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The Performance of Light: Exploring the Impact of Natural Lighting in the New UMass School of Performance

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THE PERFORMANCE OF LIGHT

EXPLORING THE IMPACT OF NATURAL LIGHT IN THE NEW UMASS SCHOOL OF PERFORMANCE

A Thesis Presented

by

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ABSTRACT

THE PERFORMANCE OF LIGHT: EXPLORING THE IMPACT OF NATURAL LIGHT IN THE NEW UMASS SCHOOL OF PERFORMANCE

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This thesis explores how natural light can be integrated with built form to create a "performance of light" in architecture. Lighting conditions from a contemporary dance piece, as well as other architectural precedents, were studied, and aspects adapted into the building's design. In addition to designing theatrical effects of light, the classroom and administrative spaces were designed to take advantage of natural light. Daylight studies were used to inform glazing design and material selection to stay within illuminance thresholds in the spaces.

This project is responding to the facility needs of the campus of UMass Amherst where the program of the dance, theater and music departments are stressed for space, are operating in below-average facilities, and are separated, making collaboration difficult. The programmatic concept driving this design purposely mixes offices, classrooms and rehearsal spaces, creating overlap and collaborative opportunities.

The use of mass timber was also an important aspect of the buildings' design. Wood brings along many benefits, such as lower embodied energy, carbon sequestration, better thermal properties, and an increase in the perceived quality of architectural spaces. The volume of wood used in the building's structural system was run through a life-cycle

analysis to determine the overall carbon footprint, in relation to the amount of steel and concrete used.

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CHAPTER I

INTRODUCTION

Many post war buildings on the UMass Amherst campus fall short of today's environmental performance standards and have not been adapted to meet academic program requirements.

The objective of the proposed UMass School of Performance is to rethink the approach to a performance-oriented building, while also using the latest technology in energy efficient design. This project will combine three departments on the University of Massachusetts, Amherst campus that are currently spread across campus in cramped and poorly performing buildings. The performance of light was explored by using natural light both in a theoretical and practical way, to echo the performance nature of the program, and to create desirable and environmentally conscience space that is attractive for students to come and study music, dance and theater. The building's structural system was conceived in mass timber, to reduce its carbon footprint and life cycle impact.

As the three departments program is analyzed, connections between were discovered, suggesting ways that spaces could be shared. The introduction of new teaching and learning styles questions the architecture of classroom and performance spaces that have remained unchanged for decades. This building explores new designs for these types of spaces. Much of the building's structural system utilizes glulam and CLT in place of steel, but hybrid systems with steel or concrete will still be used when efficiency or strength is valued over carbon footprint.

CHAPTER II

LITERATURE REVIEW

Properties of Light

Much of the way that humans perceive the world is affected by light. "Light is revealed to the human eye through interactions with material, while material visually exists only in the presence of light. This interdependence between material and light, form and intangible atmospheres, defines the visual environments we inhabit." [1] Light is a complex subject, but the principles can be broken down into several categories.

Illuminance

Illuminance is the amount of light that falls on a surface, measured in footcandles or lux. It is independent of the material property of the surface or object. Illuminance is important in architecture as it is what gives form its perceptible qualities to the human eye, and gives depth to space. It allows us to navigate through space, as well as perform tasks in space. Illuminance plays a large role in our emotional response to space: "our intrinsic fear of the dark or gravitation toward light has influenced the ways in which our society places faith in light as a means to establish safety and provide emotional reassurance." [1] Levels of illuminance can also be used to create hierarchy in space, through varying lighting levels. Think of the transition from street to sitting in a restaurant. The street light has the highest lighting levels, while the lights over the restaurant table are most like dimmer, creating a more private and intimate space.

Luminance

[1] Descottes, Hervé, and Cecilia E. Ramos. 2011. Architectural lighting: Designing with light and space, ed. Becca Casbon. New York, New York: Princeton Architectural Press.

Luminance is the amount of light reflected back to the human eye from a surface. It is measured in foot-lambert or candela per square meter, and is dependent upon the material color and surface texture. Luminance plays a large role in material selection in architecture, as the color of surfaces can have a large effect on how light is distributed around the space. This also allows surfaces or objects to become secondary light sources, as they can reflect light that is cast onto them, much like how a full moon reflects the sun's light onto the earth.

Color and Temperature

The color and temperature of light is closely linked to our perceptions of time and space. Cool, blue light is associated with sunrise and morning sun, while warm light is associated with evening sun and sunset. "Our circadian rhythms are governed by a daily cycle of light and dark whose nuanced colors evolve with the passing of time."[2] We can estimate the time of day and year based on the color of light, and the position of the sun. Use of artificial light in architecture can be used to alter our perceptions of time, and to create different moods.

Height

The height of light sources influences the spatial relationship between light, the surface or object receiving the sunlight, and the space in between. High sources of light, such as atrium downlighting or a streetlight, suggest more public space, while lower light sources, such as a dining room chandelier, or bedside lamp, suggest intimacy and privacy. Similar concepts apply to the movement of the sun. During midday, the overhead light creates even lighting, when lines of sight are far, and visual features most

[2] Descottes, Hervé, and Cecilia E. Ramos. 2011. Architectural lighting: Designing with light and space, ed. Becca Casbon. New York, New York: Princeton Architectural Press.

easily identifiable. During sunrise and sunset, shadows are more pronounced, or not visible at all. Lines of sight are diminished, until no light from the sun is visible, when our sense of scale is greatly diminished to what we can see in front of us.

Density

Lighting density controls the movement and rhythm of space.[3] The arrangement of lighting can be used to aid in circulation, direct the eye to a specific place, or create a spatial hierarchy. The placement of light sources can be grouped into three typologies: linear, random and organized pattern.[3] Linear organization creates a single linear light from one or multiple light sources. Up close, individual lights can be seen on an LED strip, but from far away, the light is seen as one continuous strip of light. In random organization, the placement of lights follows no logical pattern, while in an organized pattern, some form of geometric logic is followed.[3] On a larger scale, lighting density relates to development and economic prosperity. The largest amounts of light pollution can be found in cities, which are highly developed and wealthy.

Direction and Distribution

Lights are typically directed down, up, or multiple directions. Downlighting can be used to illuminate a corridor below, while uplighting can wash the ceiling, reflecting light back towards the floor, creating a more even light. The beam of light can either be concentrated, focusing on a small area, or diffuse, more evenly illuminating an area. The direction of light can be used to amplify the surface pattern and texture of a material. Light that is running parallel to a surface will show all its defects, while light running perpendicular will create an even-looking surface with minimal shadows.

[3] Descottes, Hervé, and Cecilia E. Ramos. 2011. Architectural lighting: Designing with light and space, ed. Becca Casbon. New York, New York: Princeton Architectural Press.

Light and Architecture

Without sound, or touch, an architect's work would still be a spectacle to look at, but without light, it would be a form hidden in the darkness. Light has the biggest impact on our perception of space, and it can alter depth of field, create drama,[4] or create a sense of intimacy or openness.

Light and Shadow

Lines of light, with the use of natural or artificial sources, is a basic tool for adding another layer of spatial depth on top of the built forms. As discussed earlier, linear light organization allows one's focus to follow the path of light, or it can be used to delineate spaces or surfaces, such as a cove light, breaking up the wall and ceiling plane. Alternatively, lines of light can be created by blocking the source by a lattice or screen, to create a desired pattern. Lines of light go hand in hand with shadows, as the absence of shadows is created by the presence of light.

Figure 1, Layer House - Hiroaki Ohtani

Shadows can be used to add drama and emphasize the presence of light.[4] They are transitory in nature; slowly moving, and only in the same spot twice per year. Two ways of creating shadows include carving out mass from a solid volume, or using a filter adjacent to a piece of glass or in the open air. Ronchamp, designed by Le Corbusier,

[4] Meyers, Victoria. 2006. Designing with light. London: Laurence King Publishing.

utilizes punched openings in a stark white wall to create an expressive and sculptural quality of light. The 2Y House, by Sebastián Irarrázaval, aims to integrate the forest into the daily experience of user, by creating an extended perimeter to the house, which is spanned from ground to roof by glass. The glass is hung off a timber-framed curtainwall composed of dimensional lumber. The resulting shadows creates a pattern of squares and triangles that are animated throughout the day.

Figure 2, Ronchamp - Le Corbusier. Rory Hyde

Figure 3, 2Y House - Sebastián Irarrázaval. Felipe Díaz Contardo

Apertures

The purpose of windows hasn't changed much in the history of architecture, but the technologies behind them have. Window size and placement used to be limited by how much material could be removed from the structural walls, and by the availability of glass, but those issues have been largely eliminated today. Glass is an architect's tool for connecting spaces, whether that's two interior rooms or the inside to the natural world on the outside. Recent advancements in glass, such as structural, electrochromic, and electrostatic glass, have enabled designers to use the material in ways never imagined before.

Figure 4, Clear glass operation - UMass Design Building. Alex Schreyer

Figure 5, Tinted glass operation - UMass Design Building. Alex Schreyer

Windows can be used to bring daylight in, while providing views out. Skylights allow for excellent daylighting, while reducing the area of glazing compared to traditional side lighting. Modernism took advantage of glass and steel to create glass-box skyscrapers that maximized views to the outside, and brought in the most amount of daylight. With increasing concerns about climate change and the large amounts of energy that these types of building consume for space heating and cooling, the amount of glass used on the exterior envelope must be carefully designed to manage views, daylight, occupant comfort, and thermal performance.

How Architecture Impacts Learning

The average American spends 90% of his or her time indoors,[5] which highlights the importance of the built environment on the health and well-being of the occupants. Academic buildings are important in their own way, since the interior environment has a great impact on how well students learn. The standard way of learning for decades has been teacher-centered, where students sit, listen, and practice a task until it is perfected. In the last decade, philosophy on learning has shifted more toward learning by doing, or project-based learning. In this method, students team and work on problems together, then share their results with the rest of the class.[6] This shift in learning styles necessitates a shift in learning environments, as the type of space designed for a teacher or professor to lecture to students will not function as well for team-based learning. A study by C. Kenneth Tanner looks at how circulation, large group meeting places, daylight and views, and instructional neighborhoods affect the academic achievement of third-grade students. While the subjects and physical environment of this study are different from a higher education building, such as a university building, the design implications of the findings should be considered when designing an academic building for college-level students.

Areas of circulation that were deemed to be crowded, because of too many people or too little space, were found to exhibit excess levels of stimulation, stress and arousal, a reduction in desired privacy levels, and loss of control.[7] As group-based learning continues to grow, spaces that foster social interaction are important. Large group spaces provide places for students to study and hangout, where they can identify and establish a

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[5] Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development. Healthy housing reference manual. Atlanta: US Department of Health and Human Services; 2006

[6] Tanner, C. Kenneth. "Explaining Relationships among Student Outcomes and the School's Physical Environment." Journal of Advanced Academics 19.3 (Spring 2008): 441-471.

[7] Wohlwill, J. F., & van Vliet, W. (1985). Habitats for children: The impacts of density. Hillsdale, NJ: Lawrence Erlbaum Associates.

sense of ownership of the place. In a more populated area, people tend to want a place to escape to, for quiet contemplation and increased privacy, while in a more rural area, people are more likely to want to get together to socialize.[8] In a study measuring the required personal space for undergraduate students, researchers found that closeness to other students produced less discomfort when the space was more open. This exemplifies the need to provide large common spaces, such as media centers, dining areas, common areas, or auditoriums.[9] "An instructional neighborhood is a place that includes large group (approximately 20–30 students) and small group areas, spaces for student and teacher planning, wet areas for art, a hearth area, and toilets for the students and teachers."[10]

Spaces specializing in a specific type of learning activity were emphasized over spaces were all the learning happened in one space. Example spaces include workstations and research space for individual students, central gathering spaces and presentation areas, cooperative learning spaces, and quite private areas. Teachers should have offices where they can offer individual support, lesson plan, or make phone calls to parents. Having spaces that area flexible enough to support changing instructional strategies is important for schools to be able to adapt to future change.[10] Just as the design of the space can greatly affect the performance of learning, material choices can affect indoor air quality, acoustics and human health.

[8] Wohlwill, J. F., & van Vliet, W. (1985). Habitats for children: The impacts of density. Hillsdale, NJ: Lawrence Erlbaum Associates
[9] Cochran, C. D., Hale, D., & Hissam, C. (1984). Personal space requirements in indoor versus outdoor locations. Journal of Psychology, 117, 121–123.
[10] Tanner, C. Kenneth. "Explaining Relationships among Student Outcomes and the School's Physical Environment." Journal of Advanced Academics 19.3 (Spring 2008): 441-471.

Presence of Wood and Learning

Many scientific studies have looked at the impacts of nature and health, and have found that exposure to nature reduces stress, blood pressure, heart rate and aggression.[11] Nature also increases one's ability to focus and perform concentrative and creative tasks. The effects of nature materials on human health is a topic that has not seen the same kind of analysis as nature and health. A study conducted by the University of British Columbia and FPInnovations has shown a connection between wood and human health. Four office environments were created, one with natural wood finishes, and the other with white finishes. Each of those environments had one version with plants inside, and another with non-natural artifacts.[12] Subjects participated in office performance tasks in the different rooms conditions, and the results showed that stress levels, as measured by sympathetic nervous system activation, was lower in the wood rooms in parts of the study.[12]

Not only does wood contribute to lower stress levels than other building materials, but its' color and texture helps to create a warm, natural and more calming aesthetic. The use of wood in academic design can lead to more unique and enriching buildings that can have an impact on students beyond what is measurable in a scientific study. Officials at the Ministry for Education in Japan have been exploring how wood promotes learning. In a three-year study in 700 schools, researchers looked at how building materials affected the learning environment.[13] They found that flu outbreaks had been reduced in wood-framed schools, and that students and teachers felt less fatigue in wood buildings compared to reinforced concrete structures.

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[11] Eg. see Hartig et al. (2003), Laumann et al. (2003), and Kou and Sullivan (2001).

[12] Fell, D. -. FPInnovations. "Wood and Human Health." Wood & Human Health Series.1 (2011).

[13] rethink Wood. "Wood and Indoor Environment." (July 2015).

Another study aimed to analyze the effect of wood on students' stress levels. Two classrooms in an Austrian school were fitted out with solid wood finishes, while another two rooms with standard materials served as a control. The students in each set of rooms had their heart rates monitored six times through the school year, at identical times each day. The results indicated that the heart rates of students in the solid wood classrooms significantly decreased while students in the control classrooms saw an increase in heart rate.[14] Perceived stress of students from interactions with teachers was also shown to decrease in the solid wood classrooms. This study was the first of its kind, and showed the potential impacts of wood on student health in an academic setting.

A study in 2013 assessed how architecture students perceived different building materials through vision and touch. Now the educational background of architecture students gives them a lot more knowledge about these materials than the average person, but the differences between the materials is what is important. 116 people evaluated six materials samples, which included blue stone, brickwork, concrete, plasterwork, steel and wood. The response to two of the attributes, massive and warm, are shown in the graphs below. The responses were gathered through three conditions of experiencing the materials; visual, tactile, and general (both).[15]

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[14] C. Kelz, Grote V, Moser M, Interior wood use in classrooms reduces pupils' stress levels, Institute of Physiology, Medical University of Graz, Austria; Human Research, Institute for Health, Technology and Prevention Research, Weiz, Austria

[15] Wastiels, L., et al. "Touching Materials Visually: About the Dominance of Vision in Building Material Assessment." International Journal of Design 7.2 (2013): 31-41.

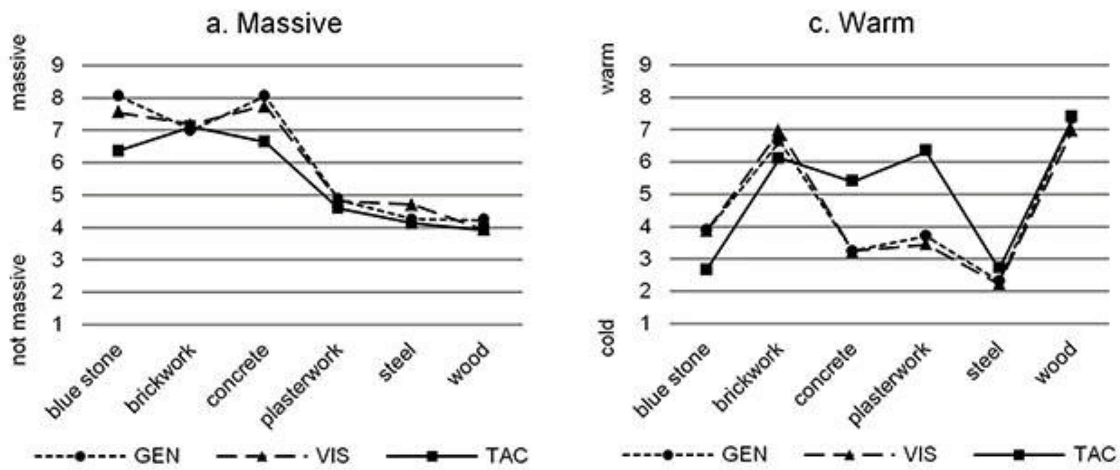

Figure 6, Mean response to two attributes of the building materials, for three conditions (general, visual, tactile). Wastiels, 2013

The general observation of the massive attribute is that wood and steel rank close together, while concrete and bluestone rank the highest. For the warm attribute, wood consistently ranks the highest, with brick not far behind. Blue stone, concrete and steel rank the lowest on this analysis. This ranking system is important, because it shows the general perception that different building materials have on people. If a designer is aiming to create a warm space, abundant amounts of steel or concrete might not help with that. Participants also used words to describe expressive meanings for the different materials, which can be seen in the figure below.

Materials	General evaluation (GEN)	Visual evaluation (VIS)	Tactile evaluation (TAC)
Expressive meanings			
brickwork	trendy(1), modern(1), busy(1), aggressive(1)	enjoyable(2), traditional(2), modern(1), simple(1)	aggressive(1), traditional(2)
blue stone	luxurious(4), old(4), old-fashioned(2), lively(1), sad(1)	pleasant(1), classic(1), luxurious(4), sensual(1)	neutral(1), impersonal(1)
concrete	industrial(2), modern(2), open(1), sad(1), old(1)	unpleasant(2), simple(1), industrial(1), lively(1)	cozy(1), old(1)
plasterwork	neutral(9), pure(3), sterile(1)	neutral(4), simple(3), pure(3), modern(2), new(2), timeless(1)	neutral(1), banal(1), simple(1)
steel	industrial(7), modern(5), unpleasant(3), energetic(1)	industrial(3), modern(3), pure(1), austere(1)	clean(1), distant(1), industrial(1)
wood	natural(4), pleasant(3), neutral(1), fragile(1)	enjoyable(2), natural(2), honest(1), lively(1), playful(1)	(un)pleasant(2), cozy(1)

Figure 7, Expressive meanings mentioned by participants during the evaluation of the building materials. Wastiels, 2013

Repeating meanings for concrete included industrial, unpleasant, and old. Meanings for steel included industrial and modern, Meanings for wood included natural, pleasant, and enjoyable. The natural meaning that participants paired with wood agree with other studies, where the natural aspect of wood in a learning environment was found to lower stress and create a more calming atmosphere.

Acoustics

Unwanted noise in a learning environment negatively affect the ability for students to read, write, listen, and focus on the task at hand. A study comparing schools built between 1977 and 2005 to three different standards of school design found that many classrooms are not comfortable places to acquire knowledge or be mentally focused.[16] The location of school yards and recreational spaces in relationship to classrooms contributed to unwanted noise, while material choices in the building allowed for voices and noise to be carried between classrooms and hallways. Another source of noise comes from within the same space, when the noise from students or teachers talking in one area can be heard in another area where students are studying by themselves, where a quiet environment is key to being able to focus. These results bring up the importance of how sound impacts learning in a classroom environment. First, noise outside of the learning space must be reduced or eliminated before it gets to the space; and second, the form and material of interior details plays an important role in how sound is transmitted inside a room.

[16] Lewinski, P. "Effects of Classrooms' Architecture on Academic Performance in View of Telic Versus Paratelic Motivation: A Review." Frontiers in Psychology 6.746 (2015).

Daylight & Views

An aspect of architecture that has less to do with material choices is the effect of daylight and views on occupant comfort and productivity. A study of students in schools in the United States found that students learning with more daylight in their classrooms progressed 21% faster in math and reading tests compared to those in classrooms with no daylight.[17] This is an outcome that can't be measured in terms of dollars, but is equally as important. In some building types, financial terms that are affected by human performance may outweigh the energy savings from proper daylight design. In addition to daylight windows and skylights, solar tubes can be installed into existing buildings more easily, while controlling glare. While it may seem obvious, when given a choice, people like to sit near windows so that they have a view to the outside. The optimal height of a view window is between 30 inches and 90 inches above the floor.[18] Views of 50 feet or more are recommended to change focal length for eye health.[19]

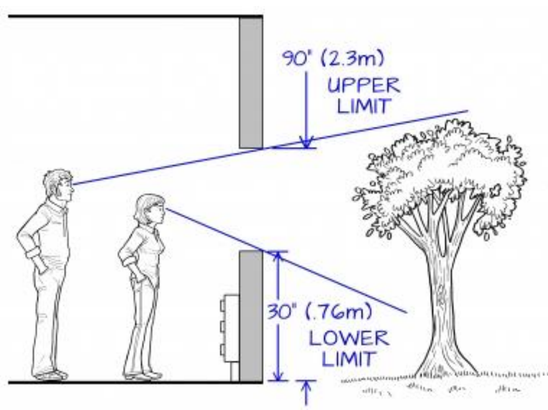

Figure 8, Optimal dimensions for view window. Autodesk Sustainability Workshop

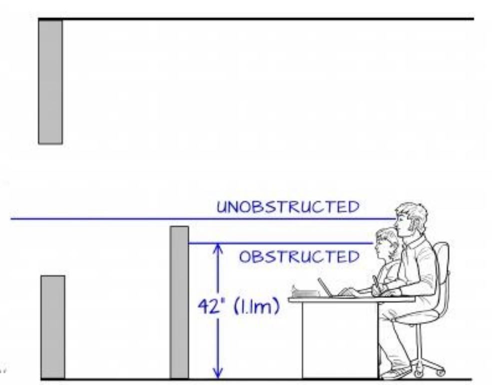

Figure 9, Average eye level of sitting person. Autodesk Sustainability Workshop

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[17] Rose, Warren. "Bringing in the Sunlight." American School & University 85.8 (2013): 26-29.

[18] Y. Aminu Dodo, M. Zin Kandar, D. Remaz Ossen, J. D. Jibril, A. Haladu Bornoma, A. Ibrahim Abubakar, "Importance of a View Window in Rating Green Office Buildings", Advanced Materials Research, Vol. 689, pp. 180-183, 2013

[19] Fielding, Randall, and Prakash Nair. The Language of School Design: Design Patterns for 21st Century Schools. 3rd ed. United States: Designshare, Inc, 2009.

On the other hand, a window that is posited higher up in a wall provides daylight deeper into the space. This illustrates the balance between providing views to the outside for the building occupants while providing enough daylight through daylight windows. A window that serves one purpose may not fulfill the other. A skylight brings in large amounts of daylights, but this does not serve as a view window. A method often employed to accomplish both tasks is by placing a daylight window over a view window, in combination with a light shelf, which brings light further into the space, while reducing glare inside.

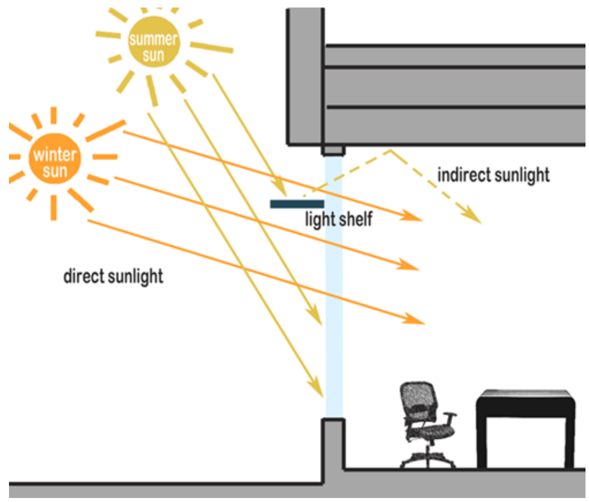

Figure 10, View window & daylight window with light shelf. Source

Too much daylight can be a problem. High illuminance values can lead to furniture damage, distractions from glare, and thermal discomfort.[20] In places where artificial lighting is used, full-spectrum lights should replace fluorescent and tungsten bulbs whenever possible. The closer to daylight artificial light can reach, the greater the reduction in imbalances caused by poor lighting, and the body will be better able to regulate its circadian rhythm.[21]

Color & Temperature

The effect of people's exposure to color is an interesting, and often conflicting, subject for researches. It is generally agreed upon that red and yellow colors increase

[20] Lewinski, P. "Effects of Classrooms' Architecture on Academic Performance in View of Telic Versus Paratelic Motivation: A Review." Frontiers in Psychology 6.746 (2015).
[21] Alexander, C., Ishikawa, S., & Silverstein, M. (1977). A pattern language. New York: Oxford University Press.

stimulation and alertness, while blue and green colors promote balance and calmness.[22] In multiple studies, the color red was found to hinder cognitive performance the most out of all colors. Literature reviews have found that optimal temperatures for learning environments are between 68°F and 74°F, with a relative humidity of 50%.[23]

Seat Arrangement

The physical arrangement of space also affects students' comfort levels, which can impact performance. In a study by Douglas and Gifford (2001), students were shown images of various classroom design, and asked to evaluate them. The three factors that affected the results the most were socialpetal arrangement (seating that allows for greater social interaction among students and teachers), views to the outdoors and comfortable seating. The following images demonstrate successful seating options used in the UMass Integrated Learning Center (ILC).

Figure 11, ILC - Seating with views to the outdoors. William Neumann

[22] Lewinski, P. "Effects of Classrooms' Architecture on Academic Performance in View of Telic Versus Paratelic Motivation: A Review." Frontiers in Psychology 6.746 (2015).

[23] Earthman, Glen. "School facility conditions and student academic achievement," in Williams Watch Series: Investigating the Claims of Williams v. State of California, Los Angeles,CA: UCLA's Institute for Democracy, Education, and Access. (2002)

Figure 12, ILC - Technology Classroom, William Neumann

Figure 13, ILC - 120 seat classroom. William Neumann

Adaptability & Flexibility in Buildings

One of the most important questions about buildings is what happens to them after they are built. Stuart Brand's *How Buildings Learn* looks at how to better design buildings so that they are more adaptable to serve purposes not seen in the initial design, in the near or distant future. Buildings are described as a series of layers, called the Six S's. Site – the geographical setting, structure – foundation and load-bearing elements, skin – exterior surfaces of the building, services – the working utilities of the building, space plan – interior layout, including walls, ceilings, floors and doors, and finally stuff – furniture that can be easily moved. The closer the layer is to site, the harder and fewer times it is changed in the long run, while the closer the layer is to stuff, the more adaptable it is.

Technology changes so fast that some office buildings see a complete rewiring every seven years on average.[24] These spaces have adapted to use drop ceilings and raised floors, which keep the utilities behind an array of easily removable panels. Another concept that the author introduces is scenario-buffered building design. This process deeply involves the users of the building. Future uses that might never have been imagined in a normal round of programming will surface here, and the implications they might have can dramatically shift aspects of the design.

The principles of adaptability and flexibility in buildings are important to consider in the exploration of this thesis. Academic buildings typically have longer lifespans than most buildings if designed well, but if they are designed too tightly for a specific purpose, or become too expensive to maintain, the university will feel the strain and demolition

[24] Brand, Stewart. How Buildings Learn: What Happens After They're Built. New York: Penguin, 1995.

may come sooner than planned. The academic performance building that this thesis explores shall take into account the ever-changing nature of department programs on a university campus. If a department grows bigger over the years, and must move out, what will happen to the empty space? If it is designed in such a way that a new group of users can move in without completing a major renovation, then the building has fulfilled its job.

Similar to seeing a building as a series of layers, there are ways to design flexibility into architecture, as discussed in *Flexible Housing: The Means to an End*, by Jeremy Till and Tatjana Schneider. This reading specifically focuses on housing, but the principles can be applied to a broader scope of architecture. The achievement of flexible housing is explained in two ways. The first is how to design inflexibility out of design, and the second is to design flexibility in. Flexible housing is described as "housing that can adapt to the changing needs of the user." [25] Designing inflexibility out can be achieved through three strategies. The first is reducing the amount of internal load-bearing partitions. The second is the reduction of non-accessible services, and the last is the reduction of rooms that only serve a single purpose.

Designing flexibility into design was broken down into seven categories. Space: Design undefined space that can be finished by the future tenant/user. Construction: Rely on simple and robust construction techniques that place specialized elements that are easily accessible, so that you don't have to call in several trades to perform one job. Design for adaptation: Project future uses that can be accommodated into the design. Layers: Make the layers of a building (structure, skin, services, etc) clearly identifiable,

[25] Jeremy Till and Tatjana Schneider (2005). Flexible housing: the means to the end. Architectural Research Quarterly, 9, pp 287-296

so they are easier to work with in the future. Typical plan: The typical speculative office allows for the highest degree of adaptation because of the open floor plan and easily accessible services. Services: Careful placement of services, such as in a drop ceiling or raised floor will ease service upgrades in the future. Hard and soft uses also affect the ease at which occupants have control over the building. Soft use is described as allowing the users to adapt the plan according to their needs, with the designer working in the background. Hard use is described as the designer working in the foreground, determining how spaces can be used over time.

Most academic architecture is programed in two ways: specialized buildings with a single purpose, such as a studio or science lab, and more flexible learning-type spaces, such as a classroom. If the above principles, designing flexibility in, and designing inflexibility out, could be implemented more effectively into multi-use academic buildings, departments could more easily expand or switch from one building to another, without a costly renovation to meet the needs of the new group. Drop ceilings are a common tool to allow easy access to utilities in the ceiling, and raised floors are becoming more prevalent as the amount of digital infrastructure in buildings increases as our dependency on computers and the internet rises. These two methods of construction allow for flexible utilities above and below the occupied space, but the issue of flexible walls is rarely seen. Depending on the type of construction, interior partitions made out of dimensional lumber and gypsum board are not too difficult to demolish if reconfiguring a space, but CMU walls or metal studs wall with many utilities running through complicate the process. By following these techniques, academic buildings would expand their useful lifespans, and save universities time and money in the long run.

Just as important to academic buildings as flexibility is the expressive nature of its sustainable features, in relation to how well they actually perform. In *Taking Shape*, by Susannah Hagan, the expressiveness of a building's sustainable features is compared to how well the building performs. What this means is that a building can express a lot of green-looking features that to the public can make it seem like it's an energy-efficient building, but the actual performance could vary greatly from the general perception. On the other hand, a rather mundane looking building with small windows could run very efficiently, due to well insulated walls and a low window-to-wall ratio. The public would perceive this as an ordinary building, but looks can be deceiving. This type of situation brings up the important issue of balance in how a structure looks like it performs, and how it performs. Putting a green roof on might get everyone excited about this feature, but it may perform worse than an ordinary roof in certain climatic conditions. Many educational institutions, including UMass, strive to make their buildings as "green" as possible, but in places where the public faces of the organization is the buildings themselves, aesthetics of high performing features can often take precedence over practical operation of the features.

Just as there is a balance in utilizing green features on a building, this also applies to features that are energy wasters. A prime example is floor-to-ceiling curtain walls. They look great from the outside and inside, but the amount of heat lost in winter and heat gain in summer does not make them energy efficient or economical in most parts of the world. Newer technology such as triple pane windows or double-skin facades boost the efficiency of these systems, but at a much higher cost.

As this thesis moves forward into the design phase, the concepts discussed by Hagan are important to consider as the building progresses from conceptual design through design development. At each stage of design, it will be important to consider the energy saving techniques that can be implemented, as well as the aesthetic values that add or subtract from the design. Energy wasting features should only be implemented in key areas where the aesthetic value is deemed more important than the annual energy loss. If a feature performs well and looks great, then that is a win-win situation.

Sustainability & Energy

Resiliency in Wood Buildings

Pushing beyond sustainability is resiliency. The American Institute of Architects (AIA) described that "a resilient building in a non-resilient community is not resilient." To be truly sustainable, the building has to be considered in a larger context for it to function at its highest level. As defined by the National Institute of Building (NIBS), AIA, ASHRAE, American Society of Civil Engineers (ASCE) and other organizations, resilience is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." Disasters often cause major damage and financial loss, but much of this can be prevented with cost-effective mitigation features and advanced planning.[26]

Wood buildings make sense in high seismic regions because they weigh considerably less than a concrete or steel building, so the forces on the building will be less during a seismic event. The foundations, hold downs, and structural connections do not have to handle the same kind of forces as with a heavier building. Typical light-frame construction has the added benefit of many nailed connections, which exhibit a ductile behavior, instead of sudden failure. The repetitive nature of wood framing creates multiple load paths that are better at resisting seismic forces.[26] Japan conducted seismic test of a seven-story CLT structure back in 2007, and found that the building performed quite well. Based on these this and other tests, CLT may be more resilient in a disaster than other heavy construction materials.[27]

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[26] reThink Wood. "Building Resilience: Expanding the Concept of Sustainability." Continuing Education (2016): 24 Jul, 2016.
[27] Douglas, Brad, and Erol Karacabeyli. CLT Handbook: Cross-Laminated Timber. Pointe-Claire, QC: FPInnovations & Binational Softwood Lumber Council, 2013.

Fire-resistance of timber structures can be achieved in two ways; through charring, or encapsulation. For timber beams, columns and panels, the charring of the wood protects the inside of the member during exposure to fire. "Charring is a process in which the outer layer of wood reaches its ignition temperature, ignites and burns continuously. In this chemical reaction, the heat removes hydrogen and oxygen from the solid wood, leaving a layer of char that is now mainly composed of carbon. This char layer has low conductivity which results in a sharp thermal gradient across the char layer. Beyond the char layer, a layer known as the pyrolysis zone forms, where the rise in temperature of the char layer causes decomposition of the wood in this zone. The inner core is only slightly affected by the temperature rise resulting mainly in moisture loss."[28]

Charring Diagram

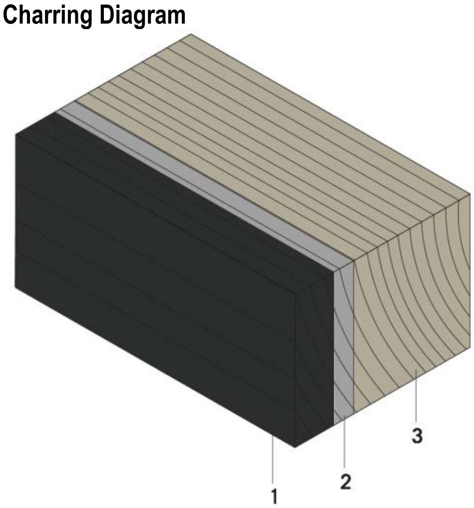

Figure 14, Charring diagram. Tall Wood

1. Char layer
2. Pyrolysis zone
3. Natural wood

Charring Structural Design Diagram

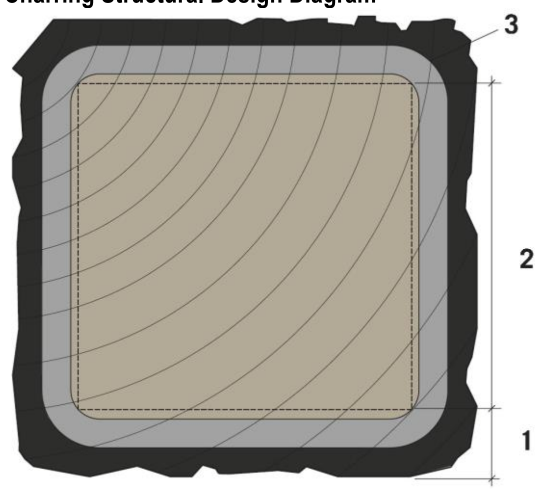

Figure 15, Charring structural design diagram. Tall Wood

1. Sacrificial layer (char layer and pyrolysis zone; no structural capacity)
2. Residual section (structural capacity retained)
3. Rounded corner

[28] mgb Architecture + Design, and Equilibrium Consulting. The Case for Tall Wood Buildings. LMDG Ltd & BTY Group, 2012.

When exposed to fire, CLT and LSL panels char at a rate of .65mm/min, and .635mm/min for glulam elements. This rate can be used to achieve the desired fire rating for the structural member. The other method for fire-resistance of timber construction is encapsulation. Typically used for timber panels, a membrane system (gypsum board), is applied over the exposed wood. The downside to this method is that the wood is covered up, but it is more accepted by building and fire officials, as further tests for charring are needed to find out how these new building materials endure during fire. Fire tests of a 10 foot by 10 foot, five-ply CLT wall covered on each side with gypsum board lasted over three hours while loaded with 87,000 pounds of force.

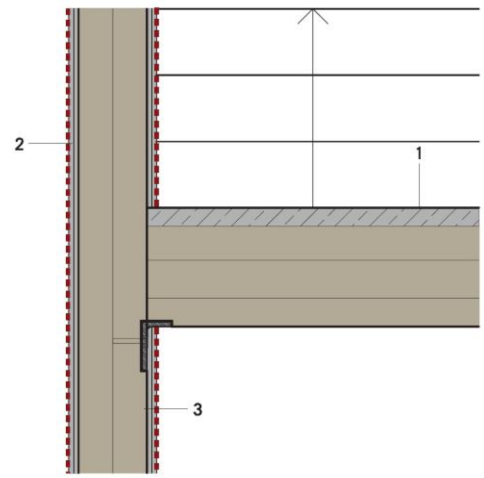

Figure 16, CLT wall at stairwell. Tall Wood

1. Stair: Timber panel + concrete topping.
2. Wall: Mass timber panel + 2 layer 5/8" gypsum board.
3. Recessed steel ledger.

The result from this has spurred revisions in the 2015 version of the International Building Code. Even more recent was a test for a glulam beam to glulam column connection for the future Framework Building in Portland, Oregon. The two tests showed that the assembly could exceed the two-hour fire rating, while allowing some of the timber to be exposed.[29] The combination of these tests will allow for the construction of high-rise mass-timber buildings in the United States.

Energy Objectives in Wood Buildings

While wood not only has a lighter carbon footprint than other building materials, and sequesters carbon while it grows, wood is inherently better at thermal performance

29 Gallivan, Joseph. "Burn Baby Burn! Framework Moves Ahead." Oregon Business Tribune, 2016.

due to its material properties. The versatility of wood also means that there are insulation methods that aren't available for other construction methods. Energy codes continue to become more demanding as time goes on, and "many of the new requirements exceed the cost-effective thermal insulation limits of traditional wood-frame construction." [30] Luckily, wood building materials can easily adapt to new building methods and detailing techniques to meet current and future energy requirements.

Assemblies such as locating insulation on the outside of the framing, framing deeper cavities filled with insulation, or constructing details that are more thermally efficient, give wood an edge of energy efficiency over steel and concrete. Nowadays, steel or concrete structural elements that protrude through the thermal envelope must be thermally broken to prevent thermal bridging, but wood's lower thermal conductance means that the same assembly made of wood performs much better. Mass timber panels have the advantage over similar assemblies out of concrete with their higher thermal resistance values. This means that they can further contribute to the thermal performance of the exterior envelope.

Wood Use and Foresting

With the increase in mass timber construction in the last five years, and the future rise of this type of construction, will forests be able to sustainably provide wood without reaching deforestation? The answer is yes. Compared to other conventional building materials, such as concrete, steel and glass, wood has a significantly lower embodied energy, contributing less water and air pollution than other materials. Forests are large carbon sinks, converting CO2 back into oxygen. Young trees grow much faster than older

[30] reThink Wood. "Meeting and Exceeding Energy Objectives in Wood Buildings." Architectural Record November 2014.

trees, taking up carbon much quicker. As a tree reaches the end of its life and starts to decay, it slowly releases stored carbon. Natural events such as wildfires, disease or flooding releases the stored carbon much more rapidly. When a tree is harvested and run through the manufacturing process, approximately 50% of the dry weight is carbon. When that product is used in the construction of a building, that amount of carbon is kept out of the atmosphere for the lifetime of the building or longer, if the wood is reused at the end of the building's life.[31]

The use of wood can have a profound impact on climate change, through reducing greenhouse gas emissions and storing carbon. In comparing wood to concrete, concrete has 57% more embodied energy than wood, emits 81% more greenhouse gases, and produces 350% more water pollution.[32] In addition, even though wood harvesting and production emit CO_2, the amount of carbon that the wood is storing and replacing other materials are enough to offset that difference. At the end of a building's life, the wood can be reused in smaller applications, or burned to produce energy.[31] In the United States, biofuels accounted for 75% of the energy required at wood production facilities in 2010,[31] which lessens the environmental impact of the wood industry.

North America is not running out of forests, and for the last 50 years, forest growth has exceeded forests harvesting in the U.S. and Canada.[31] According to the National Report on Sustainable Forests, published in 2010, the U.S. has about 751 million acres of forest area, which is roughly one third of the country's total land area. 44% of the forests are publicly owned, while the remaining area is owned by private landowners. The rate of urban development has been increasing, which has been

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[31] Patterson, Dave, and Roxane Ward. "The Impact of Wood use on North American Forests." (Oct 2015).
[32] mgb Architecture + Design, and Equilibrium Consulting. The Case for Tall Wood Buildings. LMDG Ltd & BTY Group: 2012.

consuming woodlands in return for developing that land. In the future, there must be incentives for private landowners to hold onto their forests, to protect them from deforestation. In Canada, local governments regulate the harvest levels in forests, which helps with forest health and longevity. "Wood is the only building material that has third-party certification programs in place to demonstrate that products being sold have come from a responsibly managed resource."[33] As of January of 2015, more than 500 million acres of forest in the U.S. and Canada are certified under one of four internationally recognized programs. They include the Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), Canadian Standards Association's Sustainable Forest Management Standards (CSA), and American Tree Farm System (ATFS). Half of the world's certified forests are in North America.

Life Cycle Assessment

Buildings consume over 40% of the energy produced in the United States, use 75% of the electricity, and account for nearly half of all CO2 emissions. These statistics highlight the impact that the built environment has on our planet, and the importance of reducing the environmental impact that buildings have. "Life cycle assessment (LCA) is an internationally recognized method for measuring the environmental impacts of materials, assemblies, or whole buildings, from extraction or harvest of raw materials through manufacturing, transportation, installation, use, maintenance, and disposal or recycling."[34]

[33] Patterson, Dave, and Roxane Ward. "The Impact of Wood use on North American Forests." (Oct 2015).
[34] reThink Wood. "Building Materials Matter." (2012).

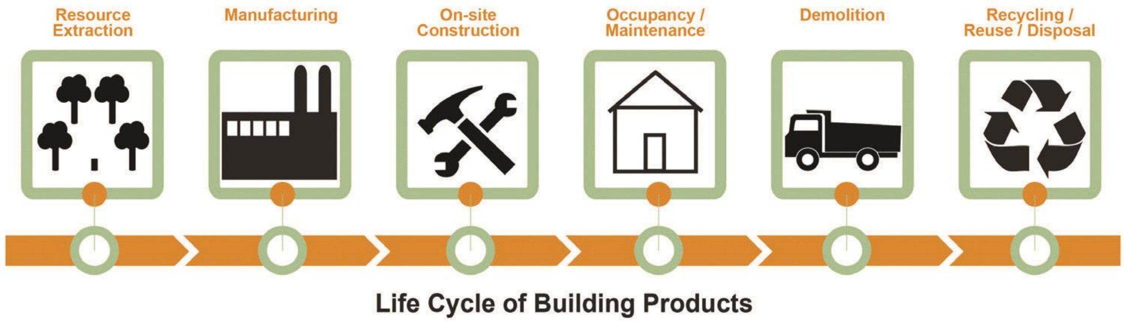


Figure 17, Building product life cycle. Naturally:wood

A decade ago, energy efficiency of buildings was the primary goal for reducing a buildings' carbon footprint. Increasingly, designers have been considering the whole life cycle of the building, from natural resource extraction to building demolition or recycling. The main argument for using wood is that it requires less energy to harvest and manufacture than steel or concrete, and wood stores carbon, keeping CO2 out of the atmosphere for the lifetime of the building. Wood can also be more easily reused or recycled than steel or concrete. It is also one of the few building materials that is renewable. Sustainably certified forestry's can provide more than enough wood to meet our demand for buildings. Manufacturing of wood products is less intensive than steel or concrete, which must be heated to extreme temperatures to achieve the right chemical composition.

Lumber mills have figured out how to get the most out of every tree, and wood scrap is used as biomass, which is burned to generate electricity to power sawmills. "Dovetail Partners Inc., which provides information about the impacts and trade-offs of environmental decisions, calls the North American lumber industry 50 to 60 percent energy self-sufficient overall."[35] Tools are available for building professionals to measure the impacts of building choices. Athena Impact Estimator can model over 1,000

[35] reThink Wood. "Building Materials Matter." (2012).

structural and envelope assemblies with life cycle data, and Carbon Calculator by Wood Works can calculate the carbon offset from the wood products used in a building.

Passive Design Strategies

Building Massing and Orientation

The massing of a building is one of the biggest influencers on thermal performance and energy usage. The type of massing used depends on the building type and climate. Massing where the exterior surface area is reduced will see reduced energy consumption from conduction heat gain and loss compared to a longer, thinner building with a greater surface area. Buildings which have higher space heating and cooling loads, compared to other energy uses, such as a single family home, will benefit from a more compact massing. On the other hand, buildings with high internal loads, such as an office or data center, can benefit from a larger surface area, depending on the climate. Massing should be considered from the beginning of the design of the building, since it will have the greatest impact on the building's performance.

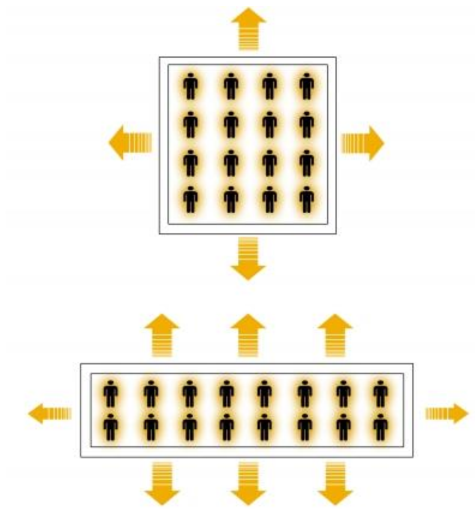


Figure 18, Thinner buildings lose more of their internal heat to the outside. Autodesk

Passive Heating Strategies

Direct solar gain is heat from the sun that is absorbed and contained within a building. This can occur from the sun heating up the building envelope from the outside, and that heat being conducted through to the inside, or sun shining through a window, heating up the space inside. Solar gain is highly desirable in cold climates, where the sun can lower mechanical heating loads, but unwanted in warmer, cooling-dominated climates. Temperate climates benefit from direct gain in the winter, but not the summer, so the building's massing and shading system must be carefully design.

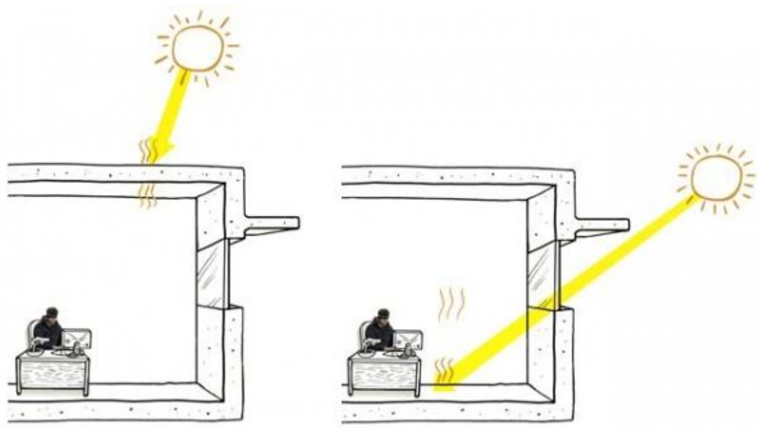


Figure 19, Direct gain through the envelope or a window. Autodesk

Direct gain through a window can be achieved by placing large amounts of glazing on the south side of the building. In northern climates, the high summer sun can be effectively blocked by appropriate shading, while the lower winter sun can penetrate the glazing, heating up the space inside.

Solar gain can be effectively managed with thermal mass. Climates that see a wide fluctuation in day and night temperatures can benefit from thermal mass, as the mass absorbs excessive radiation during the day, and releases it back into the space at night. This strategy uses the principle of thermal lag. In climates that are always hot or always cold, thermal mass may be a drawback, as

Figure 20, Stored heat in the thermal mass after the sun is gone.

the mean day temperature will either be too high or too low.[36] As much of the mass as possible should be in direct sunlight to absorb the maximum amount of radiation. The mass can be extended beyond the glazing area to help transfer heat throughout the building.

Technologies that utilize thermal mass include trombe walls and sunspaces. A trombe wall consists of a wall with a high thermal mass, a layer of glazing offset from the wall, and vents at the top and bottom of the wall. During the day, the sun heats up the thermal mass, radiating heat into the room, while also forming a convective current. During the night, the vents can be shut, to reduce heat loss in the cavity space and prevent a reverse convective air loop.

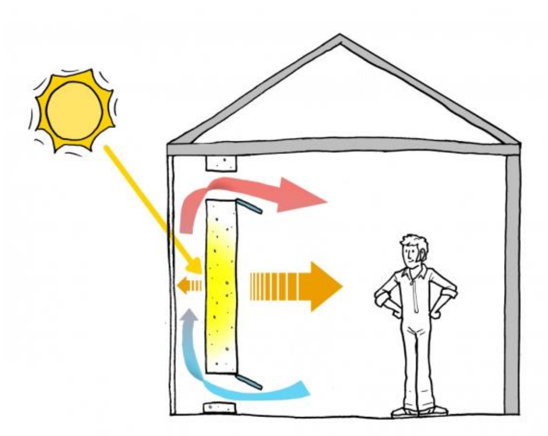


Figure 21, Trombe wall daytime operation. Autodesk

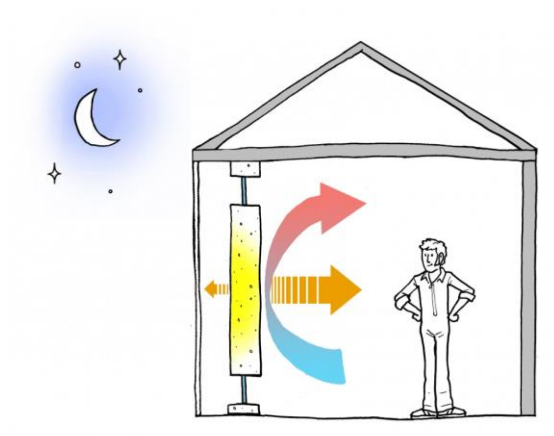


Figure 22, Trombe wall nighttime operation. Autodesk

Similar to a trombe wall, a sunspace has a larger area between the glass and thermal mass, which serves as habitable space. The cavity space can be sealed off at night to preserve the heat in the main space, but if the area is to remain habitable at night, additional insulation and high performing windows are needed to retain more of the heat at night.

[36] Billing, et al. "Autodesk Sustainability Workshop."

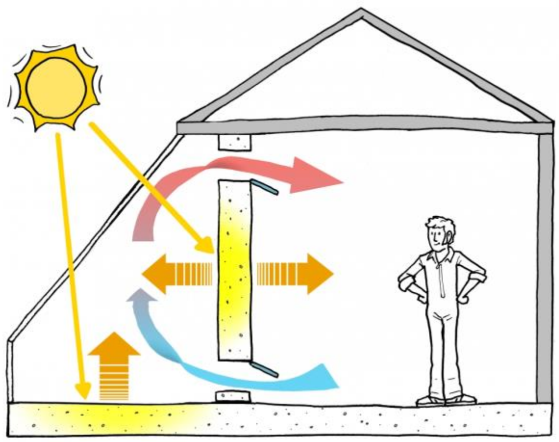


Figure 23, Daytime sunspace operation. Autodesk

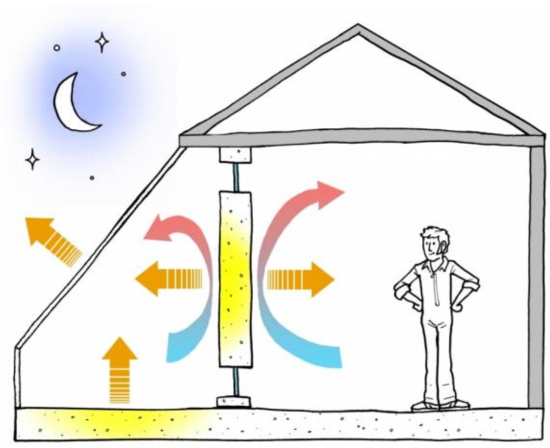


Figure 24, Daytime sunspace operation. Autodesk

Additional building techniques that utilize thermal mass include water walls and solar chimneys. Water walls allow heat to be transferred quickly through the mass, as the water forms convection currents as it heats up. In addition to heat, the water can also bring light into the space. If designed correctly, a solar chimney can heat air in the cavity between the thermal mass and the glazing, where it will rise and be vented out the top. This current of air will pull air from the room, aiding in passive ventilation.

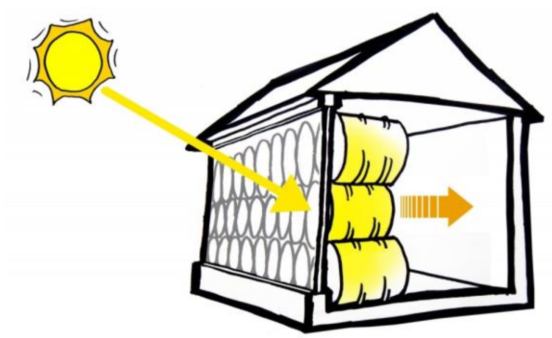


Figure 25, Water barrels forming a trombe wall. Autodesk

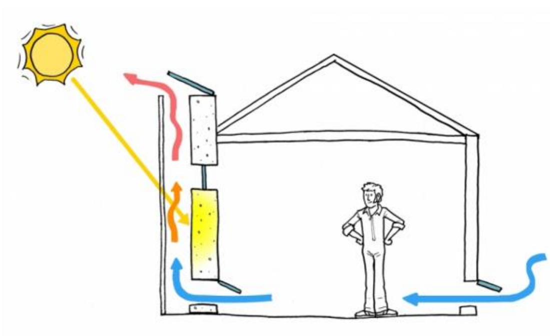


Figure 26, Trombe wall acting as a solar chimney. Autodesk

The types of glazing used can affect how much heat can pass through a window. In cold climates, the U-value of the window is the most important factor to consider. In warmer climates, the solar heat gain coefficient plays a bigger role, as a window that lets too much heat gain through can overheat the adjacent space.

Passive Cooling Strategies

Natural ventilation relies upon outside air movement and pressure differences in the building to both cool and ventilate a building. It allows buildings to reduce their cooling loads without relying on mechanical systems. Drier climates can make use of natural ventilation the best, while humid climates should not utilize natural ventilation. Sites that have high levels of exterior noise or air pollution should also limit their use of natural ventilation.

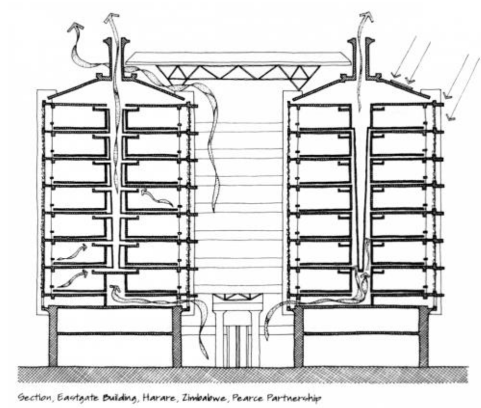


Figure 27, Natural ventilation strategies in a multistory building. (Image from Sun, Wind, and Light, by G.Z. Brown and Mark DeKay, published by Wiley)

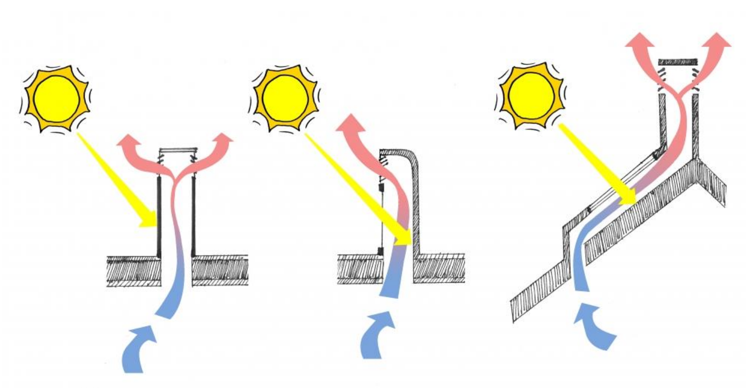


Figure 28, Solar chimney designs that utilize the stack effect. Autodesk

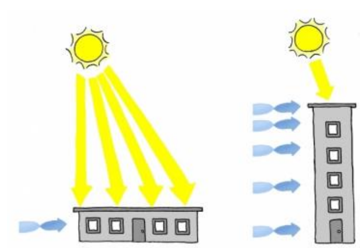
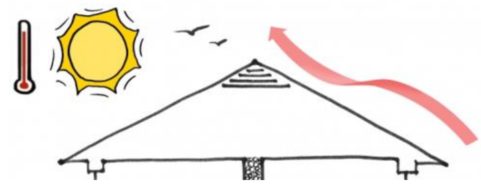


Figure 29, Passive ventilation effectiveness - deep versus tall and thin buildings. Autodesk

The massing of the building also affects the effectiveness of natural ventilation. Buildings with a deep plan will have a harder time getting air into the core, while taller, thinner buildings will find it easier to utilize natural and stack effect ventilation.

Night purging is another technique that uses natural ventilation. During the day, windows are closed, and thermal mass in the building slowly heats up. At night, the windows are opened, using wind and stack ventilation to flush out the warm building air with cold outside air. In the morning, the windows are closed, and the cycle repeats. Night ventilation can be aided by solar chimneys or mechanical fans. Night purging is only effective in climates with a large difference in day and nighttime temperatures. It is not recommended to use night purging in warm and humid climates, as humid air must be removed through air conditioning during the daytime.



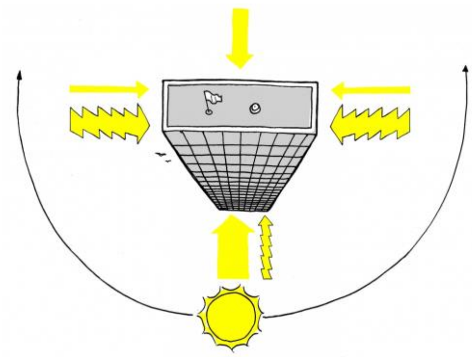


Figure 31, Useful daylight (straight arrows). Autodesk

Figure 30, Night purging daytime and nighttime operation. Autodesk

Lighting and Daylighting

Using daylight is a good way to lower a building's dependence on artificial lights, while providing a higher quality light. Daylight is the diffuse light from the sky, but sunlight, direct light from the sun, is unwanted, as it can cause glare and overheating. From a massing point of view, it is advisable to orient a building east-west, with the longer sides facing north and south, as this reduces the amount of glare the building will see at sunrise and sunset, and it is much easier to shade southern sun.

Single-story buildings can utilize skylights to bring daylight into deeper spaces, but multi-story buildings should rely upon thinner floor plates or taller windows to bring in more light. Using a higher amount of windows that are located around a space will help to evenly distribute daylight. Having windows that reach up to the ceiling allows the light to reach even deeper into the space, since daylight typically reaches 2.5 times the height of the window into the space. North-facing windows bring in more uniform light, although not as bright as south facing windows. Besides for skylights, other aperature types can bring in light through the buildings roof which include clerestories, monitors, or sawtooth roofs.

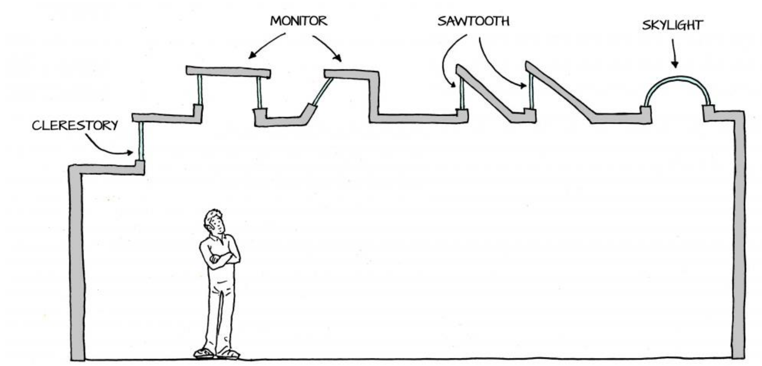


Figure 32, Top lighting strategies. Autodesk

In effective daylighting design, daylighting and view windows shall be differentiated. View windows must be at eye level, so the building occupants can see out of them, while daylight windows benefit from being higher up in the wall or roof. Light shelves are an effective tool to direct daylight further into the space, while blocking direct sun from coming through the view window. When a light shelf is oriented vertically, it is known as a baffle. They are best used in top lighting to distribute daylight.

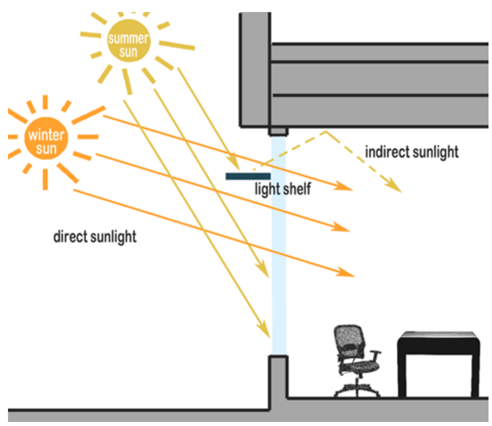


Figure 33, Light shelf redirecting light. Autodesk

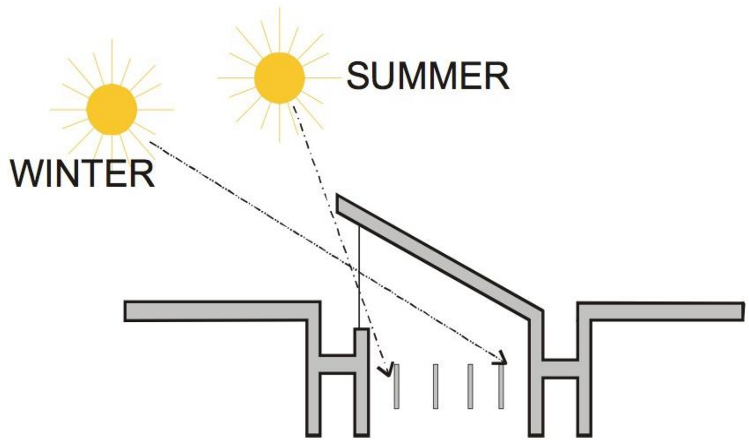


Figure 34, Using baffles in a roof monitor. Autodesk

Theater Design

Theaters come in many forms, depending on the performance type. This affects the size and shape of the auditorium and stage, and how many seats it holds. The size of the front of house and back of house areas is greatly affected by the type of theater, and the amount of seating. Typical theater types are described below.

Opera House

Opera houses usually hold opera and ballet companies, and typically seat between 1,800 and 2,000 people. They frequently have a horseshoe-shaped auditorium, with a well-equipped stage and orchestra pit.[37]

Figure 35, Opera House Linz auditorium. Dirk Schoenmaker

Concert Hall

Classical music is typically played in a concert hall. They usually seat between 1,500 and 2,000 people and take on a shoebox or vineyard form.

Figure 36, Shoebox auditorium - Stavanger Concert Hall. Stavanger Aftenblad

Figure 37, Vineyard auditorium - Bing Concert Hall. Jeff Goldberg / Esto

[37] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

Recital Room

Recital rooms are used for smaller scale classical music performances, with seating ranging from 200 to 600 people. They are typically rectangular in form.

Figure 38, New Pavilion for the McGill University Schulich School of Music. Saucier + Perrotte Architectes

Drama Theater

Drama theaters have the widest variation in form and seating, as does the field of drama. Seating can range from 100 up to 1,200, and the stage can take on many forms, including arena, in-the-round, thrust, end stage, or traverse.

Figure 39, Perelman Performing Arts Centerc - WTC. REX

Musical Theaters

As the name implies, these theaters house large-scale musical attractions, and typically seat between 1,500 and 2,000 people.

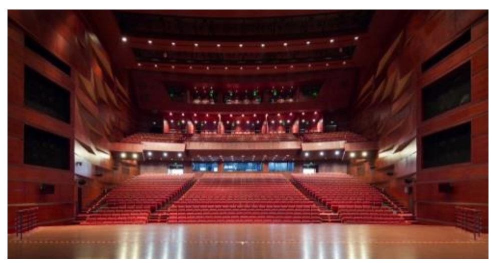


Figure 40, Bayuquan Theatre. DSD

Entertainment Venues

These theaters hold popular entertainment, like concerts or circus displays, and seating can range from 1,500 to 12,000 plus.

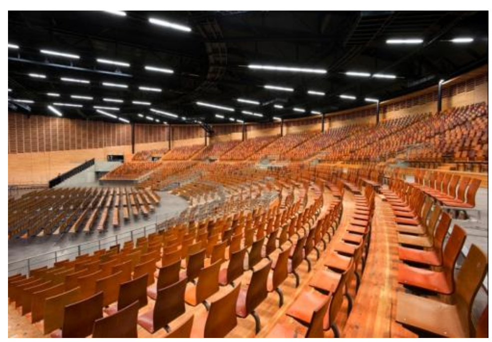


Figure 41, Limoges Concert Hall. Bernard Tschumi Architects

Theater Components

A typical theater building can be divided into three areas: the auditorium and stage, front of house, and back of house. The program of this thesis has the added component of classroom and administration spaces, which have to be carefully integrated into the typical theater spaces.

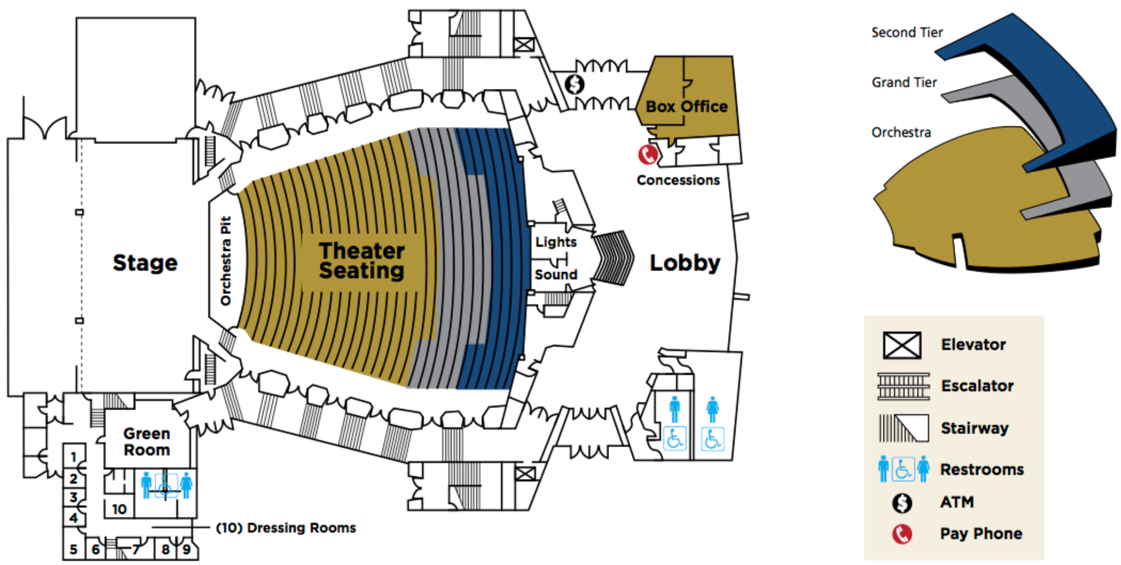


Figure 42, Floorplan showing FOH, auditorium and backstage areas for Sacramento Convention Center - Community Center Theater. SCC

Auditorium & Stage

The auditorium is where all the action happens, and the relationship between the stage and audience depends on the type of performance going on. For the audience, it is most important that every audience member can hear and see from any seat in the theater. Seating can be achieved through fixed or flexible seating, and the stage can take on a variety of forms. The formats of auditoriums are described in the sections below. The volume and reverberation of the auditorium is related to the volume of the room.

Different performances require different volume and reverberation requirements, so the size of the auditorium is driven by this factor.

Front of House

The front of house (FOH) encompasses the foyer and all the support functions needed for holding a large number of people before they move into the auditorium. Circulation and signage must be clear, as many people who are seeing the show will have not been there before. Public areas in the FOH include the lobby/foyer, reception and box office, restrooms, coat storage, food service, etc. Support areas for the FOH include offices, equipment storage, kitchens and cold/dry storage for food, janitorial storage, etc.

Back of House

The purpose of the back of house area is to support the performers, production and technical staff that are running a show. These areas should be kept out of view from the public, to preserve the mystique of the performance on stage.[38] Circulation is key here, as movement between the stage and delivery doors, shop, and dressing rooms determines the success of the area. Backstage areas can include dressing rooms with showers, toilets and lockers, costume and wardrobe, green room, scene dock, prop and

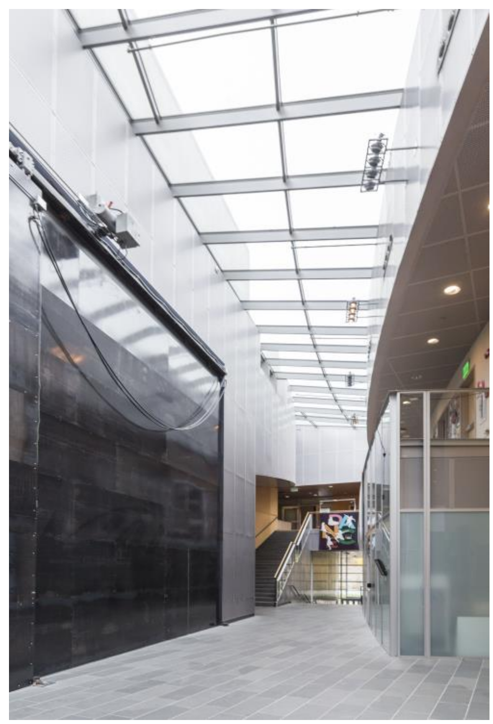


Figure 43, Stage access door - Williamstown Theater. Dylan Brown

[38] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

scenery storage, shop and loading dock. Larger theaters should have a separate entrance for performers and staff, to improve access to preparation areas, and increase security.

Auditorium Formats

Proscenium Theater

In the Proscenium theater model, the audience and stagehouse volumes are separate, but adjacent. The audience views the performance through the proscenium opening, which can be thought of as a giant picture frame. Above the stage is the stagehouse or flytower, where scenic elements can be suspended or flown around the stage. The proscenium format remains the primary theater model for large-scale performances and elaborate scenery effects.[39]

[39] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

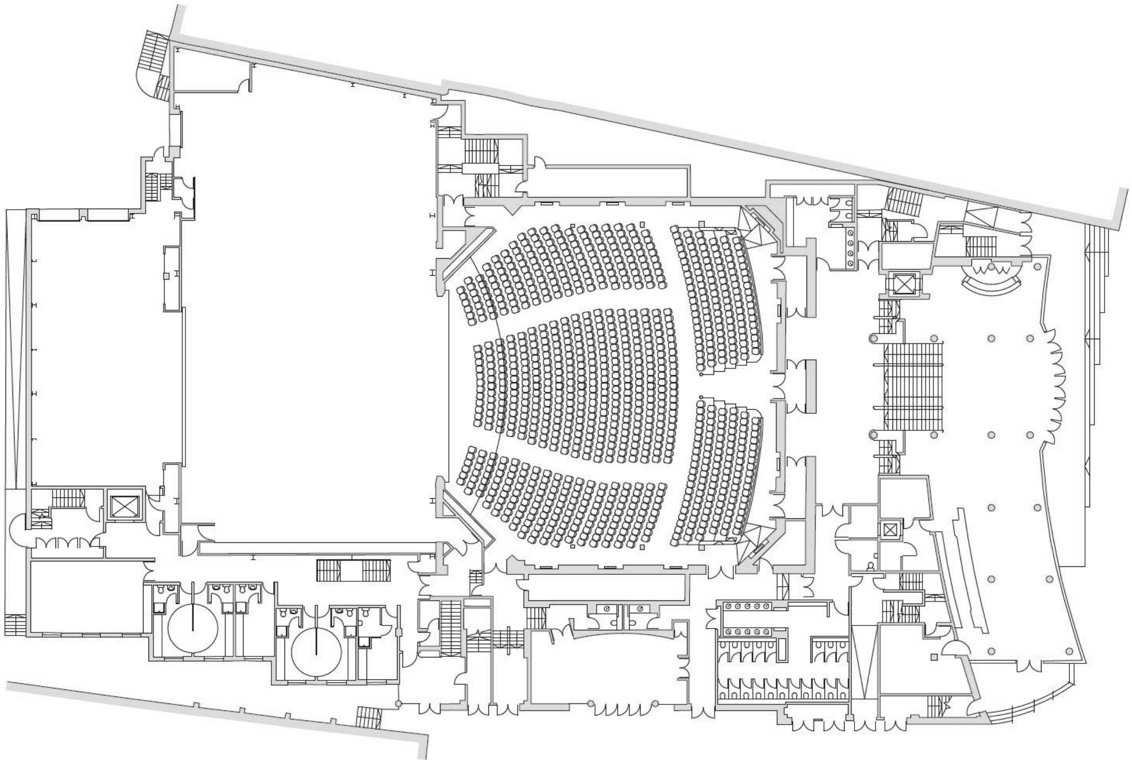


Figure 44, Festival Theatre - Edinburgh, Scotland. LDN Architects

End Stage

The end stage is a variation on the proscenium theater model. The audience is positioned directly at the end of the stage, and often share the same physical space as the performers, without the presence of a proscenium opening.

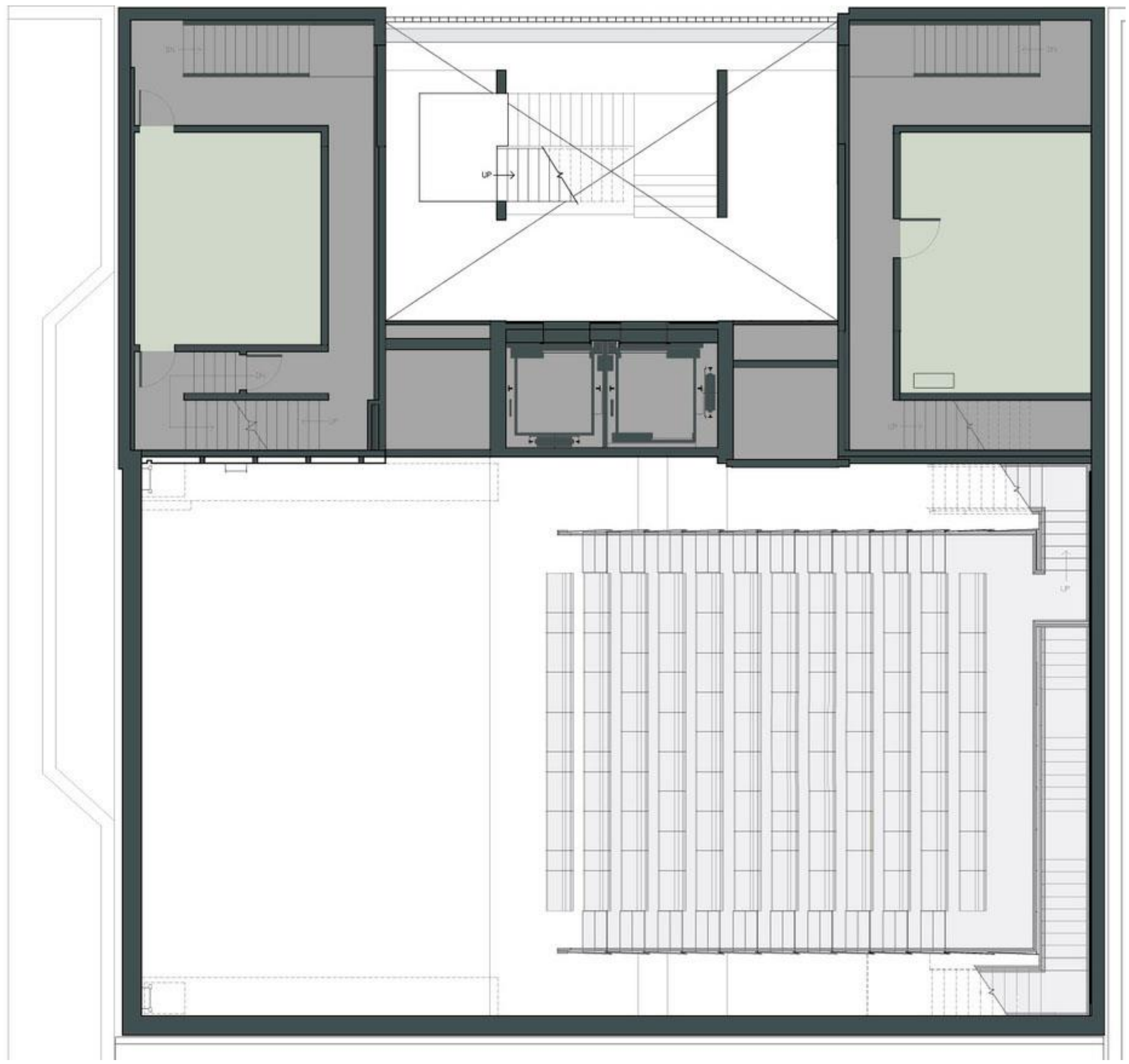


Figure 45, Baryshnikov Arts Center, Jerome Robbins Theater. think!

Corner / Wide Fan Stage

In a corner or wide fan stage model, the stage is positioned in the corner of the room, creating a 90 to 135-degree seating arrangement. This allows the performers to have a closer connection with the audience, while still placing the stage walls or backdrop to the backs of the performers. The extreme side seating and sightlines limits the staging and set design, but there is potential if designed well.[40]

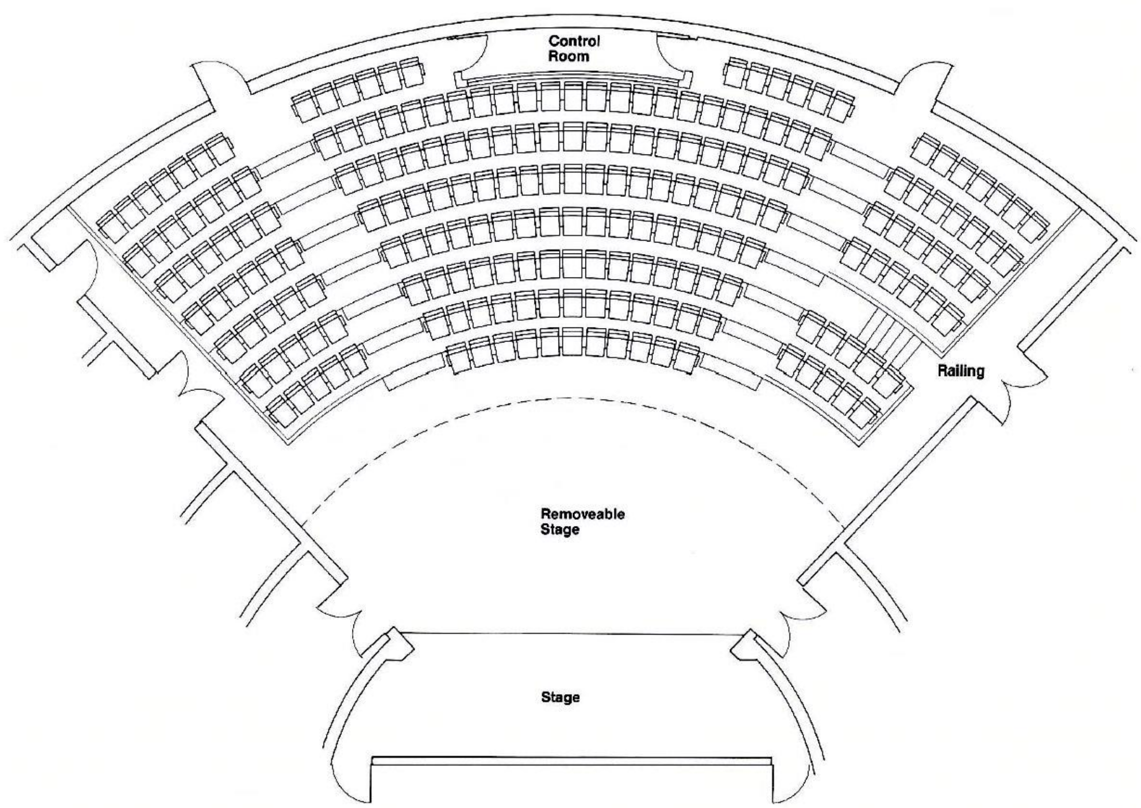


Figure 46, Wide fan / corner stage theater. Theatre Solutions Inc

Amphitheater

An amphitheater wraps the audience around the center stage, and is often used for outdoor venues, where the space can be carved into the landscape. A Greek amphitheater wraps the audience 220 degrees around the stage, while a typical Roman theater has 180

[40] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

degrees of encirclement. Today, amphitheater is commonly used as a generic term for an outdoor performance area.

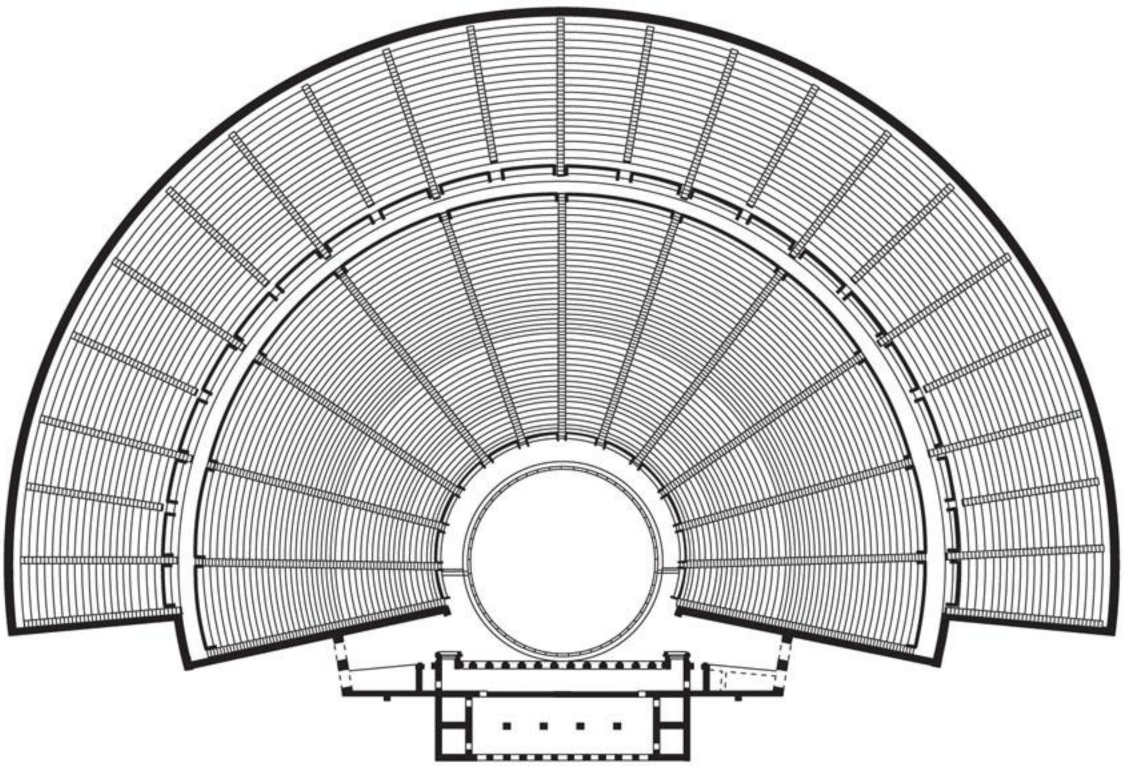


Figure 47, Amphitheater in Epidaururs (Epidauros, Greece)

Thrust Stage

In a thrust stage, the audience is positioned around three sides of the stage. Spectators on one side provide the backdrop for the people on the other. Performers can enter through the rear of the stage, or through the audience. The three-sided nature of the seating gives the audience a unique perspective.[41] The resulting performances that are held in these types of stages are more three-dimensional in nature.

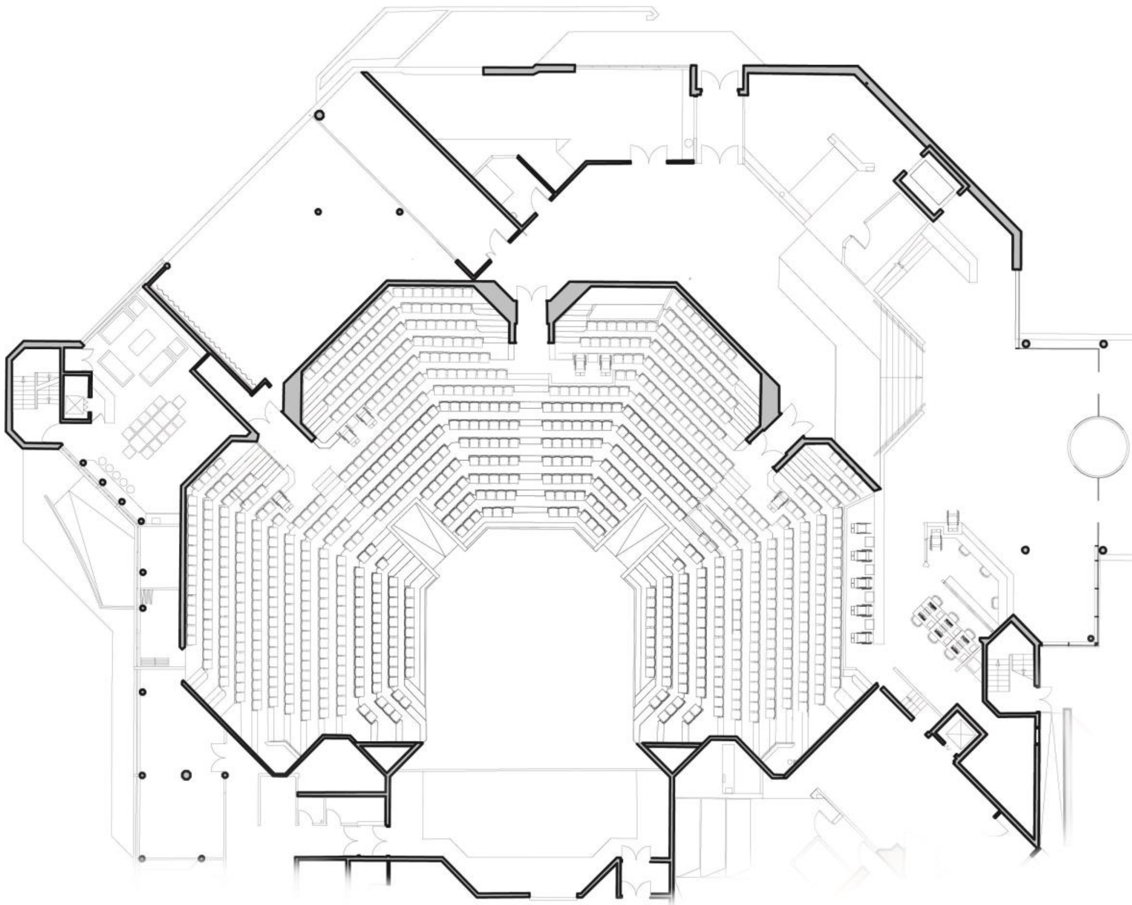


Figure 48, The Crucible Theatre, Sheffield, UK. RHWL, London

In-the-Round

In-the-round places the stage in the middle of the auditorium, with the audience wrapping 360 degrees around. Scenery and props are minimal, as not to block views from

[41] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

any angle, and the performers enter and exit through the audience. Performances such as dance or a circus can better utilize this type of stage.

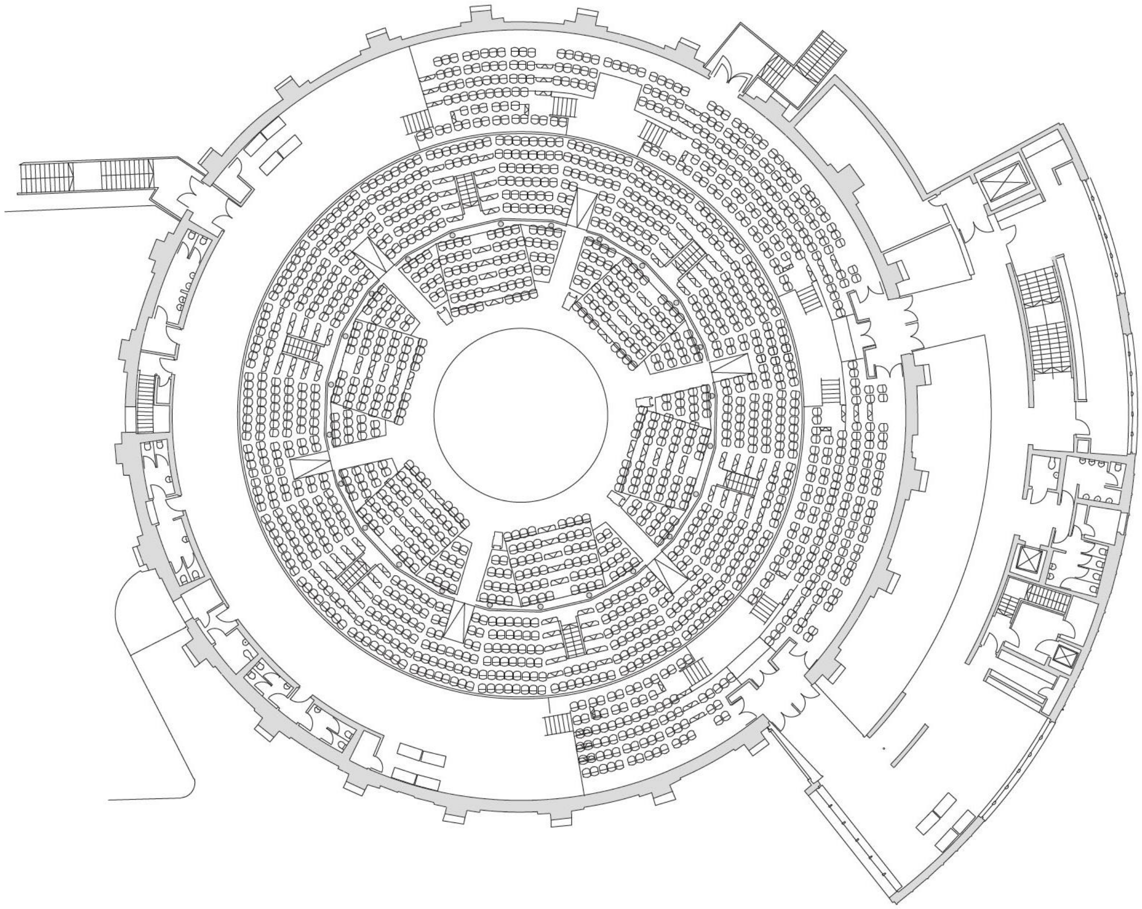


Figure 49, The Roundhouse, London, UK. John McAslan + Partners

Courtyard

The courtyard theater model came out of the English Renaissance, where much of the work of Shakespeare was held. Traditionally they were compact, multi-leveled and open to the sky.[42] The stage was typically thrust out into the auditorium, and two to three levels of shallow seating wrapped around the perimeter. Their compact nature means the audience is much closer to the action than in classical theater designs.

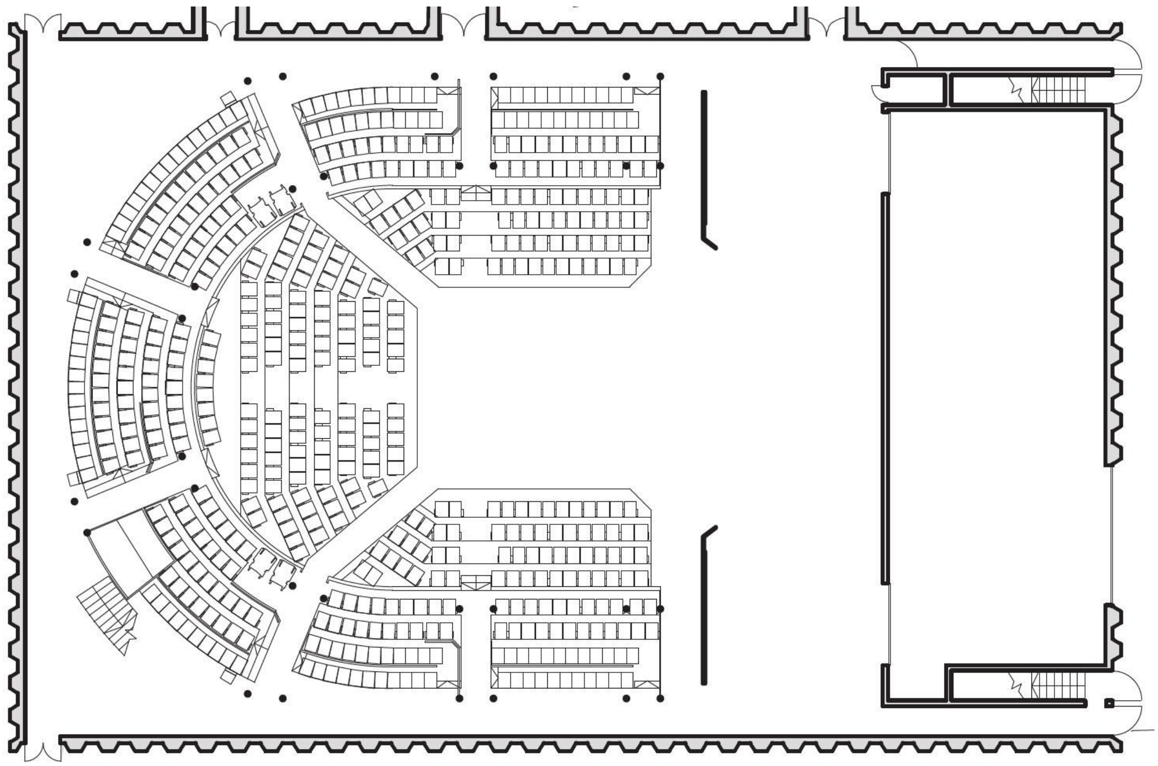


Figure 50, The Courtyard Theatre floor plan. Ian Ritchie Architects

Architectural Precedents

[42] Association of British Theatre Technicians. Theatre Buildings: A Design Guide. Ed. Judith Strong. New York, NY: Taylor & Francis, 2010.

Taipei Performing Arts Center - OMA

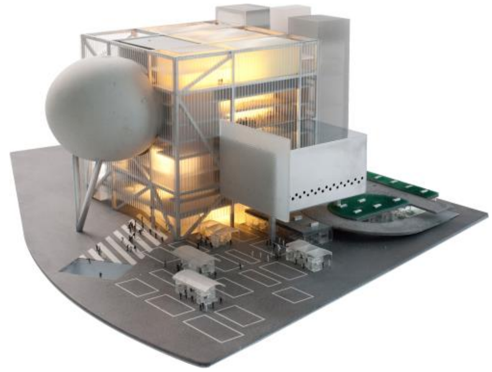


Figure 51, TPAC physical mode. OMA

Still under construction, the Taipei Performing Arts Center (TPAC) consist of three theaters plugged into a central volume, where they can share stage accommodations, allowing for more flexibility in programming and performances.[43] The center contains one 1,500-seat theater in the shape of a sphere, and two 800-seat theaters. TPAC follows OMA’s typically geometric influence, where two rectangular volumes and a sphere are inserted into a central cube clad in corrugated glass.

Figure 52, TPAC multiform theater. OMA

Figure 53, TPAC grand theater. OMA

The introduction of movable walls and flexible seating means that the Grand and Multiform theaters can merge into one space, which allows for a stage up to 100 meters long to be used. The building’s form is driven primarily by program and functional requirements, where it retains a relatively simple geometric exterior.

[43] Basulto, David. "OMA's taipei performing arts center breaks ground." Archdaily. 17 February, 2012.

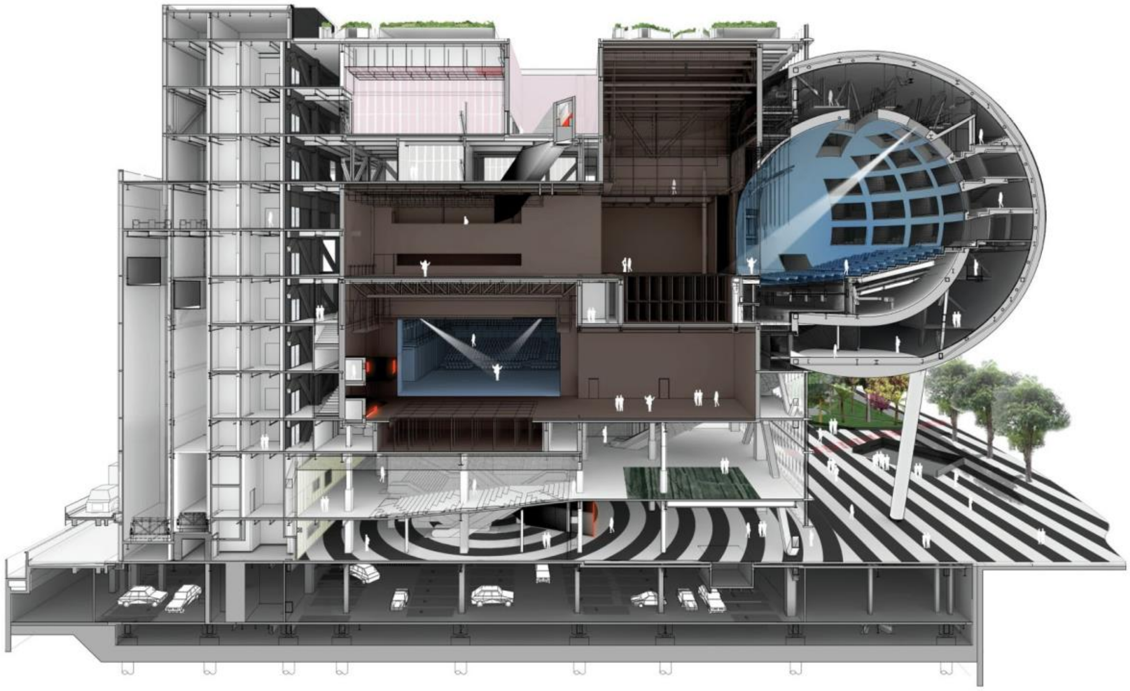


Figure 54, Sectional perspective through proscenium playhouse. OMA

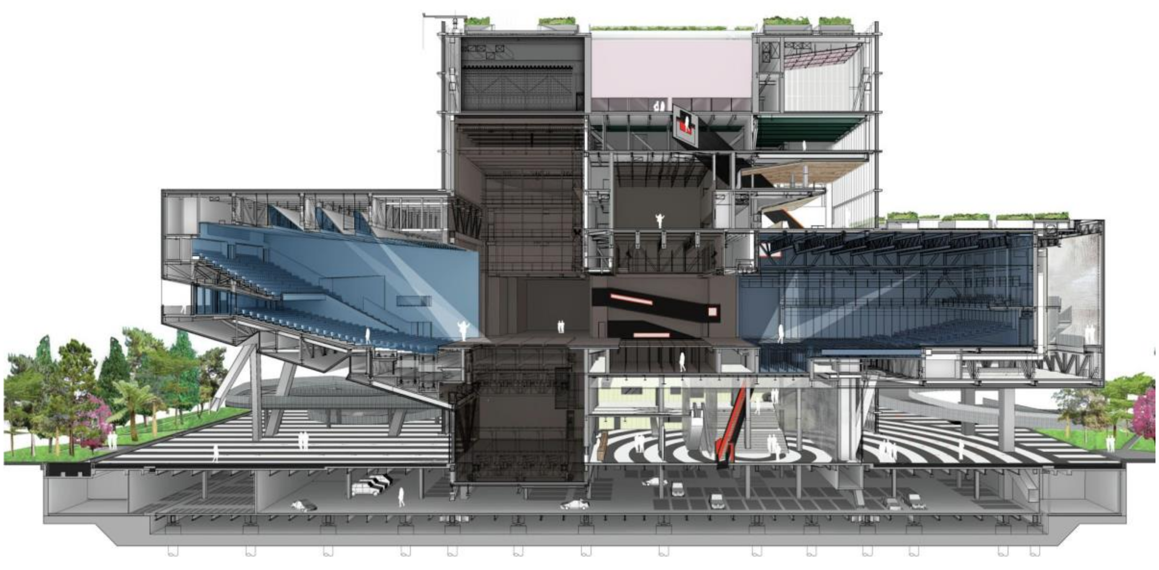


Figure 55, Sectional perspective through super theater. OMA

Royal Welsh College of Music and Drama - BFLS

The Royal Welsh College of Music and Drama is the national music and drama conservatoire of Wales. It houses a 450-seat concert hall, a 180-seat theater, rehearsal studios and an exhibition gallery. The building connects the two performance spaces with a generous daylit foyer, where the cedar slatted façade continues through the curtainwall, forming a continuous loop. The concert hall uses the circular geometry of the building to house the back of house facilities on either side of the hall, while the theater's changing rooms, showers, and staging area are behind the stage.

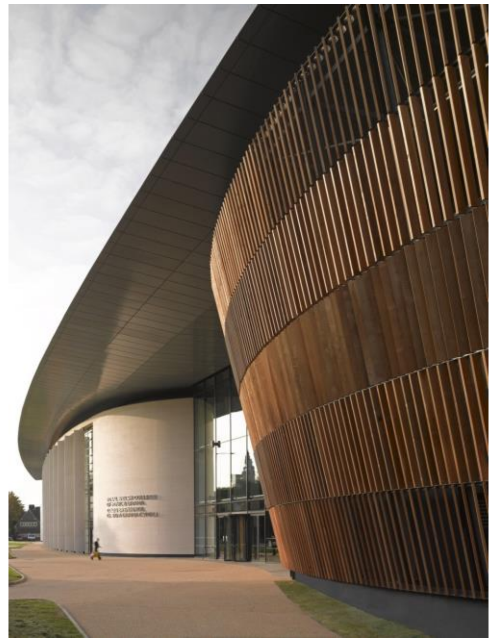


Figure 56, The building facade is a timber screen built from cedar wood slats. BFLS

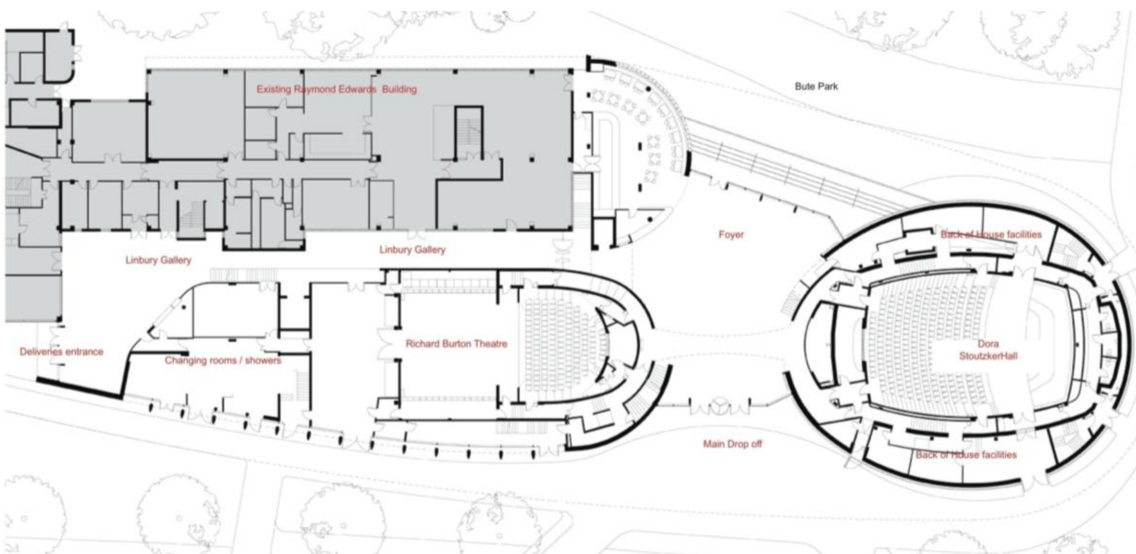


Figure 57, Ground floor plan showing concert hall and theater. BFLS

The concert hall uses wood paneling to provide an acoustically excellent space, as well as a rich and warm aesthetic.

Figure 58, Use of wood as an acoustical treatment is beautifully displayed in the concert hall. BFLS

Figure 59, The theater utilizes multiple levels of seating to accommodate 180 people. BFLS

Jackson Hole Center for the Arts – Stephen Dynia Architects

The Jackson Hole Center for the Arts is an addition that adds music practice rooms, theater support areas, and a 500-person theater to the existing arts center. From a material perspective, the building uses a combination of concrete, wood and glass to match the existing structure, and reflect the natural setting of Jackson, Wyoming.

Figure 60, Exposed concrete and wood slat siding reflect the natural setting of the center. Ron Johnson

The main theater features two levels of seating, which can accommodate 200 people below and 300 above. For smaller performances, only the lower tier of seating is used. The design tucks the lobby underneath the theater balcony seating, allowing for an efficient use of space.

Figure 61, 500-person flexible theater. Ron Johnson

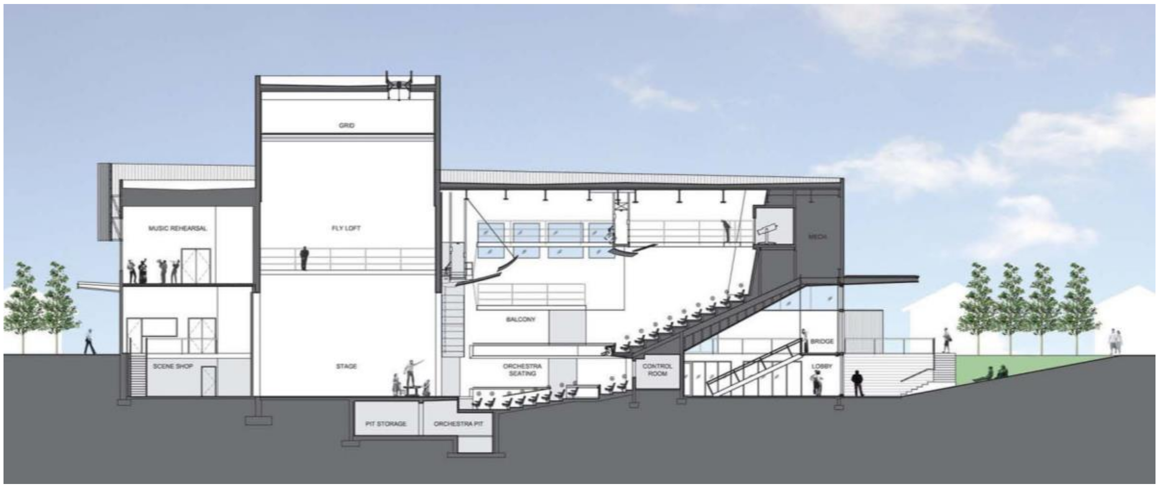


Figure 62, Section through lobby, theater and back of house. Stephen Dynia Architects

The building is designed in a linear fashion, with the outdoor terrace leading to the lobby, then to the theater seating. The scene shop and dressing rooms are at the back.

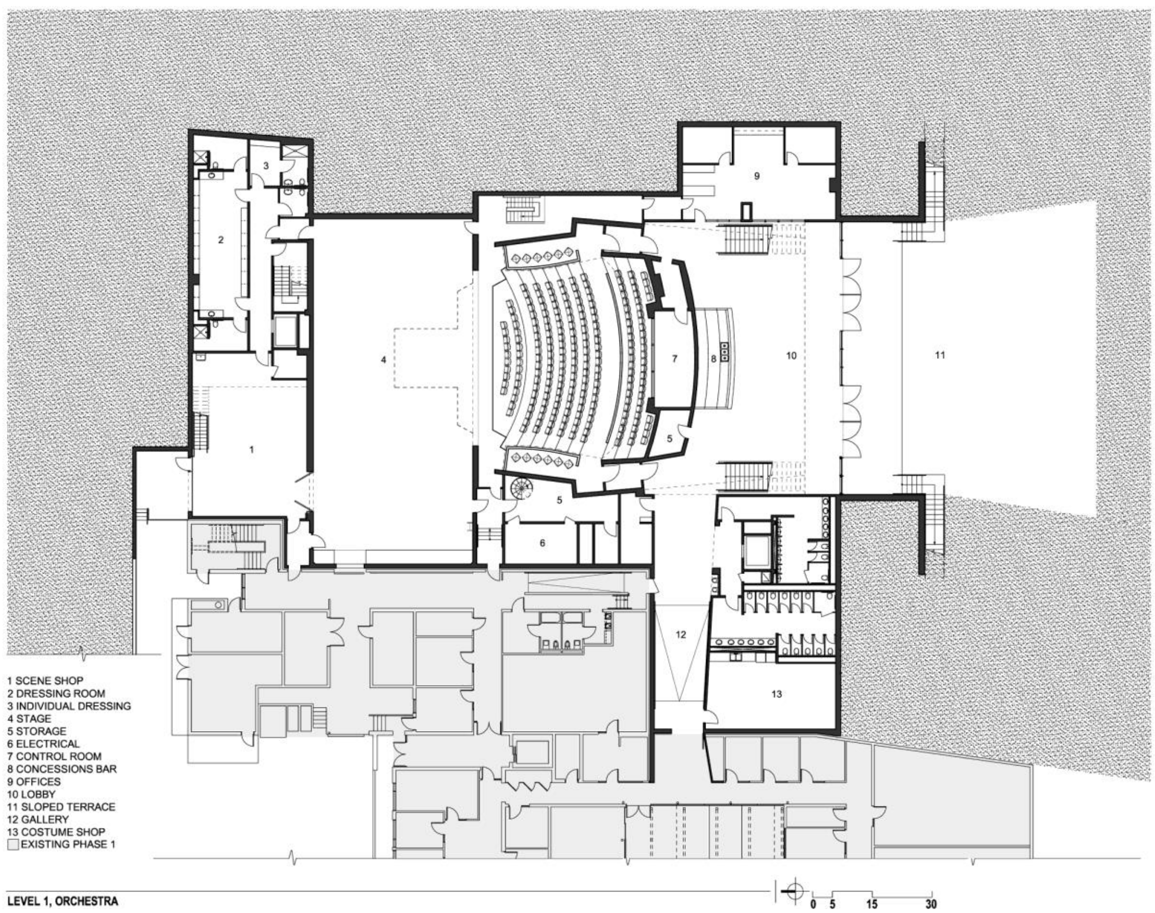


Figure 63, Level 1 Plan. Stephen Dynia Architects

Ballet am Rhein – gmp Architekten

Ballet am Rhein is located in Düsseldorf, Germany, and houses space for 50 professional dancers and 55 students. The architectural style and material palate of exposed concrete references the industrial history of the site and local context. The building's compact footprint holds two ballet rooms, three practice rooms, changing and restrooms, a physiotherapy room, and an apartment for guest artists. One of the large ballet rooms has bleacher-style seating, allowing for performances as well as regular practices. The entrances to the ballet rooms are located away from the mirror walls, as to not disturb any dance rehearsals going on.

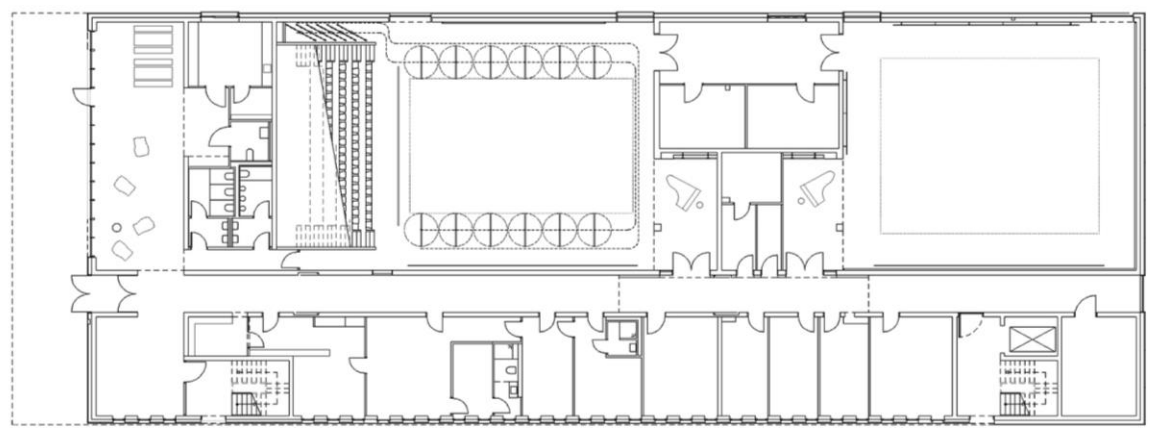


Figure 64, 01 Floor Plan - ballet rooms are located at the top of the plan. gmp Architekten

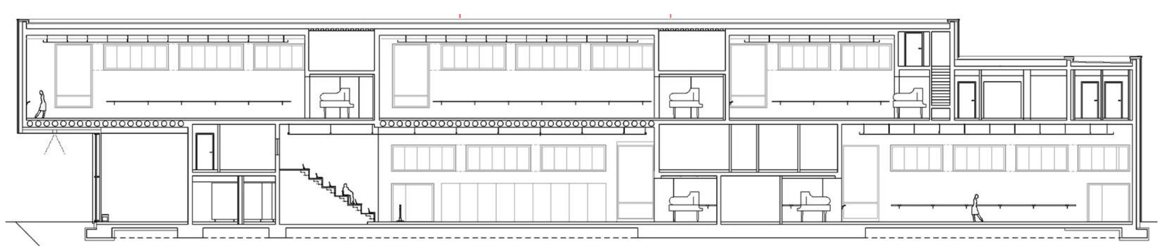


Figure 65, Section showing flexible ballet room below and rehearsal spaces above. gmp Architekten

Figure 66, ballet room with full-size stage dimensions and bleacher seating. Marcus Bredt

Figure 67, Practice room with full-length mirror wall. Marcus Bredt

Dance School Aurélie-Dupont – Lankry Architectes

Figure 68, The building form occupies the narrow space between the adjacent buildings. Julien Lanoo

The municipal school of dance in Joinville-le-Pont, France, is situated between a four-story apartment block and a supermarket. The site is narrow and deep, deeply influencing the form of the building. To optimize the use of space, the architects positioned the circulation on the southern side, with the dance studios situated on the northern side, receiving excellent daylight. Curtains run along both walls of the studios allow the mirror wall or wall-mounted ballet bar to hidden depending on the type of practice going on. This is a feature that the UMass dance department requested in the right-size study.

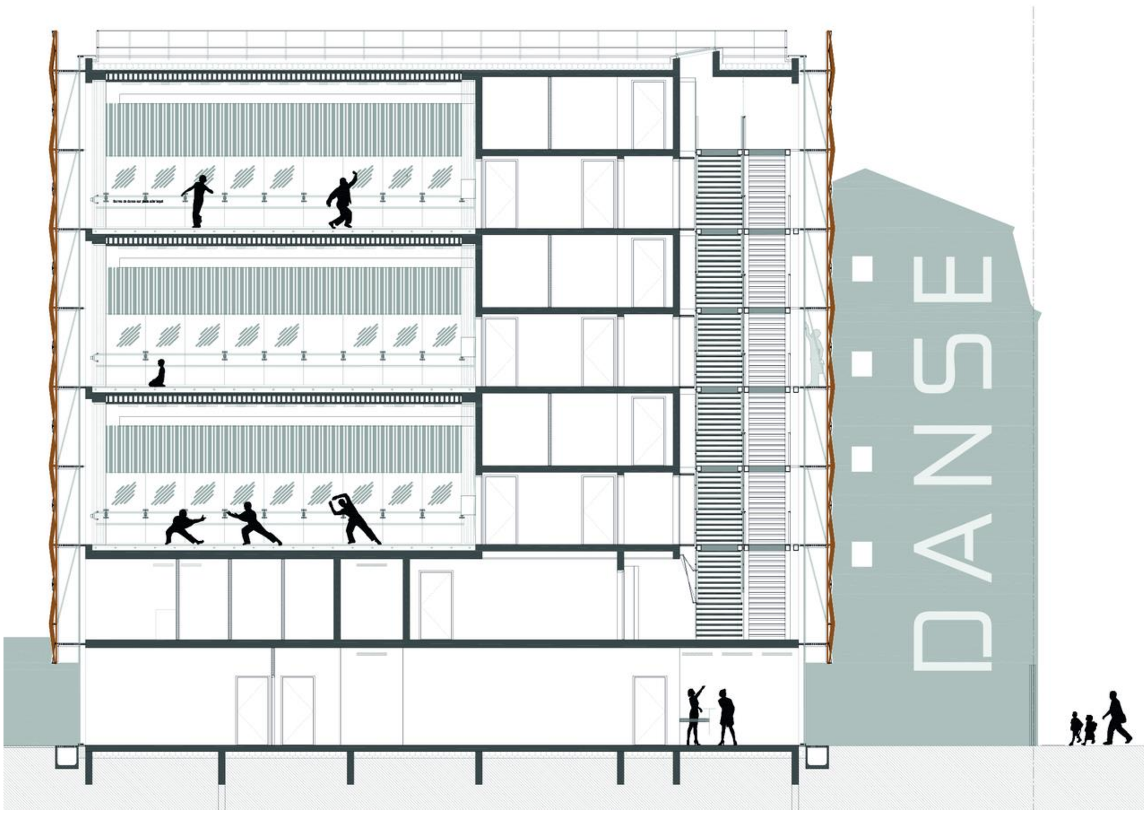


Figure 69, Section showing dance studios on the north and stair core on the south side. Lankry Architectes

Figure 70, North facing studio with ballet bar and mirror wall. Julien Lanoo

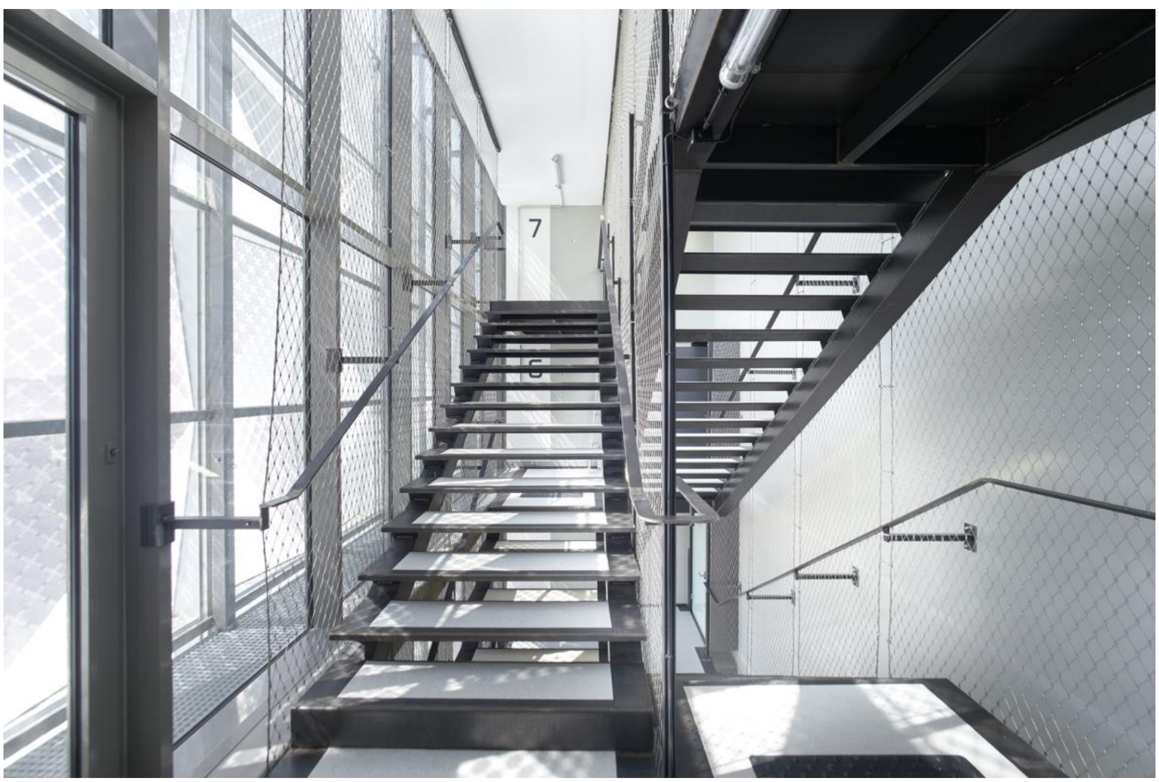


Figure 71, South facing stair core designed in a minimalist style, showing raw materials. Julien Lanoo

In addition to department-related buildings, such as theater and dance studios, precedents that used light and shadows as a feature of the architecture were looked at as well.

Chapel of St. Ignatius, 1997 – Steven Holl Architects

Figure 72, Chapel of St. Ignatius. Kate Jiranek

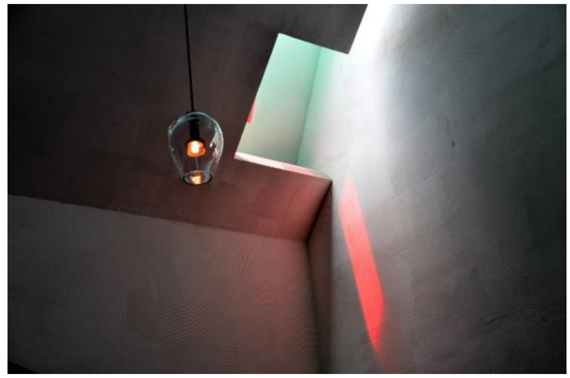


Figure 73, Chapel of St. Ignatius. Kate Jiranek

The chapel of St. Ignatius, by Steven Holl Architects is designed as a series of light volumes that correspond to different parts of the Catholic service. Each of the volumes sculpts a different direction of light, from the north, east, south and west. A baffle inside each "bottle of light," reflects the daylight to the inside of the chapel. Only the reflected light makes its way inside, being a different color depending on the color of the baffle. The moving sun and clouds makes the light inside oscillate between light and dark.

Bell-lloc Winery, 2007 – RCP Arquitectes

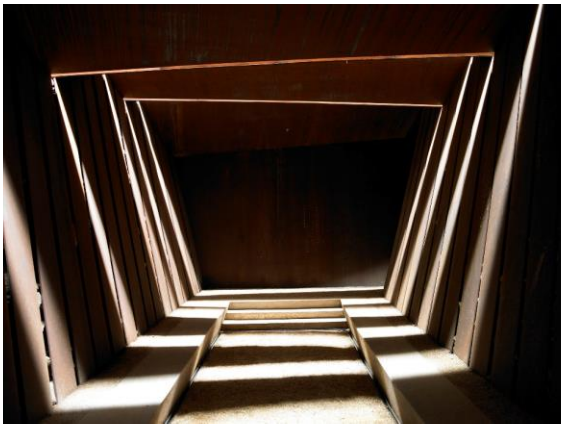


Figure 74, Bell-lloc Winery. Eugeni Pons

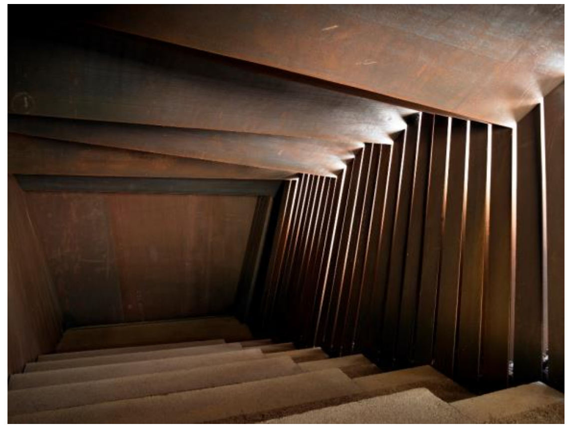


Figure 75, Bell-lloc Winery. Eugeni Pons

Located in Palamós, Girona, Spain, the Bell-lloc Winery by RCP Arquitectes is designed as a promenade from the outside road to the underground world of wine. The natural materials aid in the feeling of earth and ground in this winery. Different spaces are connected by a network of paths, emphasizing the journey through the space. The geometry is carefully shaped to create unique moments of light and darkness that surround the viewer in a cool, isolated space.

Maritime and Beachcombers Museum, 2011 – Mecanoo

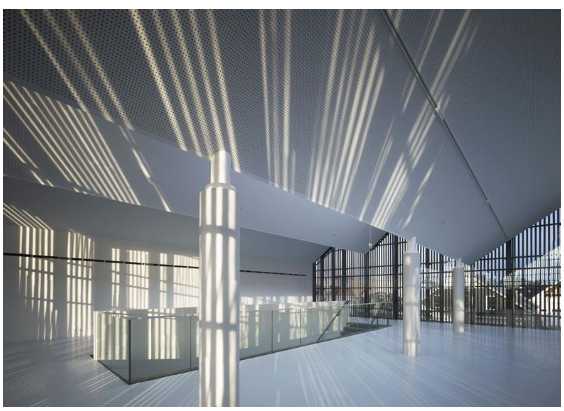


Figure 76, Maritime and Beachcombers Museum. Mecanoo

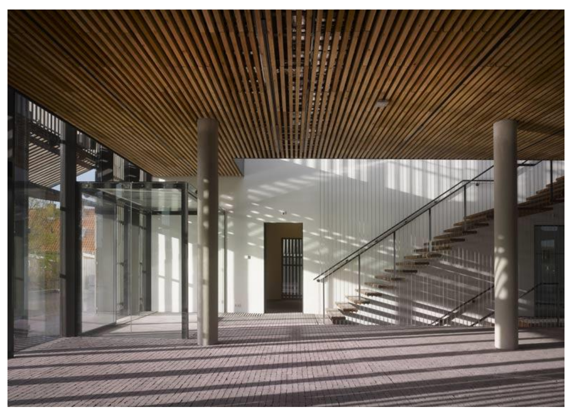


Figure 77, Maritime and Beachcombers Museum. Mecanoo

The Maritime and Beachcombers Museum in Texel, The Netherlands, makes use of four playfully joined gables that play on the rhythm of the surrounding roof tops.[44] The façade consists of a vertical wood screen, which casts a variety of shadows inside, depending on the time of day. The screen takes the ordinary view out to the surrounding neighborhood and creates a dynamic play of shadow and light against the sky.

Pulitzer Arts Foundation – Tadao Ando

Completed in 2001, the Pulitzer Arts Foundation was Tadao Ando's second building in the United States. Its use of concrete and daylight makes it a signature Ando building. In one of the gallery spaces, there is a narrow skylight along the edge of the exterior wall, that lets a sliver of light through onto the floor. Depending on the time of day, the piece of light gets longer and shorter, and changes its position between the wall and the floor. The feature acts as a sundial, never casting sun in the same place twice in one day.

Figure 78, Pulitzer Arts Foundation - 1:24 PM

Figure 79, Pulitzer Arts Foundation - 2:13 PM

Figure 80, Pulitzer Arts Foundation - 3:51 PM

[44] Mecanoo. "Kaap Skil, Maritime and Beachcombers Museum."

Louvre Abu Dhabi - Jean Nouvel

Louvre Abu Dhabi utilizes a parasol, creating a rain of light down upon the space under the dome, which is a modern interpretation of traditional Arabic architecture.[45] The dome is made up of an inner and outer layer, which creates light and shadows that are constantly changing shape, and even the speed at which the shadows move, as the one layer of the dome is higher than the other. Depending on the interior conditions, the rays of light are visible as they pass through the dome, creating a heaven-like and calm place inside.

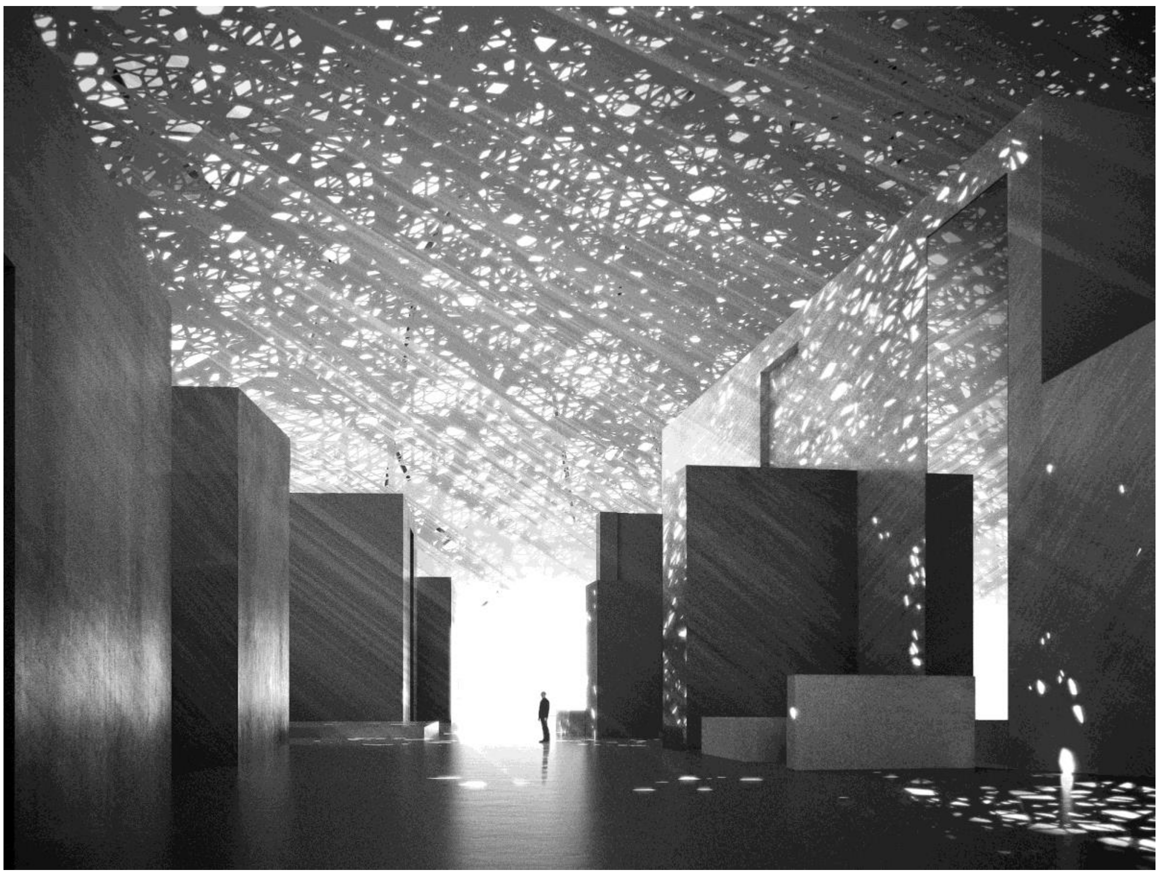


Figure 81, Rays of Light - Jean Nouvel

[45] Ateliers Jean Nouvel. "Louvre museum abu dhabi (united arab emirates)." 2017.

CHAPTER III

SITE ANALYSIS

UMass Master Plan

In 2012, the campus developed a master plan to serve as a guide for sustainable future development, and to reinforce the vision that Chancellor Holub established.[46] His vision was to raise the status of the campus to become one of the best research universities in the country: hiring 250 new faculty members and bringing in 3,000 new students in the next ten years. The UMass campus is situated on over 1,400 acres of land, with over one million GSF of building space. There are around 12,000 parking spaces, and a total population of over 30,000 people. Key elements of the master plan include building a beautiful pedestrian friendly campus through the preservation of open space, reinforcing key circulation paths through campus, adding and upgrading facilities, developing a mixed-use campus, and utilizing sustainable practices in energy generation, construction and transportation.

Site Selection

Site selection for the new UMass School of Performance took the following factors into consideration:

1. Development type (situated on infill/brownfield or greenfield)
2. Condition of existing buildings if being torn down
3. Proximity to campus core
4. Proximity to parking and bus stop

[46] Wilson Architects, et al. UMass Amherst, Campus Master Plan. UMass Amherst Campus Planning, April 2012.

5. Access to pedestrian and vehicular circulation

After consider these factors, two sites were identified; the Thompson/Machmer area across from the Student Union, and the Bartlett site to the west of Herter. The Bartlett site was chosen because of its location in the core of the academic campus, access to pedestrian and vehicular circulation, proximity to the Haigis Mall bus stop and Massachusetts Avenue parking lots, and the poor condition of Bartlett Hall. Along with Hills, Bartlett is on the universities demolition list. With the completion of the South College renovation and addition, the English and Art History departments will move out, leaving Bartlett empty. The two sites are outlined in the map below, with the Bartlett site being the southernmost outlined area.

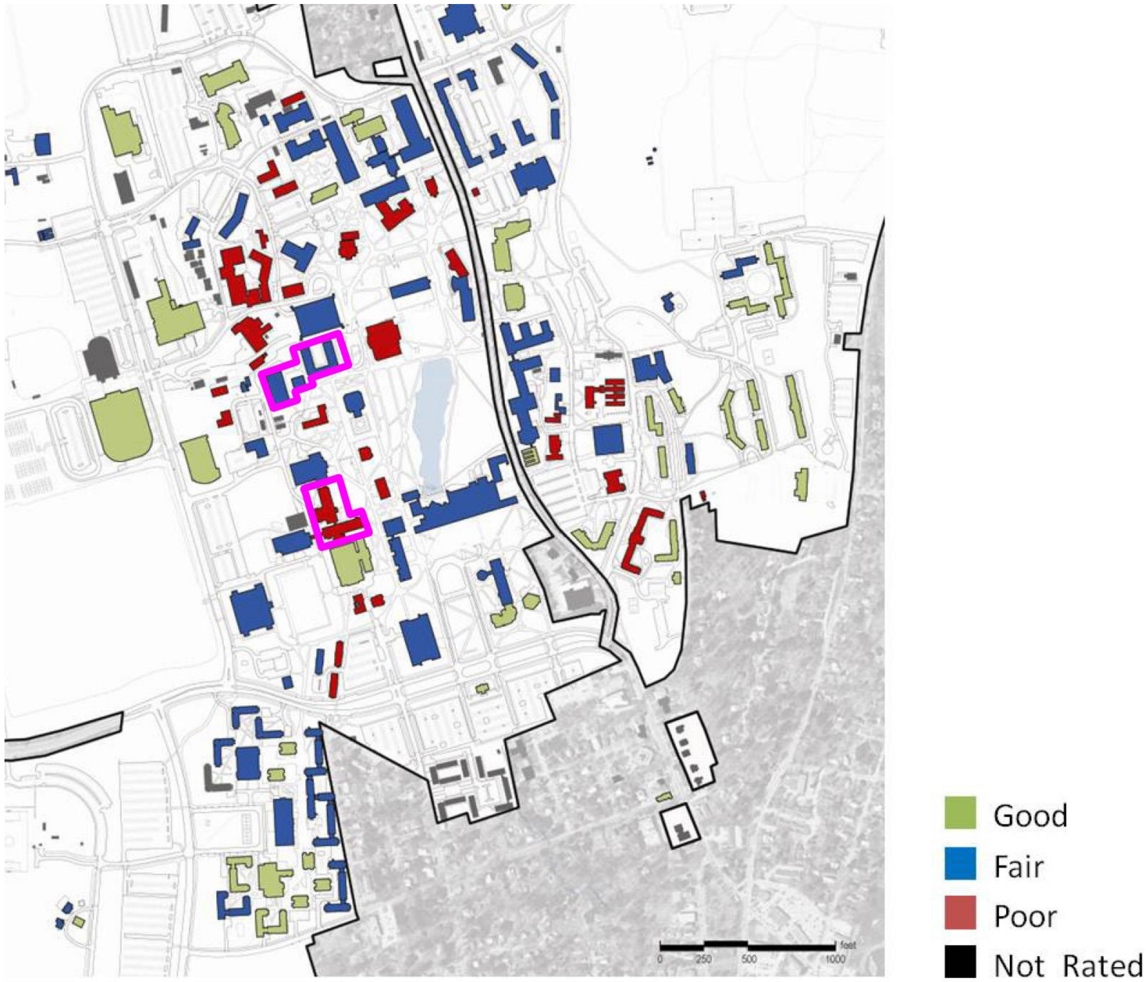


Figure 82, Campus Building Conditions Map. UMass Campus Planning

Figure 83, UMass Master Plan 2012. UMass Campus Planning

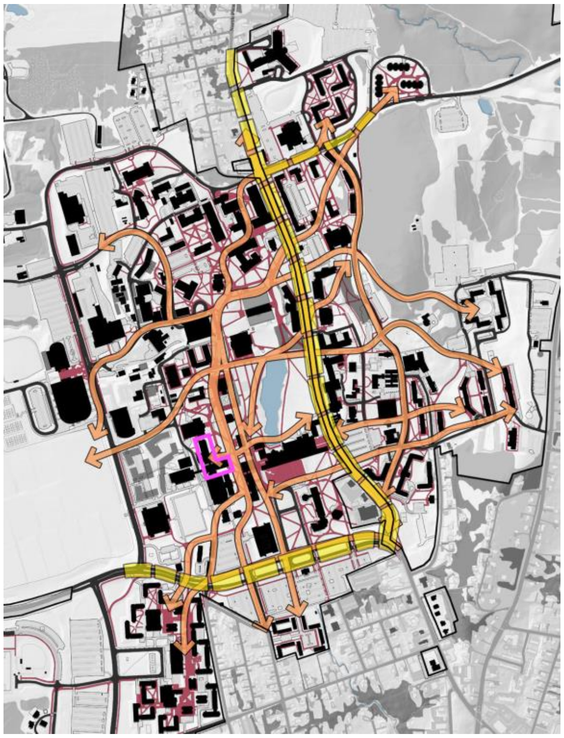


Figure 84, Pedestrian & Vehicle Circulation. UMass Campus Planning

Figure 85, Campus Open Space Plan. UMass Campus Planning

UMass Amherst Site

The site is approximately 83,000 square feet (1.9 acres). The east side of the site is one level higher in elevation than the west side of the site. The site is longer in the north to south direction, which makes building massing for passive design and daylight more challenging, as the ideal building orientation is east-west. As the program requires many performance spaces with a need for controlled lighting, these areas could be located on the site where access to daylight or direct solar gain is not possible.

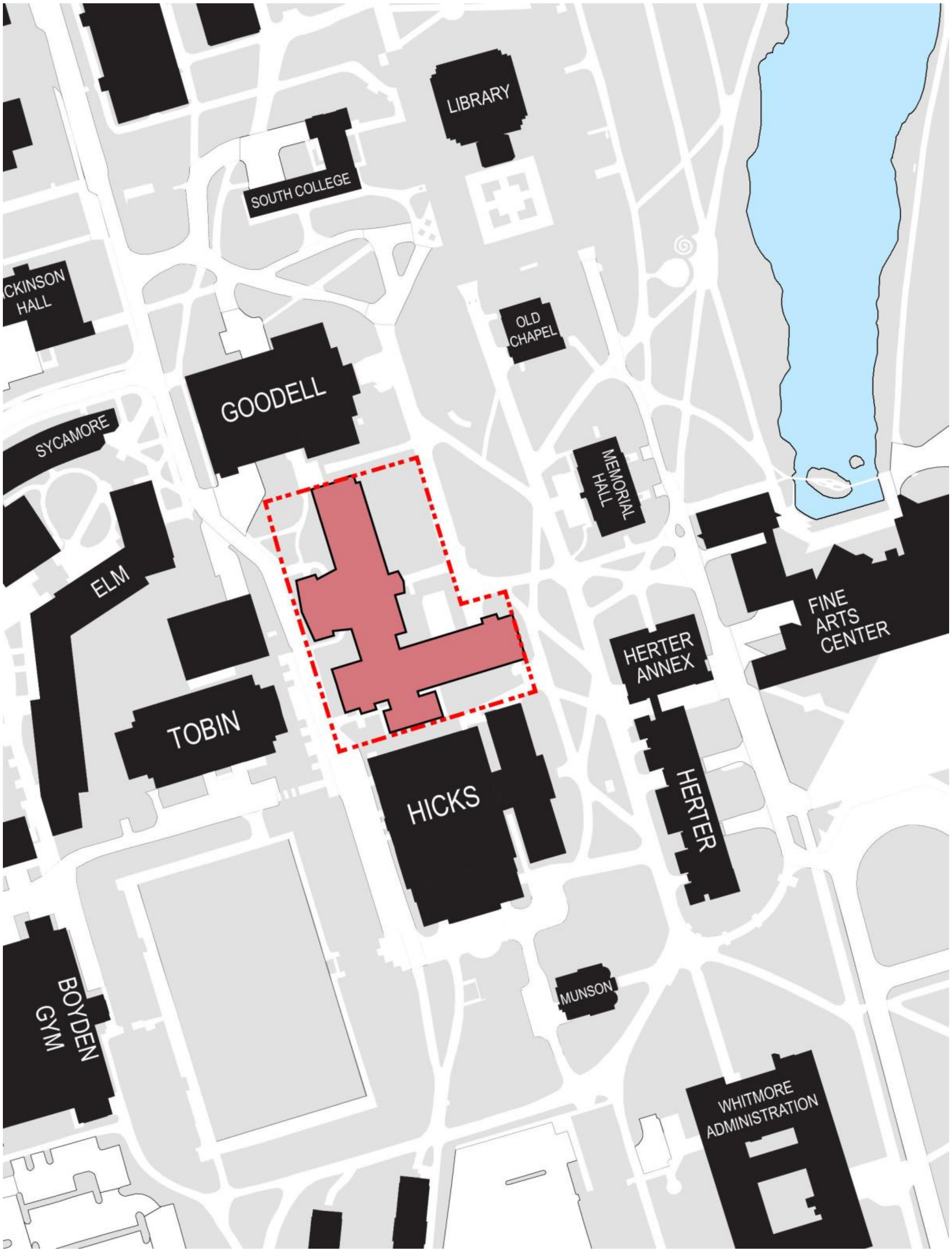


Figure 86, Figure/Ground Diagram. Red indicates buildings to be demolished.

The site is set back enough from adjacent buildings that there are no significant shadows cast during spring/fall, summer, or winter. The massing of the proposed building could have an impact on shadows cast at Goodell if it is more than a few stories tall.

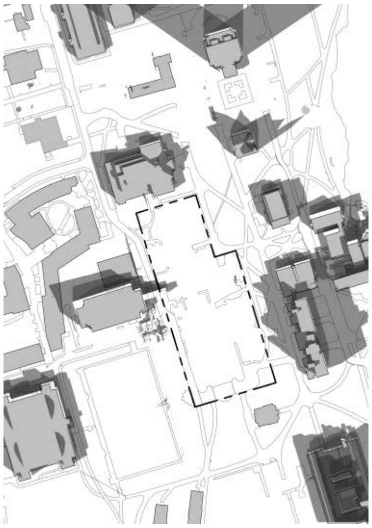


Figure 87, Spring Shadow Study

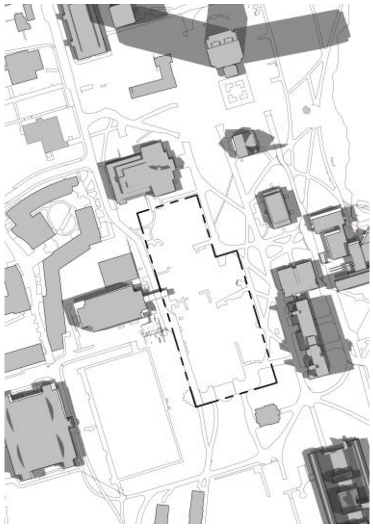


Figure 88, Summer Shady Study

Figure 89, Winter Shadow Study

A large building massing in the north side of the site would cast shadows onto Goodell during the winter, creating undesirably conditions inside. The site is located on the southwestern edge of the academic core. To the west, is the Honors College academic complex, which generates large amounts of pedestrian traffic around and through the site. Tobin is also connected to Bartlett via an elevated enclosed bridge. This pedestrian link will also be demolished, as the new departments will have no need to connect to the Psychology department in Tobin. Students walking from the southwest residential area to classes that are on the north side of the campus parking garage will often walk along Hicks Way, which runs along the west side of the site. Desirable views are to the east, where a strip of green space runs from Whitmore Administration to Machmer, and to the west, where the sloping down topography provides views towards the Connecticut River Valley.

Figure 90, East side of Bartlett. Dylan Brown

Figure 91, View of Bartlett from the north west. Dylan Brown


Figure 92, Bridge between Bartlett and Tobin. Dylan Brown

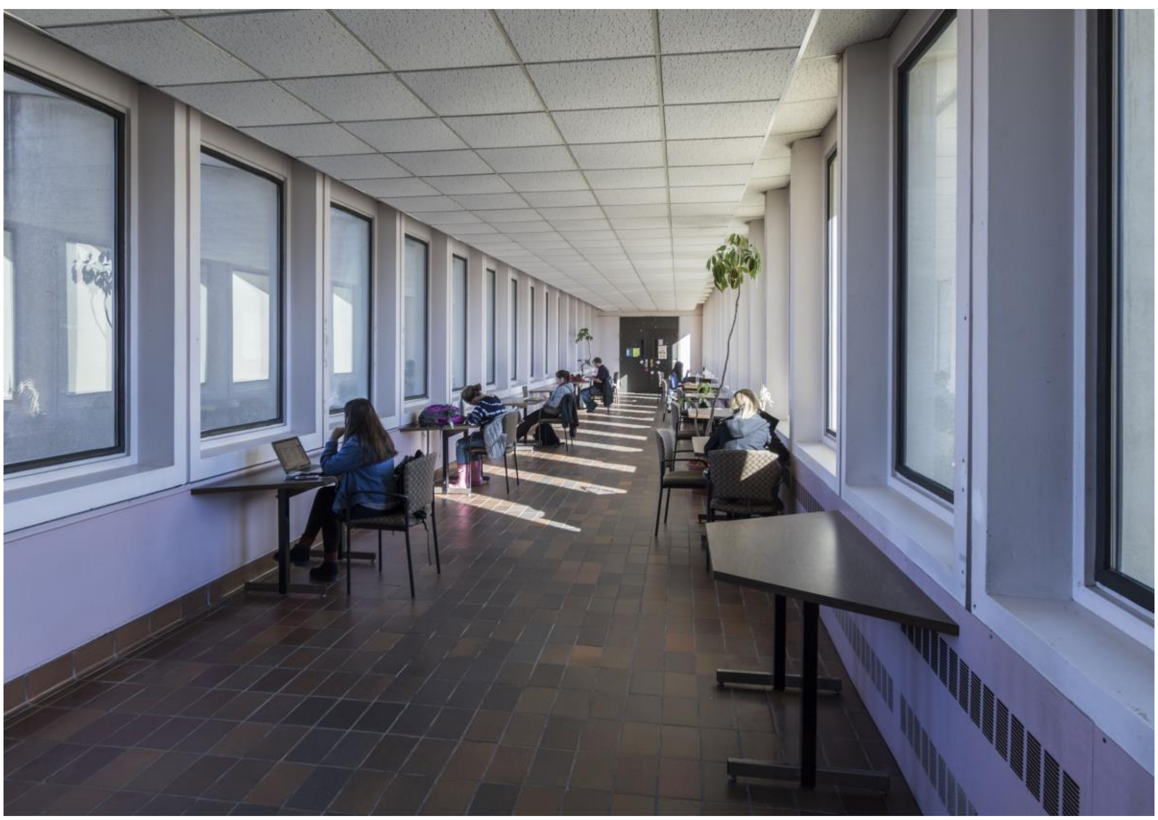


Figure 93, Students studying in the Tobin pedestrian bridge. Dylan Brown

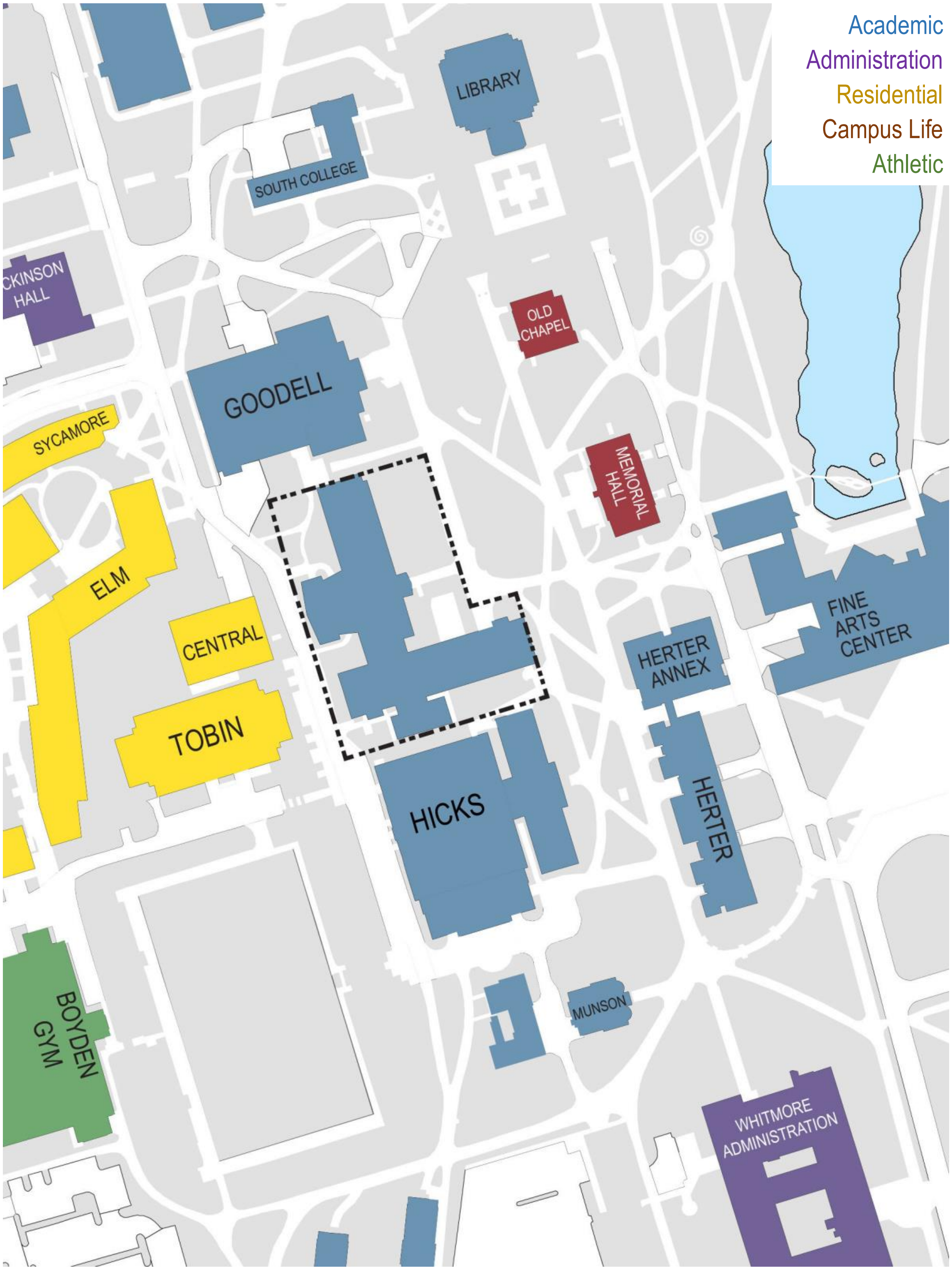


Figure 94, Campus Buildings by Use Type

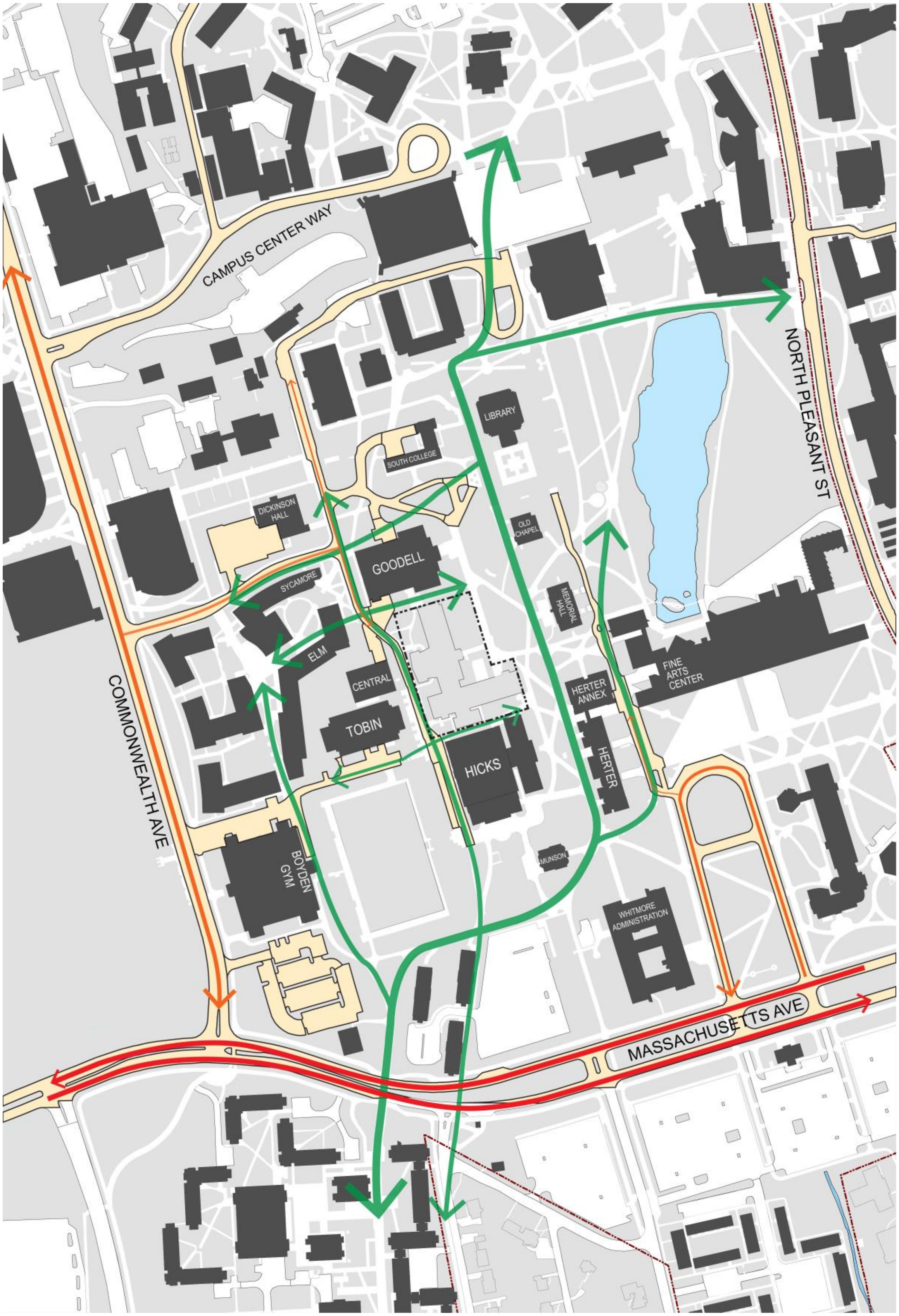


Figure 95, Major Pedestrian & Vehicular Circulation Routes

The main determining factor that was used to locate the large performances spaces was the proposed site circulation, shown below. Two diagonal routes were traced through the site. The path to the north connected the Honors College complex to the Herter and Fine Arts Center area, while the southern route connected the heavy pedestrian route running parallel to Hicks with the academic lawn leading to the library.

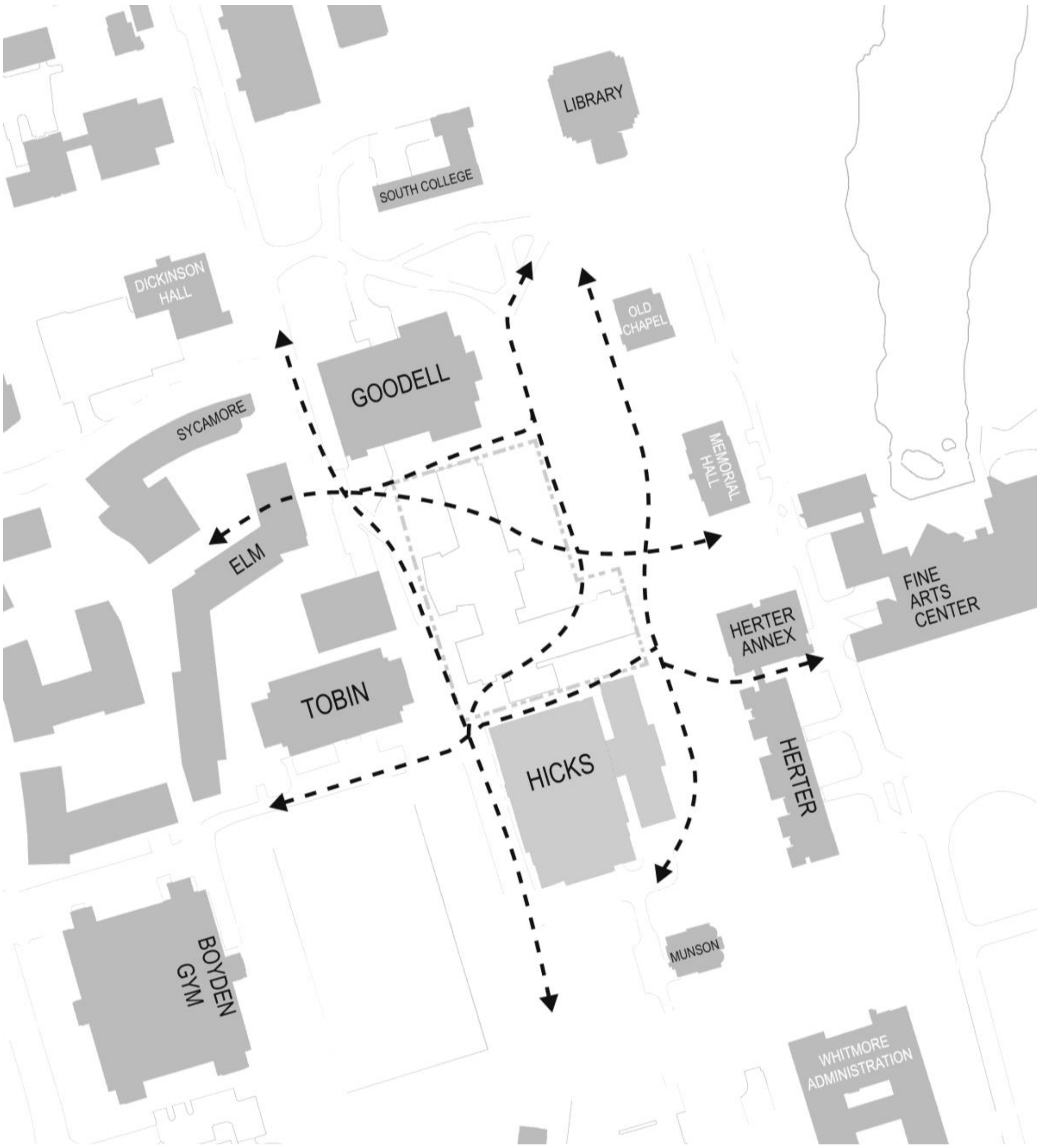


Figure 96, Proposed site circulation.

Weather Analysis

Amherst is in IECC climate zone 5A, which is a moist climate with heating degree days between 5400 and 7200. Using a base temperature of 65°F, this location has an average of 7100 heating degree days, and 900 cooling degree days. Last years (fall 2015 through summer 2016), was a warmer year than average, which resulted in 5764 heating degree days (19% decrease), and 1050 cooling degree days (17% increase).

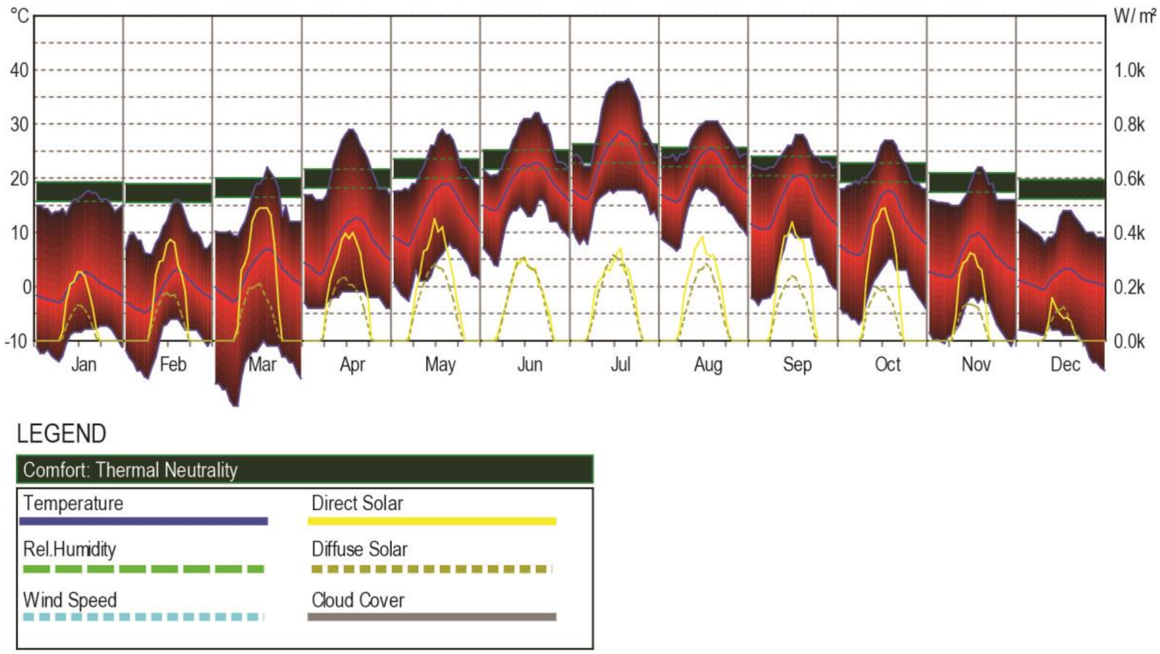


Figure 97, Monthly Diurnal Averages - Chicopee Falls/Westover AFB

The psychometric chart displays the different passive design strategies that can be utilized in this climate. The yellow outline represents the thermal comfort range that can be maintained inside the building depending on the exterior weather conditions. The other outlines show how different passive techniques can extend the thermal comfort inside the building. Natural ventilation and thermal mass with night purging are effective strategies in this climate.

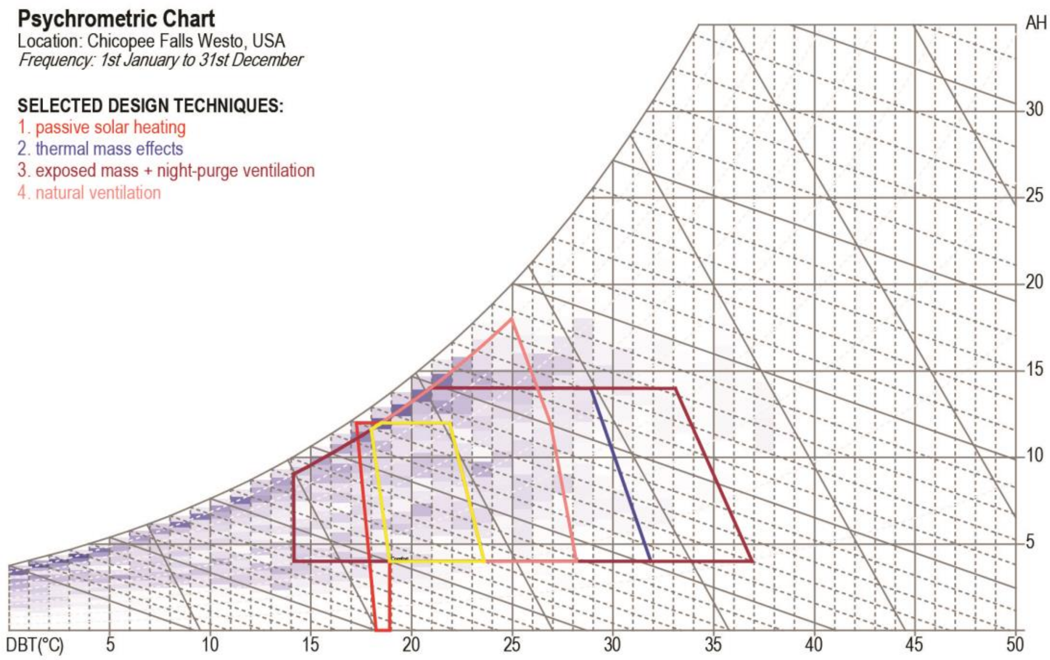


Figure 98, Psychometric chart of the local climate

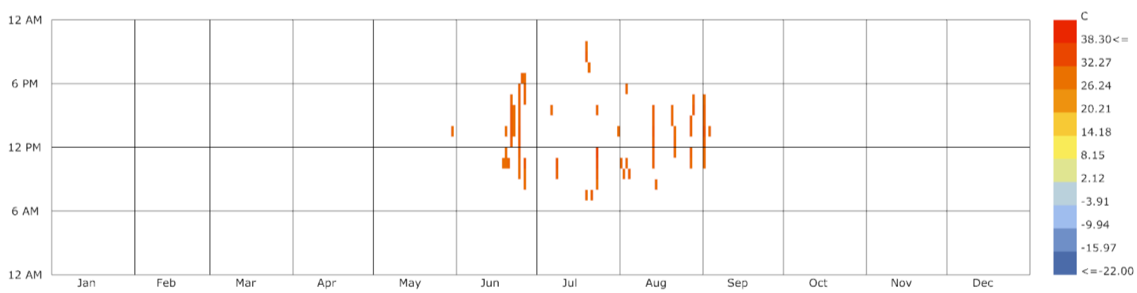


Figure 99, Time of the year when temperature is greater than 80°F, and humidity is greater than 60%.

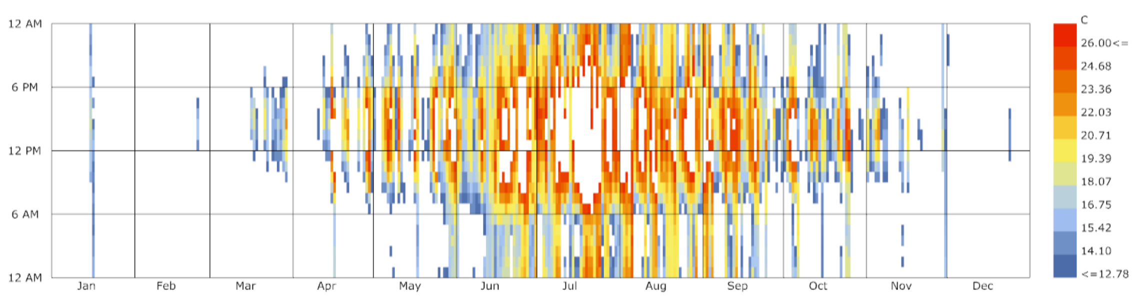


Figure 100, Times of the year when temperature is between 55°*F* and 80°*F*.

Wind Speed and Direction

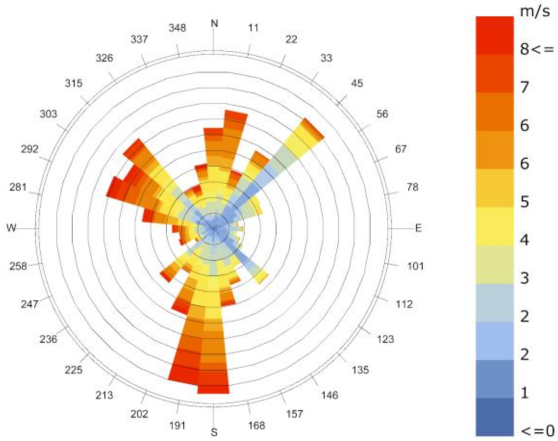


Figure 101, Spring Wind Speed Diagram

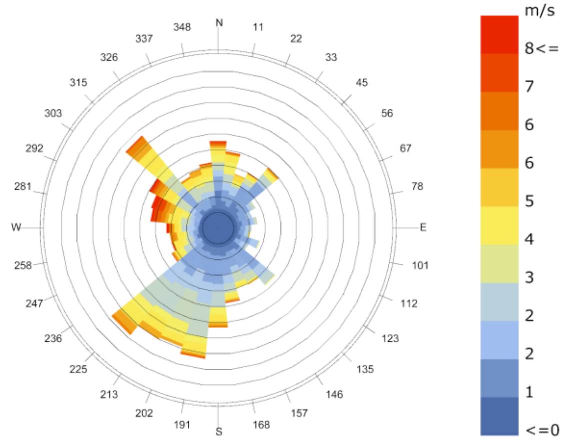


Figure 102, Summer Wind Speed Diagram

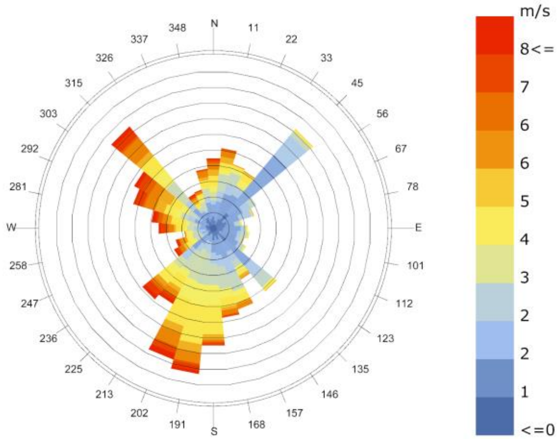


Figure 103, Fall Wind Speed Diagram

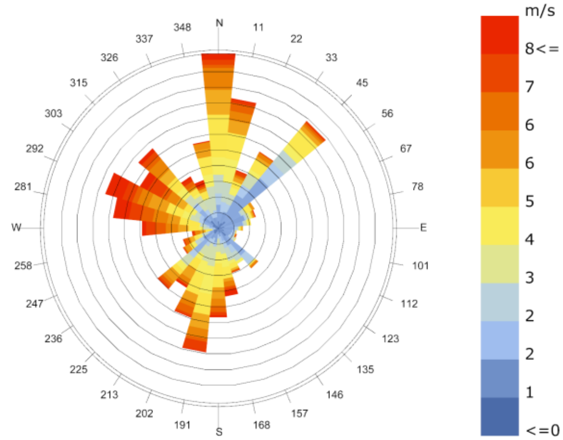


Figure 104, Winter Wind Speed Diagram

The prevailing winds on the site during the summer are from the south and southwest, south during the fall, north and south during the winter, and south during the spring. The site is largely unobstructed on the south-west, south, and northeast sides. Herter flanks the site to the southeast, while Tobin, the honors complex, and Goodell lie to the west and north.

Wind Temperature

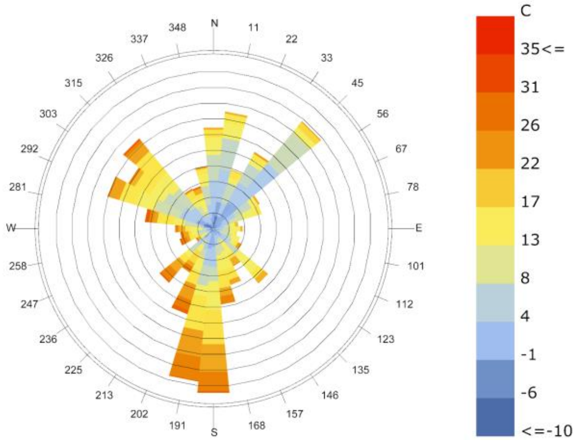


Figure 105, Spring Wind Temperature Diagram

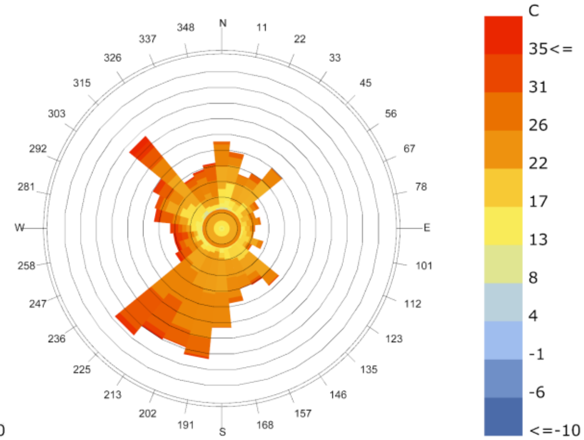


Figure 106, Summer Wind Temperature Diagram

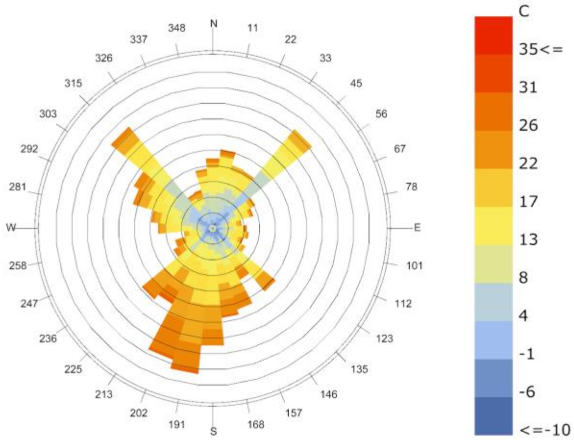


Figure 107, Fall Wind Temperature Diagram

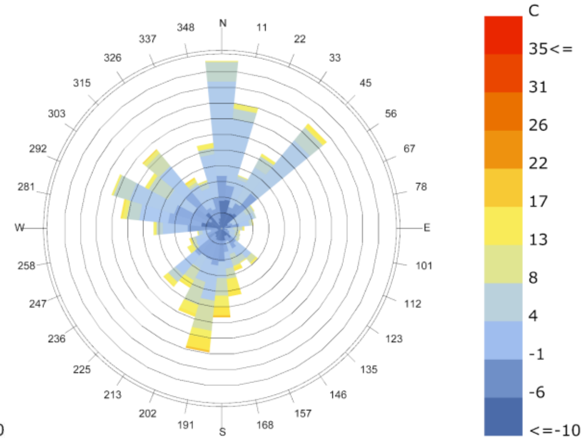


Figure 108, Winter Wind Temperature Diagram

During the spring, winds warmer than 70 tend to come from the south, while winds cooler than 45 come from the northeast. During the summer, winds between 60 and 80 dominate from the southwest, while winds warmer than 90 are more prevalent from the west-southwest. During fall, cooler winds tend to come from all directions, while warmer winds are dominant from the south. During winter, cooler winds are dominant from the north, while warner winds occur more often from the south.

CHAPTER IV

PROGRAM

The purpose of the programming phase was to identify departments on campus that where either operating in undesirable or undersized spaces. The Comprehensive Academic and Classroom Facilities Plan for the University of Massachusetts was analyzed to find out which department (s) could best use a new building. Burt Hill was hired to conduct the study, and architecture firm out of Boston, and it was published in December of 2009. During a thesis review meeting in the research phase, it was mentioned that that the natural sciences, as well as the humanities and fine arts needed more space. The functions and student services that occupy the Student Union are also in need of a new space, but it was later decided to focus only on an academic department.

Humanities and Fine Arts was chosen over the sciences, due to the greater variety of spaces in that department, and a greater familiarity with the department operations. Within the college, there were three departments that shared similar programs and uses. The plan identified key findings which included rehearsal and recital spaces for music, dance and theater. These three departments all utilized performance spaces in their programs, and the study of the students in those programs often results in a performance being shown to the public. This also includes large auditoriums and seating venues. After the departments in need of more space were identified, the types and sizes of spaces they used was identified.

The Academic and Classroom plan conducted in-depth studies of each department, looking at their current needs and spaces, and then developing a space plan that was right-sized for their departmental needs. Spaces were grouped into three different categories, based on type. Office/admin/conference, research, and learning environments. None of the three departments utilized any research space, so the other two were the focus of the analysis. Spaces that the three departments occupy is listed below, which demonstrates how spread out across they are.

- Ag. Engineering Building (Music & Dance)
- Bartlett Hall (Music & Dance, Theater)
- Cold Storage Building (Music & Dance)
- Fine Arts Center (Music & Dance, Theater)
- Totman Phys Ed Building (Music & Dance)

Figure 109, Buildings in red indicated the location of the three departments.

Music

The music department occupies the Fine Arts Center, sharing the space with theater. The Fine Arts Center was designed for music, but much of the practice rooms have been converted to offices. The design of building limits accessibility, and daylighting is poor, due to the glazing design, and location of much of the program in the lower levels.

Figure 110, FAC Room 36 - Class Lab

Figure 111, FAC Room 140A - Computer Lab

Meetings that took place between the Burt Hill staff, UMass campus planning, and the music faculty revealed key information about the growth of the department. Much of the department’s long-term goals hinged on the ability to increase student enrollment. Critical departmental needs discovered during those meetings is summarized below.

- Two large rehearsal rooms, comparable in size to FAC room 36.
- Three additional classrooms, each large enough to accommodate 60 students.
- Additional faculty offices, to free practice rooms now used for offices.
- Rehearsal space for chamber ensembles – each requiring two hours per week.
- Large storage room for secure storage of university-owned instruments in individual lockers. At present most instruments are housed in faculty offices, making them difficult to track and secure.
- Additional practice rooms and rehearsal rooms for non-music majors/minors, and for the general student body.
- 80 seat music classroom with moderate acoustic isolation.

Dance

The dance department occupies leftover spaces in the Totman Gym, a gym at the north end of campus. This space was not designed to hold dance, as the department uses the gymnasium stage and a basement space with a column grid running through the studio space. Totman is also half a mile away from the Fine Arts Center, which greatly reduces collaboration and space sharing between music and dance.

Figure 112, Totman Room 11 - Dance Office Services. Burt Hill

Figure 113, Totman Room 13 - Dance Studio. Burt Hill

The dance department is primarily limit by poor facilities. Critical needs discovered during meetings with the faculty is summarized below.

- Locker rooms with private locker space for students and instructors are needed.
- Performances require dressing areas, showers, mirrors, lights, etc. for the students/performers.
- Studio Theater: a large dance studio that can change into theatrical performance space that would include seating (risers) for 200-250 people.
- One studio for hard shoes (tap, ballroom) (includes upright piano, sound equip): 40’ x 40’.
- One studio for ballet (includes barres, mirrors, grand piano): 40’ x 50’.
- Small warm up/prep studio for faculty and students.

- Storage space for video/sound equipment, props and floors.
- Additional offices and classroom space.

Theater

The theater department occupies the Fine Arts Center, with storage space in the basement of Bartlett Hall. The Fine Arts Center was designed to hold theater, but space is limited, and the building's lack of windows and needed upgrades for finishes and HVAC reduce the quality of the space. The program is spread out across three floors, and includes the Rand and Curtain theaters.

Figure 114, FAC Room 11 - Costume Shop

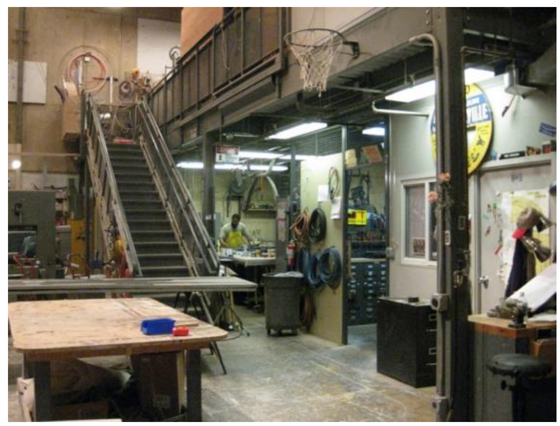


Figure 115, FAC Room 24 - Shop

Critical space needs discovered through meetings with the theater faculty are summarized below.

- Rehearsal and classroom space is a dire need.
- Space is also needed for Grad Students to work and meet with students.
- Additional classrooms and studio spaces for theater-specific classes.
- Larger assembly area for fly sections and props.

Proposed Program

The proposed site circulation, discussed in the site analysis was used to orient the large performance spaces on the site. They are situated in the core, surrounded by circulation space on all sides. Classroom and administrative space occupies the perimeter. Spaces from the three departments were broken up into eight categories, and organized according to the program diagram below.

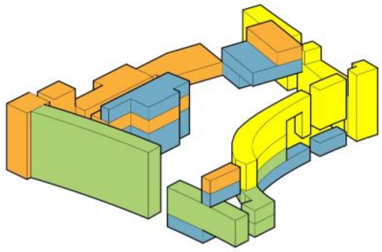


Figure 116, Classroom and administrative space.

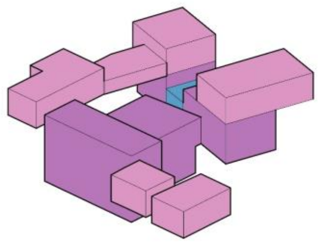


Figure 117, Large rehearsal and performance spaces.

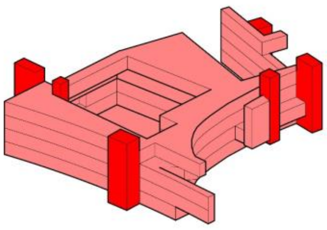


Figure 118, Horizontal and vertical circulation.

Space Type	Count	Square Feet
Administration	79	1,421
Circulation	19	65,571
Classroom	27	18,589
Music Practice Rooms	61	12,009
Large Rehearsal / Dance Studios	6	13,617
Theater/Recital Hall	5	17,995
Service	54	30,035
Mechanical	3	8,092
	Total	**167,329**

Approximately 94,000 square feet is dedicated for enclosed rooms, while 65,571 square feet is for circulation. The ratio of circulation space is high, as much of it functions as spill-out space for crowds entering or exiting the theaters, and some can also function as additional public performance space.

CHAPTER V

DESIGN

<u>Conceptual Design</u>

Conceptual design was used to study more abstract information relating to dance, music and theater. The easiest subject to transform from observations into architectural forms is dance, because the movement and position of the human body can be easily abstracted into an architectural or structural form. The rhythm or volume of music could be used to generate a pattern, while theater is more complex subject. Theatrical performances combine sound and music, producing an experience that is more than just the dance or music on their own. The play of light on the stage, movement and circulation of figures, the individual body positions of the performers, and the emotional journey of the performance are elements that can be analyzed.

Three different studies were done, relating to body positions (dance), movement/light (theater), and rhythm (music). The figure study proved to be the most useful for translating dance into tectonics, where the results could inspire aspects of the timber structure. The movement & light study was most useful for the overall concept of the building, while the sound study produced interesting results, but was not as useful.

Waveform Study

Three music samples were taken from the UMass Music department's website, and run through a waveform generator, which creates an image of the waveforms from the audio file.

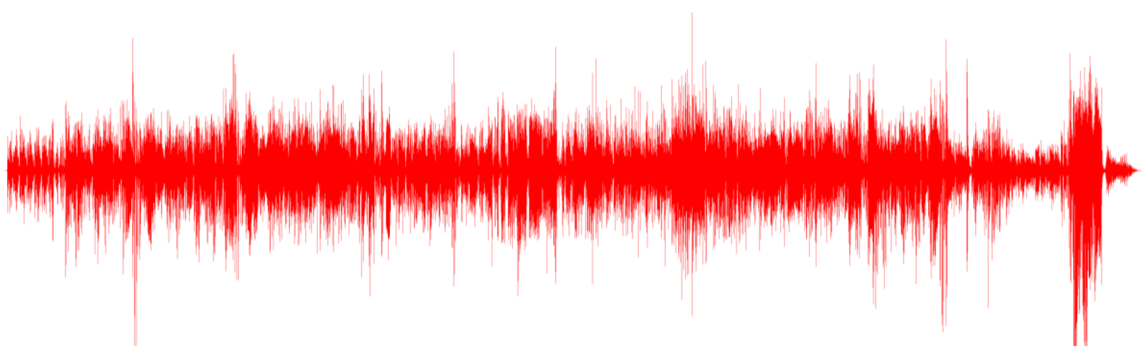


Figure 119, Alex Lee Clark's The Big Lebowski Suite, "Walter Sobchak"

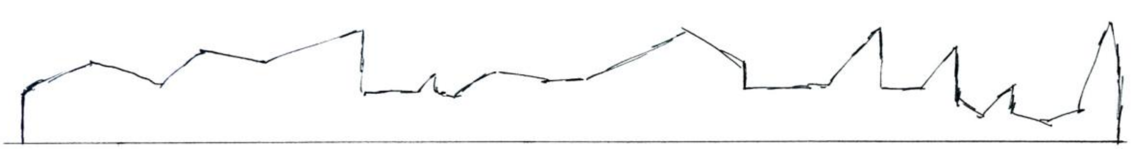


Figure 120, Abstracted trace of The Big Lebowski Suite

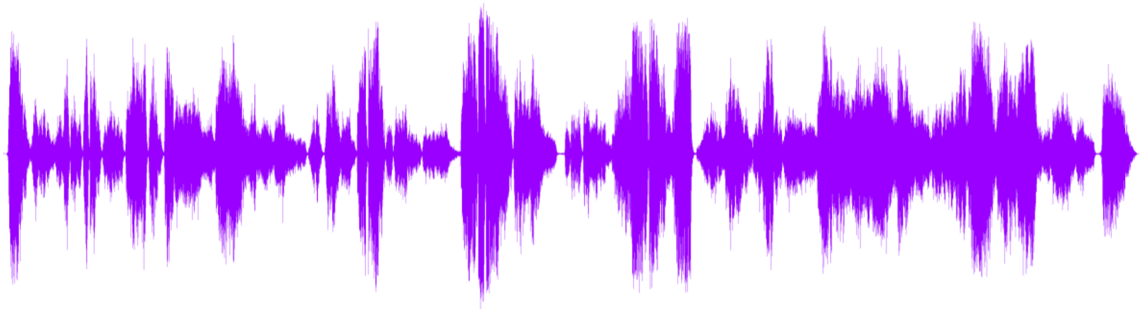


Figure 121, Monteverdi's Anime Mia Perdona

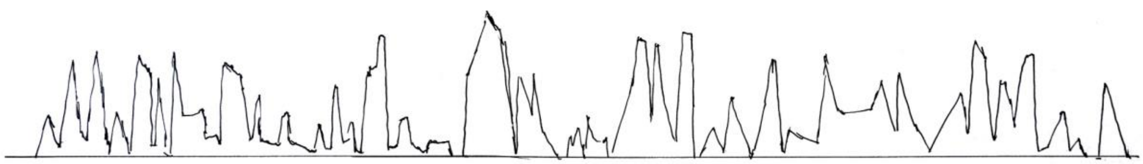


Figure 122, Abstracted trace of Anime Mia Perdona

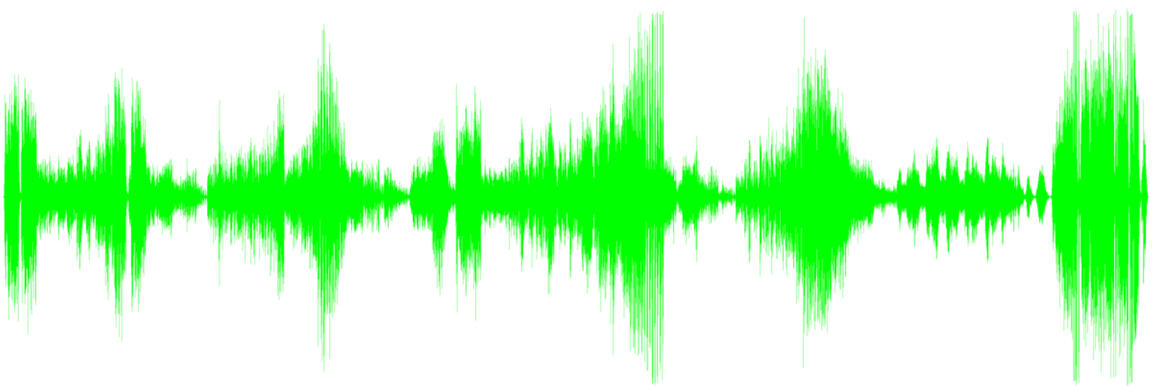


Figure 123, Dvorák's Serenade for Strings

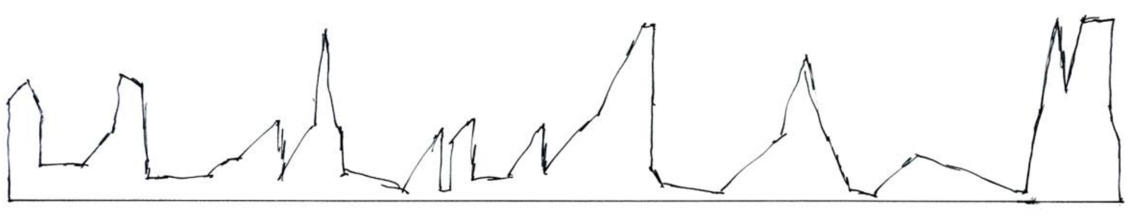


Figure 124, Abstracted trace of Serenade for Strings

The exercise of tracing the waveform images produced interesting-looking forms, but the usefulness of the results was limited in this project.

Figure Study

Body positions from three different types of dance were analyzed, and abstracted into structure. Four of the studies are shown in the tables below. The top row includes images from the performances, with the quick sketch in the next row. The third row shows the basswood model of the sketch, and the last image is a rendered view with shadows.

Dance of the Sugar Plum Fairy (Nutcracker)
Bolshoi Ballet – 2010

Paulina Macias – Toxic, 2014
Style: Jazz

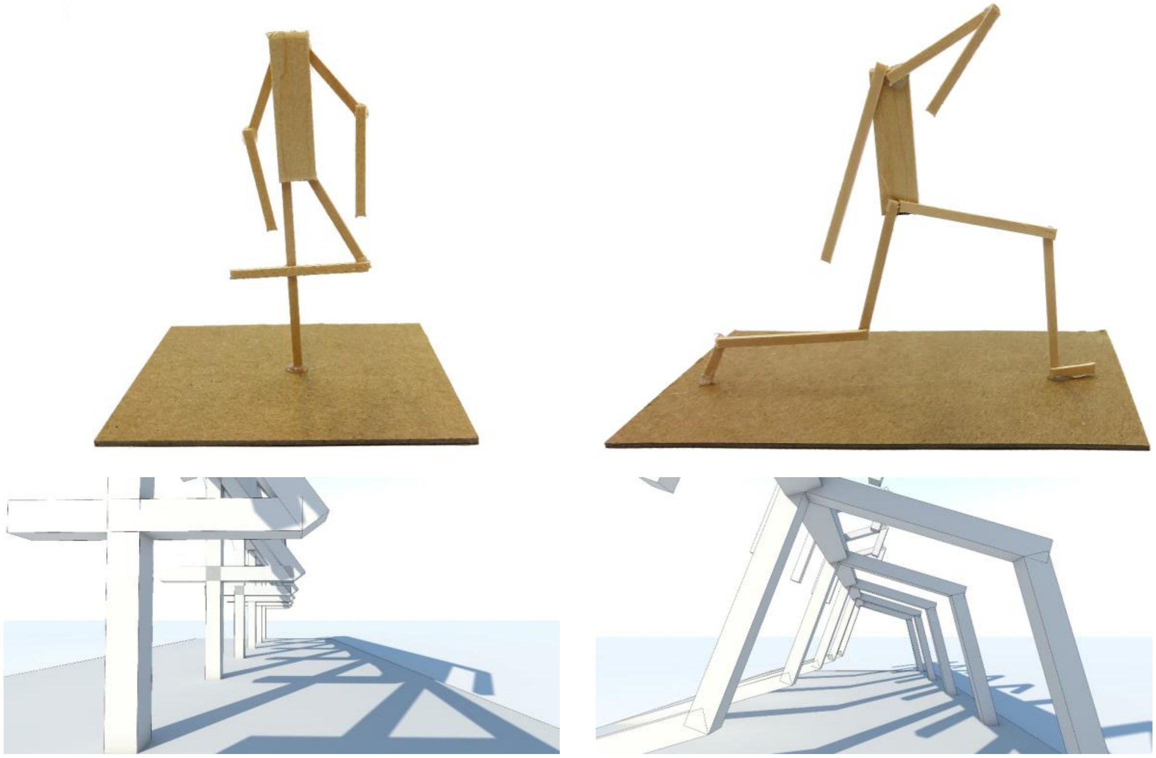


Table 1, Movement Studies

Room with a View – MN Dance Company
December 2014

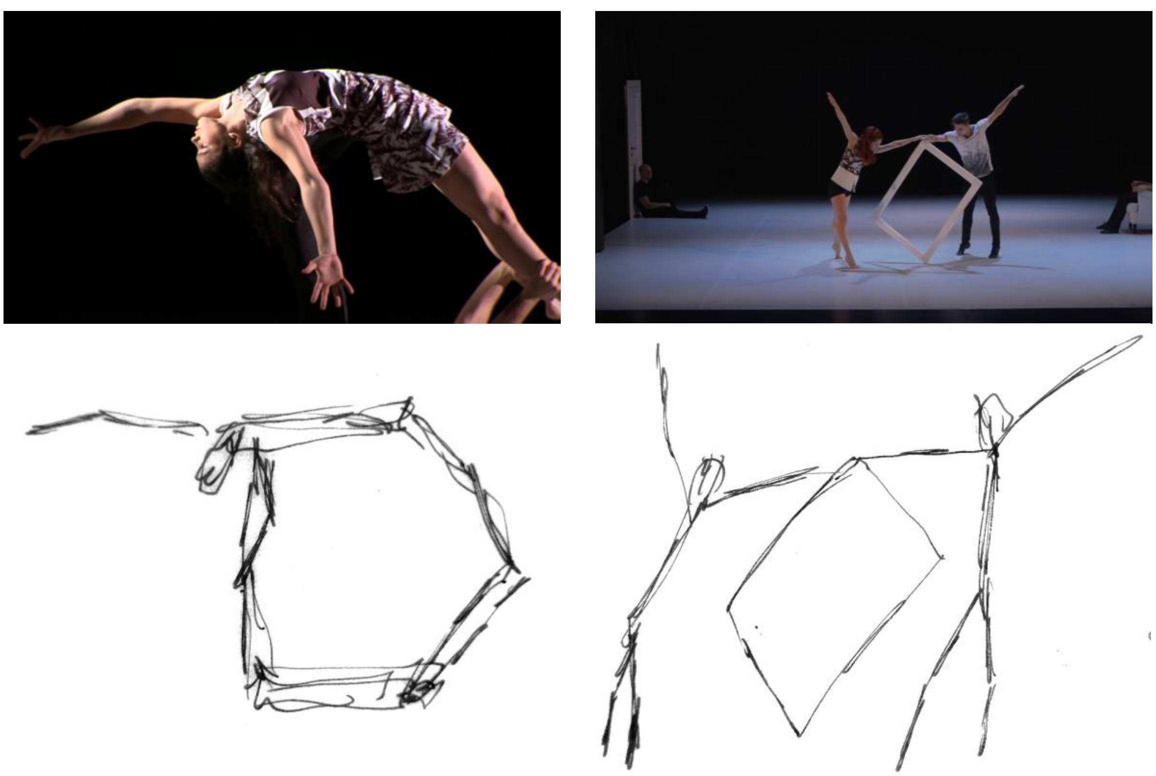


Table 2, Movement Studies Cont.

Movement & Light

A *Room with a View*, performed in 2014 by the MN Dance Company, served as the theatrical performance analyzed for this study. The show is based on the novel *Ich nannte ihn Krawatte* (*I Called Him Tie*) by Austrian writer, Milena Michiko Flašar. The performance "tells of contemporary existence marked by the anxiety brought on by the social system's lack of compassion."[47] The images below are from different points in the performance. The position and movement of the performers, as well as the lighting conditions are studied in each scene.

[47] MN Dance Company

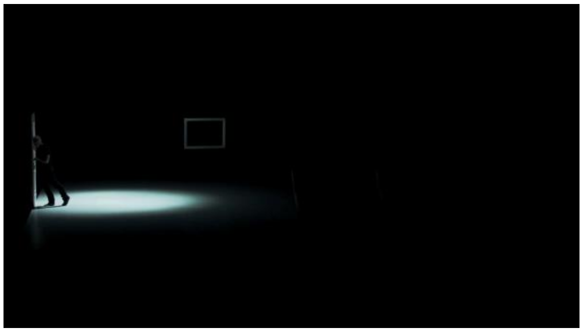


Figure 125, A lone figure leans against a door. A single light source shines on the door, radiating out towards the middle of the stage. A picture frame sits still in the background.

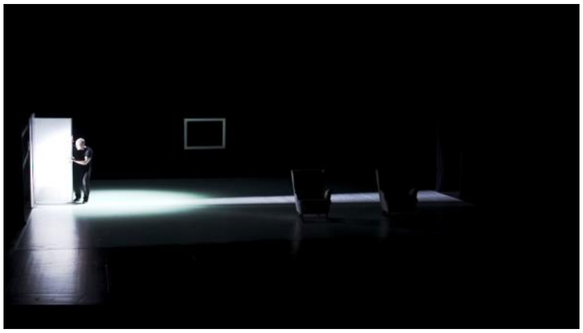


Figure 126, The lone figured has opened the door, casting a different beam of light out from the opening. Two chairs are revealed on stage right by the extra light.

Figure 127, Two couples stand opposite each other on stage right. One holding the picture frame, while the other gets out of the chairs. The lone figure sits against the door on stage left. The stage is lit with more light from the left, casting long shadows from the performers and chairs.

Figure 128, 11 performers occupy the stage, using the two chairs as a center piece. The lone figure sits on the ground, looking at the performers. A single light source shines from above, casting a cool light, with shadows directly below the figures. The picture frame is barely visible on the left.

Figure 129, Three performers occupy the stage, dancing around the picture frame. The lone figure sits in front of the three, with his back to the audience. A single light source shines from above, except casting the stage with warm light this time.

The actions of the performers, combined with the lighting, creates certain moods throughout performance. The amount of light, beam angle, and color temperature had the biggest influence on the mood. These conditions are valuable information for moving forward in the creation of the parti for the performance building.

The next step involved using forms and strategies found in the performances and case studies, and modeling simple study models to see how light and shadow interacted in them. Most of the models consisted of a long rectangular box, with different shapes cutout of the walls and roof, casting shadows on the floor and walls. In general, the lighting was found to be uniform when there were more openings, and the space inside the box was smaller, letting the light reflect off more of the closer surfaces. The lighting was more dramatic when there were a smaller number of openings, and the space inside the box was bigger, letting the light travel further, reducing the ability for the surfaces to reflect light back.

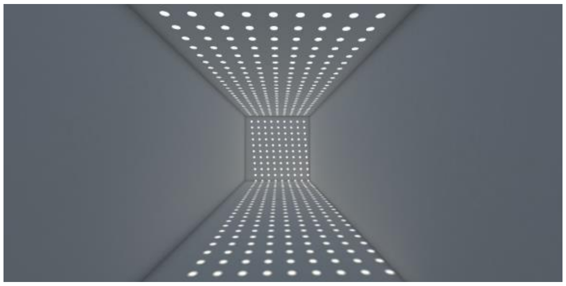


Figure 130, Circular grid


Figure 131, Big circle

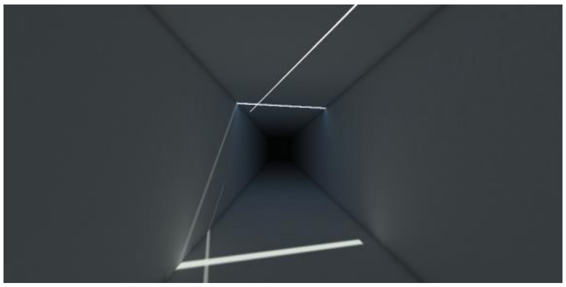


Figure 132, Perpendicular lines

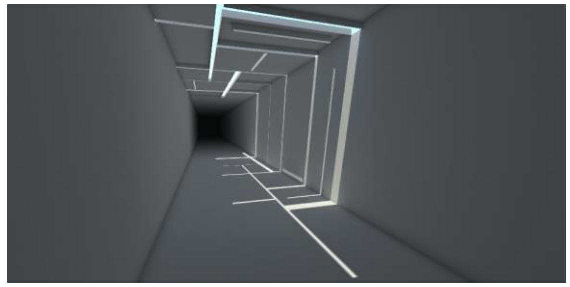


Figure 133, Rectangular bands

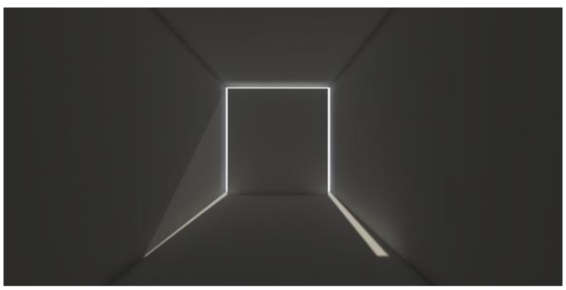


Figure 134, Edge lighting

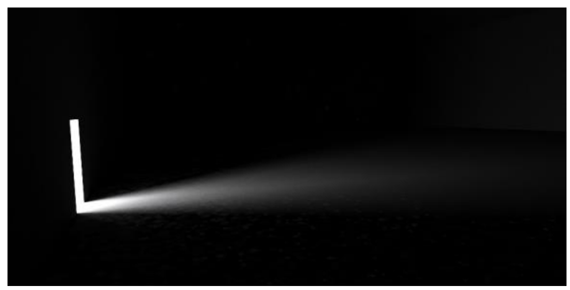


Figure 135, Light through a single opening

A second method involved using a perforated screen in place of cut out shapes. The first screen study involved a cube with a rectangular lattice on the roof and two walls. The shadows were animated from sunrise to sunset, and the following three images show the lighting conditions during the morning, midday, and evening. The biggest discovery from this study was the change in shadow shape when the light change from being overhead, to coming from the side. Shadows that were normally rectangular in one lighting condition got stretched out when the source of the light rotated by 90 degrees. This occurrence can be taken advantage of, as a form can produce two different shadows, depending on the angle of the light.

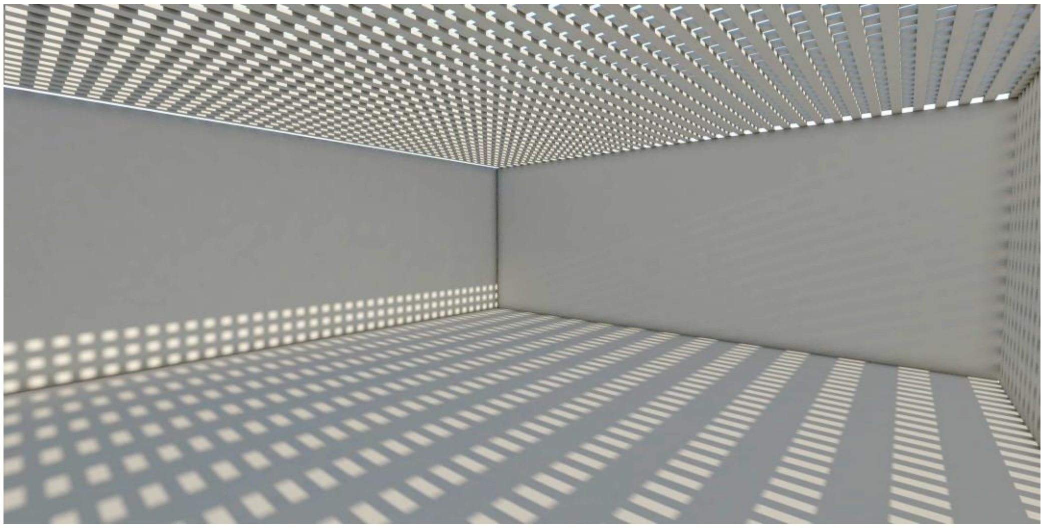


Figure 136, Morning lighting conditions

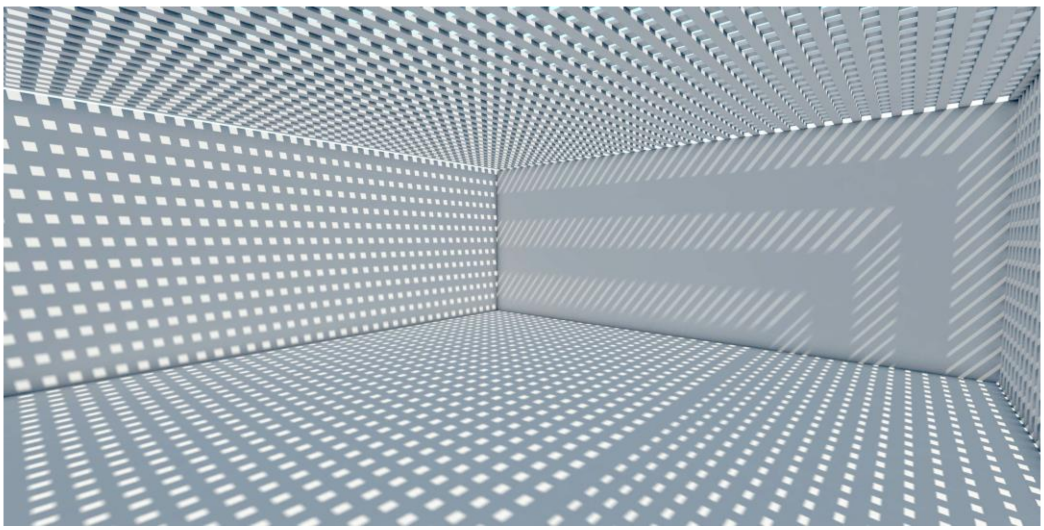


Figure 137, Midday lighting conditions

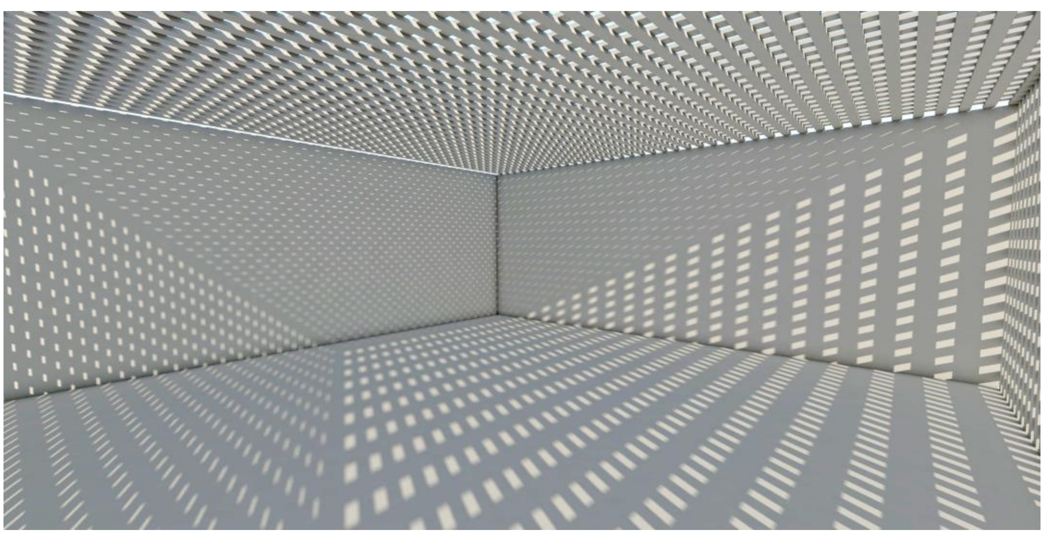


Figure 138, Evening lighting condition

Another screen, that was based off the dome of the Louvre Abu Dhabi, was explored. A series of randomly oriented shapes were stacked into four layers, creating the necessary height to have the light and shadows moving at different speeds on the ground surface. Two different time periods are shown below for the same scene, showing the variety of lighting patterns that can be created with this design.

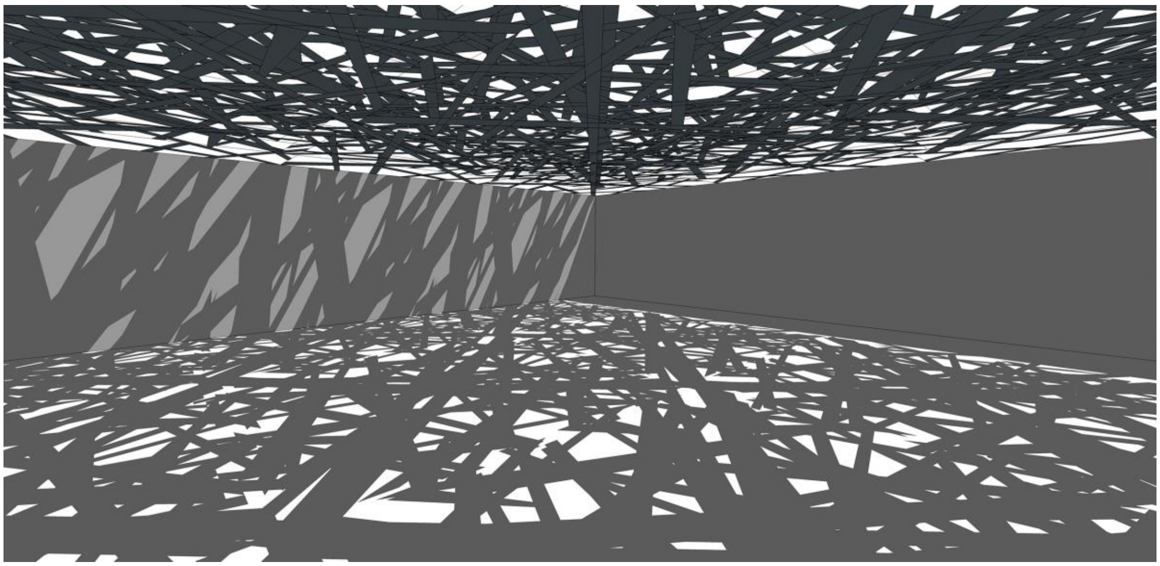


Figure 139, Shadows during morning sun.

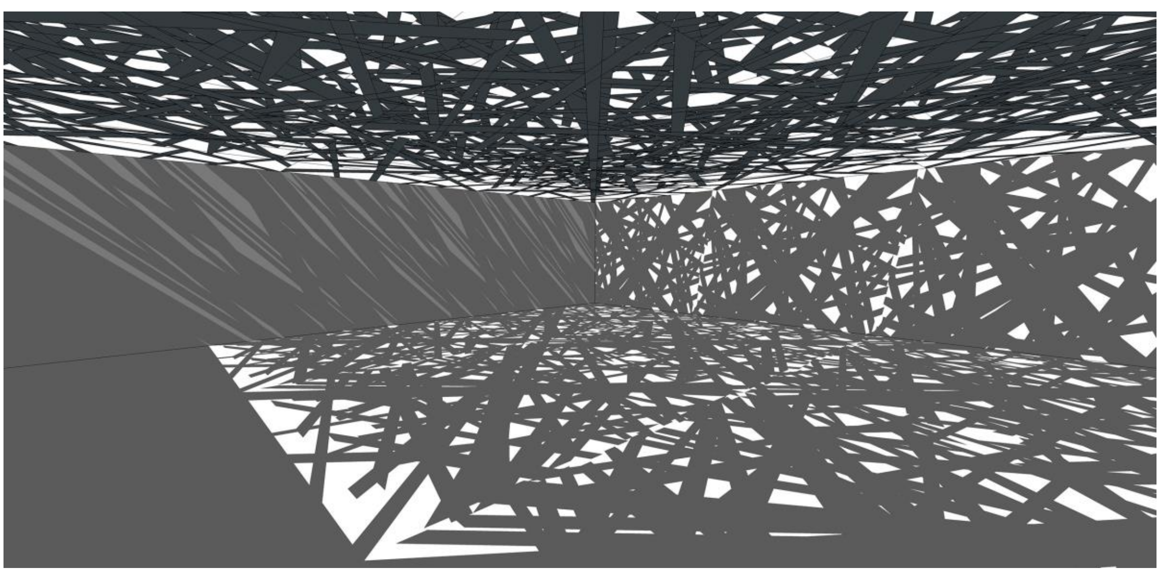


Figure 140, Shadows during afternoon sun.

Schematic Design

From the beginning, the overall form of the building was driven by the location of the large performance spaces. The proposed site circulation from site analysis was used to test different positions of the performance spaces. Four variations of the theater spaces are shown below. All of them take advantage of the cross-site pedestrian circulation to orient the theater spaces. The last image, on the bottom right, shows the final design.

Figure 141, Parti - Version 1

Figure 142, Parti - Version 2

Figure 143, Parti - Version 3

Figure 144, Parti - Version 4

In the fourth parti model, the forms of the curving office block on the right side of the model and dance studios on the top right changed very little between this model and the final building design. The large rehearsal spaces in the bottom and left side of the photo moved around a bit, but the overall building shape was formed at this point. The site plan below shows how the ground floor performance spaces work with the overall site circulation.

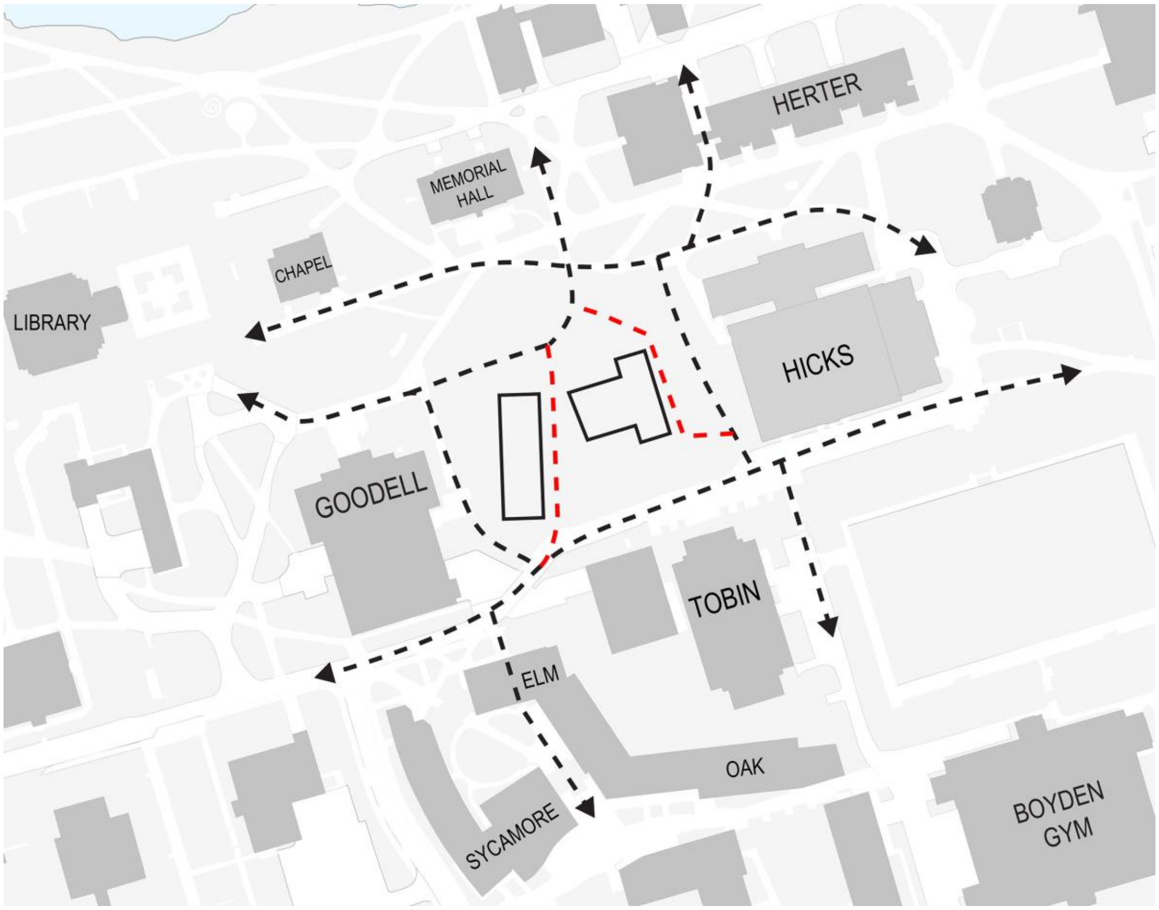


Figure 145, Performance spaces with site circulation.

The next steps involved applying similar methods for integrating natural light in a theatrical way, as was discovered in the previous precedent studies, and adapting them to this project. With the location of the ground floor performance spaces and office block on the opposite side of the large theater, two large atriums formed, allowing the performance of natural light to be explored in these spaces. Initial studies of the academic atrium (southern five-story atrium flanked by offices), used similar methods for cutting out shapes in the walls and roof to shape the light in the space.

Figure 146, Light study on physical parti model.

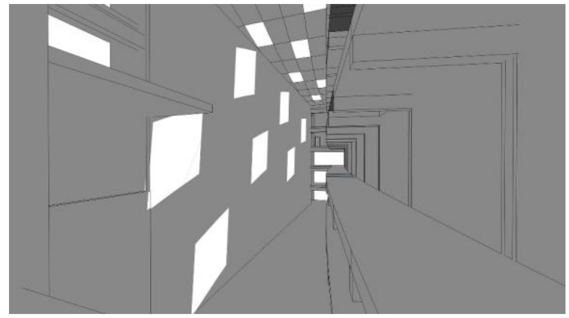


Figure 147, Similar study on SketchUp model.

The same type of studies was applied to the main atrium (between the large theater and small / studio theaters). Large rectangular openings were cut in the roof to see what type of patterns of light and shadow fell on the floor and walls.

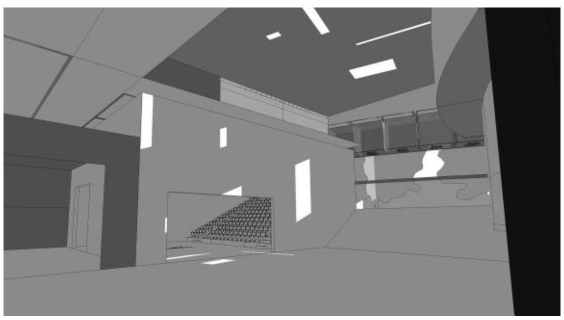


Figure 148, Main atrium light study in SketchUp.

Figure 149, Main atrium light study with physical model.

It was decided that a screen would be used to filter light into the main atrium, like the dome on Louvre Abu Dhabi, instead of the cut-out openings from a solid roof. This would allow a perforated screen of varying patterns to be used to filter light before it passes through the roof glazing, into the atrium below. There were two ways in which the screen could be designed. The first was that it would drape over the entire roof, covering the atriums and part of the outdoor roof garden. This would also allow it to transition from the roof to the façade, to make one integrated piece. The alternative was just to utilize the screen over the main atrium, and use it to filter light going into the glass box that encased the atrium. This approach was chosen over the former, as this would reduce the amount of roof glazing, and was much more feasible in terms of its design.

Figure 150, Light study with physical model and wooden screen.

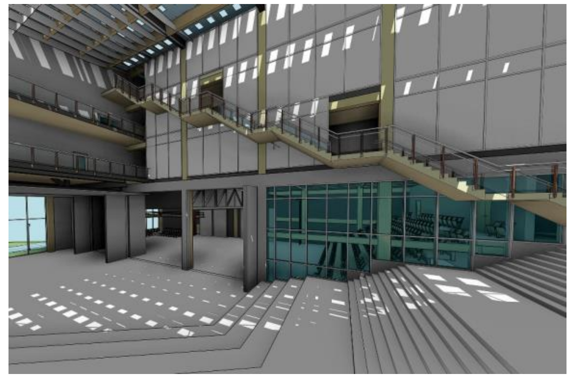


Figure 151, Light study in Revit with a perforated roof screen.

Other areas of the building that saw significant design changes included the fourth-floor rehearsal spaces, and flexible theater spaces. Glazing was modeled in dance studios, providing daylight and views out to the north and south. The small theater also rotated so it could share its backstage area with the studio theater. Large sliding doors allowed the spaces to be opened into one large theater, with an audience on both ends.

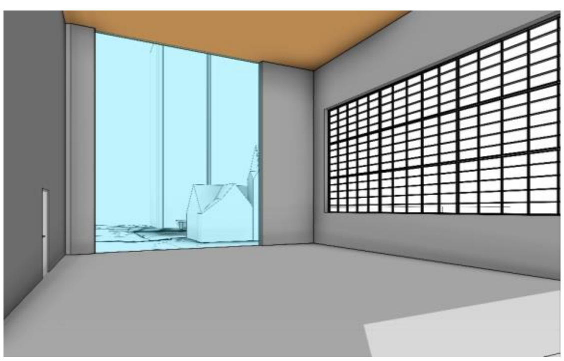


Figure 152, Ballet studio with north views of the campus.

Figure 153, Studio theater with doors opened to the small theater.

Design Development

The refinement of the main atrium and academic atrium continued through design development, which is the focus of the following sections.

Main Atrium Design

The main atrium screen went through 11 iterations of the perforation pattern, of different shapes, sizes and pattern density. Grasshopper was used to generate the patterns, as it would be too much work to draw by hand. Squares, circles and triangles were all explored, but squares were selected as the geometry was more appropriate with the rest of the building.

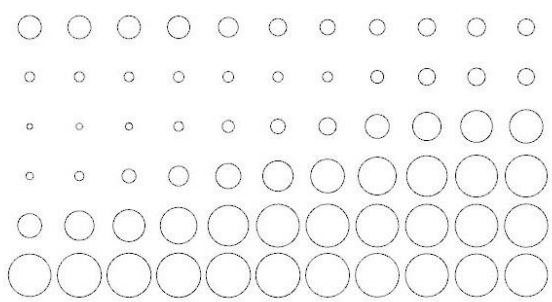


Figure 154, Circle perforation

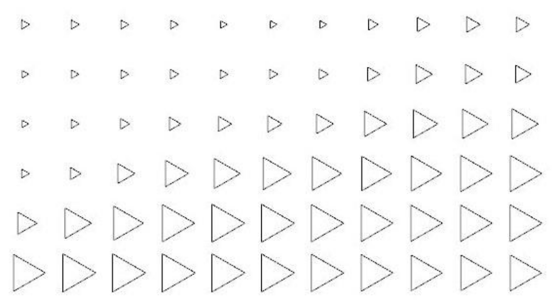


Figure 155, Triangle perforation

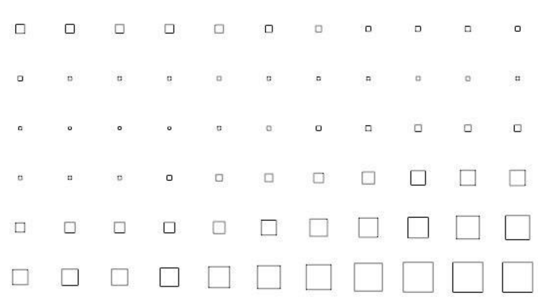


Figure 156, Smaller square perforation

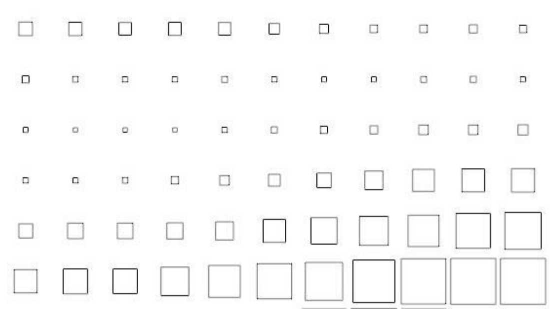


Figure 157, Bigger square perforation

The image sampler component in Grasshopper used a grayscale image to determine the size of the opening in the perforation.

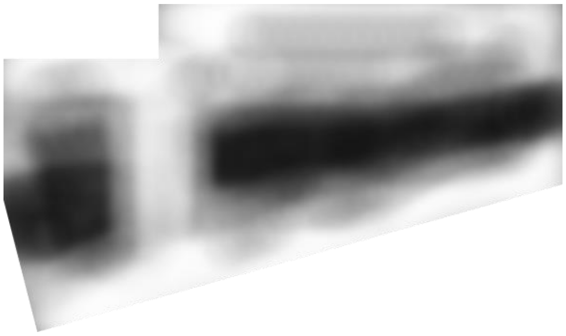


Figure 158, Grayscale image used to generate perforation.

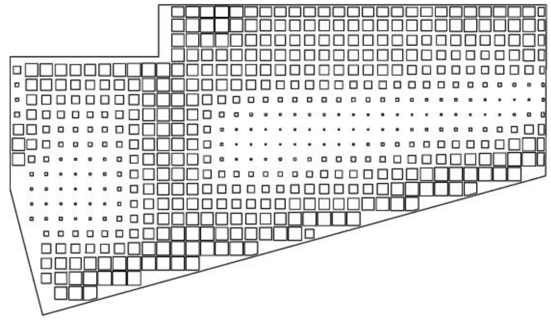


Figure 159, Resulting perforation.

Even though the openings are smaller in the center of the screen, that is not enough to block excessive direct sun on the steps in the main atrium. This resulted in the creation of a baffle system that hung below the roof glazing. This system, which ran both parallel and perpendicular to the structural roof members, varied in depth and spacing, to block light from reaching the steps, and allow more light through against the atrium walls.

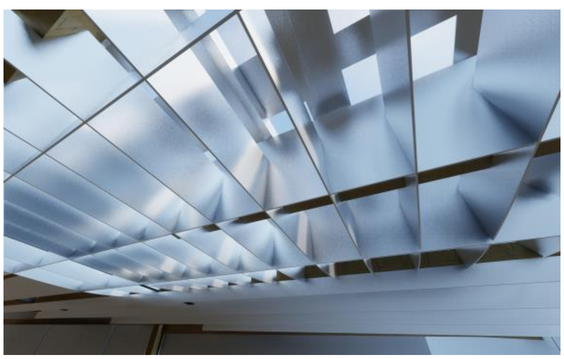


Figure 160, Deeper baffles in the middle of the atrium.

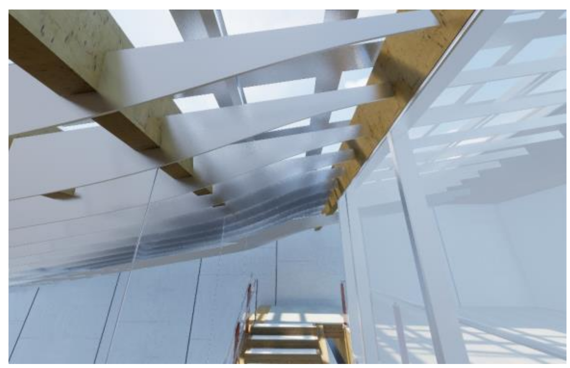


Figure 161, Shallower baffles along the edge of the atrium.

The geometry of the perforated screen, combined with the roof structure and baffle system creates a variety of shadows on the walls and floor, even over a small amount of time. The following series of three images show the north facing wall, and the resulting shadows over a span of two and a half hours.

Figure 162, Shadows on June 21 at 2:15 PM.

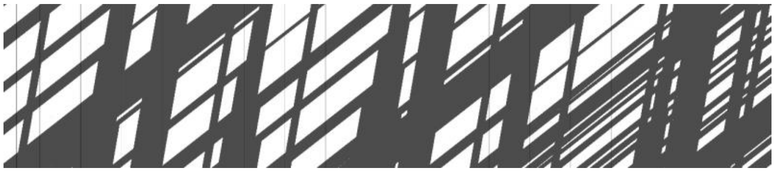


Figure 163, Shadows on June 21 at 3:30 PM.

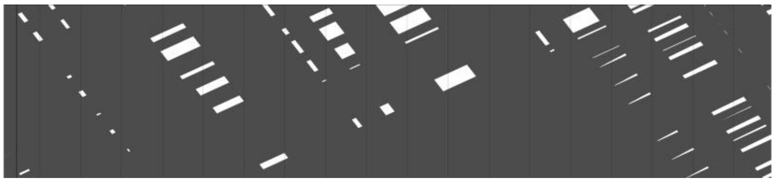


Figure 164, Shadows on June 21 at 4:40 PM.

The wall surfaces in the main atrium are kept lighter in material, to reflect more light around the space. A curtainwall along the south-facing wall spans from the third floor up to the roof, using frosted glass, so shadows and light are still visible on its surface, while still illuminating the corridors behind.

Figure 165, Main atrium as viewed from the second-floor ramp.

Academic Atrium Design

Earlier lighting studies included openings in the south wall as well as the roof. This would enable lower winter sun to penetrate horizontally, in addition to overhead summer sun shining through from above. The images below show the combined light patterns generated by the wall and roof openings in the atrium.

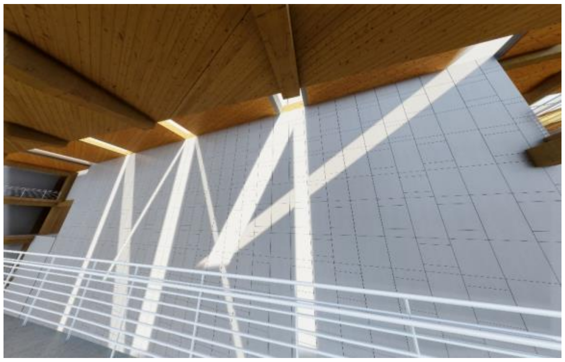


Figure 166, Combined light paths on June 21.

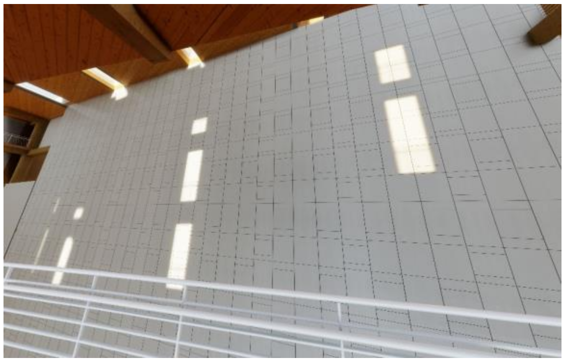


Figure 167, Combined light paths on December 21.

The section below shows the relationship between the large performance spaces and atriums. The academic atrium (left) is five stories tall, while the main atrium (right), ranges between four and five stories.

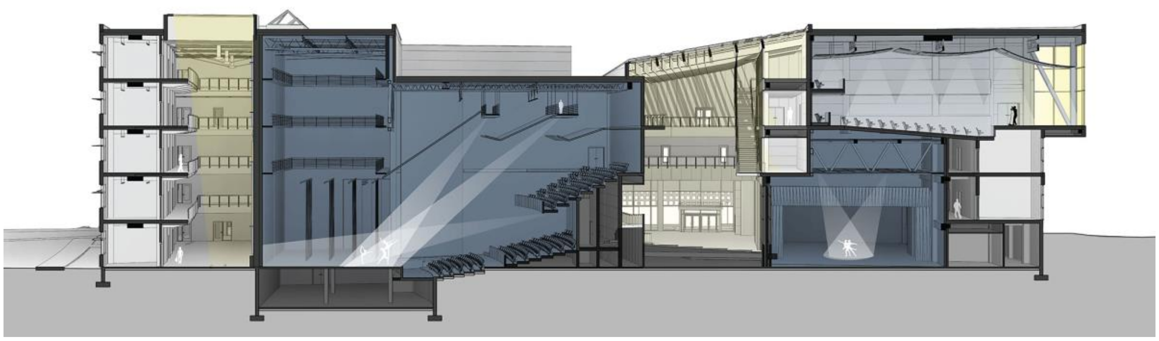


Figure 168, Perspective section through theaters and atriums.

It was later decided to abandon the openings in the south wall, and focus only on top lighting, as this would eliminate the awkward office shapes created by the openings, and strengthen the overall move. The time and location in which light penetrated the furthest through each opening was used to carve out the wall, and horizontal projections were used to mark the months in which sunlight reached a certain point in the atrium.

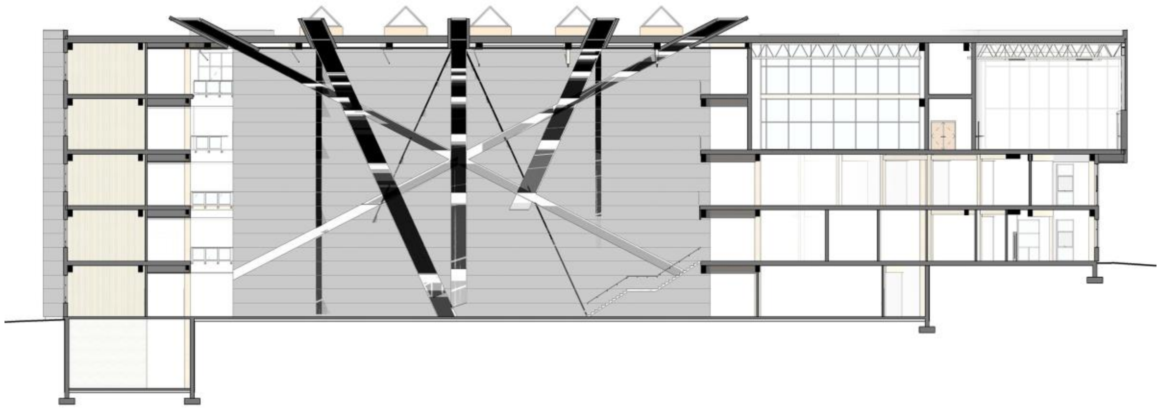


Figure 169, Darker bands represent more frequent sun.

Three of the openings allow light to reach all the way to the ground, so the floor material changes to indicate the reach of the light. During the day, this atrium feature relies upon natural light, but during night, the carved-out space is backlit, demonstrating that artificial light can also be incorporated into its use.

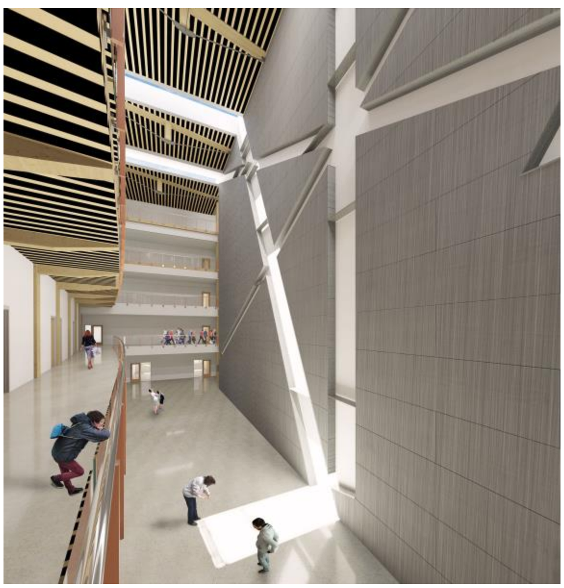


Figure 170, Sunlight reaching the floor.

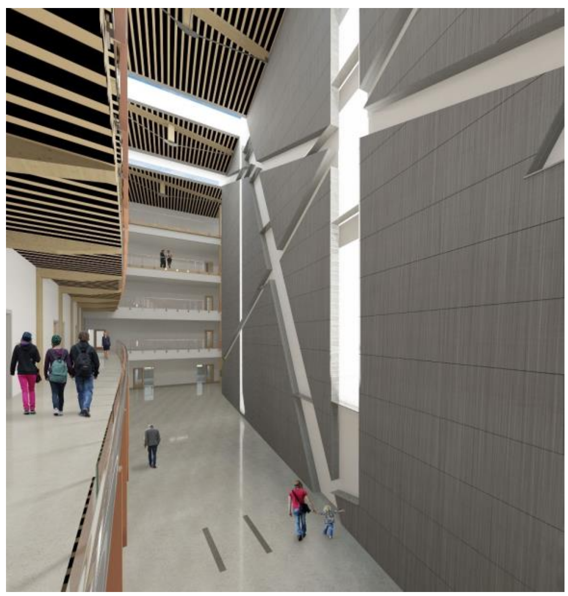


Figure 171, Sunlight reaching the July 21 projection.

West Glazing Screens

On the west facades where the glazing ratio is high, vertical screens, similar to the main atrium, are used to minimize afternoon glare, and filter artificial light shining out at night. The screens are made from Corten steel, and are hung off the curtainwalls.

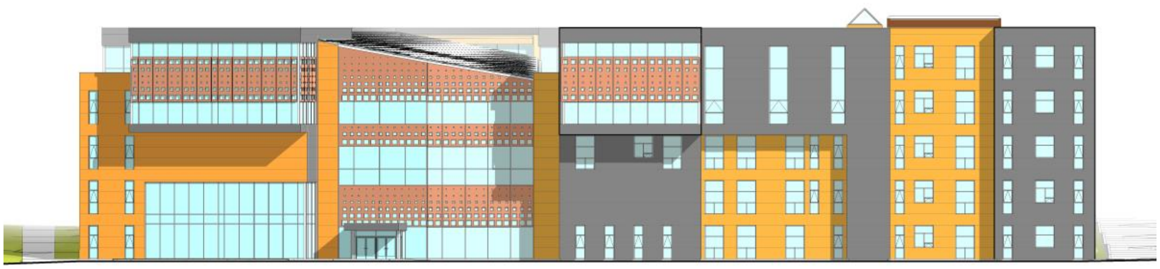


Figure 172, West elevation showing Corten steel screens.

The typical screen, which can be found on the large ensemble rooms, start at an elevation of seven feet above the floor, allowing for views out, and reach 21 feet above the floor. The top portion of glazing, above the top of the screen is frosted glass, allowing diffuse light through, but eliminating glare. The same screens are also used on the west façade of the atrium, which is glazing from the ground floor up to the roof.

Flexible Theaters

The main feature of the small theater, studio theater, and main atrium is the ability to open the doors between them, and form a larger space. This allows for three primary modes of operation. In the independent mode, each theater is used independently, and both are sealed off from the atrium. In the double theater mode, the doors between the spaces are opened, allowing for one large space, with a stage area of around 100 feet by 50 feet. In the open configuration, all the doors are opened, connecting both theaters to the main atrium floor.

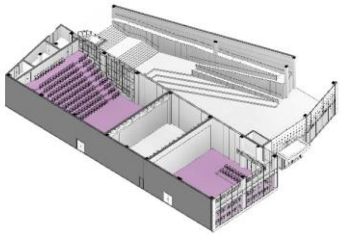


Figure 173, Independent configuration

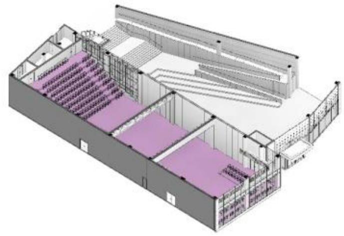


Figure 174, Double theater configuration

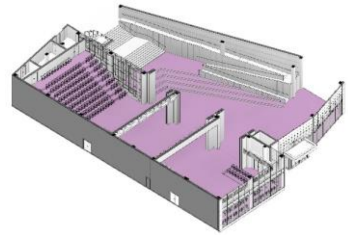


Figure 175, Open configuration

Daylight Analysis

Daylight analysis was used to help design the office and practice room spaces. These rooms make up much of the perimeter floor area, so ensuring they were designed to make the most of daylight was important for reducing electrical lighting dependency.

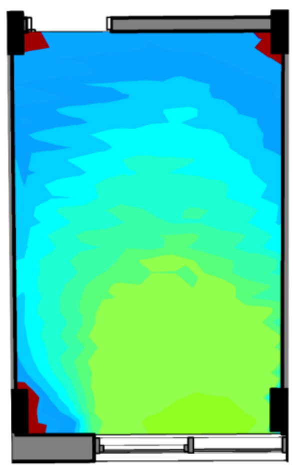


Figure 176, Typical south-facing office space.

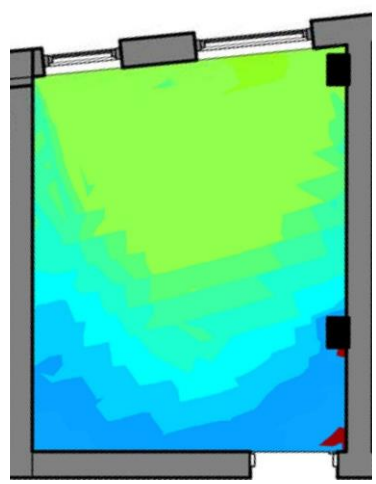


Figure 177, Typical north-facing practice room.

Glazing: 33%
9 AM: 75% within threshold (300-3000 LUX)
3 PM: 97% within threshold (300-3000 LUX)

Glazing: 41%
9 AM: 97% within threshold (300-3000 LUX)
3 PM: 99% within threshold (300-3000 LUX)

A typical south facing office, and north facing practice room was chosen for conducting lighting analysis to improve the daylighting performance of the rooms. Environmental Quality credit seven, option two of LEED version 4 was selected as the performance metric for running these tests. Analysis were performed at 9 AM and 3 PM, and the percent of the floor area within 300 to 3,000 LUX was calculated. Lower than 300 LUX means that area was not adequately lit, and above 3,000 means that glare is occurring. The typical office space stays within the LUX thresholds for 75% and 97% of the floor area, and the practice room between 97% and 99% of the floor area.

Final Review Boards

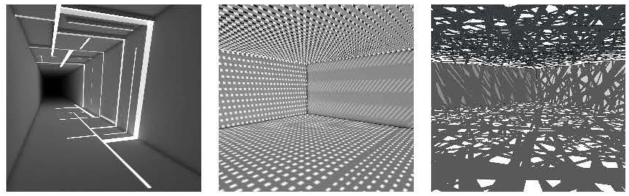
The thesis oral presentations took place on April 12, 2017, in the atrium of the UMass Design Building. Each board is 24” x 48”.

THE PERFORMANCE OF LIGHT

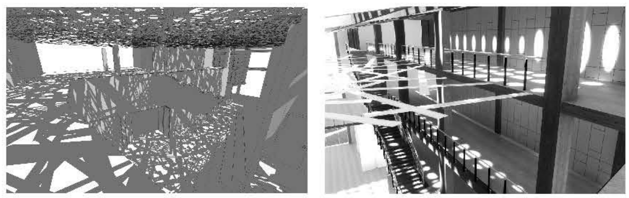
Dylan Brown
Masters Thesis
Spring 2017

PERFORMANCE ANALYSIS

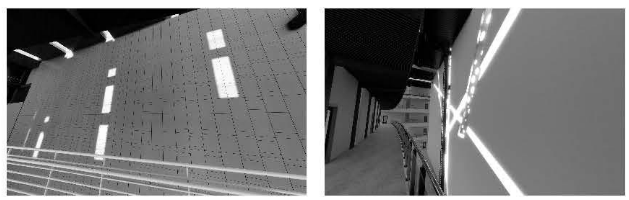
LIGHTING STUDIES



MAIN ATRIUM LIGHTING PROPOSALS



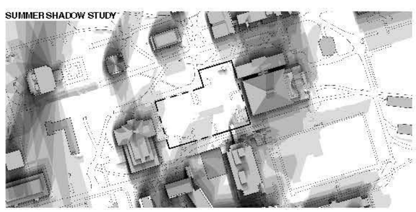
ACADEMIC ATRIUM LIGHTING PROPOSALS



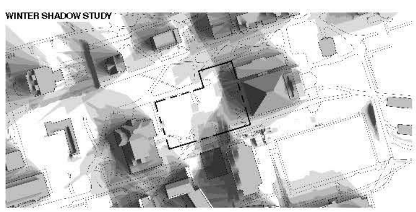
SITE

Amherst is located in IECC climate zone 5A, which is a moist climate with average heating degree days of 7100 and average cooling degree days of 900. Prevailing winds from spring though the fall are from the south, and north and south during the winter.

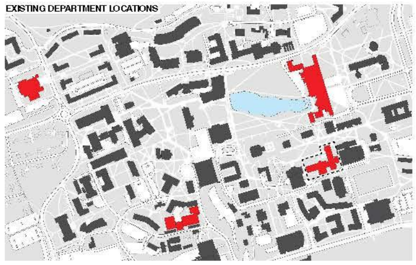
SUMMER SHADOW STUDY

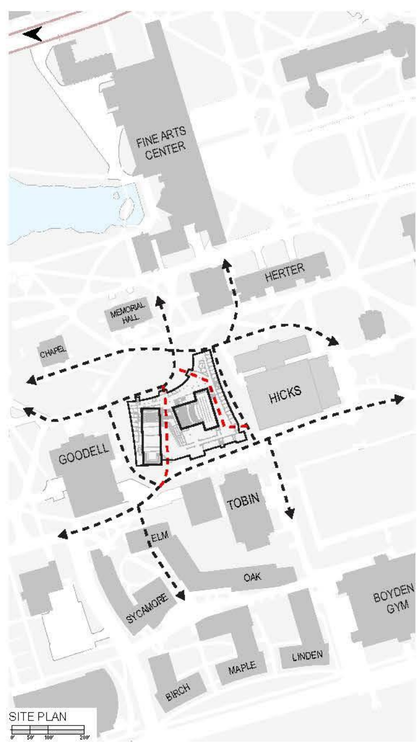


WINTER SHADOW STUDY



EXISTING DEPARTMENT LOCATIONS





SITE PLAN

PROGRAM

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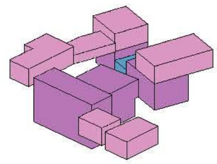
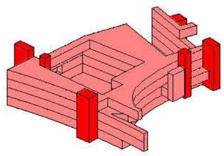
Masters Thesis
Spring 2017



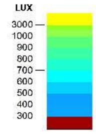


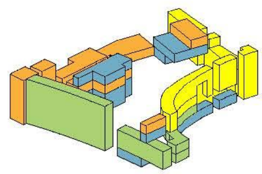
LEED v4 EQc7 opt 2 was used as the target metric for daylighting performance. Window placement and glazing ratios were adjusted in the office and practice rooms to achieve desired LUX values.

TYPICAL SOUTH-FACING OFFICE (33% GLAZING)

9 A.M: 75% within threshold |300-3000 LUX|

3 PM: 97% within threshold |300-3000 LUX|



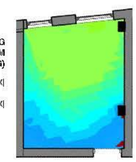


SPACE TYPE	COUNT	TOTAL SQUARE FOOTAGE
Administration	79	1,421
Circulation	19	65,571
Classroom	27	18,589
Music Practice Rooms	61	12,009
Large Rehearsal	6	13,617
Theater/Recital Hall	5	17,995
Service	54	30,035
Mechanical	3	8,092
Total		167,329 SF

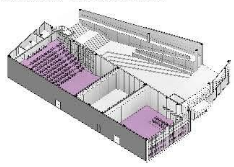
TYPICAL NORTH-FACING PRACTICE ROOM (41% GLAZING)

9 A.M: 97% within threshold |300-3000 LUX|

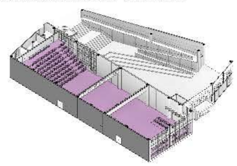
3 PM: 99% within threshold |300-3000 LUX|



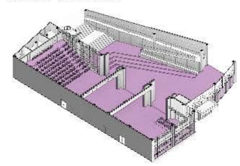
INDEPENDENT CONFIGURATION

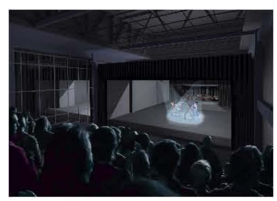


DOUBLE THEATER CONFIGURATION



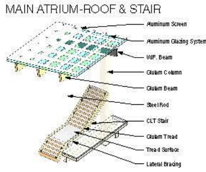
OPEN CONFIGURATION



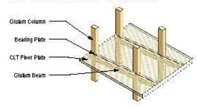


STRUCTURE

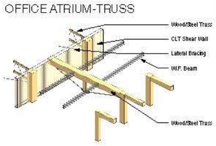
MAIN ATRIUM-ROOF & STAIR



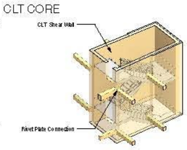
TYPICAL STRUCTURAL BAY

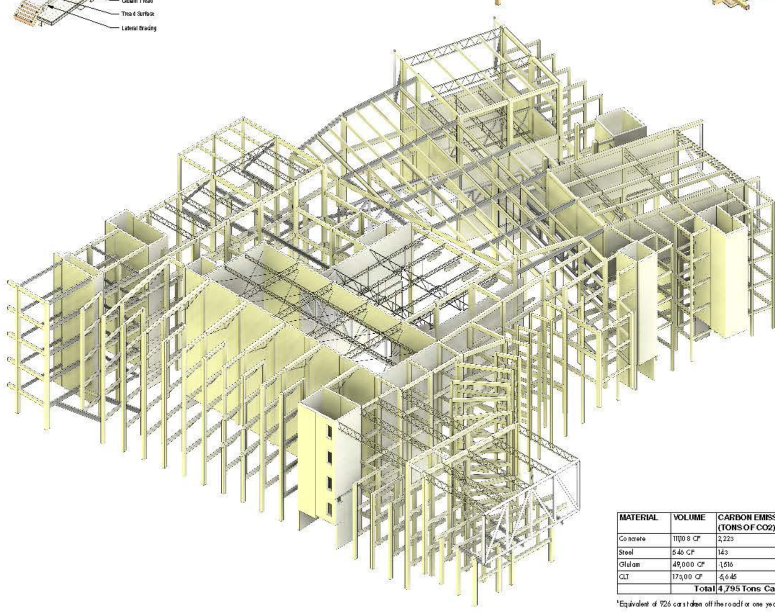


OFFICE ATRIUM-TRUSS



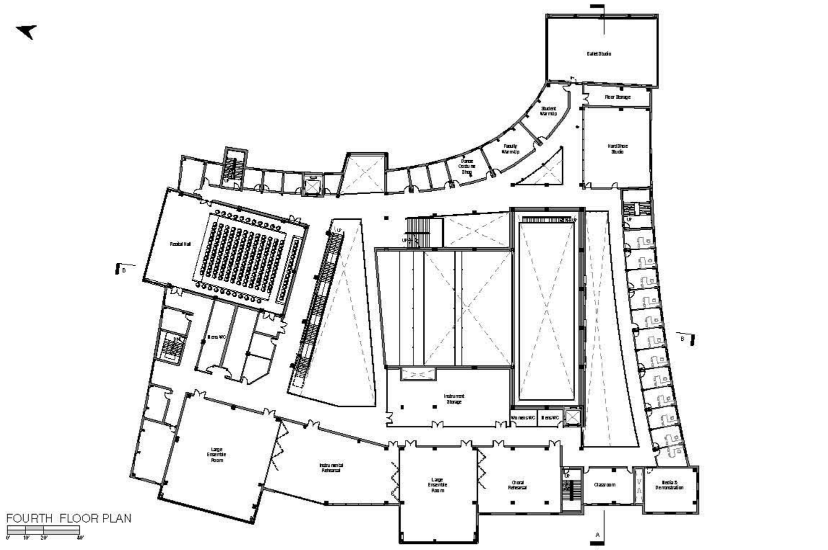
CLT CORE



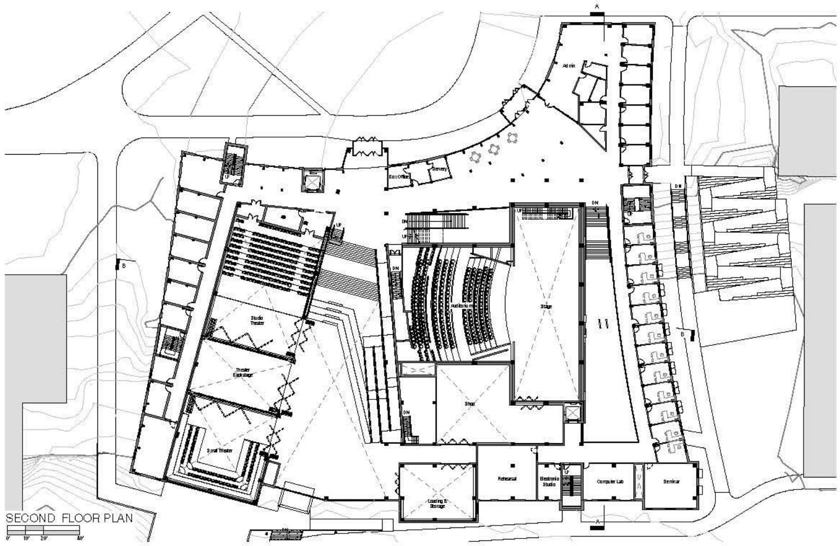


MATERIAL	VOLUME	CARBON EMISSIONS (TONS OF CO2)
Concrete	111,108 CF	2,223
Steel	546 CF	143
Glulam	49,000 CF	-1,516
CLT	173,00 CF	-5,645
	Total	4,795 Tons Captured*

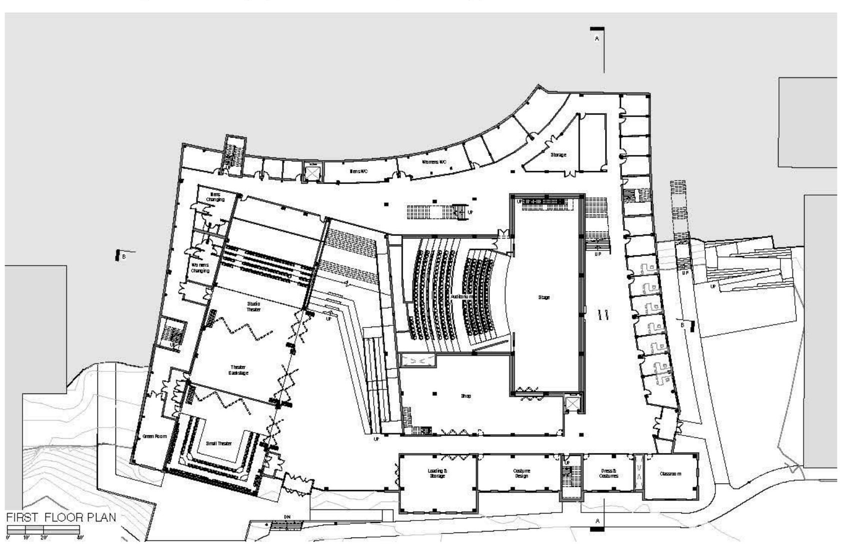
*Equivalent of 926 cars taken off the road for one year.



FOURTH FLOOR PLAN



SECOND FLOOR PLAN



FIRST FLOOR PLAN

LIGHT CARVING

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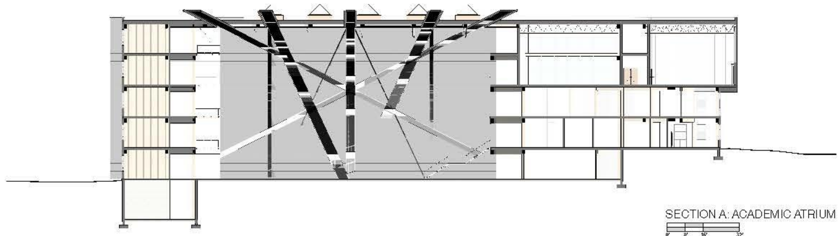
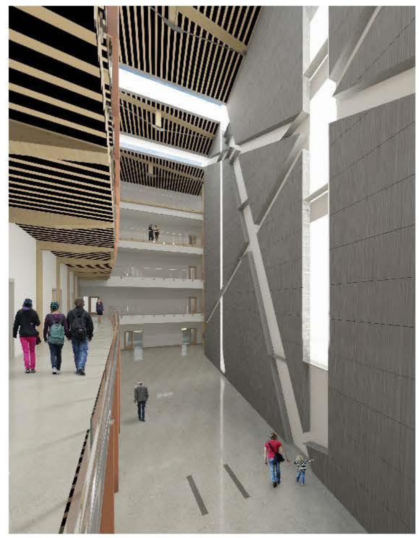
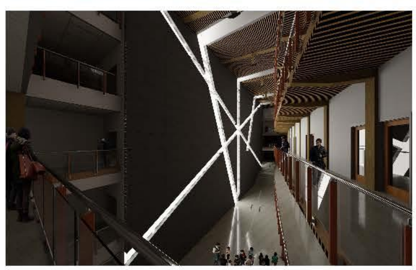
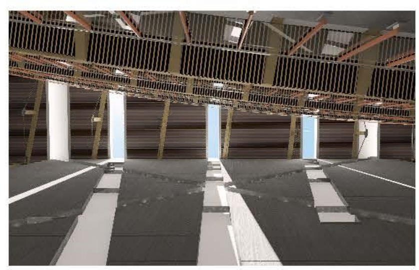
Masters Thesis
Spring 2017

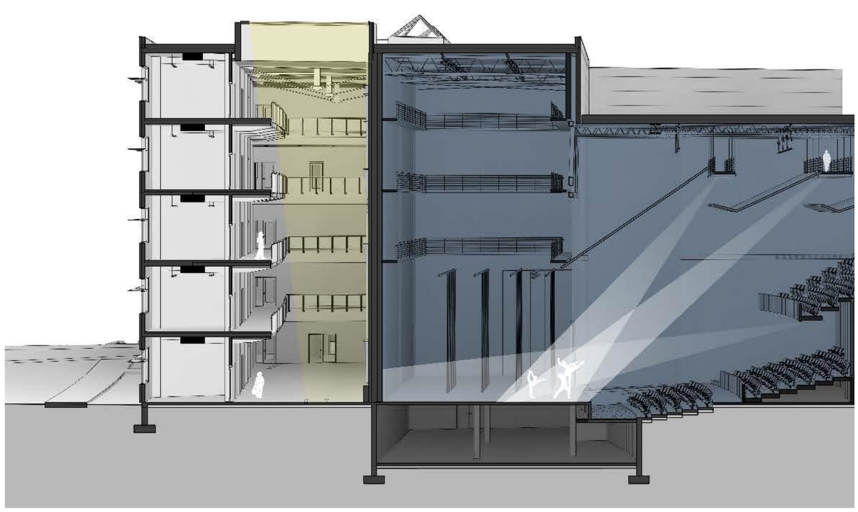


SECTION A: ACADEMIC ATRIUM



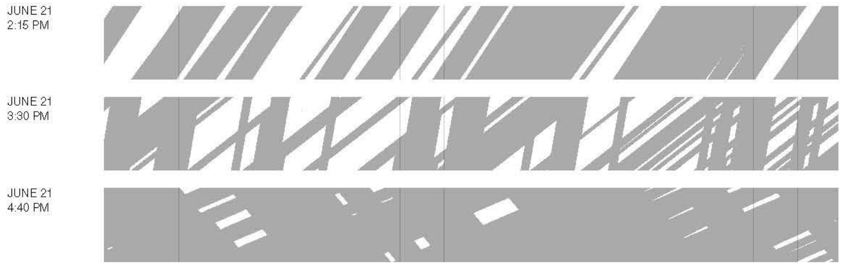


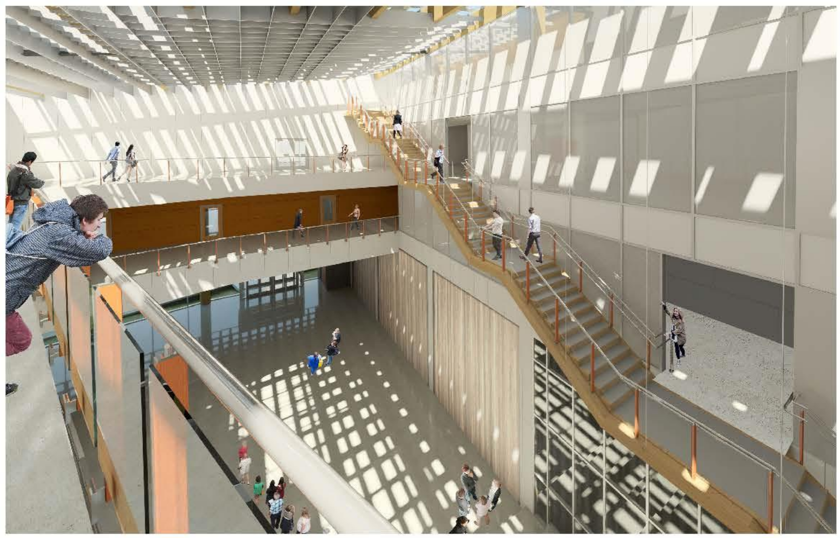




PLAY OF LIGHT

Dylan Brown
Masters Thesis
Spring 2017



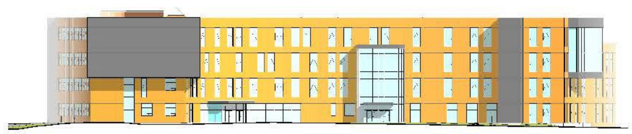


SECTION B: LARGE THEATER, RECITAL HALL AND ATRIUM'S

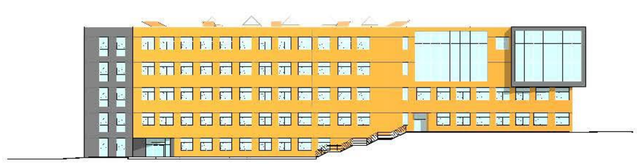
PERFORMANCE SPACES

Dylan Brown
Masters Thesis
Spring 2017

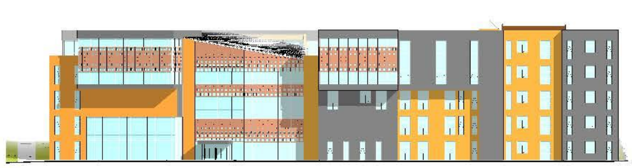
NORTH ELEVATION



EAST ELEVATION



SOUTH ELEVATION



WEST ELEVATION

CHAPTER VI

CONCLUSION

The objective of this thesis project was to explore the impact of natural light, and how it could be used in a theatrical way in an academic building with a performance oriented program. The two atriums were the focus of this exploration, and utilized concepts developed from simple lighting studies to manipulate light. The rooftop screen above the main atrium filters light into the space below, and generates an every-changing pattern of light on the walls. The five skylights in the academic atrium allow light to enter at specific times of day, and it functions as a time keeper, throughout the day and the months. Based on the depth of the sun into the atrium, the time of year can be found within a couple days of accuracy. The experience created by these two atriums, combined with the proposed pedestrian circulation patterns that cut diagonally through the building ensures that students passing by would be intrigued enough to make the trip through, instead of navigating around the building.

Earlier research about designing flexibility out of a space, and designing flexibility in is exemplified by the design of the atrium and north-side theater spaces, as their doors can be opened to configure the stage in any number of ways. The same approach is used for the west-facing rehearsal spaces on the fourth floor. Large operable doors span the walls between them, allowing one large 10,000 square foot room, 220 feet long, to be made from the four rehearsal spaces.

The building's programing goal is to bring all three departments together, in one school of performance. This cohesion is achieved by the intermingling of spaces from all three departments. Classroom and administrative space is organized by size, and the flexibility of the theater spaces ensures that they can adapt and be used interchangeable by any of the departments.

The UMass School of Performance Building brings together music, dance and theater in a space that celebrates natural light.

APPENDIX A

STRUCTURE & TECTONICS

The use of wood in the building industry has been rapidly growing over the last 10 to 20 years, largely in part to the introduction of new mass timber technologies such as glulam and CLT, but also the push from climate change to use more sustainable products in the construction of buildings. This section will analyze building forms and construction techniques utilizing mass timber. *The Case for Tall Wood Buildings*, published in 2012, analyzes "how mass timber offers a safe, economical, and environmentally friendly alternative for tall building structures."[48] The report introduces a structural system of mass timber to be used in a FFTT (Find the Forests Through the Trees) building system. The three types of wood composites that can be used in the FFTT system as wood panels are CLT, LSL and LVL.

CLT (Cross Laminated Timber)	**LSL (Laminated Strand Lumber)**	**LVL (Laminated Veneer Lumber)**
"CLT consists of several layers of boards stacked crosswise (at 90 degrees) and glued together on their wide faces and, sometimes, on the narrow faces as well. A cross-section of a CLT element has at least three glued layers of boards placed in orthogonally alternating orientation to the neighboring layers. In special configurations, consecutive layers may be placed in the same direction, giving a double layer to obtain specific structural capacities. CLT products are usually fabricated with three to seven layers or lamella."[48]	"Laminated strand lumber is a structural composite lumber manufactured from strands of wood species or species combinations blended with an adhesive. The strands are oriented parallel to the length of the member and then pressed into mats using a steam injection press."[48]	Laminated veneer lumber is made up of layers of wood veneers laminated together using a waterproof structural adhesive. The manufacturing process consists of rotary peeling a log into veneers that are then dried and graded for strength and stiffness. After the graded veneers are coated with adhesive they are laid up into a billet that is then fed into a hot press that cures the adhesive under heat and pressure. The cured and compressed billet then leaves the hot press and is ripped into boards.[48]
		

Table 3, Properties of mass timber panels. Mgb Architecture + Design, 2012

[48] mgb Architecture + Design, and Equilibrium Consulting. The Case for Tall Wood Buildings. LMDG Ltd & BTY Group: 2012.

These three types of wood composites have different structural properties, but each one could be used in the FFTT system with little or no changes. The above materials are used to compose large structural timber panels that are part of the system. In addition to the mass timber panels, glulam columns and wide flange beams are integrated into each floor, while the foundation is constructed out of concrete.

The FFTT system uses a balloon-framing style of construction, substituting small studs with large panels. It also uses a "strong column - weak beam structural approach,"[49] which was developed by Michael Green from mgb Architecture + Design and Eric Karsh of Equilibrium Consulting. The strong column represents the solid timber panels, and the weak beam is the steel beams connecting the panelized core and walls to the columns. As shown in the exploded diagram below, a solid wood core can be connected to a grid of glulam columns or solid timber panels using steel beams to allow for more ductility.

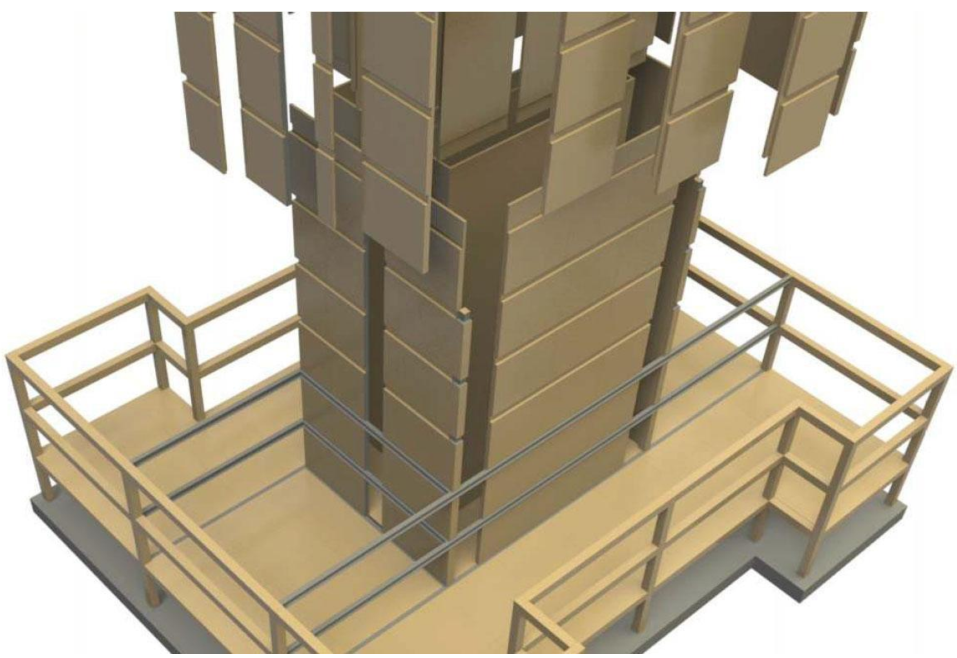


Figure 178: Hybrid structure of tall timber tower. Mgb Architecture + Design, 2012

[49] mgb Architecture + Design, and Equilibrium Consulting. The Case for Tall Wood Buildings. LMDG Ltd & BTY Group: 2012.

When the tower gets taller, glulam columns are replaced with structural interior and exterior timber panels, because of the increased compressive strength. The two floor plans below show a glulam column-based plan for a 12-story building, and a timber panel-based plan for a 30-story building. The open column plan would be better suited for commercial buildings, where flexibility in the plan is essential, while the structural interior walls in the 30-story plan lends itself more to a residential application.

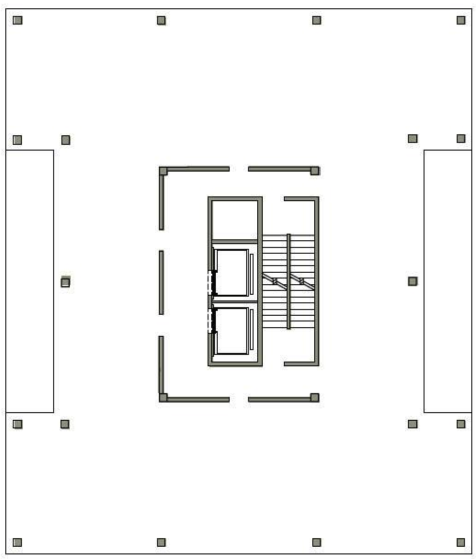


Figure 179, 12 Story Building, Typical Floor Plan. Mgb Architecture + Design, 2012

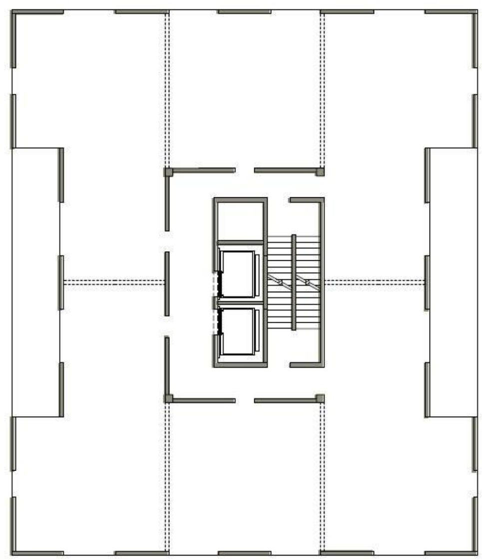


Figure 180: 30 Story Building, Typical Floor Plan. Mgb Architecture + Design, 2012

For non-loading bearing partitions, fully insulated double stud walls are used to minimize vibrations between spaces, and where solid timber panels are used, mineral wool insulation on each side of the panel achieves the same job.

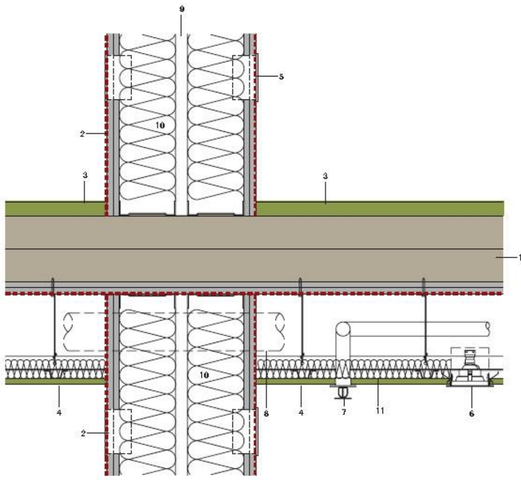


Figure 181, Double Stud Wall Assembly. Mgb Architecture + Design, 2012

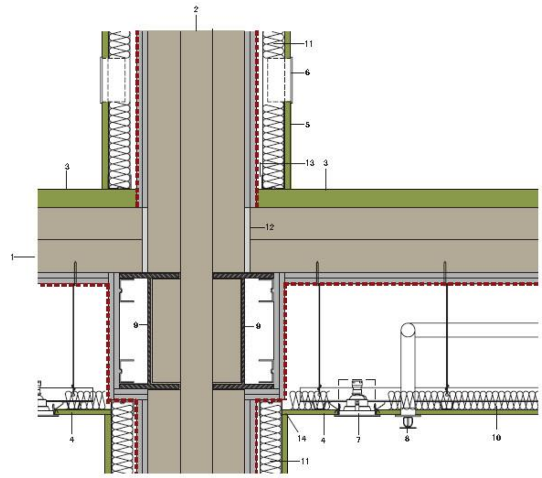


Figure 182, Timber Panel Wall Assembly. Mgb Architecture + Design, 2012

The engineering and product testing completed because of this report has demonstrated that tall buildings can use wood as a structural material, at least up to 30 stories. Constructing buildings of this size with wood will capture an enormous amount of carbon, due to wood absorption of CO2 during its growing phase, and the lighter environmental impact of wood harvesting and manufacturing. Due to wind and seismic forces, steel beams had to be used to allow for greater ductile connections between the exterior columns or panels, and the timber panel core.

Mass timber can not only be used for high-rise construction, but engineered and hybrid systems can be used to span long distances, for use in larger structures. The following sections discuss components and systems used in wooden roof construction, but many of the techniques can be applied to floors as well.

Wood Roof Components

At its basic level, a wooden roof is composed of three components; weatherproofing, structural sheathing, and structural framing. The framing and sheathing hold up the roof, and the weatherproof barrier keeps the inside dry. The sheathing layer can be made out panels, such as OSB or plywood, solid decking, such as tongue & groove lumber, or larger panel products, like SIPS, CLT, LVL, or LSL panels.

Figure 183, Plywood Sheathing. Dylan Brown

Figure 184, Tongue & Groove Decking. Dylan Brown

Figure 185, CLT Roof Panel. Alex Schreyer

The structural framing layer of rafters and purlins can be constructed out of the following; dimensional lumber, glulam, prefabricated I-Joists, or composite lumber (laminated veneer lumber, parallel strand lumber, laminated strand lumber, and oriented strand lumber.) These materials can be assembled in a wide variety of ways, which will be explored in the following section.

<u>Wood Roof Systems</u>

Metal plated trusses can be made from dimensional lumber, glulam, composite lumber, or composites with other materials. The chords and webs can be joined together with truss plates, or nuts and bolts. There are many variations on the type of truss that can be used. Some of those trusses are shown below.

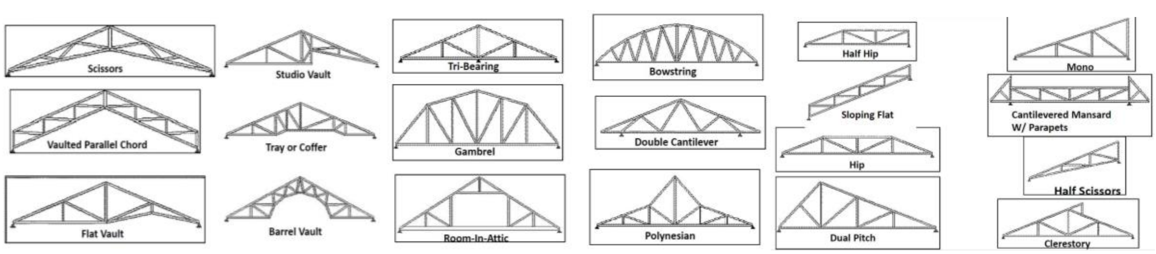


Figure 186, Different types of wooden truss systems.

Many of the trusses above are assembled with dimensional lumber and truss plates. The following examples express different wood components with different connections. The federal police building in Oberschleißheim, Germany, has two helicopter hangars that utilizes a four-meter-deep glulam truss, which holds up a two-meter-deep glulam purlin. The webs and chords of the truss are connected by internal knife plates held in place by bolts and pins.

Figure 187, Glulam heavy timber truss. Steffen Wirtgen

At the Dubai Sports Arena, in the UAE, glulam trusses are tensioned with stainless steel tension rods. This hybrid truss system uses two materials to create a strong but lightweight span for the sports arena.

Figure 188, Wood and steel hybrid truss. Structural Timber Solutions LLC

Arches

Figure 189, Three hinge glulam arch. Western Wood Structures

An alternative to creating long spans with trusses is the arch. It is best used for creating arch-shaped roofs, with high ceilings. The Bulk Terminal Building in Portland, Oregon uses a three-hinge arch to span a 160-foot distance, while providing a high vaulted-space. The structure can also be thinner, since the steeper the arch, the more efficient the structure is at transferring loads from the apex to the ground. Another structure that pushes the boundary of the strength of glulam is the Richmond Olympic Oval. Spanning 330 feet, the glulam arches are held in place with the assist of a steel truss. The roof also uses standard building materials; one million board feet of 2x4's, and 19,000 sheets of plywood.

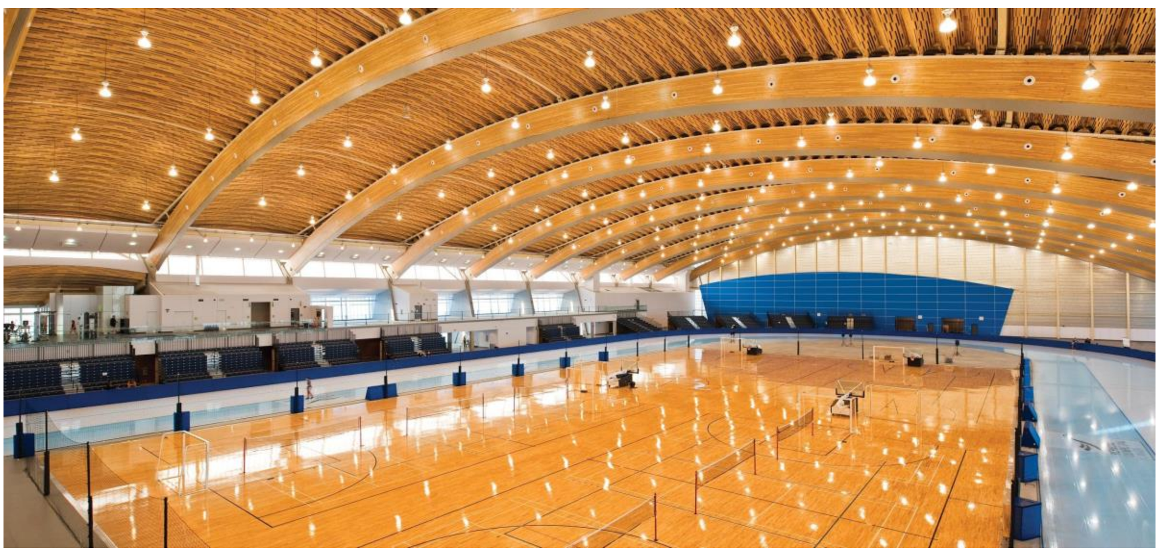


Figure 190, Richmond Olympic Oval. Cannon Design

As evident by this exploration into wooden roof systems, there are many choices out there for achieving optimal structural design, as well as enhancing the tectonic expression of the building.

Prefabrication and Modular Construction

One of the beneficial aspects of using timber in building design is faster construction by using prefabrication or modular design. Most people think of prefabricated walls made dimensional lumber and plywood, but CLT's use as a mass timber panel is seeing similar applications on a larger scale. The public's general perception of prefabrication is that it results in boring architecture, as many repetitive elements are used to save cost and speed up construction. "In a well-designed structure, it can be impossible to tell that any level of prefabrication was used at all."[50]

Most visitors of the Candlewood Suites at Redstone Arsenal in Huntsville, Alabama aren't aware that the building their staying in uses cross-laminated timber for 100% of its structure. The CLT is hidden behind typical floor, wall and ceiling furnishings, so you'd never get a chance to see it. The structure for the 62,688 square foot hotel was completed in 10 weeks by a team of 11 people. Construction time was cut by 37 percent, and crew size by 40 percent.[51]

[50] WoodWorks. "Prefabricated and Modular Construction." (2014).
[51] reThink Wood. "Wood: Hospitality Flair and Performance." 2016.

Figure 191, Exposed CLT during Construction.

Figure 192, Completed façade.

Since wood is lightweight, prefabricated elements can be assembly with just a small team of carpenters and a crane operator. Building assemblies in factories before they get to the job site means the work can be done in a climate-controlled environment, and greater control over the fabrication allows for better quality control. The Woodlands at Harvest Hill, a senior housing project in Lebanon, New Hampshire, used prefabrication to shorten their construction time to just a few months, for a 167,230 square foot building. Trusses and 2x6 wall assemblies, some close to 50 feet in length,[52] were trucked in to the site, allowing for the construction to be completed on time, during the winter in New Hampshire.

Completed in 2012, Lifecycle Tower One in Austria was a pioneer in its construction methods, serving as a pilot project for future construction. It was the first eight story timber building in the country, and implemented a new

Figure 193, Workers hoisting a prefabricated floor section into place.

[52] WoodWorks. "Prefabricated and Modular Construction." 2014

prefabrication method for the structure.[53] Glulam/concrete composite wall and floor units were manufactured off-site and then assembly by crane. Each floor panel took only five minutes to lay into place. The building core was constructed in traditional concrete, as building codes in Austria didn't allow for a solid wood core. Just a few years ago, mass timber construction was not widespread, and building codes had not adjusted for this new type of construction. The code still groups heavy timber with light frame, which limited the height and area of mass timber buildings. Since then, building codes have adjusted to allow greater flexibility in the design of wood buildings. As a result of this, bigger and taller buildings have been proposed that utilize CLT or glulam as their primary structural material. As opposed to the concrete core in Lifecycle Tower One, the elevator and stair shafts in the UMass Design Building are made out of CLT panels, which passed building and fire codes due to a dual layer of gypsum board surrounding the shafts.

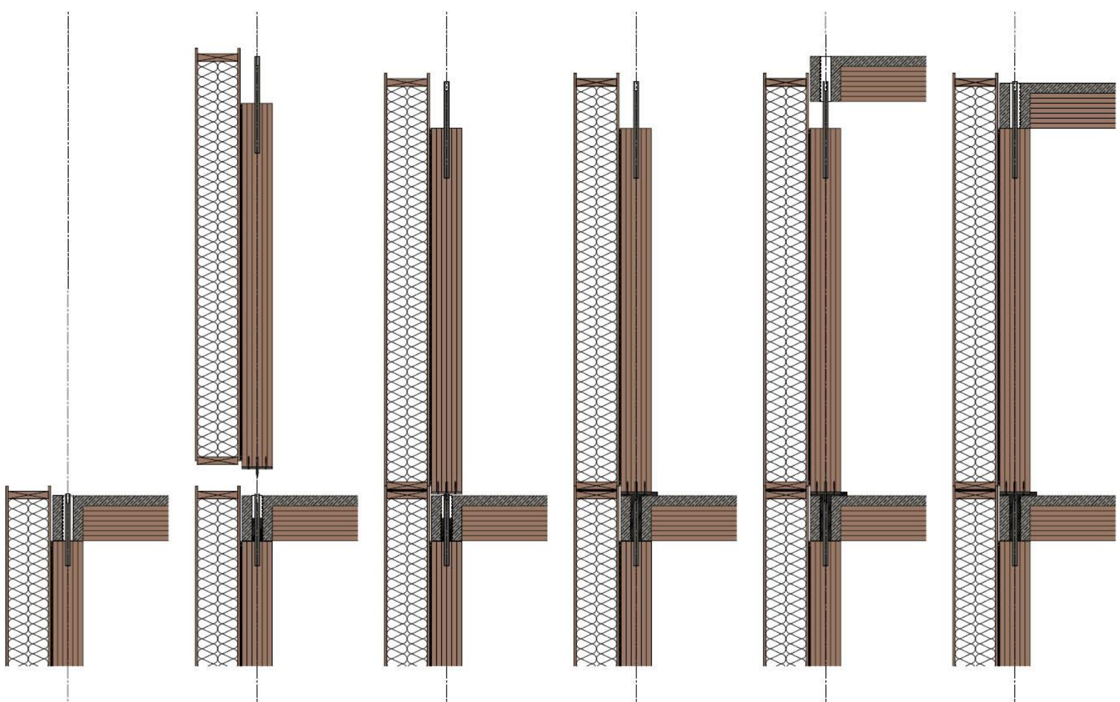


Figure 194, Wall and floor assembly process – Lifecycle Tower One. Hermann Kaufmann ZT Gmbh, 2012

[53] Hermann Kaufmann ZT Gmbh. "LifeCycle Tower - LCT ONE." (2012).

Tectonics in Architecture

New timber composites and structural systems have introduced new ways of designing strong and beautiful systems that can take on loads and shapes not previously imagined. For example, architects have could use the process of laminating timber together to create glulam components of any shape and size. At the Michael Smith Laboratories at the University of British Columbia, the architects used the properties of glulam to create a uniquely shaped timber that became the focus of the atrium.

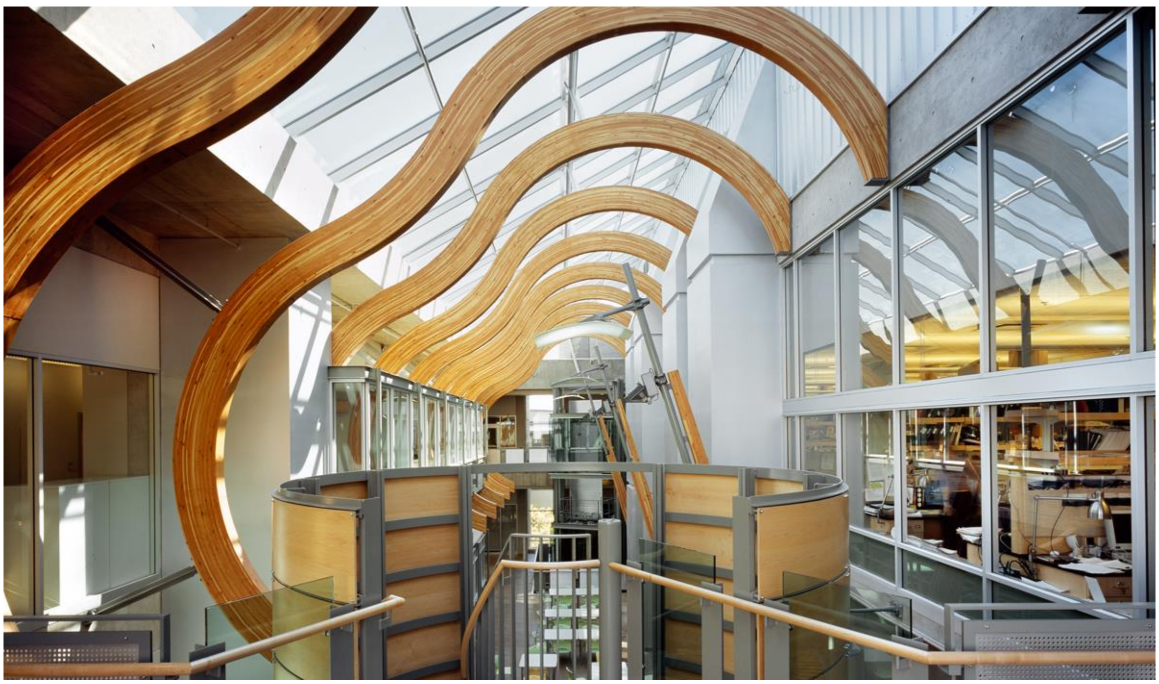


Figure 195, Atrium of the Michael Smith Laboratories Building at UBC. Henriquez Partners Architects

In *Informal* by Cecil Balmond, more innovative and dynamic ways of designing structure in architecture are discussed. He explored ways of breaking free from the rectilinear framework of traditional structural elements, using the Kunsthal, a museum in the Netherlands, as an example. He begins by asking why structure needs to be spaced out equally. Why not let the informal into the design of the structure? Balmond breaks his ideas down into four proposals that are visible in the building. They are brace, slip, frame and juxtaposition.

Brace is concerned with a series of diagonals that run between two parallel lines. Instead of repeating the same pattern, why not stagger the diagonals around the cross section of the structure? Curves can also be introduced as structural elements, and in some cases, they may be even more efficient than columns and beams.

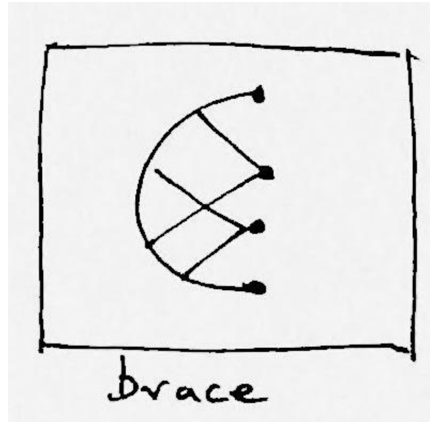


Figure 196, Brace. Cecil Balmond

The next category was slip. Slip is taking a repeating array of elements, such as a grid, and "slipping" them past each other. Because structural systems are over engineered, they have a bit of play in them, which means columns and beams can be moved around or removed while still maintaining the integrity of the whole.

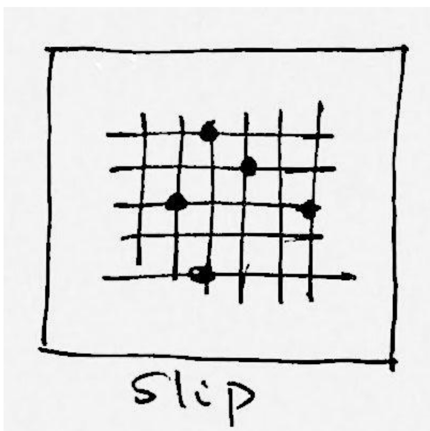


Figure 198, Slip. Cecil Balmond

Balmond uses slanting columns to describe frame. When a column leans, a force has to be exerted on it to prevent it from falling over. When it is a whole series of columns, an even bigger force is needed to prevent collapse. This force can be counteracted by using a sloped floor or roof to stabilize the structure.

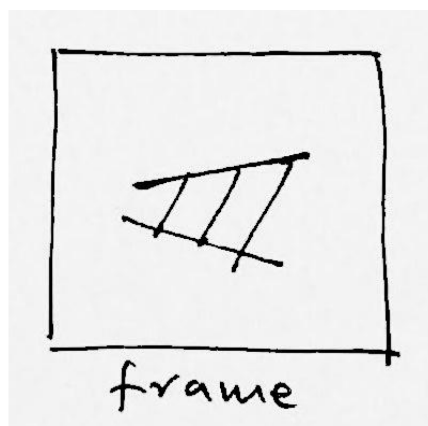


Figure 197, Frame. Cecil Balmond

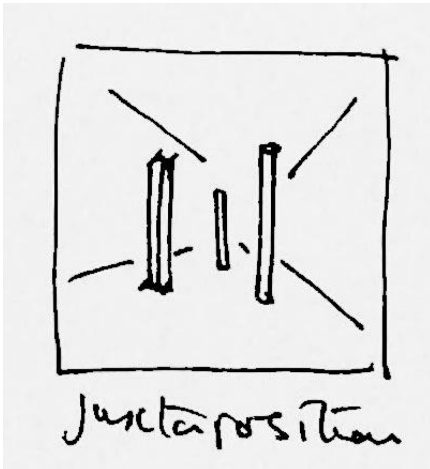


Figure 199, Juxtaposition. Cecil Balmond

The last type of shift is juxtaposition. A change in material, form, or position in a repeating series can create a juxtaposition that creates a "disturbance," adding drama to an area that would otherwise blend in with the rest of the structure.

For any of Balmond's proposals, the first step is exposing the structure. Many older academic buildings are very monolithic structures, with many uniform exterior and interior partitions, with little expression of the structure. This results in buildings that are monotonous and plain. They are not exciting buildings to work or learn in, and no one looks forward to spending their time in them. When the structure is exposed, the four proposals above can be implemented in various ways, creating unique and special moments for visitors as they move throughout the space. James Kunstler, a critic of suburban sprawl, brought up the idea of creating spaces that are worth caring about.[54] He was referring to urban design in his lecture, but the same idea applies to architecture. An architect can design a building in a way that they think is successful, but in the end, it is ultimately the public that decides if it a place worth caring about. Exposing structure and designing unique moments into the design is one way to create interesting spaces that will bring people back.

A recent example on the University of Massachusetts, Amherst campus is the Integrated Science Building. Designed by Payette, a multistory atrium with several bamboo-clad "tree houses", contrast with exposed aluminum and steel structural framing,

[54] Kunstler, James Howard. "The Ghastly Tragedy of the Suburbs." TED 2004. California, Monterey. 2016. Lecture.

creating an exciting atmosphere for people walking though the building, or students studying in the public spaces.

Figure 200, UMass Integrated Sciences Building – Multistory atrium with exposed steel framing. Warren Jagger

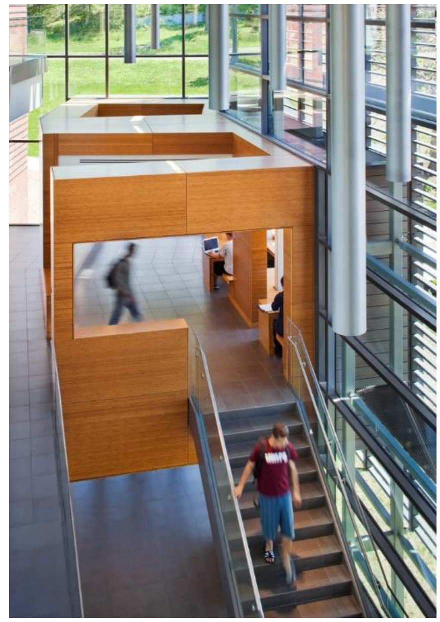


Figure 201, UMass Integrated Sciences Building – bamboo "tree house". Warren Jagger

APPENDIX B

WOOD PROPERTIES

All buildings are constructed using materials. Which materials are chosen largely depends on the use in the building, price, aesthetic value, etc. In the context of this thesis, material choice is explored through the view of the material's impression and aesthetic value on the user, and the environmental impact of the material. The materials investigated in this section will include organic materials, such as wood, and mined materials, such as rock and metals. Other composite materials, such as masonry and concrete will also be explored, due to their earth-like qualities.

Types of Wood

Trees can be classified into two groups: gymnosperms, and angiosperms. Gymnosperms include trees that produce softwood, which are typically known as conifers in North America. Angiosperms include trees that produce hardwood lumber, and are mostly deciduous trees (broadleaf), meaning they drop their leaves in the fall.[55] Typical hardwoods and softwoods are listed below.

Gymnosperms (Softwoods)

- Southern Yellow Pine
- Douglas-fir
- Western Hemlock
- Eastern Spruce
- Eastern White Pine
- Western Red Cedar

Angiosperms (Hardwoods)

- White Oak
- Yellow Birch
- Black Walnut
- Black Cherry
- Bamboo
- Basswood

[55] Hoadley, R. Bruce. Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown, CT: The Taunton Press, 2000.

The general classification of hardwood and softwood can't be used to compare the material properties against each other. A good indicator of strength is its density, which is shown for a variety of wood types below.

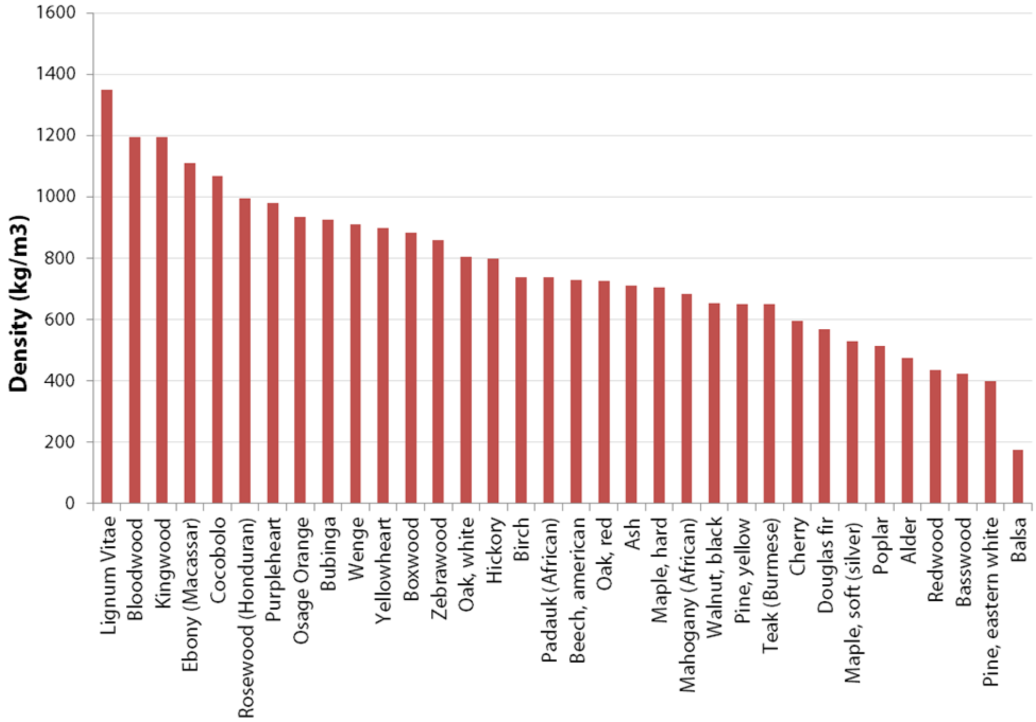


Figure 202, Density of different types of wood.

Denser woods are stronger, but are harder to work by hand. This is the reason basswood and balsa wood are common model-making materials, while a hardwood floor might be made of oak. Tree growth typically reaches its peak in the spring, when the air is cool and groundwater is plentiful (springwood). Growth slows down in the summer when the heat rises and water supply drops (summerwood / latewood).[56] A tree that is continually subjected to cool, moist conditions will grow faster than a tree in a warm, dryer condition, but its wood will not be as strong. When a cut is made in a piece of lumber, a softwood will typically have a course and uniform grain structure, while a

[56] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

softwood will show patterns of rays and vessels.[56] Certified wood comes from forests that are managed for their long term sustainability and economic viability.[57] The most prevalent certification program is the Forest Stewardship Council (FSC). It is also important for the chain of custody between forest and the final user to be monitored, so that the product is not combined with other non-FSC certified products, or swap out with non-certified products.

Indoor Air Quality

All building products off-gas, or release chemicals in the form of a gas. While some materials give off more toxic materials than others, the lower the amount of off-gassing, the healthier the interior environment will be. "Sealing buildings for energy efficiency and using off-gassing building materials containing urea-formaldehyde, vinyl, and other new plastic surfaces, new glues, and even wallpapers create toxic environments. These newly sealed environments were not refreshed with makeup air and resulted in the accumulation of both chemical and biologic pollutants and moisture leading to mold growth, representing new threats to both short-term and long-term health."[58] More stringent energy codes have pushed the limit of airtightness in buildings, so proper ventilation is essential for removing VOC's from inside buildings. Traditional pressed wood products, such as plywood, particleboard and MDF, off-gas formaldehyde, which can cause health problems such as eye and nose irritation, sore throat, watery eyes, blocked sinuses, runny nose, and sneezing.[59]

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[57] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.
[58] Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development. Healthy housing reference manual. Atlanta: US Department of Health and Human Services; 2006
[59] Australian Department of Health: National Industrial Chemicals Notification and Assessment Scheme. "Formaldehyde in pressed wood products safety FactSheet." April, 2016.

Wood structural panels and engineered wood products differ in their contribution to indoor air quality. "Large-scale chamber tests have shown that formaldehyde emission levels in wood structural panels are no higher than the levels found naturally in the environment."[60] This means that the use of engineered wood products such as glue-laminated timber (glulam), cross-laminated timber (CLT), LVL, LSL do not release chemicals into the air at any higher of a rate than natural conditions. This makes them perfectly suitable for buildings where indoor air quality is a major concern.

Wood is a hypoallergenic material, and its smooth surfaces mean it's harder for particles to build up on it, as opposed to softer materials like fabric. Just as materials acting as a thermal mass can moderate temperature by absorbing heat, wood can moderate humidity by absorbing or release moisture into the air.[60]

Acoustical Properties

Since wood is not as dense as concrete or steel, less sound is transmitted through the material due to direct striking, and the softer surface can absorb more sound as well. Strategies such as insulated staggered-stud walls or double-stud walls allow high (sound transmission class) STC values to be achieved while keeping the construction simple and affordable. The below table lists STC for bare CLT walls and floors, for different thicknesses.

Number of Layers	Thickness in.	Assembly Type	STC	IIC
3	3.74-4.53	Wall	32-34	NA
5	5.31	Floor	39	23
5	5.75	Floor	39	24

Table 4, Sound insulation performance of bare CLT floors and walls. CLT Handbook

60 rethink Wood. "Wood and Indoor Environment." (July 2015).

Section 1207 of the 2015 International Building Code specifies the minimum sound insulation requirements for common interior walls, partitions and floor/ceiling assemblies between adjacent dwelling units and sleeping units or between dwelling units and sleeping units and adjacent public areas such as halls, corridors, stairways or service areas.

Assembly Type	Airborne Sound		Structure-borne Sound	
Wall	STC	50	NA	
	FSTC	45 (field measured)		
Floor	STC	50	IIC	50
	F STC	45 (field measured)	FIIC	45 (field measured)

Table 5, IBC minimum requirements for sound insulation for assemblies. 2015 IBC

Unless a CLT panel is very thick (more than seven layers), extra layers must be added to the panel to meet sound insulation requirements. Some examples of wall and floor systems are described below, which meet the STC and IIC rating of 50.[61]

CLT Wall Assembly: 3-ply CLT panel with mineral wool gap.

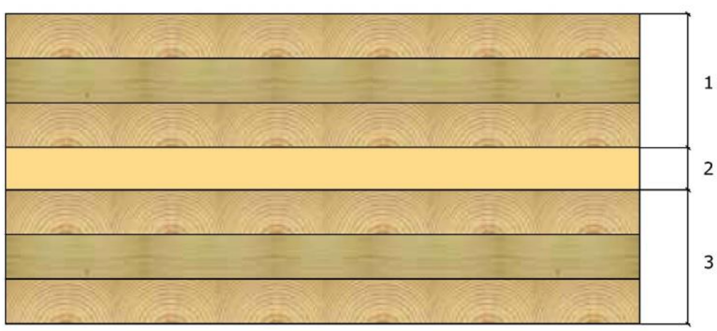

Figure 203, 3-ply CLT panel with mineral wool gap. CLT Handbook

Assembly Description from Top to Bottom	STC
1. 3-layer CLT panel of 3 3/4 in. ~ 4 1/2 in. (95 mm ~ 115 mm) 2. Mineral wool of about 1.18 in. (~ 30 mm) 3. 3-layer CLT panel of 3 3/4 in. ~ 4 1/2 in. (95 mm ~ 115 mm)	48 - 50

Table 6, 3-ply CLT panel with mineral wool gap. CLT Handbook

[61] Douglas, Brad, and Erol Karacabeyli. CLT Handbook: Cross-Laminated Timber. Pointe-Claire, QC: FPInnovations & Binational Softwood Lumber Council, 2013.

CLT Wall Assembly: 3-ply CLT panel with 2 in. x 3 in. studs/mineral wool gypsum board.

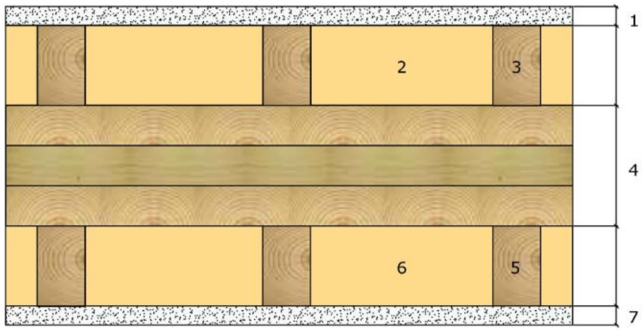

Figure 204, 3-ply CLT panel with studs/mineral wool gypsum board. CLT Handbook

Assembly Description from Top to Bottom	STC
1. Gypsum board of 5/8 in. (15 mm) 2. Mineral wool of about 2.36 in. (~ 60 mm) 3. Lumber studs of 2 in. x 3 in. (38 mm x 63 mm) at least 16 in. (400 mm) o.c. 4. 3-layer CLT panel of 3 3/4 in. ~ 4 1/2 in. (95 mm ~ 115 mm) 5. Mineral wool of about 2.36 in. (~ 60 mm) 6. Lumber studs of 2 in. x 3 in. (38 mm x 63 mm) at least 16 in. (400 mm) o.c., 7. attached to CLT and gypsum boards 8. Gypsum board of 5/8 in. (15 mm)	58 or above depending on CLT thickness

Table 7, 3-ply CLT panel with studs/mineral wool gypsum board. CLT Handbook

CLT Floor Assembly: 5-ply CLT panel with acoustic infill and concrete topping.

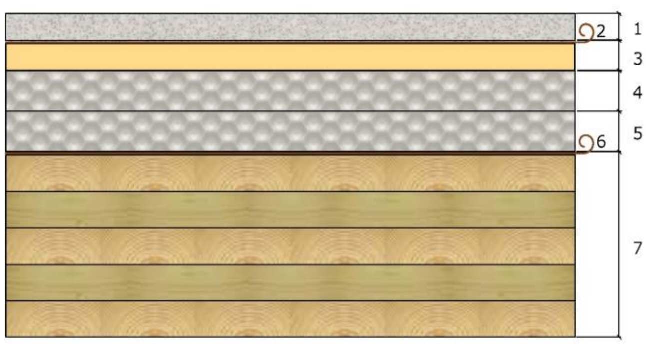

Figure 205, 5-ply CLT panel with acoustic infill and concrete topping. CLT Handbook

Assembly Description from Top to Bottom	STC	IIC
1. Prefabricated concrete topping of 0.79 in. (20 mm) 2. Kraft paper underlayment 3. Subfloor ISOVER EP2 of 1 in. (25 mm) 4. Honeycomb acoustic infill FERMACELL of 1.18 in. (30 mm) 5. Honeycomb acoustic infill FERMACELL of 1.18 in. (30 mm) 6. Kraft paper underlayment 7. 5-layer CLT panel of 5 5/16 in. (135 mm)	64	60

Table 8, 5-ply CLT panel with acoustic infill and concrete topping. CLT Handbook

Adhesives

Just as important as the wood is the adhesive that hold the composite together. In a study at the Lulea University of Technology in Sweden, it was found that the shear strength of the adhesives was lower in colder temperatures, and the strength of each adhesive varied considerably at temperatures lower than -20°C.[62] Some of the adhesives (PUR) experienced a gradual decrease in shear strength as temperature decreased, while others saw greater variability (EPI, MUF1).

The progression in the wood products industry means that VOCs and off-gassing are lower than they've ever been. As discussed previously, the formaldehyde emission levels in structural wood panels was found to be no higher than what is found naturally in nature. In today's construction market, and influence from the U.S. Green Building Council and Living Building Challenge, many designers and consumers are looking for products that are petroleum-free. LEED is updating their emphasis on product life cycle, and will be adding Environmental Product Disclosure, a new certification which requires manufactures to list information about the materials in their products.[63] The Living Building Challenge already has a similar certification, known as the "Red List". These are materials that are prohibited to be used in the construction of a Living Building, and are on the list because they either pollute the environment, bio-accumulate up the food chain until reaching toxics levels, or harm construction or factory workers.

In a research study looking at more sustainable binder options for wood composites, engineered biopolymers were found to be compatible with existing resin

[62] Wang, Xiaodong, et al. "Impact of Cold Temperatures on the Shear Strength of Norway Spruce Joints Glued with Different Adhesives." European Journal of Wood and Wood Products 73.2 (2015): 225-33.

[63] Tseitlin, Alexander, et al. "Advancement in Sustainable Resin Binders for Wood Composites using Engineered Bio-Polymers." 68th International Convention Forest Products Society. Québec City, Canada, August 2014.

technologies, with substitution levels between 10 and 90 percent. The mechanical properties of the wood composites are met or exceeded with the engineered biopolymers, and the carbon footprint is reduced by 33 percent on a chemical comparison.

APPENDIX C

TIMBER PRECEDENTS

Earth Sciences Building - Perkins + Will

The Earth Sciences Building at the University of British Columbia is a 170,000 square-foot, five-story building that holds the departments of atmospheric sciences, statistics, and the pacific institute of mathematical sciences. Designed by Perkins + Will and engineered by Equilibrium Consulting, it was the largest panelized wood structure in North America at its completion in 2012.

Figure 206, Exposed mass timber structure during construction. Credit

One of the main focal points of this building is the free-floating five-story stair in the main atrium (figure 207). The stairs have three cantilevered scissor runs that required some complex engineering to be solved. CLT was first considered for both the stair runs and the landings, but due to high torsional and shear forces at the landing, this material was not going to handle the forces.[64] Concrete or steel would have been able to handle these forces, but the stair was envisioned in wood from the beginning.

[64] Karsh, Eric; Gafner, Bernhard. "The Flying Stair at the University of British Columbia's Earth Sciences Building," Internationales Holzbau-Forum 2012

Figure 207, UBC free-floating stair. Martin Tessler

Glulam was selected for the stair landings due to its higher stiffness. The HSK-System (Holz-Stahl-Komposit-System) was used to connect the glued edge laminated panel runs to the glulam landings. In the figure to the right, a stair run and landing is being connected, with the steel HSK plates sliding into the slots cut into the timber panels. After the segments are lined up, epoxy is pumped between the plates and the wood. After drying, it forms an incredibly strong bond.

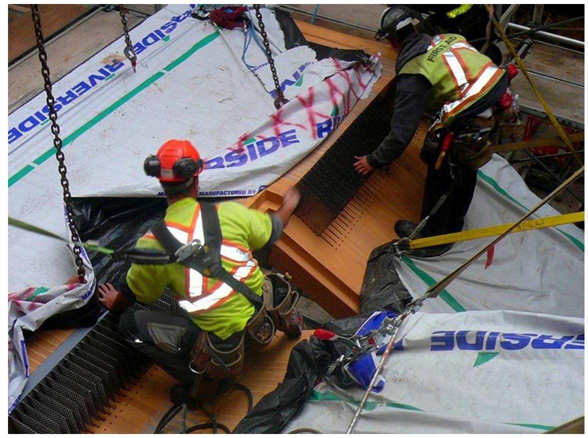

Figure 208, Stair assembly with HSK plates visible. Equilibrium Consulting

The composite system used for the floor is another interesting aspect of this building. The floor is constructed using the HBV-System (Holz-Beton-Verbund System), which combines wood and concrete. "The composite floor system in the ESB construction consists of 89 mm thick LSL panels topped with foamed board insulation and 100 mm of reinforced concrete. The composite action is achieved by securing perforated steel HBV-shear connectors into slots cut into the face of the wood panels. These plates extend past the layer of the insulation to support the reinforcing bars for the concrete topping."[65] This system is 50% lighter than concrete, which allows for

Figure 209, Wood-concrete composite floor undergoing testing. Equilibrium Consulting

[65] "Innovating with Wood, A Case Study Showcasing Four Demonstration Projects." Canadian Wood Council, Mar. 2012. Web. 5 Mar. 2016.

longer spans. LSL was chosen over CLT because of its availability in the Canadian market.

At the time of design and construction, the British Columbia building code did not allow for an all heavy-timber framed building. To work around this problem, the building was fitted with sprinklers, the timbers were engineered to account for the loss of strength during a fire, and the steel connections between the timbers were concealed within the members, to limit their exposure to fire. In addition, "a fire retardant coating was applied where necessary to alter the surface burning characteristics of the interior wood finishes to more closely meet the standard required in a noncombustible building."[66] As described earlier in this thesis, new tests have demonstrated that certain unprotected mass timber system can surpass a two-hour fire rating. This demonstrates the rapid progression that the mass timber building industry is making.

UMass Design Building - Leers Weinzapfel Associates

Completed in 2017, the UMass Design Building will be the first mass timber building of its size in the United States. Designed by Leers Weinzapfel Associates, the 87,000 square-foot building will house the architecture, landscape architecture, and building and construction technology programs. This building is the first in the US to utilize a wood-concrete composite floor system. A typical floor has a five-ply CLT panel, with an inch of rigid

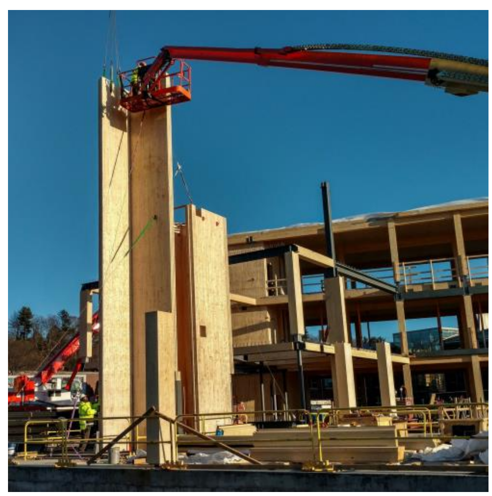

Figure 210, Assembly of CLT shaft walls. Alex Schreyer

[66] "Innovating with Wood, A Case Study Showcasing Four Demonstration Projects." Canadian Wood Council, Mar. 2012. Web. 5 Mar. 2016

insulation above, topped off by four inches of cast-in-place concrete. This type of composite was found to have excellent sound absorption quality at the Earth Sciences Building. The Design Building also uses CLT panels for the stair and elevator shaft walls, which was admitted by code with a double layer of gypsum board wrapping the shafts. The connection between the wood and the concrete is known as HBV. A perforated steel plate is glued into slots cut in the wood, while concrete poured on the wood surface cures around the other side of the steel plate, forming a composite with exceptional strength and stiffness, with a lower weight than an equivalent concrete section. The concrete slab experiences compression, while the wood experiences tension.

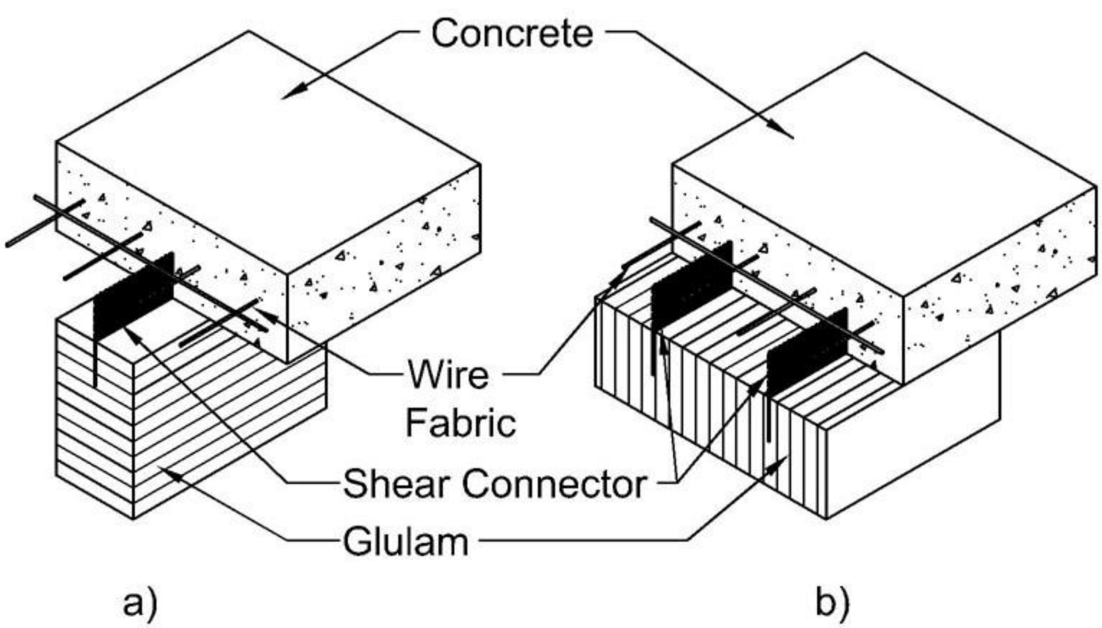

Figure 211, HBV System. UMass BCT

Alongside the HBV system is the HSK system which was used in the construction of the atrium stair in the Earth Sciences Building at the University of British Columbia. The HBV system uses the same type of metal plate, but to connect metal to wood. The perforated steel plates are wielded to a metal structural member, and the plates slide into slots cut into the wood. The space is filled with an epoxy to form a strong connection. This type of connection can be seen at the UMass Design Building where the CLT shaft walls sit on the concrete floor slab. In the photo below, exposed slots in the wood can be seen above and below the steel plate. This is where the perforated steel plates slid into, forming the wood-steel composite adhesive system (HSK).

Figure 4: Steel plate bolted to concrete. Alex Schreyer

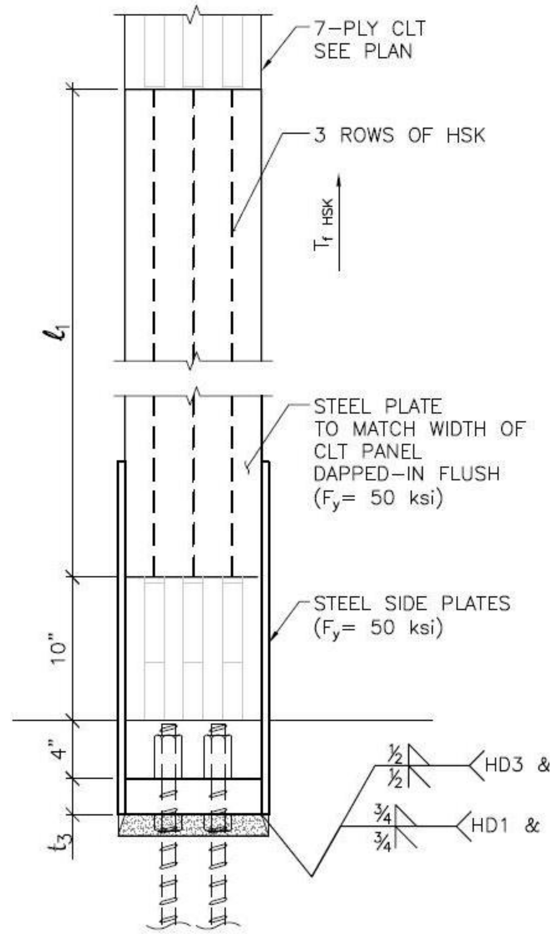

Figure 5: Section showing plate with HSK-System. Leers Weinzapfel Associates

Other features of the Design Building are the wooden zipper trusses that hold up the roof terrace above the main atrium, and the exposed wooden columns, beams, floor deck and mechanical equipment in the studio spaces showcases the beauty of the wood.

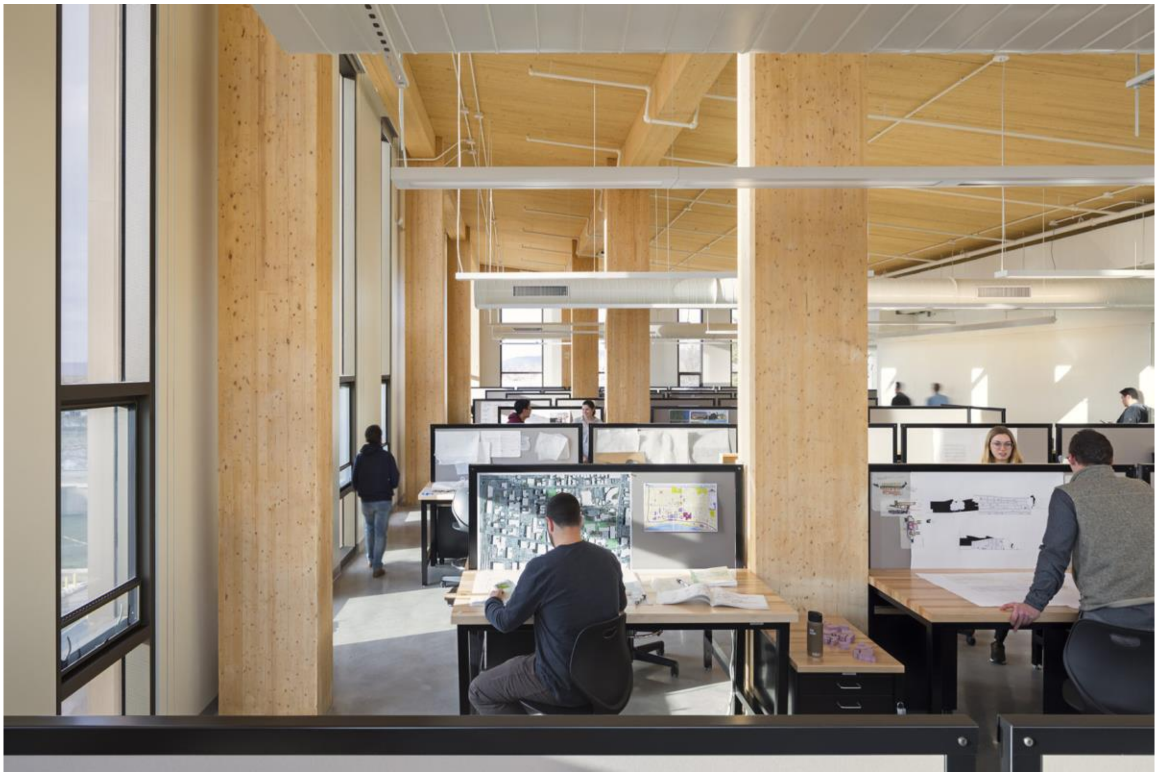

Figure 212, Exposed timber in the studio spaces. Leers Weinzapfel Associates

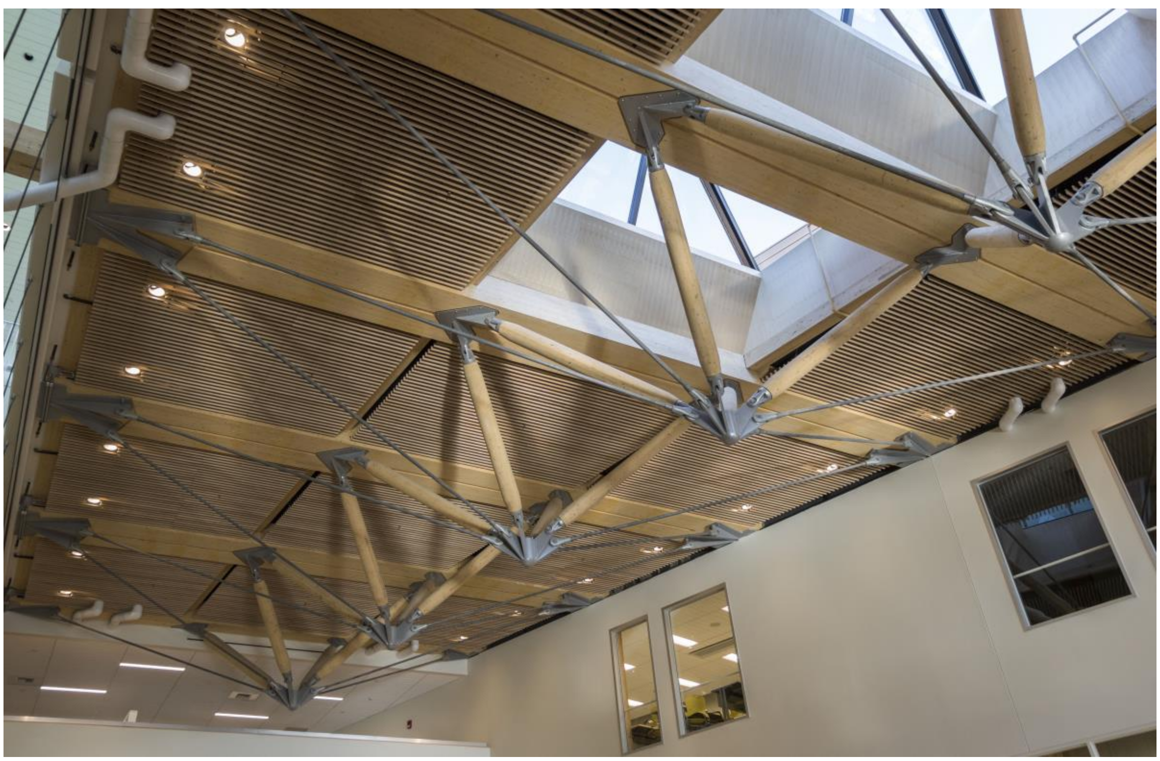

Figure 213, Zipper truss in the atrium. Dylan Brown

<u>Centre for Interactive Research on Sustainability - Perkins + Will</u>

The Centre for Interactive Research on Sustainability (CIRS) is located at the University of British Columbia in Vancouver. It was designed to be the most sustainable building in North America, by utilizing passive design strategies, and energy demand reduction. The building also reaches 100% natural daylight and ventilation for all occupants. CIRS is LEED Platinum Certified and is targeting the Living Building Challenge. The building is also net positive in energy, water, strucural carbon and operational carbon.

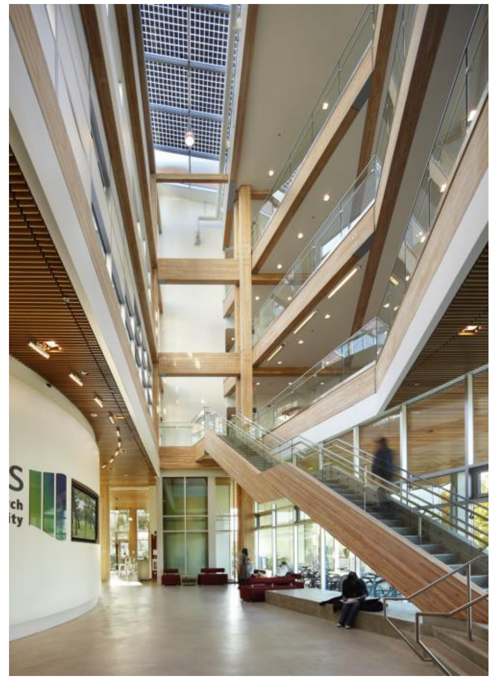

Figure 214, Four-story atrium showcasing the exposed timber structure. Martin Tessler

A living roof occupies the auditorium roof, and a a rainwater collection system provides more than enough water to last the year. The building's U-shaped footprint allows for maximum daylight penetration, and the strucural system is expressed throughout the building.

Figure 215, second level courtyard with living roof. Martin Tessler

Figure 216, Exposed timber beams and floor panels. Martin Tessler

Figure 217, Photovoltaic cells integrated into skylights provide an attractive, yet functional system. Martin Tessler

Figure 218, The day-lit auditorium uses glulam arches as an alternate to steel beams or trusses. Martin Tessler

APPENDIX D

MATERIAL GUIDE

Wood Composites

Wood composites take the structural properties of conventional solid-lumber members to new limits. Manufacturing waste and lower-grade trees can be incorporated into building products, while providing more consistent material properties and greater strength.[67] Conventional panel products such as plywood, OSB and particleboard have been around for more than 50 years, but new manufacturing technology and the need to develop stronger and more efficient products has seen the rise of laminated veneer lumber, glued laminated timber, I-joists, and cross-laminated timber.

Plywood

Plywood is a sheet material were an uneven number of layers are glued together in alternating directions. The thin layers, called plies, are usually composed of wood veneers.[67] The crossply construction method helps to create a more uniform strength across both sides of the board. Classification of plywood consists of exterior and interior grades, and softwood or hardwood plywood.

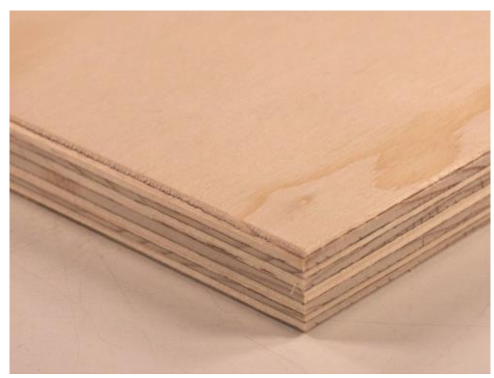

Figure 219, Plywood layer construction.

[67] Hoadley, R. Bruce. Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown, CT: The Taunton Press, 2000.

Advantages	Plywood panels are available in sizes greater than any natural board. The crossply construction method reduces the chances of splitting when being nailed at the edge, and makes it more resistant to warping, cracking and twisting.[68]
Disadvantages	Non-treated plywood is susceptible to water damage if left outside or in contact with water.

Oriented Strand Board (OSB)


Figure 220, OSB surface pattern.

OSB is manufactured by compressing layers of wood strands together with an adhesive. This construction technique ensures dimensional stability across both orientations, like plywood.

Advantages	The structural variations in the board are less than plywood. Delamination's or soft spots in the panels are non-existent.[68]
Disadvantages	OSB is more sensitive to moisture than plywood. When exposed to water, the edges of the panel swell more than the center. OSB is not recommended for use as a subfloor under tile.[68]

Particleboard


Figure 221, Particleboard cross-section.

Particleboard is formed by spraying wood particles with adhesive, forming them into a mat and compressing the mat between two heated plates.

[68] Fisette, Paul. "Choosing between Oriented Strandboard and Plywood." UMass Amherst: Building and Construction Technology (2005): 2016.

Advantages	The properties of particleboard are uniform across the whole surface. It is cheaper than plywood or OSB, so it is common for furniture or cabinetry where a veneer will be applied.
Disadvantages	Unless bonded with a more water-resistant resin, particleboard swells when in contact with water. It should not be used for exterior applications. Particleboard has lower structural properties than OSB, plywood or solid-wood boards, so more support must be used when it is put under a bending load.

Medium-Density Fiberboard (MDF)

MDF is a composite wood panel that is made of wood fibers and wood-fiber bundles that are bonded with synthetic resin. Typical applications include kitchen cabinets and furniture, where a veneer will be applied.

Figure 222, MDF boards.

Advantages	Compared to particleboard, it has a more uniform density through the panel, which means its edges can hold fasteners better.
Disadvantages	Low grade panels can swell and crumble when exposed to water, similar to particleboard. It is denser than OSB or plywood, which means a similar sized panel weighs more. The resins in the panel off-gas formaldehyde, a carcinogen.

Parallel Strand Lumber (PSL)

PSL is made of veneer scraps that are sprayed by a waterproof adhesive, and fed into a press, where the glue is microwave-cured under pressure.[69]

Figure 223, PSL beam.

[69] Hoadley, R. Bruce. Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown, CT: The Taunton Press, 2000.

Advantages	The composite nature of PSL allows for cross-section sizes and lengths greater than traditional dimensional lumber, as well as uniform strength and reliability.
Disadvantages	The surface of PSL is quite rough, and the density of the material is greater than the species it substitutes, due to the adhesives.

Laminated Strand Lumber (LSL)

Figure 224, LSL beams.

LSL is similar to OSB except for its shape. Thin strands from low-grade logs are bonded together by injecting steam into the resin. A typical production of LSL results in a billet that is 8 feet wide, up to 5 ½ inches thick, and 48 feet long.[70] The billet is then ripped into smaller sizes depending on the use. LSL is seeing an increased use as studs or columns in taller walls were conventional lumber is insufficient.

Advantages	Small-diameter trees that are not big enough for conventional sawn lumber products can be utilized for LSL production, reducing waste. The uniform material properties allow the billets to be cut down with little waste.[70]
Disadvantages	Is costlier than traditional solid wood studs.

[70] Hoadley, R. Bruce. Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown, CT: The Taunton Press, 2000.

Laminated Veneer Lumber (LVL)

LVL is manufactured by joining veneers of Douglas-fir or southern yellow pine together. An adhesive bonds the veneers together under heat and pressure.[70]

Figure 225, LVL timber.

Advantages	LVL has higher uniform properties than solid-sawn lumber of similar dimensions, and much longer lengths are available.
Disadvantages	More expensive than solid-wood studs of a similar size.

Glued Laminated Timber (Glulam)

Glulam is composed of two or more layers of dimensional lumber laminated together with moisture-resistant structural adhesives. This process allows any desired size to be laminated, up to the size of the machinery that can transport it to the site. Wood can also be laminated into non-natural shapes; such as curves or arches. During production, the quality of the wood that is going into each timber is closely monitored, and the strongest wood-type can be placed where the member will experience the most stress. At larger sizes, solid timbers are simply not available, or do not meet the required structural properties as compared to glulam.[71]

Figure 226, End of glulam beam.

[71] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Advantages	Structural members can be larger and longer than the source tree, and the beams can be designed to handle specific amounts of stress while under load. Glulam has a greater aesthetic appeal than most composite lumber products, which makes it desirable to use for exposed structural members.[72]
Disadvantages	More expensive than similar sized solid lumber members.

I-Joists

Figure 227, I-joist size options.

In a typical I-joist, a dimensional lumber flange is held between a web of plywood or OSB. This system replaces the traditional dimensional lumber used in floor joists for light-frame construction[73]. The I-joist is able to span greater distances than solid lumber of similar size due to its efficient use of material.

Advantages	The greater depths of I-joists allow larger spans than conventional lumber would allow. The joist weighs less than a member of solid lumber of the same size.
Disadvantages	More expensive than similar sized solid lumber members.

Cross-Laminated Timber (CLT)


Figure 228, CLT panel.

CLT is composed of several layers of lumber boards stacked crosswise and glued together on their wide faces.[73] Typical manufacturing widths are 2 feet, 4 feet, 8 feet and 10 feet, with panel lengths restricted by transportation limitations.

[72] Hoadley, R. Bruce. Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown, CT: The Taunton Press, 2000.
[73] Douglas, Brad, and Erol Karacabeyli. CLT Handbook: Cross-Laminated Timber. Pointe-Claire, QC: FPInnovations & Binational Softwood Lumber Council, 2013.

Advantages	CLT is quickly becoming an alternate to concrete and steel, with similar structural properties, and a much smaller carbon footprint. CLT can be used in pre-fabrication to replace traditionally-framed wooden structures, requiring less manpower and a shorter construction time.
Disadvantages	Its relative short life span in the building industry means that many building codes haven't adapted yet to the new material.

Phenolic Wood

Figure 229, Phenolic wood panel.

Phenolic wood panels are produced by immersing paper reinforced with cellulose fibers in a thermosetting resin, and subjecting it to high temperatures and pressures. The panels resist scratches, impacts and stains well, and has a standard class-B fire rating.

Advantages	Are very durable and weather resistant. Their constrictive nature means they can be made in almost any color or finish desired.
Disadvantages	Long-term performance, specifically UV degradation and durability is still unknown.

Wood-Plastic Composites

Figure 230, WPC decking.

Wood-plastic composites (WPC) are made from wood fibers and various types of plastics that are mixed with other ingredients, such as ultraviolet stabilizers, pigments, lubricants or biocides.[74] The products are shaped into their final form by being heated and pressed, extruded, or injection molded. The material uses rapidly renewable or waste materials in its production, and some even uses recycled content.[74] WPCs are usually used for exterior decking or railings.

Advantages	WPCs have more consistent material qualities, and are largely free from defects. They also have superior moisture resistance, and lower maintenance. Sizes are available to match conventional solid wood decking.
Disadvantages	WPC expands and contracts more with changes in temperature, so the installation has to account for the thermal movement. The plastics added into the board reduce the stiffness of the lumber, which means more supportive members must be used to hold the PWC lumber.

Metals, Masonry, Stone and Concrete

Centuries ago, masonry played a much bigger role in construction than it does now. Back then, it served as a structural material, which limited the height of buildings. Iron and steel quickly phased brick out as a structural material, and today it is often used as a finish for facades, wrapping around columns, or landscaping paths and steps. Bricks are held together with mortar, which is composed of portland cement, hydrated lime, sand and water. Portland cement is the bonding agent, while the lime improves workability, and water aids in the curing of the lime and cement.

Unlike large concrete or steel elements, bricks can easily be manipulated, and are similar in dimensions to the human hand. Bricks are formed by extracting clay and shale from open pits, crushing and screening the material to an even consistency, and then

[74] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

tempering it with water, to produce a clay.[75] Bricks can be molded by pressing the clay into a mold, or extruding through a die into a rectangular column, where a wire automatically cuts the material into bricks. The bricks are then dried for one to two days in a low-temperature kiln. The bricks then go into a higher temperature kiln, where the bricks are dehydrated and turned into a ceramic material when exposed to temperatures between 1800°F to 2400°F.

The raw materials for bricks are found abundantly on earth, but the Portland cement and lime used in the mortar are energy-intensive products to make. Little waste is produces in brick production, since leftover clay can be recycled back into the production process. Brick masonry is a durable form of construction that requires relatively little maintenance and can last a very long time.[75] When a building is demolished that used bricks, still intact bricks can be cleaned of mortar and reused. Brick is also an effective thermal mass, due to its high density.

In addition to brick, stone is a common natural building material that has been around since the inception of the earth. Stone is usually quarried out of the earth, and shaped down to size. It is geologically classified into three categories. Igneous rock, that was deposited in a molten state. Sedimentary rock was deposited by the action of the water and wind. Metamorphic rock was formerly igneous or sedimentary rock, but was transformed by heat and pressure.[75] In the construction industry, ASTM C119 classifies stone into six groups: granite, limestone, quartz-based, slate, marble, and other.

[75] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Granite


Figure 231, Rough granite.

Granite is the most common quarried igneous rock in North America. Crystals form a mosaic pattern, and it is available in an array of colors including gray, black, pink, red, brown and green.[76] Its surface can be polished smooth, or left coarse.

Advantages	Granite is hard, strong, durable and nonporous. It is one of the toughest types of stones. It is desirably in places where it will touch the ground, or be exposed to extreme weathering.
Disadvantages	Is more expensive than other stones due to its density, which affects transportation costs and difficulty cutting.

Limestone

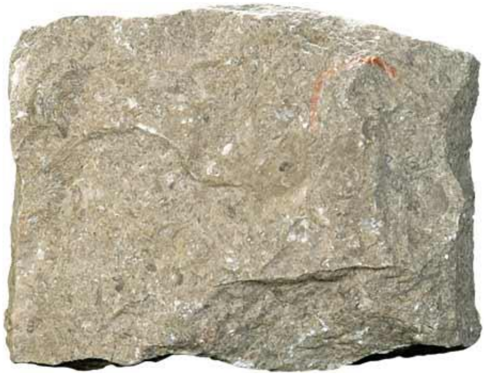
Figure 232, Limestone

Limestone is one of the two main sedimentary rock types used in construction. In the United States, Missouri and Indiana are major producers of limestone, in addition to France, Germany, Italy, Spain, Portugal and Croatia. Limestone is composed of calcium carbonate or a combination of calcium and magnesium carbonates. Both were formed from the remains of skeletons or shells of marine life. Colors range from white through gray and buff to red. When quarried, limestone contains groundwater and is porous, but over time, the water evaporates and the rock becomes harder.[76]

Advantages	It is readily available, and easy to cut or carve.
Disadvantages	It is the weakest type of building stone, and very heavy. Acid rain and other pollutants can accelerate the deterioration of the stone.

Quartz-Based Stone

Sandstone is also a sedimentary rock type formed from deposits of quartz sand. Color and physical properties can vary greatly depending on the cementing material that holds the rock together. In the U.S., sandstone is mainly quarried in New York, Ohio and Pennsylvania. Familiar forms of sandstone include brownstone and bluestone.

Figure 233, Sandstone layering.

Advantages	Is highly suitable for paving and wall copings.[76] Quartzite, which was originally sandstone, is harder than granite, and more resistant to chemical weathering.
Disadvantages	Cannot be highly polished.

[76] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Slate


Figure 234, Slate roof tiles.

Slate is a dense, hard stone formed from clay. The rock has closely spaced planes of cleavage, which makes it easy to split into sheets for use as paving stones or roof shingles.[77] Slate is commonly quarried from Vermont, Virginia, New York, Pennsylvania and parts of Canada. Colors include black, gray, purple, blue, green and red.

Advantages	Can be split into thin sheets. It is an excellent roofing material due to its waterproof properties and durability. Compared to conventional roofing materials, slate has the lowest embodied energy.
Disadvantages	For roofing, they're more expansive than other materials, weigh more, and need to be installed correctly if the system is going to last.

Marble

Marble is a recrystallized form of limestone that is easily carved and polished. It is available in almost every color, displaying beautiful veining patterns. In North America, marble comes from Alabama, Tennessee, Vermont, Georgia, Missouri and Canada.


Figure 235, Marble surface pattern.

Advantages	Can be highly polished.
Disadvantages	Long exposure to marble dust is known to cause health problems.

[77] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Other


Figure 236, Travertine surface pattern.

The last group includes less commonly used stones, such as travertine, alabaster, greenstone, serpentine and soapstone. Travertine is a form a limestone deposited by ancient mineral springs.[78]

Metals

The use of metal as a mass building material grew rapidly with the introduction of the Bessemer process in 1855, which burned out the impurities in iron, producing steel. The amount of carbon contained in an allow greatly affects its strength and how brittle or malleable the metal is. In the steel production process, iron ore is mined from the earth and then fed into a blast furnace. The furnace combines the iron ore, coke, and crushed limestone. The coke is burned by large amounts of air forced into the bottom of the furnace, where the oxygen helps to lower the carbon content of the iron. The limestone forms a slag with impurities in the ore, which then flows out of the furnace at the bottom, where the iron and slag are separated.

In the production of steel, the molten iron is combined with oxygen, where even more carbon and impurities are removed, producing steel. In the production of wide-flange beams, hot steel ingots are fed through a series of machines that progressively shapes the edges of the material to form the familiar I-shaped profile. Producing steel from iron ore is a very energy intensive process, and one ton of steel produces an average of two tons of CO2.[78]

[78] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Steel


Figure 237, Mild steel used for structural members.

Steel is any range of alloys of iron that contain less than two percent carbon. Steel used for structural purposes is called mild steel, and contains less than .3 percent of carbon, with small amounts of manganese, silicon, phosphorus, sulfur, oxygen and nitrogen.

Advantages	High tensile and compressive strength. Thinner structural members can be make compared to other metals, at a lower cost, due to its high strength.
Disadvantages	High embodied energy. Is not corrosive resistant on its own – stainless steel is more expensive to manufacture.

Aluminum


Figure 238, Aluminum cladding.

Unlike steel, which is an alloy, aluminum is its own periodic element, although alloys can be made from aluminum. It is rare to find the metal in its pure state in the environment because of how chemically reactive the material is. Like iron, ores containing aluminum, such as bauxite, are refined to produce aluminum oxide. This is then purified to produce aluminum. Aluminum's low density and corrosion resistant nature make it an ideal material for curtain wall mullions and cladding systems.[79] Aluminum can easily be extruded to form a variety of shapes.

[79] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Advantages	Aluminum has a low density and is resistant to corrosion. It is the third most abundant element in earth's crust, behind silicon and oxygen.
Disadvantages	It is more expensive than steel, and due to its lower density, is not as strong. It does not bend as much as steel, meaning it is more prone to breaking under stress.

Copper

Copper is a soft, malleable metal with a high thermal and electrical conductivity. Copper's durability and corrosive resistant nature make it an ideal material for roofs, roof flashings, cladding, and plumbing pipes and fixtures. Copper has a red-orange metallic appearance, but under prolonged exposure to air or seawater, the metal will oxidize, forming a layer of verdigris, giving the metal its green color.

Figure 239, Copper plumbing pipe.

Advantages	Highly durable and corrosion resistant, yet can be worked easily due to its high malleability. Copper also has a lower thermal expansion rate, which means it shrinks and expands less than other metals.
Disadvantages	Has a higher initial cost than other metals.

Zinc


Figure 240, Zinc standing seam roofing.

Zinc is the fourth most commonly used metal in use, and the majority is mined in the form of ore in China, Australia and Peru. It is highly malleable, and in architectural applications, most of the material is coming from recycled sources. When other metals are galvanized, they are coated with a layer of zinc, which forms a tough outer layer that protects the metal underneath from corrosion.

Advantages	Is highly malleable. Can take a beating without being punctured. In architectural uses, its high recycled content makes it a good choice for building trying to achieve LEED certification.
Disadvantages	Cannot be used for structural purposes.

Concrete

Besides for water, concrete is the most widely used material on earth.[80] Cured concrete forms a rock-like material that is produced by mixing coarse and fine aggregates, Portland cement and water. During the curing process, water reacts with the cement to form strong crystals that bind the aggregates together. Hydrations occurs during this process, meaning that heat is given off as water evaporates out of the mixture. In its initial phase, its liquid nature enables it to be poured or cast into any shape imaginable, and is used in everything from slabs and foundations, walls, cladding

[80] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

systems, structural systems, paving systems, and more. The strength of concrete was truly realized with the introduction of steel rebar to add tensile strength. The structural and flexibility of concrete comes with its drawbacks. The production of portland cement releases huge amounts of carbon dioxide into the atmosphere.

Cast-In-Place Concrete

Concrete that is cast on-site allows designers unlimited possibilities in the form the concrete will take.[81] Formwork enables shapes to be cast that are otherwise too large to precast, or too irregular. Cast-in-place is regularly used for footings, foundations, slab on grade, or slab toppings over floor or roof decks. The selection of the formwork can control the texture that is left on the concrete after the forms are removed.

Figure 241, Cast-in-place concrete footing. Dylan Brown

Advantages	Can be formed into any shape, while creating continuity between all parts of the cast concrete. Different types of concrete and the use of reinforcing bar allow the forms to handle large amounts of force that other structural systems cannot handle.
Disadvantages	Is one of the heaviest types of construction. Cast-on-site buildings are slower to build than buildings using precast elements, because formwork has to be built, the concrete poured, and then time has to pass for it to cure. It is also exposed to the temperature and weather of the site, which may not be in favor of pouring concrete.

[81] Allen, Edward, and Joseph Iano. Fundamentals of Building Construction: Materials & Methods. Fifth ed. New Jersey: John Wiley & Sons, 2009.

Precast Concrete


Figure 242, Precast concrete stair runs.

Precast concrete elements are cast and cured in factories, transported to the construction site, and then assembled together. Factories offer higher quality control, protection from the elements, and quicker production runs due to a higher level of automation. Since the forms used for precast elements can be reused many times, the unit price per precast element is lower. Higher strength concrete and steel are typically used in precast elements, while the steel can be pretension in the factory, producing larger spans with a more efficient use of concrete.

Advantages	Factories enable higher quality control and protection from the elements during casting. Units can be more structural efficient, and steel pretension before the concrete is poured.
Disadvantages	Precast concrete elements are still heavy, which makes them difficult to transport to the site and hoist into place. Precast doesn't offer the same flexibility in concrete form design.

Glass Fiber Reinforced Concrete


Figure 243, GFRC façade cladding.

Glass fiber reinforced concrete (GFRC), is high-strength glass fibers that are embedded in concrete. The introduction of fibers into the concrete gives the material higher flexural and tensile strengths, allowing much thinner shapes to be formed.[82] GFRC is typically used for cladding or decorative elements.

Advantages	Lighter and thinner panels can be produced, that reduced the weight put on the buildings structural system. A variety of shapes and patterns can be designed with GFRC, where normal concrete would simply not hold together.
Disadvantages	More expensive than traditional façade systems.

[82] Aksamija, Ajla. Sustainable Facades: Design Methods for High Performance Building Envelopes. New Jersey: John Wiley & Sons, 2013.

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