Natural Light

Impact and performance through Materials

Research by: Khalat J. Fayaq

In partial fulfillment of the requirements for obtaining the **consultancy certificate** in architecture

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Natural Lighting – Impact and performance By Materials

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NATURAL LIGHT

EXPLORING THE IMPACT OF NATURAL LIGHT AND THE PERFORMANCE BY MATERIAL

A Research by

KHALAT JALAL

Submitted to the Kurdistan Engineering Union - Sulaimaniyah in partial fulfillment of the requirements for obtaining the consultancy certificate in architecture.

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ABSTRACT

NATURAL LIGHT: EXPLORING THE IMPACT OF NATURAL LIGHT AND THE PERFORMANCE IMPROVEMENT

FEB 2021

This research explores how natural light can be integrated with built form to create a“performance of light” in architecture. Lighting conditions from a contemporary living space, 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 houses , buildings and Academic buildings 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.

The use of daylight in architecture not only meets mental and physical needs of human, but also reduces the fossil energy consumption. From this perspective, Iran’s rich architecture has valuable achievements and experience that requires recognition and introduction to the architecture community of Iran and the world. Although Iran is among the richest country in terms of energy resources, improper use and waste of them imposes irreparable damage to the country's annual budget as far as the construction sector, by using over 40 % of the total energy produced in the country and 30 % of the proceeds from sale of oil, has the highest level of energy consumption. Since electricity has the greatest share of energy consumption in buildings, providing new ways to reduce energy consumption is necessary. In the meantime, the use of natural light in spaces plays an effective role in energy efficiency and prevention from electricity dissipation, because usual solutions in the present era, i.e. the use of electric lighting systems, cause heating the space and physical damage (eye) in addition to their high cost. In this paper, we account the benefits of using natural light in buildings, and then explain how to use natural light in architecture. At the end, we will present and describe new ways to use this natural resource.

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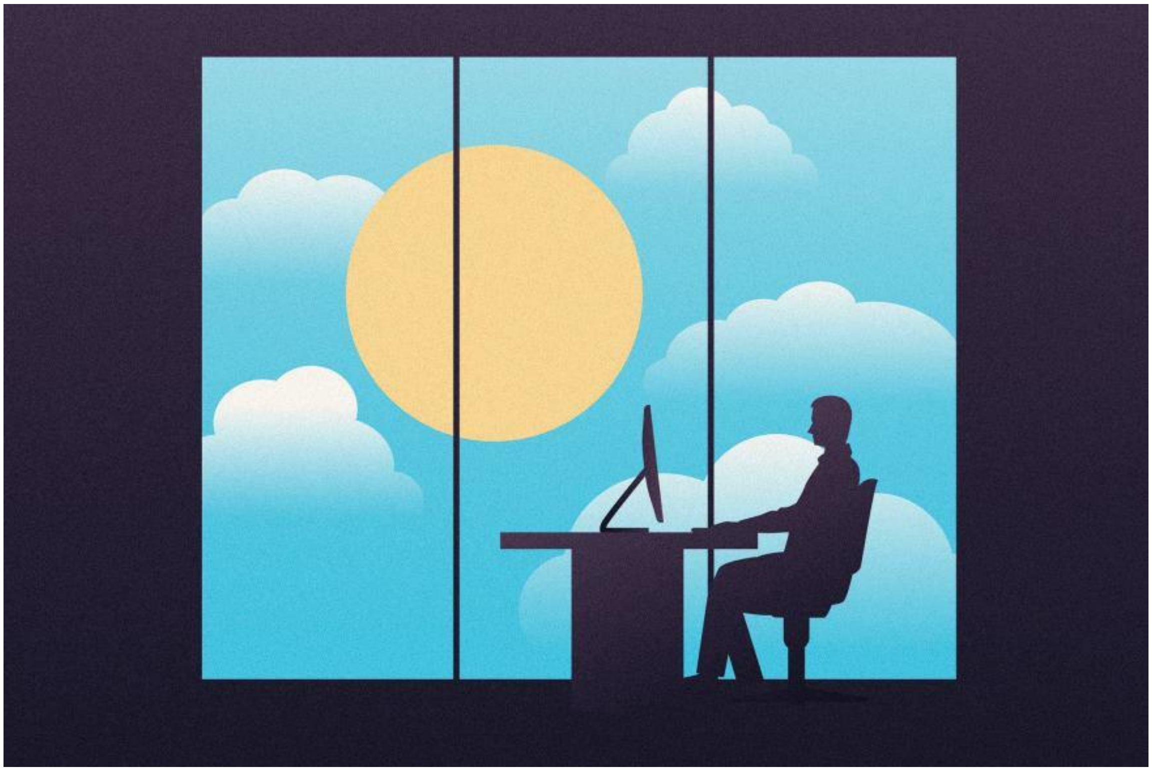
The Benefits of Natural Light



In 1862, Henry David Thoreau wrote, “In Wildness is the preservation of the world.” If he were to see our modern cities, our buildings, and what remains of the wild, perhaps his reaction would be similar to what David Orr, the Paul Sears distinguished professor of environmental studies and politics at Oberlin College, noted in his book Design on the Edge: The Making of a High-Performance Building (The MIT Press, 2006): “Modern designers filled the world with buildings and developments divorced from their context, existing as if in some alien realm disconnected from ecology … and place.” In cities today, daylight might be the last trace of Thoreau’s idea—and might be, in fact, the preservation of wildness.

In the practice of architecture, daylighting refers to the use of natural light, be it brilliant sunlight or muted overcast light, to support the visual demands of building occupants. In “Daylight Dialect,” which I wrote for Architectural Lighting in March 2008, I noted that daylighting purists argue that for a space to be considered daylit, it must use natural light as the primary source of daytime illumination, create a visually and thermally comfortable place connected to outdoor phenomena, and persistently maximize electric lighting energy savings while minimizing peak energy demand. The rest of us, however, might consider a space daylit if it simply has a window with a view.

Daylighting, Efficiency, and Productivity

Daylighting has been touted for its many aesthetic and health benefits by designers and researchers alike. Scientists at the Lighting Research Center (LRC), in Troy, N.Y., for example, have reported that daylit environments increase occupant productivity and comfort, and provide the mental and visual stimulation necessary to regulate human circadian rhythms.

Utilizing natural light can lead to substantial energy savings. Electric lighting in buildings consumes more than 15 percent of all electricity generated in the United States, according to the U.S. Department of Energy and the U.S. Energy Information Administration. Spaces outfitted with daylight-sensing controls can reduce the energy used for electric lighting by 20 percent to 60 percent, according to the studies "Photoelectric Control: The Effectiveness of Techniques to Reduce Switching Frequency" (2001) and "Summertime Performance of an Automated Lighting and Blinds Control System" (2002), both of which are published in the journal *Lighting Research & Technology*; and "The New York Times Headquarters Daylighting Mockup: Monitored Performance of the Daylighting Control System" (2006), which was published in the journal *Energy and Buildings*.

Independent field studies published in the past two decades have also shown a range of results, from outperforming predicted savings by 56 percent to experiencing an uptick in energy usage due to increased voltage of some dimming ballasts or lights left powered on after hours even though they were daylight controlled to an off setting. Given these findings, as well as the known thermal interdependencies associated with daylight glazing, a strategy to integrate daylight into a building can reduce or increase its total energy consumption.

"Daylight can also be too much of a good thing," says Joseph Park, national sales manager for the commercial window treatments division at Lutron Electronics, headquartered in Coopersburg, Pa. A building that has aggressive daylighting goals but is poorly operated will likely use more energy and might subject its occupants to excessive glare and thermal stress. On the other hand, Lisa Heschong, managing principal at TRC Companies—which acquired Heschong's namesake California-based consulting firm, Heschong Mahone Group (HMG), in January 2013—says that when she interviews workers in daylit retail, commercial, and education spaces, "they consistently report how they love working there, and hope they never have to transfer elsewhere."

Along with happier workers, substantial financial and human-performance benefits have been associated with increased daylight. In 2003's "The Benefits of Daylight Through Windows," LRC researchers discussed anecdotal evidence that commercial real estate with no windows leases for about 20 percent less—or $2 to $4 per square foot less—than spaces with windows.

The 1999 study "Skylighting and Retail Sales: An Investigation Into the Relationship Between Daylighting and Human Performance" and the 2002 study "Daylighting Impacts on Retail Sales Performance," both by HMG, are arguably two of the most robust investigations into daylight and its effects on retail sales to date. The studies concluded that the presence of skylights was the third-most-important criteria of five observed and statistically significant factors in increasing sales volume; the first and second were hours of operation per week and years since the last retrofit, respectively.

In the 1984 *Science* article "View through a Window may Influence Recovery from Surgery," Roger Ulrich, now a professor of architecture as well as a co-founding director of the Center for Health Systems and Design at Texas A&M University, reported that surgery patients in rooms that had windows facing trees recovered 8.5 percent faster and took fewer analgesics than did those patients whose view was a brick wall. Subsequent research by others has substantiated the results for patients who stayed in general hospital rooms.

In a 1999 study "Daylighting in Schools: An Investigation into the Relationship between Daylighting and Human Performance," commissioned by the Pacific Gas and Electric Company, HMG found a high correlation between schools that reported improvements in student test scores—upwards of 10 percent—and those that reported increased daylight in the classroom. The findings sparked discussion on the influence attributable to daylighting, or the daylighting effect size. HMG attempted to pinpoint the relationship in a look-back paper "Daylighting Impacts on Human Performance in School," published in *Leukos, the Journal of the Illuminating Engineering Society* in 2002. Though HMG and research collaborator RLW Analytics found a statistically significant relationship between lighting conditions and student test scores, they could not definitively explain the effect. Peter Boyce, LRC's head of the human factors program, likewise cautioned against prematurely drawing scientific relationships in his 2005 *Leukos* article, "Reflections on Relationships in Behavioral Lighting Research."

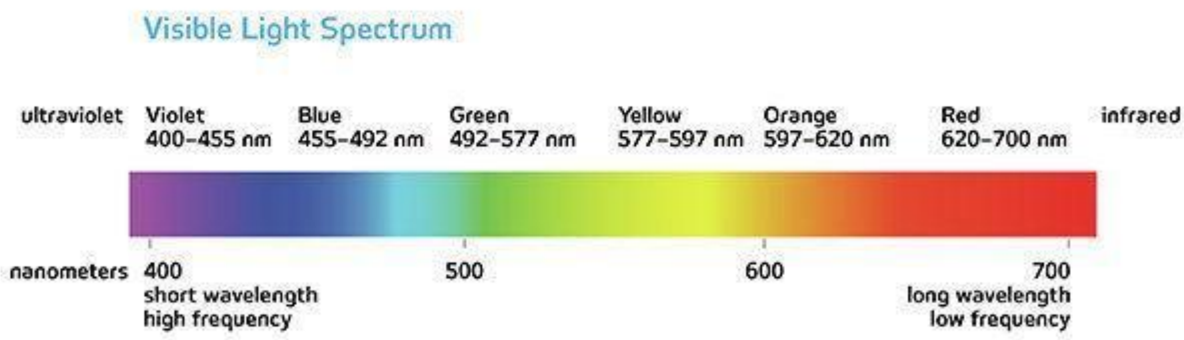
For its part, HMG could not replicate exactly the results of its 1999 study in a 2003 follow-up, but they still found evidence that an "ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, support better outcomes of student learning."

As Lutron's Park notes, poorly daylit and glaring spaces can have detrimental effects. While these decreases in performance have yet to be quantified, I have found in the course of my doctoral research that occupants in environments they describe as having "just uncomfortable" glare rather than the "most preferred" conditions did report a 10 percent decrease in their own perceived productivity.

Despite all the research mentioned, a quantitative relationship between daylighting and human health and productivity remains elusive. "Productivity is incredibly difficult to quantify in terms of time and money," Park says. Yet, it is the factor that decision-makers most often value when choosing whether to include daylight and advanced controls for lighting and blinds. A belief that daylighting is beneficial does exist, but hard evidence is still scarce. This is due, in large part, to the difficulty in conducting research tied to the dynamic nature of daylight, along with the myriad other variables that are difficult to control in the field. Is it the amount of light that matters, or is it the variability, the view, or the connection to nature?

Overall, the available research suggests that a successful daylighting design—one that factors in taming glare and solar heat gain—is likely to improve worker satisfaction, mood, and productivity. "The right balance can be achieved through the use of active daylighting control strategies, [such as] automated shades, as well as passive strategies, [such as] light shelves or louvers," Park says. "The markets for automated shades, light shelves, and dynamic glazing are increasing rapidly within the industry." These technologies mitigate the dynamic movement of direct sunlight while admitting diffuse daylight inside the space.

Recent research has underscored the effect of daylight on human health and biological functions. According to the U.S. Environmental Protection Agency, humans in modern cities spend upwards of 90 percent of their lives indoors. If they are occupying statically, perhaps stagnantly, lit environments, they can become disassociated with the natural outdoor cycles and variation of illuminance levels.



Daylight and the Circadian Cycle

The biological processes that regulate our sleep–wake cycle make up our circadian system. Primarily through the use of the neurohormone melatonin, our circadian system regulates our patterns of alertness and sleepiness. Without exposure to normal 24-hour light–dark cycles, a person's sleep–wake cycle can stray by as much as two hours per day.

The cumulative effect of this can be significant. An imbalanced sleep–wake cycle may produce advanced or delayed sleep-phase disorders and lead to chronic sleep debt. In "The Benefits of Daylight Through Windows" (2003), LRC investigators also noted that "[p]eople with chronic sleep debt feel permanently tired and are unlikely to work effectively." Furthermore, in the 2006 longitudinal study "Light at Night—Cancer Risks of Shift Work," researchers from Thomas Jefferson University (TJU), in Philadelphia, and the Mary Imogene Bassett Hospital, in Cooperstown, N.Y., found an increased rate of breast cancer in night-shift workers that resulted from the suppression of the pineal gland’s production of melatonin.

A lack of daylight inside a building doesn’t necessarily spell doom for its occupants. Exposure to bright light at the appropriate time of day and for the appropriate duration can alleviate these disorders. Daylight just happens to be one resource that can provide this exposure with the timing and duration that is most beneficial for humans. Darkness at night, not just brightness during the day, is also critical to a healthy sleep–wake cycle.

In order to minimize melatonin suppression, “one should keep exposure to light at night as short as possible, as dim as possible, and as warm or red as possible,” says Steven Lockley, an associate professor of medicine in the division of sleep medicine at Harvard Medical School and at Brigham and Women’s Hospital in Boston. With this in mind, daylighting design in spaces with sleeping quarters should also consider accommodating nighttime darkness.

The discovery of both a novel retinal photoreceptor in the human eye and the photopigment melanopsin has renewed the attention paid to circadian research and has drawn substantial interest from the lighting community. In the 2001 paper “Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor,” TJU researchers found that the circadian system is most sensitive to short-wavelength (bluer) light, ranging from 446 to 477 nanometers (see “Visible Light Spectrum” above). They also found evidence supporting the existence of a photopigment that mediates circadian photoreception, now coined as cirtopic vision. Cirtopic vision complements scotopic vision (which is rod-dominated, dim-light vision, with a peak of 507 nanometers) and photopic vision (which is cone-dominated, bright-light vision, with a peak of 555 nanometers).

Since photopic vision is critical to visual tasks, most electric light sources are designed to support it. However, short-wavelength light of 460 nanometers has been found to increase alertness as compared to longer-wavelength light of 555 nanometers. Furthermore, multiple studies have shown that students who did not receive short-wavelength visible light in the morning had delayed melatonin production and sleep onset in the evening by about 30 minutes.

Integrating Daylight with Design

While daylight is a variable, often unpredictable, light source with a spectrum that depends on solar position and sky conditions, it is also rich in the short-wavelength portion of the visible spectrum found to support both alertness and circadian sleep–wake entrainment. As a result, daylight in buildings may support human health and well-being, particularly for people in northern latitudes who occupy areas near a window or other daylight sources. But regardless of latitude or exposure duration, daylight may support human alertness and productivity. At the same time, it is important to remember that it is the daily—and possibly the seasonal—variation associated with the day–night light and dark cycles that supports human health. Lighting manufacturers, for one, have jumped on the bandwagon and attempted to mimic these cycles through electric light sources and lighting systems.

Designers can glean two points from this trove of research. First, daylit spaces hold the potential to yield substantial benefits, including increased energy savings, increased revenue in retail applications, and improvements to human health and productivity. Second, several important factors ranging from design to installation and operation must be carefully addressed in order to realize these benefits.

Many resources are available to guide decision-making in daylighting design but three tasks that are critical to a successful daylighting installation are: the control of direct sunlight at visual task areas during all occupied hours; the provision of balanced luminance on interior surfaces, particularly between perimeter windows and key vertical surfaces within the interior volume; and the provision of sufficient ambient daylight illumination for visual tasks. Modeling and testing design decisions with the increasing selection of daylighting software tools are also important. Once a design is executed, ensure operational success by educating building occupants and operators on the intent of the daylighting design, how to use lighting controls, and how to access and use shading controls.

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 acomplex 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 footcandlesor 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.

[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

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 andspace. 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 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.

[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.

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 up lighting 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.

Chapter II

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, 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 curtain wall

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

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

Figure 5, Tinted glass operation

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 Kurdish people spends 70% of his or her time indoors, 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. 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[5] 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 peopleor too little space, were found to exhibit excess levels of stimulation, stress and arousal, a reduction in desired privacy levels, and loss of control. 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 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 exemplifiesthe need to provide large common spaces, such as media centers, dining

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

areas, common areas, or auditoriums. “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.” [6]

Spaces specializing in a specific type of learning activity were emphasized over spaces were all the learning happened in one space. Example spaces include workstationsand 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

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

Presence of Materials 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 FP Innovations has shown a connection between material 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 withnon-natural artifacts. 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.

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. 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.

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).

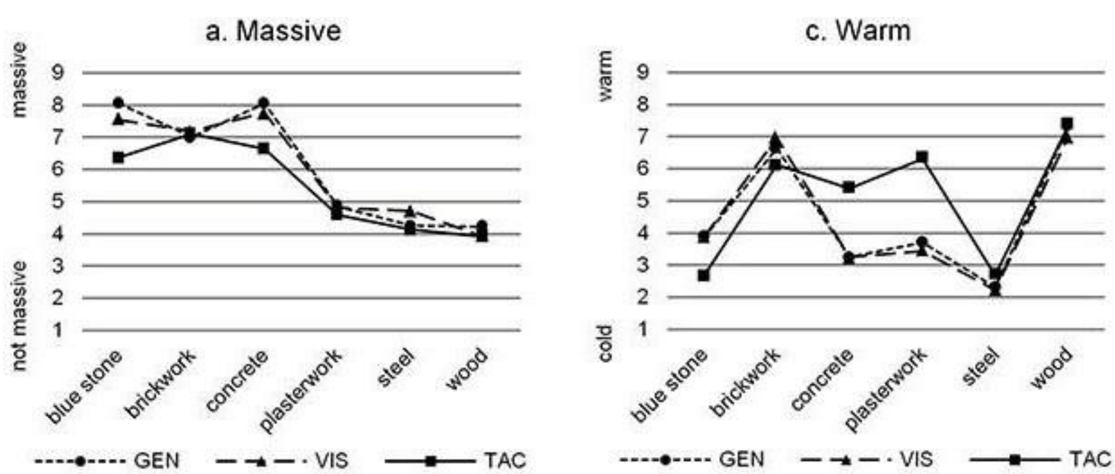


Figure 6, Mean response to two attributes of the building materials, for three conditions (general, visual, tactile). Wastiels, 2013

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.[7] 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.

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[7] 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.[8] 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.[9] Views of 50 feet or more are recommended to change focal length for eye health.[10]

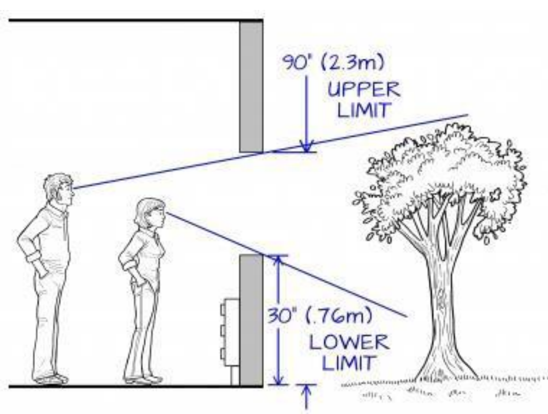

Figure 8, Optimal dimensions for view window. Autodesk Sustainability Workshop

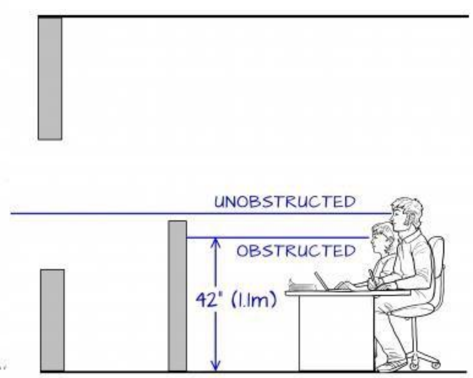

Figure 9, Average eye level of sitting person. Autodesk Sustainability Workshop

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

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

[10] 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.

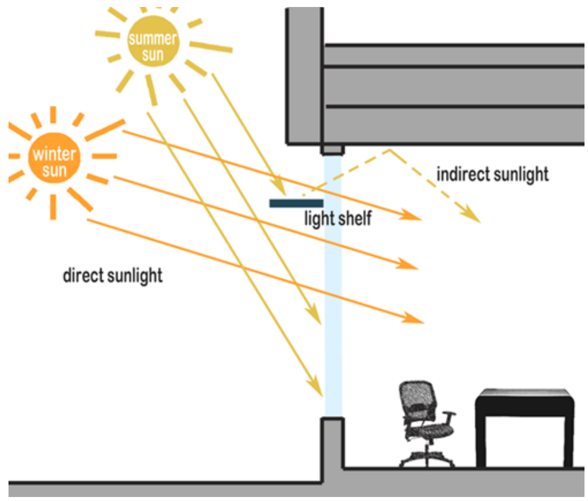

Figure 10, View window & daylight window with light shelf. Source

Too much daylight can be a problem. High illuminance values can lead to furniture damage, distractions from glare, and thermal discomfort.[11] 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.[12]

Color & Tempreature

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 stimulation and alertness, while blue and green colors promote balance and calmness.[13] Inmultiple 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%.[14]

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

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

[12] Alexander, C., Ishikawa, S., & Silverstein, M. (1977). A pattern language. New York: Oxford University Press.

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

[14] 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)

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

Figure 12, ILC - Technology Classroom, William Neumann

Figure 13, ILC - 120 seat classroom. William Neumann

Chapter III

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.[15] 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 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.

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

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." [16] 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, so they are easier to work with in the future. Typical plan: The typical speculative officeallows 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 allowingthe 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.

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

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.

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.[17]

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.[18]

[17] reThink Wood. "Building Resilience: Expanding the Concept of Sustainability." Continuing Education (2016): 24 Jul, 2016. [27]

[18] Douglas, Brad, and Erol Karacabeyli. CLT Handbook: Cross-Laminated Timber. Pointe-Claire, QC: FPInnovations & BinationalSoftwood 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

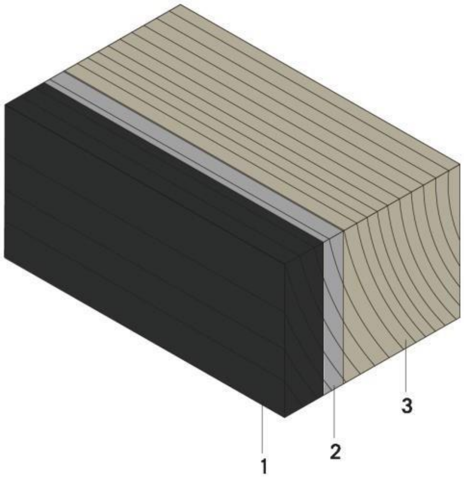

Figure 14, Charring diagram. Tall Wood

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

Charring Structural Design Diagram

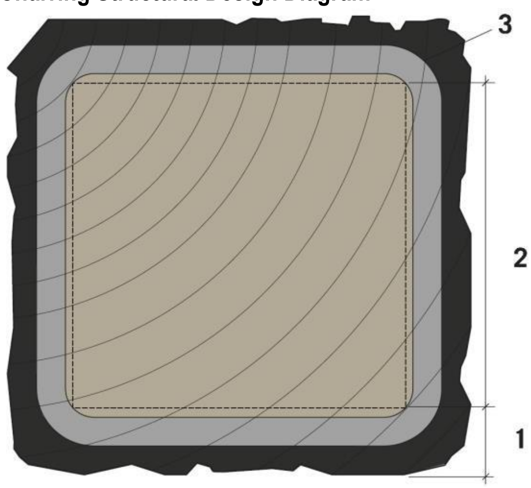

Figure 15, Charring structural design diagram. Tall Wood

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

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.

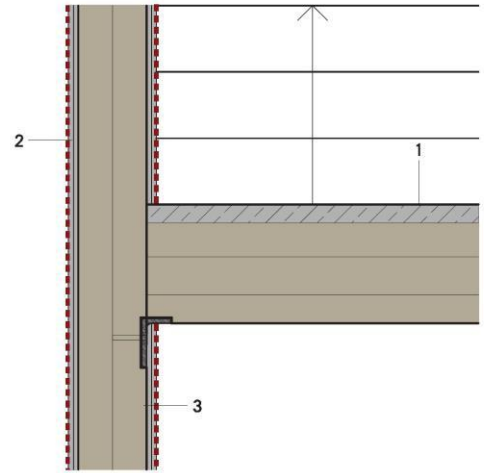

Figure 16, CLT wall at stairwell. Tall Wood

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

Life Cycle Assessment

Buildings consume over 60% of the energy produced in the Kurdistan, use 75% of the electricity, and account for nearly half of all CO_2 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."[19]

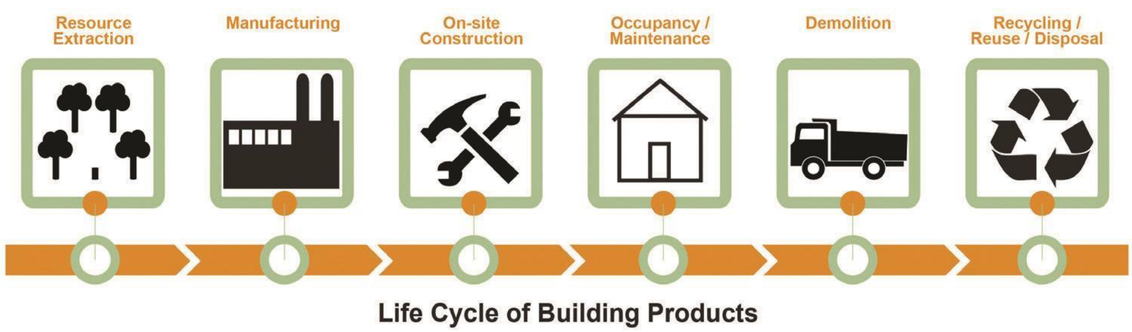

Figure 17, Building product life cycle. Naturally:wood

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

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."[20] Tools are available for building professionals to measure the impacts of building choices. Athena Impact Estimator can model over 1,000 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.

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

Passive Design Strategies

Building Massing and Orientation

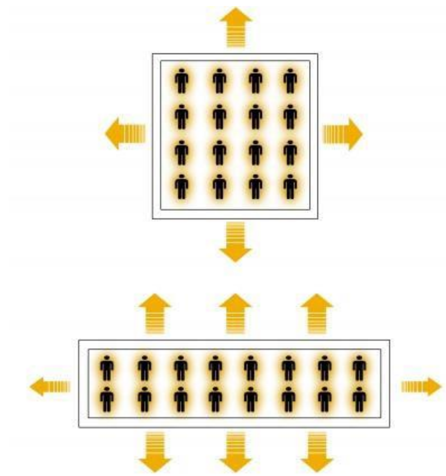


Figure 18, Thinner buildings lose more of their internal heat to the outside. Autodesk

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 heatgain 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.

<u>Passive Heating Strategies</u>

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.

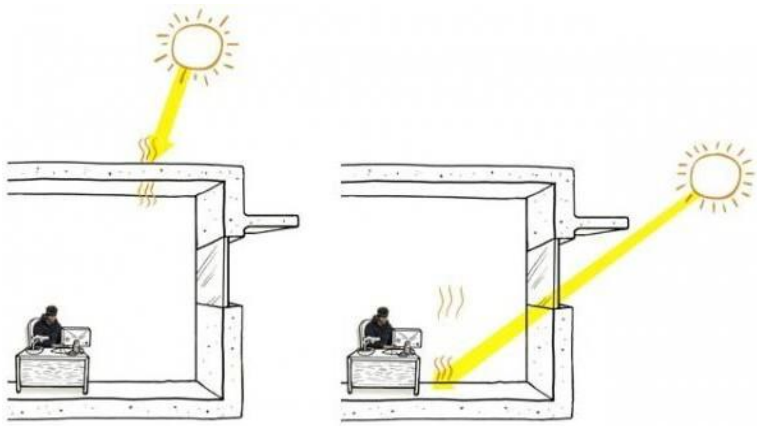


Figure 19, Direct gain through the envelope or a window. Autodesk

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 canbe effectively blocked by appropriate shading, while the lower winter sun can penetratethe glazing, heating up the space inside.

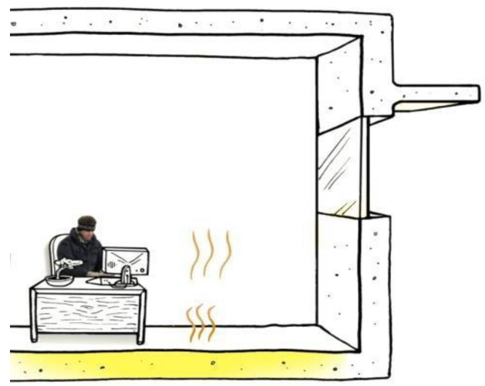


Figure 20, Stored heat in the thermal mass after the sun is gone.

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 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.

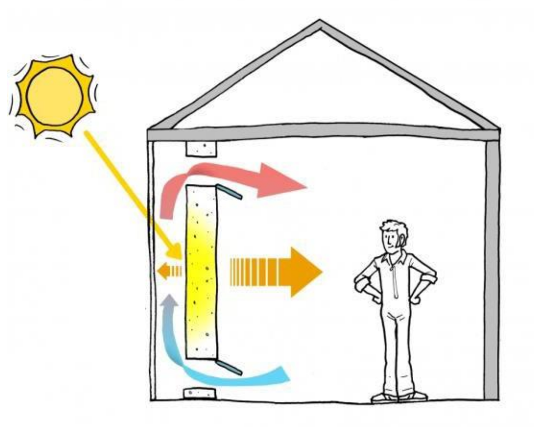


Figure 21, Trombe wall daytime operation. Autodesk

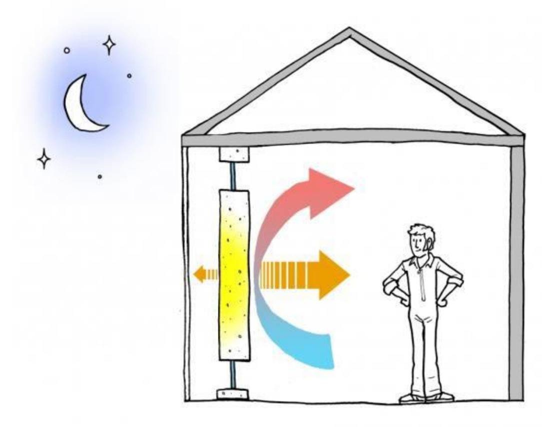


Figure 22, Trombe wall nighttime operation. Autodesk

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.

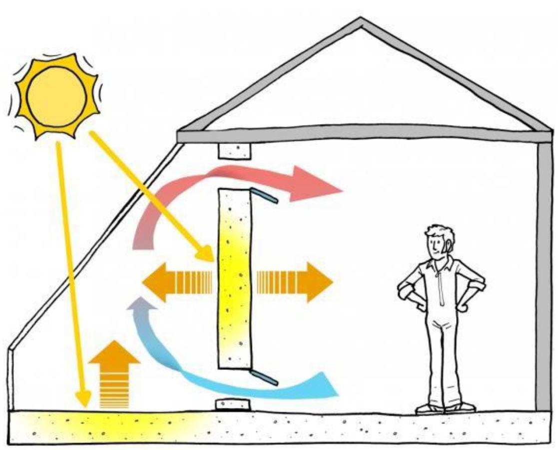


Figure 23, Daytime sunspace operation. Autodesk

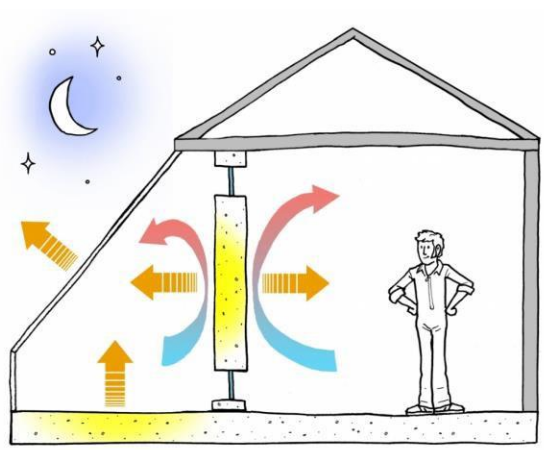


Figure 24, Daytime sunspace operation. Autodesk

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 thewater 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.

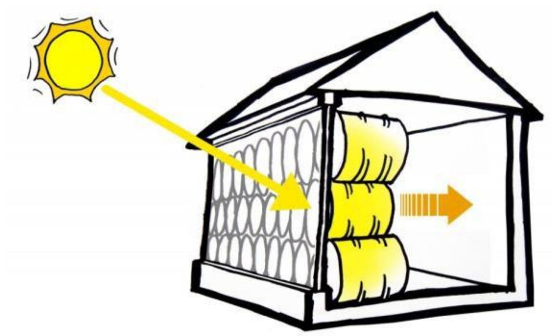


Figure 25, Water barrels forming a trombe wall. Autodesk

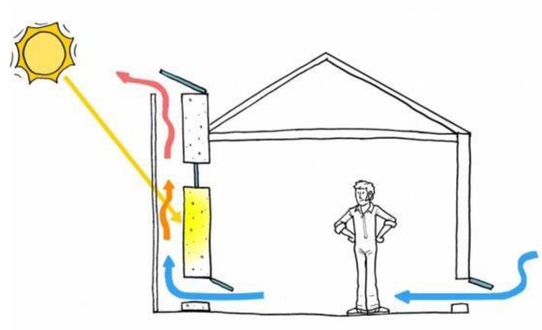


Figure 26, Trombe wall acting as a solar chimney. Autodesk

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

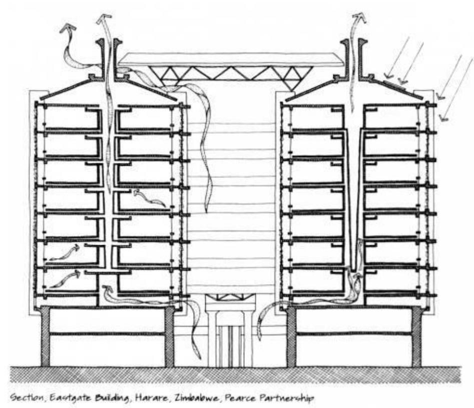


Figure 27, Natural ventilation strategies in a multistory building. (Image from Sun, Wind, and Light, by G.Z. Brown and Mark DeKay, published by Wiley)

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.

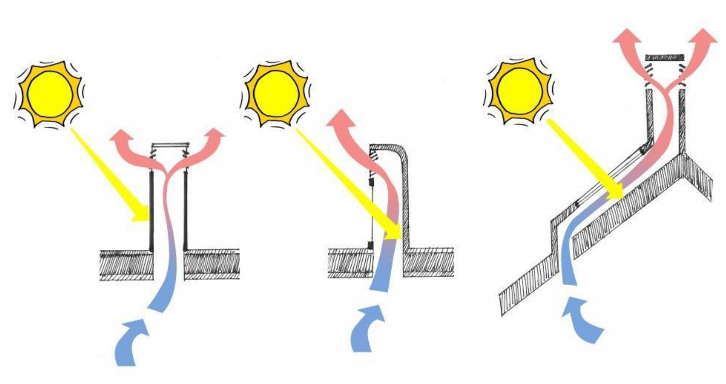


Figure 28, Solar chimney designs that utilize the stack effect. Autodesk

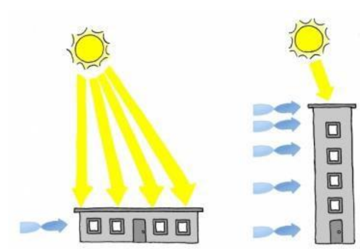


Figure 29, Passive ventilation effectiveness - deep versus tall and thin buildings. Autodesk

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, windowsare 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.

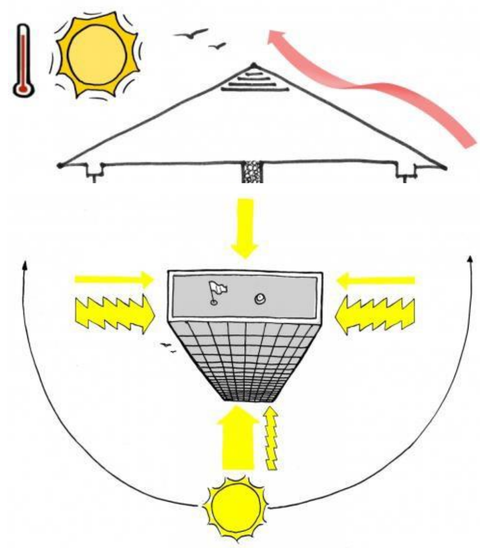


Figure 31, Useful daylight (straight arrows). Autodesk

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.

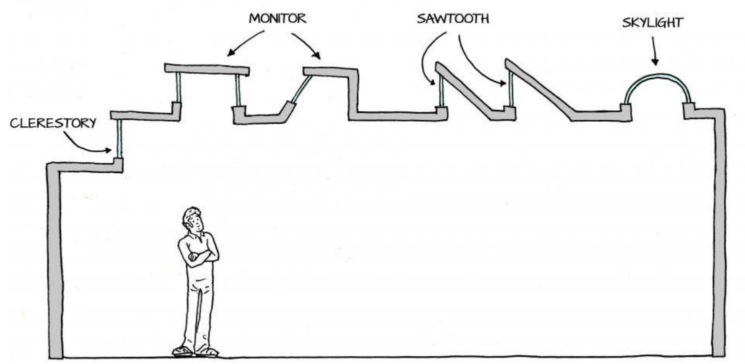


Figure 32, Top lighting strategies. Autodesk

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.

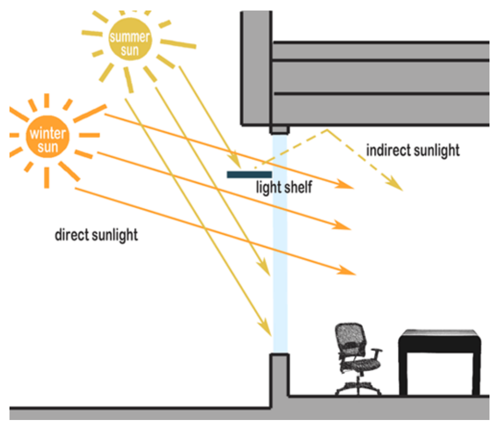


Figure 33, Light shelf redirecting light. Autodesk

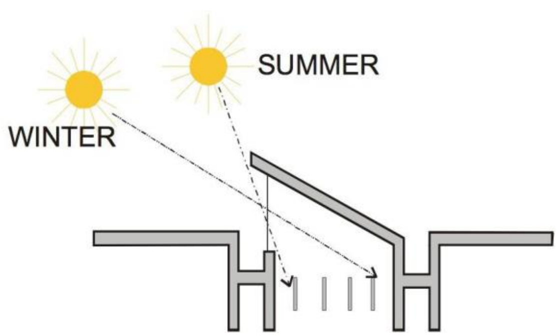


Figure 34, Using baffles in a roof monitor. Autodesk

Chamter IV – Some Design Samples

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 ofthe front of house and back of house areas is greatly affected by the type of theater, andthe 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.[21]

Figure 35, Opera House Linz auditorium. Dirk Schoenmaker

Concert Hall

Classical music is typically played in a concert hall. They usually seat between1,500 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

[21] 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 scaleclassical 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 variationin form and seating, as does the field of drama. Seating can range from 100 up to 1,200, and thestage 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 houselarge-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 integratedinto the typical theater spaces.

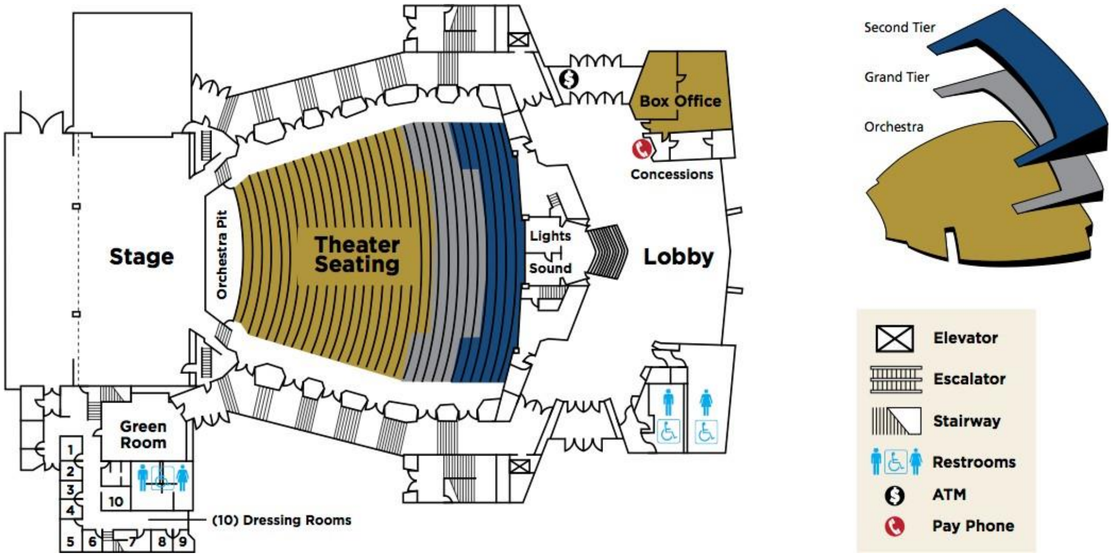


Figure 42, Floorplan showing FOH, auditorium and backstage areas for Sacramento Convention Center - Community Center Theater. SCC

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 functionsneeded 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.[22] 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 andwardrobe, green room, scene dock, prop and scenery storage, shop and loading dock. Larger theaters should have a separate entrancefor performers and staff, to improve access to preparation areas, and increase security.

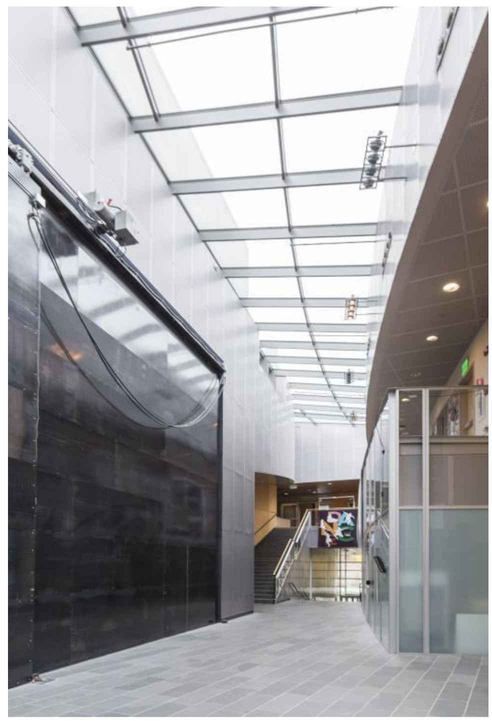


Figure 43, Stage access door - Williamstown Theater. Dylan Brown

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

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 thestage. The proscenium format remains the primary theater model for large-scale performances and elaborate scenery effects.

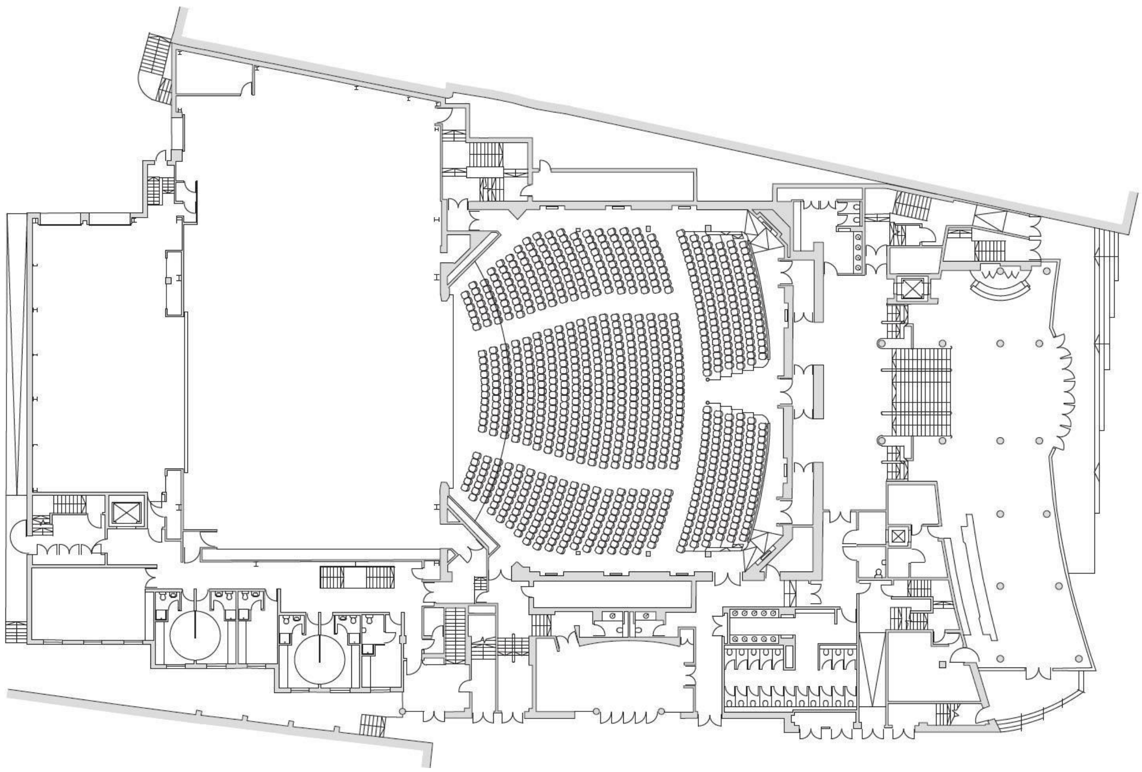


Figure 44, Festival Theatre - Edinburgh, Scotland. LDN Architect

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.

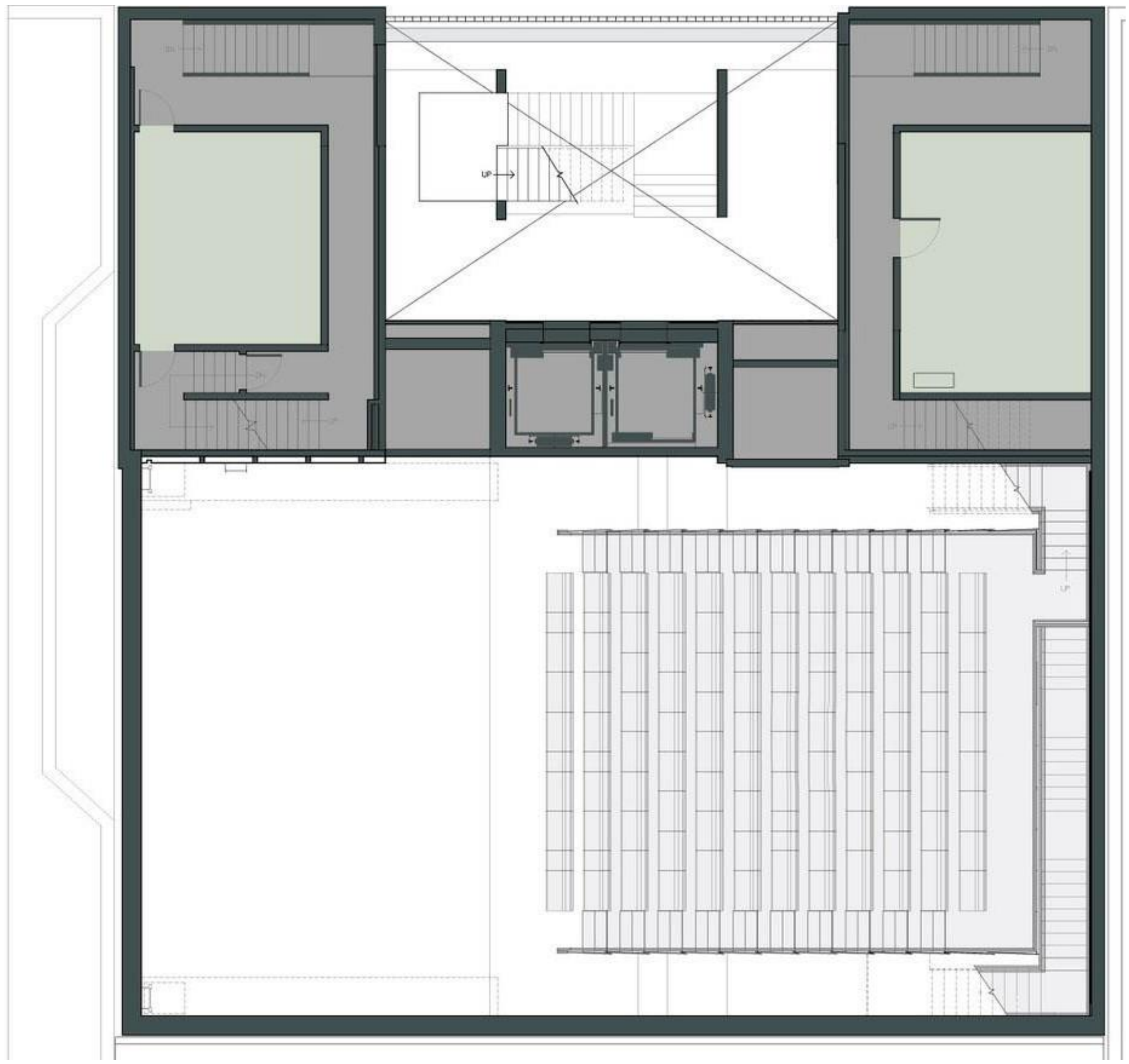


Figure 45, Baryshnikov Arts Center, Jerome Robbins Theater. think!

Corner / Wide Fan Stage

In a corner or wide fan stage model, the stage is positioned in the corner of theroom, 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 limitsthe staging and set design, but there is potential if designed well.

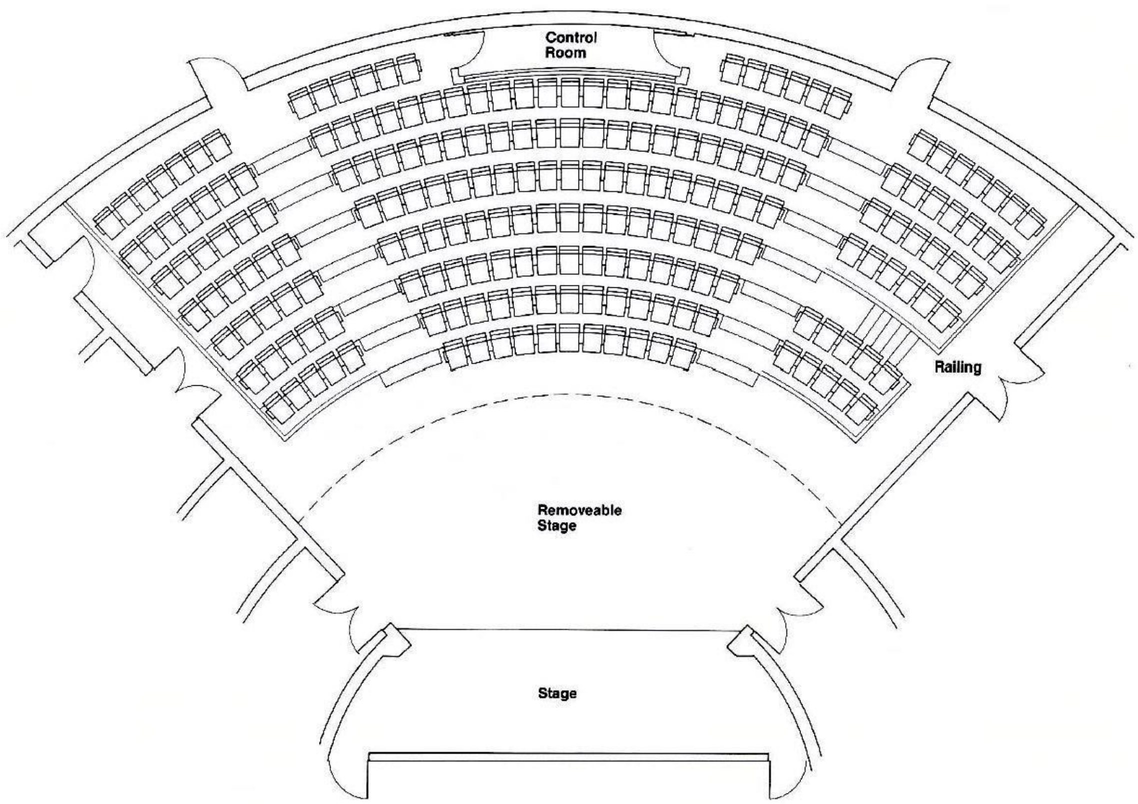


Figure 46, Wide fan / corner stage theater. Theatre Solutions Inc

Amphitheater

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

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

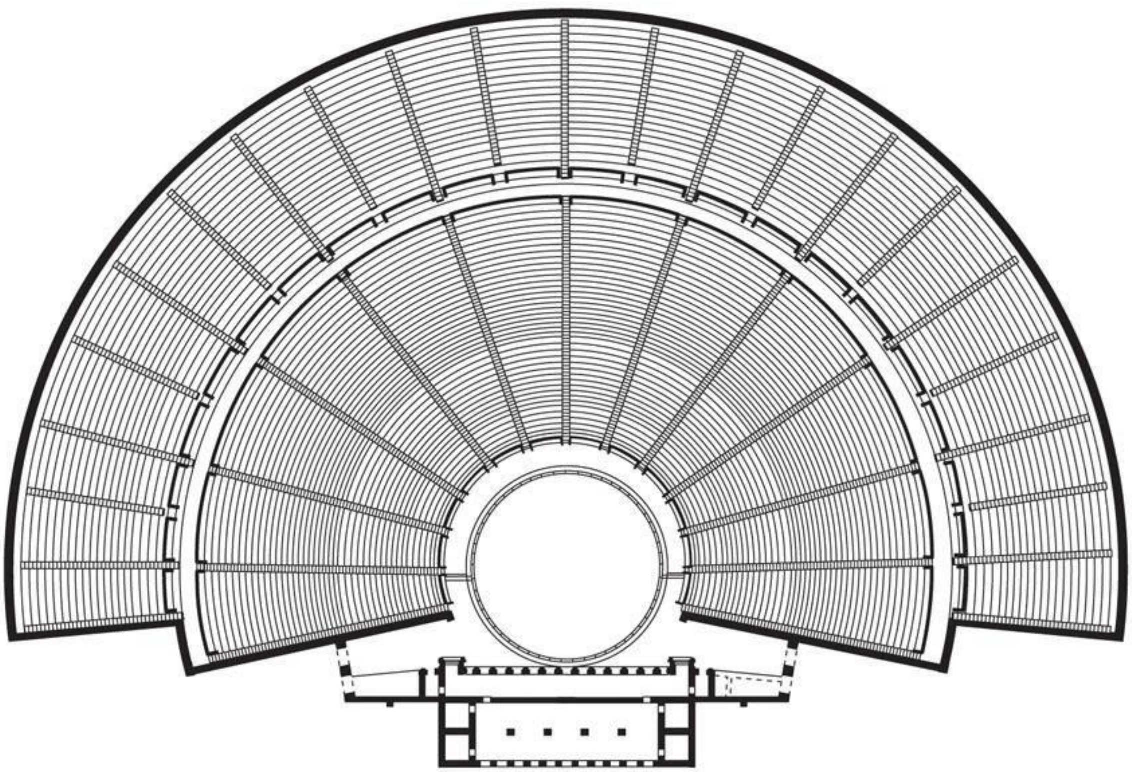


Figure 47, Amphitheater in Epidaururs (Epidauros, Greece)

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.

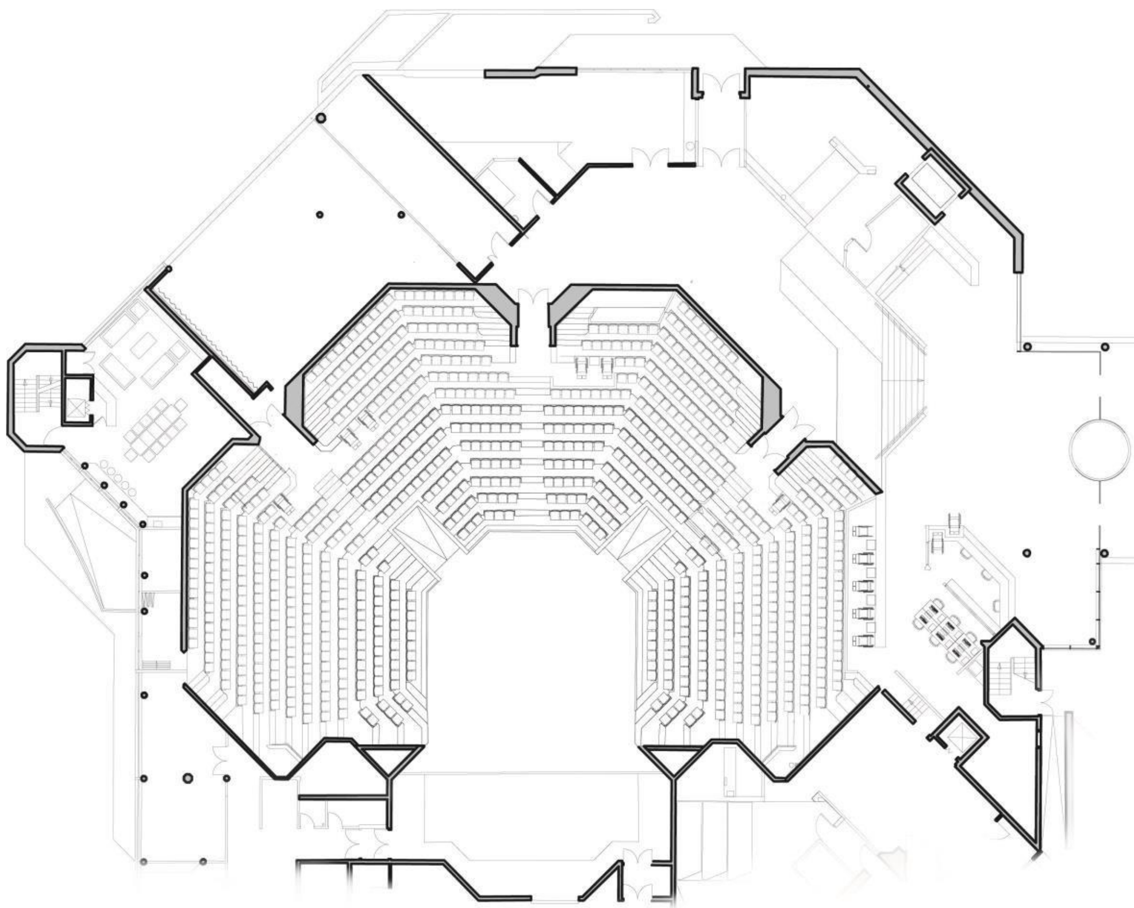


Figure 48, The Crucible Theatre, Sheffield, UK. RHWL, London

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 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.

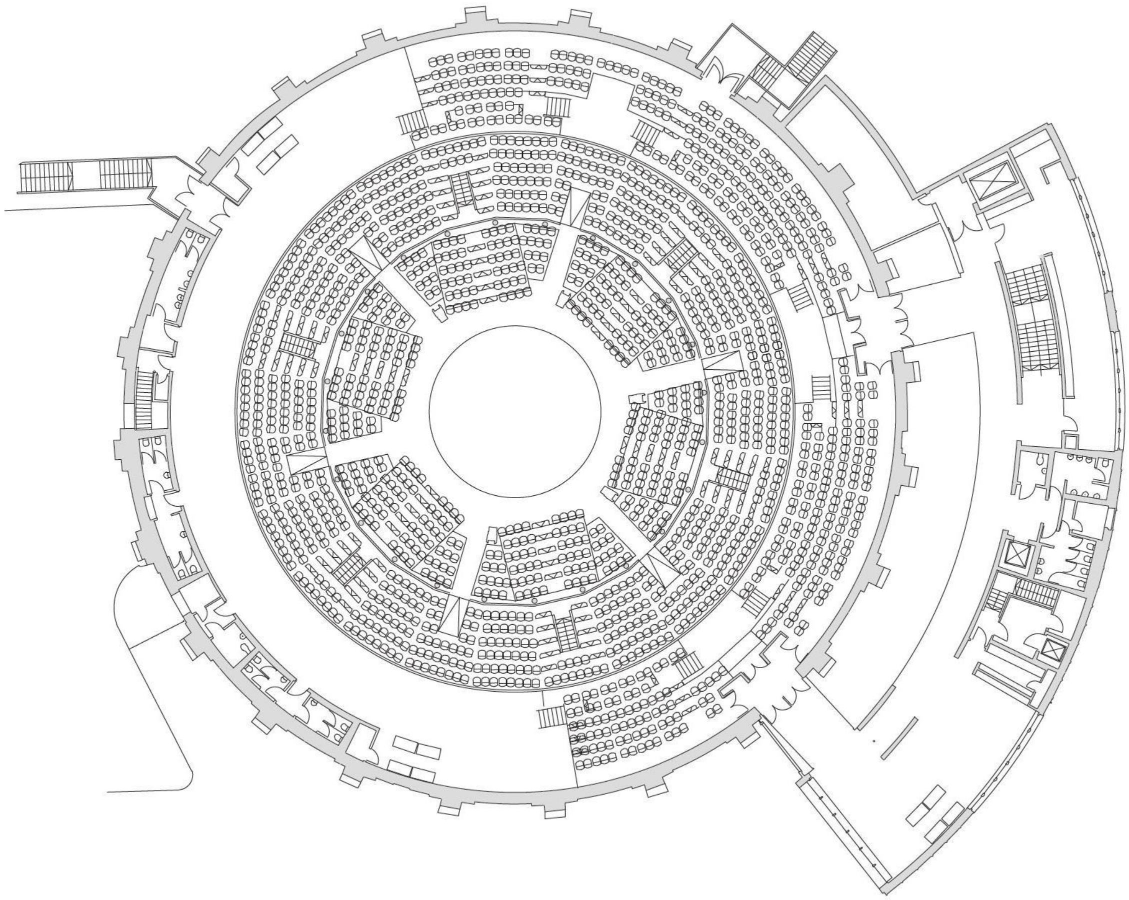


Figure 49, The Roundhouse, London, UK. John McAslan + Partner

Courtyard

The courtyard theater model came out of the English Renaissance, where much ofthe 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.

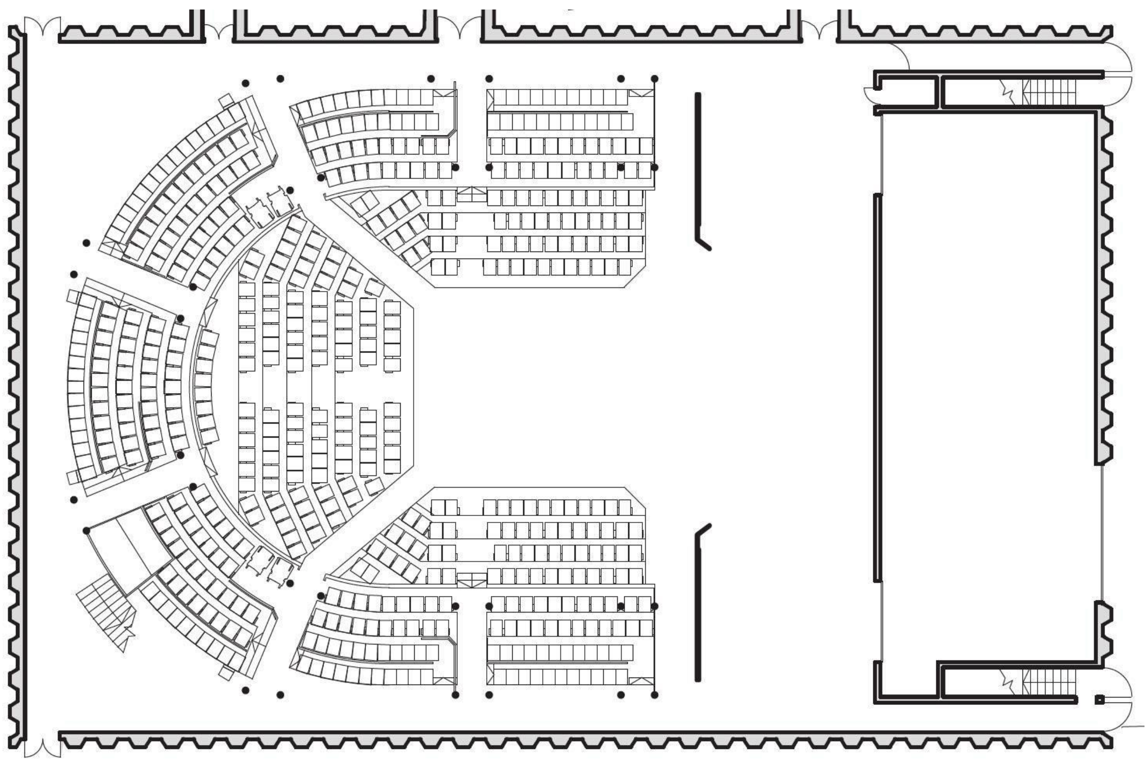


Figure 50, The Courtyard Theatre floor plan. Ian Ritchie Architects

Chapter V - Architectural Precedents

Taipei Performing Arts Center - OMA

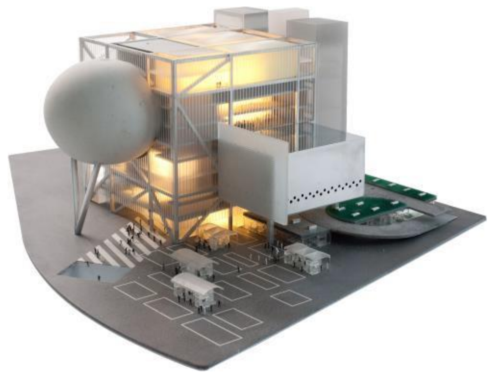


Figure 51, TPAC physical mode. OMA

Still under construction, the Taipei Performing Arts Center (TPAC) consist of three theaters plugged into a central volume, where theycan 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.

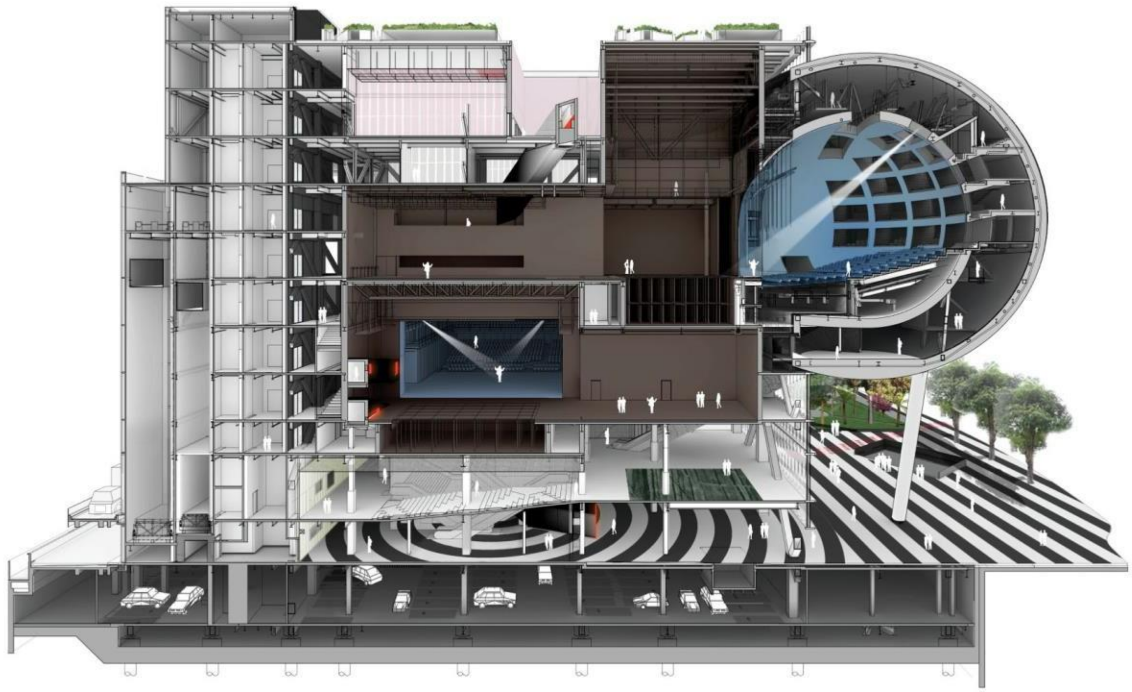


Figure 54, Sectional perspective through proscenium playhouse. OMA

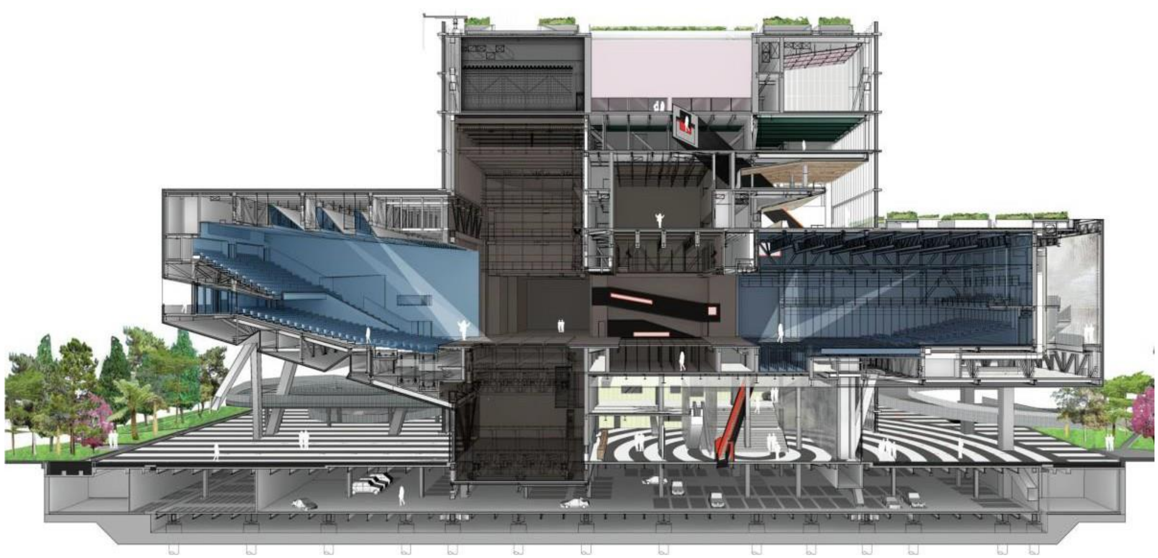


Figure 55, Sectional perspective through super theater. OMA

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 daylitfoyer, 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.

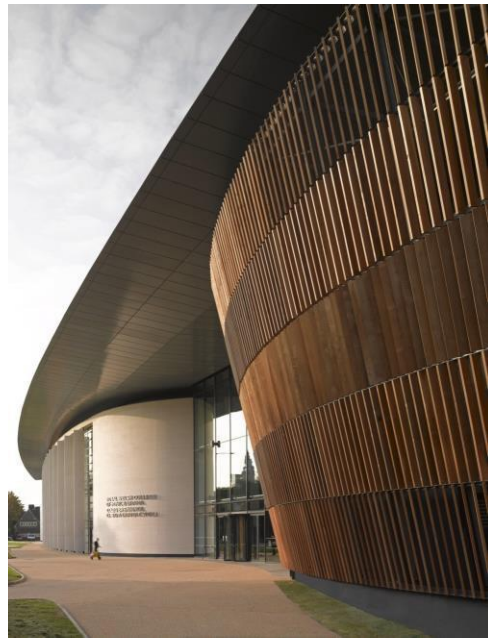


Figure 56, The building facade is a timber screen built from cedar wood slats. BFLS

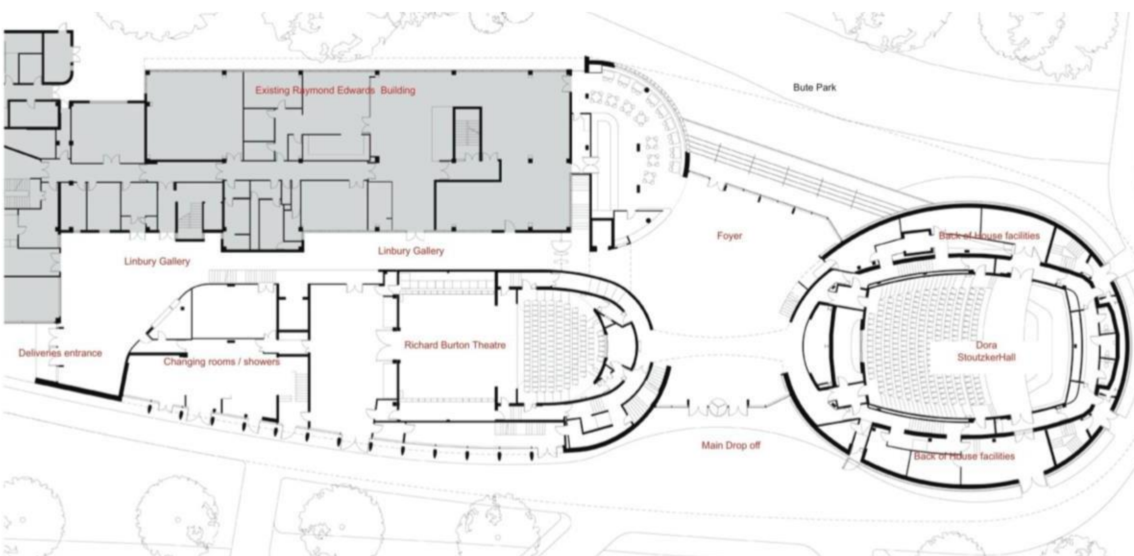


Figure 57, Ground floor plan showing concert hall and theater. BFLS

The concert hall uses wood paneling to provide an acoustically excellent space, aswell 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 belowand 300 above. For smaller performances, only thelower 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

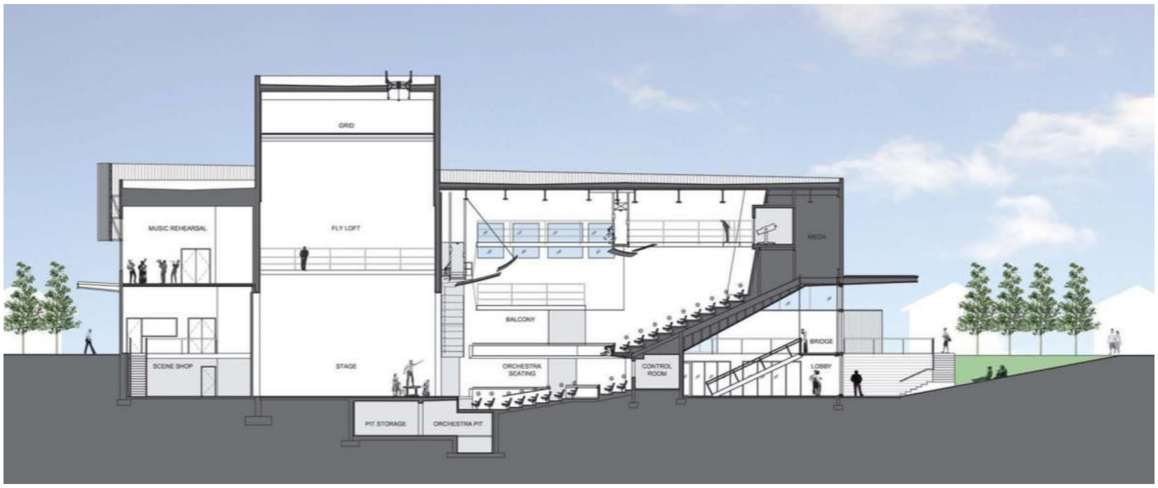


Figure 62, Section through lobby, theater and back of house. Stephen Dynia Architects

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.

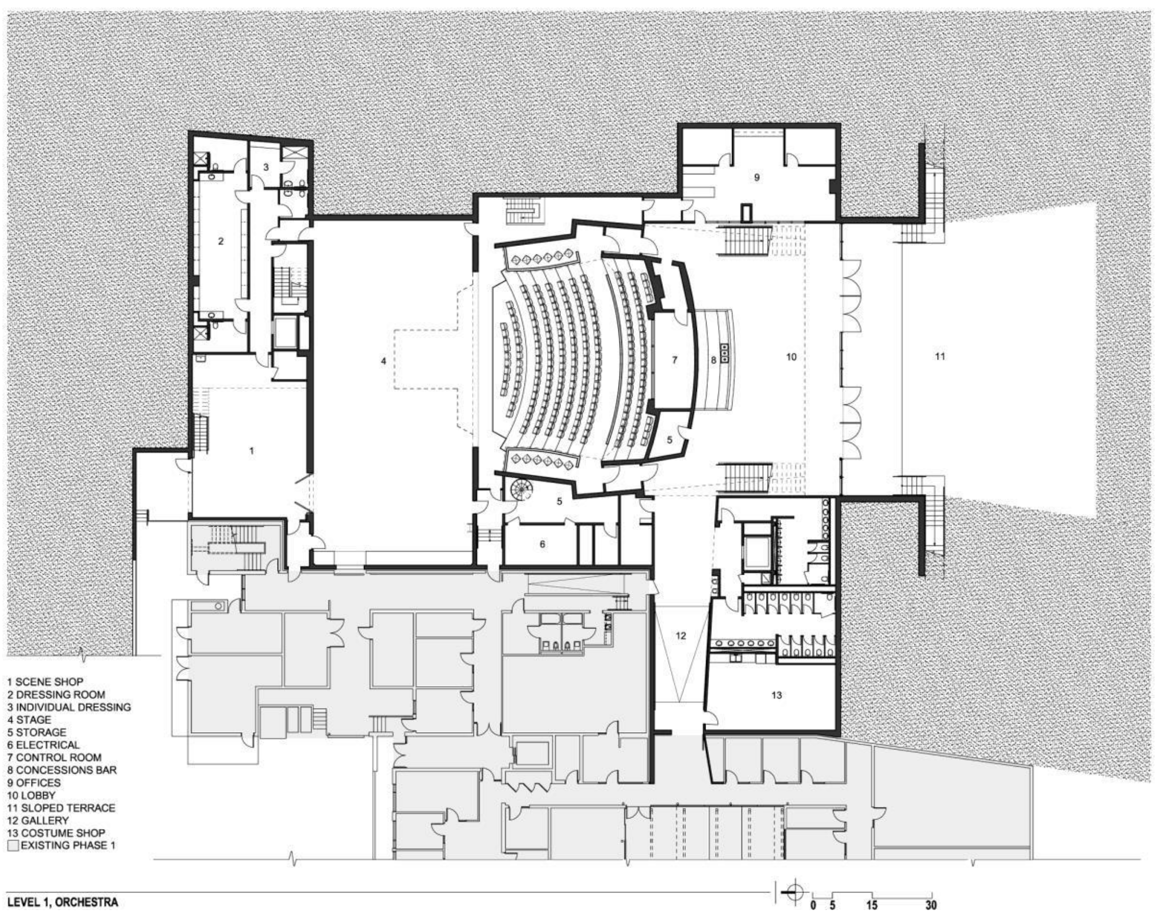


Figure 63, Level 1 Plan. Stephen Dynia Architects

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.

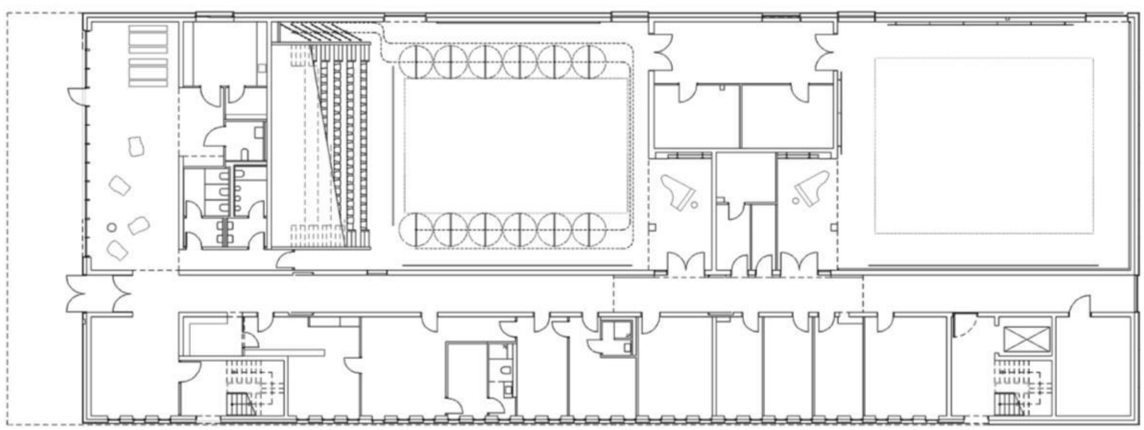


Figure 64, 01 Floor Plan - ballet rooms are located at the top of the plan. gmp Architekten

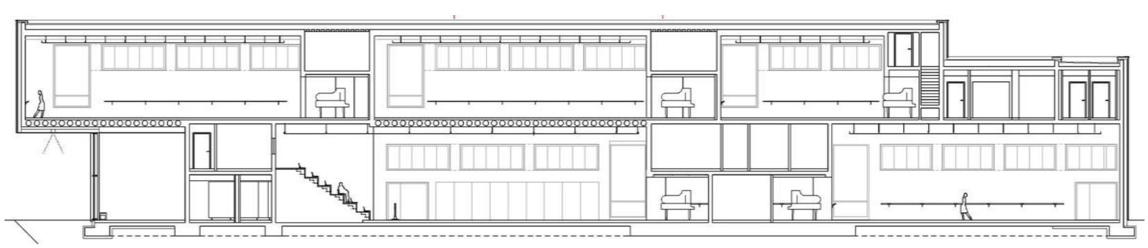


Figure 65, Section showing flexible ballet room below and rehearsal spaces above. gmp Architekten

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

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 Andobuilding. 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 walland the floor. The feature acts as a sundial, never casting sun in the same place twice inone 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

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.

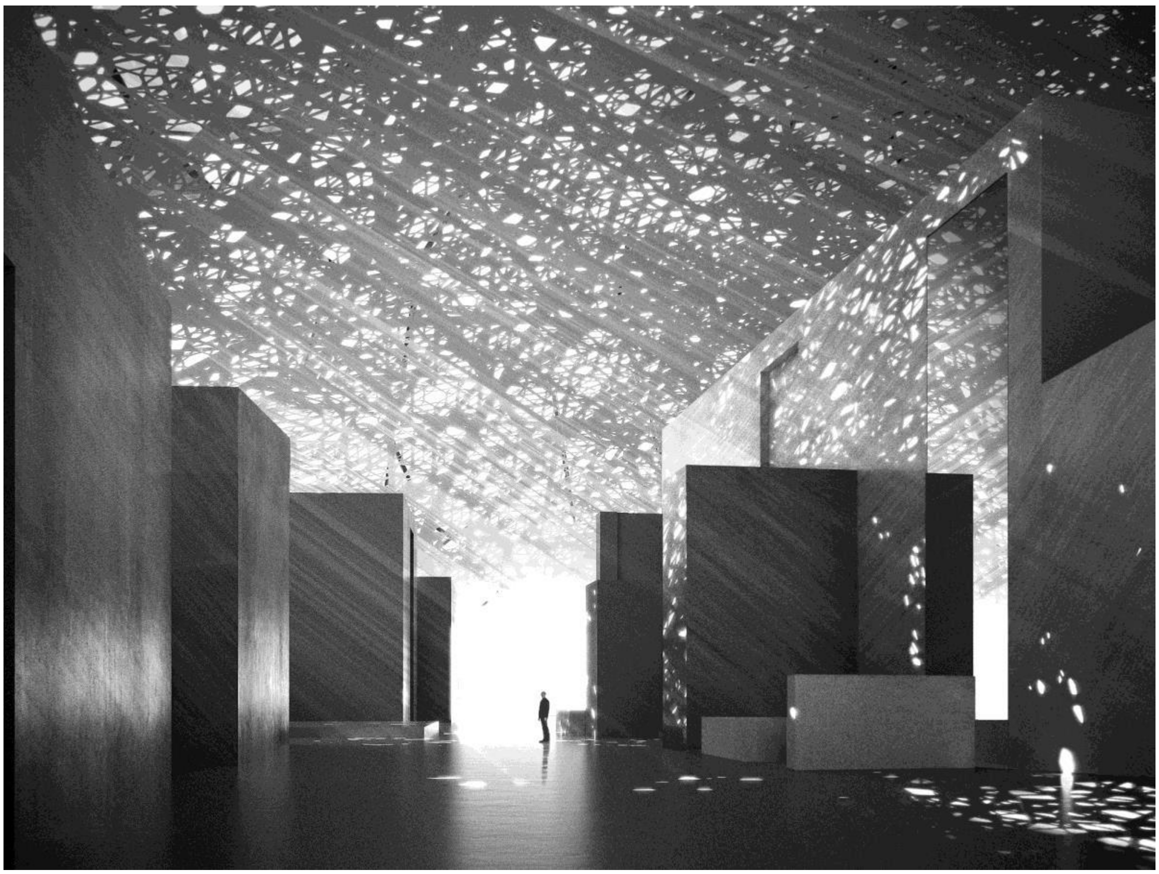


Figure 81, Rays of Light - Jean Nouvel

CHAPTER VI

DESIGN

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.

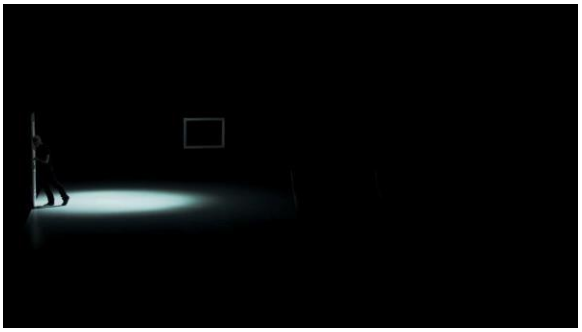


Figure 125, A lone figure leans against a door. A single light source shines on the door, radiating out towards the middle of the stage. A picture frame sits still in the background.

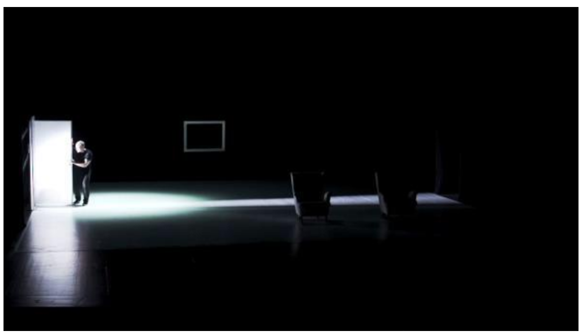


Figure 126, The lone figured has opened the door, casting a different beam of light out from the opening. Two chairs are revealed on stage right by the extra light.

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.

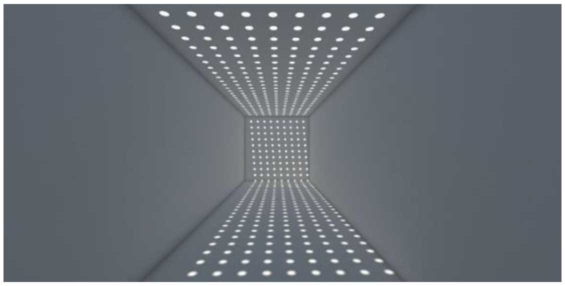


Figure 130, Circular grid


Figure 131, Big circle

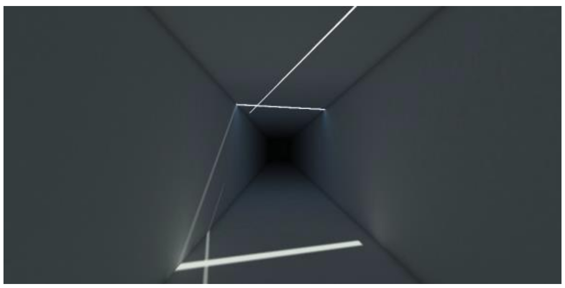


Figure 132, Perpendicular lines

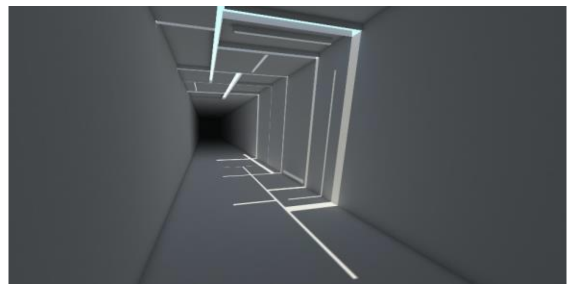


Figure 133, Rectangular bands

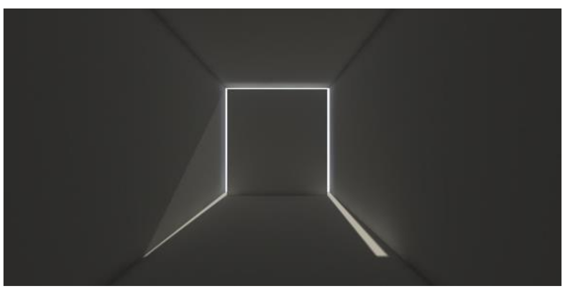


Figure 134, Edge lighting

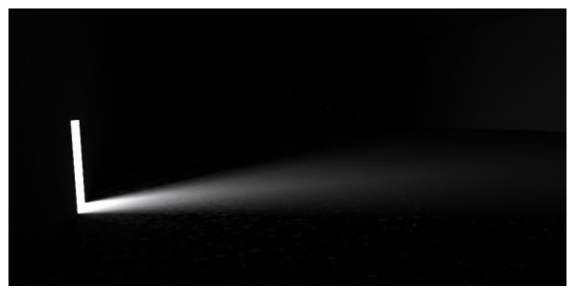


Figure 135, Light through a single opening

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.

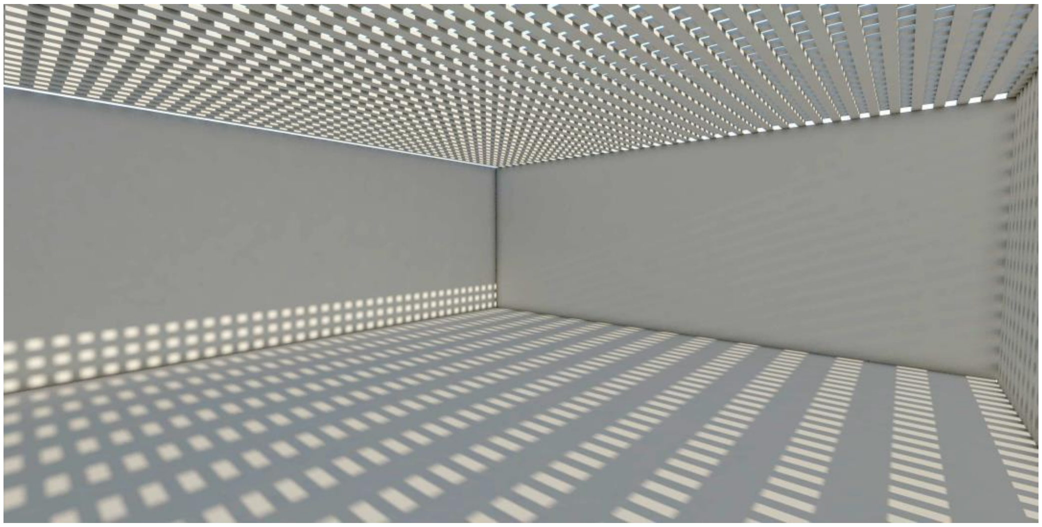


Figure 136, Morning lighting conditions

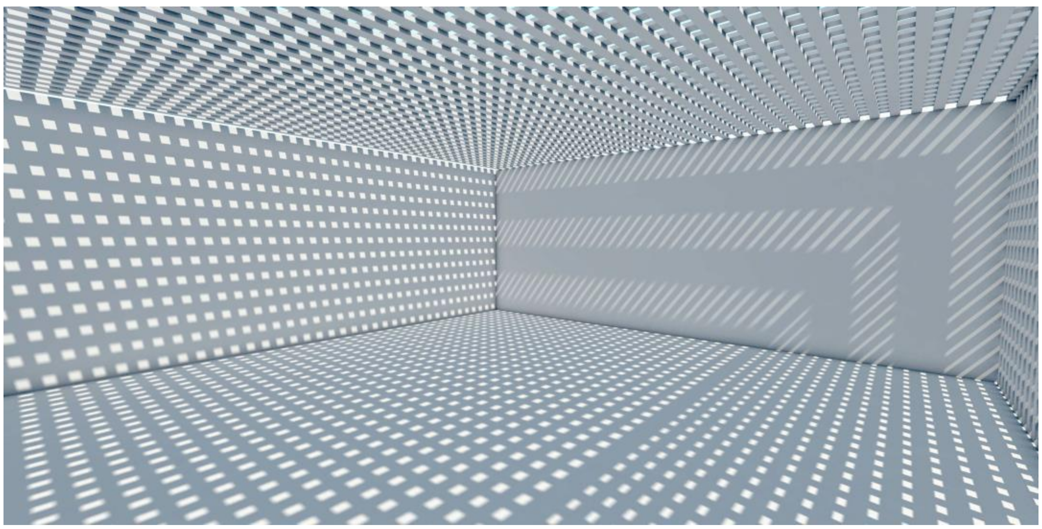


Figure 137, Midday lighting conditions

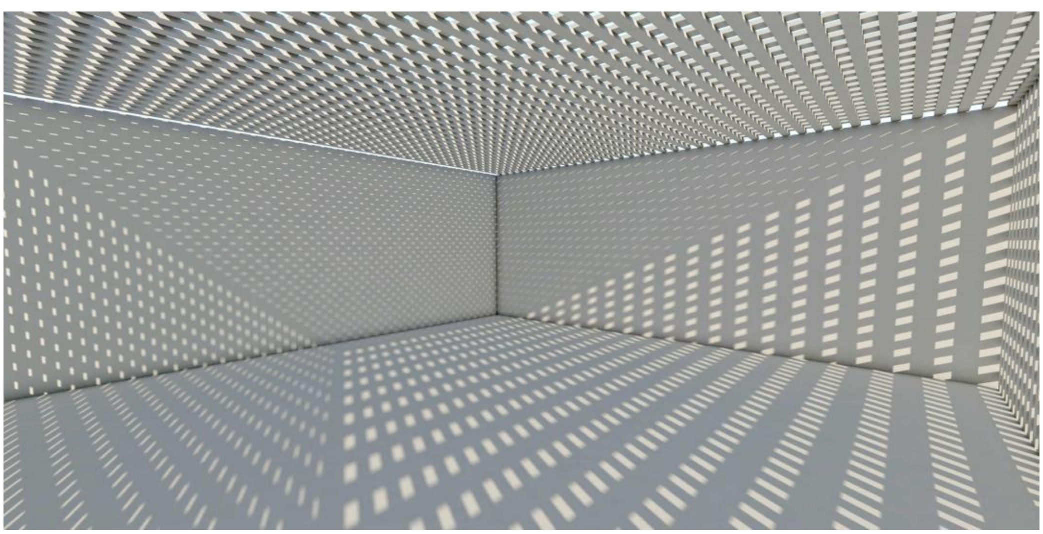


Figure 138, Evening lighting condition

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.

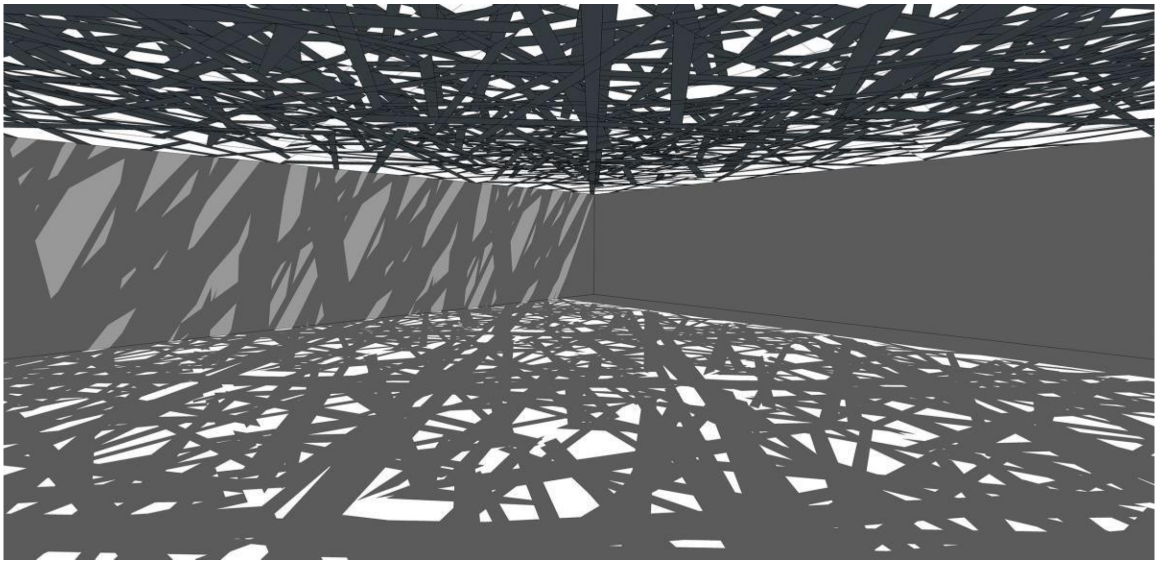


Figure 139, Shadows during morning sun.

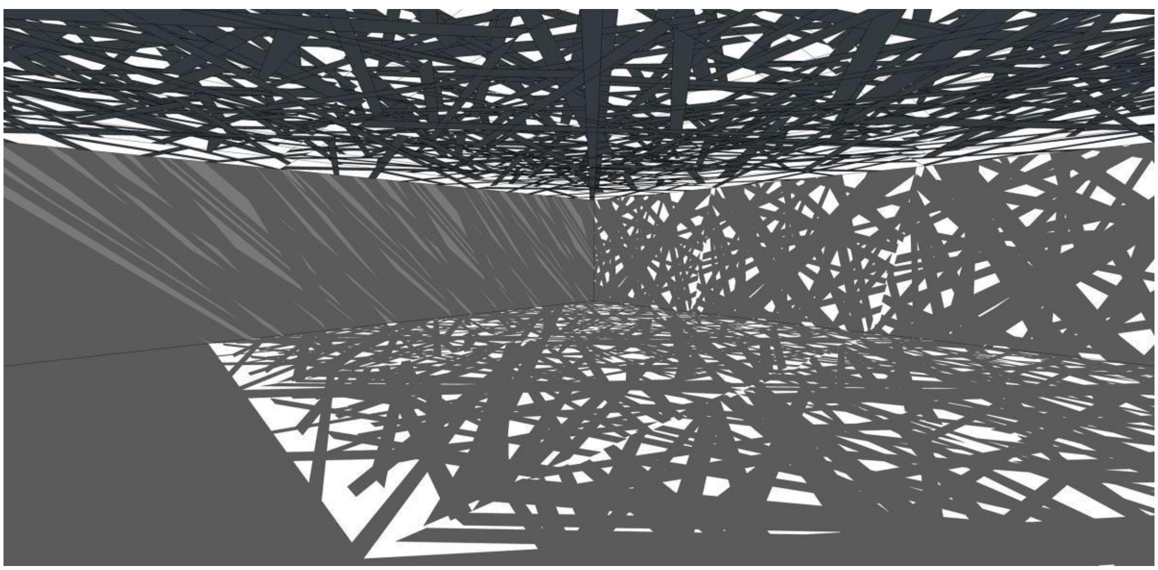


Figure 140, Shadows during afternoon sun.

Design Development

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

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.

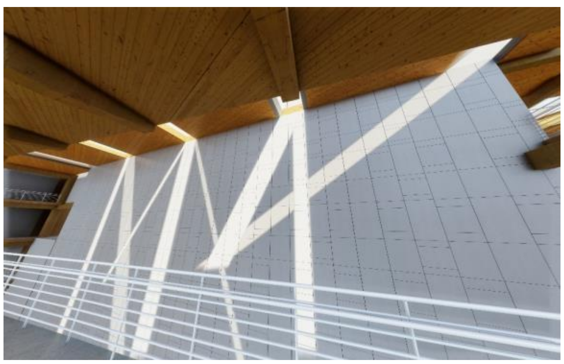


Figure 166, Combined light paths on June 21.

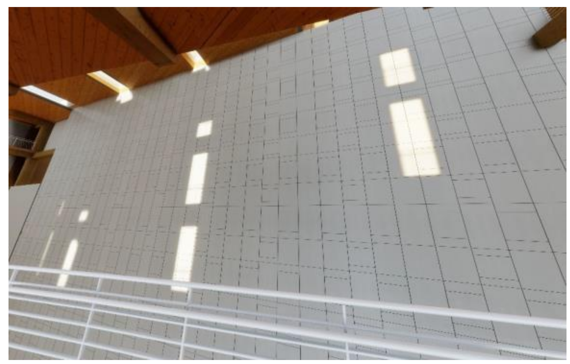
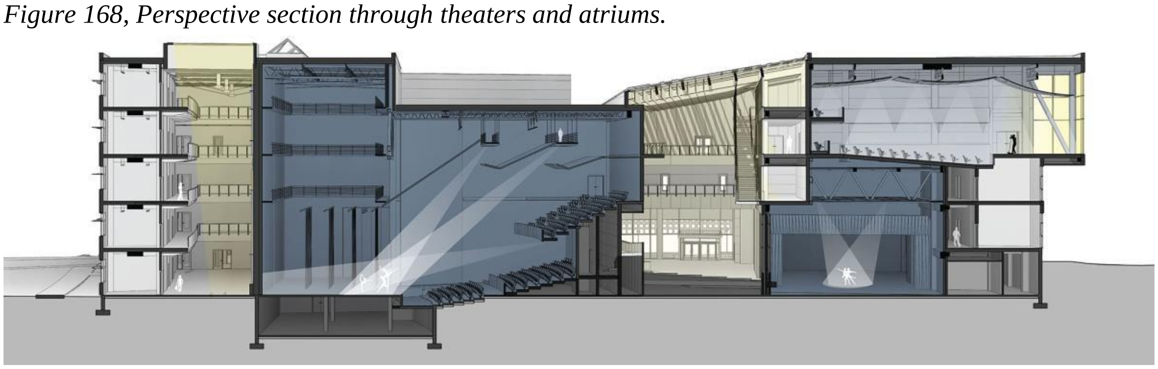


Figure 167, Combined light paths on December 21.

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 ontop 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.

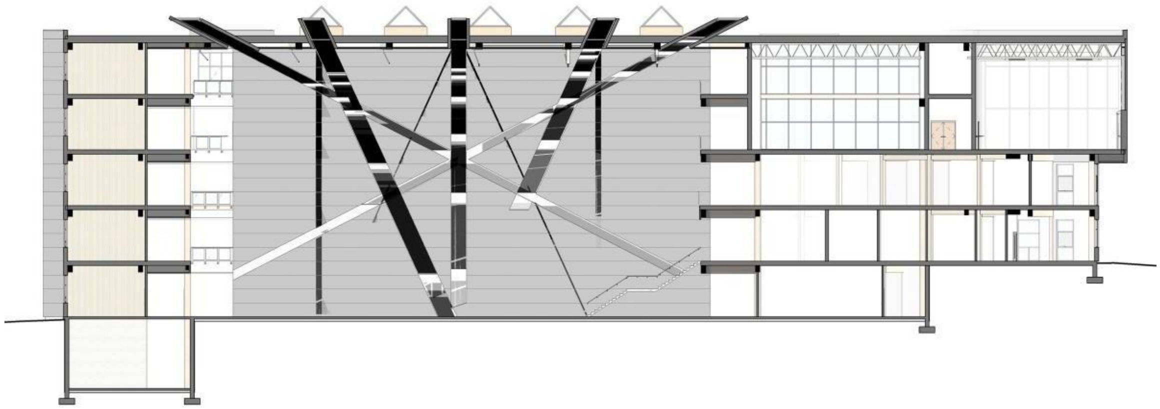


Figure 169, Darker bands represent more frequent sun.

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, demonstratingthat artificial light can also be incorporated into its use.

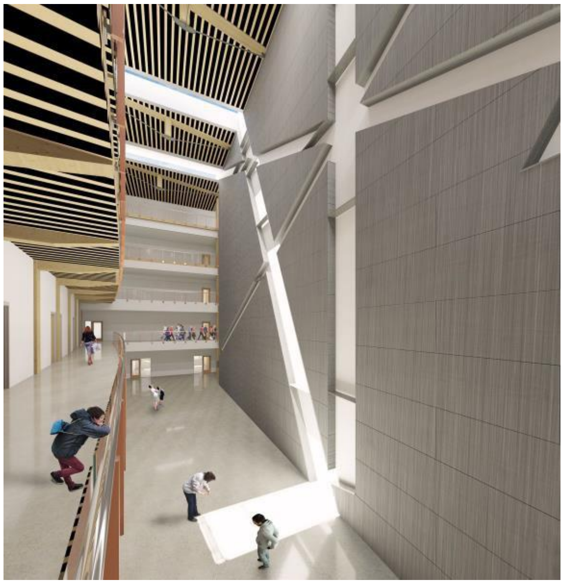


Figure 170, Sunlight reaching the floor.

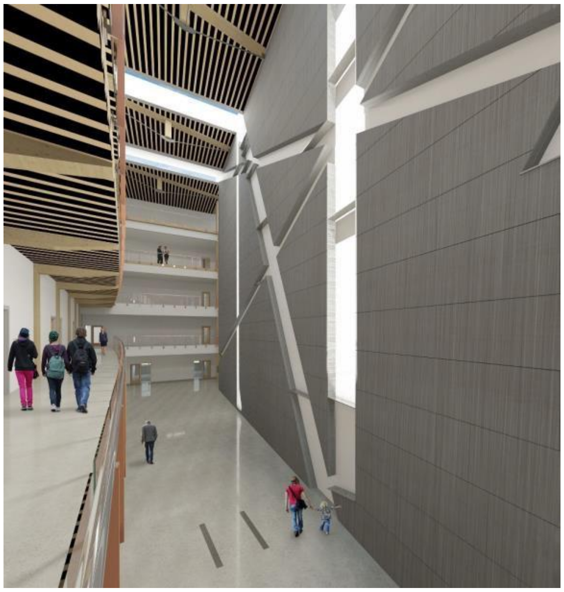


Figure 171, Sunlight reaching the July 21 projection.

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 designedto make the most of daylight was important for reducing electrical lighting dependency.

Figure 176, Typical south-facing office space.

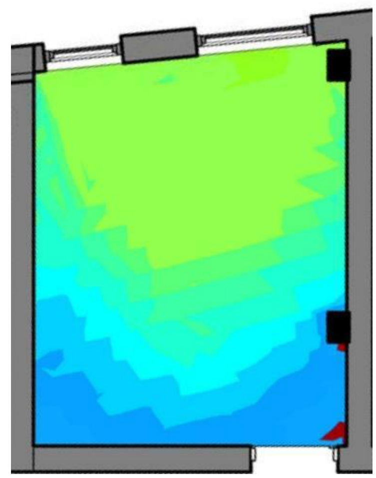


Figure 177, Typical north-facing practice room.

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.

Conclusion

The objective of this research 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-changingpattern of light on the walls. The five skylights in the academic atrium allow light to enterat 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, combinedwith 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.

CHAPTER VII

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 previouslyimagined. 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 ofglulam to create a uniquely shaped timber that became the focus of the atrium.

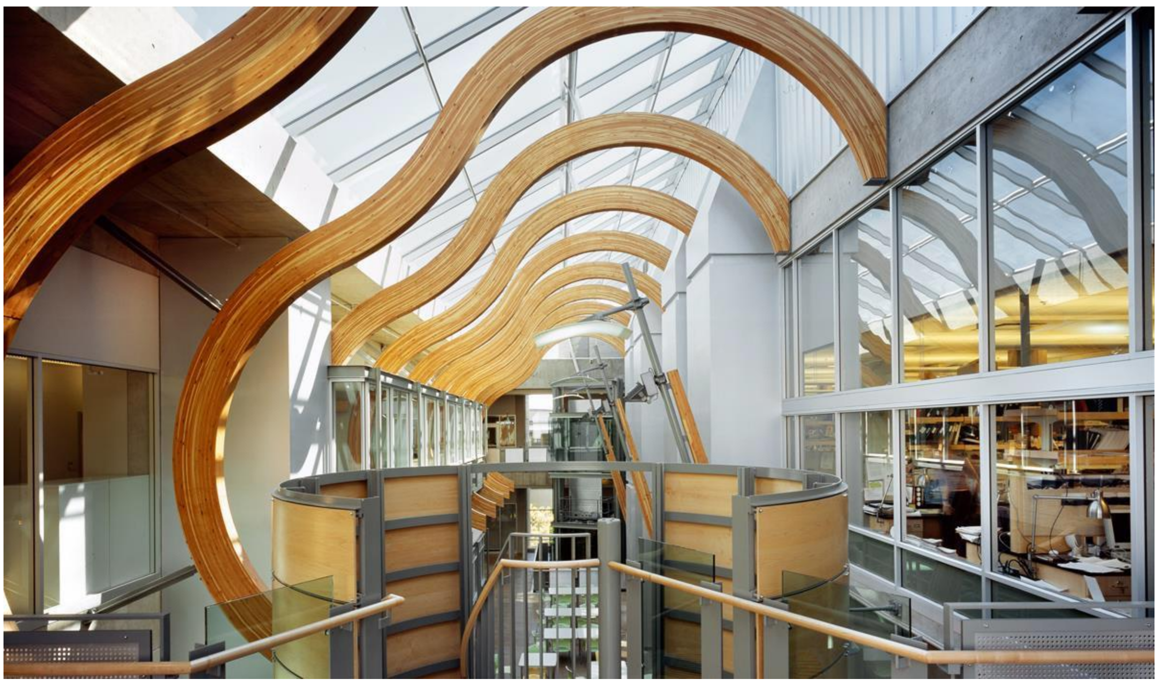


Figure 195, Atrium of the Michael Smith Laboratories Building at UBC. Henriquez Partners Architects

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.

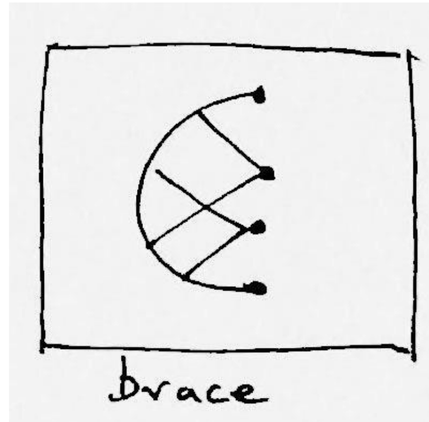


Figure 196, Brace. Cecil Balmond

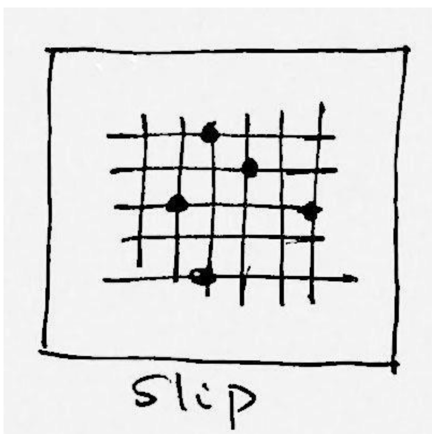


Figure 198, Slip. Cecil Balmond

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.

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.

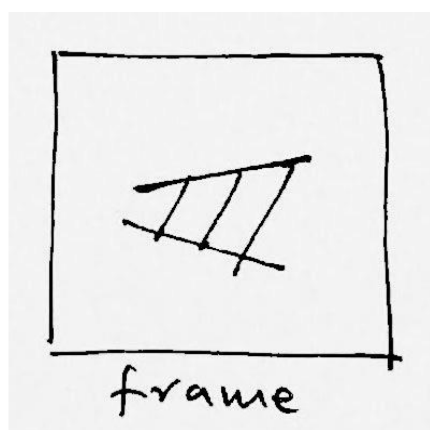


Figure 197, Frame. Cecil Balmond

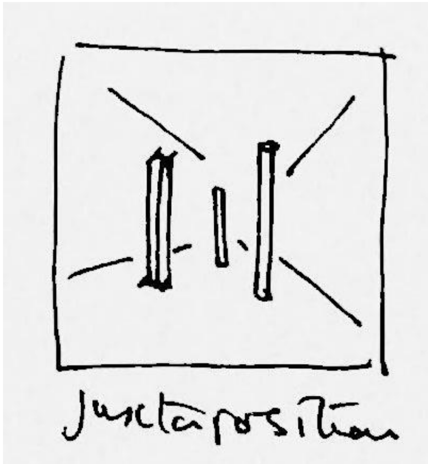


Figure 199, Juxtaposition. Cecil Balmond

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

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 andresulted 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.

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.

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

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 beadded 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.

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

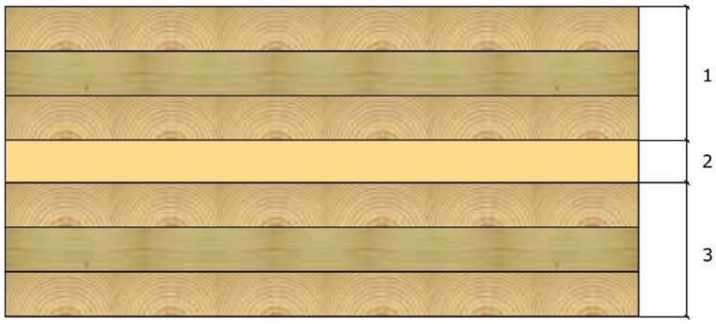


Figure 203, 3-ply CLT panel with mineral wool gap. CLT Handbook

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

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

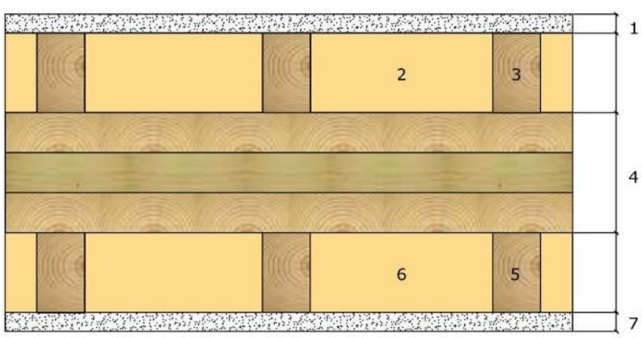


Figure 204, 3-ply CLT panel with studs/mineral wool gypsum board. CLT Handbook

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.

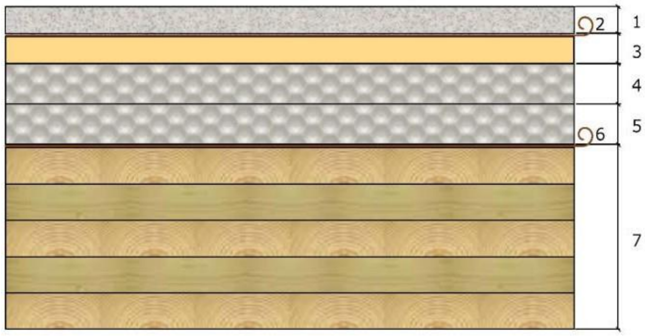


Figure 205, 5-ply CLT panel with acoustic infill and concrete topping. CLT Handbook

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

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.

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 systems, structural systems, paving systems, and more. The strength of concrete was trulyrealized 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, ortoo 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 theforms 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.

Precast Concrete

Precast concrete elements are cast and cured in factories, transported to the constructionsite, and then assembled together. Factories offerhigher 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.

Figure 242, Precast concrete stair runs.

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.

Marble

Marble is a recrystallized form of limestone that is easily carved and polished. It isavailable 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.

Limestone

Limestone is one of the two main sedimentary rock types used in construction. In the United States, Missouri and Indiana are majorproducers of limestone, in addition to France,

Figure 232, Limestone

Germany, Italy, Spain, Portugal and Croatia. Limestone is composed of calcium carbonate or acombination 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 groundwaterand is porous, but over time, the water evaporates and the rock becomes harder.

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.

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.

Figure 231, Rough granite.

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.

Steel

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.

Figure 237, Mild steel used for structural members.

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.

Metals

The use of metal as a mass building material grew rapidly with the introduction ofthe 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.

Aluminum

Unlike steel, which is an alloy, aluminum isits own periodic element, although alloys can be made from aluminum. It is rare to find the metal inits 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 isthen purified to produce aluminum. Aluminum's low density and corrosion resistant nature make it an ideal material for curtain wall mullions and cladding systems. Aluminum can easily be extruded to form a variety of shapes.

Figure 238, Aluminum cladding.

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

Figure 239, Copper plumbing pipe.

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.

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.

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.

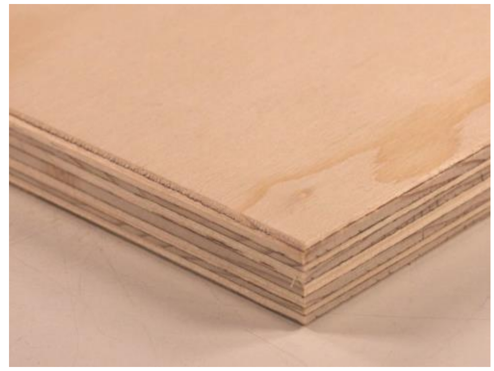


Figure 219, Plywood layer construction.

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)

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

Figure 220, OSB surface pattern.

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

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

Figure 221, Particleboard cross-section.

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 thatare 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 apress, where the glue is microwave-cured under pressure.

Figure 223, PSL beam.

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. 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.

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 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.

Quartz-Based Stone

Sandstone is also a sedimentary rock typeformed from deposits of quartz sand. Color and physical properties can vary greatly depending onthe 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.

Slate

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

Figure 234, Slate roof tiles.

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.

Zinc

Zinc is the fourth most commonly used metal in use, and the majority is mined in the formof 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.

Figure 240, Zinc standing seam roofing.

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.

Glass Fiber Reinforced Concrete

Glass fiber reinforced concrete (GFRC), ishigh-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. GFRC is typically usedfor cladding or decorative elements.

Figure 243, GFRC façade cladding.

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.

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