

ONLINE ARCHITECTURAL SKETCHING INTERFACE FOR SIMULATIONS

By

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ABSTRACT

Daylighting plays a significant role in architecture; its creative and efficient use offers aesthetics visuals, increased productivity, and reduced energy demand. However, poor implementation of daylighting systems can have adverse effects such as visual discomfort, solar heat gain, and an absence of energy savings.

As a result, architects turn to daylight analysis to predict daylight's affects on architectural spaces prior to construction. However, there are several challenges in daylight analysis that make prediction non-trivial and time intensive. Specifically, there are numerous factors to consider when visualizing daylight in an interior space. Daylight can vary depending on the season, the time of day, the cardinal direction of fenestrations, the geographic location , the spatial geometry, and the reflectance of materials.

Traditional approaches to daylight analysis require either the construction of physical scale model or development of virtual 3D models. Both methods are time intensive and can cause delays in the fast-paced schematic design phase of architecture.

I present a novel online sketching interface for simulations (OASIS) that is easily accessible to non-experts, providing them with the ability to generate 3D models for daylight simulation from 2D architectural sketches. This online sketching interface allows users to both quickly create 3D models and perform qualitative daylight analysis.

I propose that the online sketching interface for simulations(OASIS) is accessible and easy-to-use for both experts and novices. Additional, I speculate that OASIS a step in the right direction as an early design tool for daylighting analysis. My contributions include the development of OASIS, the conduction of an online pilot user study, and the analysis of results from that study.

CHAPTER 1

INTRODUCTION

Daylighting is the use of natural light and building geometry for aesthetically pleasing visuals and the creation of productive environments. However, daylighting is much more than just pleasing visuals and productive environments. Daylighting is also an environmental sustainability design practice for the creation of greener buildings and reduction power consumption. Similarly, daylighting can also be seen an economic means to reduce a building energy demands or increase worker productivity to generate capital. Despite the variety of definitions, daylighting will always refer to the use of daylight to met an architectural purpose.

Firstly, to understand what drives daylighting research a brief overview of daylight's advantages is necessary. In short, daylight is mainly valued as a source of illumination however recent studies show that daylight also offers economic and health benefits. Secondly, I explain why architects struggle with the design of daylighting systems. By and large, daylighting is challenging by virtue sunlight's dynamic nature. Moreover, daylight used incorrectly can cause occupants both visual and thermal discomfort. Lastly, I review architectural practices used in the design of daylighting system for the purpose of better following the advances . Briefly, architects exercise sketching techniques, follow rules-of-thumb, and consult daylighting visualizations to help guide the design of effective daylighting systems. All things considered, the motives that drive architects and building owners to employ daylighting systems also drive researchers to developer better tools for the design and analysis of daylight in architectural spaces.

1.1 Benefits And Motivations Behind Daylighting Systems

There are many benefits to using daylight over traditional electrical lighting. Recent studies show exposure to sunlight, offered readily through daylighting systems, has a variety of health benefits; benefits such as the stimulation of vita-

min D production and maintenance of healthy circadian rhythms. In addition to health-related benefits there are economic motives that drive architects and building owners to implement daylighting systems. Some economic motives include increases in worker productivity and overall reduced building energy demands. In short, daylighting system offer both economic incentives for building owners and health benefits for occupants.

1.1.1 Vitamin D

Vitamin D is an essential fat-soluble secosteroid required for healthy human functions. It aids in the absorption of calcium and other minerals. Vitamin D plays a significant role in the mineralization of bone[1]. Prolonged vitamin D deficiency can result in many serious diseases. Adults suffering from vitamin D deficiency can develop osteomalacia – the softening of bones. Children deprived of vitamin D can develop harmful diseases such as rickets. Children diagnosed with Rickets suffer from poor bone mineralization and are prone to bone fractures and deformity[2].

There are many ways to meet daily vitamin D requirements. For example, skin tissue is capable of creating vitamin D on its own, certain foods contain high concentrations of the vitamin, and dietary supplements fortified with vitamin D are readily available[1]. Human skin has a built-in mechanism that helps synthesize vitamin D through the exposure of Ultra Violet(UV) light. Light rich in UV hitting the surface of the skin will begin the processes of vitamin D synthesis. Synthesis through the exposure to sunlight meets most daily vitamin D requirements. Foods we consume are usually rich in vitamin and minerals. However, vitamin D occurs in significant concentrations in very few natural food items, such as fatty fish, particular species of mushrooms, and beef liver. Because of vitamin D's scarcity in naturally occurring food items and the harmful effects of deficiency vitamin D in children, companies fortify common breakfast food with vitamin D – such as orange juice, milk, and cereals. Lastly, Vitamin D can also be taken in pill form as a dietary supplement.

Working typical office hours in windowless environments decrease exposure to

daylight and increases the risk of vitamin D deficiency. Living an indoors lifestyle coupled with the widespread usage of sunscreen products created a vitamin D deficiency pandemic. Our skin does not synthesize vitamin D efficiently. Wearing sunscreen with an SPF of 15 absorbs 99% of UVB radiation and consequently, reduce the ability to synthesize vitamin D by as much as 99%[3].

Architectural daylighting can help alleviate this risk by creating buildings with apertures and geometry that promote deep penetration of natural lighting into a building's interior. Daylight is rich in UV radiation required for vitamin D synthesis. Daylighting systems could, in theory, help occupants keep occupants healthy by passively enabling occupants to meet their daily vitamin D requirements.

1.1.2 Circadian Photobiology

Daylighting has influence over our circadian photobiology. Circadian photobiology is the human experience hormonal and behavioral changes throughout a roughly 24-hour cycle. The hypothalamic suprachiasmatic nucleus (SCN) in the brain, which relies on input from non-rod/non-cone photoreceptor systems located in our retina, regulates these non-image forming light responses. These non-rod/non-cone photoreceptors are excited by exposure to alternating periods of light and dark. They specifically respond to lighting conditions found in daylight[4, 5].

Electrical lighting varies from daylight a couple of biologically important ways[4]. Daylight offers a higher levels of illumination, a wider spectrum of electromagnetic radiation, and a temporal variation in lighting. Firstly, sunlight in conjunction with skylight, measures anywhere between 10 to 100 thousand lux[6]. However, the government agency of Occupational Safety and Health Administration (OSHA) set 322 lux as the minimum of lighting requirement for typical office work[7]. Lighting conditions that do not excite photoreceptors responsible for maintaining our circadian rhythm are essentially biological darkness[8]. Secondly, the spectrum of light emitted by artificial lighting lacks short wavelength electromagnetic radiation found in

sunlight. Varying wavelengths of electromagnetic radiation affects melatonin levels in humans as much as varying intensity of light. Melatonin suppression is necessary because it plays a role in sleep-wake cycles, body temperature regulation, alertness, and blood pressure[9]. Studies show melatonin suppression varies most through exposure to short wave electromagnetic radiation [10]. Consequently, daylighting systems offer the advantage of exposure to short wavelength electromagnetic radiation needed for melatonin suppression. Lastly, exposure to light during periods of the day asynchronous to our circadian rhythm can result in shifts in our sleep-wake cycles. These shifts, known as phase shifts, triggers melatonin suppression at particular times. For instance, morning light exposure triggers melatonin suppression resulting in the feeling of alertness[4]. However, exposure to light at asynchronous times of day results in a phase shift. An unexpected phase shift can have symptoms similar to jet lag and significantly hinder productivity[4]. Daylight availability during those crucial morning hours could potentially have significant impacts on employee productivity.

1.1.3 Increased Productivity

Studies show daylighting systems increase both the productivity and comfort of occupants[11]. Daylighting increases workplace productivity and satisfaction through a variety of means. To begin, the human eye as image processing system has evolved over millions of years to work optimally under full spectrum illumination provided by sunlight and skylight. It is not surprising that the human visual system works better using daylight as a source of light. A visual task, such as reading, generally require less illumination when using daylight as opposed to electrical lighting[6]. Additionally, daylight provides superior color rendering. Our visual system is tuned to differentiate colors under full spectrum illumination. Differentiating colors under low illumination or fluorescent lighting is not as reliable as compared to daylight[6]. There are current electrical lighting systems that provide full spectrum light, however, these systems are very costly when compared to daylight. Moreover, occupants enjoy being near windows since it gives them information about their

outdoor environment – including the time of day, weather conditions outdoors, and activities happening outside. Having a workstation near a window could evoke a feeling of importance in occupants. This feeling of importance increases worker satisfaction and could possibly increase productivity[8]. Overall, the satisfaction of occupants is important to architects and managers, because adverse environmental factors hinder productivity in a workspace.

These gains provide a financial benefit to companies investing in daylighting systems. However, focus groups and interviews with professionals conducted show that architects prioritize the comfort and productivity of a building's inhabitants over a building's sustainability[11]. Meaning building designers see daylighting as means to make occupants comfortable through use of natural lighting, rather than as an eco-friendly lighting system.

1.1.4 Reduced Energy Demands

There are direct economic gains from daylighting systems. Energy saving from reducing electrical illumination use save building owners money. It is important to note that daylighting systems do not directly save capital, rather daylighting systems give building owners the opportunity to conserve energy by using sunlight as an alternative or supplement to electric illumination. Electricity companies charge peak hour rates during the afternoon when demand for electricity is highest. During these hours alternative sources of light, such as daylighting, become cost effective. It is hard to estimate how much energy savings with daylighting systems. Simulations are an important tool architects use to determine energy cost saving during the design development processes. Lighting usually accounts for about 25-40% of a total building energy demands. According to one study daylight can save up to 52% of energy on a wall adjacent to a window[8].

Using daylight as an alternative or supplement to electrical lighting requires some form of daylight management. Daylighting management requires dimming

systems that dim electrical lighting during the peak hours when daylight is most available. Some simulation results show that when there no lighting management in place, power consumption from lighting can exceed 50% of a building's total power demand. However, those simulations also show daylighting can save a building up to 18% to 55% of a building heating and lighting demand[12]. Without a dimming system, the window of time in which daylighting is cost effective is significantly smaller. Other simulation results showed energy savings of 60% with daylighting and dimming control strategies[13].

Also, dimming lights result in reduced thermal output from lighting fixtures. Which in turn reduces the total cooling load required in space. The reduced cooling load also contributes to energy saving in daylighting systems[8]. In addition to reducing the cooling load, daylighting can also be used for heat gains during the winter. Daylighting systems exploit the shallow sun angle in the winter months and allow winter sunlight into a building. Heating a large space is expensive, and sunlight can aid in heating[12].

1.2 Challenges Of Designing Daylighting Systems

Daylight has many benefits over traditional electrical lighting, however, reaping those benefits is not effortless. There are many factors architects have to consider when designing a daylighting system. Choices made during the early stages of design can have extensive impact on the effectiveness of a daylighting system. Likewise, design choices can also result in visual discomforts for occupants and economic loss for building owners. By and large, architects planning daylighting systems are required to analyze numerous designs' affect on daylight. Furthermore, architects have to be cautious of sunlight's dangers to both occupants and building owners.

1.2.1 Factors That Affect Daylighting

Illumination of an architectural space via daylight is dependent on numerous factors including building-wide design choices, room-specific choices, and temporal

variations. These factors make it difficult to access the quality of a design in terms of daylighting.

Building-wide Design Choices The cardinal orientation of a building is a choice that directly affect how daylight will illuminate architectural spaces. In the northern hemisphere, windows facing the south cardinal direction experience direct daylight throughout the day. On the other hand, north facing windows do not experience this effect. Rather north facing windows experience indirect diffuse illumination from the sky. The opposite is true in the southern hemisphere. In the south, north facing windows experience direct daylight and south facing windows experience diffuse indirect light. Likewise, windows facing east experience morning sunlight and windows facing west experience evening sunlight. Variations in eastward and westward lighting are a result the sun's eastwards to westwards path across the sky[6]. See Figure 1.1 for an illustration.

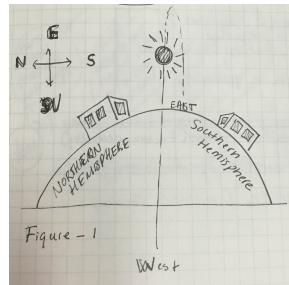


Figure 1.1: This illustration shows why windows facing southward in the northern hemisphere experience direct daylight and windows facing northward do not. It also shows the converse, north facing windows in the southern hemisphere experience direct lighting, however those facing southward do not.

Aside from building orientation, building elevation can affect daylighting as well. Varying building elevation can change how daylight illuminates an architectural space. For example, a building located well above sea level will experience a slight difference in daylighting compared to a building below sea level. Daylight usually enters a space either perpendicular to a flat window pane or at a downwards angle starting from the Sun and ending at the floor and walls. However, a skyscraper could potentially have daylight enter a space at an upwards angle towards the ceiling

due to its increased elevation.

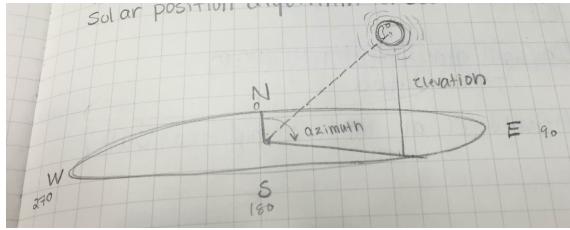


Figure 1.2: Illustration to show elevations and azimuth used to find the sun's position in the sky

$$E = \sin^{-1}(\sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(HRA)) \quad (1.1)$$

$$A = \cos^{-1}\left(\frac{\sin(\delta)\cos(\phi) - \cos(\delta)\sin(\phi)\cos(HRA)}{\cos(E)}\right) \quad (1.2)$$

Just as important as building orientation and elevation, where a building is geographically built has direct impact on daylighting. Specifically, the path the sun travels across the sky varies with geographic location and time. Equation-1.1 and equation-1.2 are commonly used in daylighting to calculate the sun's position in the sky. The elevation angle, given by Equation-1.1, is the angle between the horizon and solar zenith, as illustrated in Figure 1.2. δ in equation-1.1 and equation-1.2 refers to the solar declination angle. Lastly, ϕ is the latitude of interest in both equations and HRA is the hour angle in local solar time. The azimuth angle, as shown in Figure-1.2, is the angle between the cardinal north direction and the direction the sun projected down towards the horizon. The azimuth can be found once the elevation angle has been found, as show in equation-1.2. As shown in both equations, the sun's position in the sky is relative to longitude, latitude, and temporal variables.

Room-specific Design Choices Room-specific design choices also have an impact on the daylight. The geometry of an interior space directly affects the distribution of daylight in a room. Geometries can be designed to diffuse direct lighting for uniform illumination and occupant comfort. Similarly, shading devices and material

properties of interior objects can affect daylighting. Shading devices, such as blinds can not only help diffuse direct lighting but also help redirect lighting up towards the ceiling, where it can be diffusely reflected back down towards occupants. Also, a careful selection of both the color and the material of interior items such furniture, walls, and ceiling can affect daylight's distribution in an interior space.

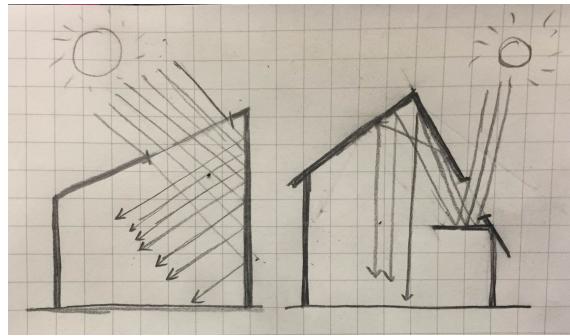


Figure 1.3: Left: a common skylight placement on the roof of a building. The angled roof is designed to let daylight diffuse as it reflects on towards the floor. Right: A light shelf that helps redirect daylight up towards the ceiling, where it can be diffused and reflected back down on towards the floor.

In addition to material and shading devices, window placement and size directly influence daylighting. Larger windows and skylights allow more light to enter a space, however, poses the risk of over-illumination and glare for occupants inside. Likewise, the glazing material used to treat windows can also be used to control the amount and distribution of daylight entering a space. The glass used in commercial buildings are glazed to block a significant portion of light from entering a space. Glazing are used because direct sunlight would cause over-illumination, thermal discomfort, and harm to the occupants situated near windows. Special glazing can also be used to help diffuse lighting up towards the ceiling and away from occupants. The choices that architects make in room-specific design significantly affect the daylighting.

Temporal Variation It is obvious that daylight varies from sun raise to sun set. Less obviously, daylight also varies throughout the year. The Sun's position in the sky is shallower during winter season than in the summer season. Due to this,

during the winter months daylight enters a room at a shallower angle allowing light to travel deeper than in the summer months.

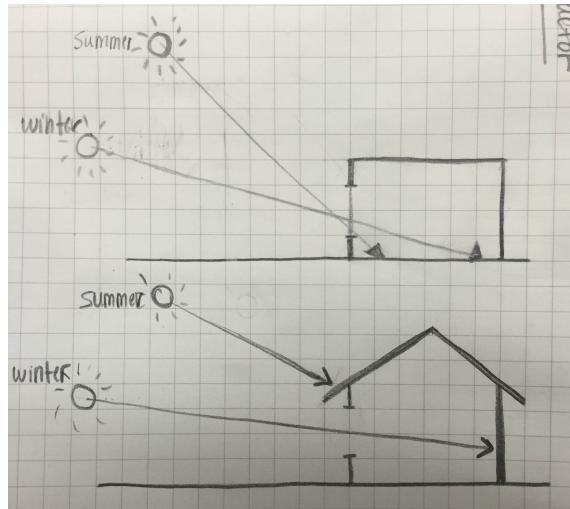


Figure 1.4: Top: illustration to visualize the difference in light penetration during the winter and summer seasons. Bottom: a common daylighting technique is extending the roof to block light during the summer season, but not during the winter season.

Architects interested in sustainability, exploit this by extending the roof thus allowing daylight to enter during the winter and blocking direct daylight during the summer as shown in Figure-1.4. Weather conditions also play an important role in the distribution and intensity of daylight. During clear days, direct sunlight can enter a room and cause over illumination and glare. However during cloudy days, sunlight is diffused by clouds resulting in daylight that is more uniform and diffuse. Weather conditions also vary by location, for example in upstate New York, cloudy skies are common, however in Florida clear skies are more frequent. A Daylighting systems would be more efficient in locations with clearer skies then in locations where clear skies are uncommon.

Overall, daylight varies due to many factors. It varies depending on temporal factors, room-specific design choices, and building-wide decisions. These numerous factors make the distribution of daylight in a architectural space non-trivial to predict. These difficulties pose a real challenge in the designing of effective daylighting systems.

1.2.2 Adverse Daylighting Effects

As previously discussed, daylighting systems offer occupants a variety of benefits. However, poorly implemented daylighting systems can result in discomfort to occupants and increases in a building's energy demand.

Occupant Discomfort Human vision can be understood and compared to an image processing systems. We require strong contrast and ample illumination to be able to clearly view and process symbols. The performance of visual task, such as reading, varies depending on the illumination provided and clarity of the font. Under-illumination can make reading difficult and reduce worker productivity[14]. Under illumination can occur in daylighting systems when daylight available is below a threshold to perform a specific visual task. The Occupational Safety and Health Administration (OSHA) set mandatory minimums on illuminations for common settings including offices, hallways, and warehouses to name a few. Offices for example require a minimum of 322 lux. Similarly, hallways and warehouses have lower minimums set because there is no need to focus on fine details[7].

Another visual discomfort that can occur from poor daylighting is glare. Glare is a reduction of contrast due a disproportionate amount of illumination from glare sources compared to illumination on a visual task. Glare is hard to account for in the early design stages of architecture because glare is dependent on not only sources of illumination but also on viewpoint. Specifically, there are two main forms of glare – disability glare and discomfort glare.[6] Disability glare occurs when a glare source is intense enough that it rendered the viewer momentary blind. This kind of glare commonly occurs when driving at night and cars are passing in the opposite lane. The strong light emitted from headlights would reduce the contrast of the road ahead and might result in momentary blindness. Likewise, discomfort glare is similar to disability glare but much less dangerous. Discomfort glare is also caused from bright glare sources, such as the Sun or light reflected from the Sun, that making visual task difficult to perform. Unlike disability glare, discomfort glare does not cause momentary blindness. Prolonged exposure to discomfort glare when

focusing on a visual task, however, significantly reduces both worker productivity and worker satisfaction[14]. Another visual discomfort, common in office environments, includes veiled reflection. Veiled reflections are the result of light reflecting off a surface directly into the eyes of the viewer. For example reading an article from a glossy magazine in direct sunlight is challenging because at certain viewpoints the gloss on the page reflects light into your eyes reducing the contrast between both the black and white letters. Veiled reflections, like glare, are difficult to predict because they are viewpoint dependent.

Lastly, occupants sitting near windows can experience thermal discomfort at certain times of day. Daylight can be useful in warming up a space during the winter, however can also cause discomfort during the summer. Not only does unattained solar heat gain cause occupants discomfort, solar heat gain can also discomorts building owners.

Economic Loss Another possible adverse product of daylighting systems is unintended solar heat gain. Solar heat gain is the increase in temperature inside a space due to daylight. If too many windows are installed in particular location, a room can experience unintended solar gains. To counter solar heat gain, cooling system must work at a higher load then usual resulting in increased energy usage. Furthermore, windows unless insulated well can result in heat loss during the winter. Rooms with many windows might let in a lot of daylight, but might also come at the cost of increased heating cost during the winter months.

Lastly, occupant behavior can result in lose of investment capital for building owners. Occupants exposed to the visual discomforts of daylight can choose use window blinds to block daylight out entirely. If blinds are lowered then electrical lighting is used in place of daylight. The use of electrical lighting, given available daylight, results in reduced energy savings for the building owners. Moreover, daylighting systems are expensive to design and implement and as a result the initial cost is generally greater then using traditional electrical lighting. If occupants con-

tinuously choose electrical lighting over daylight, the break even point of the initial investment in a daylighting system is pushed back further – essentially costing the building owner capital. Architects are then faced with the challenge of not only making visually pleasing lighting conditions, but also avoiding discomforts caused by daylight.

1.3 Daylighting In The Architectural Design Processes

The architecture of a building from concept to construction is no easy task. As a result, architecture firms generally break down the architectural design process into 5 manageable phases[15]. Daylighting affects all phases of the architecture design process, however choices made in the early design of an architectural lay the foundations of a daylighting system. Our focus lies in the early stages of the design processes: the schematic design phase. Nevertheless, we will briefly cover all of the architectural design process to give the reader a better understanding on the significance of the schematic design phase.

1.3.1 5 Phases of Architectural Design Processes

To give the reader a better context of where the schematic design phase occurs in the architectural design process the topic is briefly covered here. The five phases of the architectural design process are: the schematic design phase, the design development phase, the construction documents phase, the bidding phase, and the construction administration phase. During the schematic design phase architects consult with clients to understand project specification and goals. Architects then produce drawings, sketches, and scale models of possible designs to show the client. A design from the schematic design phase is expanded upon in the design development phase. More details are added to the sketches, window placements, and utility systems are laid out. With client approval, architects then begin creating formal construction documents. During the construction document phase, architects generate documents that are later used by contractors as blueprints. Once the blue prints are complete architects search for possible construction contractors. During the bidding phase architects take bids from contractors interested in the project.

After contractors are found the architects oversee construction project. This final phase of the architectural design processes is known as the construction administration phase. Daylighting plays a role in each phase of the architectural design process, however, the choices made in the schematic design stage lay the foundation for an efficient daylighting system.

1.3.2 Daylighting In The Early Design Phase

During the schematic design phase architects employ a variety of strategies and techniques to guide their designs for optimal use of daylight. Firstly, rules-of-thumb and simple calculations are used during the early stages of design, when building form, space, and order are conceptualized. Secondly, architects can analyze sketches to predict the distribution of daylight in interior spaces. With enough practice sketching becomes a fast and easy way to express visual concepts. As a result, sketching is still the main medium during the early design phase, when being able to quickly express ideas is crucial.

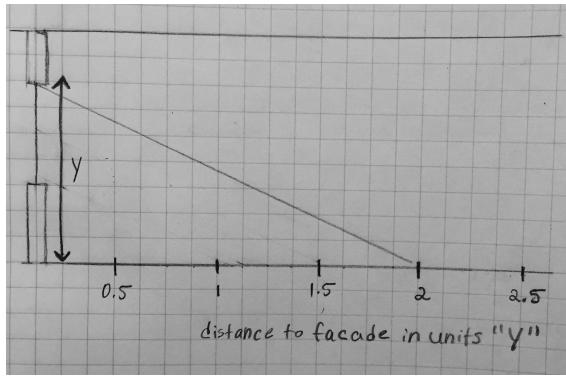


Figure 1.5: Verified rule-of-thumb: The depth of usable daylight is 1.5 to 2 times the window-head-height. Here the windows-head-height is depicted as y .

Rules-of-Thumb A rule-of-thumb is a general suggestion, usually acquired through experience, that architects follow when designing spaces. Many rules-of-thumb are widely accepted in practice, however, only few have been validated[16]. Furthermore, many designers using these rules-of-thumb do not have an understanding of the underlying principles behind them[17]. Nevertheless, these rules are still used in practice because of ease to incorporate into designs, and general effectiveness.

Some common rules-of-thumb include simple suggestion about where to locate people within a space. For example, it is suggested that designers take advantage of the floor area within the daylight zone by situating people within it. [8] Moreover, architects suggest visual task be placed near the building parameters[8]. To elaborate, the daylight zone is a range of space where illumination from daylight provides a comfortable workspace. The daylight zone does not take direct daylight into consideration, but rather diffuse skylight. A validated rule-of-thumb is regularly used to find the rough range of the daylight zone[16]. The daylight zone extends to about 1.5 to 2 times the window-head-height away from the wall containing the window, as illustrated in Figure-??.

Another common rule-of-thumb is the elongation of the east-west axis of a building. The elongation of a building along the east-west axis is supposed to avoid solar heat gain and create more room for north facing windows[8]. As explained previously, north and south facing windows, depending on your location, can provide either day-round diffuse or direct daylight. However daylight from east and westward windows vary significantly throughout the day. As a result another general rule of thumb is that south and north facing windows are the preferred over east and westward windows[18].

Daylight distribution and comfort within an interior space depends on more than just window placement and size. A general rule-of-thumb is that light colored interior surfaces help reduce the contrast between windows and interior spaces[8]. Moreover, the reflectance property of walls, windows, floors, and furniture impact daylight distribution. One more rule-of-thumb is that ceiling have a reflectance of at least 80%, walls of at least 50-70%, floors of at least 20-40%, and furniture of at least 25-45%[18].

It is important to note that rules-of-thumb, while not all validated help guide daylighting design due to ease of use these suggestions offer and the ability to abstract away the complexities of daylight.

Sketch Analysis Sketches are the primary medium architects use to convey visual ideas during the schematic design phase. Sketches help externalize concepts

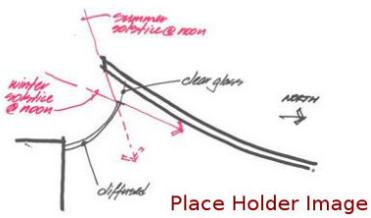


Figure 1.6: Example of brainstorming daylighting on sketches

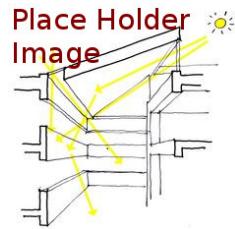


Figure 1.7: Example of brainstorming daylighting on sketches

and ideas for both problem solving and rough daylighting analysis[19, 20]. It is not surprising that sketches are also widely used in the brainstorming of daylighting system. Figures 1.6 and ?? are some common examples of how architects use sketches to problem solve and do a rough prediction of daylight distribution. To do a rough prediction of where daylight will fall in a sketch, architects first draw a cross section of their imagined space. They then using specialized protractors, architects can deduced at angle the sun will enter a space in their sketch[21]. Drawing multiple rays parallel to the sun angle onto the sketch and calculating where those rays reflect, will give designers an idea of the distribution of light in the room. More examples of these kinds of illustrations are shown in Figure-1.3.

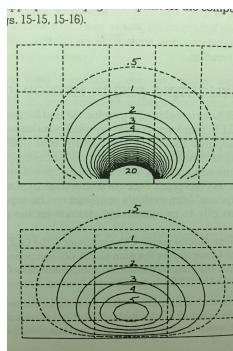


Figure 1.8: This is the overlay used to trace contour lines in the GDDM method. There are many and simple calculations are used to decide which overlay to use.

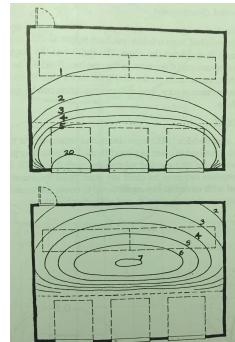


Figure 1.9: This is a finalized sketch with combined overlays show the distributions of daylight in a space.

Sketches can also be used for more than just brainstorming general forms and geometries of architectural spaces. Detailed analysis, with the aid of specialized

tools, can be done on sketches as well. One such method is the Graphic Daylighting Design Method (GDDM)[22, 23]. The GDDM method can be used to predict daylight illumination given an overcast. The GDDM shows not only where lighting will fall but also the intensity of lighting using contour lines. To use GDDM, first architects draw a floor plan of the room, making note of where windows are located. Using a series of specialized overlay architects can draw contour lines defining both daylighting distribution and intensity such as seen in Figure 1.8 and 1.9. These analytical sketches allow architects to reflect on their designs and make renovations to improve lighting conditions. The GDDM technique and other basic sketch-based brainstorming strategies help architects perform analysis on sketches quickly during the earliest stages of design.

1.3.3 Daylighting After The Early Design Phase

Daylight plays a role in every phase of the architectural design process. For example during the design development phase architects will create either scale physical models of a building or create 3D virtual models. These models are used for much more detailed analysis compared to analysis during the schematic design phase. More information about these detailed daylighting analysis methods is covered in the next chapter.

CHAPTER 2

RELATED WORKS

2.1 Virtual Heliodon

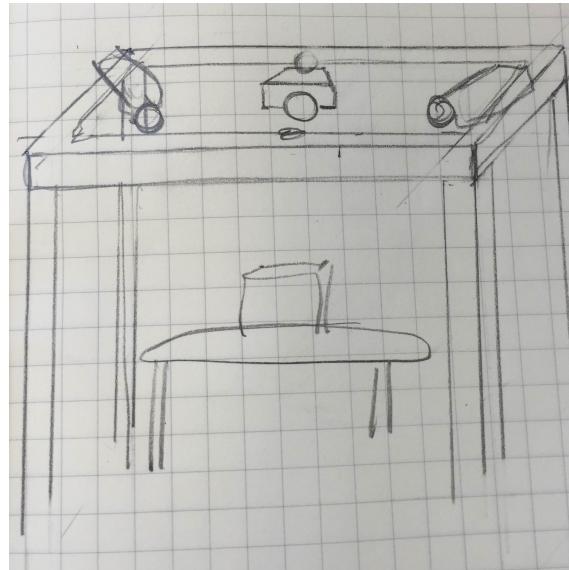


Figure 2.1: Overview of the Virtual Heliodon. Note the projector arrangement and circle table at the center.

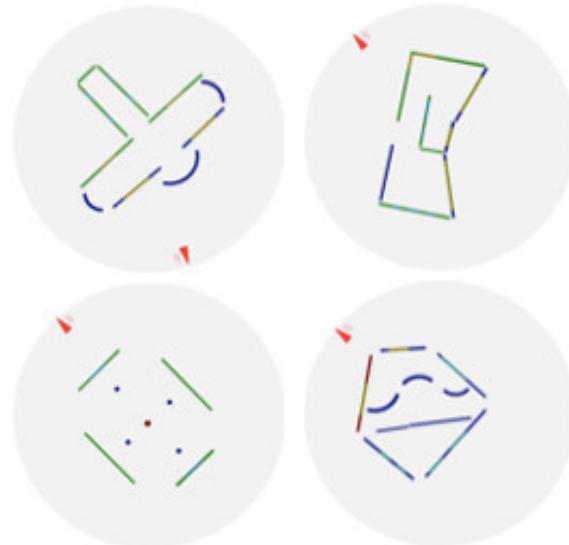


Figure 2.2: Example physical sketches created by users on the Virtual Heliodon

The Virtual Heliodon is a spatial augmented reality with a tangible user interface for the early collaborative design of interior spaces with daylighting[24, 25, 26, 27, 28]. Succinctly, the Virtual Heliodon is composed of multiple projectors, a circular table, and a collection of foam primitives. A large chassis holds the projectors above the table top at evenly spaced intervals. These projectors all face towards the table top at the center of the system; The configuration of the Virtual Heliodon is shown below in Figure-?? This tangible user interface lets users physically engage with wall primitives. Users can define architectural spaces by moving and rotating wall primitives on the table top. Some architectural spaces created on the Virtual Heliodon are shown in Figure-??. Then a network of computers use the projectors to display daylighting simulation renderings onto the foam primitives placed on the table. In order to project on all wall primitives on the table top multiple projects in varying positions are used. Projecting daylighting rendering directly onto wall primitives creates an augmented reality environment that gives users a sense of immersion[27]. The virtual Heliodon has gone through evaluations and has been proven to be engaging and valuable as an educational daylighting tool[27].

2.2 Physical Sketch Interpretation Algorithm

Cutler et al. conducted evaluations on the effectiveness of physical sketch interpretation algorithm used in the Virtual Heliodon[25]. This studies compared user's intended interpretation of the physical sketches to both the algorithm's interpretation and other user's interpretation. In brief the study concluded that on average the physical sketch interpretation algorithm matched users intended interpretation 78% of the time given non-ambiguous models[25]. Aside from ambiguous sketches, the Virtual Heliodon provided reliable 3D geometries that matched user's intended floor plan designs. OASIS uses the same physical sketching interpretation algorithm employed in the Virtual Heliodon.

Interpreting sketches is not the only method of turning concepts into 3D models. Traditionally, both parametric and geometric modeling are used to create 3D models of architectural spaces. Daylighting analysis tools such as Home Energy

Efficient Design tool(HEED) and eQuest use parametric modeling to generate 3D models of an architectural space[29, 30]. Parametric modeling is the creation of model from a template by specifying the parametric such as wall lengths, walls heights, and window positions through numerical entry. Both HEED and eQuest are intended for use in the schematic design phase and offer a large variety of energy analysis measures. Due to the high cost of effort in parametrically designing an architectural space, both HEED and eQUEST feature wizards to guide users through the process. Geometric modeling is another modeling approach used by many architectural modeling software. SketchUp and AutoDesk are both popular architectural design tools that use geometric modeling for the generation of architectural spaces. Geometric modeling gives users the ability to create 3D objects by modifying basic shapes visually; This modeling approach is similar to modeling with clay. The process of imagining a space and geometrically modelings that space in software is non-trivial. Being able to geometrically model complex 3D geometries is an art that requires precision and a deep understanding of the geometric tools available. As a result, the modeling of architectural designs in software is usually pushed back into the design development phase when fewer iterations a design are required[17].

In practice, manual sketches are still used during the early design phase, because of the speed & efficiently sketching offers designers[17]. As a result researcher has been done on architectural sketching interfaces. LightSketch and the VR SketchPad project both incorporate architectural sketches into the early design phase[31, 32]. Specifically, LightSketch shares much in common with OASIS. LightSketch gives users the ability to draw walls, windows, and interior lighting elements to define architectural spaces[32]; The drawings are interpreted and turned into 3D models. Users can then perform daylighting analysis and generate renderings from generated 3D models. LightSketch, however, is limited to shoe-box geometries for rooms. Users cannot freely design a wide variety of non shoe-box of floor plans as is possible in the VR SketchPad project and the Virtual Heliodon. The VR SketchPad project supports the creation of 3D models of a wide variety of architectural spaces[31]. Furthermore the VR Sketchpad was available as an online

tool, similar to OASIS. The VR SketchPad project however does not distinguish between interior and exterior spaces but instead just renders objects where users sketch them. Sketches in the Virtual Heliodon get converted into water-tight models that are required for daylighting simulations.

2.3 Daylighting Render LSVO

In addition to using the Virtual Heliodon’s physical sketch interpretation algorithm, I use the Virtual Heliodon’s GPU photon mapping rendering engine[33, 26]. This rendering engine is specialized to provide viewpoint independent daylight renderings at interactive rates. The Virtual Heliodon’s rendering engine takes advantage of NVidia’s Optix GPU ray tracing framework for the parallelization of photon mapping[34]. Concisely, photon mapping is the approximation of global illumination by tracing rays outward from emitters and then gathering photons after several bounces to calculate indirect illumination per triangle or patch[35]. When photons leave emitters their position and direction are chosen at random, however, a photon’s intensity is a function of its direction as defined by the International Commission on Illumination’s sky models[36]. Other daylighting renderer, such as Radiance require more time to produce clear and noise-free results[37]. However, Radiance is validated and a result Radiance is widely used as a back-end component to several daylighting tools[38, 17]. While, the Virtual Heliodon’s rendering engine has not been directly validated against Radiance, the rendering engine has been validated against a radiosity based render. This radiosity based renderer, used in previous versions of the Virtual Heliodon, was validated against Radiance[39]. In brief, the Virtual Heliodon’s rendering engine serves our needs as a fast renderer for qualitative analysis during the early stages of design.

2.4 Related Software

OASIS shares goals in common with many other daylighting analysis software. Increased value on sustainability and energy efficiency drives the development of simple analysis tools for use in the early design phase of the architectural design

processes. One such piece of software is AutoDesk’s latest early design tool, Project Vasari[? ?]. Project Vasari is a stand alone geometric modeling tool with a similar interface as AuthoDesk’s Revit[?]. Project Vasari, unlike Revit, was designed for energy analysis during the conceptual design of architectural spaces. As a result, Project Vasari comes packaged with win. client, daylighting, and whole building energy analysis visualizations. Another tool with similar features is Ecotect – an AutoDesk plug in[40]. Ecotect offers a collection of useful visualizations such as sun paths, previews of building shadows, and daylighting factor visuals. SketchUp is another notable conceptual design tool[41]. Although SketchUp does not directly support energy analysis and advance daylighting features, there are a handful of plug ins that do. for example VE-Ware by IES is a free energy and carbon plug in for SketchUp and Revit[?]. VE-Ware, given a model created in SketchUp will generate detailed energy analysis reports. Generally, energy analysis plug ins that support daylighting measurements, exist for most major architectural modeling softwares. For instance, Rhinoceros, as general 3D Modeling tool commonly used for creating architectural models, supports plugs in such as LadyBug for basic energy analysis[? 42]. Also, another noteworthy extension to SketchUp includes Lightsolve[43]. While Lightsolve is not officially a SketchUP plug in, it does support importing models directly from SketchUp. LightSolve is noteworthy because the tool’s main focus is on daylighting analysis. Anderson et al. developed Lightsolve as an early design daylighting analysis tool that gives designers not only annual metrics but also qualitative renderings of their designs. Within the application designers could analyze both quantitative illumination metrics of particular locations in a design but also view renderings of those locations from multiple viewpoints. Lightsolve also provides visual sun positions and elevation information on the same page as the daylighting metrics and renderings. All of these visual elements on the same display offers designers a better understanding of daylighting conditions within their designed architectural spaces[44]. On the whole, all of these tools offer rich and informative daylighting analysis during the conceptual design of architectural spaces. However they all in some way rely on geometrically created models. During the conceptual/early design stages of architectural design, the ability to express concepts

as 3D models quickly is invaluable. As a result , researchers have investigated faster and more initiatives ways to generate 3D models for daylighting analysis.

CHAPTER 3

Feature Design

3.1 Online Sketching Interface

3.1.1 Overview

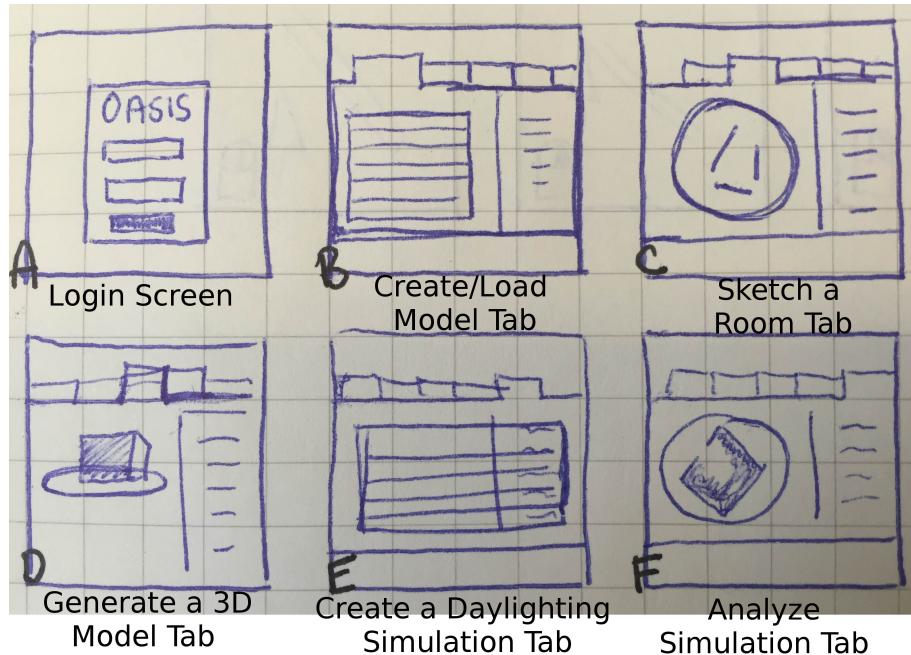


Figure 3.1: This is an overview of the tabs and menus available on OASIS.

The novel online sketching interface used in OASIS host a variety of features. The sketching interface, as seen in figure-3.1 was designed to be both familiar and intuitive to users. I used RibbonJS, a JavaScript port of Microsoft's Ribbon user interface, in order to present tools to users in a familiar fashion^[1]. In brief, the user interface is segmented into five main pages. Each of these pages are accessible through respective tabs located the top of the Ribbon, as shown in Figure-???. Each tab, and respective page, allows users to interact with different portions of our system pipeline. Navigation between pages can be both linear and non-linear. I recommend that first time users follow pages and tabs linearly. After a successful login, the first page users are directed to is the *Create/Load Model* page. The *Cre-*

ate/Load Model page contains a selectable list of users' previously created sketches and a button start a new sketch.

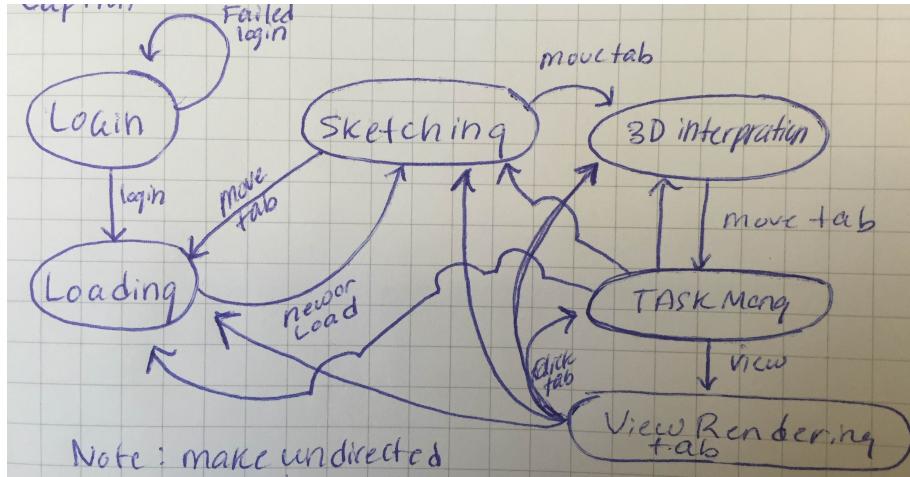


Figure 3.2: State diagram between pages and menus on OASIS.

Given users follow our interface linearly, the next page encountered is the *Sketch a Room* page. In the *Sketch a Room* page, the user can sketch floor plans to define an architectural space. After the user has created a sketch, the next page encountered is the *Generate 3D Model* page. On the *Generate 3D Model* page, the user will view a 3D interpretation of their sketch. The user can then generate day-light renderings by navigating to the *Create Daylighting Simulation* page. While on the *Create Daylighting Simulation* tab the user can either create new renderings or view previously created renderings. Figure-3.2 illustrates how page navigation can be used both linearly and non-linearly in OASIS. All in all, we follow familiar user interface visuals and behavior to reduce the learning curve of using our tool and allow users to quickly run daylighting analysis with the least cost of effort.

Another framework used in our sketching interface is RaphaelJS[]]. Raphael JS is a 3D vector graphics library for JavaScript. I use RaphaelJS to create 2D graphics of objects users places into sketches. I also use RaphaelJS because it supports vectorized lines and shapes, allowing our interface to be re-sizable with lost of visual quality. I also use Raphael FreeTransform in conjunction with RaphaelJS[]]. The

FreeTransform extension is used to create FreeTransform handles on furniture items so that users may easily rotate and reposition furniture items where they please. Figure-3.4F demonstrates the handles FreeTransform generates for object manipulation.

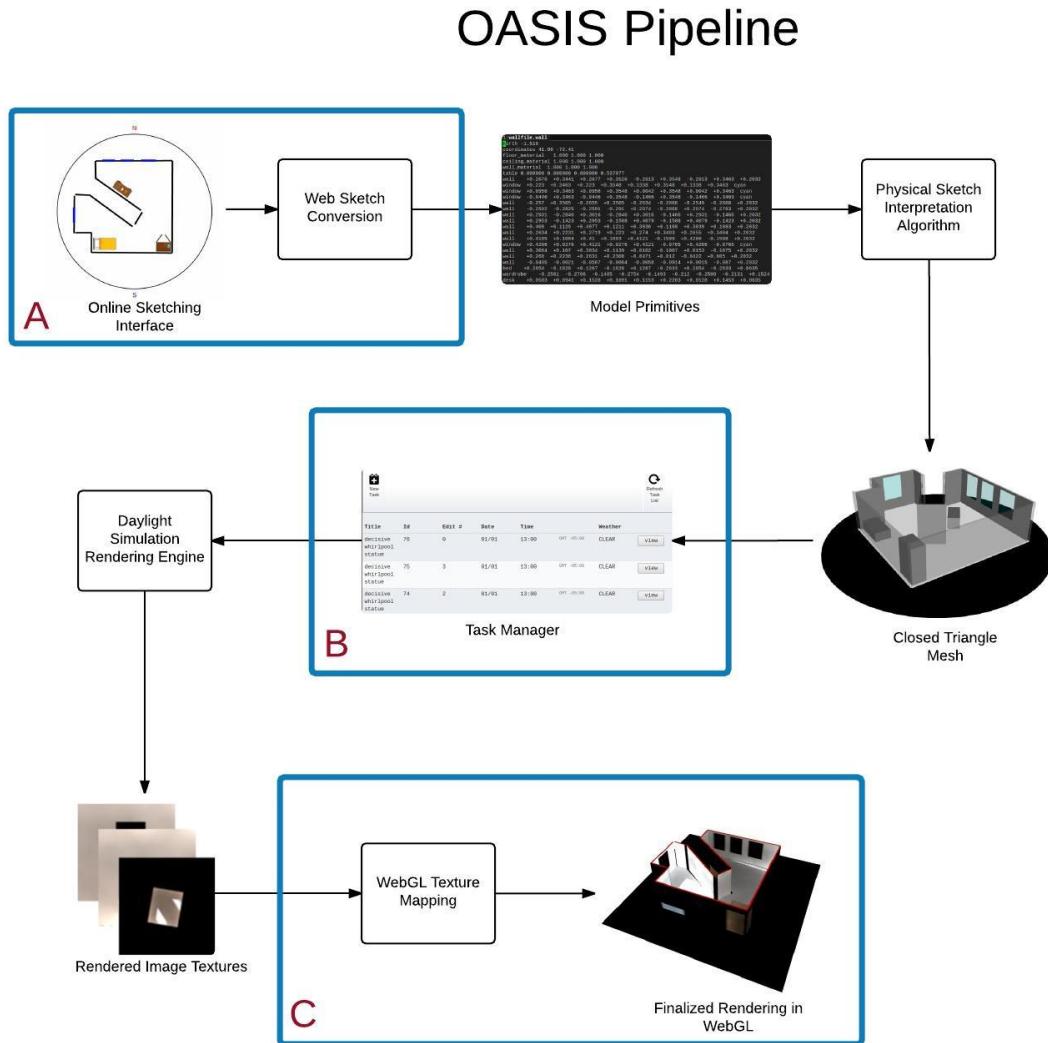


Figure 3.3: OASIS pipeline diagram with the author's contributions noted in blue.

As mentioned before, OASIS is an alternative interface to the Virtual Heliodon. The system pipeline in Figure-3.3 illustrates the components involved in OASIS. In addition, Figure-3.3 notes all portions of OASIS that I directly contributed to. The

physical sketch interpretation algorithm that the Virtual Heliodon uses to generate watertight 3D meshes for simulations requires sketches be given as a collection of model primitives. Model primitives are stored in an intermediary primitives file where each line describes a wall, window, or furniture item in a sketch. In the Virtual Heliodon the intermediary primitives file is created by a simple computer vision algorithm that detects walls, windows, and tokens through colored markers placed on the top of all physical primitives. In our sketching interface I directly create this intermediary primitives file through the conversion of user created Raphael Objects. Figure-3.3A illustrates where the conversion occurs in our system pipeline. When users convert their sketches into 3D models, the physical sketch interpretation algorithm reads in the generated intermediary primitives file. The physical sketch interpretation algorithm outputs a closed triangle mesh that users can view in the *Generate 3D Model* page. Given confirmation that a 3D generated model matches the user's intention, the user can create a daylight simulation request in the *Create Daylighting Simulation* page. This portion of the system pipeline is illustrated in Figure-3.3B. After the submission of a daylight simulation request, I use the daylight simulation rendering engine to produce texture images. These texture images capture illumination in a viewpoint independent manner. On the *Analyze Daylighting* page, I map these texture images into the scene to display a 3D daylight rendering of users' generated models. Figure-3.3C illustrates where texture mapping occurs in the system pipeline. In brief, our pipeline shows that OASIS is an alternative interface to the main components in the Virtual Heliodon.

3.1.2 Usability Features

There are direct and indirect usability features in our online architectural sketching interface. At first, users could create walls and windows by drag and dropping them into the canvas as showing in figure-3.4. Users could then further manipulate walls and windows by both rotating and scaling items though use the FreeTransform handles. Figure-3.4 illustrates the parallels between how users place walls into a scene in both the Virtual Heliodon and in the first version of our online sketching interface. Both Figure-3.4A and D illustrate how users have to select

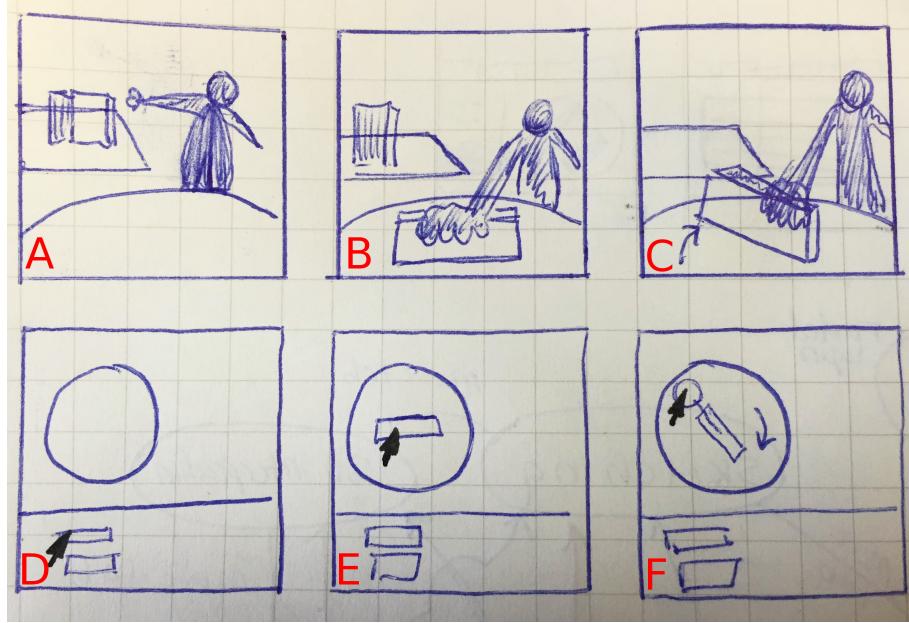


Figure 3.4: Similarities between old drag and drop interface and the Virtual Heliodon’s Tangible User Interface.

a primitive from a collection of primitives in both the Virtual Heliodon and first version of our online interface. Figure-3.4B and E show how users have to place selected primitives on a surface, such as the physical table top or the online interface’s canvas in a similar manner. Figure-3.4C and F demonstrate how users adjust either physical primitives through physical interaction or online primitives though the manipulation of FreeTransform handles. However, despite mimicking how wall primitives were placed in the Virtual Heliodon, early feedback showed that this approach was both unintuitive and did not translate well into our online sketching interface.

My next approach mimics how users draw on paper and in most software sketching environments. Users first click on the wall button located in the ribbon of the *Sketch a Room* page as shown in Figure-3.5A. Then, as Figure-3.5B and C illustrate, by holding left the mouse button and dragging anywhere on the canvas the user is shown a preview of where a wall will be drawn. By releasing the left mouse button, the wall preview will be replaced by a drawn line, representing a wall, as Figure-3.5D depicts. Once a wall is drawn further editing is not allowed. To keep

with the spirit of sketching, windows are also placed into a sketch by being drawn similarly to walls, as shown in Figure-3.5E through G. However, unlike walls, windows need to be associated with a wall. As a result windows need to be drawn on or near a wall. In the interest of the user, windows do not need to be drawn exactly on walls. A window when drawn near a wall sharing a similar angle will automatically target and snap onto that wall, as illustrated in Figure-3.5H. This snapping feature makes drawing windows less reliant on users' precision with a mouse, but instead focuses on users' intention.

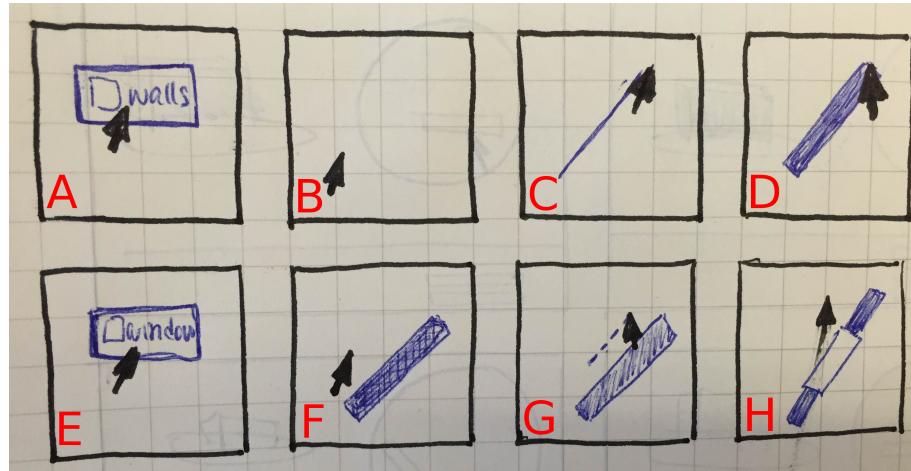


Figure 3.5: How to create walls and windows on the new online sketching interface.

Unlike walls and windows, furniture items are placed into the canvas by first clicking on a furniture button and then manipulating the newly created furniture item via translations and rotations. Furniture items can be rotated along their center axis via FreeTransform handles attached to the furniture item. Furniture items can also be translated by clicking and dragging on the item itself. The manipulations of furniture items are similar to the manipulation of walls in the original interface as shown in Figure-3.4. Item manipulation via FreeTransform handles and drag-and-drop are a common UI mechanics. Users will be familiar with these mechanisms if they have had experience using either photo editing software or slide-based presentation tools such as Microsoft PowerPoint]. The removal of all sketch based elements and furniture is simple as well. Firstly, users must click on the remove button as

illustrated in Figure-3.6A, secondly users must mouse over the item to be removed as shown in Figure-3.6B. Items to be removed upon the left mouse click are highlighted in red as shown in Figure-3.6C. No items are removed from the canvas until the users left mouse clicks on a selected item.

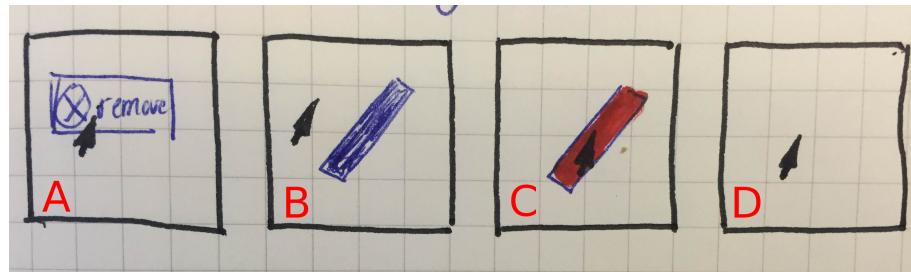


Figure 3.6: How to remove an item from the canvas.

Daylighting varies by many factors. Notably, the cardinal orientation of user sketches needs to be defined in order to simulate direct lighting. In order to define cardinal orientation users must first click on the orientation button, located in the *Sketch a Room* page's ribbon depicted in Figure-3.7A. Then users can click and drag anywhere on the canvas to define cardinal orientation. Specifically, holding the left mouse button on canvas will move the North and South labels around the circumference of the canvas to define the cardinal orientation of the sketch, as shown in Figure-3.7B through D. Moreover, daylight varies by geographical location as well as cardinal orientation. To define a geographical location we have users click on the location button next to the orientation button depicted in Figure-3.7E. Clicking the location button will bring up a map projection where users can select their model's geographical location by clicking anywhere on the map, as shown in Figure-3.7F and G. Once the user has selected a location, a red marker is placed on that location and the map disappears revealing the sketching interface, as depicted in Figure-3.7H. Users do not need to fill in exact latitude and longitude values because we intend OASIS to be an early design tool. Furthermore, daylighting varies significantly depending on what hemisphere a model is located. Daylighting also varies depending on a model's location relative to the equator. Inaccurately selecting a geographical position off by an entire state or even country will not vary daylighting result much. Figure-3.7 illustrates how a sketch's cardinal orientation

and geographical location are defined.

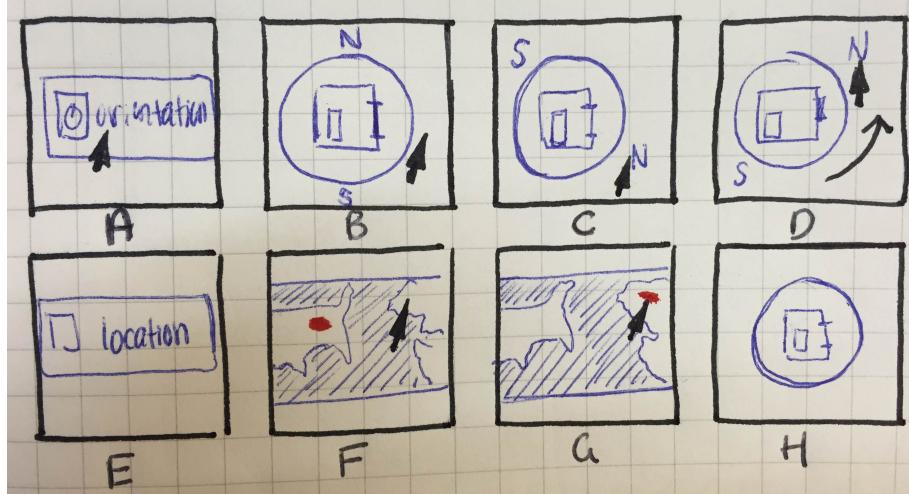


Figure 3.7: How to set the cardinal orientation and geographical location of a sketch.

Other, not so immediately obvious, usability features supported include an implied sense of scale. Adding furniture items of fixed size to the interface implies a sense of scale. Statically sized furniture items give users an idea of how big or small other element in a room are. Although daylighting is scale invariant, enforcing scale gives us, the researcher, the ability to compare real world spaces with space reproduced in our interface. Likewise, to make comparisons between users' sketches and 3D models generated by the physical sketch interpretation algorithm straightforward, I set an identical top down view for both users' sketches and interpreted 3D models. Lastly, I make sure to automatically save models when users switch between pages. Rather than manually having users save models, we decided that automatically saving models would be one less concern to the user.

3.2 3D Model Viewer

I use RaphaelJS to manage the 2D elements in our online sketching interface, however, I use WebGL to view renderings and 3D interpreted models. Specifically, I use the WebGL library ThreeJS^[1]. ThreeJS is a framework that provides useful wrappers for common WebGL functions. WebGL is supported on most web browsers including Google Chrome and Mozilla Firefox^[2]. WebGL gives us the ability to have

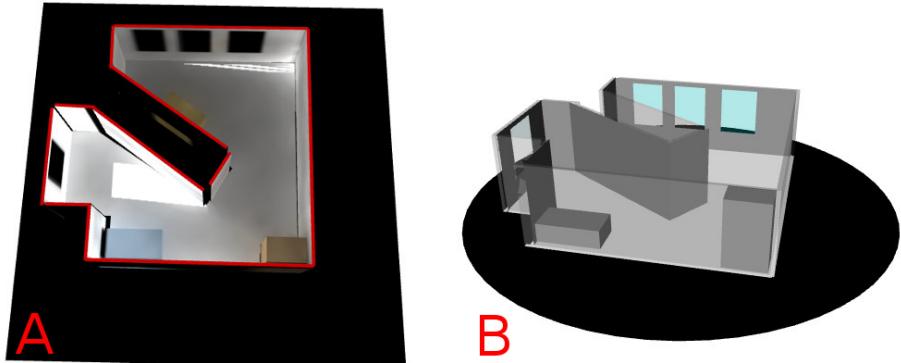


Figure 3.8: A) Navigable daylight rendering and B) 3D interpreted geometry. There are the two kinds of models we can view in our 3D Model Viewer.

our sketching interface online in a platform independent manner. The 3D viewer is used in both the *Generate 3D Model* and *Analyze Simulation* pages. Our viewer can be used to view both 3D models produced by the physical sketch interpretation algorithm and renderings produced by the daylighting rendering engine as shown in Figure-3.8. The output from both of these components are different and as a result our viewer must be able to handle both texture and non-textured models. Output produced by both the physical sketch interpretation algorithm and the daylighting rendering engine is saved as a 3D triangle mesh in a non-standard OBJ file format. The OBJ file is then parsed and rendered for viewing using ThreeJS and WebGL. Additionally, output from the daylighting rendering engine requires the extra step of texture mapping images onto walls, windows, and furniture items. Furthermore, our viewer lets users change their view of the 3D model though rotation, panning and zooming. Users can hold and drag the left mouse button to rotate a model along its center axis. To zoom into a model, users must hold first hold down a modifier key, such as the shift or ctrl, then hold left mouse button while dragging vertically across the model. Lastly, users can pan around a model using the standard keyboard arrow keys.

Aside from basic navigation, there are a couple of usability features built into the viewer. Firstly, just as with the sketching interface the viewer can be scaled to fit any web browser window without loss of quality. Also, when viewing output from the physical sketch interpretation algorithm, we render walls facing users' viewpoint

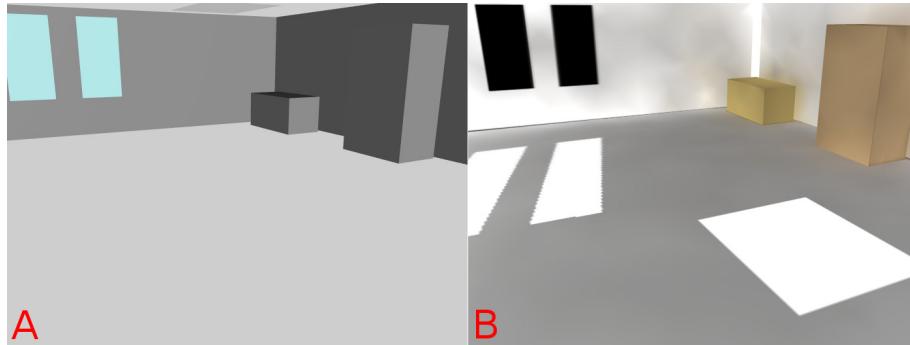


Figure 3.9: Figure A illustrates a 3D interpreted model zoomed into a first person view. Figure B is the same view in the daylight rendering of the model.

as transparent, as showed in Figure-3.8B. These transparent walls allow users to get a better view models from multiple viewpoints other than the default overhead view. Moreover, by default the ceiling is not displayed so users can peer into a 3D model from a top down view. However, when viewing output from the physical sketch interpretation algorithm, users can toggle the ceiling as viewable. This is useful if users want to see what portions of the model are interpreted as interior and exterior. The ceiling is also useful to see where skylights are located in a model. Toggling the ceiling is also useful when zooming into the model to visualize a space from first person point of view – as shown in Figure-3.9. Additionally, when viewing daylighting renderings, users can toggle between a regular rendering and a rendering with false color visualizations that aid in identifying portions of a room that suffer from over and under illumination. Users can toggle between these false color visualizations and renderings by clicking on the analysis button located on the *Analyze Daylighting* page’s ribbon. Previous work on over and under illumination visualizations by Nasman et al. is used to render blue checkerboard textures on locations suffering of under-illumination and red checkerboard textures on locations suffering of over-illumination[26]. Figure-3.10 illustrates an example of toggling between false color rendering and normal daylighting rendering. In short, the 3D model viewer gives users basic navigation functionality, in addition to a handful of other useful features.

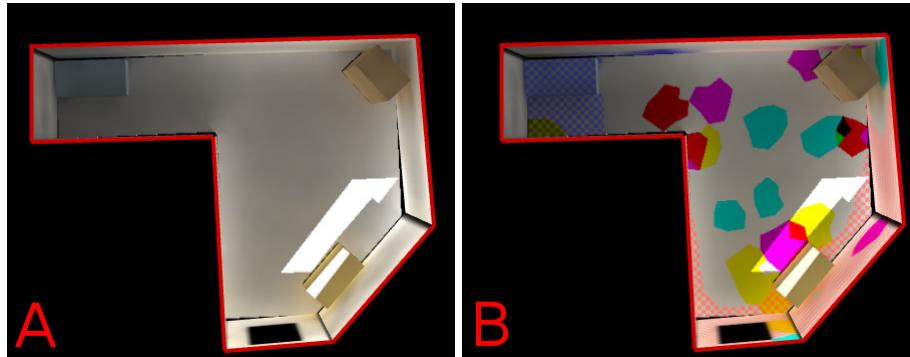


Figure 3.10: An example of false color renderings. A) Is a model that suffers from under illumination in the left most portion. B) Is the same model with false color visualizations toggled. Blue checker-board overlays are used to denote under-illumination and red checkerboard overlays are used to note over-illumination.

3.3 Task Manager

Creating a Request After users convert their architectural sketches to 3D models, users can then navigate to the *Create Daylighting Simulation* page. On the *Create Daylighting Simulation* page there is a task manager where users can create request for daylighting simulations and view previous renderings. Figure-3.11 demonstrates how users can create request for daylighting simulations on the task manager. Users can create request by clicking the new task button located in the ribbon on the *Create Daylighting Simulation* tab, as denoted in Figure-3.11A. As show in Figure-3.11B, clicking the *New Task* button will create a new row in the table of previously created task. Some parameters need to be defined before submitting a rendering request to the server. Since daylighting varies temporally the date, time, and timezone must be defined prior to submitting a request. Given a model’s geographical location we approximate the timezone, however, users can set any timezone they wish. Once task are submitted users will be informed of a task’s status by either displaying *running* or *in queue* as illustrated in Figure-3.11C. The *running* status means the submitted task is currently being processed by the server and the *in queue* status means the task is currently in line to processed by the server. Once renderings are complete and texture are available, a task’s status will be replaced with a view button, as show in Figure-3.11D. Upon clicking the view button the user will be directed to the *Analyze Simulation* page where the user’s

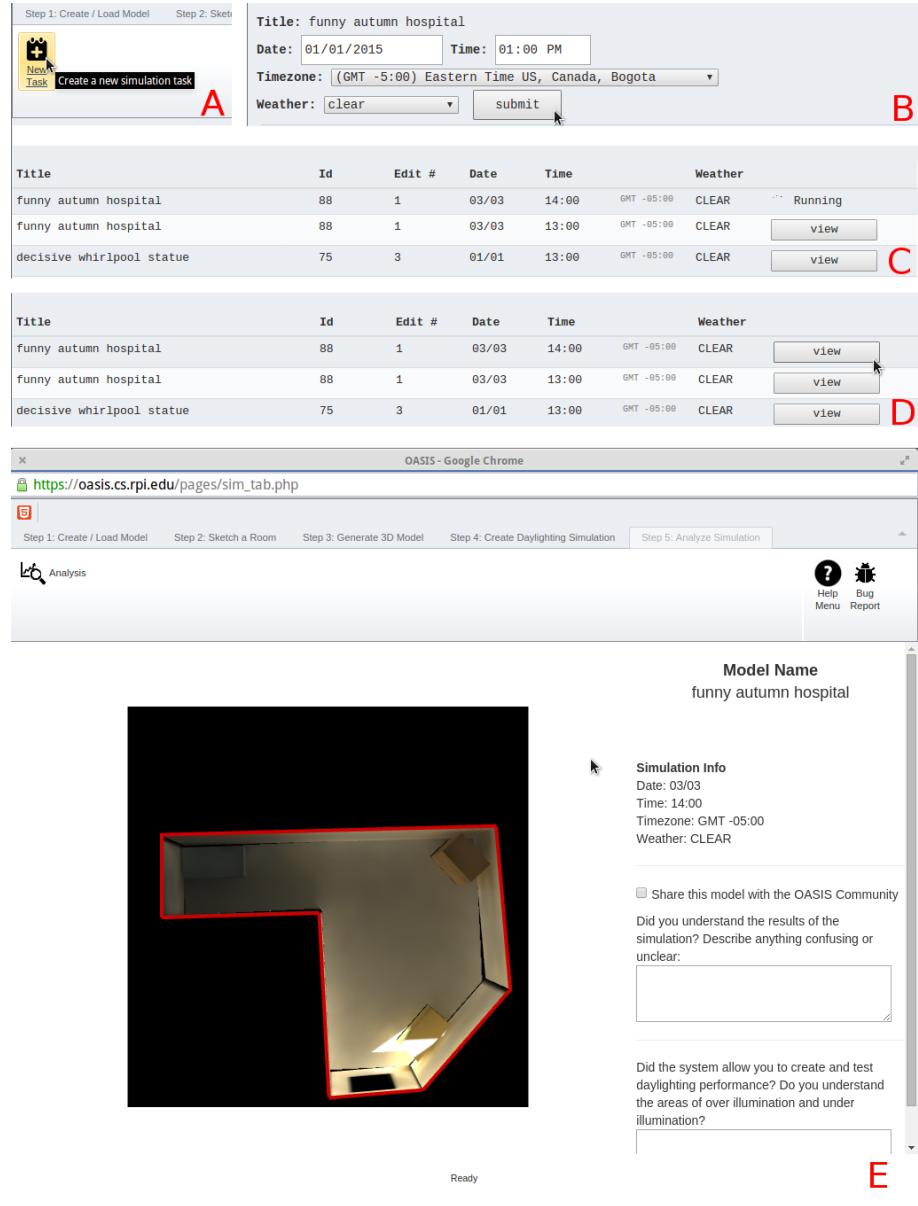


Figure 3.11: How to create a request for daylighting simulations.

rendering will be viewable. The *Analyze Simulation* page is shown in Figure-3.11E.

Client Server Approach For rendering we follow a client-server model, since calculating global illumination required for daylighting simulation is too computationally expensive to run interactively on most user's machines. Users define a set of parameters per rendering request and then submit a request to the server. The server is aware of all pending request and processes all request in a first come first

serve manner. The model, including the the set of input parameters, is then passed along to the daylighting rendering engine. Once the renderings are complete, the daylighting rendering engine places cameras into the scene to capture the illumination on the walls, furniture, and floor as images. The images captured by the cameras are saved as image textures. We then remap these textures onto the walls, furniture items, and floor in the WebGL 3D model. Another important usability feature added was the caching of previous rendering on the machine hosting our online sketching interface. The caching of previous renderings allows user to quickly view previous renderings without having to rerun the simulations on the server.

CHAPTER 4

Pilot User Study

4.1 Pilot Study Motivation and Goals

Aside from creating an interface for simulations and analysis, I also made preparations for a pilot user study aimed at answering a few evaluation questions about the usability of our online interface. Specifically the first question we are looking to answer is whether OASIS is accessible. The second question we are looking to answer is whether OASIS is an easy to use interface for both novices and users with relevant modeling experience. Lastly, we are investigating if OASIS is a step in the right direction as an early design tool for daylighting analysis. In addition to questions pertaining to the online interface's usability, I am also interested in analyzing the perceived accuracy of the physical sketch interpretation algorithm when using non-physical sketches. Furthermore, I would also like to collect qualitative feedback on users' understanding of simulation results. Also, I would like to analyze the general performance of our system; As an early design tool it is imperative that we deliver both sketch interpretations and model renderings quickly. Our eventual goal is that OASIS will be an iterative design tool for creativity solving daylighting problems and exploring initial designs with a minimal cost of effort. Moreover, the hope is that this pilot user study will provide us valuable feedback to improve OASIS as an early design tool for daylighting.

4.2 Previous User Studies

The physical sketch interpretation algorithm has gone through three previous user studies [28, 27]. Two of those studies are direct elevations of the physical sketch interpretation algorithm's accuracy on physical sketches. These two studies are featured in *Interpreting Physical Sketches as Architectural Models*[28]. The first study aims at analyzing the range of designs possible with physical sketches on the Virtual Heliodon. The second study aims at analyzing the accuracy of the physical

sketch interpretation algorithm on ambiguous sketches. In our pilot user study I do not explicitly attempt to analyze the accuracy of the physical sketch interpretation algorithm with non-physical sketches. Yet, I hope that some quantitative feedback will verify that users' intentions are matched at rates similar to these previous studies. It is also important to note that while these previous studies gathered over 300 physical sketches, they did so from a medium sized pool of users. This pool of users varied from 13 to 30 participants across all previous user studies. It is also important to note that these studies each took, on average, 2 months to complete data collection. Moreover, the pool of users these two studies drew upon were comprised of mostly students at Rensselaer Polytechnic Institute. Similarly, the *Evaluation Of User Accuracy In A Tangible User Interface For Architecture Design* was comprised of 6 architecture students and 7 non-architecture students. While, I do not expect to match the number of models produced per users, I hope that the overall number of models produced will be both quantitatively larger and from a broader range of users. In addition, the accessibility and autonomy of our online interface will make the marginal cost of collecting data per users smaller than the tangible user interface on the Virtual Heliodon.

4.3 Accessibility Design for OASIS

There were various frameworks considered for OASIS. Our requirement of accessibility to a broad range of users, however, limited our choices. Software that uses OpenGL, or another graphics libraries, would require installation. Having an installer and system requirements would be barrier of entry to participating in our study. In addition, trying to support multiple platforms would be time intensive and would increase the marginal cost of adding features to OASIS. WebGL and ThreeJS are relatively new graphics libraries that are supported on most modern web browsers. The availability of WebGL and our requirement of accessibility led me to make OASIS a web-based application. Additional benefits of using a web-based application include having a platform independent framework, no installation process, and globally applied updates. Having a web-based application lends itself to using a client-server architecture. In OASIS I leverage the server to both ser-

vice our web page and run computationally expensive processes on behalf of clients. Namely, these computational expensive processes are the physical sketch interpretation algorithm and the daylight rendering engine. Both of these processes are computed on a specialized lab machine rather than locally on users' machines. Our lab machine, unlike most clients running our application, is equipped with an Nvidia GeForce GTX 780 graphics card, 64 GB of RAM, and a 12 core processor. This makes the CPU-intensive process of the physical sketch interpretation algorithm and GPU-intensive processes of the daylight rendering engine faster than on most client machines. Interface related computation rely on the client's machine including the manipulation of 2D images, the creation of rendering request for the server, and the visualizing of 3D models. My hope is that leveraging the server to run computational expensive components in OASIS will prevent potential participants from opting out of our pilot user study due to hardware limitations and will provide a homogeneous user experience across all platforms.

4.4 User Feedback Collection in OASIS

In OASIS I collect two types of data from users. Both active and passive data are collected from users while they use our tool. Active data refers to the feedback, models, and comments user actively provide. Passive data refers to data not actively provided by users, such as the length of time a user spends on a page, the average wait time before rendering request are handled, and other information about users usage of our application. We collect both types of data to get a clearer idea of how users perceive OASIS and how users interact with our tool.

The active feedback data collected from users can be organized as either user-specific questions, model-specific questions, renovation-specific questions, and render-specific questions. User-specific questions refer to questions associated with users. For example questions pertaining to user's past experience and education. User-specific questions also include questions that ask users about their subjective opinion of certain components of OASIS. All user-specific questions as well as all feedback questions can be viewed in the appendix. Model-specific questions refer to questions about user created models. Model-specific questions include asking

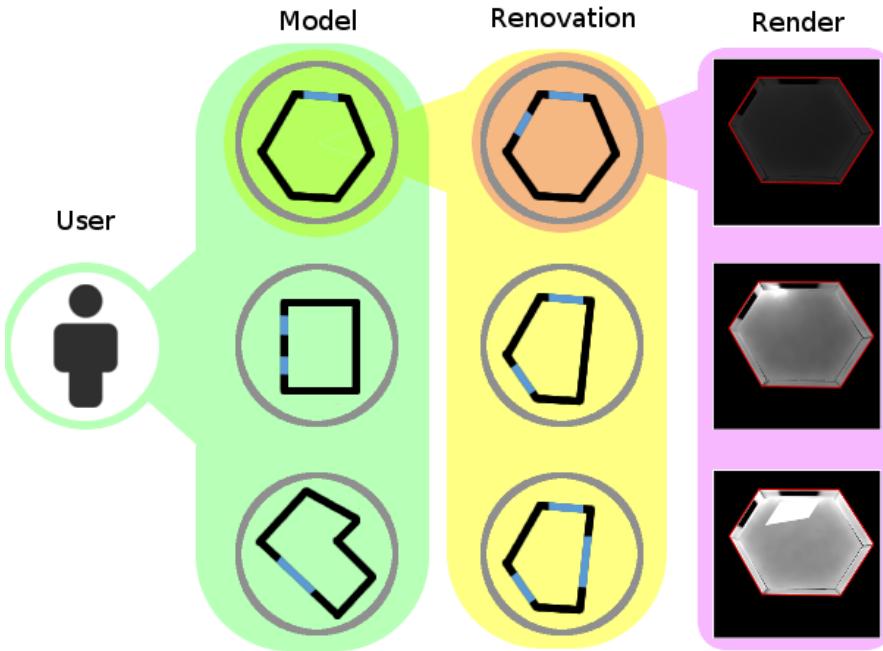


Figure 4.1: Relationship between users, models, renovations, and renderings. Users are associated with a set of models, models are associated with a set of renovations, and renovations are associated with a set of renderings.

users to elaborate on specific models and asking users to rate how confident they are regards to their accuracy of creating models. OASIS allows users to make multiple renovations on previously created models. Some of the questions I ask are renovation-specific, such as if the physical sketch interpretation algorithm correctly matches users' intentions on a specific renovation of a model. Lastly, users can run several renderings per renovation. As a result I also ask users renovation-specific questions. The relationship between users, models, renovations, and renderings can be seen in Figure-4.1. As mentioned before we also collect passive data. Specifically, we collect how long users spend on each page of our interface and how long users wait for both physical sketch interpretations and daylight renderings.

4.5 Data Collection

In order to collect feedback on OASIS we have to first host the application online, and then bring potential users' attention to the application. As with an study, we must invite users to participate in order to collect feedback. Personally

inviting individuals to use our tool might be cumbersome and slow going, so we hope inviting users in mass via popular social media networks, such as Facebook and Reddit, will result in increased user participation. One advantage of using social media networks is that some organized by users' interest. We use this organization to target users who might have an interest in daylighting or architecture. Figure-?? list a few relevant Reddit communities and their respective sizes that we plan to advertise OASIS to.

Reddit Forum	Subscribers
Beta	10,1455
InteriorDesign	78,750
RPI	3,939
Floorplan	1,175
UserExperienceDesign	1,128
GreenArchitecture	607
YoungArchitects	236

Additionally, many feedback questions asked pertain to users creating models of Rensselaer Polytechnic Institute. We plan our advertising our tool on campus as well as online. As done in previous studies we wish to leverage the Rensselaer Polytechnic Institute School of Architecture in order to collect feedback from users with formal education in Architecture. Again, we plan to use user feedback collected both actively and passively to analyze if OASIS is accessible to a wide range of users. In addition, we plan to use the feedback to investigate the usability of our online interface. Lastly, we want to use collected qualitative user feedback to review if OASIS is a step in the right direction as an early design tool.

CHAPTER 5

Pilot User Study Results And Analysis

5.1 Participant Background Feedback

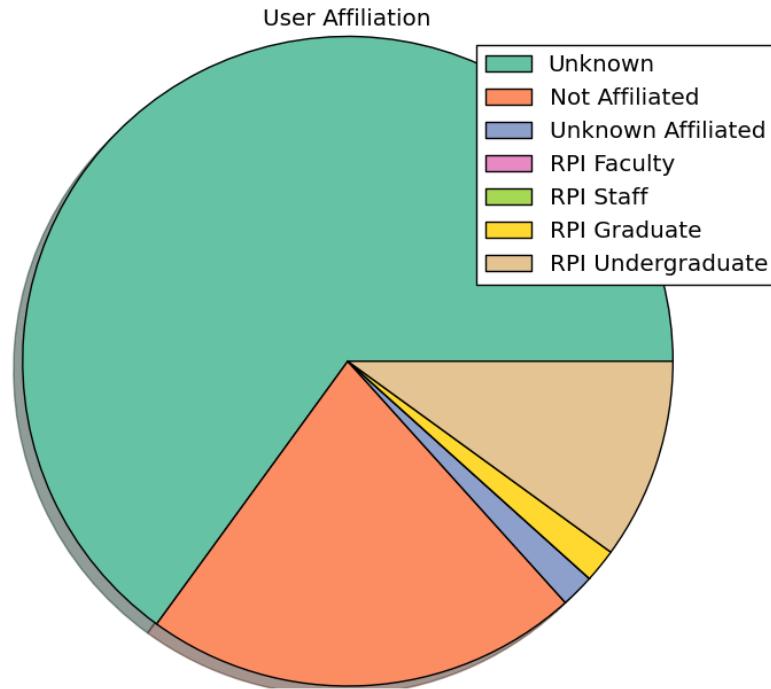


Figure 5.1: User affiliations of participants on OASIS

In the two week timespan that OASIS was publicly available 57 users registered and participated in our pilot user study. I recruited participants for our pilot user study on large social media outlets such as Facebook and Reddit. Both of these social media outlets have a wide range of users with varying experiences. Not to mention, one of the online outlets I recruited participants from is unofficially affiliated with Rensselaer Polytechnic Institute (RPI). Figure-5.1 demonstrates the affiliation of participants who registered on OASIS. As shown in Figure-5.1 a majority of participants that provided their affiliation are not affiliated with RPI. This is a big change from previous user studies, where all the participants were RPI affiliated. Additionally, Figure-5.1 shows that the majority of participants that are affiliated with Rensselaer Polytechnic Institute, are undergraduate. It is also interesting that

the majority of participants choose not to provide information on their affiliation with RPI. Specifically, 65% of participants did not provide feedback on their affiliation, and not all participants who claimed to be affiliated with RPI specified how they were affiliated; About 2% of participants have unknown affiliations with RPI. The difference between RPI affiliated participants and non-RPI affiliated participants could be a direct results of how and when we recruited participants for the pilot user study. During the pilot user study we advertised towards non-RPI affiliated social media outlets first and RPI affiliated social media outlets last. There was more time recruit non-RPI affiliated participants than RPI affiliated participants.

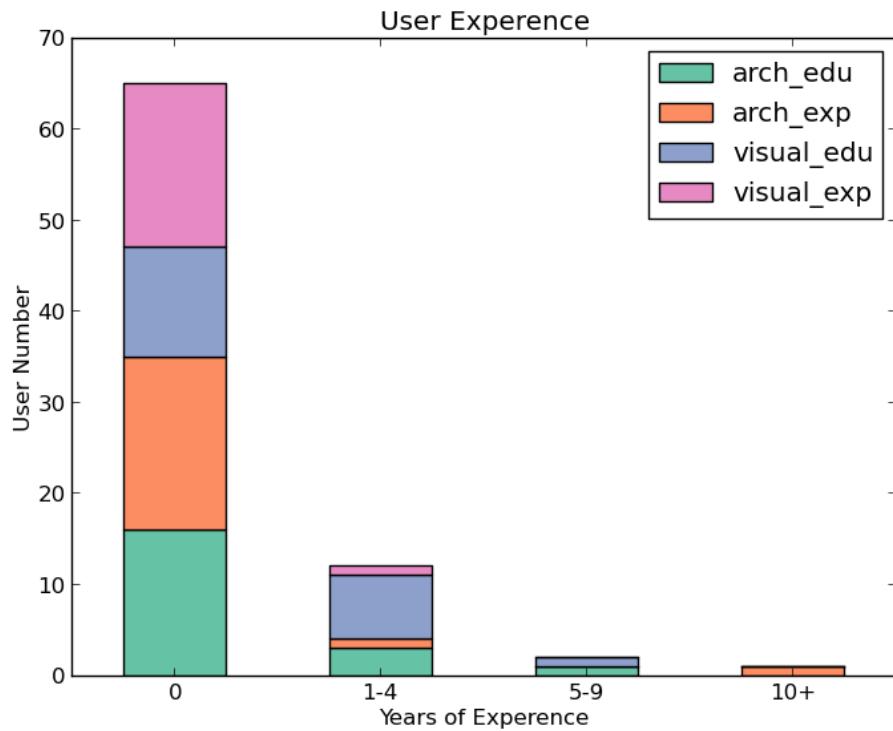


Figure 5.2: Architecture and visual arts experience of OASIS participants

Similarly, I asked our participants about their experience with architecture and visual arts. Figure-5.2 shows the distribution of participants' formal education and job experience in both fields of architecture and visual arts. A majority of our participants expressed that they have no experience with any of the related fields; As a result, these participants will be referred to as non-experts. Also a majority of

those participants that have experience, generally have only 1-4 years of exposure to formal architecture education or form visual arts education. However, there is one user registered on OASIS that claims to have over 10 years of job experience in architecture. Aside from asking about architecture and visual arts experience, I also let participants elaborate on other relevant experiences. Some of our participants have had experience in civil engineering, electrical engineering, studio arts, user experience design, and architectural engineering with focus in lighting. While our current set of participants does not have much experience with architecture, they do encompass a board range of related fields.

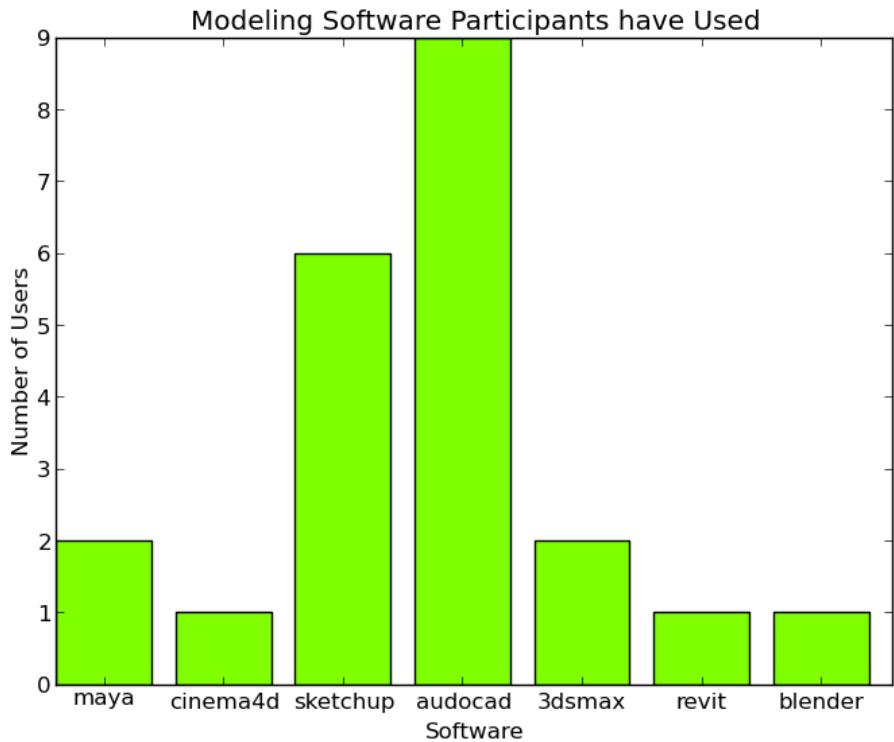


Figure 5.3: Participants' experience with 3D Modeling Softwares

Furthermore, I also asked participants to provide a list of 3D modeling software they have had exposure to. As seen in Figure-5.3 participants have had the most experience with AutoCad[] and SketchUp[]. A few participants have had experience with 3dsMax[] and Maya[]. Again, we let participants elaborate on their experience with other 3D modeling software. Other 3D modeling software, not shown in Figure-

5.3, that participants have had experience using include SolidWorks[], AGI32[], Dialux[], and Daysim[]. Note that AGI32, Dialux, and Daysim are not specifically 3D modeling tools but rather used for daylight analysis and performance. From user feedback collected in our pilot user study on participants' affiliations, experience in related fields, and exposure to modeling software, determine that OASIS is accessible to a wide variety of users.

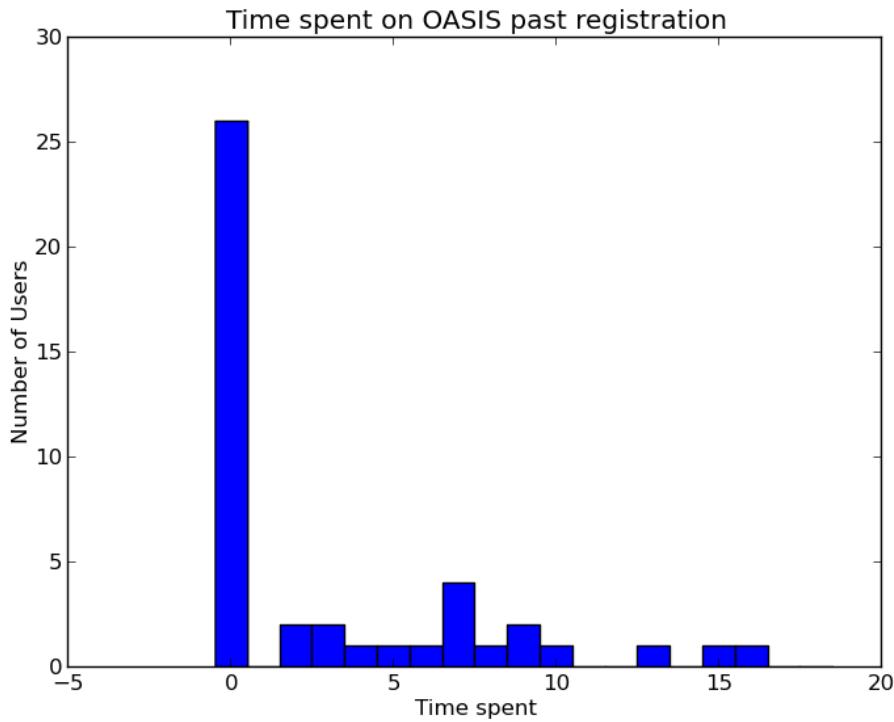


Figure 5.4: Distribution of time spent on OASIS per user

In addition to trying understand if OASIS is accessible, I also wanted feedback on the usability. Analyzing data on how participants spend time their on OASIS can provide insight on user behavior. Figure-5.4 illustrates the distribution of participants in relation to their time spend on OASIS. From Figure-5.4 is it clear that the majority of users registered and participating in the pilot user study spent no time on the actual interface. On the other hand, the average time spent per participant is about 12 minutes, excluding participants that do not spend longer than a minute on OASIS past registration. Although our user retention rate is low, I suspect that the

voluntary nature, anonymity, and absence of renumeration in our pilot user study plays a significant role in the large number of participants who register and do not use OASIS.

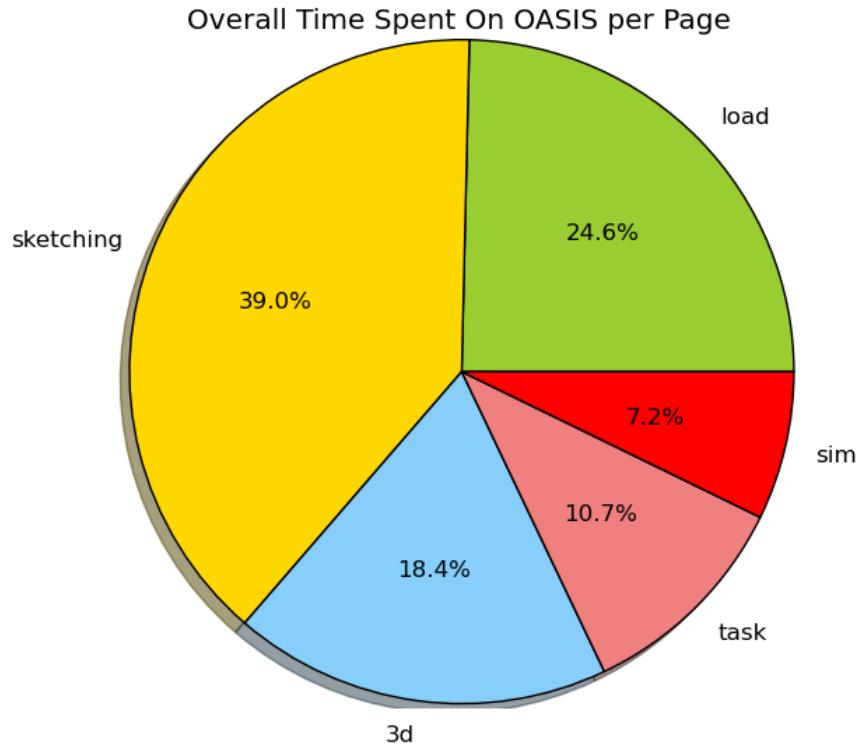


Figure 5.5: Breakdown of time spent on OASIS pages

Furthermore, we have no data on user participation in similar online user studies targeting similar social media outlets. Equally important, Figure-5.5 illustrates participant time spend on OASIS per page. Moreover, Figure-5.5 shows that participants spend 36% of their time on the *Sketch a Room* page. Next participants spend 23% of their time on the *Create/Load Model* page. It is important to note that first-time users have the option of viewing a short tutorial video; the 1 minute long tutorial video coupled with redirection to the *Create/Load Model* page after logging in, could directly contribute to the large portion of time participants spend on the *Create/Load model* page. Surprisingly, the page participants spend the least amount of time is on the *Analyze Simulation* page. On the *Analyze Simulation* page user can view daylight renderings of user designed models. On average participants spent only 8% of their time analyzing their designed models; when compared to the 25%

of time participants spend on viewing 3D interpretations on the *Generate 3D model* page, the time spend on the *Analyze Simulation* page seems remarkably low. The difference between time spend on these two pages could stem from the fact that the *Analyze Simulation* page is the final page new users visit when navigating OASIS linearly. Furthermore, all of the temporal data collected on pages in OASIS could be effected by time spent writing feedback questions, multi-tasking while leaving OASIS running in the background, and leaving OASIS before visiting all pages.

5.2 Usability Feedback

Most of the feedback collected on the usability of OASIS is qualitative. Quantitative boolean feedback would not fully capture how participants are experiencing our sketching interface; As a result, I collect qualitative feedback to gain insight into how users perceive OASIS. Figure-?? list feedback collected from 14 participants concerning what participants found fun or interesting in our sketching environment. Overall, 6 of the participants mentioned that the interface was either fun or easy-to-use. However, some participants found window placement non-intuitive; other participants had difficulty with the limited primitives we provide. While, we did not explicitly ask what they found difficult in the interface in this specific feedback question, their response will be taken into consideration. The participant who found window placement difficult states that they tried to “leave a gap between walls to define where to place windows”. I suspect that the participant, with this issue, must have skipped the tutorial video or not consulted the any of the help options on OASIS. By the same token the other participant, concerned with the limited options on OASIS, I speculate is comparing our tool to other more fully featured modeling softwares. As stated before, we intent for OASIS to be an early design tool for use during the schematic design phase of architecture. As a result, for the pilot study I did not prioritize our selection of furniture items, but choose a three pieces of furniture found commonly in bedrooms. Interestingly, our only participant with over 10 years of architectural job experience stated that the sketching interface was “very simple” and that that they never encountered modeled that could not be interpreted. Other participants claim they find specific features interesting, includ-

ing the furniture items we support, skylights, and the daylight simulations.

We also asked participants to provide additional features we could add to our sketching interface to extend the flexibility of OASIS. The two of the most common features requested by participants are the addition of doors on the sketching interface and a wider variety of furniture items. Also, some participants desired more control over primitives on the sketching interface. Including both drag and drop mechanics on walls after initial placement and the precise manipulation of furniture dimensions. Additionally, our sole participant with over 10 years of architecture experience suggest we offer control over window heights, ceiling heights, and window finishes. These features are most commonly found in daylighting analysis software and are features important if I plan to define OASIS as a tool for daylighting analysis. Interestingly, an unanticipated situation with participants' feedback was discovered when analyzing the feedback for this question. A few of our 14 participants provided duplicate responses from previously asked questions. Figure-?? displays all responses collected that were not duplicate responses to previous questions.

In addition to collecting feature request feedback, I also ask participants to describe some designs that they were unable to create due to system limitations. Figure-?? shows participants feedback on limitations of design in our sketching interface. The most common design limitation observed was the absence of doors in our sketching interface. From the feedback collected, it seems that participants assumed that they could not design multi-room sketches because of the lack of doors in the sketching interface. In actuality, previous user studies have confirmed that the physical sketch interpretation algorithm can handle multi-room designs[]). Other design limitations participants claimed to face included the lack of light shelves in our interface, the inability to place one piece of furniture on top of another, and unavailability of control over scale. Again, participants also expressed that our selection of furniture items limited designs.

Overall, the main take away from participant feedback concerning design lim-

itations is that doors are essential to communicate to users that our sketching interface supports multi room designs. On a similar note Figure-?? list out participant feedback regarding disliked elements of our sketching interface. A common dislike in our sketching interface was the absence of scale. Currently, we convey scale indirectly through statically sized furniture items, however feedback suggest that we make scale more explicit to users. Interestingly, a participant expressed dislike with our interface because we do not support keyboard shortcuts for common actions, such as undo. Other dislikes with our sketching interface include the limited collection of furniture we support, absence of doors, the inability to move walls after initial placement, and the lack of accuracy when selecting a geographical locations for sketches.

Lastly, we asked participants if there were any elements in our interface that were hard to use. Feedback from that question can be seen on Figure-??. Many participant responded to this question with stating nothing was hard to use on OA-SIS. However, a few users experienced software bugs with the interface and used this feedback question as a means to report them to us. Aside from a few fixable software bugs, of which did not impact the entire system, a participant found the redundancy of Raphael FreeTransform handles confusing. FreeTransform handles are three white circles that are overlaid onto furniture items when clicked in our sketching interface. One circle appears at the center of the furniture item, and the two other circles are placed perpendicularly some distance away from the furniture item, as illustrated in Figure-3.4F. As of now, these two perpendicular handles are used solely to rotate items. Participant feedback help us note overlooked redundancies in our interface such as two rotation FreeTransform handles that perform the same action.

To completely analyze the feedback collected from our sketching interface we must understand that omission of feedback could potentially be used to communicate feedback. For example, when asked about negative aspects of our interface many users choose to respond with “no” or “none”. However, some participants,

whom readily provide feedback, may decide to omit feedback for specific questions to communicate an implied “no”. Ambiguous omissions of feedback proses a problem for analysis. For example I cannot assume that users imply there are no negative elements on our sketching interface based on user omission of specific feedback questions, although participants may intentionally omitted feedback. Improvements in how I collect participant feedback need be made to remove ambiguity in omitting feedback. On a similar note, participants’ feedback sometimes does not directly answer corresponding questions asks. Occasionally, participants’ feedback would be more appropriate as the response to another question. I suspect that participants do no revise feedback after submitting and as a result some of our responses seem similar for multiple questions.

Despite all of this, the sketching interface garnered overall positive feedback from our participants. Many participants, especially the non-experts, claimed that the interface was easy to use and interesting.

5.3 Model Based Feedback

There are currently 73 models on OASIS and on average each user generates 1.25 models. The distribution of the number of models made per user is illustrated in Figure-5.6. From Figure-5.6 we can see that most of our participant only crated a single model. A handful of participants, however, created more than 9 models on our interface. While the number of models per users is relatively low, the number of renovations per models show that on average there are 1.9 renovations per model created. Meaning that about half of our participants renovate their models at least more than once. Figure-5.7 show the distribution of models and the number of renovations on Analysis of individual models is out of the scope of this thesis, however, I do display some user created models in Figure-5.8.

After creating a 3D model participants can voluntarily provide feedback concerning the accuracy of our interpretation. Participants can state the interpretation of their sketches were either a initially matched their intentions, a match after a

performing adjustments as renovations, or not a match at all. I hypothesized that as models grew more complex the accuracy of our interpretation algorithm would decrease. Figure-5.9 illustrates model complexity in relation to matching user intentions. Model complexity is the sum of the number of primitives in a sketch. Figure-5.9 is interesting because models regardless of complexity seem to always match users initial intentions without requiring renovations. Even models with 20 to 29 primitives seem to always match. While the data is strongly indicative that our physical sketch interpretation algorithm is accurate, I believe that more feedback is required before any statically significant conclusions can be drawn. From Figure-5.9 and the fact that there are 73 models on OASIS, but only fewer responses makes it is clear that participants do not answer this specific feedback question readily. In order to better gauge our accuracy, changes to the interface need to be made to persuade participants to answer this feedback question.

Aside from categorical quantitative feedback, we also ask participants to quantitatively describe their overall impressions of the system's effectiveness in construction 3D models from user sketches; Figure-?? displays results from this feedback questions. Of the 16 participants that provided feedback on the effectiveness of the physical sketch interpretation algorithm, 14 stated that the system generally matched their intentions. One participant stated that they only saw 2D versions of the interpretation. I presume this could be caused from the user either not rotating their model or limited WebGL support on their web browser. I do not collect meta data on participants' web browsers or cursor movements, so currently there is no explanation of problem encountered by this participant. Two participants mentioned the lack of support for doors hindered the effectiveness of generating 3D models. One participant linked us an image in their feedback, that displayed a rendering issue they had encountered. The detail of some of the qualitative feedback provided from participants was higher than originally expected. A take away from participants taking screen shots, hosting images online, and linking images of problem renderings to us is that I would provide an easier means to attribute feedback to models.

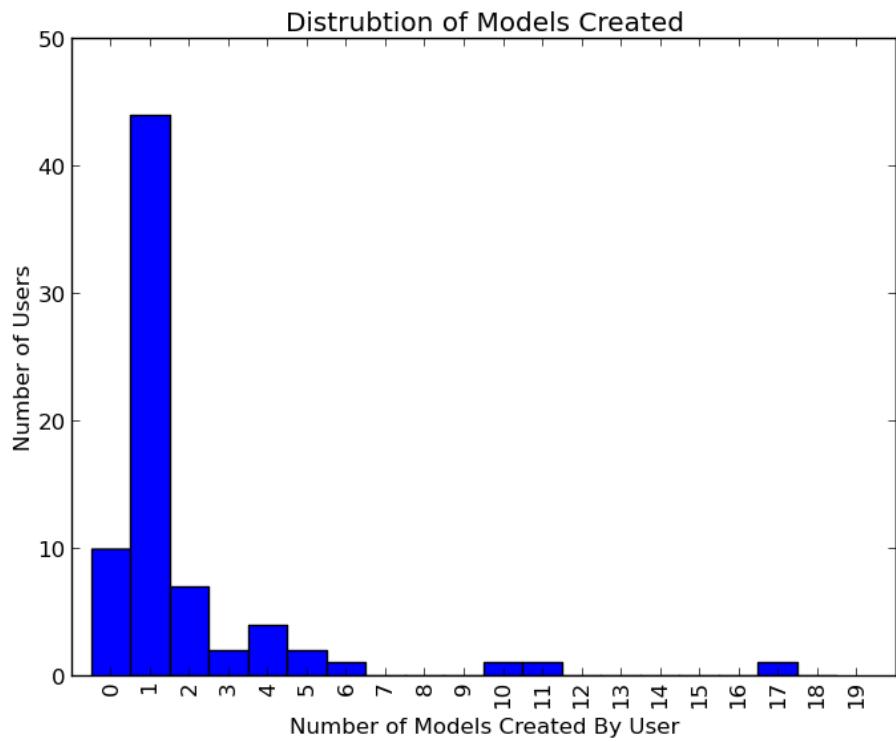


Figure 5.6: The distribution of models created on OASIS

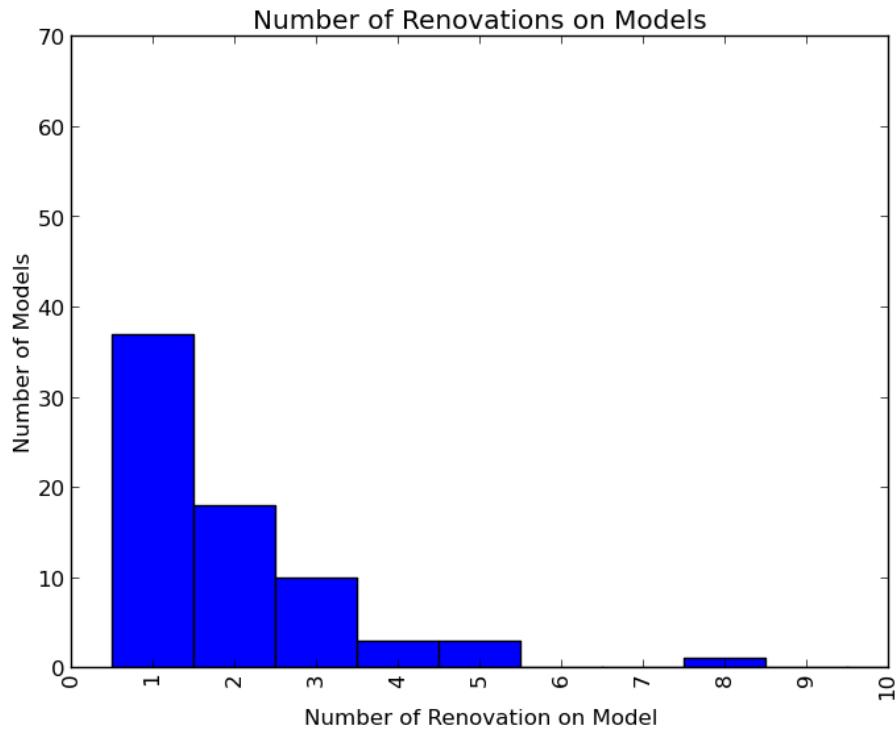


Figure 5.7: The distribution of renovations created on OASIS

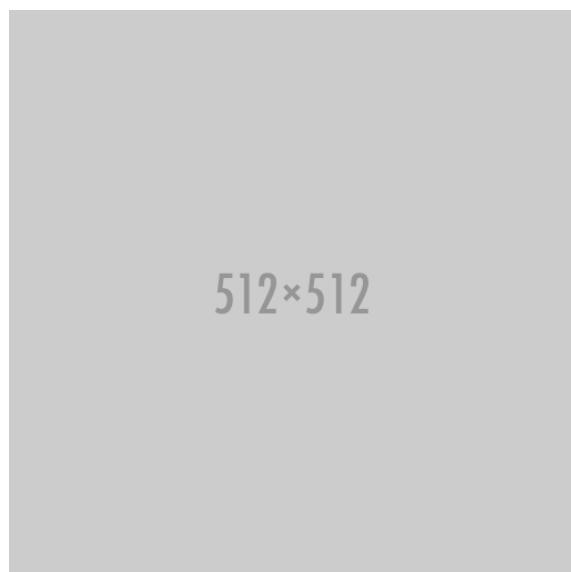


Figure 5.8: Examples of some users created models on OASIS

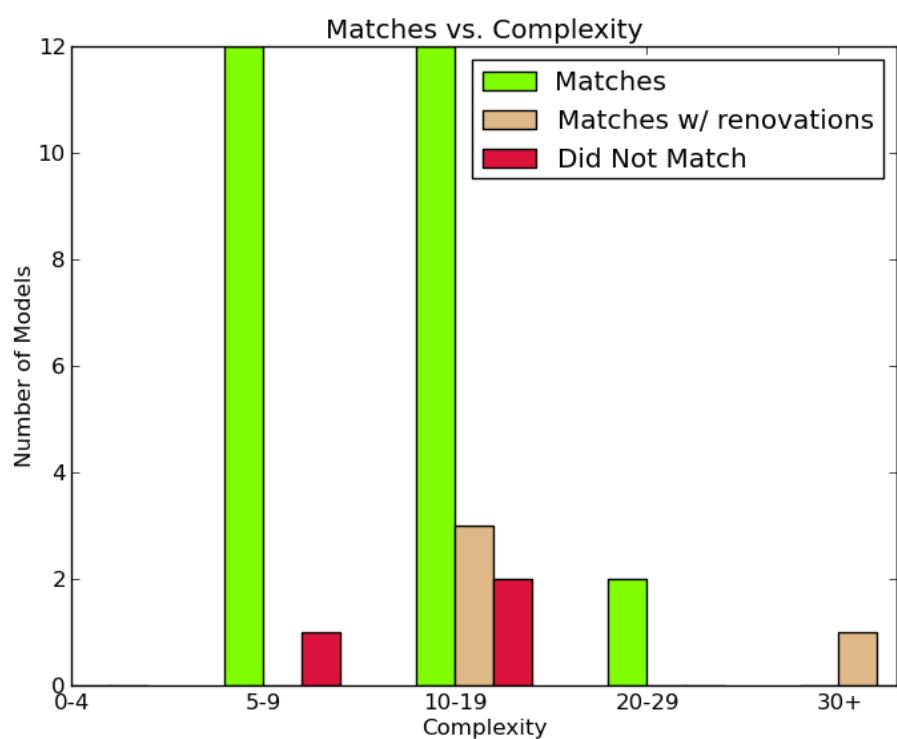


Figure 5.9: Accuracy in relation to model complexity

Moreover, we asked users to describe cases where models were incorrectly interpreted by our physical sketching algorithm. Figure-?? presents participant feedback about these failure cases. Eight participants provided feedback on failure cases, however, some feedback provided prove hard to analyze. Particularly, three participants provided feedback making references to problems on specific models without images or model titles for us to associate the feedback with. Only one participant provided a hyper-link to an image of a model they encountered problems. I suspect the other two participants believed OASIS kept track of which model users were viewing when providing feedback. This particular feedback question is a general system wide question, so I intentionally did not anticipate that users would associate this question with the model currently being viewed by the participant. Additionally, two other responses claim there were no issues in our interpretations of their sketches. Furthermore, another participant misinterpreted the question and stated that the lack of lofted beds in the system was a limitation to their design. We already made note of a similar request earlier in the previous section and choose not to discuss it here. Another participant brought a visualization problem to our attention. Namely, the problem is that transparent windows are only visible from certain viewing from certain angles in our 3D model. The same participant also stated that the floor of models was not visible when viewing a model from underneath the floor. That concern however, was a design choice intentionally made. I believed that if users wanted to see into their model from the floor upwards they could only do if the backside of the floor was no rendered. Rendering the backside of floor would make viewing the model from underneath imposable.

In brief, feedback on failure cases demonstrated the importance of linking feedback to models in the system rather than simply describing those cases through just written feedback. Descriptions of a failure cases without reference models proved to be ambiguous and unhelpful in diagnosing users' issue.

5.4 Daylighting Analysis Feedback

The final set of qualitative feedback I collect in our pilot user study, concerns participant experience with daylighting in OASIS. Specifically we ask participants

if they understood the results of daylight simulations and to describe anything they found unclear or confusing about our visualizations. Figure-?? contains user feedback about participant comprehension of simulation results. Note that the feedback collected in Figure-?? is associated with a specific rendering. I anticipated that users would understand some simulations results for a given rendering but not understand others renderings, so I associated this feedback question with renderings rather than users or models. Surprisingly, participants' responses between renderings did not vary. Out of the 10 participant that provided feedback 9 claimed to understand the simulation results. One participant expected daylight from a north facing window at noon in the norther hemisphere; This participant might not have known that there is no direct sunlight from northern-facing fenestrations in the northern hemisphere. Users misconceptions about daylight are not in the scope of this thesis, but, are covered in a previous users study on the tangible users interface on the Virtual Heliodion[]]. Lastly we asked participants if they system allowed them to both test daylighting performance and understand over and under illumination visualizations. Figure-?? shows that of 10 participants that provided feedback seven were positive statements. In general participants understood over and under illumination and claimed that OASIS was useful for daylighting performance and analysis. More interestingly, our most experienced user claimed that they did not see OASIS was not effective for daylight performance. The user did not understand what standard under and over illumination was relative to. Consequently, OASIS do not currently support adjusting thresholds for under and over illumination. Adjusting these thresholds for common actives, such as office work, are left as future work. In the course of this pilot user study, the feedback from our participant with over 10 years work experience in architecture was constructive to where we hope to take OASIS as a design tool. Similarly, the feedback from the non-experts is invaluable in regards to user interface decisions we are to make a direct result of this study.

REFERENCES

- [1] A. C. Ross *et al.*, “The 2011 report on dietary reference intakes for calcium and vitamin d from the institute of medicine: what clinicians need to know,” *The Journal of Clinical Endocrinology & Metabolism*, vol. 96, no. 1, pp. 53–58, 2011.
- [2] J. Pettifor, E. Daniels, D. Feldman *et al.*, “Vitamin d deficiency and nutritional rickets in children.” *Vitamin D.*, pp. 645–662, 1997.
- [3] M. F. Holick and T. C. Chen, “Vitamin d deficiency: a worldwide problem with health consequences,” *The American journal of clinical nutrition*, vol. 87, no. 4, pp. 1080S–1086S, 2008.
- [4] M. Rea, M. Figueiro, and J. Bullough, “Circadian photobiology: An emerging framework for lighting practice and research,” *Lighting Research and Technology*, vol. 34, no. 3, pp. 177–187, 2002.
- [5] K. Thapan, J. Arendt, and D. J. Skene, “An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans,” *The Journal of physiology*, vol. 535, no. 1, pp. 261–267, 2001.
- [6] C. L. Robbins, *Daylighting. Design and analysis*, 1st ed. New York, NY: Van Nostrand Reinhold, New York, NY, 1985.
- [7] *Occupational Health and Environmental Controls*, Online, Occupational Safety and Health Administration Std., part Number 1926.56. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=1
- [8] R. Leslie, “Capturing the daylight dividend in buildings: why and how?” *Building and Environment*, vol. 38, no. 2, pp. 381–385, 2003.
- [9] J. J. Gooley *et al.*, “Exposure to room light before bedtime suppresses melatonin onset and shortens melatonin duration in humans,” *The Journal of Clinical Endocrinology & Metabolism*, vol. 96, no. 3, pp. E463–E472, 2010.
- [10] G. Brainard *et al.*, “Effect of light wavelength on the suppression of nocturnal plasma melatonin in normal volunteers,” *Annals of the New York Academy of Sciences*, vol. 453, no. 1, pp. 376–378, 1985.
- [11] G. Menzies and J. Wherrett, “Windows in the workplace: examining issues of environmental sustainability and occupant comfort in the selection of multi-glazed windows,” *Energy and Buildings*, vol. 37, no. 6, pp. 623–630, 2005.
- [12] M. Bodart and A. De Herde, “Global energy savings in offices buildings by the use of daylighting,” *Energy and Buildings*, vol. 34, no. 5, pp. 421–429, 2002.

- [13] P. Ihm, A. Nemri, and M. Krarti, "Estimation of lighting energy savings from daylighting," *Building and Environment*, vol. 44, no. 3, pp. 509–514, 2009.
- [14] P. Boyce, S. Berman, B. Collins, A. Lewis, and M. Rea, "Lighting and human performance: A review," *Washington (DC): National Electrical Manufacturers Association (NEMA) and Lighting Research Institute*, 1989.
- [15] V. Bazjanac, "Architectural design theory: Models of the design process," *Basic questions of design theory*, vol. 3, p. 20, 1974.
- [16] C. F. Reinhart, "A simulation-based review of the ubiquitous window-head-height to daylit zone depth rule-of-thumb," in *Building Simulation*, vol. 106, no. 3, 2005.
- [17] A. D. Galasiu and C. F. Reinhart, "Current daylighting design practice: a survey," *Building Research & Information*, vol. 36, no. 2, pp. 159–174, 2008. [Online]. Available: <http://dx.doi.org/10.1080/09613210701549748>
- [18] C. Reinhart, "Gsd 6332 rules of thumb i." [Online]. Available: <http://isites.harvard.edu/fs/docs/icb.topic466781.files/l04.6332.rulesofthumb.pdf>
- [19] M. Suwa and B. Tversky, "What do architects and students perceive in their design sketches? a protocol analysis," *Design studies*, vol. 18, no. 4, pp. 385–403, 1997.
- [20] K. J. Yancy, "The daylighting design process tools for predicting daylight and techniques for making sound decisions about daylight during design," *The National Institute of Building Sciences*, 2010. [Online]. Available: "https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST2_023.EE7-1.pdf"
- [21] C. James, A. Flippin, and A. Schmitt, "Sun angle calculator," Jul. 27 1976, uS Patent 3,971,915. [Online]. Available: <https://www.google.com/patents/US3971915>
- [22] M. S. Millet, C. Adams, and J. Bedrick, "Graphic daylighting design method: including clear sky conditions," *Proc. Annu. Meet.-Am. Sect. Int. Sol. Energy Soc.;(United States)*, vol. 5, no. CONF-801016-(Vol. 2), 1980.
- [23] F. Moore, *Concepts and practice of architectural daylighting*. Van Nostrand Reinhold Company, 1985.
- [24] Y. Sheng, T. C. Yapo, C. Young, and B. Cutler, "Virtual heliodon: Spatially augmented reality for architectural daylighting design," in *Virtual Reality Conference, 2009. VR 2009. IEEE*. IEEE, 2009, pp. 63–70.

- [25] B. Cutler, T. C. Yapo, and Y. Sheng, “Inferring architectural designs from physical sketches: Application to daylighting analysis,” in *Proc. Intelligent User Interfaces (IUI) Sketch Recognition Workshop*, 2009.
- [26] J. Nasman and B. Cutler, “Physical avatars in a projector-camera tangible user interface enhance quantitative simulation analysis and engagement,” in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops*, 2013, pp. 930–936.
- [27] ——, “Evaluation of user interaction with daylighting simulation in a tangible user interface,” *Automation in Construction*, vol. 36, pp. 117–127, 2013.
- [28] B. Cutler and J. Nasman, “Interpreting physical sketches as architectural models,” *Advances in Architectural Geometry 2010*, pp. 15–35, 2010.
- [29] J. Hirsch, “equest, quick energy simulation tool: Introductory tutorial,” 2010.
- [30] M. Milne *et al.*, “A drag-and-drop energy design tool,” in *FORUM-PROCEEDINGS-. AMERICAN SOLAR ENERGY SOC & THE AMERICAN INSTITUTE OF ARCHITECTS*, 2001, pp. 569–574.
- [31] E. Y.-L. Do, “Vr sketchpad,” in *Computer Aided Architectural Design Futures 2001*. Springer, 2001, pp. 161–172.
- [32] D. Glaser *et al.*, “A sketch-modelling program for lighting analysis,” *Chiu, Tsou, Kvan, Morozumi, and Jeng editors. CAAD Futures*, pp. 371–382, 2003.
- [33] E. Li, “Photon mapping for architectural daylighting simulation of interior spaces,” Ph.D. dissertation, Citeseer, 2011.
- [34] S. G. Parker *et al.*, “Optix: a general purpose ray tracing engine,” *ACM Transactions on Graphics (TOG)*, vol. 29, no. 4, p. 66, 2010.
- [35] T. Hachisuka, S. Ogaki, and H. W. Jensen, “Progressive photon mapping,” *ACM Transactions on Graphics (TOG)*, vol. 27, no. 5, p. 130, 2008.
- [36] C. C. I. DE LECLAIRAGE, “Spatial distribution of daylightluminance distributions of various reference skies,” 1994.
- [37] D. R. Compagnon, “Radiance: a simulation tool for daylighting systems,” *The Martin Centre for Architectural and Urban Studies University of Cambridge Department of Architecture*, 1997.
- [38] C. F. Reinhart and M. Andersen, “Development and validation of a radiance model for a translucent panel,” *Energy and Buildings*, vol. 38, no. 7, pp. 890–904, 2006.

- [39] Y. Sheng, T. C. Yapo, and B. Cutler, “Global illumination compensation for spatially augmented reality,” in *Computer Graphics Forum*, vol. 29, no. 2. Wiley Online Library, 2010, pp. 387–396.
- [40] A. Marsh, “Ecotect (software),” *Australia: Western University*, 2007.
- [41] D. Tal, *Google Sketchup for site design: a guide to modeling site plans, terrain and architecture*. John Wiley & Sons, 2010.
- [42] M. S. Roudsari, M. Pak, A. Smith, and G. Gill, “Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design,” in *Proceedings of the 13th International IBPSA Conference Held in Lyon, France Aug*, 2013.
- [43] M. Andersen *et al.*, “An intuitive daylighting performance analysis and optimization approach,” *Building Research & Information*, vol. 36, no. 6, pp. 593–607, 2008.
- [44] M. Andersen, J. Gagne, and S. Kleindienst, “Informing well-balanced daylight design using lightsolve,” *CISBAT11: CleanTech for Sustainable Buildings from Nano to Urban scaleLausanne, S*, 2011.