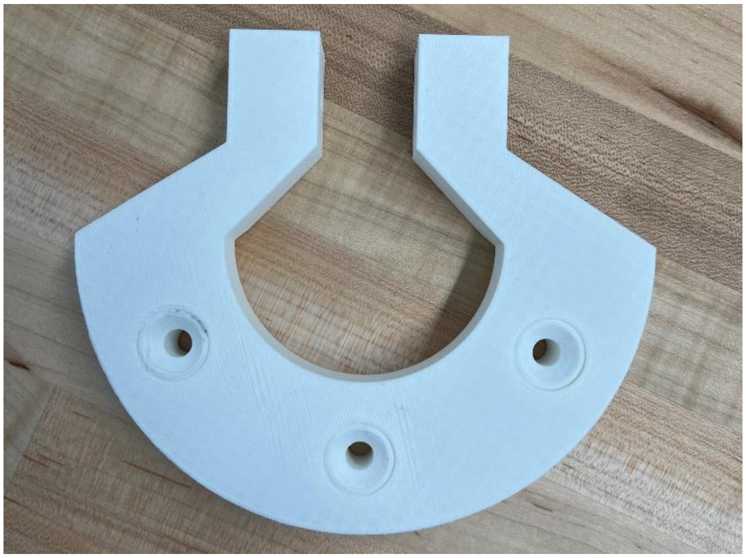

Figure 68. Panel and beam connections

5.3.5. Fabric

The fabric we used is the Therma foam White Drapery Lining & Blackout Fabric. It is composed of 70% polyester and 30% cotton with 54/100 in width (*Thermafoam White Drapery Lining & Blackout Fabric*, n.d.). The total fabric used is seven yards to make nine triangular panels.

Figure 69. Therma foam White Drapery Lining & Blackout Fabric

5.3.6. Final Structural Design

The structural structure was designed to support the dead weight of the roof, walls, and motors, and lateral forces were also considered for stability. To have a stable and easy to install structure to resist lateral and vertical loads, we decided to use 80/20 aluminum extrusions from the manufacturer 80/20 (*T-Slotted Profiles - Framing Options*, n.d.). The structural model and analysis were based on the extrusion's engineering properties and investigated with the aid of the structural engineering software RISA-3D.

5.3.6.1. RISA-3D

The design of the structural frame to support the walls and ceiling of the PEACE space was based on the philosophy of Allowable Stress Design (ASD). This approach required calculating and comparing the actual and allowable internal member forces for various combinations of design loads. From the manufacturer's catalog, we know some of the engineering properties of the extrusion that will be used in the calculation, such as material strength, alloy composition, the moment of inertia, estimated area, and member weight per inch of length.

The total load of one equilateral triangular panel is about 1.43 lb. We calculated the total weight of each wall and ceiling from the detailed drawings and applied the distributed load on the beams and columns of the structural framework to determine the appropriate size of each beam and column member in RISA-3D. Initially, the proposed framing was a simple box configuration that used 19-foot and 17-foot-long beams along the perimeter of the ceiling, and these were supported by four 9-foot-tall columns (one column in each corner of the structure). We tested four square extrusions, 1010, 1010S, 1515, and 1515S, but the deflections for each of the four extrusions were too high when compared with the limit of L/240 equal to 0.95 inches.

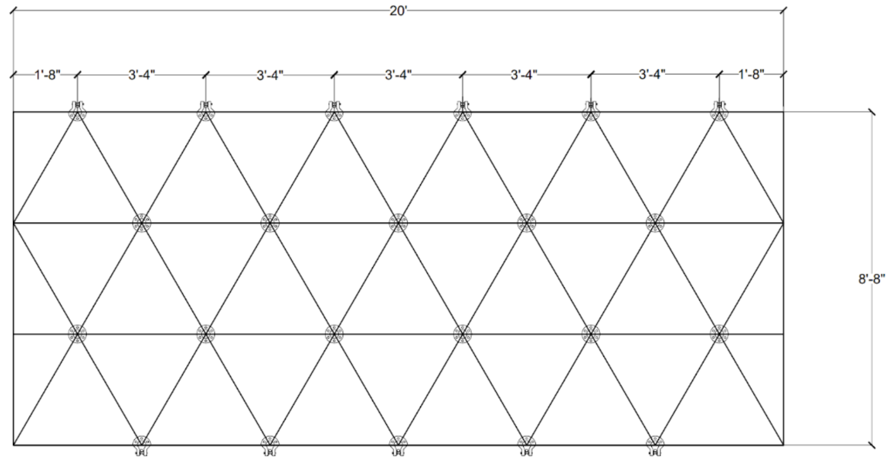

Figure 70. Detail drawing of East and West wall

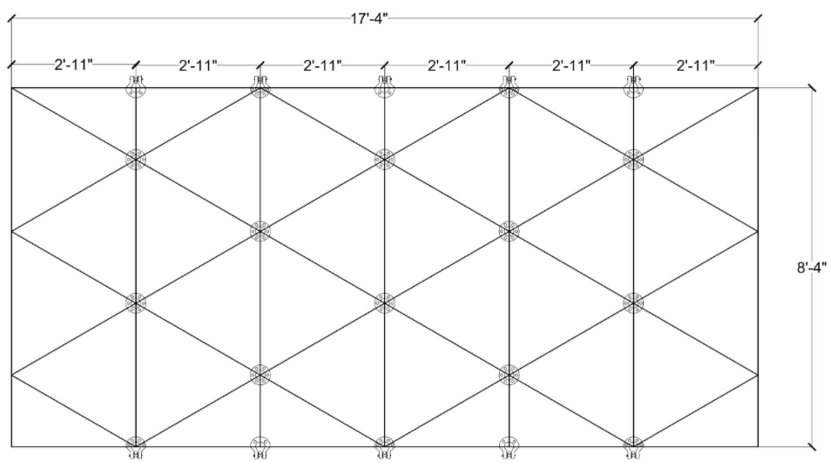

Figure 71. Detail drawing of North wall

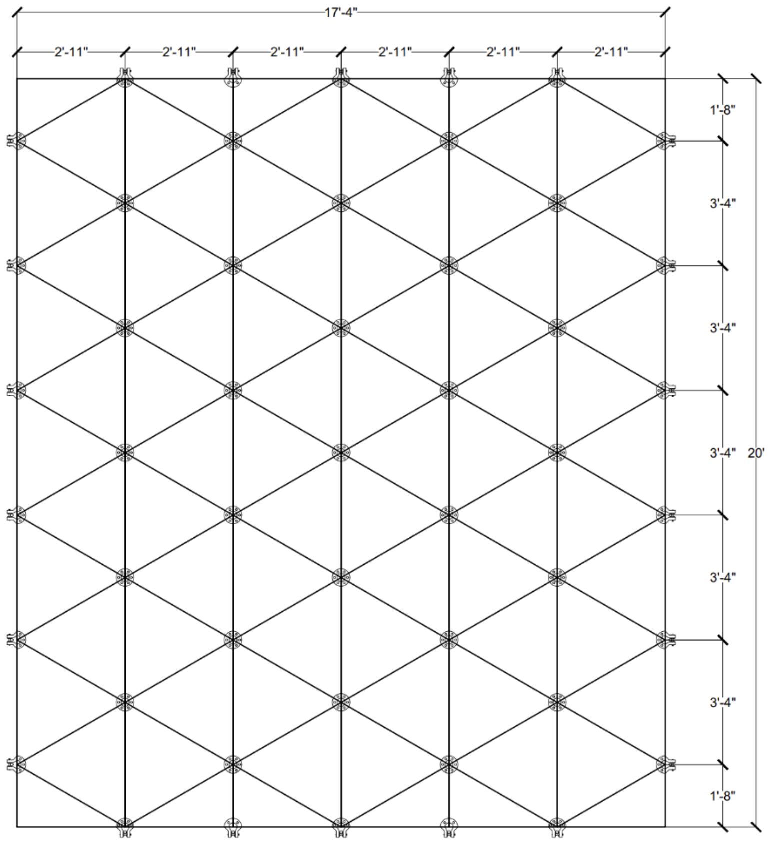

Figure 72. Detail drawing of ceiling plan

Table 7. Total weight of each wall and roof and loading on different number of joint

	East and West Wall		North Wall		Roof
Total Weight (lb)	58		47		107
Self-standing / Number of Top Joints	6	8	6	8	21
Weight of Each Joint (lb)	14.5	10.9	14	10.5	9.2

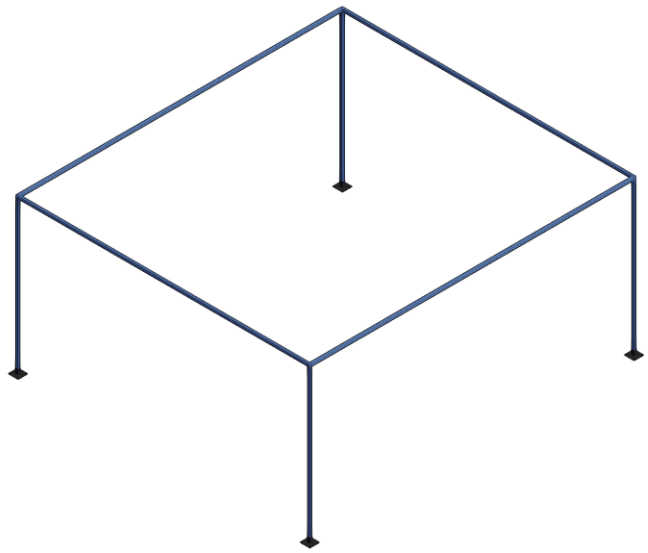

Figure 73. Basic framework with 4 beams and 4 posts

Accordingly, we also calculated the bending, shear stress, and deflection by adding more beams and posts to distribute the load from the top of the structure down to the supporting floor (Figure 74, 75, 76, and 77). 1515 extrusion was used to compare the results for different structural grids. Table 8 shows that the configuration with seventeen beams in a two-way grid supported by ten posts has the smallest design ratio (actual/allowable internal member forces) and, consequently, the best results.

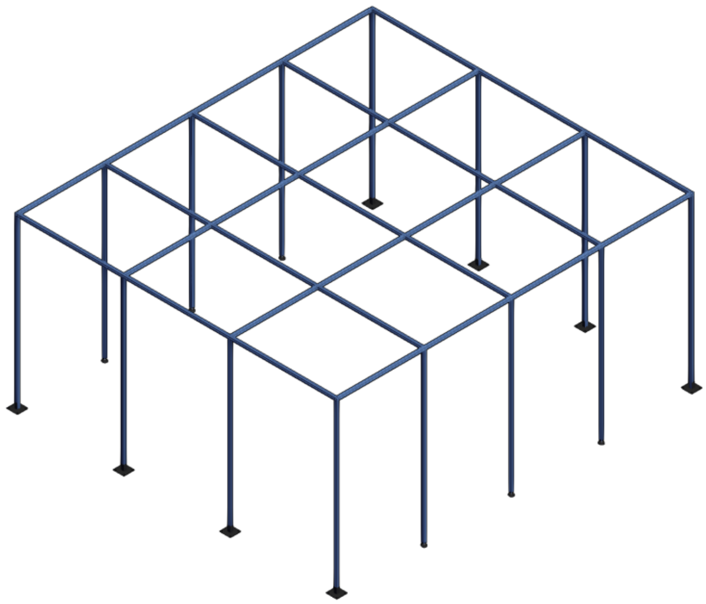

Figure 74. Framing added 17 beams and 10 posts

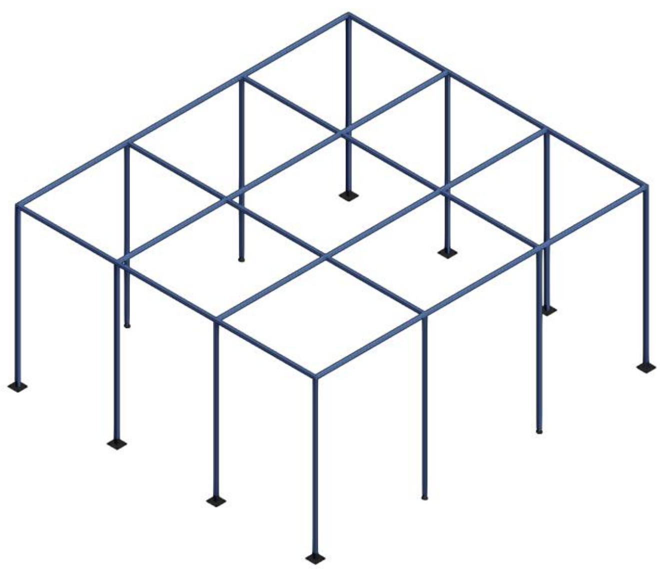

Figure 75. Framing added 12 beams and 8 posts

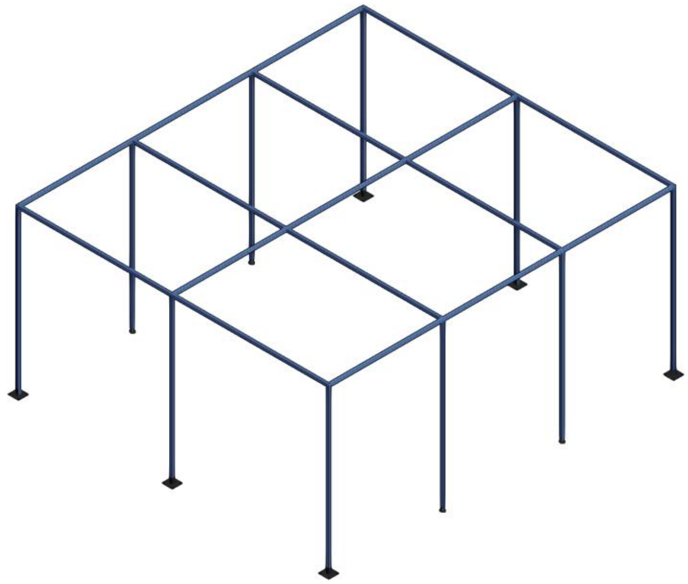

Figure 76. Framing added 7 beams and 6 posts

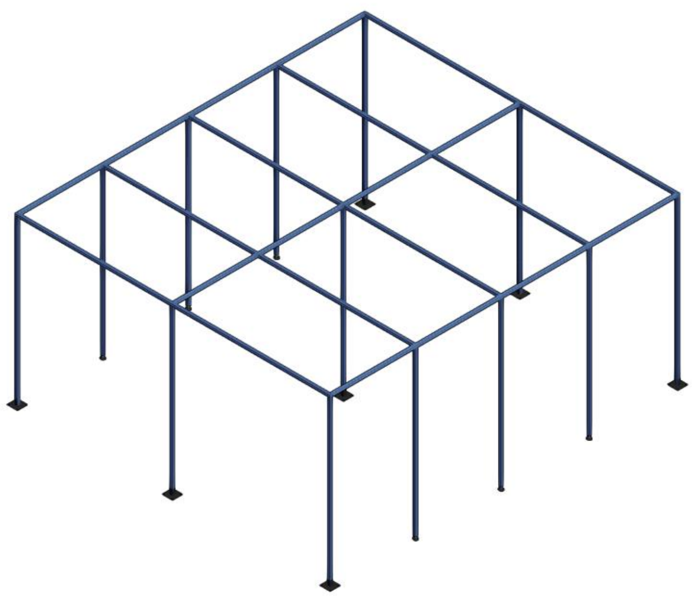

Figure 77. Framing added 10 beams and 8 posts

Table 8. Design ratio of different grid

	Ratio
Framing added 17 beams and 10 posts	0.015
Framing added 12 beams and 8 posts	0.017
Framing added 7 beams and 6 posts	0.028
Framing added 10 beams and 8 posts	0.028

After the most effective configuration of beams and columns was determined, RISA-3D was then used to determine the best member size. We listed several properties in a table for various member sizes (Table 9). To calculate the distributed load on each beam, we used the tributary area to calculate the roof load and took the extrusion weight to define the beam weight. The total wall weight was divided by the number of segments to get the total wall weight on each beam, expressed in units of pounds (lbs). Then, adding the roof load, beam weight, and wall weight divided by the beam length results in the distributed load each beam in pounds per foot (lb/ft) for input into RISA (Appendix D).

Table 9. Material properties

Yield Strength (min)	Tensile Strength	Elasticity	Shape Factor
35000	38000	10200000	1.65

Extrusion	Moment of inertia	Surface area	Weight (lb/in)	19 ft weight
1010s	0.0463	0.437	0.0424	9.6672
1010	0.0442	0.435	0.0424	9.6672
1515s	0.2631	1.138	0.1109	25.2852
1515	0.2542	1.152	0.1123	25.6044

The worst deflection is located at the center of the structure. The deflection limit of L/240 = 0.85 inches, where L is the total width for the enclosure (17 feet or 204 inches). The result from RISA shows that 1030 profiles for beams and columns are the best size since it has a relatively low beam deflection and lower cost.

For the lateral loading, we checked the effects of wind load and the seismic load as defined by *ASCE 7*. Since the structure will be placed in a room, the wind load is relatively small, but we checked the wind load for completeness. The total weight of this structure is about 772 lbs., and this was considered in conjunction with a horizontal seismic load of 58 lbs. and a horizontal wind load of 0.015 lbs applied to the top of structure. Each load combination, dead load + seismic and dead load + wind, was investigated by checking the UC Max and Shear UC to determine whether the members pass or not. A ratio less than 1.0 means the member can support the combined loads and there would not be failure. Other results from code check, such as Pnc/Om, Pnt/Om, Mnyy/Om and Mnzz/Om are the design capacities divided by the Omega safety factors based on ASD 13th, 14th, and 15th Edition code checking. The final results indicated that the maximum ratio is 0.354 and maximum shear is 0.684.

Additionally, we tested if the 1030 extrusion could resist an accidental or spurious lateral load due to someone falling against the structure. For this, we applied a single 150-pound lateral load randomly to one column with the dead load. The results showed that the columns in the four corners and the middle two columns along the 19 feet side will fail. We decided to change these six columns into 1530 extrusion which could resist more lateral load. The results indicate that the column with 1030 and 1530 t-slot profile is under the requirement. The room selected is in WPI robotics engineering department. To fit the new dimension of the room, we have resized the beam and posts.

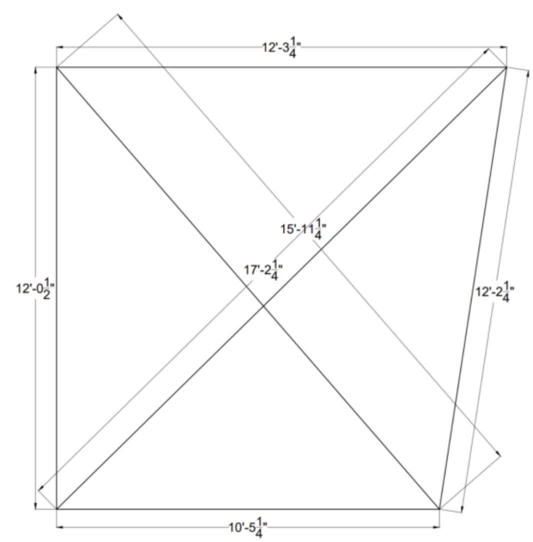

Figure 78. Room dimension

Repeat the same steps as previously, calculate the distributed load on each beam, 7.5 lb/ft, and run the analysis with individual 150 lbs point load. We compared the maximum deflection of 1020, 1030, 2020, and 1515 extrusions. Table 10 shows that 1030 and 2020 have relatively low deflection. Then we compared the max ratio and shear of 1030 and 2020. The results in table 11 indicate that 1030 will fail when the load is applied on the 2, 4, and 6 posts. Therefore, 2020 extrusion is the final structure material.

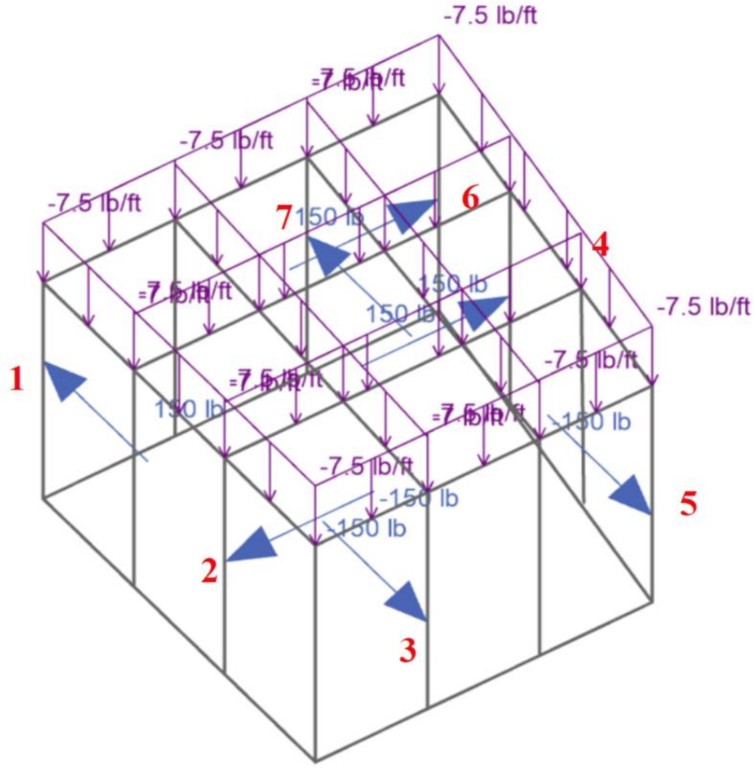

Figure 79. RISA model with dead load and point load

Table 10. Maximum deflection of selected extrusions

Extrusion	*Max deflection*
1020	1.46
1030	0.171
2020	0.265
1515	0.581

Table 11. Maximum ratio and shear of 1030 and 2020 extrusion

	1030		*2020*	
Point Load	Max ratio	Max shear	Max ratio	Max shear
1	0.399	0.821	0.479	0.487
2	1.195	0.764	0.444	0.434
3	0.603	0.777	0.548	0.531
4	1.014	0.742	0.546	0.448
5	0.618	0.697	0.509	0.483
6	1.092	0.652	0.476	0.394
7	0.582	0.895	0.5	0.488

Shear and bending stress were also calculated in RISA. The shear stresses are calculated as V/As, where “As” is the effective shear area, and “V” is the value of the internal shear force at the section of interest. The program defines As by multiplying the total area by the shear stress factor. This factor is calculated automatically for most cross sections but must be entered for arbitrary members. The maximum shear stress is 675.43 lbs and the allowable shear force is 12629.54 lbs.

The bending stresses are calculated using the familiar equation M * c / I, where "M" is the bending moment, "c" is the distance from the neutral axis to the extreme fiber, and "I" is the moment of inertia. RISA-3D calculates and lists the stress for the section's extreme edge with respect to the positive and negative directions of the local y and/or z axis. A positive stress is compressive, and a negative stress is tensile. The maximum bending moment from RISA is 358.6 and the allowable bending is 21875 lbs.

5.3.6.3 Summary

Overall, the calculations for structural analysis and member sizing were completed in spreadsheets and RISA-3D software. The load combinations were run in RISA-3D. Adequate structural strength and performance were determined by comparing the maximum member results in shear, bending and deflection with allowable values. Allowable values for member strengths were defined by yield strength divide by shape factor. An allowable deflection limit of L/240 was imposed.

5.3.7. Cost of Prototype

The cost of prototype was calculated with the aid of Excel spreadsheet. Listed all the material brought and used to calculate the total cost. The material used in prototype includes wood frame, fabric, machine screws, insert nut, wood glue and staple gun. All the connections were printed by the 3D printer. The table below provides the detailed cost of each material and component as well as the total cost of the prototype. The total cost of prototype is $282.09.

Table 12. Material quantity and cost of prototype

Material	*Required Quantity*	*Total Cost ($)*
Fabric	7 Yard	55
0.75 in. x 1.5 in. x 11 ft Poplar Wood	7	123.2
0.75 in. x 1.5 in. x 9 ft Poplar Wood	2	28.8
1/4 in.-20 x 2-1/2 in. Zinc Plated Machine Screw	15	6.4
1/4 in.-20 x 2-1/2 in. Zinc Plated Machine Screw	9	3.84
1/4 in.-20 Zinc Plated Insert Nut	8	7.74
T50 Staple Gun	1	19.98
Staples	1	4.17
Wood Glue	1	6.48
Steel Pipe	2	18.5
Pipe Cap	2	7.98
	Total Cost	282.09

6. Conclusion

We designed a library in a neighborhood surrounded by schools for the use of the residents and students. One of the rooms was used to create an immersive space for experimentation and research. A couple of prototypes of panels and connections were investigated to determine the final dimensions. RISA-3D was used to provide the final structure dimensions and analysis. 2020 extrusions are the recommended member sizes to construct the structural framework for the PEACE project.

In the future, the structure can be assembled and put into use. The addition of the motor allows the roof panels to move freely. Use the projector to add lights, experiment with VR, and collect the needed data.

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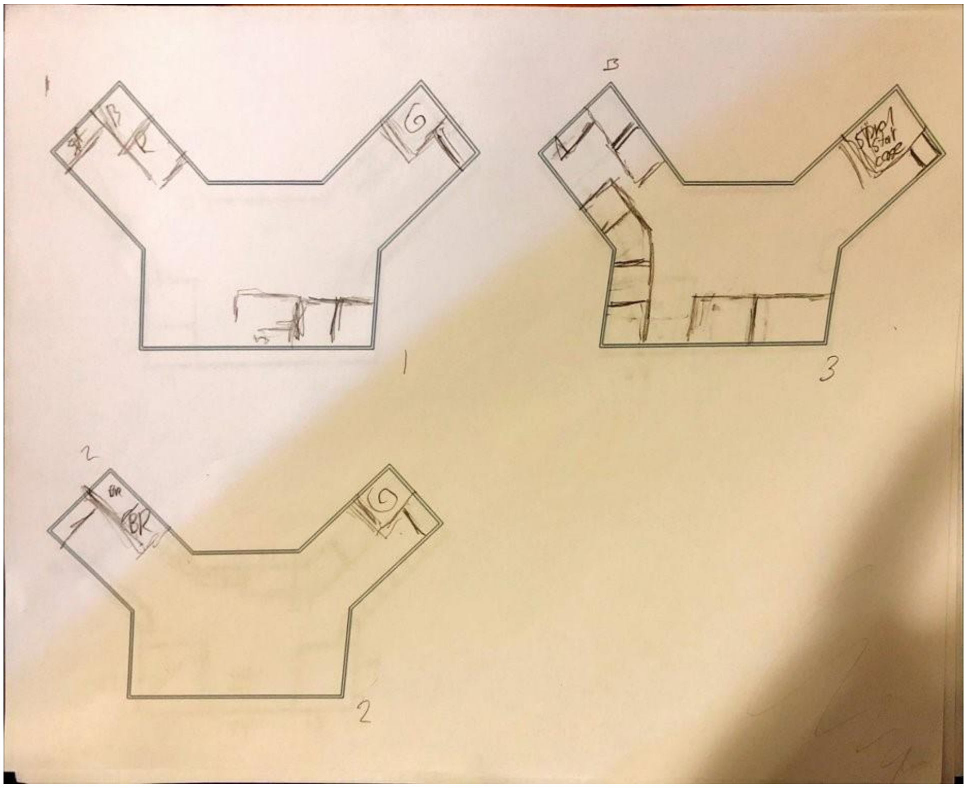
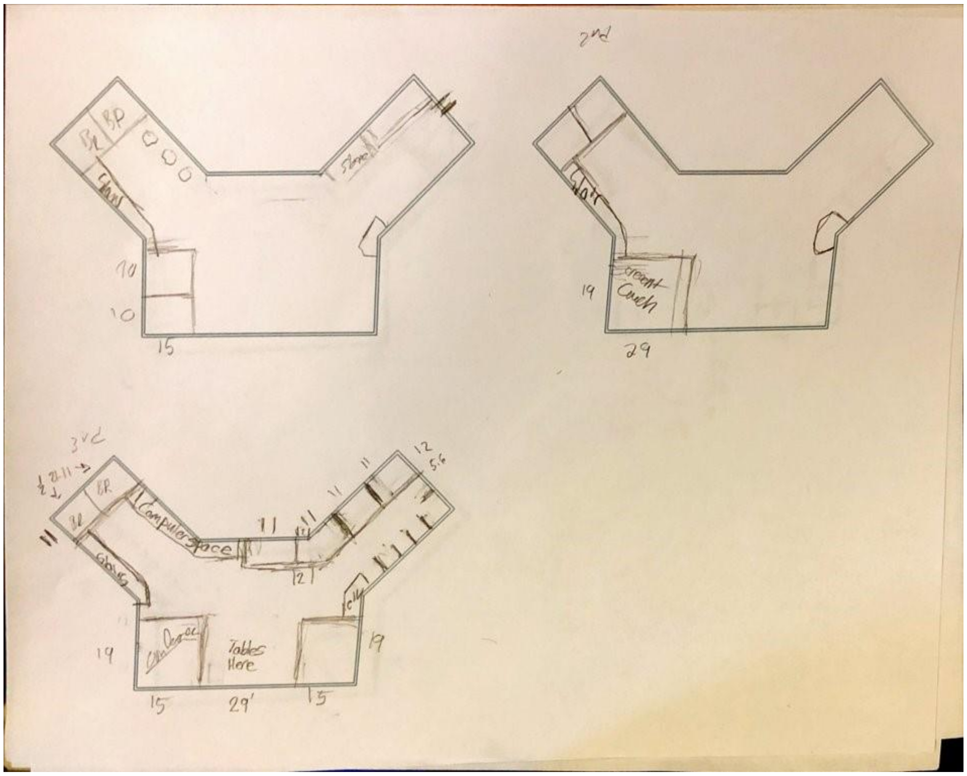
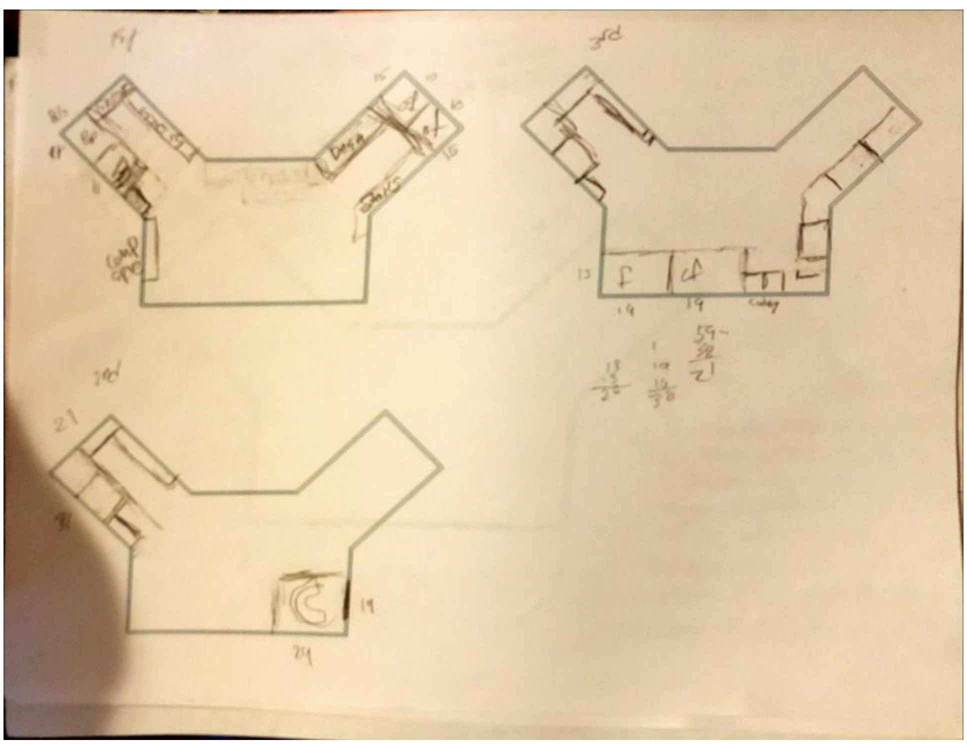
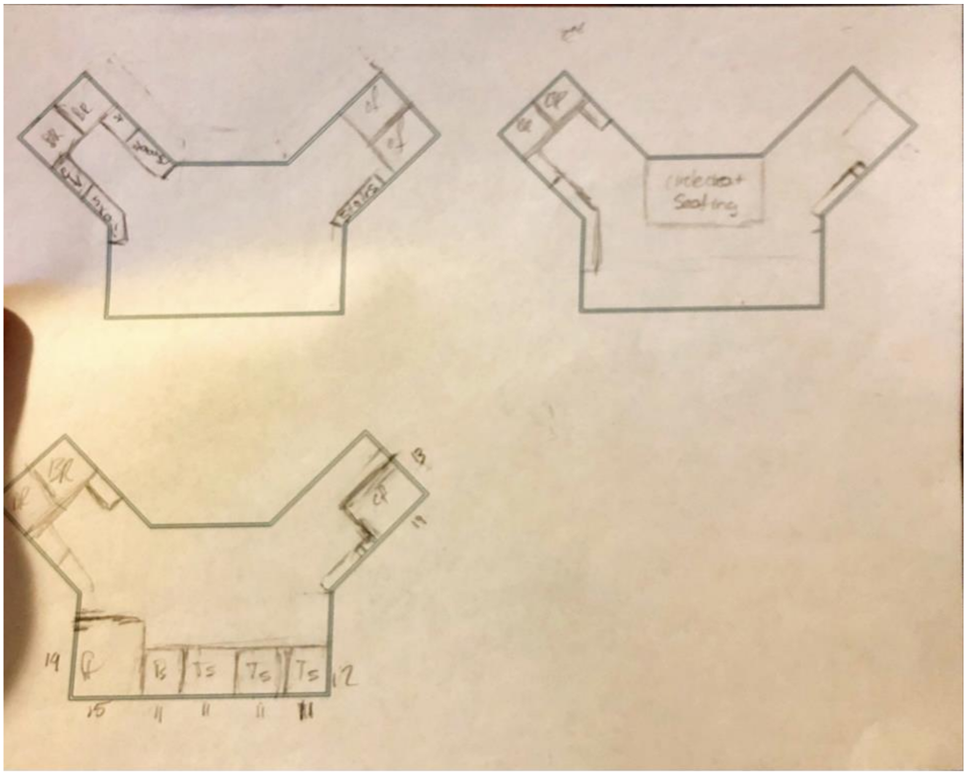
Appendix

Appendix A: Preliminary Floor-layout Sketches

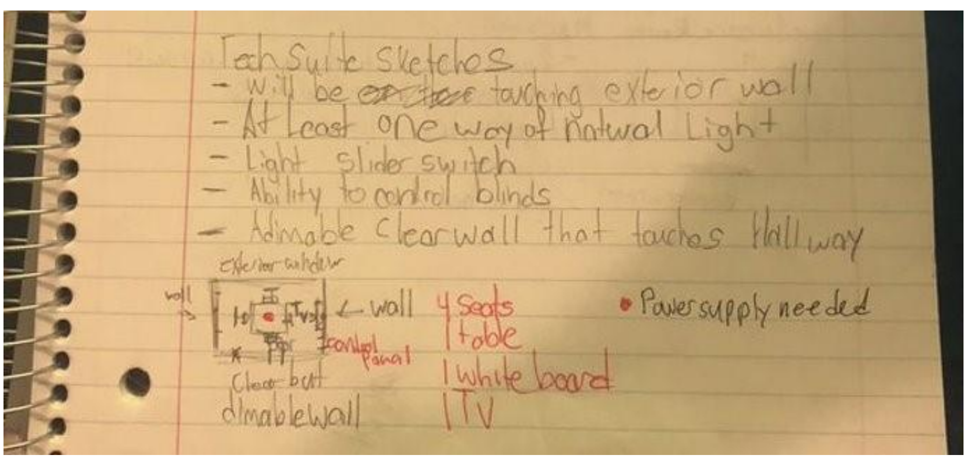


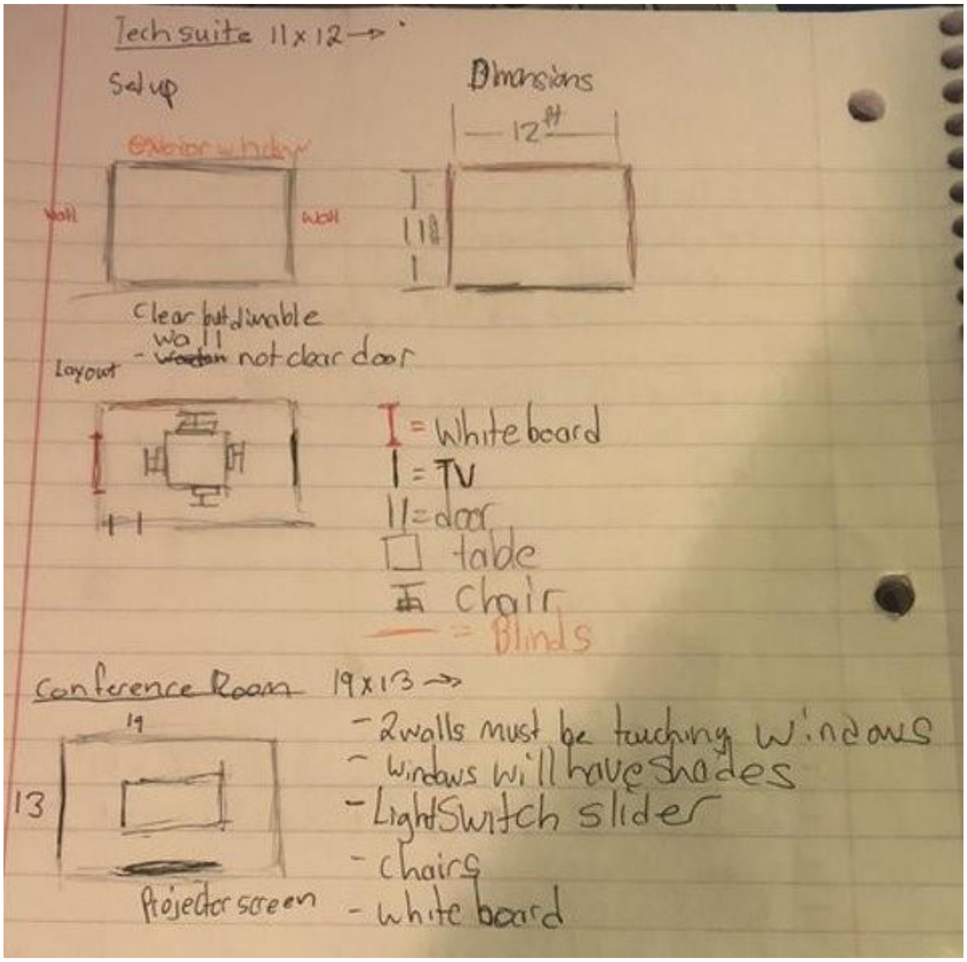

2nd
Computer space
Tables Here
3rd
29'

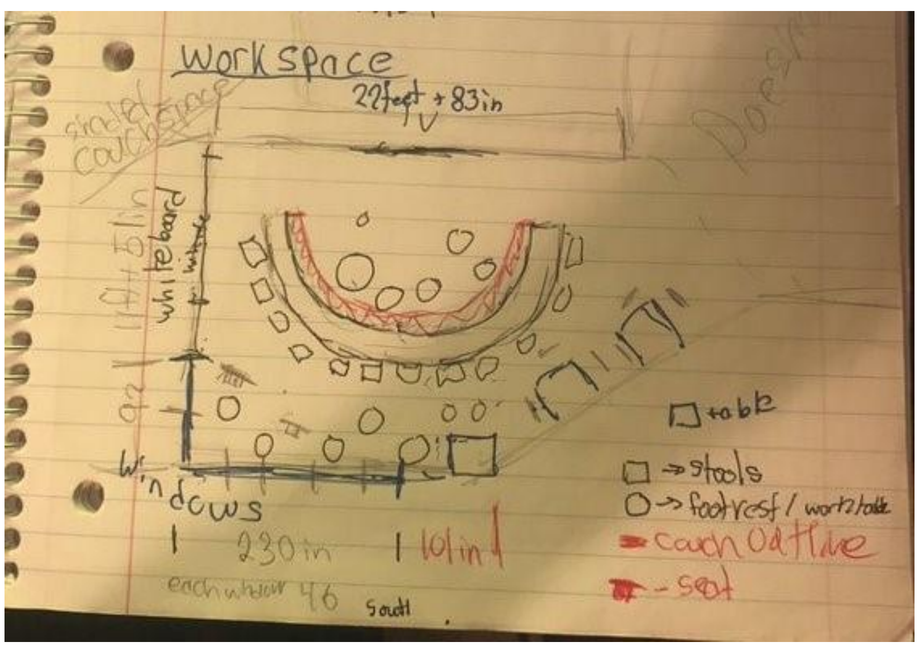




Appendix B: Preliminary Sketches for rooms that were planned to be tested in (conference room and tech suite)




Tech suite 11x12
Set up
Dimensions
12 ft
11 ft
Wall
Wall
Clear but dimable
wall
not clear door
Layout
= Whiteboard
= TV
= door
table
Chair
= Blinds
Conference Room 19x13
19
13
Projector screen
- 2 walls must be touching windows
- windows will have shades
- LightSwitch slider
- Chairs
- white board


Workspace
22feet + 83in
TV
whiteboard
windows
230in
101in
South
table
→ stools
→ footrest / work table
couch Outline
- seat

Appendix C: Calculation of distributed load on each beam

Extrusion Number		*Size (ft)*	*Area (in2)*	*Roof Weight (lb)*	*Wall Weight (lb)*	*Beam Weight (lb)*	*Total load (lb)*	*Distributed load (lb/ft)*
1020 S	Length	5.67	7.83	2.67	16.67	5.01	24.34	4.29
	Width	4.75	5.64	1.92	15.00	4.20	21.12	4.45
1020	Length	5.67	7.83	2.67	16.67	5.23	24.56	4.33
	Width	4.75	5.64	1.92	15.00	4.38	21.30	4.48
1030 S	Length	5.67	7.83	2.67	16.67	7.50	26.83	4.73
	Width	4.75	5.64	1.92	15.00	6.28	23.20	4.88
1030	Length	5.67	7.83	2.67	16.67	7.57	26.90	4.74
	Width	4.75	5.64	1.92	15.00	6.34	23.26	4.90
2020	Length	5.67	7.83	2.67	16.67	8.15	27.48	4.85
	Width	4.75	5.64	1.92	15.00	6.83	23.75	5.00
2020S	Length	5.67	7.83	2.67	16.67	8.02	27.36	4.82
	Width	4.75	5.64	1.92	15.00	6.72	23.64	4.98
2040	Length	5.67	7.83	2.67	16.67	15.19	34.53	6.09
	Width	4.75	5.64	1.92	15.00	12.73	29.65	6.24
2040S	Length	5.67	7.83	2.67	16.67	14.89	34.22	6.04
	Width	4.75	5.64	1.92	15.00	12.47	29.39	6.19
1515	Length	5.67	7.83	2.67	16.67	7.64	26.97	4.76
	Width	4.75	5.64	1.92	15.00	6.40	23.32	4.91
1515	Length	5.67	7.83	2.67	16.67	7.64	26.97	4.76
	Width	4.75	5.64	1.92	15.00	6.40	23.32	4.91
1530	Length	5.67	7.83	2.67	16.67	13.78	33.11	5.84
	Width	4.75	5.64	1.92	15.00	11.54	28.46	5.99
1530S	Length	5.67	7.83	2.67	16.67	13.51	32.84	5.79
	Width	4.75	5.64	1.92	15.00	11.31	28.24	5.94
1545	Length	5.67	7.83	2.67	16.67	19.92	39.25	6.92
	Width	4.75	5.64	1.92	15.00	16.68	33.60	7.07
1545S	Length	5.67	7.83	2.67	16.67	19.47	38.81	6.84
	Width	4.75	5.64	1.92	15.00	16.31	33.23	7.00

Appendix D: Highest beam deflection in structure

Column / Beam	*1020*	*1030*	*2020*	*2040*	*1515*	*1530*	*1545*	*Allowable Deflection*
1020	0.604							0.85
1020s	0.587							0.85
1030	0.553	0.243						0.85
1030s	0.524	0.234						0.85
2020	0.521	0.235	0.381		0.761	0.307		0.85
2020s	0.521	0.235	0.381		0.76	0.308		0.85
2040	0.434	0.204	0.324	0.139	0.645	0.261		0.85
2040s	0.421	0.197	0.313	0.132	0.628	0.245		0.85
1515	0.575	0.249	0.374	0.162	0.842			0.85
1515s	0.573	0.249	0.411	0.162	0.839			0.85
1530	0.486	0.223	0.325	0.15	0.715	0.291		0.85
1530s	0.485	0.223	0.325	0.149	0.713	0.29		0.85
1545	0.435	0.202	0.323	0.137	0.649	0.26	0.124	0.85
1545s	0.434	0.202	0.323	0.137	0.648	0.259	0.124	0.85