

# **ONLINE ARCHITECTURAL SKETCHING INTERFACE FOR SIMULATIONS**

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## **ACKNOWLEDGMENTS**

## ABSTRACT

Daylighting plays a significant role in architecture. Daylight's creative and efficient use offers aesthetic visuals, increased productivity, and reduced energy demand. However, daylight can also 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 effects on architectural spaces. 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 windows, 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 early 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 a 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 more than just pleasing visuals and productive environments. Daylighting is also an environmental sustainability design practice for creating greener buildings and reducing power consumption. Similarly, daylighting can also be seen as an economic means to reduce a building's energy demands or increase worker productivity to generate capital. Despite the variety of definitions, daylighting will always refer to the use of daylight to meet 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 of 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 systems for the purpose of better understanding current advances in daylighting research. 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 develop 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 reducing 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. Similarly, 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 way 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 synthesis 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 exposure to sunlight meets most people's 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 foods 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 decreases exposure to daylight and increases the risk of vitamin D deficiency. Living an indoors lifestyle coupled with the widespread usage of sunscreen products, has 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, reduces the ability to synthesize vitamin D by as much as 99%[3]. Additionally, sunlight received through a glass window be non-helpful for vitamin D synthesis. Glass, while not a suitable form of total UV protection, filters out a percentage of UVB light[?] necessary for vitamin D synthesis.

Architectural daylighting can help alleviate this risk by creating buildings with apertures<sup>1</sup> and geometries 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 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 of 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 located in our retina, regulates these non-image forming light responses. These non-rod/non-cone photoreceptors are excited by the exposure to alternating periods of light and dark. They specifically respond to lighting conditions found in daylight[4, 5].

Electrical lighting varies from natural daylight in a couple of biologically significant ways[4]. Daylight offers a higher level of illumination, a wider spectrum of electromagnetic radiation, and a temporal variation in lighting. Firstly, sunlight in

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<sup>1</sup>Apertures is an architecture term used to refer to opening in building, such as windows and skylights.

conjunction with skylight<sup>2</sup>, 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 lighting requirement for typical office work[7]. Lighting conditions that do not excite photoreceptors responsible for maintaining our circadian rhythm, such as lighting conditions below 100 lux, are considered biological darkness[8, 4]. Secondly, the spectrum of light emitted by artificial lighting lacks the short wavelength electromagnetic radiation found in sunlight. Specific wavelengths of electromagnetic radiation significantly affects melatonin levels in humans. Melatonin suppression is important because it has significant influence in sleep-wake cycles, body temperature regulation, alertness, and blood pressure[9]. Studies show melatonin suppression varies most through the 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 specific times in our sleep-wake cycle. For instance, morning light exposure triggers melatonin suppression resulting in the feeling of alertness[4]. However, exposure to light at asynchronous times in our sleep-wake cycle 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 impact 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 both sunlight and skylight. It is not surprising that the human visual

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<sup>2</sup>Skylight is the diffuse illumination provided by sunlight scattered in the atmosphere.

system works better using daylight as a source of light compared to other sources of illumination. A visual task, such as reading, generally require less illumination from daylight than illumination from 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 lighting conditions or fluorescent lighting is less accurate than differentiating colors under daylight[6]. There are current electrical lighting systems that provide full spectrum light, however, these systems are costly when compared to daylight. Moreover, occupants enjoy being near windows; Windows give occupants information about their outdoor environment – including the time of day, weather conditions outdoors, and activities happening outside. Additionally, 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 productivity gains provide an indirect financial benefits to companies investing in daylighting systems. Furthermore, focus groups and interviews with professionals involved in the architectural design process show that architects tend to prioritize the comfort, health, and productivity of occupants over a buildings sustainability[11]. However, careful design of daylighting systems can still provide large direct financial benefits by reducing power consumption.

#### **1.1.4 Reduced Energy Demands**

There are direct economic gains from daylighting systems. Specifically, longterm energy conservation from reducing the usage of electrical illumination can save building owners significant capital. 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. In some cases, electricity companies charge peak hour rates during the afternoon when demand for electricity is at its highest. During these peak

hours alternatives sources of light, such as daylighting, become cost effective. It is hard to estimate how much energy savings is possible by adding a specific daylighting system. Simulations are an important tool architects use to determine electrical demand 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]. Adding windows to an architecture space doesn't always help reduce energy demand. Moreover, windows can even hurt energy savings via unwanted solar heat gain in the summer and heat loss in the winter.

Using daylight as an alternative or supplement to electrical lighting requires daylight management. Automatic daylight management consist of dimming systems that control the intensity of electrical lighting during peak hours when daylight is most readily available. Some simulation results show that in the absence of daylight management power consumption from lighting can exceed 50% of a building's total power demand. However, those simulations also show that daylight can reduce up to 18% to 55% of a building's heating and lighting demand[12]. Without a dimming system, the interval of time in which daylighting is cost effective is significantly reduced. Other simulation results showed energy savings of 60% with daylighting coupled with automatic dimming control strategies[13]. A major disadvantage of automated dimming systems is the lack of control of illumination and it's distribution. It is impossible to satisfy all occupants' personal illumination preference[?], as a result automatic dimming systems attempt to a meet generalized lighting requirement for a given space. This generalization might satisfy some occupants, but leave others uncomfortable.

Also, dimming lights result in reduced thermal output from lighting fixtures<sup>3</sup>. 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

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<sup>3</sup>Thermal radiation produced from incandescent lighting generates significant amounts of heat, however, florescent and LED lighting are more efficient and do not produce comparable thermal output

reducing the cooling load, daylighting can also be used for intentional solar heat gain during the winter, while preventing unintentional solar heat gain during the summer. Daylighting systems exploit the shallow sun angle in the winter season by using roof overhangs that let direct sunlight into a building during the winter months and blocking direct sunlight during the summer months. Heating a large space during the winter is expensive, and leveraging solar heat gain can aid in keeping heating cost down[12]. Figure-1.4B illustrates how roof overhangs can be used to accomplish this common daylight energy saving technique.

## 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 design stage 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 assess the quality of a design in terms of daylighting.

**Building-wide Design Choices** The cardinal orientation of a building is a choice that directly affects how daylight will illuminate architectural spaces. In the northern hemisphere, windows facing the south cardinal direction experience both direct sunlight and indirect skylight throughout the day. On the other hand, north facing

windows do not experience only diffuse skylight. The opposite is true in the southern hemisphere. In the south, north facing windows experience both direct daylight and skylight and south facing windows experience only diffuse skylight. Likewise, windows facing east experience direct morning sunlight and windows facing west experience direct evening sunlight. The temporal variations in eastward and westward direct sunlight are due to the sun's westwards path across the sky[6]. See Figure-1.1 for an illustration.



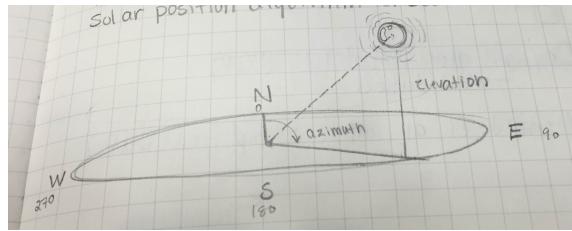
**Figure 1.1:** This illustration shows why windows facing southward in the northern hemisphere experience direct daylight and windows facing northward do not. It also shows the converse, north facing windows in the southern hemisphere experience direct lighting, however those facing southward do not.

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.

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

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

Equally important, the location of where a building is geographically built has direct impact on daylighting. Specifically, the path the sun travels across the sky

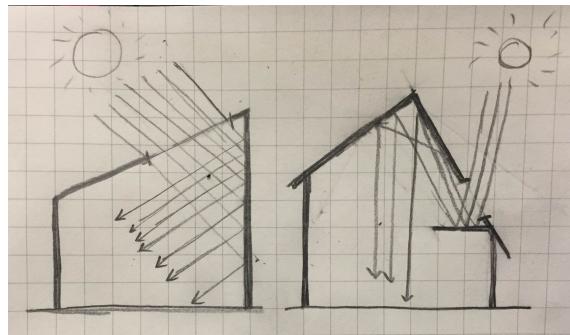


**Figure 1.2:** Illustration to show elevations and azimuth used to find the sun's position in the sky

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.  $\delta$  in equation-1.1 and equation-1.2 refers to the solar declination angle. Lastly,  $\phi$  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 projected sun from the horizon. The azimuth can be calculated once the elevation angle has been found, as shown in equation-1.2. As shown in both equations, the sun's position in the sky is relative to longitude, latitude, and temporal variables. Similarly, surrounding vegetation and buildings can have influence of daylight in an architectural space. For example, adjacent building can either occlude or reflect direct daylight into an architectural space, depending on the location and reflective properties of the nearby building. Moreover, adjacent buildings not only occlude direct sunlight but also block access to skylight. The occlusion skylight can greatly reduce the amount of daylight available for use in architectural space. The same is true for vegetation. Trees, and similar vegetation, can be used to provide shade and diffuse harsh direct sunlight.

**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, as illustrated in Figure-???. 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 the distribution of daylight 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, these windows pose 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 daylighting.

**Temporal Variation** It is obvious that daylight varies from sunrise to sunset. 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-1.4A illustrates the difference in light penetration during the winter and 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.

As stated previously 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-1.4B. 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 diffuse daylight. 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.

In brief, daylight 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 design 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 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 and the clarity of the symbols being read. Under-illumination can make reading difficult and reduce worker productivity[14]. Moreover, 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 environments 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 for prolonged periods of time[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 not only dependent on the source 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. Unlike disability glare, discomfort glare does not cause momentary blindness. However prolonged exposure to discomfort glare when focusing on a visual task can significantly reduce 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, daylight can also cause discomfort during the summer.

Overall, there are various ways daylight can have adverse effects on occupant's comfort. As a result architects invest significant time and effort in daylighting analysis to prevent occupants from experiencing these adverse effects. Not only can occupants experience discomfort, but building owners can suffer economic loss from improperly created daylighting systems.

**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 gain. To counter solar heat gain, cooling systems must work at higher loads than usual resulting in increased energy usage. Furthermore, windows unless insulated well can result in heat loss during the winter seasons and nights. There several strategies architects can use to mitigate heat loss during the night. For example using thick drapes, shades, and shutters can provide layers of insulation to keep warm air inside from direct contact with the colder window. Additionally, there are specialized window glazing available that can help reduce heat loss during the winter and night. Ultimately, rooms with many windows

might provide ample daylight during the daytime but carry the risk of significant heat loss during chilly nights and the winter months.

Lastly, occupant behavior can result in the lost of investment capital for building owners. Occupants exposed to the visual discomforts of daylight can choose to use window blinds to block daylight out entirely and rely solely on electrical lighting. The use of electrical lighting, given available daylight, results in reduced energy savings for building owners. As mentioned previously, daylighting coupled with automated dimming systems can help prevent occupants from the visual discomforts of over illumination. However, having no control over automated dimming systems can cause occupants discomfort and result in coup d'état in which occupants only rely on electrical lighting.

Moreover, daylighting systems are expensive to design and implement and as a result the initial cost is generally greater than using traditional electrical lighting. If occupants continuously 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 architectural design of a building from concept to construction is no easy task. As a result, architecture firms and schools generally break down the architectural design process into five manageable phases[15]. Daylighting affects all phases of the architecture design process; however, choices made early in the design of an architectural space lays 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 The Five Phases Of The Architectural Design Processes

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 are defined, 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 the 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 the 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.

**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



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

widely accepted in practice, however, 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 they are generally effective and straightforward to apply during the early stages of design.

Some common rules-of-thumb include simple suggestions 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 tasks be placed near the parameter of a building[8]. To elaborate, the daylight zone is a range of space where daylight can comfortably illuminates a 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<sup>4</sup> away from the wall containing the window, as illustrated in Figure-1.5.

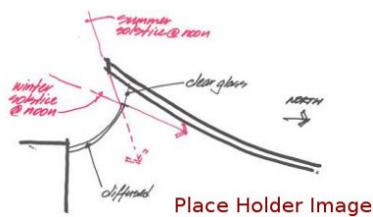
Another common rule-of-thumb is the elongation of the east-west axis of a building. The elongation of a building along the east-west axis is design choice meant to avoid solar heat gain and create more room for north facing windows[8].

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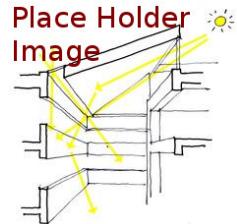
<sup>4</sup>The window-head-height is a term that refers to the height from the floor to the top of a window.

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. Consequently, 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 the interior of a space[8]. Moreover, the reflectance property of walls, windows, floors, and furniture impact daylight distribution. One more rule-of-thumb is that the ceiling should 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 formally validated, help guide daylighting design. The straightforwardness of these suggestions and the ability to abstract away the complexities of daylight make rules-of-thumb an invaluable tool to building designers.



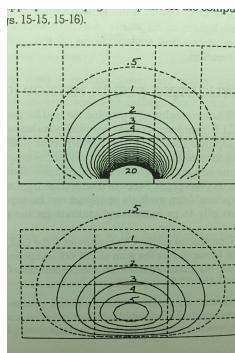
**Figure 1.6:** Example of brainstorming daylighting on sketches



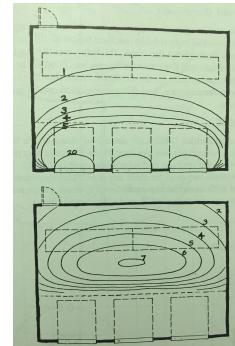
**Figure 1.7:** Example of brainstorming daylighting on sketches

**Sketch Analysis** Sketches are the primary medium architects use to convey visual ideas during the schematic design phase. Sketches help externalize concepts and ideas for both problem solving and rough daylight analysis[19, 20]. It is not surprising that sketches are also widely used in the brainstorming of daylighting system. Figure-1.6 and Figure-?? are some common examples of how architects use sketches

to problem solve and roughly predict daylight distribution. To do a rough prediction of where daylight will fall in a sketch, the architect would first draw a cross section of their imagined space. Though the use of specialized protractors, the architect can calculate where the sun is in relation to their cross sectional sketches[21]. Then by tracing multiple rays parallel to the sun angle into apertures in their cross sectional sketch, the architect can estimate the initial surface where direct lighting will occur. Then by continuously tracing reflected rays off the initial surface into the cross sectional sketch architects can better estimate how light will distribute in given space. Examples of these analytical sketches 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 sky. The GDDM shows both lighting distribution and intensity through using contour line visualizations. To use GDDM, first the architect would draw a floor plan of the room, making note of where windows are located. Using a series of specialized transparent overlays the architect can trace contour lines defining both daylighting distribution and intensity such as seen in Figure 1.8 and 1.9. These analytical sketches allow architects to evaluate 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.

## 1.4 Chapter Summary

There are a myriad of motives that draw the attention of architects, building owners, and researchers to daylighting systems. Research is continuously discovering health benefits of regular exposure to daylight including the promotion of vitamin D synthesis, the suppression of melatonin , and the regulation of the human circadian rhythm. Additional studies show that there are economic incentives to implementing daylighting systems. Some economic incentives come in the form of increases in worker productivity; While other economic incentives take the form of energy savings from reducing demand of electrical lighting. Motivations aside, daylighting systems are difficult to implement due to the dynamic nature of the sun. The distribution of daylight in an architectural space is dependent on many factors including (but not limited to) the cardinal direction of fenestrations, geometry of architectural spaces, the reflective properties of interior surfaces, and geographic location of a proposed space. Moreover, daylight varies not only throughout the day, but also throughout the year. While architects may be tempted to design architectural spaces with many apertures for maximal daylight, architects also have to juggle the risk posed by daylight as well. Poor choices in daylighting systems can result in discomfort to occupants, as well as lost of capital for building owners. To help overcome the difficulties of daylighting, architects use a variety of simple rules known

as rules-of-thumb during the early stages of design. For more detailed daylight analysis architects use analytical sketches and techniques to quickly estimate how daylight will be distributed inside of a conceptualized architectural space. Current daylighting research is aimed at the creation of daylighting analysis tools that will help architects better handle the challenges posed by daylight. These daylighting analysis tools are discussed in more detail in the following chapter.

## CHAPTER 2

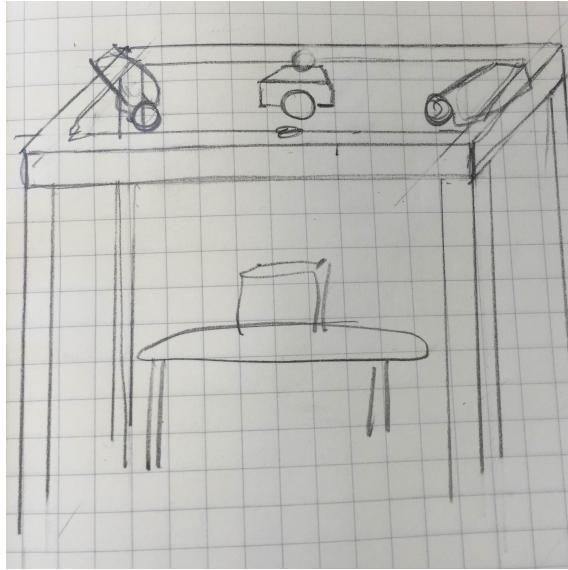
### RELATED WORKS

The online architectural sketching interface for simulations (OASIS) is an alternative interface for key algorithms originally developed for the Virtual Heliodon. The Virtual Heliodon is a spatial augmented tangible user interface for daylighting analysis. Both the Virtual Heliodon and OASIS rely on the physical sketch interpretation algorithm and the daylight rendering engine. The physical sketch interpretation algorithm is used to convert physical sketches, in the Virtual Heliodon’s tangible user interface, to water-tight triangle meshes. These triangle meshes are then used as input for the daylight rendering engine. The daylight rendering engine is a scalable renderer that uses GPU-accelerated photon mapping to produce daylight visualizations at interactive frame rates. Furthermore, while there are many well established architectural tools for daylight analysis, there exist only a handful of tools that are used in the early stages of design. We will discuss how both OASIS and the Virtual Heliodon share common goals with some of these more popular daylight analysis tools.

#### 2.1 Virtual Heliodon

The Virtual Heliodon is a spatial augmented reality system with a tangible user interface for the early collaborative design of interior spaces with daylighting[24, 25, 26, 27, 28]. The Virtual Heliodon is composed of multiple projectors, a circular table, and a collection of foam primitives. A large frame 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-2.1 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-2.2. After the creation of a physical sketch, a network of computers use projectors to superimpose daylight renderings onto foam primitives

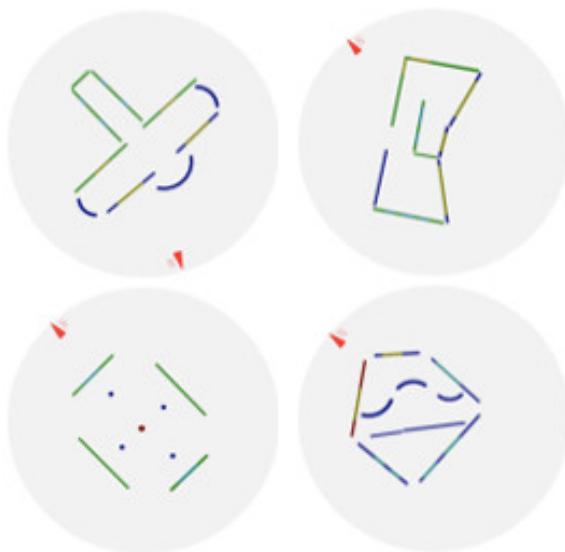
placed on the table top. The Virtual Heliodon requires multiple projectors in varying positions along the frame to superimpose renderings onto all of the wall primitives. Projecting daylight renderings directly onto wall primitives creates an augmented reality environment that gives users a sense of immersion[27]. The Virtual Heliodon has gone through a few evaluations and has been shown to be engaging and valuable as an educational daylighting tool[27].



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

## 2.2 Physical Sketch Interpretation Algorithm

A previous study evaluated the effectiveness of the physical sketch interpretation algorithm used in the Virtual Heliodon[25]. This study compared users' intended interpretation of physical sketches to both the interpretation from the physical sketch interpretation algorithm and human subjects. In brief, the study concluded that on average the physical sketch interpretation algorithm matched users' intention 78% of the time given non-ambiguous models[25]. Aside from ambiguous sketches, the Virtual Heliodon provided reliable 3D geometries that matched users' intended floor plan designs. For this reason OASIS uses the same physical sketching interpretation algorithm employed in the Virtual Heliodon.



**Figure 2.2:** Example physical sketches created by users on 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. Daylight analysis tools such as the Home Energy Efficient Design tool (HEED) and eQuest use parametric modeling to generate 3D models of architectural spaces[29, 30]. Parametric modeling is the creation of a model from a template by specifying parameters 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 measurements. 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. Specifically, HEED allows users to “draw” the floor plan of a building by filling in a 2D square grid. Filled in portions of the grid are used to define the floor plan of a building. The main disadvantage of this interface is the limitation of only supporting axis aligned models. Additionally, the interface on eQUEST only allows users to pick from a small set of template models including rectangular models, L shaped models, and U shaped models.

On a related note, geometric modeling is another 3D modeling approach commonly used to create complex architectural designs in software. Geometric modeling

gives users the ability to create 3D objects by modifying basic shapes visually. The process of geometrically modeling a conceived architectural 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, where there are fewer large changes in design[17]. SketchUp and AutoDesk are both popular architectural design tools that use geometric modeling for the generation of architectural spaces[41? ].

In practice, sketching is still used during the early design phase of architecture because of the unmatched speed & efficiently it offers designers[17]. Architectural sketching interfaces were developed as an alternative to parametric and geometric modeling. LightSketch and the VR SketchPad project both use an architectural sketching interface[31, 32]. Specifically, LightSketch shares much in common with OASIS. LightSketch gives users the ability to draw walls, windows, and interior lighting elements in order to create 3D architectural spaces[32]; the 2D drawings are then interpreted and turned into 3D models through different methods than the Virtual Heliodon's physical sketch interpretation algorithm. Users can then perform daylight analysis and generate renderings from those 3D models on LightSketch. LightSketch uses Radiance as its daylight rendering engine and as a result renderings can take several minutes to complete. LightSketch, however, is limited to shoe-box<sup>5</sup> geometries. Users cannot freely design non shoe-box floor plans, as is possible in the VR SketchPad project and the Virtual Heliodon. The VR SketchPad project supports the creation of a wide variety of 3D models for early visualization and exploration of architectural spaces.[31]. Also, VR SketchPad project was available as an online tool, similar to OASIS. The tool also supported a broad vocabulary of furniture item. Users could draw furniture items into the scene using this vocabulary and the VR SketchPad project would interpret the furniture drawings and choose the appropriate 3D furniture models to place into the scene. A limitation of the 3D models generated from the VR SketchPad project is that the

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<sup>5</sup>Shoe-box is a term used to generalize rooms that are rectangular prisms in shape.

models are only extrapolated from drawn sketches and as a result cannot be used for simulations. Explicitly, the VR SketchPad project does not distinguish between interior and exterior spaces in a design but instead generates objects only where users sketch them. On the other hand, sketches in the Virtual Heliodon and OA-SIS get converted into water-tight models that are required for daylight simulations.

## 2.3 Daylight Rendering Engine

In addition to using the Virtual Heliodon’s physical sketch interpretation algorithm, I also use the Virtual Heliodon’s daylight rendering engine[33, 26]. The daylight rendering engine takes advantage of NVidia’s Optix GPU ray tracing framework for the parallelization of photon mapping[34]. The daylight rendering engine is specialized to provide viewpoint independent daylight renderings at interactive rates. 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]. Window panes are considered emitters our daylight rendering engine; windows in our system emit both direct sunlight and diffuse skylight. When photons are emitted from the window pane their position and direction are chosen at random; However, the intensity of an emitted photon is determined by its direction as defined by the appropriate International Commission on Illumination’s (CIE) sky model[36]. An addition a non-recursive ray tracing procedure is used to take into consideration the hard edges of illumination caused from direct sun light.

I choose to use the Virtual Heliodon’s daylight rendering engine over other alternatives because of three reasons. Firstly, the daylight rendering engine provided daylight renderings at interactive rates. Many alternatives available at the time required minutes to create clear daylight renderings. As an early design tool, providing renderings to designers as quickly as possible is crucial for the iterative creative design process. Secondly, the Virtual Heliodon’s daylight rendering engine was optimized to work along side the Virtual Heliodon’s physical sketch interpreta-

tion algorithm. The existence of a pipeline between both of these components was valuable as it provided an existing base for our online sketching interface. Additionally, I had unrestricted access to the Virtual Heliodon’s code base which would allow me to extend the daylight rendering engine if needed. Unrestricted access to the source of code alternative daylighting tools is not always possible. Lastly, the daylight rendering engine has an optional message passing (MPI) interface that would allow us to scale OASIS. As of right now, OASIS does not use this MPI, but should we choose to generate more detailed rendering at similar interactive rates the option of using multiple graphics cards to accelerate rendering is available.

Although I did choose to use the Virtual Heliodon’s daylight rendering engine, I was aware of Radiance; Radiance is the long-standing industry standard for daylight rendering. Moreover, radiance is a command line tool that comes packaged with many daylighting metrics and visualization options. However, the lack of an graphical user interface makes Radiance hard to use for non-experts; as a result many daylight analysis tools provide graphical interface for Radiance. More importantly Radiance is an industry standard because it is one of the few daylight rendering engines that has been validated[? ]. While, the Virtual Heliodon’s daylight rendering engine has not been directly validated against Radiance, the rendering engine has been validated against a radiosity based rendering engine. This radiosity based rendering engine, used in previous versions of the Virtual Heliodon, was validated against Radiance[39]. I choose to use the Virtual Heliodon’s daylight rendering engine because at the time Radiance required more time to produce clear and noise-free results than the Virtual Heliodon[37]. Currently research on GPU accelerated implementation of Radiance are being developed that significantly increase performance of Radiance[? ]. In the future I will look into these GPU implementations of radiance to examine if their integration into OASIS is viable and effective.

All things considered, the Virtual Heliodon’s daylight rendering engine meets our needs in OASIS as a fast scalable in-house rendering engine for qualitative and quantitative daylight analysis during the early stages of design.

## 2.4 Related Software

OASIS shares goals in common with other daylight analysis software. Increased value on sustainability and energy efficiency drives the development of early design tools for daylight and performance analysis. One such piece of software is AutoDesk’s latest early design tool, Project Vasari[? ? ]. Project Vasari is a stand alone geometric modeling software with an interface similar to AuthoDesk’s Revit[? ]. Project Vasari, unlike Revit, was designed for energy analysis during the conceptual design of architectural spaces. Project Vasari comes packaged with a suite of energy analysis visualizations, including several daylighting visualizations.

Most major architectural design tools support energy analysis plug-ins; These plug-ins come packaged with a variety of energy metrics and visualizations, including daylighting visuals. A tool with similar features to Project Vasari is Ecotect – an AutoDesk plug-in[40]. Ecotect offers a collection of useful visualizations such as sun paths, building shadow previews, and daylighting factor visuals.

SketchUp is another notable conceptual design tool that does not directly support energy analysis or advance daylighting features[41]; however there are a handful of plug-ins for SketchUp that do. For example VE-Ware by IES is a free energy plug-in for SketchUp and Revit[? ]. Given a model created in SketchUp VE-Ware will generate detailed energy analysis reports. Also, another noteworthy SketchUp extension is Lightsolve[43]. While Lightsolve is not officially a SketchUp plug-in, LightSolve does support importing models directly from SketchUp. Light-Solve is noteworthy because its main focus is on daylight analysis. Lightsolve is an early design daylight analysis tool that gives designers both annual metrics and qualitative renderings. Specifically, within the application designers can analyze both quantitative illumination metrics and view renderings from multiple viewpoints simultaneously. Lightsolve also provides visuals on the sun’s position 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 the daylighting conditions within their design[44].

Lastly, Rhinoceros is a general 3D Modeling tool commonly used for creating non-axis aligned architectural models and supports plug-ins such as LadyBug for basic energy analysis[? 42]. LadyBug supports a wide variety of energy analysis visualizations, but only has a few visualizations specific to daylighting analysis – including sun path visuals and hourly radiation studies in real time.

On the whole, all of these tools offer rich and informative daylighting analysis during the conceptual design of architectural spaces. However they all rely on geometrically created models. During the early design stage of architectural design, the ability to express concepts as 3D models quickly is invaluable. As a result , researchers have investigated faster and initiative methods to generate 3D models for daylighting analysis.

## 2.5 Chapter Summary

In OASIS I use both the Virtual Heliodon’s daylight rendering engine and the physical sketch interpretation algorithm. In order to understand why I use both of these key components, the original purpose of each component must be made clear. The physical sketch interpretation algorithm was originally used to convert physical sketches into 3D water-tight triangle meshes for use in the daylight rendering engine. The daylight rendering engine’s initial purpose was to generate daylight renderings and produce texture images that would be superimposed onto physical sketches. This method provided users a view point independent visualization of daylight within an architectural space. While there were other daylight rendering engine alternatives, we choose to use the Virtual Heliodon’s native rendering engine for its speed, compatibility, and scalability. Moreover, there are a variety of related daylight analysis tools from which architects can choose from. However, very few tools concentrate on the early design stage of architectural design. OASIS is not the most fully featured architectural modeling tool; however, it is one of the few early design tools that features a sketching interface.

## CHAPTER 3

### Feature Design

#### 3.1 System Overview

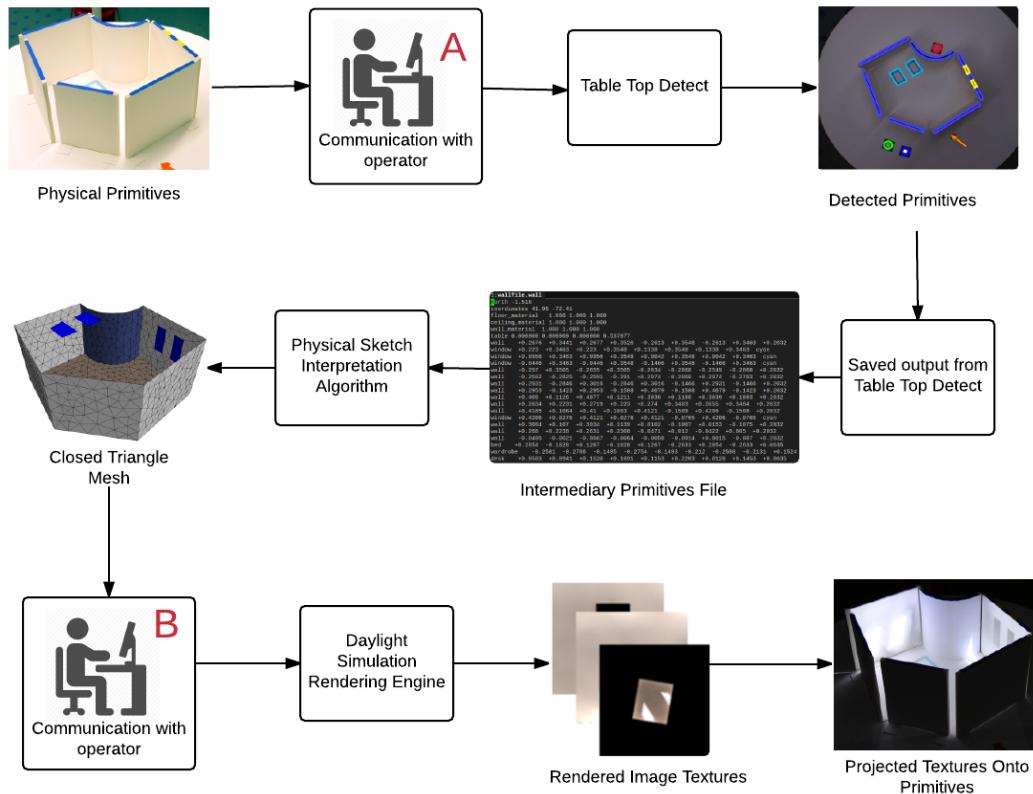
**What is OASIS** The online architectural sketching interface for simulations (OASIS) is intended to be a general early design tool for both novices and architects. OASIS provides a platform independent sketching interface that generates closed 3D triangle meshes with optimal properties for simulations. Currently, OASIS only supports daylighting visualizations; however, OASIS can be extended to support other simulations that make use of closed triangle meshes, including acoustic and thermal simulations. The main advantage OASIS offers users is an novel interface that does not require detailed geometric modeling for the creation of 3D triangle meshes and an interface to analyze simulation results. An additional advantage of using OASIS is the client-server architecture that allows users to be able to run computationally expensive simulations at interactive rates regardless of their machine specifications.

**Virtual Heliodon Pipeline** Both OASIS and the Virtual Heliodon provide a novel solution to the challenge of daylighting analysis during the early stage of architectural design. In addition to sharing the same objectives both OASIS and the Virtual Heliodon utilize the physical sketch interpretation algorithm and the daylight rendering engine. As a result it can be difficult to see where these two systems vary. In order to understand the contributions I made to OASIS we must briefly cover the system pipeline of the Virtual Heliodon. The Virtual Heliodon's system pipeline is illustrated in Figure-??. To begin, the Virtual Heliodon features a novel tangible user interface for the creation of architectural spaces. Users define architectural spaces by manipulating physical foam primitives with their hands. After users are satisfied with their architectural space they can either use a wireless clicker or communicate to the operator to run the *table top detect* process and continue to generate a closed triangle mesh from their physical sketches; Communication with the operator to run the *table top detect* process is noted in Figure-??A. The *table top*

*detect* processes is a simple computer vision program that takes an overhead image of the foam primitives and detects where those primitives are in an image. The coordinates of where those primitives are in an image are stored in an intermediate primitives file. The intermediate primitives file is used as input for the physical sketch interpretation algorithm. As mentioned previously, the physical sketch interpretation algorithm generates a closed watertight triangle mesh. Currently, there exist no user interface for the generation of daylight visualizations. Instead, an operator familiar with the system is required to generate visualizations for users, as shown in Figure-??B. After the generation of a watertight 3D mesh, users communicate to the operator the time and date they would like visualized. Depending on the time, date, and user visualization requested the operator would manually modify existing scripts to generate those visualizations on the Virtual Heliodon. These scripts would include invoking the daylight rendering engine to generate image textures to be projected onto users' physical sketches. In other words, the Virtual Heliodon does not offer much autonomy and requires an operator to both explain how to use the tangible user interface and constantly communicate with users to operate the Virtual Heliodon.

**OASIS Pipeline** OASIS is an alternative interface to the Virtual Heliodon. The system pipeline in Figure-3.2 illustrates the components involved in OASIS. In addition, Figure-3.2 emphasizes all portions of OASIS that I directly contributed to. To begin, users on OASIS generate 2D sketches consisting of lines that represent wall and windows and objects that represent furniture items. The physical sketch interpretation algorithm that the Virtual Heliodon uses to generate watertight 3D meshes for simulations require sketches be given as a collection of model primitives. Therefore, before being able to invoke the physical sketch interpretation algorithm, OASIS generates the intermediate primitives file. Model primitives are stored in an intermediate primitives file where each line describes a wall, window, or furniture item in a sketch. As mentioned previously, in the Virtual Heliodon the intermediate primitives file is created by a simple computer vision algorithm that detects walls, windows, and tokens through colored markers placed on the top of physical

## Virtual Heliodon Pipeline



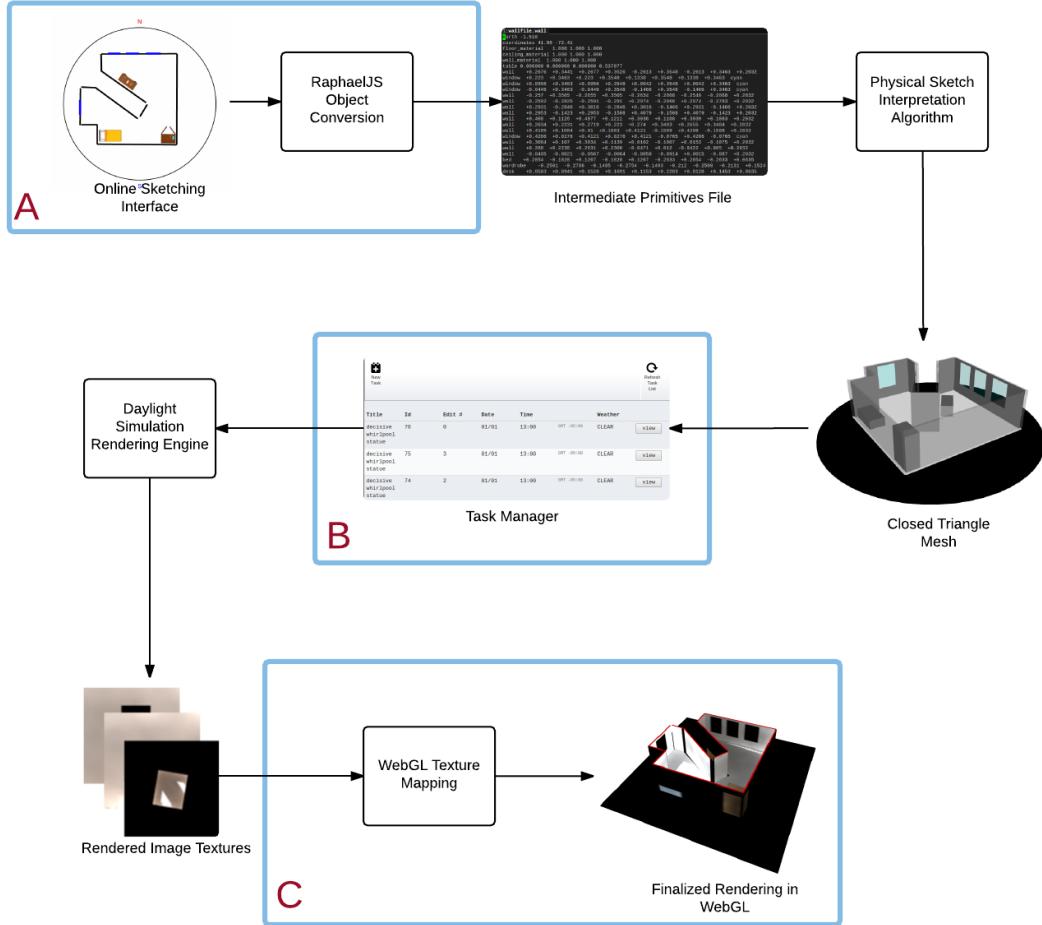
**Figure 3.1:** Virtual Heliodon's simplified pipeline. A and B are locations in the pipeline that require an experienced operator to perform technical actives on the Virtual Heliodon.

primitives. Since the sketching interface is purely in-software, I can directly create this intermediate primitives file without need of a computer vision algorithm to detect primitives. Interestingly, OASIS avoids a few limitations of the Virtual Heliodon by bypassing the need to detect physical primitives. OASIS can support a wider vocabulary of primitives because it is not bound to the detection of colored tokens. Additionally, at certain angles parallel wall primitives in close proximity to each other on the Virtual Heliodon could result in the occlusion of primitives in the overhead image. Since OASIS is an in-software solution, this problem is avoided as the position of all primitives is always known. Figure-3.2A illustrates where OASIS

generates the intermediate primitives file in our system pipeline. Given the intermediate primitives file the physical sketch interpretation algorithm outputs a closed triangle mesh that the user can view in the *Generate 3D Model* page. The user can create a daylight simulation request in the *Create Daylighting Simulation* page, given confirmation that a 3D generated model matches the user's intention. This portion of the system pipeline is illustrated in Figure-3.2B. After the submission of a daylight simulation request, I use the daylight simulation rendering engine to produce texture images. These texture images capture global illumination from a daylight simulation in a viewpoint independent manner. On the *Analyze Daylighting* page, I map these texture images onto the 3D mesh to display a daylight rendering of the user's generated model. Figure-3.2C illustrates where texture mapping occurs in the system pipeline. In brief, our pipeline shows that OASIS is an alternative autonomous interface to the physical sketch interpretation algorithm and daylight rendering engine used in the Virtual Heliodon.

**Basic Navigation and Pages** OASIS consist of six pages that users can navigate between linearly and non-linearly; these pages are illustrated in Figure-3.3. Each of these pages, with the exception of the login/register page, are accessible through respective tabs located at the top most portion of the page. Each respective page, allows users to interact with different portions of our system pipeline. For beginners it is recommended that pages are followed linearly from step 1 to step 5. Figure-3.3A illustrates the first page users encounter when opening our web application. The *Login/Registration* page is designed to be as minimal as possible to encourage users to register and try out OASIS. After a successful login or registration, the first page users are directed to is the *Create/Load Model* page. The *Create/Load Model* page contains a selectable list of users' previously created sketches and the option to create new sketches. The *Create/Load Model* page is illustrated in Figure-3.3B. Assuming users follow the pipeline linearly, users would either load previously created models or start new models. Either action would result in a redirection to the *Sketch a Room* page, shown in Figure-3.3C. The *Sketch a Room* page contains the architectural sketching interface. After the user is satisfied with their sketch they

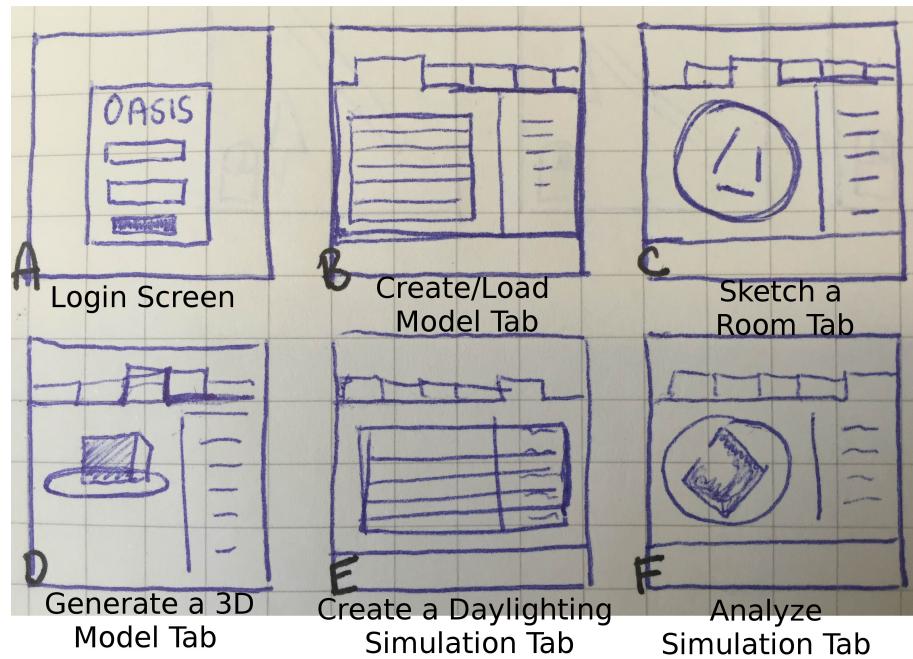
## OASIS Pipeline



**Figure 3.2:** OASIS pipeline diagram with the author's contributions noted in blue.

can proceed to the *Generate 3D Model* page. Visiting the *Generate 3D Model* page will invoke the generation of an intermediate primitives file; afterward OASIS passes the intermediate primitives file to the physical sketch interpretation algorithm. This creates a 3D watertight triangle mesh object that is displayed on the *Generate 3D Model* page. Figure-3.3D illustrates the *Generate 3D Model* page. Depending on the 3D watertight triangle mesh object created the user can either confirm their intention was met and navigate to the *Create Daylighting Simulation* page or navigate back to the *Sketch a Room* page to make alterations. On the *Create Daylighting Simulation*

page the user can either create new daylight renderings or view previously created renderings, as seen in Figure-3.3E. After the creation of a rendering users can then click on the *view* button associated with the rendering of interest. Clicking the *view* button will redirect users to the *Analyze Simulation* page. The *Analyze Simulation* page will display a daylight rendering that users can interact with for analysis. Figure-3.3F illustrates the *Analyze Simulation* page. The *Analyze Simulation* page will also host a variety of daylight visualizations that users can toggle between to perform both qualitative and quantitative daylight analysis. All in all, we hope that OASIS has a small learning curve and allows users to quickly preform daylight analysis with the least cost of effort.



**Figure 3.3:** This is an overview of the pages on OASIS.

**Importance of UI** A previous survey discovered that on average 48% of written code for a given application is made up of user interface implementation[? ]. The same survey also noticed that 50% of time spent coding an application is devoted to implementing the user interface[? ]. User interface design is important to the success and usability of any piece of software. Bottlenecks in a tool's user interface can result in user frustration and a reduction in users' productivity. As a result

OASIS is intended to provide an autonomous easy-to-use interface for interacting with the physical sketch interpretation algorithm and daylight rendering engine. Notably, we define easy-to-use as a general term that refers to the lack of formal training required to use a tool. As discussed previously, the interface in the Virtual Heliodon requires an experienced operator at all times. It is important to note that there has been attempts to give users control over the Virtual Heliodon including programming a remote clicker to trigger the *table top detection* process. However, there is currently no user interface for choosing visualizations to display and define the parameters required by those visualizations. The Virtual Heliodon, just like OASIS, aims to be an easy-to-use interface for not only the design of architectural spaces but also the generation of helpful visualizations. Requiring an operator with programming experience and background knowledge on the Virtual Heliodon may hinder users' creative iterative design process. By and large, the user interface can make or break an application and as a result we stress the importance of interfaces that are both autonomous and easy-to-use.

## 3.2 Sketching Interface Design

### 3.2.1 Sketching Walls and Windows

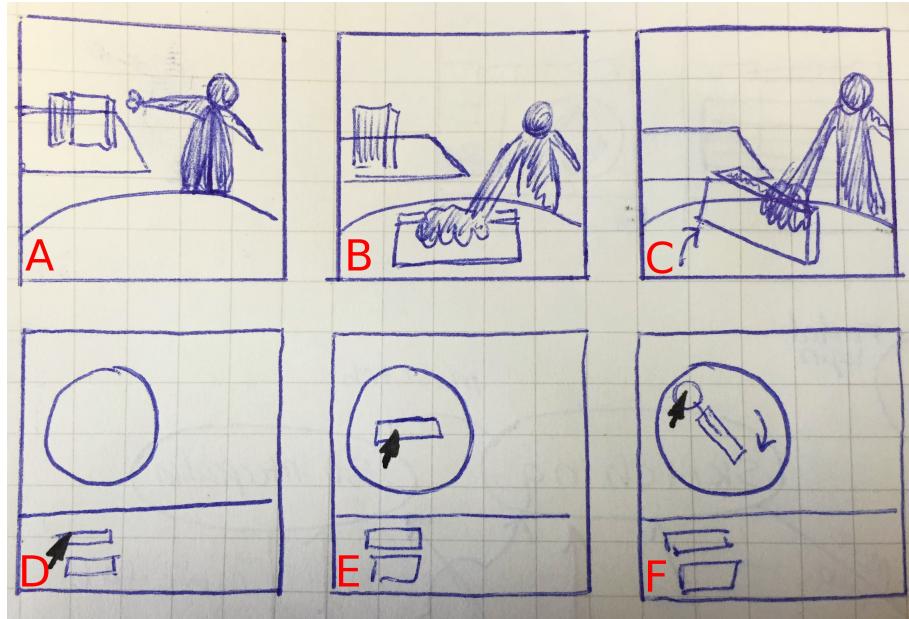
The boundaries that define an architectural space are composed of walls and other dividing objects. The boundaries of an architectural space must be well defined, in order to produce a 3D watertight triangle mesh. The physical sketch interpretation algorithm differentiates the interior and exterior of a sketch in the process of generating a 3D watertight triangle mesh. Consequently, the physical sketch interpretation algorithm requires walls to perform this differentiation[28]. The interface that allows users to define where walls in windows are placed in a sketch is important to the generation of 3D watertight triangle meshes and the overall usability of OASIS.

OASIS mimics physical drawing via a click-draw-release procedure. The click-draw-release procedure is illustrated in Figure-3.5. In order to draw walls users must first toggle the *wall drawing* mode on OASIS; Toggling the *wall drawing* mode is

done by clicking on the *wall* button located at the top of the *Sketch a Room* page, as illustrated in Figure-3.5A. Then, as Figure-3.5B and C illustrate, by holding the left 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 a window needs 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 their input device, but rather focuses on users' intention.

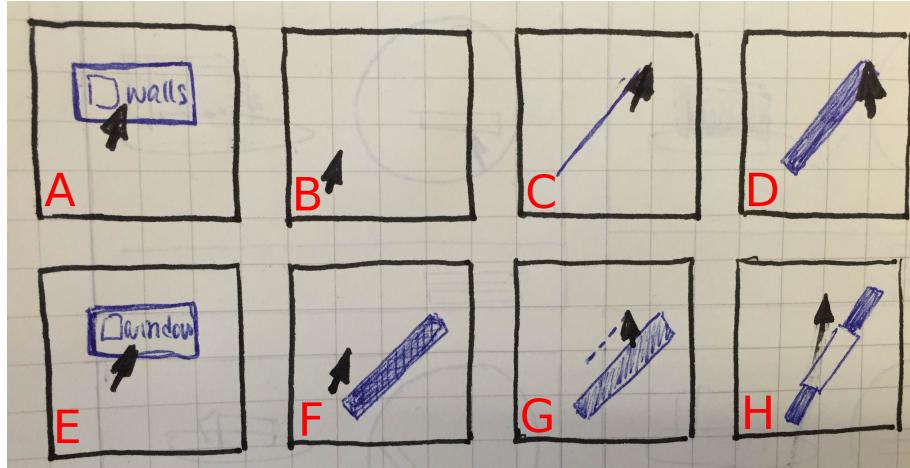
An alternative interface that was implemented but not used, allows users to create walls and windows via a drag-and-drop procedure; The drag-and-drop procedure is illustrated in figure-3.4D through F. Users could then further manipulate walls and windows by both rotating and scaling them through the use of Free-Transform handles. FreeTransform handles are three white circular handles that are overlaid onto walls and windows. One circle appears at the center and another circle is placed some distance away from the wall or window, as illustrated in Figure-3.4F. The circular handle in the center can be used to translate the primitive to anywhere on the canvas. The circular handle off the side of the primitive is used to both scale and rotate the primitive to a desired length and angle. Moreover, Figure-3.4 illustrates the parallels between how users place walls into a scene in both the Virtual Heliodon and via the drag-and-drop procedure. Both Figure-3.4A and D illustrate how users have to select a primitive from a collection of primitives in both the Virtual Heliodon and via the drag-and-drop procedure. 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. Figure-3.4C and F demonstrate how users

adjust either physical primitives through physical interaction or the manipulation of FreeTransform handles. However, despite mimicking how primitives were placed in the Virtual Heliodon, our eventual goal with OASIS is to pursue the most intuitive interface for drawing walls and windows. The drag-and-drop procedure focused on mimicking user interaction on the tangible user interface. Overall, further testing, such as A/B testing, would be required before any conclusions can be drawn as to which interface is more intuitive.



**Figure 3.4:** Similarities between the drag-and-drop procedure and the Virtual Heliodon’s Tangible User Interface.

Additionally, OASIS is currently undergoing the investigation of a new sketching interface that would allow users to draw free form lines, shapes, and letters. Using this new sketching interface users could traditionally draw walls and windows to define architectural sketches on OASIS. User’s drawing accuracy can vary dramatically depending on the input devices users are drawing with; common input devices includes computer mouses, touch screens, and pen-based drawing tablets. This new interface is investigating how to correct users’ sketches to generate the intermediate primitives file required to create 3D closed meshes for simulations. Extensive A/B testing between these three methods of sketching walls and windows would be



**Figure 3.5:** How to create walls and windows via the click-draw-release procedure.

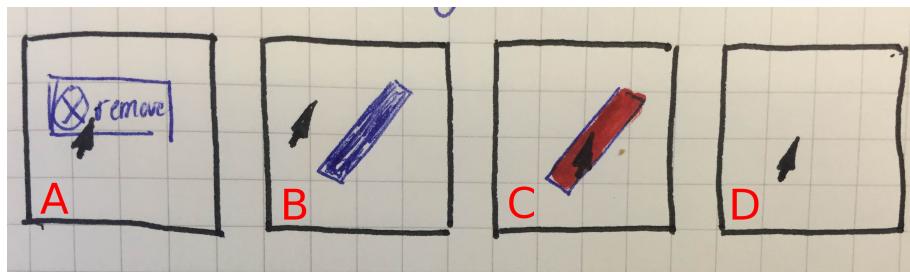
required to decide which interface is most intuitive to users.

**Furniture Placement** Another difference between OASIS and the Virtual Heliodon is the support of furniture items. Walls and windows are not the only elements that affect daylighting; furniture can also occlude, diffuse, and reflect daylight. Moreover, daylight distribution is scale invariant and as a result the Virtual Heliodon did not concern itself much with communicating to users a sense of scale. We currently support statically sized furniture items in OASIS, such as beds, desks, and wardrobes. These furniture items are used to indirectly communicate a sense of scale to users. Since furniture items cannot be made larger or smaller, users are forced to sketch architectural spaces in respect to the size of furniture items. Furthermore unlike walls and windows, furniture items are placed into the canvas by first clicking a furniture item button; these buttons are located on the top of the *Sketch a Room* page. After choosing a furniture item, OASIS will place the item at the center of the canvas. Furniture items use the same drag-and-drop procedure as mentioned previously in Figure-3.4. Users can manipulate furniture items via both 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. Item manipulation via drag-and-drop procedures are a common UI mechanism. 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[? ].

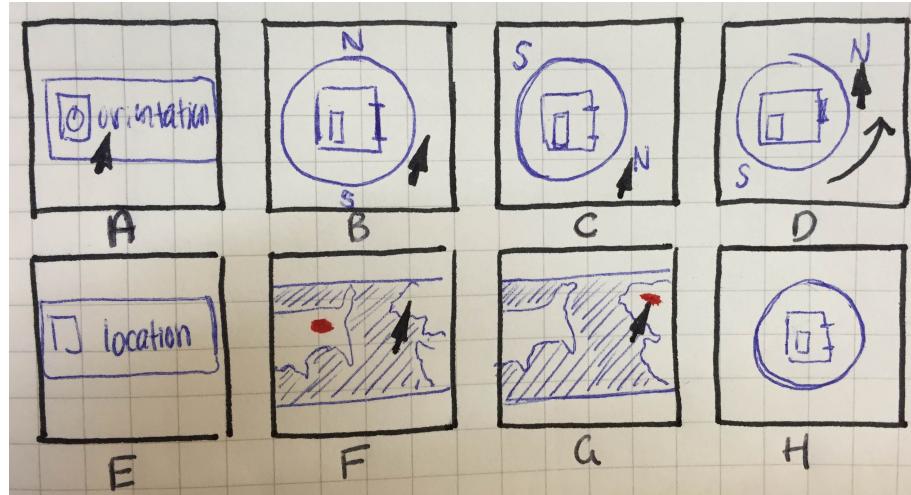
Additionally, OASIS is currently undergoing the investigation of a new sketching interface that would allow users to draw free form lines, shapes, and letters for not only wall and window placement but also furniture placement. This interface would allow users to freely draw symbols, that represent furniture items, to determine the position and angle a furniture item will be placed into the canvas. Interpreting symbols is non-trivial and more research is required before A/B testing can be conducted to determine the advantages of freely drawing furniture items.

**Removal of Elements** OASIS also supports the removal of walls, windows, and furniture items. Since users cannot reposition their drawn walls and windows after their initial placement, the ability to remove and redraw a wall or window is essential. The removal of all sketch based elements and furniture is done via a click-to-remove process. To remove items users must first 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 button click are highlighted in red as shown in Figure-3.6C. No items are removed from the canvas until the user's left mouse button clicks on a selected item. An alternative removal mechanism would allowed users to drag walls and windows and "drop" elements off the canvas. This alternative removal mechanism is intended to mimic the Virtual Heliodon's tangible user interface. While, OASIS does not support this drag-to-remove procedure, implementing and A/B testing against this procedure would help us understand which removal procedure users find the most intuitive.



**Figure 3.6:** How to remove an item from the canvas via the click-to-remove procedure.

**Cardinal Orientation** The cardinal orientation  $a$  of a window has significant impact on daylight distribution in an architectural space. In OASIS and all daylight analysis tools require that users define cardinal orientation in a architectural space. 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. Furthermore, the Virtual Heliodon allows the user to place a north arrow token onto the tabletop to define the cardinal orientation of a physical sketch. An analogous procedure would require users sketch an arrow on OASIS in order to define the cardinal orientation of their sketches. Other options include manually typing the model's degree offset from the north arrow; This procedural method of defining the cardinal orientation is common in other daylight software. Testing would be required to conclude which method of defining cardinal orientation is most intuitive to users.



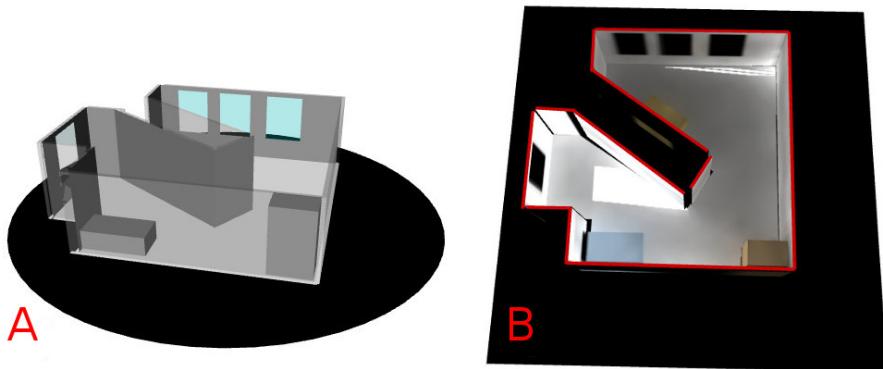
**Figure 3.7:** How to set the cardinal orientation and geographical location of a sketch.

**Geographical Positioning** Daylight distribution is not only dependent on an architectural space's cardinal orientation, but also from its geographic location. South facing windows in the northern hemisphere experience direct sunlight for most of the day, however north facing windows do not. In the southern hemisphere, the opposite is true; North facing windows experience direct sunlight and south facing windows do not. Additionally, the sun's highest point in the sky varies from buildings located in the tropics and buildings located outside them. For these reasons it is important that in OASIS we provide users a way to define a sketch's geographical location. To define a geographical location users must 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 the 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 results much. Figure-3.7 illustrates how a sketch's cardinal orientation and geographical location are defined. The Virtual Heliodon offers no analogous interface to define geographic location of sketches. All sketches in the Virtual Heliodon are set to Troy, NY. Most daylight analysis software allows users choice from a variety of major cities to define a model's geographic location; others allow users the ability to input exact geographic coordinates. Again, testing would be required before any conclusions can be drawn about which method is most intuitive to users for defining the geographic location of models.

### 3.3 3D model viewer

**Sketch Interpretation Viewer** The sketch interpretation viewer is located on the *Generate 3D Model Page*. This is a simple viewer that displays the 3D watertight

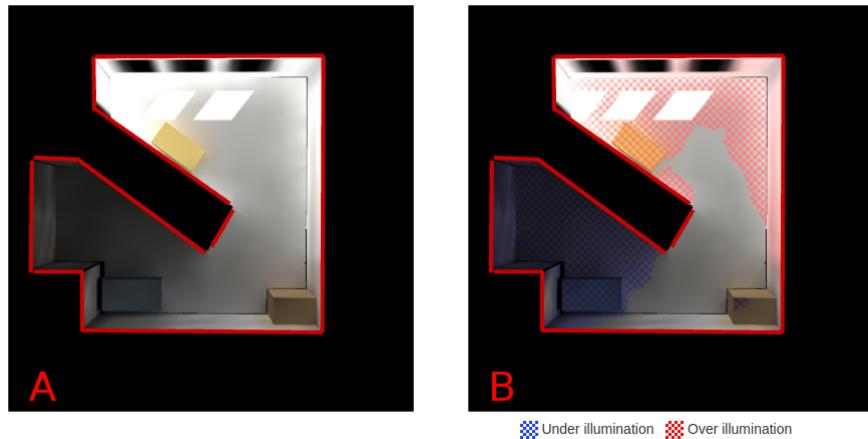
mesh created from users' architectural sketches. Users can zoom, rotate, and pan on this viewer. Additionally, walls facing the viewer are rendered transparently so that users can view the inside of their sketch from any view point, as seen in Figure-??A. It is important to display this information to users because, although the physical sketch interpretation algorithm generally matches users' intentions, there are cases where the 3D watertight mesh does not match users' intentions. Allowing users to view the interpretation of their model, before continuing to analyzing an unintentional architectural space, will save users time. Additionally it would provide users a chance to make alterations, so that the physical sketch interpretation algorithm better understands users intention; this can be accomplished by better defining an architectural space or simplifying complex models to lesser levels of detail. Alternative interfaces have been considered, however not pursued at this time. An alternative interface would actively invoke the physical sketch interpretation algorithm upon any updates to a sketch. An up to date interpretation of their sketch would be visible to users as they actively sketch out their model. Live interpretations would let the user know exactly when a generated model deviates from the user's original intention; Knowing exactly when the interpretation between the user and our algorithm deviates would allow the user to make alterations to their sketch without having to guess as to which elements in the sketch contributed to the misinterpretation. The development of such an interface is left as future work.



**Figure 3.8:** On the left is an example of the sketch interpretation viewer and on the right is an example of the daylight rendering viewer.

**Daylight Rendering Viewer** The daylight rendering viewer is located on the *Analyze Simulation* page. This viewer supports the same navigation controls as the sketch interpretation viewer. However, there are two visualization modes users can choose from on the daylight rendering viewer; this viewer supports daylight renderings and false color visualizations. These two visualization modes are illustrated in Figure-???. In Figure-??B the false color visualization brings users attention to areas that suffer from over and under illumination. This feature was ported from the Virtual Heliodon and displays a textured checkerboard image on surfaces that fall below or above specific thresholds in relation to the daylight rendering engine's illumination values[27]. Red checkerboard patterns are used to represent over illumination and blue checkerboard patterns for under illumination. Our intention as an early design tool is to have users analyze the daylight visualization results on the *Analyze Simulation* page. From their analysis users are either satisfied with the distribution of daylight in their model or choose to make renovations. Improvements include making alterations to diffuse lighting if over illumination is a problem. Additionally, improvements could include making windows larger or changing the orientation of the room to make better use of daylight. Overall, the daylight rendering viewer should not be the final step on users' work flow in OASIS, but instead be a point of evaluation that communicates to users where problems lie so that they may go back and make edits to their design and continue the cycle of the creative iterative design process.

**Share A Model Viewer** Current work is being done on a *Share A Model* viewer. This viewer would allow users to share models via generated URLs. The purpose of this viewer is two fold. Firstly, I suspect it would make sharing models between users much easier than sharing accounts or taking screenshots of OASIS and replicating sketches via tracing. In essence this feature would allow users to fork models from other users. Secondly, I hope this feature would allow users to share models between non-users, including family and friends. Rather than taking screenshots, non-users can visit the URL provided from a user and view the 3D rendering of a model without needing to sign up for an account. Figure-3.10 illustrates the viewer in its



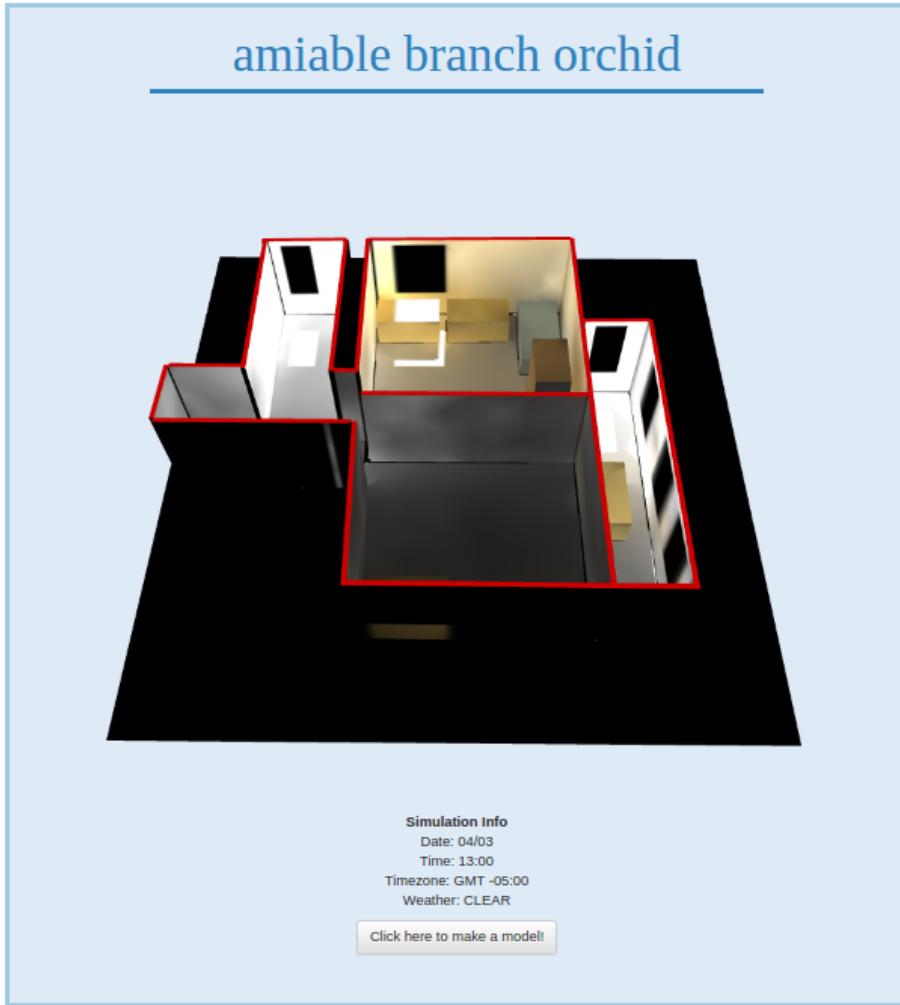
**Figure 3.9:** The two visualization modes of the daylight rendering viewer. On the left is a daylight rendering of a model and on the right is a false-color visualization of a model highlighting areas that suffer from over and under illumination.

current state. As mentioned, this stand alone viewer is currently under development.

### 3.4 General Web Application Design

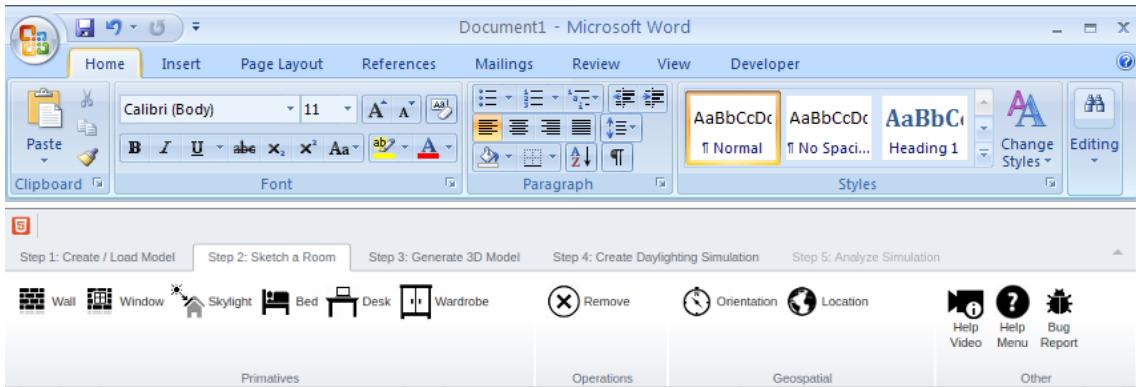
**Ribbon Design Choice** As mentioned previously in section-3.1 the user interface of any tool is of great significance. For that reason I choose to use a ribbon interface to organize the pages and tools on OASIS. The Ribbon interface is common to contemporary Microsoft products and even a few other daylight analysis tools[? ]. The hope is that organizing tools and pages in an interface that might be familiar to users would make using OASIS easier. Figure-3.11 illustrates the similarities between our interface and Microsoft Word.

**Nonlinear Navigation in OASIS** Although we recommend beginners navigate pages on OASIS linearly, nonlinear navigation is also supported. For example, non-first time users can log into OASIS and jump directly to the *Generate a 3D Model* page. This page will display the last model the user was working on before leaving OASIS. Similarly, a non-first time user logging back into OASIS can jump to the *Sketch A Room* page and the last sketch the user was working on before leaving OASIS will be displayed. Users can nonlinearly move between the *Create/Load Model*

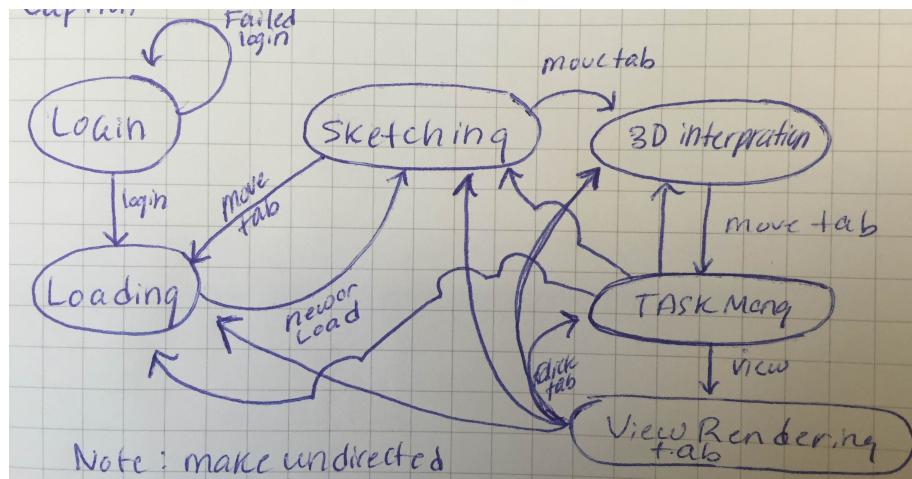


**Figure 3.10:** Share A Model viewer in its current state of development. No user registration is required to view a model.

page , the Sketch A Room page , the *Generate a 3D Model* page and the *Create A Daylight Simulation* page without state changes to OASIS. However, the *Analyze Simulation* page is only reachable through the viewing of a daylight simulation from the *Create A Daylight Simulation* page. Additionally, when viewing the daylight renderings of a model on the *Analyze Simulation* page a state change occurs. Viewing a rendering has the same effect as loading a sketch; this change will be reflected if a user navigates to the *Generate a 3D Model* page or the *Sketch A Room* page. Figure-3.12 illustrates the navigation between pages on OASIS. Overall, OASIS supports nonlinear navigation to save advance users time from having to follow pages linearly.



**Figure 3.11:** On the top is Microsoft Word’s ribbon and on the bottom is OASIS’ version of a ribbon.



**Figure 3.12:** This is a navigation diagram between pages and menus on OASIS.

### 3.5 Problems Encountered

**Computational Intensive Procedures** One of the first problems encountered in the design of OASIS was the fact that both the physical sketch interpretation algorithm and daylight rendering engine are computationally expensive. Furthermore, the daylight rendering engine requires specialized graphical processing hardware. Porting both of these components to work on multiple platforms would have been time intensive and hard to maintain. As a result we provide a server-client architecture for the generation of 3D models and daylight visualizations. Users define a set of parameters per rendering request and then submit a request to the server. The server is aware of all pending requests and handles all requests in a first come first serve manner. The model and the input parameters are then passed along to

the daylight rendering engine. We then map the output textures onto the walls, furniture items, and floor in the 3D model displayed on OASIS. Another important usability feature added was the caching of previous renderings on the machine hosting OASIS. The caching of previous renderings allows users to quickly view previous renderings without having to rerun the simulations on the server.

### Saving Models Safety

### Training Users

## 3.6 Implementation

### Frameworks Used

#### WebGL

**RaphaelJS** 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.

#### RibbonJS

## 3.7 Chapter Summary

## 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

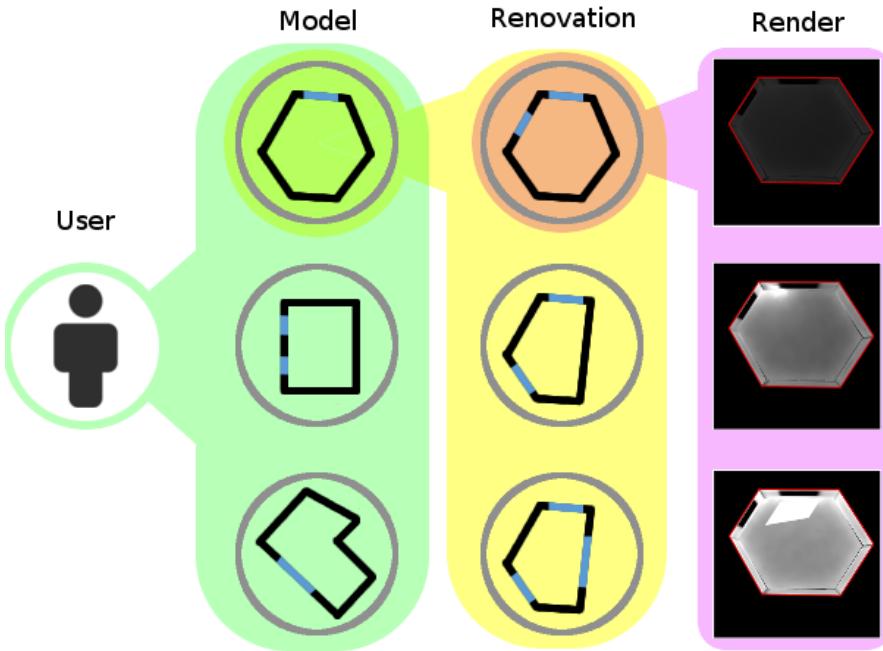
There were various frameworks considered for OASIS. Our requirement of accessibility to a broad range of users, however, limited our choices. Software that uses OpenGL, or another graphics libraries, would require installation. Having an installer and system requirements would be barrier of entry to 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.

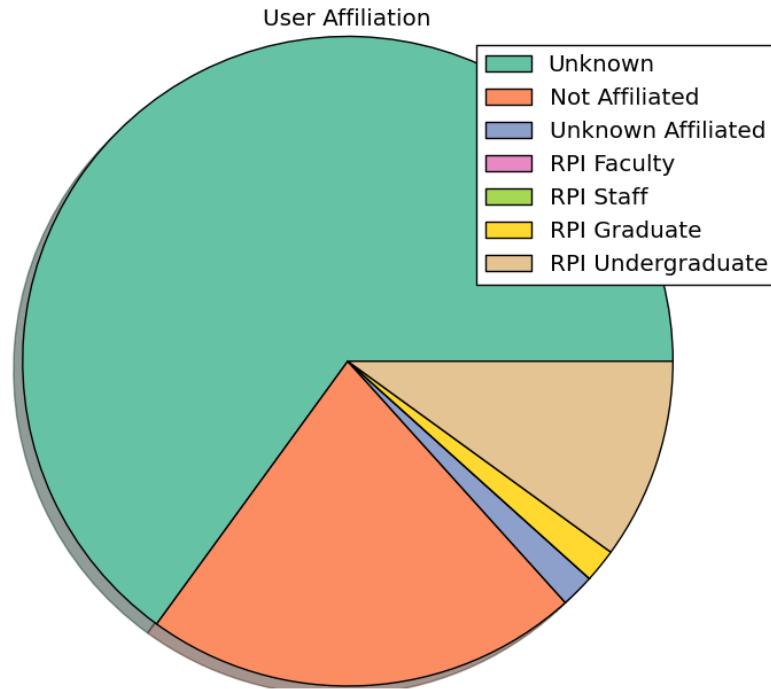
Reddit Forum	Subscribers
Beta	10,1455
InteriorDesign	78,750
RPI	3,939
Floorplan	1,175
UserExperienceDesign	1,128
GreenArchitecture	607
YoungArchitects	236

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

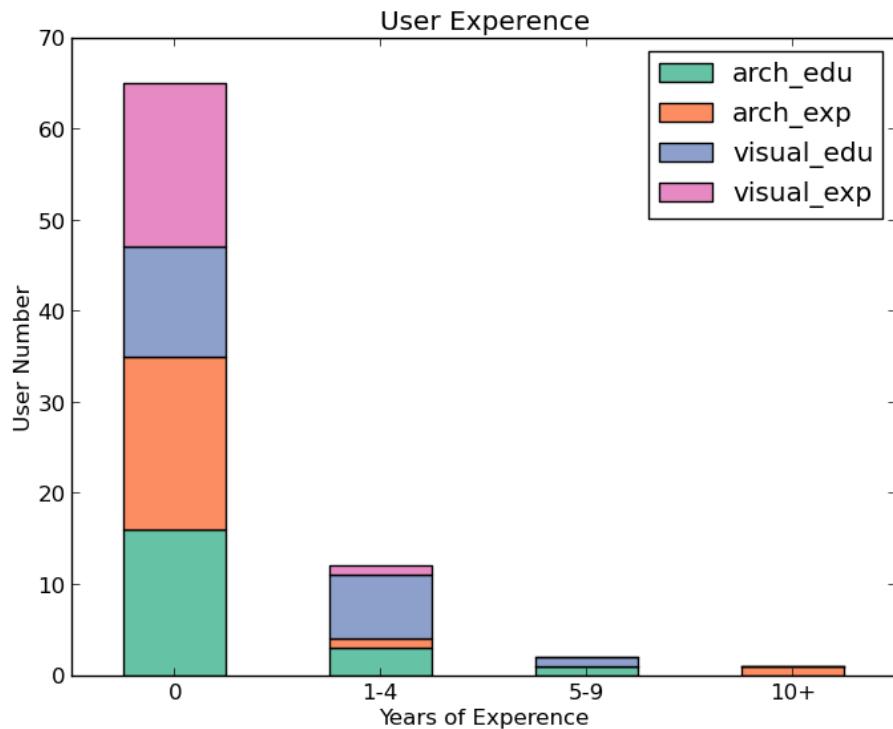
### 5.1 Participant Background Feedback



**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

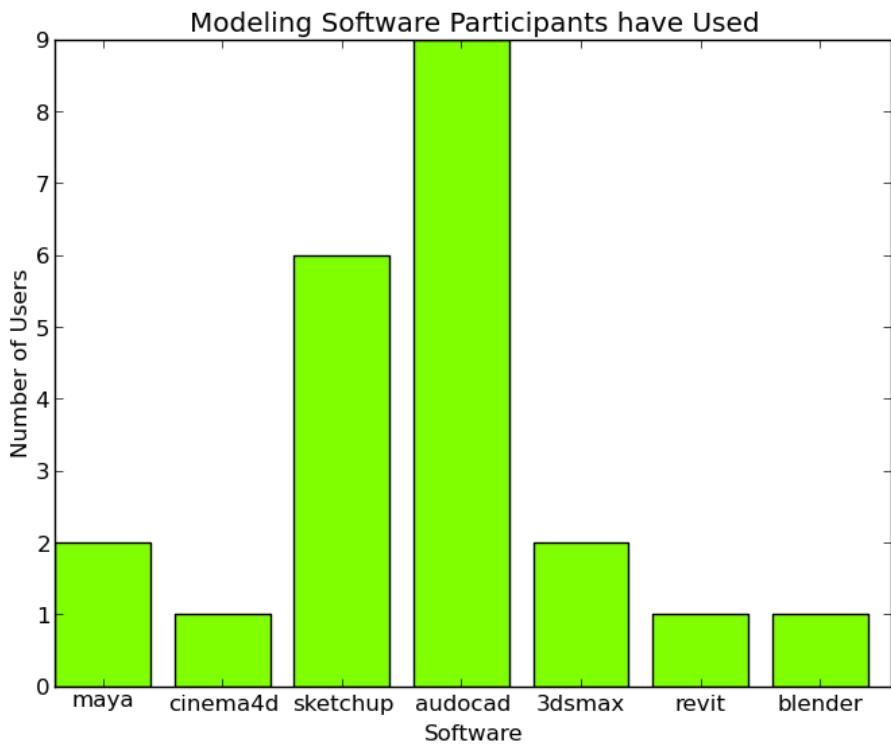
the majority of participants choose not to provide information on their affiliation with RPI. Specifically, 65% of participants did not provide feedback on their affiliation, and not all participants who claimed to be affiliated with RPI specified how they were affiliated; About 2% of participants have 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

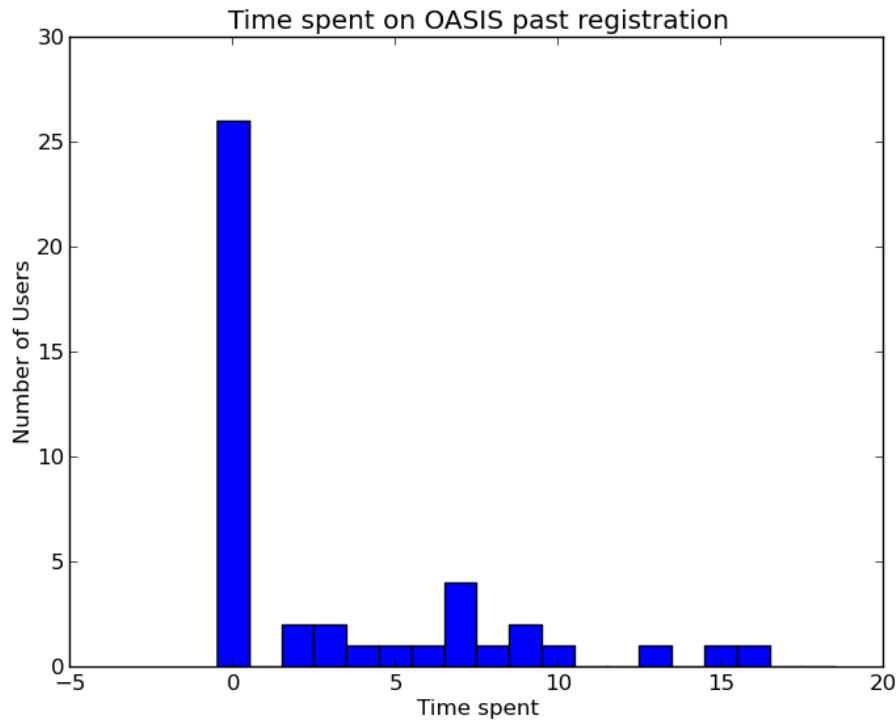
those participants that have experience, generally have only 1-4 years of exposure to formal architecture education or form visual arts education. However, there is one user registered on OASIS that claims to have over 10 years of job experience in architecture. Aside from asking about architecture and 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-

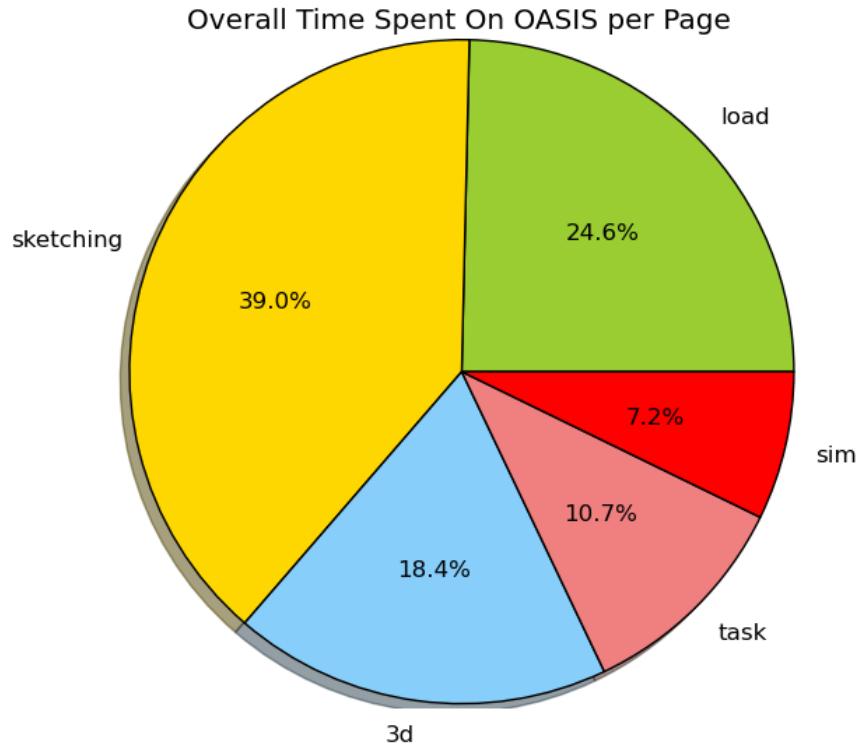
5.3, that participants have had experience using include SolidWorks[], AGI32[], Dialux[], and Daysim[]. Note that AGI32, Dialux, and Daysim are not specifically 3D modeling tools but rather used for daylight analysis and performance. From user feedback collected in our pilot user study on participants' 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 spent on the *Analyze Simulation* page seems remarkably low. The difference between time spent 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

Username	Response
galarodo	The beds/desks/wardrobes are good images and helpful when determining the scale
dcheung3	Creating the structure was interesting
damamani	The objects have very easy buttons to adjust orientation and position. This app is great for arranging new apartments to visualize where to get sunlight
kyoko.usagi	Kind [of] like the skylight option to be honest
mike smith	the furniture
tranthang	you can customize the room and have the light orientation
Solyha	It took me a few tries to get the windows in. I didn't realize you had to put a wall in and the window on top of that. I was leaving a space for the window.
Jan Selz	It was easy to understand the intent but a challenge to work with limited options.
ktran101	This was fun. Definitely interesting
durkeejw	Very simple, never ran into a "you can't do this"
flowerJane	It's really easy to figure out how to use the features.
mindykay	I find this tool extremely convenient to use and it's really fun to sketch new designs for future interior design plans!
qjkxkcd	It's very easy to use. The interface is very intuitive.
alanlang	the day-lighting simulation

**Table 5.1:** Feedback to the question: What did you find fun or interesting in this sketching environment?

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. Table-5.1 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 they never encountered modeled that could not be interpreted. Other participants claim they find specific features interesting, including 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 or 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.

Username	Response
dcheung3	Addition of precise measurements of the walls and windows would be good. Have more options on items besides desk and wardrobe. Be able to distinguish between open entrance ways and doorways.
Jan Selz	I only see items to create a bedroom. There should be additional items to create other types of rooms. It was also uncomfortable, not to be able to place a door.
ktran101	Maybe there can be more options for other pieces of furniture? Or just blocks that can represent it.
durkeejw	Window size, ceiling height, window surface finishes
flowerJane	Change the width and height of furniture, click and drag the walls
mindykay	Possibly adding the ability to install doors!

**Table 5.2:** Feedback to the question: What additional features should be added to the system to allow greater flexibility in design?

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. Table-5.2 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. Table-5.3 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[1]. 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 limitations is that doors are essential to communicate to users that our sketching inter-

Username	Response
galarodo	Lofted beds with desks underneath
dcheung3	Doors for enclosure
ryasoa	Add television and couch
damamani	I'd like to be able to connect the walls together and select all of them. I didn't have the ability to scale the objects. I also would've like to have the ability to move the walls around. There is no undo button or keyboard shortcut.
kyoko.usagi	No doorway, kinda important + furniture options kinda would help create the ambiance
mike smith	multiple rooms
tranthang	circular designs
Solyha	I would like to put in the items that hang on the wall to see how long they might be in direct sunlight.
Jan Selz	
ktran101	perhaps more furniture options.
durkeejw	Light shelves
mindykay	I was not able to make more than one room, since I can't put int a door.
qjkxkcd	Reflective surfaces would add to a model's accuracy (e.g. glass/mirror/water). But maybe those are beyond the scope of this tool.

**Table 5.3:** Feedback to the question: Describe some designs that you were not able to create due to system limitations.

face supports multi room designs. On a similar note Table-5.4 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 accurately when selecting a geographical locations for sketches.

Lastly, we asked participants if there were any elements in our interface that

Username	Response
dcheung3	There wasn't any real-time measurements when making the walls and windows that would have been beneficial in capturing more accurate model.
damamani	I'd like more objects.
kyoko.usagi	no doors [equal] not proud
mike smith	nope
tranthang	Cant move the walls
Solyha	I would like a graph in the background so that I could be more accurate with the dimensions.
Jan Selz	I have a Building Information Modeling program open in the background.,I kept wanting to use commands and shortcuts for that program and it was difficult to simply just draw.,(more personal issue than program issue)
mindykay	Nope!
qjkxkcd	The location selector could be easier to use accurately but I guess it's not really important. An "undo" feature might be handy also.

**Table 5.4:** Feedback to the question: Was there anything you did not like about working in this sketching environment?

were hard to use. Feedback from that question can be seen on Table-5.5. 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 commu-

Username	Response
galarodo	Nope
dcheung3	No, everything was very straight forward and user-friendly.
damamani	No,The user interface is very simple and easy.
kyoko.usagi	at first I couldn't put the walls in like I was stuck in the confine space of the circle, but I know that I would make it bigger. But I got the hang of it I guess
mike smith	nope
tranthang	N/A
Solyha	At first the “buttons” would not stay highlighted so I did not know if I was in the right mode at first. I wish you could move an item like the desk after it is placed to refine its location. I had to delete it and them put another one in when I was trying it out.
Jan Selz	It is very intuitive.
durkeejw	no, very easy
mindykay	None!
qjkxkcd	Were (typo in the question) + Apparently walls can be removed with the “Remove” operation, but it seems like furniture can’t be + Also, when furniture is added, there are 3 white points that can be used to manipulate it; the center one controls the position, and both of the others rotate the object. Is one meant to resize it? Or are they supposed to do the same thing

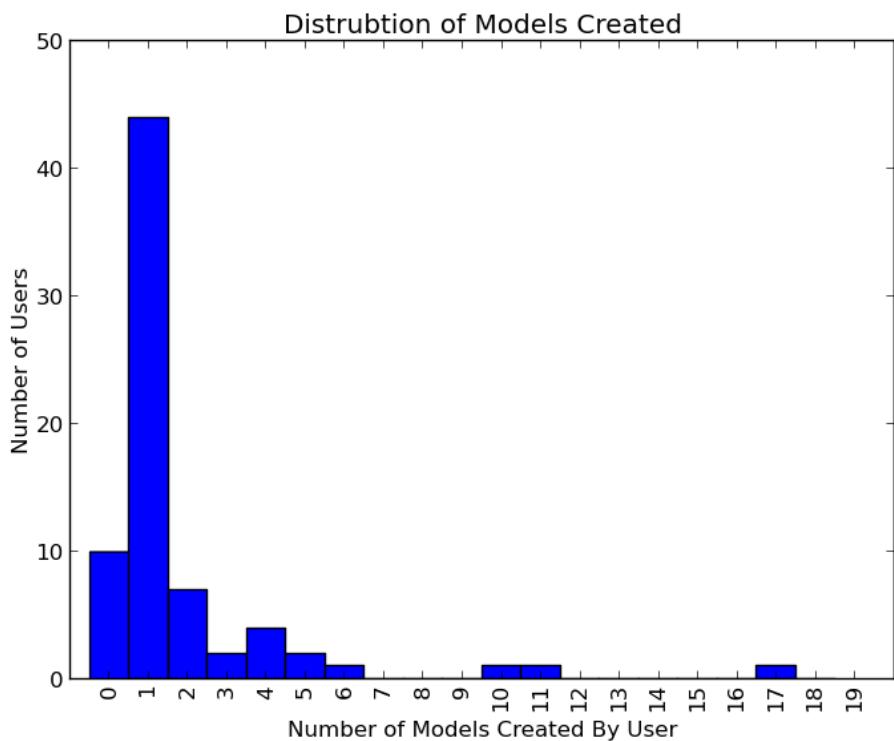
**Table 5.5:** Feedback to the question: Where there any elements of the user interface that were hard to use or confusing?

nicate 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.

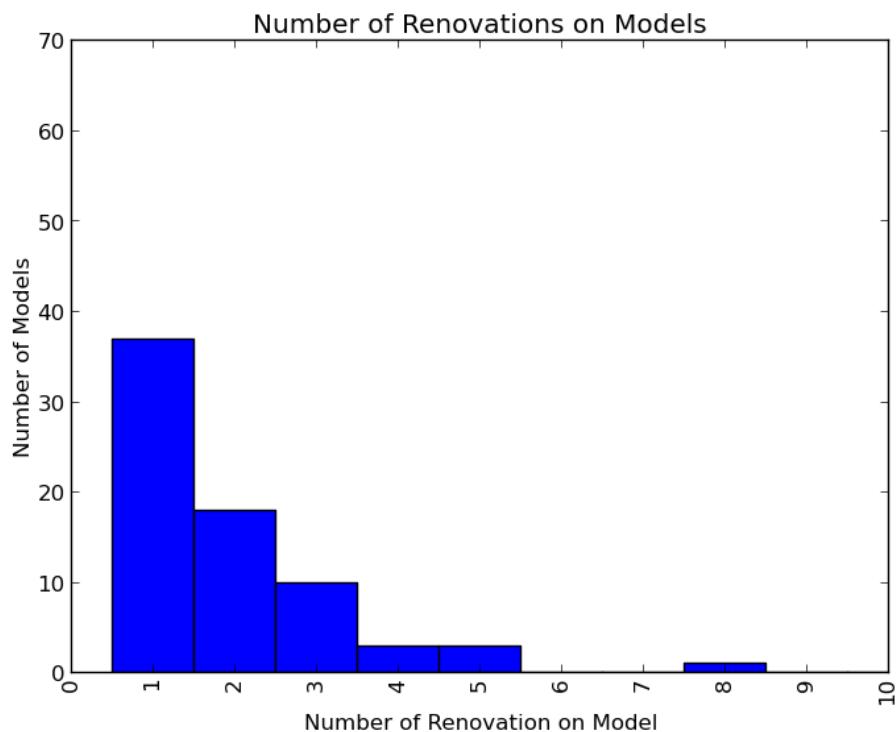
Despite all of this, the sketching interface garnered overall positive feedback from our participants. Many participants, especially the non-experts, claimed that the interface was easy to use and interesting.

### 5.3 Model Based Feedback



**Figure 5.6:** The distribution of models created on OASIS

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 ren-

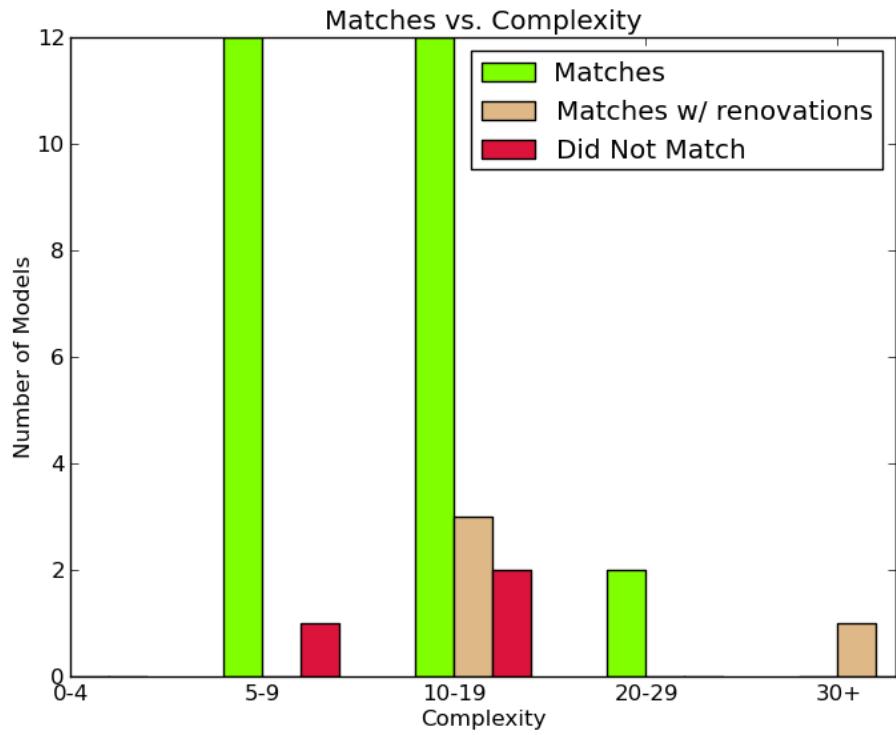


**Figure 5.7:** The distribution of renovations created on OASIS

ovations 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.



**Figure 5.8:** Examples of some users created models on OASIS



**Figure 5.9:** Accuracy in relation to model complexity

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.

Username	Feedback
qq	Can't make doors. Walls seem slanted in model visualization, which is probably intended.
Solyha	I still only see 2D
durkeejw	good, easy, fast
qjkxkcd	Model matched 2d representation from step 2. There was kind of a funky rendering issue ( <a href="http://imgur.com/COBtYgv">http://imgur.com/COBtYgv</a> ). (This was resolved when I remembered to add a final wall to close the room) + Also, when typing in this text box, using the arrow keys to navigate around text also pans the image around.
flowerJane	It was really fast and it rendered nicely
Jan Selz	Proportions of items and volume created seem to match the design intent.
mike smith	the program does a good job constructing the 3D model
ryasoa	It worked very well
damamani	Very good 3-D modeling but Step two needs some additional features to connect the walls properly.
principealberto	It is
tranhang	It well windows and furniture it is place windows fine
dcheung3	Overall the 3D model does capture my sketch
alanlang	the 3D match my design
mindykay	This is really amazing! The 3D design is exactly what I was aiming for!
kyoko.usagi	I mean yes this kind of matches, but no doors is not in my intended design. That's why it failed. But the effectiveness is pretty spot on
galarodo	Accurate to the design. Room was little bit wider (beds further apart) but requires to many edits to fix. Deleting walls and re-drawing them

**Table 5.6:** Feedback to the question: Describe your overall impression of the system's effectiveness in constructing a 3D model from your design.

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; Table-5.9 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.

Username	Feedback
Solyha	There is no window on the west wall. The window in the center wall should not be the whole length of the wall only 0.75% of the wall.
qjkxkcd	Part of the room is kind of an L-shape. When viewed from certain angles, it looks like one wall extends farther than it does in the 2d representation ( <a href="http://imgur.com/qnGfydB">http://imgur.com/qnGfydB</a> ). (Note: this was also fixed by completing the wall which was previously left open) + Also the window is only visible looking out from inside the room (the wall looks solid from the outside). + And it might be by design, but the black circle base is only visible when looking at the model from above, not below.
mike smith	i did not find nothing wrong yet
damamani	The location of objects were placed accordingly to the sketch.
dcheung3	one of the wall was not connecting
kyoko.usagi	No doors, like why no doors?
galarodo	No option to make a lofted bed that is the same height as the wardrobe!
raarming	the walls

**Table 5.7:** Feedback to the question: Describe cases where the system incorrectly interpreted your design intentions.

Moreover, we asked users to describe cases where models were incorrectly interpreted by our physical sketching algorithm. Table-5.7 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 impossible.

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. Table-5.8 contains user feed-

Username	Feedback
damamani	Simulation worked perfectly
alanlang	I understood the simulation
dcheung3	Yes, I understand the results of the simulation.
h.tran1990	Yes, this is very well thought out and it is a great program
flowerJane	I thought that maybe there would be light shining through since I set the time to 12 pm, but there was none
durkeejw	Yes, Straightforward
alanlang	i understood the simulation
dcheung3	Yes, I understand the results of the simulation. From the data, it would seem that the rooms are over illuminated and this simulation clearly indicates as such.
ryasoa	I understood the results of the simulation. I think something that needs to be taken into consideration is the reflection of other buildings because while the simulation looks very nice + ( I prefer the dark at this time) my room is VERY bright at this time and I think it may be due to the surrounding building reflections
mindykay	Everything was perfect! As expected. The analysis part is really convenient as well! + I wish there was an ability to close the application to ensure my feedback was saved. I see it was saved because it says it at the bottom of the screen, but it be nice to have an exit button to close the window and ensure that all feedback was marked down.

**Table 5.8:** Feedback to the question: Did you understand the results of the simulation? Describe anything confusing or unclear.

back about participant comprehension of simulation results. Note that the feedback collected in Figure-5.8 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[].

Username	Response
rolyha@verizon.netyes	
Solyha	No- it's very dark for 1 pm
durkeejw	No. What light levels are considered “over” or “under”?
Jan Selz	I can see a small amount of illumination in the corner. It does make sense for only having a North facing window.
mike smith	the program works as i expected
ryasoa	Yes, understood both
tranthang	Yes, it is great simulations and a great experience
dcheung3	Yes, the system allowed me to create and test daylighting performance. Yes i have a better understanding the area of over illumination and under illumination.
mindykay	Yes, this application definitely shows how my space would be illuminated
alanlang	the simulation was clear.

**Table 5.9:** Feedback to the question: Did the system allow you to create and test daylighting performance? Do you understand the areas of over illumination and under illumination?

Lastly we asked participants if they system allowed them to both test daylighting performance and understand over and under illumination visualizations. Figure-5.9 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.

# CHAPTER 6

## Conclusion and Future Works

### 6.1 Conclusion

We performed a pilot user study to determine if OASIS was accessible, easy-to-use, and a step in the right direction as an early design tool for daylighting. Firstly, feedback from the study, which spanned only 2 weeks, demonstrates OASIS was accessible to a broad range of users outside of the tradition pool of architecture students used in previous user studies[1]. Similarly, there was no feedback concerning problems with accessing our online sketching interface. Secondly, user feedback from our pilot user study showed that OASIS was both easy-to-use and fun. However, it is also important to note that our pool of participants consist mostly of non-experts. Whether our sketching interface was easy to use for experts remains unknown. Lastly, most feedback collected from participants concerning the effectiveness of OASIS for daylighting analysis was positive – with over 90% of participants stating that OASIS was effective and clear. Conversely, one participant with 10+ years job experience in architecture stated that OASIS was not useful for daylight analysis. This participant, however, was not clear as to why OASIS was not effective for daylighting analysis. Before any conclusion can be drawn, I believe we need to collect more feedback from experts and advertise our online tool towards users with architectural experience. In brief my contributions include the creation of a novel architectural sketching interface for simulations that is both accessible and easy-to-use for non-experts to perform qualitative daylighting analysis. In addition I conducted an online pilot user study and analyzed the results from that study. Moreover, I created an online framework for the physical sketch interpretation algorithm and daylight rendering engine used in the Virtual Helidon.

## 6.2 Future Work

### 6.2.1 Improved Evaluations of OASIS

My pilot user study was meant to be a short study to test key features of OASIS and understand problems users would encounter when using OASIS. Future user studies aimed at evaluating future iterations of OASIS in more detail can learn from mistakes made in this pilot user study. Firstly, the amount of users who registered and did not create a single model on OASIS is high. Despite lack of data on the retention rate of similar user studies, there are a few strategies that can be used to increase the number of users on OASIS. Goal driven user feedback may increase users interest in creating models on OASIS, sharing those models, and providing insightful feedback. Disguising user studies as goal driven games has had successes in the crowd sourcing line drawings in previous research[1]. Having users use OASIS to fix a problem caused by daylighting, such glare in an office, with a scoring mechanism might incentive users to use OASIS as experts would. Coupled with sharing features, that let users share 3D models or their scores would help OASIS self advertise itself to other users. Additional, making registration easier or even optional, for the first model, could increase user retention. Similarly, in our pilot study we encountered problems user made assumptions about feedback and models being viewed. Adding in a share feature, such as an automatically generated link that displays a model, would make sharing problem models much easier in feedback responses. Lastly, there was problem with users omitting feedback that could potentially communicate something to researchers. Making some feedback questions non-optional or inbreeding the feedback into the interface would make user intentions clearer.

### 6.2.2 Improvements To The Online Sketching Interface

Despite my original hypothesis not being met, the pilot user study did provide us feedback about what usability features to prioritize for future work. Firstly, the most requested feature in our sketching interface was support for doors. As mentioned previously, the physical sketch interpretation algorithm can interpret multi-room sketches. However, the lack of doors on the sketching interface communicated

that we do not support multi-rooms sketches to many of our users. Additionally, the study revealed that room designs were greatly limited by the small number of furniture items in the system. While, OASIS is not meant to be a fully features daylighting analysis software, providing user a wider variety of furniture items would aide in the design of spaces other than bedrooms. Another common concern was scale, users wanted either control of scale in their sketches or more explicit communication of scale in our sketching interface. Giving users control of scale and providing an overlay of grid-lines on the sketching interface might better communicate scale of architectural spaces better than the currently indirect sense of scale through statically sized furniture items.

Unrelated to results from our user study, OASIS is an online sketching interface for simulations. As of right now, the only true sketching features we support are straight walls. Future work can be done to make our interface a full support sketching environment. Users in this sketching environment can draw not only straight walls, but also curved walls of any shape, in addition to sketching in windows and furniture items, similar to LightSketch[]]. Such a system would require some form of sketch recognition and a vocabulary or training sketches for common furniture items. Advantage so such a system would be one step closer to emulating how architects currently plan daylighting in the early design phase through rough pencil and paper sketches.

### 6.2.3 Improvements To Daylighting Visualizations

OASIS incorporates the daylight rendering engine from the Virtual Heliodon. The daylight rendering engine uses a GPU ray tracing framework, known as NVidia Optix[], to perform photon mapping at interactive rates. In the pipeline of the daylight rendering engine standard daylight metrics such as the daylight factor, daylighting glare probability, and luminous flux per unit area, can be calculated and visualized in various ways. Future work can focus on creating informative daylight visualizations optimized for our online viewer.

## 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](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](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.

## **APPENDIX A**

## **APPENDIX**

### **A.1 User-Specific Questions**

1. Are you affiliated with Rensselaer Polytechnic Institute?
2. How are you affiliated with Rensselaer Polytechnic Institute?
3. Years of formal education in Architecture?
4. Years of formal education in Visual Arts?
5. Years of job experience in architecture? (including internships)
6. Years of job experience in Visual Arts? (including internships)
7. Have you used any of the following modeling software?
  - (a) SketchUp
  - (b) AutoCAD
  - (c) Rhino
  - (d) Maya
  - (e) 3DS Max
  - (f) Cinema 4D
  - (g) Blender
  - (h) Revit
  - (i) Other
8. Years of experience with modeling software?
9. Other relevant education / experience?
10. Are you colorblind?

11. Is it okay if we follow up with additional questions about specific models you created in our system?
  - (a) If so, please enter your email address
12. What did you find fun or interesting in this sketching environment?
13. What additional features should be added to system to allow greater flexibility in design?
14. Describe some designs that you were not able to create due to system limitations?
15. Was there anything you did not like about working in this sketching environment?
16. Were there any UI elements that were hard to use or confusing at first?
17. Describe your overall impression of the software for determining the interior vs exterior space in your designs?
18. For the cases when the systems interpretation of the interior/exterior of your design was incorrect where was the system wrong?
19. Did the system allow you to create and test daylighting performance with respect to over or under illumination?

## A.2 Model-Specific Questions

1. What category does this model fall into?
  - (a) Dorm
  - (b) Bedroom
  - (c) Living room
  - (d) Apartment / House
  - (e) Classroom

(f) Office

(g) Lobby

(h) Other

2. What dorm is this a model of? (Optional)

(a) BARH (Burdett Avenue Residence Hall)

(b) Barton Hall

(c) Beman Lane Undergraduate RAHP Apartments

(d) Blitman Residence Commons

(e) Bray Hall

(f) Bryckwyck Floor Plans

(g) Cary Hall

(h) Colonie Apartments

(i) Commons

(j) Crockett Hall

(k) Davison Hall

(l) E-Complex

(m) Hall Hall

(n) Nason Hall

(o) North Hall

(p) Nugent Hall

(q) Quadrangle (The Quad)

(r) Sharp Hall

(s) Single RAHP

(t) Stacwyck Apartments

(u) Warren Hall

- (v) Other
3. What floor number? (Optional)
  4. What room number? (Optional)
  5. When was the last time you visited this space? (Optional)
    - (a) Less than a week ago
    - (b) Less than a month ago
    - (c) Less than a year ago
    - (d) Less than 4 years ago
    - (e) More than 4 years ago
  6. How often did you visit this space?
    - (a) Once
    - (b) Occasionally
    - (c) Multiple times a week
  7. How confident are you in modeling this space? (scale of 1 to 5)

### A.3 Renovation-Specific Questions

1. Does the 3D generated model match your intentions?
  - (a) Matched my intentions exactly ( no revision required )
  - (b) Did not match my intentions initially ( revisions were required )
  - (c) Failed to match my intentions ( even after revision )

### A.4 Render-Specific Questions

1. Did you understand the results of the simulation, was there anything confusing or unclear?