ONLINE ARCHITECTURAL SKETCHING INTERFACE FOR SIMULATIONS

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ACKNOWLEDGMENTS

ABSTRACT

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

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

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

I present a novel interface that is easily accessible to non-experts providing them with the ability to generate 3D models for daylighting simulation from 2D architectural sketches. This online interface allows users to both quickly create 3D models and analysis daylighting simulation results. I propose that this interface will aid both experts and non-experts during the schematic design phase where ease of expressing 3D geometries and speed of analyzing simulation results is most significant.

My contributions includes the development of this online interface, the conduction of a large-scale user study, and the analysis of that study.

CHAPTER 1
INTRODUCTION

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

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

1.1 Benefits And Motivations Behind Daylighting Systems

There are many benefits to using daylight over traditional electrical lighting. Recent studies show exposure to sunlight, offered readily through daylighting systems, has a variety of health benefits; benefits such as the stimulation of vitamin 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 to implementing daylighting systems. Some economic motives include increases in worker productivity and overall reduced building energy demands. In short, daylighting system offer both economic incentives for building owners and health benefits for occupants.

1.1.1 Vitamin D

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

There are many may 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 the exposure to sunlight meets most daily vitamin D requirements. Foods we consume are usually rich in vitamin and minerals. However, vitamin D occurs in significant concentrations in very few natural food items, such as fatty fish, particular species of mushrooms, and beef liver. Because of vitamin D's scarcity in naturally occurring food items and the harmful effects of deficiency vitamin D in children, companies fortify common breakfast food with vitamin D – such as orange juice, milk, and cereals. Lastly, Vitamin D can also be taken in pill form as a deity supplement.

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

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

1.1.2 Circadian Photobiology

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

Electrical lighting varies from daylight a couple of biologically important ways[4]. Daylight offers a higher levels of illumination, a wider spectrum of electromagnetic radiation, and a temporal variation in lighting. Firstly, sunlight in conjunction with skylight, measures anywhere between 10 to 100 thousand lux[6]. However, the government agency of Occupational Safety and Health Administration (OSHA) set 322 lux as the minimum of lighting requirement for typical office work[7]. Lighting conditions that do not excite photoreceptors responsible for maintaining our circadian rhythm are essentially biological darkness[8]. Secondly, the spectrum of light emitted by artificial lighting lacks short wavelength electromagnetic radiation found in sunlight.Varying wavelengths of electromagnetic radiation affects melatonin levels in humans as much as varying intensity of light. Melatonin suppression is necessary because it plays a role in sleep-wake cycles, body temperature regulation, alertness, and blood pressure[9]. Studies show melatonin suppression varies most through exposure to short wave electromagnetic radiation [10]. Consequently, daylighting systems offer the advantage of exposure to short wavelength electromagnetic radiation needed for melatonin suppression. Lastly, exposure to light during periods of the day asynchronous to our circadian rhythm can result in shifts in our sleep-wake cycles. These shifts, known as phase shifts, triggers melatonin suppression at particular times. For instance, morning light exposure triggers melatonin suppression resulting in the feeling of alertness[4]. However, exposure to light at asynchronous times of day results in a phase shift. An unexpected phase shift can have symptoms similar to jet lag and significantly hinder productivity[4]. Daylight availability during those crucial morning hours could potentially have significant impacts on employee productivity.

1.1.3 Increased Productivity

Studies show daylighting systems increase both the productivity and comfort of occupants[11]. Daylighting increases workplace productivity and satisfaction through a variety of means. To begin, the human eye as image processing system has evolved over millions of years to work optimally under full spectrum illumination provided by sunlight and skylight. It is not surprising that the human visual system works better using daylight as a source of light. A visual task, such as reading, generally require less illumination when using daylight as opposed to electrical lighting[6]. Additionally, daylight provides superior color rendering. Our visual system is tuned to differentiate colors under full spectrum illumination. Differentiating colors under low illumination or fluorescent lighting is not as reliable as compared to daylight[6]. There are current electrical lighting systems that provide full spectrum light, however, these systems are very costly when compared to daylight. Moreover, occupants enjoy being near windows since it gives them information about their outdoor environment – including the time of day, weather conditions outdoors, and activities happening outside. Having a workstation near a window could evoke a feeling of importance in occupants. This feeling of importance increases worker satisfaction and could possible increase productivity[8]. Overall, the satisfaction of occupants is important to architects and managers, because adverse environmental factors hinder productivity in a workspace.

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

1.1.4 Reduced Energy Demands

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

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

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

1.2 Challenges Of Designing Daylighting Systems

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

1.2.1 Factors That Affect Daylighting

Illumination of an architectural space via daylight is dependent on numerous factors including building-wide design choices, room-specific choices, and temporal variations. These factors make it difficult to access the quality of a design in terms of daylighting.

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

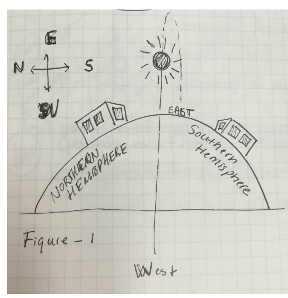

Figure 1.1: This illustration shows why windows facing southward in the northern hemisphere experience direct daylight and windows facing northward do not. It also shows the converse, north facing windows in the southern hemisphere experience direct lighting, however those facing southward do not.

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

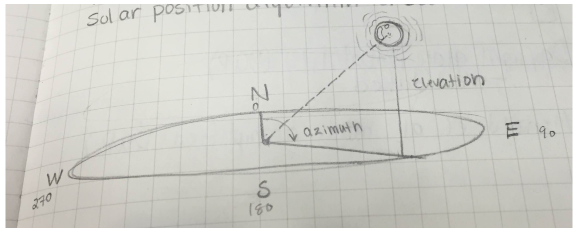

Figure 1.2: Illustration to show elevations and azimuth used to find the sun's position in the sky

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

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

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

Room-specific Design Choices Room-specific design choices also have an impact on the daylight. The geometry of an interior space directly affects the distribution of daylight in a room. Geometries can be designed to diffuse direct lighting for uniform illumination and occupant comfort. Similarly, shading devices and material properties of interior objects can affect daylighting. Shading devices, such as blinds can not only help diffuse direct lighting but also help redirect lighting up towards the ceiling, where it can be diffusely reflected back down towards occupants. Also, a careful selection of both the color and the material of interior items such furniture, walls, and ceiling can affect daylight's distribution in an interior space.

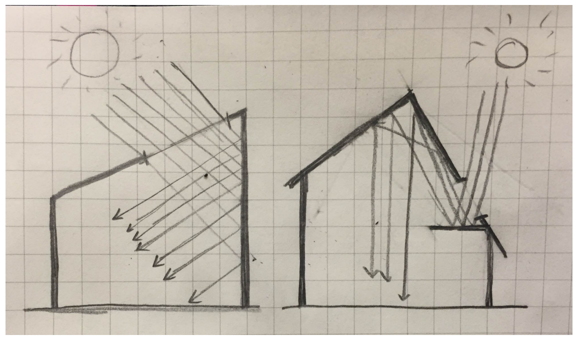

Figure 1.3: Left: a common skylight placement on the roof of a building. The angled roof is designed to let daylight diffuse as it reflects on towards the floor. Right: A light shelf that helps redirect daylight up towards the ceiling, where it can be diffused and reflected back down on towards the floor.

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

Temporal Variation It is obvious that daylight varies from sun raise to sun set. Less obviously, daylight also varies throughout the year. The Sun's position in the sky is shallower during winter season than in the summer season. Due to this, during the winter months daylight enters a room at a shallower angle allowing light to travel deeper than in the summer months.

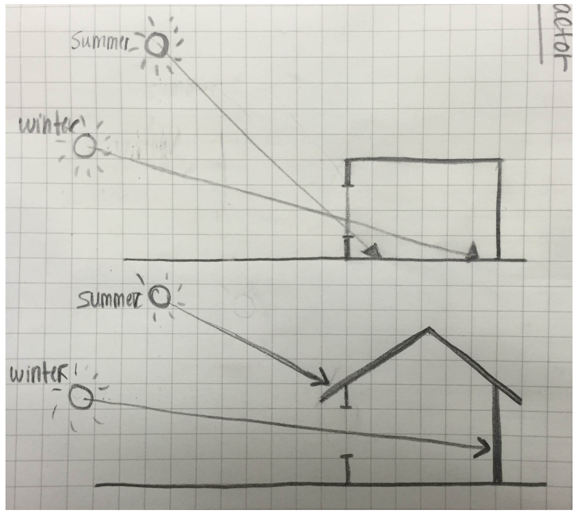

Figure 1.4: Top: illustration to visualize the difference in light penetration during the winter and summer seasons. Bottom: a common daylighting technique is extending the roof to block light during the summer season, but not during the winter season.

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

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

1.2.2 Adverse Daylighting Effects

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

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

Another visual discomfort that can occur from poor daylighting is glare. Glare is a reduction of contrast due a disproportionate amount of illumination from glare sources compared to illumination on a visual task. Glare is hard to account for in the early design stages of architecture because glare is dependent on not only sources of illumination but also on viewpoint. Specifically, there are two main forms of glare – disability glare and discomfort glare.[6] Disability glare occurs when a glare source is intense enough that it rendered the viewer momentary blind. This kind of glare commonly occurs when driving at night and cars are passing in the opposite lane. The strong light emitted from headlights would reduce the contrast of the road ahead and might result in momentary blindness. Likewise, discomfort glare is similar to disability glare but much less dangerous. Discomfort glare is also caused from bright glare sources, such as the Sun or light reflected from the Sun, that making visual task difficult to perform. Unlike disability glare, discomfort glare does not cause momentary blindness. Prolonged exposure to discomfort glare when focusing on a visual task,however, significantly reduces both worker productivity and worker satisfaction[14]. Another visual discomfort, common in office environments, includes veiled reflection. Veiled reflections are the result of light reflecting off a surface directly into the eyes of the viewer. For example reading an article from a glossy magazine in direct sunlight is challenging because at certain viewpoints the gloss on the page reflects light into your eyes reducing the contrast between both the black and white letters. Veiled reflections, like glare, are difficult to predict because they are viewpoint dependent.

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

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

Lastly, occupant behavior can result in lose of investment capital for building owners. Occupants exposed to the visual discomforts of daylight can choose use window blinds to block daylight out entirely. If blinds are lowered then electrical lighting is used in place of daylight. The use of electrical lighting, given available daylight, results in reduced energy savings for the building owners. Moreover, daylighting systems are expensive to design and implement and as a result the initial cost is generally greater then using traditional electrical lighting. If occupants 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 architecture of a building from concept to construction is no easy task. As a result, architecture firms generally break down the architectural design process into 5 manageable phases[**?**]. Daylighting affects all phases of the architecture design process, however choices made in the early design of an architectural lay the foundations of a daylighting system. Our focus lies in the early stages of the design processes: the schematic design phase. Nevertheless, we will briefly cover all of the architectural design process to give the reader a better understanding on the significance of the schematic design phase.

1.3.1 5 Phases of Architectural Design Processes

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

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

1.3.2 Daylighting In The Early Design Phase

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

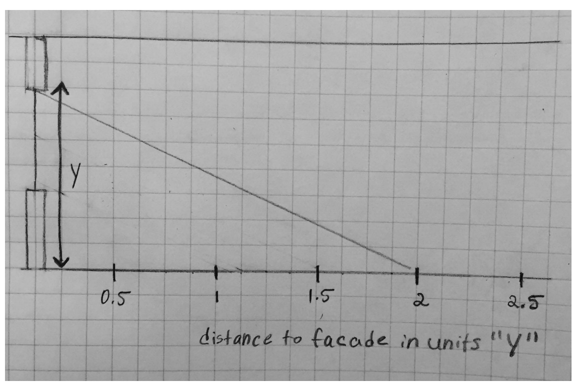

Figure 1.5: Verified rule-of-thumb: The depth of usable daylight is 1.5 to 2 times the window-head-height. Here the windows-head-height is depicted as y.

Rules-of-Thumb A rule-of-thumb is a general suggestion, usually acquired through experience, that architects follow when designing spaces. Many rules-of-thumb are widely accepted in practice, however, only few have been validated[15]. Furthermore, many designers using these rules-of-thumb do not have an understanding of the underlying principles behind them[16]. Nevertheless, these rules are still used in practice because of ease to incorporate into designs, and general effectiveness.

Some common rules-of-thumb include simple suggestion about where to locate people within a space. For example, it is suggested that designers take advantage of the floor area within the daylight zone by situating people within it. [8] Moreover, architects suggest visual task be placed near the building parameters[8]. To elaborate, the daylight zone is a range of space where illumination from daylight provides a comfortable workspace. The daylight zone does not take direct daylight into consideration, but rather diffuse skylight. A validated rule-of-thumb is regularly used to find the rough range of the daylight zone[15]. The daylight zone extends to about 1.5 to 2 times the window-head-height away from the wall containing the window, as illustrated in figure-**??**.

Another common rule-of-thumb is the elongation of the east-west axis of a building. The elongation of a building along the east-west axis is supposed to avoid solar heat gain and create more room for north facing windows[8]. As explained previously, north and south facing windows, depending on your location, can provide either day-round diffuse or direct daylight. However daylight from east and westward windows vary significantly throughout the day. As a result another general rule of thumb is that south and north facing windows are the preferred over east and westward windows[17].

Daylight distribution and comfort within an interior space depends on more than just window placement and size. A general rule-of-thumb is that light colored interior surfaces help reduce the contrast between windows and interior spaces[8]. Moreover, the reflectance property of walls, windows, floors, and furniture impact daylight distribution. One more rule-of-thumb is that ceiling have a reflectance of at least 80%, walls of at least 50-70%, floors of at least 20-40%, and furniture of at least 25-45%[17].

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

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

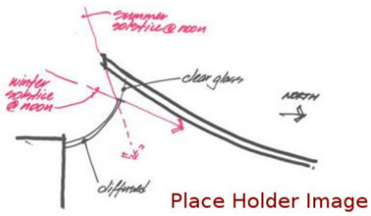

Figure 1.6: Example of brainstorming daylighting on sketches

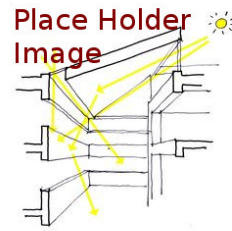

Figure 1.7: Example of brainstorming daylighting on sketches

and ideas for both problem solving and rough daylighting analysis[18, 19]. It is not surprising that sketches are also widely used in the brainstorming of daylighting system. Figures 1.6 and **??** are some common examples of how architects use sketches to problem solve and do a rough prediction of daylight distribution. To do a rough prediction of where daylight will fall in a sketch, architects first draw a cross section of their imagined space. They then using specialized protractors, architects can deduced at angle the sun will enter a space in their sketch[20]. Drawing multiple rays parallel to the sun angle onto the sketch and calculating where those rays reflect, will give designers an idea of the distribution of light in the room. More examples of these kinds of illustrations are shown in figure-[**?**].

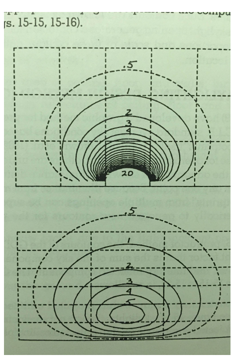

Figure 1.8: This is the overlay used to trace contour lines in the GDDM method. There are many and simple calculations are used to decide which overlay to use.

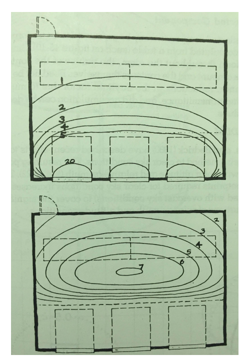

Figure 1.9: This is a finalized sketch with combined overlays show the distributions of daylight in a space.

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)[21, 22]. The GDDM method can be used to predict daylight illumination given an overcast The GDDM shows not only where lighting will fall but also the intensity of lighting using contour lines. To use GDDM, first architects draw a floor plan of the room, making note of where windows are located. Using a series of specialized overlay architects can draw contour lines defining both daylighting distribution and intensity such as seen seen in figure 1.8 and 1.9. These analytical sketches allow architects to reflect on their designs and make renovations to improve lighting conditions. The GDDM technique and other basic sketch-based brainstorming strategies help architects perform analysis on sketches quickly during the earliest stages of design.

1.3.3 Daylighting After The Early Design Phase

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

CHAPTER 2
RELATED WORKS

2.1 Virtual Heliodon

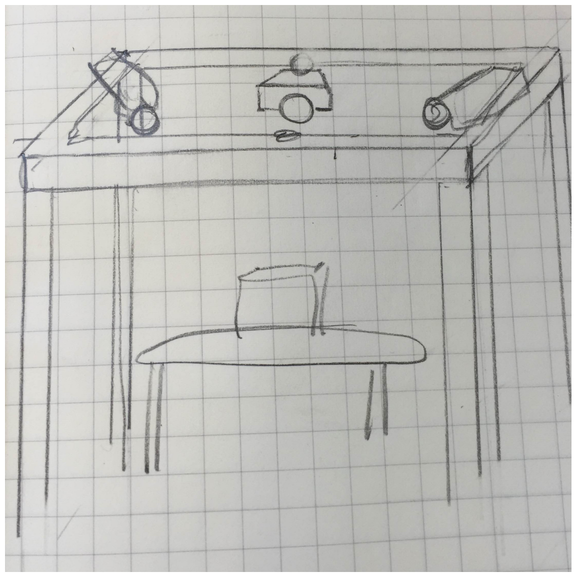

Figure 2.1: Overview of the Virtual Heliodon. Note the projector arrangement and circle table at the center.

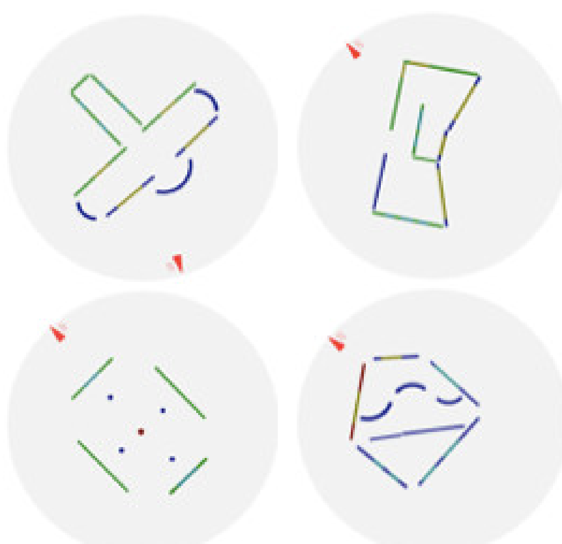

Figure 2.2: Example physical sketches created by users on the Virtual Heliodon

The Virtual Heliodon is a spatial augmented reality with a tangible user interface for the early collaborative design of interior spaces with daylighting[23, 24, 25, 26, 27]. Succinctly, the Virtual Heliodon is composed of multiple projectors, a circular table, and a collection of foam primitives. A large chassis holds the projectors above the table top at evenly spaced intervals. These projectors all face towards the table top at the center of the system; The configuration of the Virtual Heliodon is shown below in figure-**??** This tangible user interface lets users physically engage with wall primitives. Users can define architectural spaces by moving and rotating wall primitives on the table top. Some architectural spaces created on the Virtual Heliodon are shown in figure-[**?**]. Then a network of computers use the projectors to display daylighting simulation renderings onto the foam primitives placed on the table. In order to project on all wall primitives on the table top multiple projects in varying positions are used. Projecting daylighting rendering directly onto wall primitives creates an augmented reality environment that gives users a sense of immersion[26]. The virtual Heliodon has gone through evaluations and has been proven to be engaging and valuable as an educational daylighting tool[26].

2.2 Physical Sketch Interpretation Algorithm

Cutler et al. conducted evaluations on the effectiveness of physical sketch interpretation algorithm used in the Virtual Heliodon[24]. This studies compared user's intended interpretation of the physical sketches to both the algorithm's interpretation and other user's interpretation. In brief the study concluded that on average the physical sketch interpretation algorithm matched users intended interpretation 78% of the time given non-ambiguous models[24]. Aside from ambiguous sketches, the Virtual Heliodon provided reliable 3D geometries that matched user's intended floor plan designs. OASIS uses the same physical sketching interpretation algorithm employed in the Virtual Heliodon.

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

Efficient Design tool(HEED) and eQuest use parametric modeling to generate 3D models of an architectural space[28, 29]. Parametric modeling is the creation of model from a template by specifying the parametric such as wall lengths, walls heights, and window positions through numerical entry. Both HEED and eQuest are intended for use in the schematic design phase and offer a large variety of energy analysis measures. Due to the high cost of effort in parametrically designing an architectural space, both HEED and eQUEST feature wizards to guide users through the process. Geometric modeling is another modeling approach used by many architectural modeling software. SketchUp and AutoDesk are both popular architectural design tools that use geometric modeling for the generation of architectural spaces. Geometric modeling gives users the ability to create 3D objects by modifying basic shapes visually; This modeling approach is similar to modeling with clay. The process of imagining a space and geometrically modelings that space in software is non-trivial. Being able to geometrically model complex 3D geometries is an art that requires precision and a deep understanding of the geometric tools available. As a result, the modeling of architectural designs in software is usually pushed back into the design development phase when fewer iterations a design are required[16].

In practice, manual sketches are still used during the early design phase, because of the speed & efficiently sketching offers designers[16]. As a result researcher has been done on architectural sketching interfaces. LightSketch and the VR SketchPad project both incorporate architectural sketches into the early design phase[30, 31]. Specifically, LightSketch shares much in common with OASIS. LightSketch gives users the ability to to draw walls, windows, and interior lighting elements to define architectural spaces[31]; The drawings are interpreted and turned into 3D models. Users can then perform daylighting analysis and generate renderings from generated 3D models. LightSketch, however, is limited to shoe-box geometries for rooms. Users cannot freely design a wide variety of non shoe-box of floor plans as is possible in the VR SketchPad project and the Virtual Heliodon. The VR SketchPad project supports the creation of 3D models of a wide variety of architectural spaces[30]. Furthermore the VR Sketchpad was available as an online tool, similar to OASIS. The VR SketchPad project however does not distinguish between interior and exterior spaces but instead just renders objects where users sketch them. Sketches in the Virtual Heliodon get converted into water-tight models that are required for daylighting simulations.

2.3 Daylighting Render LSVO

In addition to using the Virtual Heliodon's physical sketch interpretation algorithm, I use the Virtual Heliodon's GPU photon mapping rendering engine[32, 25]. This rendering engine is specialized to provide viewpoint independent daylight renderings at interactive rates. The Virtual Heliodon's rendering engine takes advantage of NVidia's Optix GPU ray tracing framework for the parallelization of photon mapping[33]. Concisely, photon mapping is the approximation of global illumination by tracing rays outward from emitters and then gathering photons after several bounces to calculate indirect illumination per triangle or patch[34]. When photons leave emitters their position and direction are chosen at random, however, a photon's intensity is a function of its direction as defined by the International Commission on Illumination's sky models[35]. Other daylighting renderer, such as Radiance require more time to produce clear and noise-free results[36]. However, Radiance is validated and a result Radiance is widely used as a back-end component to several daylighting tools[37, 16]. While, the Virtual Heliodon's rendering engine has not been directly validated against Radiance, the rendering engine has been validated against a radiosity based render. This radiosity based renderer, used in previous versions of the Virtual Heliodon, was validated against Radiance[38]. In brief, the Virtual Heliodon's rendering engine serves our needs as a fast renderer for qualitative analysis during the early stages of design.

2.4 Related Software

OASIS shares goals in common with many other daylighting analysis software. Increased value on sustainability and energy efficiency drives the development of simple analysis tools for use in the early design phase of the architectural design processes. One such piece of software is AutoDesk's latest early design tool, Project Vasari[? ?]. Project Vasari is a stand alone geometric modeling tool with a similar interface as AuthoDesk's Revit[?]. Project Vasari, unlike Revit, was designed for energy analysis during the conceptual design of architectural spaces. As a result, Project Vasari comes packaged with win. client, daylighting, and whole building energy analysis visualizations. Another tool with similar features is Ecotect – an AutoDesk plug in[39]. Ecotect offers a collection of useful visualizations such as sun paths, previews of building shadows, and daylighting factor visuals. SketchUp is another notable conceptual design tool[40]. Although SketchUp does not directly support energy analysis and advance daylighting features, there are a handful of plug ins that do. for example VE-Ware by IES is a free energy and carbon plug in for SketchUp and Revit[?]. VE-Ware, given a model created in SketchUp will generate detailed energy analysis reports. Generally, energy analysis plug ins that support daylighting measurements, exist for most major architectural modeling softwares. For instance, Rhinoceros, as general 3D Modeling tool commonly used for creating architectural models, supports plugs in such as LadyBug for basic energy analysis[? 41]. Also, another noteworthy extension to SketchUp includes Lightsolve[42]. While Lightsolve is not officially a SketchUP plug in, it does support importing models directly from SketchUp. LightSolve is noteworthy because the tool's main focus is on daylighting analysis. Anderson et al. developed Lightsolve as an early design daylighting analysis tool that gives designers not only annual metrics but also qualitative renderings of their designs. Within the application designers could analyze both quantitative illumination metrics of particular locations in a design but also view renderings of those locations from multiple viewpoints. Lightsolve also provides visual sun positions and elevation information on the same page as the daylighting metrics and renderings. All of these visual elements on the same display offers designers a better understanding of daylighting conditions within their designed architectural spaces[43]. On the whole, all of these tools offer rich and informative daylighting analysis during the conceptual design of architectural spaces. However they all in some way rely on geometrically created models. During the conceptual/early design stages of architectural design, the ability to express concepts as 3D models quickly is invaluable. As a result , researchers have investigated faster and more initiatives ways to generate 3D models for daylighting analysis.

CHAPTER 3
Feature Design

3.1 Online Sketching Interface

3.1.1 Overview

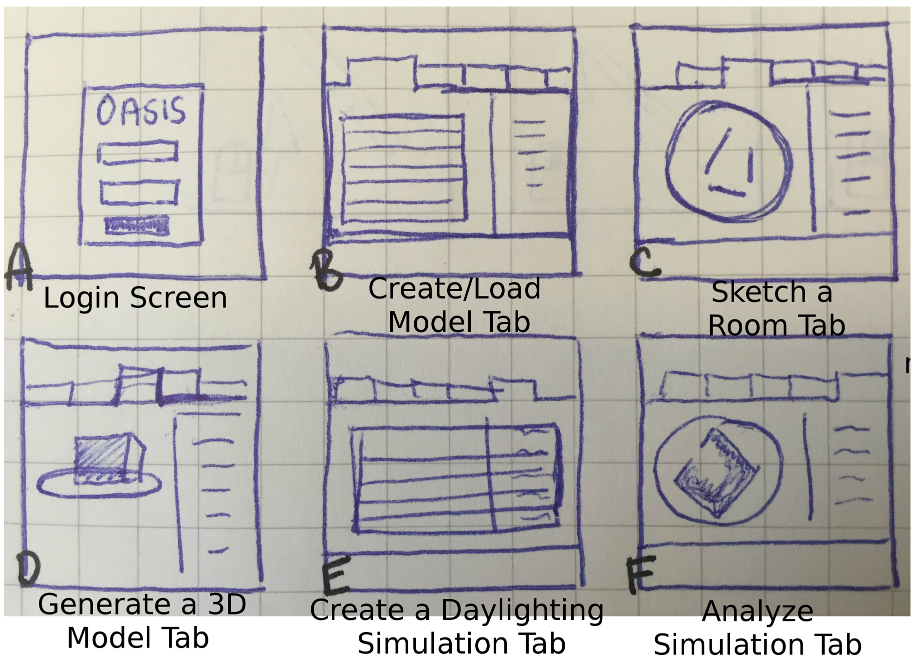

Figure 3.1: This is an overview of the tabs and menus available on OASIS.

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

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

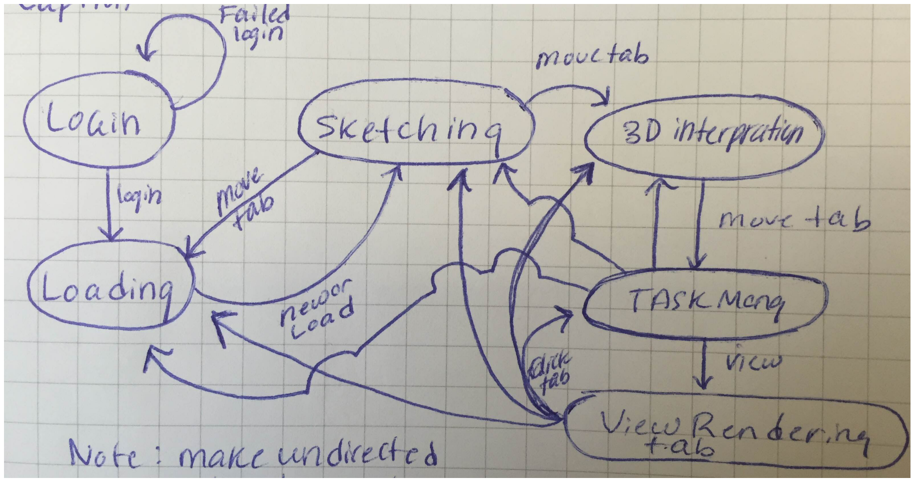

Figure 3.2: State diagram between pages and menus on OASIS.

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

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

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

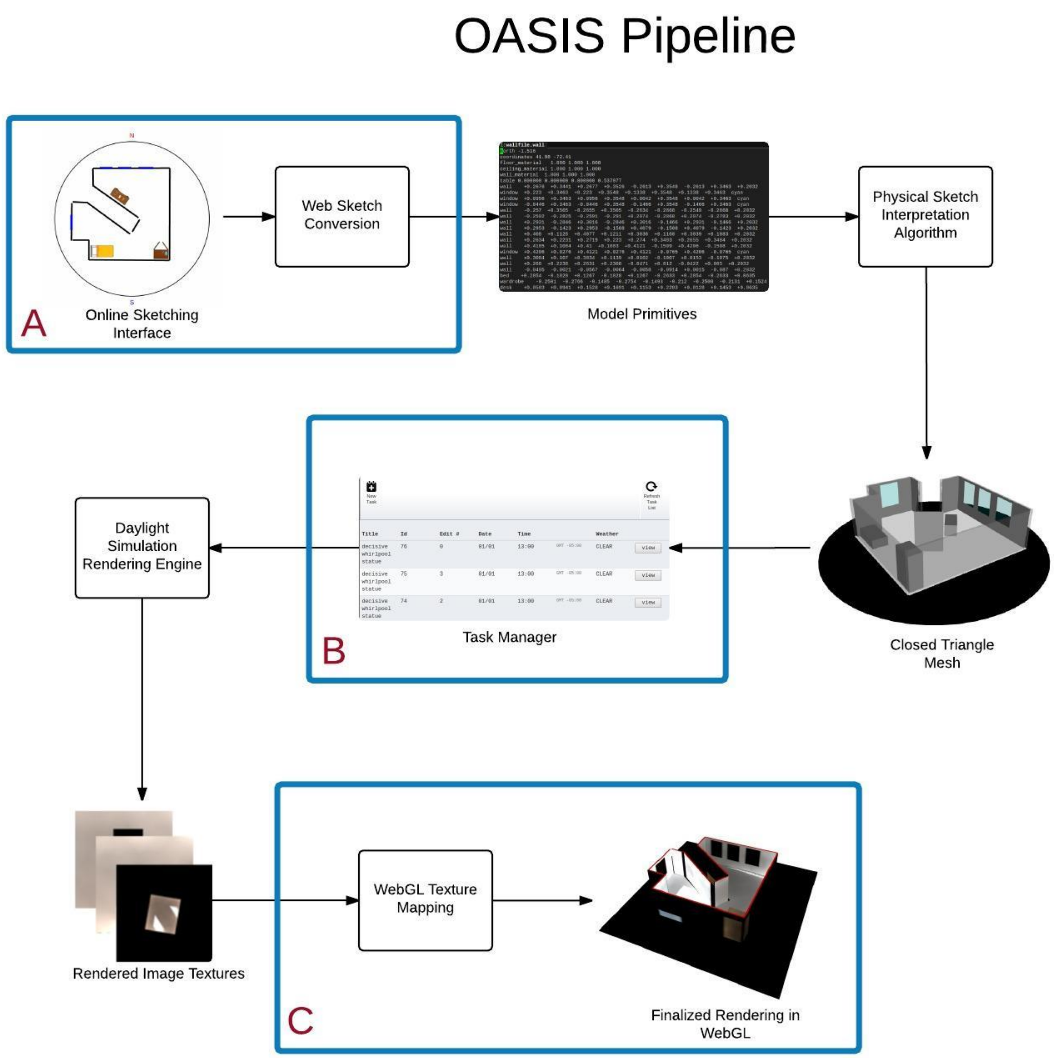

Figure 3.3: OASIS pipeline diagram with the author's contributions noted in blue.

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

3.1.2 Usability Features

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

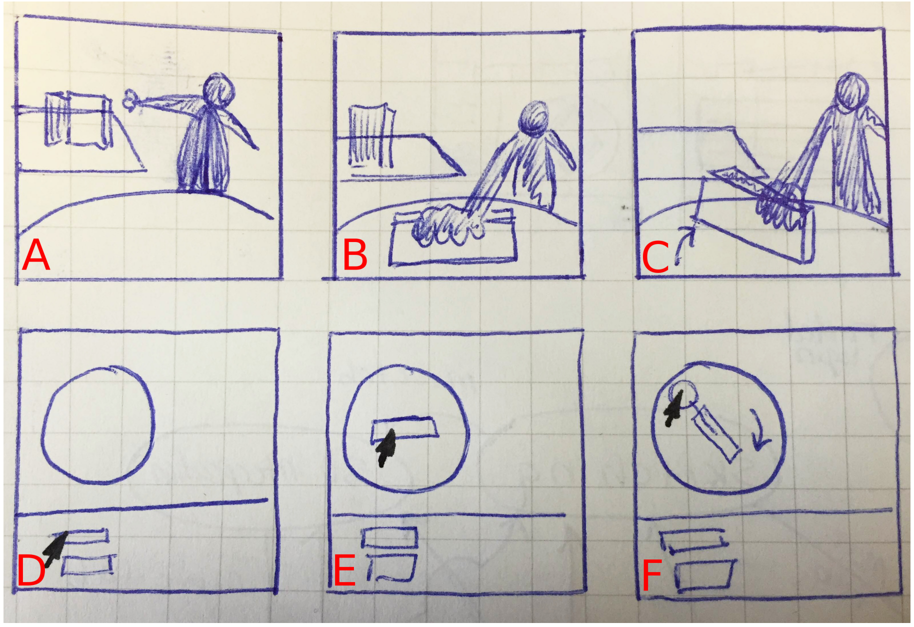

Figure 3.4: Similarities between old drag and drop interface and the Virtual Heliodon's Tangible User Interface.

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

My next approach mimics how users draw on paper and in most software sketching environments. Users first click on the wall button located in the ribbon of the *Sketch a Room* page as shown in Figure-3.5A. Then, as Figure-3.5B and C illustrate, by holding left the mouse button and dragging anywhere on the canvas the user is shown a preview of where a wall will be drawn. By releasing the left mouse button, the wall preview will be replaced by a drawn line, representing a wall, as Figure-3.5D depicts. Once a wall is drawn further editing is not allowed. To keep with the spirit of sketching, windows are also placed into a sketch by being drawn similarly to walls, as shown in Figure-3.5E through G. However, unlike walls, windows need to be associated with a wall. As a result windows need to be drawn on or near a wall. In the interest of the user, windows do not need to be drawn exactly on walls. A window when drawn near a wall sharing a similar angle will automatically target and snap onto that wall, as illustrated in Figure-3.5H. This snapping feature makes drawing windows less relent on users' precision with a mouse,but instead focuses on users' intention.

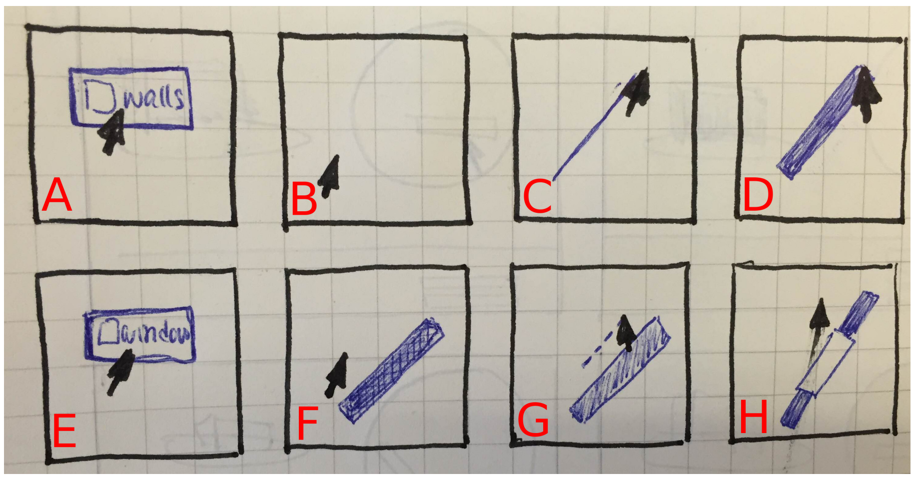

Figure 3.5: How to create walls and windows on the new online sketching interface.

Unlike walls and windows, furniture items are placed into the canvas by first clicking on a furniture button and then manipulating the newly create furniture item via translations and rotations. Furniture items can be rotated along their center axis via FreeTransform handles attached to the furniture item. Furniture items can also be translated by clicking and dragging on the item itself. The manipulations of furniture items is similar to the manipulation of walls in the original interface as show in Figure-3.4. Item manipulation via FreeTransform handles and drag-and-drop are a common UI mechanics. Users will be familiar with these mechanisms if they have had experience using either photo editing software or slide-based presentation tools such as Microsoft PowerPoint[]. The removal of all sketch based elements and furniture is simple as well. Firstly, users must click on the remove button as illustrated in Figure-3.6A, secondly users must mouse over the item to be removed as shown in Figure-3.6B. Items to be removed upon the left mouse click are highlighted in red as shown in Figure-3.6C. No items are removed from the canvas until the users left mouse clicks on a selected item.

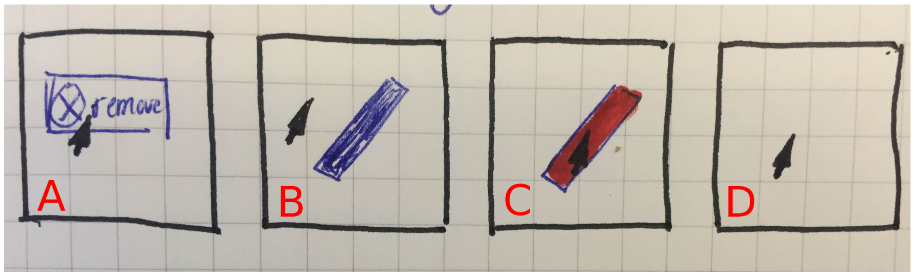

Figure 3.6: How to remove an item from the canvas.

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

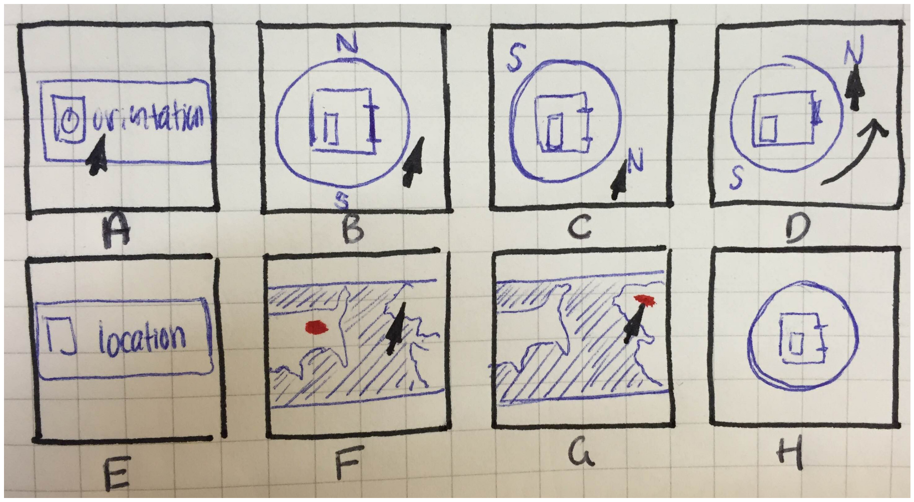

Figure 3.7: How to set the cardinal orientation and geographical location of a sketch.

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

3.2 3D Model Viewer

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

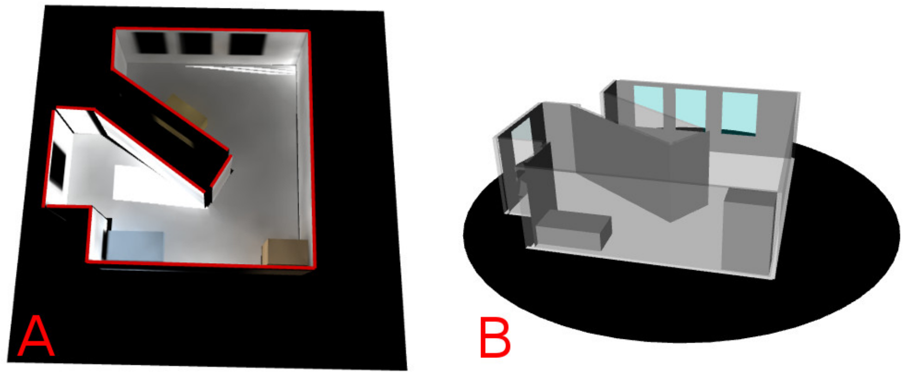

Figure 3.8: A) Navigable daylight rendering and B) 3D interpreted geometry. There are the two kinds of models we can view in our 3D Model Viewer.

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

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

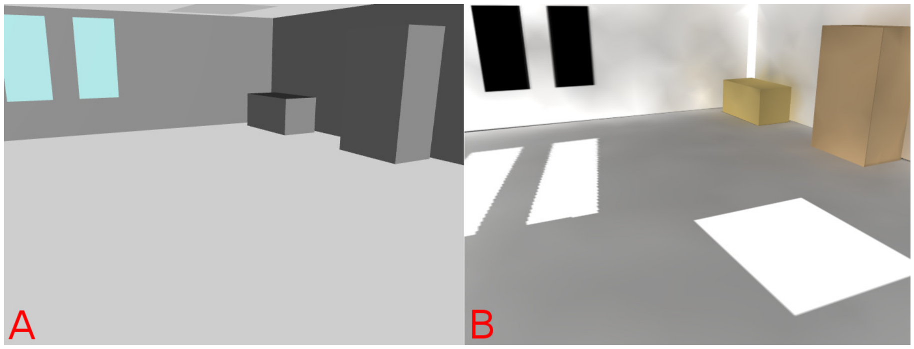

Figure 3.9: Figure A illustrates a 3D interpreted model zoomed into a first person view. Figure B is the same view in the daylight rendering of the model.

as transparent, as showed in Figure-3.8B. These transparent walls allow users to get a better view models from multiple viewpoints other than the default overhead view. Moreover, by default the ceiling is not displayed so users can peer into a 3D model from a top down view. However, when viewing output from the physical sketch interpretation algorithm, users can toggle the ceiling as viewable. This is useful if users want to see what portions of the model are interpreted as interior and exterior. The ceiling is also useful to see where skylights are located in a model. Toggling the ceiling is also useful when zooming into the model to visualize a space from first person point of view – as shown in Figure-3.9. Additionally, when viewing daylighting renderings, users can toggle between a regular rendering and a rendering with false color visualizations that aid in identifying portions of a room that suffer from over and under illumination. Users can toggle between these false color visualizations and renderings by clicking on the analysis button located on the *Analyze Daylighting* page's ribbon. Previous work on over and under illumination visualizations by Nasman et al. is used to render blue checkerboard textures on locations suffering of under-illumination and red checkerboard textures on locations suffering of over-illumination[25]. Figure-3.10 illustrates an example of toggling between false color rendering and normal daylighting rendering. In short, the 3D model viewer gives users basic navigation functionality, in addition to a handful of other useful features.

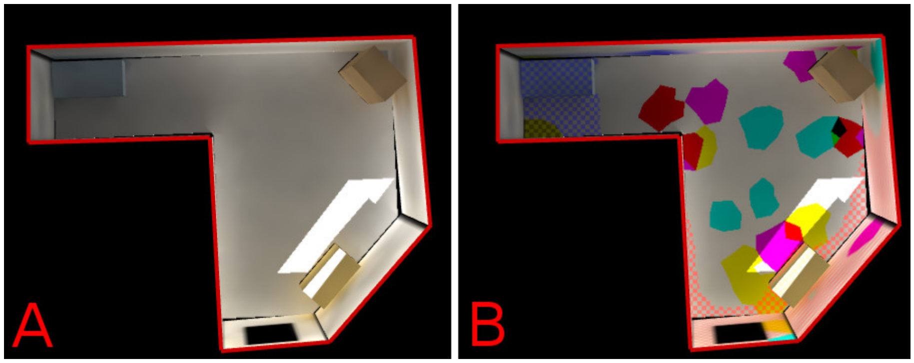

Figure 3.10: An example of false color renderings. A) Is a model that suffers from under illumination in the left most portion. B) Is the same model with false color visualizations toggled. Blue checker-board overlays are used to denote under-illumination and red checkerboard overlays are used to note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

3.3 Task Manager

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

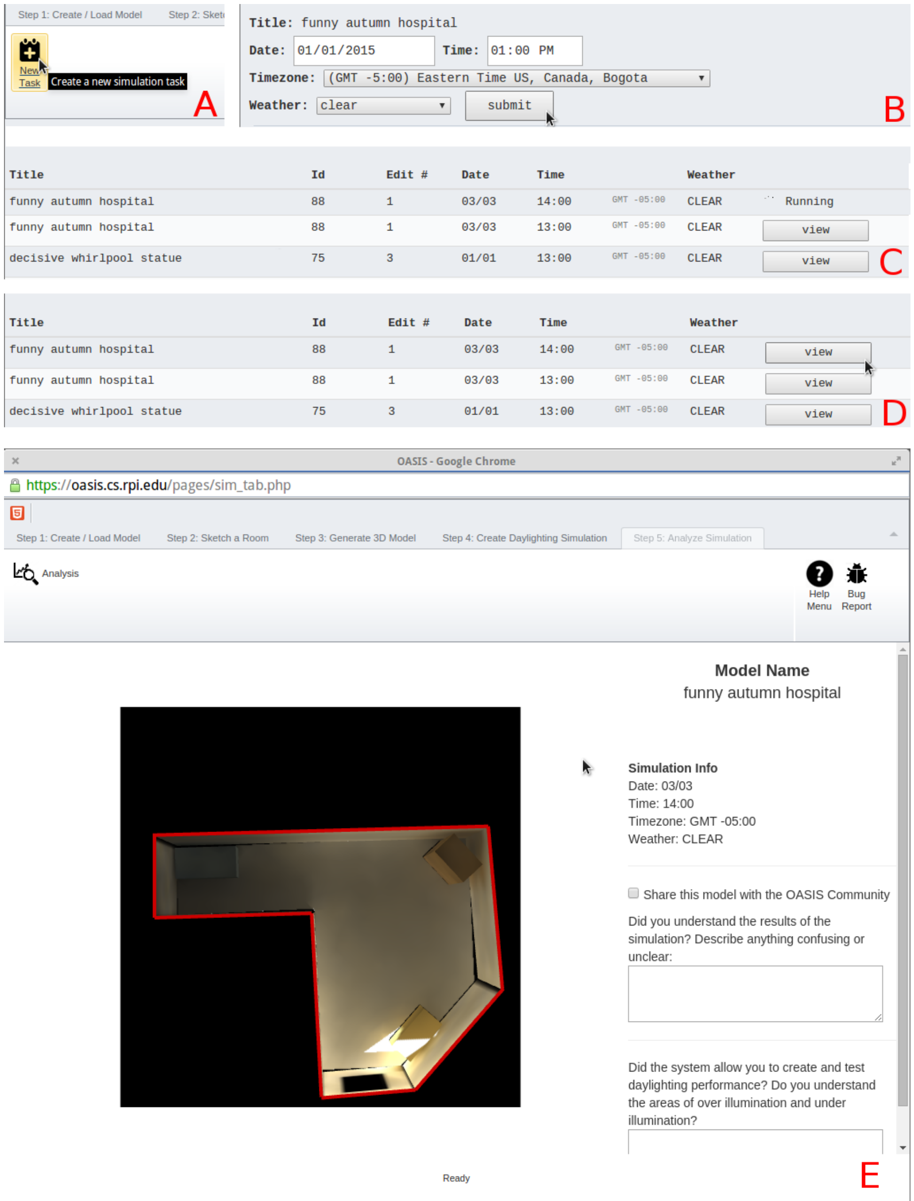

Figure 3.11: How to create a request for daylighting simulations.

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

Client Server Approach For rendering we follow a client-server model, since calculating global illumination required for daylighting simulation is too computationally expensive to run interactively on most user's machines. Users define a set of parameters per rendering request and then submit a request to the server. The server is aware of all pending request and processes all request in a first come first serve manner. The model, including the the set of input parameters, is then passed along to the daylighting rendering engine. Once the renderings are complete, the daylighting rendering engine places cameras into the scene to capture the illumination on the walls, furniture, and floor as images. The images captured by the cameras are saved as image textures. We then remap these textures onto the walls, furniture items, and floor in the WebGL 3D model. Another important usability feature added was the caching of previous rendering on the machine hosting our online sketching interface. The caching of previous renderings allows user to quickly view previous renderings without having to rerun the simulations on the server.

REFERENCES

[1] A. C. Ross *et al.*, "The 2011 report on dietary reference intakes for calcium and vitamin d from the institute of medicine: what clinicians need to know," *The Journal of Clinical Endocrinology & Metabolism*, vol. 96, no. 1, pp. 53–58, 2011.

[2] J. Pettifor, E. Daniels, D. Feldman *et al.*, "Vitamin d deficiency and nutritional rickets in children." *Vitamin D.*, pp. 645–662, 1997.

[3] M. F. Holick and T. C. Chen, "Vitamin d deficiency: a worldwide problem with health consequences," *The American journal of clinical nutrition*, vol. 87, no. 4, pp. 1080S–1086S, 2008.

[4] M. Rea, M. Figueiro, and J. Bullough, "Circadian photobiology: An emerging framework for lighting practice and research," *Lighting Research and Technology*, vol. 34, no. 3, pp. 177–187, 2002.

[5] K. Thapan, J. Arendt, and D. J. Skene, "An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans," *The Journal of physiology*, vol. 535, no. 1, pp. 261–267, 2001.

[6] C. L. Robbins, *Daylighting. Design and analysis*, 1st ed. New York, NY: Van Nostrand Reinhold, New York, NY, 1985.

[7] *Occupational Health and Environmental Controls*, Online, Occupational Safety and Health Administration Std., part Number 1926.56. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=1

[8] R. Leslie, "Capturing the daylight dividend in buildings: why and how?" *Building and Environment*, vol. 38, no. 2, pp. 381–385, 2003.

[9] J. J. Gooley *et al.*, "Exposure to room light before bedtime suppresses melatonin onset and shortens melatonin duration in humans," *The Journal of Clinical Endocrinology & Metabolism*, vol. 96, no. 3, pp. E463–E472, 2010.

[10] G. Brainard *et al.*, "Effect of light wavelength on the suppression of nocturnal plasma melatonin in normal volunteersa," *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] 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.

[16] 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

[17] C. Reinhart, "Gsd 6332 rules of thumb i." [Online]. Available: http://isites.harvard.edu/fs/docs/icb.topic466781.files/l04.6332.rulesofthumb.pdf

[18] 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.

[19] 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"

[20] 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

[21] 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.

[22] F. Moore, *Concepts and practice of architectural daylighting.* Van Nostrand Reinhold Company, 1985.

[23] 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.

[24] 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.

[25] 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.

[26] ——, "Evaluation of user interaction with daylighting simulation in a tangible user interface," *Automation in Construction*, vol. 36, pp. 117–127, 2013.

[27] B. Cutler and J. Nasman, "Interpreting physical sketches as architectural models," *Advances in Architectural Geometry 2010*, pp. 15–35, 2010.

[28] J. Hirsch, "equest, quick energy simulation tool: Introductory tutorial," 2010.

[29] 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.

[30] E. Y.-L. Do, "Vr sketchpad," in *Computer Aided Architectural Design Futures 2001*. Springer, 2001, pp. 161–172.

[31] D. Glaser *et al.*, "A sketch-modelling program for lighting analysis," *Chiu, Tsou, Kvan, Morozumi, and Jeng editors. CAAD Futures*, pp. 371–382, 2003.

[32] E. Li, "Photon mapping for architectural daylighting simulation of interior spaces," Ph.D. dissertation, Citeseer, 2011.

[33] S. G. Parker *et al.*, "Optix: a general purpose ray tracing engine," *ACM Transactions on Graphics (TOG)*, vol. 29, no. 4, p. 66, 2010.

[34] T. Hachisuka, S. Ogaki, and H. W. Jensen, "Progressive photon mapping," *ACM Transactions on Graphics (TOG)*, vol. 27, no. 5, p. 130, 2008.

[35] C. C. I. DE LECLAIRAGE, "Spatial distribution of daylightluminance distributions of various reference skies," 1994.

[36] 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.

[37] 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.

[38] 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.

[39] A. Marsh, "Ecotect (software)," *Australia: Western University*, 2007.

[40] D. Tal, *Google Sketchup for site design: a guide to modeling site plans, terrain and architecture.* John Wiley & Sons, 2010.

[41] 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.

[42] M. Andersen *et al.*, "An intuitive daylighting performance analysis and optimization approach," *Building Research & Information*, vol. 36, no. 6, pp. 593–607, 2008.

[43] M. Andersen, J. Gagne, and S. Kleindienst, "Informing well-balanced daylight design using lightsolve," *CISBAT11: CleanTech for Sustainable Buildingsfrom Nano to Urban scaleLausanne, S*, 2011.