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Authenticity of the Light Environment of the Pennsylvania Academy of the Fine Arts

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Abstract

Daylight is one of the essential elements in the human experience of architectural space, and this is especially the case with the historic buildings that predate the wide-spread use of electric light. With a historic building, the architect's original design intent for daylighting may be diminished by a variety of factors: environmental context, replacement of glazing material, soiling, window treatments, introduction of artificial light, interventions for the improvement of energy efficiency, and removal or abandonment of external shading devices such as shutters. By operating computational simulation of the indoor daylight environment on a chosen historic building, the Pennsylvania Academy of the Fine Arts, this thesis is to estimate how light quality has altered over time and how it has changed the viewer's appreciation of a space.

Disciplines

Historic Preservation and Conservation

Comments

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AUTHENTICITY OF THE LIGHT ENVIRONMENT OF

THE PENNSYLVANIA ACADEMY OF THE FINE ARTS

Jeong Eun Pae

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
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To my parents

Acknowledgment

List of Figures and Illustrations

Chapter 1: Introduction

Hypothesis

Daylight is one of the essential elements in the human experience of architectural space, and this is especially the case with the historic buildings that predate the wide-spread use of electric light. With a historic building, the architect's original design intent for daylighting may be diminished by a variety of factors: environmental context, replacement of glazing material, soiling, window treatments, introduction of artificial light, interventions for the improvement of energy efficiency, and removal or abandonment of external shading devices such as shutters. Based on the hypothesis that these factors may affect and change the light quality of the space, the goal of this thesis is to estimate how light quality has altered over time, and how it has changed the viewer's appreciation of a space using a daylight simulation model.

For this study, computational simulation is used to visualize the original light environment of an architectural space of the historic building. Two significant instances are compared and analyzed: one marks the period when the space was built and the other is the present condition. In both instances, the space has been modeled three-dimensionally using the 3D software, Rhinoceros ®, in order to conduct the simulation. On-site data was gathered to both verify and increase the accuracy of the simulation model. Based on the simulation results, recommendations were prepared with the goal of regaining the original human experience of daylight in the space.

I selected the Pennsylvania Academy of the Fine Arts (PAFA) for the daylight simulation, located in Center City Philadelphia, designed by the architect Frank Furness in

1876. The gallery spaces utilized daylight with skylights for illumination; however, over time, environmental and contextual factors have affected the original light environment of the space, making it an optimal candidate for the daylight simulation of this research.

Objectives for Application of Computational Simulation Methodologies

It is impossible to restore daylighting conditions on site as they were at the time of construction. Thus, research has been carried out through a computational simulation with a virtual environment. This simulation was conducted using the collected data of illuminance and materiality from on-site research and archival research. The simulation results allowed present and past daylighting factors to be compared and facilitated recommendations for the restoration of the original light environment.

As technology develops, the application of simulation methodologies is inevitable in the preservation field. This is especially true in the case of the light environment of the Pennsylvania Academy of the Fine Arts, since we cannot assure that simply restoring historic material can restore the authentic light environment that Furness intended. This is why simulation is a valuable tool for the research on the restoration of light quality. Only a simulation based on variety of essential factors, including material properties, location, weather data, etc., can provide a more accurate visual on how the light performance changed with time. Furthermore, by recreating the historical fabric on the virtual environment and producing simulation of the space prior to the restoration process, preservation professionals can discover some unexpected factors in daylighting, which may affect the preservation of a space.

Although computational simulation can be a helpful tool to understand the authentic environment of the space, it must be utilized carefully with the understanding of its limitations. The environments of the simulation condition cannot be the same as the real environment, and the omission of essential factors will inevitably lead to errors. Research for this study was designed to minimize such errors by calibrating the results between the simulation and on-site data to produce useful and accurate results for preservation professionals.

Justification

Humans experience space through their senses; and sight is one of those major sensory systems. Quality of light allows people to acquire the spatial sense and perception of color; consequently, the proper kind of light source and proper range of light intensity is crucial. Through research, I have found that the architect of the Pennsylvania Academy of the Fine Arts, Frank Furness, utilized daylight to create a gallery space with both aesthetic and functional value. Simulating and recreating the original space was important to understand the architect's intent on the lighting design.

The Venice Charter (1964) articulates the duty of the preservation professional as a "duty to hand [architecture] on in the full richness of their authenticity". Every preservationist has his or her own idea of authenticity. Some might insist on preserving the original materiality of the building, some might focus on the continuous usage of the space, and others might argue for minimum intervention to protect the old value of the space; these ideas differ according to the context of each historic building. With this research on

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the authenticity of the light environment, I propose another alternative in preserving the authenticity of space and call for preservationists to reconsider the meaning of the authenticity critically.

Experiential light quality as intended by the architect may be an important factor in historic buildings built before the broad utilization of artificial light. I have chosen Furness's space to focus on his design for daylight control. Moreover, utilization of daylight in the gallery space of the PAFA is especially crucial, based in Furness's skylight design. Therefore, restoration of the authentic light environment on PAFA is an important consideration, equal to restoring its materiality for historic and original value. With the architect's unique skylight design, the accessibility of the archival information of the Pennsylvania Academy of the Fine Arts made it a suitable case study for my research. Archives provided various information on skylight, and attic structures, as well as changes in its surroundings since its original construction in 1876.

Theoretically, as shown in Figure 1, the light environment of the space may have changed intentionally and unintentionally over time due to various factors. In reference to the diagram, if we consider "A" as the original amount of natural lighting and series of "B"s as the other factors affecting that change of the original light environment of a space of "A", it is unlikely to eradicate all the "B" factors. After creating the current light environment (A') and original light environment (A) in the virtual space, the final objective of the research is to transform A' to A through the implementation of recommendations.

Furthermore, it is important to retain functionality of the space as a museum, in addition to restoring the original light quality of the space. The Pennsylvania Academy of the Fine Arts has historic value and the functional value. As a result, the range of light

qualifying these values—which may conflict each other—should be considered correspondently to make informed recommendations for the restoration of the interior daylight environment.

Chapter 2: Background

Basics of Understanding Natural Light

To assess the original daylight environment of the interior space on the historic building, understanding the characteristics of daylight is crucial. The daylight changes in brightness (intensity) and tone (color of light) by time (season, time of the day), cloudiness and location. For example, the amount of the illuminance of the ground on overcast sky is about 1,100 lux, while the illuminance of the ground on sunny day reaches to 110,000 lux, fluctuating by the cloud cover (Table 1).[1]

The color of daylight is affected by the time of day which results in a different color temperature (K) of light, making yellow sky at sunset and blue sky at noon (Fig. 2-4). The wide range of daylight tone affects the color of objects, as well as the mood of space over time. Figure 3 shows the same view over different time points, resulting in the various tones over the space. The reason why the tones of the daylight vary over time is because of the spectral variations in natural light. Figure 4 shows four spectral variations in natural light: north skylight, noon daylight, noon sunlight, and sunset sky with sunlight. The color of daylight changes over time as the proportion of visible waves changes due rotation of the earth (and consequential change in the angle of daylight) and variable atmospheric conditions, including particulates.

Sunlight has three components according to the range of wavelengths: ultraviolet, visible light, and infrared (Fig. 5). Visible light or merely, light, ranges from 400 to 700nm of wavelength and is the only light humans can see. Light is bounded by ultraviolet radiation and infrared radiation in the electromagnetic spectrum. The color of the object is based on what kind of wavelength is reflected or absorbed by the object. The reflected

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[1] National Optical Astronomy Observatory. "Recommended Light Levels".
https://www.noao.edu/education/QLTkit/ACTIVITY_Documents/Safety/LightLevels_outdoor+indoor.pdf (Accessed Dec 2018)

color from the object reaches to human's eyes and is thought to be the object's color. Since the daylight is well-distributed containing all the wavelengths of visible lights ranging from 400 to 700nm, human can observe the full range of light wavelengths reflected from a certain object through the daylight, which make him/her to recognize its real color. On the other hand, artificial lights lack a certain range of wavelengths found in daylight and therefore, does not allow human to perceive its true color.[2] Figure 6 illustrates this phenomenon. Since the daylight has all range of visible light, the reflected light shows the real color of the object, which is red. However, the artificial light lacks the red color to be reflected, and therefore, the reflected light shows a different result than the daylight.[3]

Furthermore, the intensity is also important to get color data of the object. The human eye can see a range from 0.000001 lux to 100000 lux, starlight to sunlight (Fig. 7, A "cd/m^2" is same as a "lux"). However, for humans, color information can be only produced by cone photoreceptors, and minimum intensity of lux is required for the cone to perceive color.[4] As a result, a lack of luminance can result in an underappreciation of the color at the space, along with the uneven spectrum of visible light on the illuminant.

Daylighting on Museum Space

Utilizing daylight into a museum space is challenging since the design should consider two colliding factors: the light requirements for the protection of artifacts and for the appreciation of the exhibition. A good daylight design for museum is the one in the intersection of these two objectives.

Daylight includes certain ranges of rays that make artifacts fade, dry out, or become discolored or deformed if exposed to the light for long periods. This is especially true for Ultraviolet (UV) radiation, which ranges from 200-400 nm of wavelength and has an intensity which can harm the objects exposed to it.[5] Therefore, the prolonged exposure

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[2] DiLaura, David; Houser, Kevin. Illuminating Engineering Society The Lighting Handbook. page 32, 10th ed., 2011.
[3] Mac Adam, David L. "Visual sensitivities to color differences in daylight." *Josa 32*, no. 5 (1942): page 247-274.
[4] Reinhart, Christoph. Daylighting Handbook1: fundamentals, designing with the sun, page 64-65, 2014.
[5] Kaufman, John E; Jack F Christensen. IES Lighting Handbook: The Standard Lighting Guide. page 35. 5th ed., 1972.

of UV radiation on the artifacts in the museum is considered an accelerating factor of its photochemical degradation. To avoid UV radiation from damaging artifacts, museums use glass filters, absorption filters, dichroitic filters, plastic lenses or foils. Table 2 shows the range of light intensity for the collection of artifacts. Since exposure to light is the one of the factors causing damage on artifacts, collections conservators recommend that light levels on collections be controlled with respect to intensity and duration of exposure.[6] This is why light environment ranging from 150 lux to 300 lux is provided for the galleries of the Pennsylvania Academy of the Fine Arts (e.g. oil paintings, marble sculptures, etc.[7]).

Meanwhile, the light levels for appreciating the exhibition require a higher range. Table 3 is a list of some simple rules for adjusting visibility for different objects. Appreciating the artifacts is a complex work using intensive visual senses and differ by various situations. Table 3 shows the illuminance range at the gallery space stretches from 50 lux to 4000 lux according to the age of viewers and the materiality of the collections.[8]

Utilization of Daylight on Historic Buildings

Before the use of artificial lighting, architects have made an effort to better illuminate interior space using daylight. Since daylight was the only source of light, architects designed various opening designs in historic buildings, including windows,

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[6] Michalski, Stefan. Agent of Deterioration: Light, Ultraviolet and Infrared. https://www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html (Accessed Dec 2018)

[7] Leibold, Cheryl. "The Historic Cast Collection at the Pennsylvania Academy of the Fine Arts." *Antiques & Fine Art* (Spring 2010). page 186-191

[8] AIC. Levels of Susceptibility to Light Damage & Types of Materials. https://www.conservation-wiki.com/wiki/Light#UV_Light (Accessed Dec 2018)

sawtooth roofs, and skylights, to increase illumination.[9] The size and the orientation of these openings are the key components in controlling illumination.

Windows are the most common design method to increase the daylight of an interior space. The depth of the window is one of the factors that affect the light environment of the interior space, besides size and direction. At the openings in a thicker wall, light penetration is less deep and more dependent on the position of the sun. While the openings on the thinner wall allow for more illuminance of the interior space, they also allows for more direct sun light, which causes problems such as glare, affecting human comfort.[10] An additional method to change the light quality of the interior space is through the usage of sun control devices. Figure 8 shows the sorts of sun control devices which can be attached on the window: roll shades, Venetian blinds, shutters, louvers, drapes, glass blocks, low transmittance glazing, and awnings.

Clerestories and sawtooth roofs can be described as windows installed on the upper wall. The difference between clerestories and sawtooth roofs and skylights is the angle of the openings. Skylights are installed on the roof, perpendicular to the wall, while others are parallel to the wall (Fig. 9). The intensity of light on the horizontal plane is two times bigger than that on the vertical plane with an overcast sky, which makes skylights a more efficient design. However, the intensive direct sunlight is the problem that designers need to solve when utilizing skylights. By using shading devices, or diffuse glass material, skylights can avoid problems caused by direct sunlight.

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[9] American Institute of Architects. Architect's Handbook of Energy Practice- Daylighting. page 10-19. 15th edition. 2013.
[10] American Institute of Architects. "Effect of Various Window Forms on the Quality of Admitted Daylight". Architect's Handbook of Energy Practice- Daylighting., page 10. 15th edition. 2013.

Beyond the design of the opening, the material of the system is also important to attract daylight into the building. When sunlight goes through a transparent material such as glass, some of the light is reflected or absorbed by the material, while the rest is transmitted to the interior space. The ratio of reflection, absorption, and transmittance of light is based on the properties of the material and differs by the wavelengths of the light. By the harmony of the opening design and its material, the interior space has its own unique atmosphere that changes time of the day, along with the sun.[11]

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[11] Zumthor, Peter. Atmospheres: Architectural Environments, Surrounding Objects. page 56-61. 2006.

Chapter 3: Pennsylvania Academy of the Fine Arts

History of the Pennsylvania Academy of the Fine Arts

The Pennsylvania Academy of the Fine Arts (PAFA) was built in 1876, designed in the modern Gothic revival style by Frank Furness. The building, also known as Furness-Hewitt building, was the third building of Pennsylvania Academy of Fine Arts. Frank Furness was an experimental architect, a leader in the use of new materials and structural forms inspired by locomotives.[12] In the Pennsylvania Academy of the Fine Arts, the iron truss made it possible to have a skylight system that introduced daylight into interior space.

Daylight environment of galleries in Pennsylvania Academy of Fine Arts is strongly related to the context of the building. In 1876, the surrounding structures were shorter than the building, making little impact on its daylight quality. Being 70 feet in height, PAFA was once a towering fortress looming over the pedestrians; however, as Center City, Philadelphia developed over time, it is dwarfed by its surrounding buildings today (Fig. 10-14).

Today, the buildings on all four directions of the Pennsylvania Academy of the Fine Arts have impacted the light environment of its interior space. First, on the east side across North Broad St, there are two tall buildings: Pennsylvania Convention Center with the height of 168.6 ft and Aloft Hotel with the height of 268.5 ft. The adjacent buildings on the south side ranges from 226.9 to 268.4 ft. Then on the northern side of the building, there is a contemporary building for PAFA with the height of 193.8 ft. across Cherry St.

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[12] "Fearless Frank Furness." *Architectural Forum 112* (June 1960), page 109-10.

Lastly, the highest construction of the surrounding buildings, with height of 312.5 ft., is located on the west of PAFA (Fig. 15).[13]

Moreover, the decisive color palette on the interior space of PAFA is one of its most distinctive features. Furness decided carefully on the color of the interior walls, and as a result, the gallery walls were originally painted with various rich Victorian colors including rich red, blue, white and gold in detail. Around the 1930s, in the pursuit of modernization, the tiles of the gallery walls in the downstairs hall were repainted grey, and its rich Victorian-colored walls were painted in other subdued colors.[14] In Restoration Project in 1987, an effort was made to recreate the original color palette of the PAFA. The extensive color research through the historic documents and memos was conducted as following lists of events, along with the physical researches including the paint analysis for the consummate restoration.[15]

Timeline of relevant events to the simulation in PAFA[16]

> March 20, 1876: Has agreed to carpet galleries (Red with a moss pattern on)
> April 22, 1876: Opened
> November 9, 1903: Walls painted a dark red

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[13] GIS Map "Philadelphia Buildings", Institutes of Energy and the Environment in Penn State University, https://maps.psiee.psu.edu/preview/map.ashx?layer=146.

[14] Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Bampton, Alice. Frank Furness and the Pennsylvania Academy of the Fine Arts. Senior Paper, Rosemont College, Mar 9, 1981.

[15] Historical Landmark Building records. Record Group 6: Buildings 6-B 118 North Broad Street (Furness-Hewitt Building): Architect's Prospectus for the Restoration, 1973 (1 volume); Correspondence re: Renovations, 1974–75 (3 boxes in the general office files of Richard J. Boyle); Boyle, Richard. "The Restoration of the Furness Building of the Pennsylvania Academy of the Fine Arts." *Nineteenth Century* (April 1975), pp. 22-26. The Pennsylvania Academy of the Fine Arts Archive.

[16] Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Building. Broad & Cherry Sts. Scrapbook of Historical Information compiled for use by Architects planning Restoration (v. 84); Folder: PAFA Board Minute Book, Apr 12, 1874 to March 12, 1883 sample items on Interior Decoration; Folder: Pennsylvania Academy of the Fine Arts – Historic Data by George E. Thomas; Folder: Director's Minutes of PAFA; Folder: Annual Report 1952, PAFA Archive.

February 1920: Walls recovered with burlap, Main floor – wood sections repainted

October 5, 1931: Pillars formerly dark green colored to be painted grey

October 13, 1937: Walls in entrance painted grey

Around 1950: The iron roof crestings were removed

Summer 1952: The improvement in the light in the galleries under these new skylights; stair hall painted to neutral color over the time-worn stained red

Frank Furness's Intent on Daylight Design

The Pennsylvania Academy of the Fine Arts was an innovation that utilized industrial materials and construction methods that mark the turn toward modern architecture. The attempt to use uncommon material and method on the building made the skylight structure possible. [17] Moreover, vital elements were inspired from railroad construction and machinery, which marked PAFA as a futuristic building during its time.

George Thomas describes the gallery spaces and skylights with the detailed depiction of the elements and materials:

> On the main gallery, divisions in the largest room and between the central long corridor and the crossing are carried by wrought-iron U channels, bolted together and supported on columns made of iron pipes. Gallery ceilings are spanned with metal grids hung on iron rods from the steel structure overhead carrying glass plates. The surrounding perimeter iron frames of the skylights are pierced with decorative shapes to allow the flow of air into the attic. The skylights bring glowing but modulated light into every nook and cranny of the gallery level and into the teaching spaces of the lower school studios. Instead of the customary static experience of an artificially lit gallery, the Academy's spaces change of a cloud, making every visit a different experience. At the top of the building, above the skylights and invisible to most visitors, is a zone of unadorned industrial construction. The workhorses of this space are rough brick piers forming an arcade running the length of the building, with the exception of the zone interrupted by the cross gallery, which is spanned by giant steel trusses. A factory-like ventilating roof monitor runs the length of the main block to cool the building by means of banks of operable louvers joined by steel rods and operated by pulleys from the

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[17] Thomas, George E., and Alan Hess. Frank Furness: Architecture In the Age of the Great Machines. 2018. Page 39.

gallery level. Finally, the roofs above the galleries are sheathed in glass plates supported on spidery webs of iron, attenuated so as not to cast shadows on the art below.[18]

PAFA's innovative skylight structure and various condition of the daylight coming through allows the viewer's feeling on the space to change throughout the day, which makes it a unique exhibition space. *The light in the building is ever variable, changing the way that art is seen depending on the time of day, the season, and the weather,*[19] affecting to the visitor experience.

Furthermore, skylights become a guide to flow around the exhibition spaces. Starting the sequence of the exhibition at the relatively dimly-lit Foyer to the stair hall led by light from the skylight, flowing to the galleries with varying proportions, the various illumination of the space gives viewers curiosity on the next space. Michael Lewis also had a comment about the flow over the spaces:

> But such plans did more than organize function and create hierarchies of space; they also shaped a spatial sequence of expressive power—what the French termed the Marche. Each successive space was altered in proportion and character to form a dynamic progression that encouraged constant motion—motion forward, upward, toward light, toward ever bigger spaces. But Furness's sequence was highly idiosyncratic. Rather than merely flogging his visitors through his sequence, Furness alternately disconcerted them, rerouted them, or startled them. Movement-squelching gestures were everywhere: the divided entrance with a column athwart the main axis; the intermediate landing of the stairway fragmenting into three smaller flights, inviting forward and backward alternatives; and even the second-story hall, whose cross-axis is broader than the main axis, beckoning more strongly to the side than forward, thereby arresting momentum. Movement through the building was less like a stroll and more like a kind of peristaltic motion in its alternate compression and release.[20]

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[18] Thomas, George E, First Modern: Pennsylvania Academy of the Fine Arts., page 26. 2017.
[19] Thomas, George E, First Modern: Pennsylvania Academy of the Fine Arts., page 118. 2017.
[20] Lewis, Michael J. Frank Furness: Architecture and the Violent Mind. page 96-97. 2001.

The various intensity of illumination on each gallery maximizes this peristaltic effect. Therefore, the museum controls the intensity of daylight by using shutters on the skylight to make relative difference of light intensity among the galleries and stimulates the viewer's movement and maximizes the appreciation of the exhibition, matching the theme of each exhibition.

Furness' Daylighting System

The entire second floor of the building, composed of exhibiting areas with the galleries, have skylights. The glazing system is composed of two levels of glass, one for the ceiling of the galleries and the other for the roof (Fig. 16-20). The main reason why Furness applied two layers of the complex system, rather than applying simple, one-layered flat skylight, was because of weather. Due to the unignorable amount of snow during the winter season of Philadelphia, a flat skylight would not have been a good idea. Snow may serve as a dead-load on the flat roof, which would have harmed the structural safety of the building. Two-layer skylight system provided a sloped roof and allowed Furness to avoid the increase of dead-load in winter. Therefore, this clever skylight system satisfied both the structural safety and the daylight illumination of the building.[21]

The two layers of skylight system made an attic space between them, which is filled with structural truss supporting the two skylights. The attic is filled with iron truss as well as a brick arch, which elongates to the basement. These supporting structures did not interfere with the overall daylights that shined into the gallery. The rest of the grand empty

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[21] Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Eminent Victorian. Architectural Tour of the Pennsylvania Academy of the Fine Arts with the Director Tom Armstrong. 1972.

space between the brick arches and steel trusses was used later for the renovation of the enhanced HVAC system.

Restoration Project in 1976

In the 1960s, the movement to restore the Pennsylvania Academy of the Fine Arts began among the people related to the Academy, and this movement aimed to resuscitate the original splendor of the building by keeping the spatial concept of the Furness design. The PAFA was designated as a National Historic Landmark by the National Park Service in 1975, and the restoration project of this 100 year-old building began in 1976 under the well-known architect, Hyman Myers as a restoration architect, and Day & Zimmerman Associates, as a project manager. Hyman Myers aimed for a reasonable and accurate restoration, while applying the technical advancements available in 1976. The interior of the building was repainted with bright colors that matched its original color, and structures that had been added on the columns were removed (Fig. 21). This was done as a result of Myers's extensive archival research on the original condition of the building and photomicrograph research to find the original color of the interior space. The galleries are carpeted again as they were originally. Woodwork with golden oak finish was restored as well, and the original knobs, locks, hinges were cleaned in place. Skylights were re-glazed while keeping the window frame structure. Also, new flexible lightings, which are noticeable but necessary, were added due to the functionality of the gallery.[22]

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[22] Myers, Hyman. "The Buildings of the Pennsylvania Academy of the Fine Arts." *Antiques 121* (March 1982), pp. 679-89.

Hyman Myers made improvements to the building to satisfy its contemporary needs, while intelligently concealing its newly built constructions. This is shown through his usage of the attic, which he used as a place to hide the enormous ducts from the viewer's eyes. Diffuser skylights on the ceilings in galleries have blurred the newly installed systems in the attic including fire protection sprinkler system heads, decorative return air louvers, and lighting support bars.[23]

Materiality of the Skylight Glass and Artificial Lighting

During the archival research of PAFA, I have found some information on original mechanics and furnishers of the building[24]. All the listed companies are based in Philadelphia and most of them had their office in Center City. The companies related to skylight construction and gallery interior are listed as follows:

> Iron roof: Phoenix Iron Company (Fig. 22)
> Iron work, floor beams etc.: Stewart & Stevens
> Iron cove brackets: Henry G. Morris
> Plate glass and ground glass for diffusers: Benjamin H. Shoemaker (Fig. 23)
> Gas Fixtures: Thackara & Buck (Fig. 24)
> Painting and glazing: Carlile & Joy

Also, there is detailed description of the historic glass material on George Thomas's book:

> Hammered glass was made by pouring molten glass on a beaten metal plate that produced a texture that diffused light. Sizes available in Philadelphia were listed in Sloan's Architectural Review and Builder's Journal (Nov. 1868): p.321. Flooring glass in 1-1/4inch plate was available in sheets up to 24 X36 inches; hammered glass for skylighting in 1/2 inch plate was available in sizes up to 30

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23 "Architectural Tresure Is Restored", *Form & Function*, 1976
24 Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Program, Jarur. Inauguration of the New Building. PAFA Archive.

X120 inches. Committee decision, PAFA Building Committee Minutes Feb 12, 1873.[25]

From the 1976 Restoration, most of the diffuse skylights were replaced by Fisher Skylights Inc. At the architectural drawing with the details of the skylight structure at the file of *Plan Roof Accessories of Gatch Skylight 1974-1975*, there is a description of the glass material as follows:[26]

> skylight panel consists of 1/4" THK asbestos panels laminated on interior & exterior surfaces with .032" THK Aluminum embossed on exposed side with a fine pebble pattern. Anodic architectural class 1 coating is colored black on exterior surface & white on interior surface (either shim as required or increase panel thickness to 1/2").

In addition, there is a detailed section drawing of the skylight on the roof with the laminated diffusing glass, referencing from the PAFA restoration work file (Fig. 25).[27]

> 1/4" Pol. R. glass
> 9/16" Acrylic safety glazing (Laminated)
> 1/4" Pol. R. glass

Except in the conversation laboratory, all diffuser skylight glass on attic were replaced.[28]

In terms of artificial lighting of Pennsylvania Academy of the Fine Arts, some gas lighting had existed from the beginning, in addition to the space's wide use of daylight. The PAFA galleries were lighted at night by gas jets on the industrial iron rings connected to the city gas system (Fig. 26).[29] Over time, gas lights were carelessly replaced with electric lights, and then electric lights were replaced with fluorescent fixtures. The lamps

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[25] Thomas, George. First Modern: Pennsylvania Academy of the Fine Arts., page 114. 2017.
[26] Historic Landmark Building renovation project files MS. 017.002 Box 2, Folder: Myers, Hyman. Plan. Roof Accessories: Gatch skylight 1974-1975 files, Fisher Skylight, Inc. DWG. 5273. PAFA Archives
[27] Historical Landmark Building records RG. 06. Folder: PAFA Restoration Suggested Scope of work for phase 5 (Jul 18, 1975). PAFA Archives.
[28] Historic Landmark Building renovation project files MS. 017.002 Box 2, File Boyle, Richard J. Director, 1973-82 Building Restoration. PAFA Archives
[29] "Academy of the Fine Arts, Philadelphia" *Art Journal*, n.s. 2 (New York, 1876) page 202.

at the stair hall were originally lit by a lamplighter, which was turned into gas in the 1880s, and finally around the early 20th century, gas changed into electricity.[30]

Functionality as Museum

Light has a great role in the galleries of Pennsylvania Academy of the Fine Arts, when it comes to the appreciation of the exhibition and space. The utilization of daylight on the exhibiting spaces is burdensome due to two conflicting functions of the light: to conserve and to display artifacts. As mentioned in chapter 2, the artifacts are vulnerable on the direct exposure to daylight, especially ultraviolet radiation, which accelerates the deterioration process.

On the other hand, the well-lit space by controlling both daylight and artificial light may lead to giving visitors an unforgettable experience as well. The light environment of galleries of the Pennsylvania Academy of Fine Arts is regulated individually based on the concept of each space and maximizes the visitor's appreciation of artifacts. This is done by covering skylight panels and controlling the intensity of artificial lightings. Galleries vary in size and are connected with small doorways. With the different strategy of light design on each gallery, visitors can feel curious about the exhibition on the next door. Altogether, the sense of individually cozy feeling of each gallery along with the chamfered ceiling provides an easier viewing experience of the paintings.[31]

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[30] Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Eminent Victorian. Architectural Tour of the Pennsylvania Academy of the Fine Arts with the Director Tom Armstrong. 1972.
[31] Historical Landmark Building records RG. 06.01 Publications Box 5, Folder: Eminent Victorian. Architectural Tour of the Pennsylvania Academy of the Fine Arts with the Director Tom Armstrong. 1972.

Chapter 4: Analytic Methodology

Overview of Methodology

The methodology can be divided into four parts: general climate analysis, context simulation of Pennsylvania Academy of the Fine Arts, on-site research of the interior light environment, and computational simulation results of the interior light environment. From the archival research, I have found useful information such as historic drawings, photos, and documentation of the building. The simulation process integrated the historic documentation with contemporary data of weather and site context within a 3-dimentional space.

Prior to embarking on the process, I traced the architectural drawings of PAFA including plan, elevation, and sections referenced from historic drawings (Fig. 27-31). A 3-dimensional model of the PAFA was also created based on the architectural drawings, and these were specific enough to produce light environmental simulation results. In addition to the PAFA, its surrounding context was 3-dimensionally modeled (Fig. 32) with building height data obtained from a GIS map, produced by the Institutes of Energy and the Environment at Penn State University.[32]

Climate Analysis of Philadelphia

The first step, climate analysis of Philadelphia, was done by using EnergyPlus Weather (EPW) file. An EPW file,[33] contains weather information and can be used by

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[32] GIS Map "Philadelphia Buildings", Institutes of Energy and the Environment at Penn State University, https://maps.psiee.psu.edu/preview/map.ashx?layer=146 (Assessed Dec 2018)
[33] OpenStreetMap. "Weather file sources" Ladybug tools. https://www.ladybug.tools/epwmap/ (Accessed Jan.2019).

EnergyPlus, an energy simulation software developed by the U.S. Department of Energy. Rhino 3D is a software program for building 3D models, and by using Grasshopper plugin on the Rhino 3D, designers can order more complex calculation works by using components such as Ladybug and Honeybee. I used Rhino 3D software for my research, and EPW data was linked using Honeybee and Ladybug components on the Grasshopper plugin. Through these components, various kinds of environmental analysis can be done, such as: weather data visualization, radiation, wind rose, humidity, temperature, HVAC system, human comfort, and daylight analysis. For this research, I only performed daylight analysis.

As the climate difference occurs by the location, daylight is affected by geographical location. Philadelphia is within ASHRAE Zone 4A,[34] which is a mixed-humid climate zone. Figure 33 is about light intensity zones in US with the yearly light intensity in Philadelphia. Within the ASHRAE Zone 4A, the light intensity is described divided into three time points: June, March to September, and December. Sun path changes by location and season. The changes in the angle of the sun also affects the intensity of illuminance and daylight exposure time hours, creating a wide range of brightness and color palette of daylight. These wide spectrums of daylight had a great impact on the galleries of PAFA, giving viewers a new sense of space, depending on the time and weather of visit.

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[34] ASHRAE, ERRATA Sheet for ANSI/ASHRAE STANDARD 169: Climatic Data for Building Design Standards https://www.ashrae.org/File%20Library/Technical%20Resources/Standards%20and%20Guidelines/Standards%20Errat a/Standards/169-2013ErrataSheet-1-12-2017-.pdf (Assessed Dec 2018)

Figure 34-36 shows the sun path and global illuminance in Philadelphia: during the whole year, during the winter season (December to February), and during the summer season (May to August) consecutively. Comparing the data, the less intense sunlight and an acute-angled sun path to the south side is observed in winter, which also results in shorter daylight exposure time. On the other hand, severe sunlight exceeding 100,000 lux is shown in the summertime with the steeper angle of sun path from the ground resulting in longer daylight exposure time. The sun angle from the ground is particularly important in the current condition as the research area is potentially shaded by taller structures. This angle determines whether the surface of the area will be exposed to the daylight, and this angle is observed in the simulation of PAFA.

Figure 37 shows Global Horizontal Illuminance, Direct Normal Illuminance, and Diffuse Horizontal Illuminance. Global Horizontal illuminance is the total amount of illuminance calibrated on the default horizontal ground, while Direct Normal Illuminance is the amount of it from the tilted surface perpendicular from the sunlight. Global Horizontal Illuminance can be calculated as:

Global Horizontal (GHI) = Direct Normal (DNI) X cos(θ) + Diffuse Horizontal (DHI)

The cos(θ) value is closer to 1 around noon, making with the GHI value the sum of DNI and DHI; while the cos(θ) is closer to 0 when the sun rises or sets, making the GHI value closer to DHI value.

As a result, the intense sunlight over 100,000 lux, which affects to the ground in practice (the value of GHI), is focused around noon in the summertime. In addition, Diffuse Horizontal Illuminance is also focused in the summer with the amount of 30,000-6,000 lux along with the intense direct illuminance, existing consistently during the daytime.

Context Simulation

When analyzing the context with the simulation, specific attributes for the Pennsylvania Academy of the Fine Arts were revealed. First, the exterior condition of PAFA was tested. To simulate the daylight condition of the building's exterior, surrounding buildings, which are taller than the PAFA and consequently provide shade, were created in Rhino 3D by referencing the data of the height of building from Institutes of Energy and the Environment at Penn State University.[35] After the surrounding highrise buildings were modeled, the whole context including PAFA building were arranged in the 3D environment, oriented to the four cardinal directions.

Using Ladybug's Surface Hourly Solar and Sunlight Hours Analysis components, shade simulation (Fig. 38, 39) was conducted with the context modeling. I chose Jan 15 and Jun 15 to compare the shade simulation results; the two sets of time with the least and most intense illuminance. Also, the simulation was conducted on an hourly basis from the opening hours of PAFA to its closing, from 10 AM to 5 PM.

As the results show, PAFA is unlikely to be exposed to the strong sunlight during all the simulated period in January 15; while the museum is exposed to the sun during most of the simulation period in June 15. The shade analysis also illustrates that PAFA has lost its direct sunlight more in winter after the highrise development of its surrounding area.

After the shade analysis, I conducted a Sunlight Hours Analysis (Fig. 40-42), which shows how long the façade of the PAFA was exposed to the sunlight. The tested

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[35] GIS Map "Philadelphia Buildings", Institutes of Energy and the Environment at Penn State University, https://maps.psiee.psu.edu/preview/map.ashx?layer=146 (Assessed Dec 2018)

hours correspond to the opening hours of the PAFA (10 AM to 5 PM) as well. Figure 40 shows the results from the top view (showing the roof) simulated without the context of the buildings around the museum as it was in 1876, on every month of 15th. Most of the roof area except the north side of the grand central stair tower is exposed to the sunlight throughout the tested time. The north side of the galleries show six hours of sunlight exposure time in November, December, and January, and it informs the gradual decrease in sun angle from the ground.

In comparison, Figure 41 and 42 represent sunlight hours simulation coordinated with the data of the current surrounding buildings. Like the previous simulation, the tested hours of this simlation coorespond to the opening hours of the PAFA, on every month of 15th. Along with Figure 40, Figure 41 also show the results from the top view to observe the roof surface of the building, while Figure 42 is taken from a different angle to see the east and north façade as well as a part of the roof area. These sunlight hours analysis simulation results show that May, June, and July are the months that the PAFA was exposed to sunlight with relatively longer hours. During the wintertime, the building was under the shade most of the observed time, and it was exposed to sunlight less than 0.7 hours out of 7 hours. The result of sunlight hours analysis in the current context shows that the angle of the sun from the ground rises during the summertime, reducing the building's time in the shade.

The results of the simulation significantly illustrates how the construction of the highrise buildings adjacent to the PAFA obstructs direct sunlight from reaching to the skylights on the roof of the PAFA, which affects its indoor illuminance. Furthermore, the results of the exterior simulation provided data for the subsequent daylight analysis.

Gallery 10, 11, 12, 13 are on the north side of the building, with a wide range of sunlight hours along the year. Since these spaces gave the various sunlight conditions throughout the year, they were an ideal candidate for this interior daylight simulation.

On-site Research

The overall on-site investigation took place before I chose the gallery spaces for the interior daylight simulation. As Furness intended, the museum has controlled the amount of the daylight by using shutters to cover the skylights according to the concept or artworks of the exhibition. Visitors wandering the museum caught a glimpse of the exhibition in nearby galleries by seeing the changed illuminance of each gallery. In addition, regulating daylight on purpose can be part of the exhibition to impress visitors, or to make them concentrate on certain artworks. Figure 43 shows the current skylight conditions in each gallery (February 2019). Gallery 1, 3, 4, 6, 7, 10 are the galleries with the skylights without shutters, and gallery 2, 5, 8, 9, 11, 12, 13 have shutters on its skylights. From the exterior simulation, gallery 10, 11, 12, 13 were pulled out as candidates for interior daylight simulation, and gallery 10 was the only one without the shutters. Gallery 10 was the only suitable candidate for on-site analysis, consisting of the illuminance check via light meters, as its lack of shutters allowed for the measurement of daylight intensity (Fig. 44, 45).

Figure 46 shows a rectified photography of each wall on gallery 10, and Figure 47 includes photos that show color and material of its walls, floor, and columns. This gallery consists of a large polygonal skylight with several spotlights for the artworks in the gallery,

iron-pipe columns supporting riveted wrought-iron U-channels, blueish-white walls, and eggshell white ceiling chamfered on each corner.

Gallery 10 was an optimal choice for the interior daylight simulation for two reasons. First, the skylight was relatively clean with less soiling and water damage. Second, because spotlights were focused on either the artworks on the wall or on the floor, direct influence of artificial lights on the light dataloggers were minimized since the dataloggers were installed on the columns, providing a more accurate measurement of daylight. Figure 48 is a photo of the skylight ceiling and spotlights facing to the south wall. The spotlights are pointing towards the floor and walls, but not the columns on the east and the west side.

While contacting the PAFA, I have found that the museum had collected various data, including light intensity of the gallery. I have obtained the yearly data of illuminance on the gallery 6 and 10; from January 1st, 2016 to December 31st, 2016, from the Conservation Office in Pennsylvania Academy of the Fine Arts. The data were utilized as a worthy supplement to on-site research and was helpful in comparing with simulation results, as well as with my own light meter results. Therefore, to make the corresponding data, the same kind of light meter was used for my own on-site illuminance research.

The light intensity data of the gallery, which I got from the conservation office of the PAFA, as well as the one from my own research, was measured by a light meter called HOBO® U12 dataloggers. The HOBO® U12 has a measurement range of 1 to 3000 footcandles (lumens/ft2) typically, and its maximum value varies from 1500 to 4500 footcandles (lumens/ft2). The sampling rate is user-selectable, ranging from 1 sec to 18

hours, and I chose 15 minutes to record the illuminance data.[36] The unit of "lumens/ft2" can be converted into "lux" by multiplying 10.7639104175. Figure 49 is a graph showing the HOBO U12's response ratio by the wavelength related to the accuracy of a light meter. Comparing with the eye response, U12 has less response ratio within the range of 520-560nm and 570-670nm. Also, the manual states that the light meter was designed for indoor measurement of relative light levels with this graph.

The effect on spotlights, the dataloggers were installed, with the height of 9'-6", at the top of the columns of the west and east side symmetrically to each other and were left for data collection for two weeks from April 3rd to April 17th. The reasoning behind the installation of the loggers at the higher part of the column was to exclude the effect of the artificial lights which lights the paintings on the wall. The light meters installed by the museum were located on the corner of the north wall, 4'-7" from the floor. Figure 50 and 51 show the location of the installation of light meters in the gallery. Illuminance research data collected by installing light meters at the assigned gallery have been compared with the simulation data to get the valid simulation results for this research.

Interior Simulation Results

The final step for the research is to simulate the interior daylight environment based on the factors gathered through the previous steps. I ran the simulation using the factors of location, weather data, material properties, and its surrounding areas.

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[36] HOBO U12 Temp/RH/Light External Data Logger (U12-012) User's Manual, https://www.onsetcomp.com/files/manual_pdfs/13128-C%20U12-012%20Manual.pdf (Accessed March, 2019)

First, I ran the simulation with the timepoint of April 15th to match the results with the on-site data. Adjusting the simulation properties of the diffuse glass material of the skylight provided results closer to the on-site data. Area of analysis for the illuminance was selected to be the same shape as the floor of the gallery, but at a higher point (~4'-7") parallel to the floor. Illuminance data that I collected, as well as the data provided by the museum, were used to compare with the simulation results. From the on-site data, the average illuminance results are value of 658 lux on the west column; 548 lux on the east column; and 194 lux on the north wall during the observed period, from April 3rd to April 16th (Fig. 52, Table 4).

After fitting detailed properties based on real conditions, I ran a full-scale simulation that I designed to obtain the conclusion of this research. Figure 53 shows a diagram of the overall daylight simulation methodology. I set two phases: a moment of 1876 and 2019 by differentiating contextual physical modeling. Next, using simulation tools connected with Philadelphia weather file (EPW), I set four timepoints within a year, January 15th, April 15th, July 15th, and October 15th, to capture the illuminance of the interior space caused by daylight. Three timepoints within each day, 10 AM, 1 PM, and 4 PM, were also set to see the changes of light intensity throughout the day.

*Phase 1: Daylight simulation of the **current** context (Fig.54-57)*

Figure 54, 55, 56, 57 show the current context illuminance simulation results of the selected timepoints: January 15th, April 15th, July 15th, and October 15th. The January simulation shows linear illuminance over time under 300 lux, which is similar to the on-site illuminance data, which range under 100 lux. Seeing the result in April, the daylight

environment has changed significantly throughout the day. The most intense daylight is observed at 10 AM, with the value exceeding 2000 lux. The illuminance gets dimmer as time goes by. In July, the daylight environment is strongest within a year. At 1 PM, the brightest part reaches over 5000 lux, which is also seen at the 1876 context with same day and time. This means that the changes in the surrounding areas have not influenced the daylight illuminance for this date and time. In October, the amount of illuminance is similar with the result in January.

*Phase 2: Daylight simulation of the **historical** context (Fig. 58-61)*

After the comparison between the on-site data and the simulation results of the interior space with the current context, the simulation to find the daylight environment in the year of 1876 began. Figure 58, 59, 60, 61 show the historical context illuminance simulation results of the selected timepoints: January 15th, April 15th, July 15th, and October 15th, respectively. The light intensity results in January is similar to that in October; while result in April is slightly darker than that in July. All the results in phase 2 show that brightest environment is at 1 PM, and a bit darker at 10 AM. Generally, the values of intensity are higher than the values in the current context.

Chapter 5: Discussion of Results

The simulation results show a large difference of illuminance on Gallery 10 in the Pennsylvania Academy of the Fine Arts, which is related to the change in its surrounding context between 1876 and 2019. Combined with the various aspects of sunlight over time and in different weather conditions and seasons; this difference of light intensity between past and present fluctuates throughout a day and throughout a year. Overall, a significant amount of daylight in the space has diminished from 1876 to current condition, and a crucial factor that has contributed to the change in the original daylight environment on the interior space of the PAFA are the high-rise buildings in the surrounding area.

Figure 62 is a line graph describing the illuminance data of Gallery 10 based on the simulation results (Fig. 54 - 61, Table 5). The lines are composed of three moments (10 AM, 1 PM, 4 PM) for the historical context as well as the lines of the same moments for the current context. In order to restore the current context to the authentic daylight environment (i.e. restore the illuminance), the daylight simulation results at these two moments should be compared first. Table 5 shows the simulation results at the southwest corner of the gallery where one of the light meters was installed. Each column illustrates the intensity value in the historic context, the current context, and the difference between these two values; which show remarkable trends.

To examine the historic illuminance, four months were chosen and separated into two seasons: January and October as winter, and April and July as summer. In summer, the overall illuminance values exceed 1330-3330 lux at all selected timepoints, while the overall light intensity is much weaker in winter (330-1550 lux). On the other hand, the current illuminance data shows different light intensity trends. Due to the shade from the

surrounding buildings, the skylight on Gallery 10 does not get any direct light in winter, which results in an all-day illuminance of 160 lux. In summer, however, the more intense sunlight and exposure to the direct sunlight increase the illuminance to 220-2050 lux.

Even though the illuminance range is lower in winter in both contexts, restoring the light environment in winter is harder since the range of the difference throughout a day is wider in winter than in summer—the range of 170-1390 lux in winter and 1110-1890 lux in summer. In winter, the illuminance range is not high enough to appreciate the space and daylight coming through the skylights. Low illuminance makes it harder for viewers to differentiate the change of color temperature of daylight as well as the color over the space. In other words, the viewers cannot experience the space and the art in the way that the architect intended, especially in winter.

To restore the daylight environment, there are two factors to consider; the difference of the light intensity between original and current condition and the color temperature (K) of light. Since these two factors change throughout the day, the light restoration should be transformable throughout time as well. Figure 63 shows various light source spectrums which contribute to the color temperature of light throughout the day. For example, daylight is the blue light being observed around noon, and incandescent is the yellow light that appears around the sunrise and sunset hours.

Based on this information, I found some alternative light sources that mimic the daylight by using artificial lights. Installing artificial lights that illuminate in the visible light spectrum (400-700nm) and coordinating them with the daylight spectrum could be a feasible solution to restore the authentic light environment. The color temperature at sunrise and sunset (red-rich light) can be mimicked by lighting the space with incandescent,

halogen, or warm white light emitting diode (LED) lights during the morning and afternoon. Lighting the space with cool white LED can mimic the clear blue daylight (blue-rich light) around noon. This way, it is possible to match the color temperature of the light in the space to the daylight throughout a day. With a detailed method for daylight restoration, artificial light can be utilized to restore the authentic daylight environment, even with the limitations for the restoration of daylight which cannot be solved, such as the shade caused by the buildings surrounding the PAFA.

To restore the daylight environment as well as enhance the functionality of the space in a whole year, my recommendation is to increase the illuminance by about 600-2000 lux in the morning and afternoon (winter-summer), and 1200-1900 lux around noon (winter-summer), with the installation of indirect artificial lights in the attic area. As technology develops to control the light intensity automatically with sensors and central processing units (CPU)—which is called Human Centric Lighting[37]— More minutely restored authentic light would be possible.

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[37] Boyce, Peter. "Editorial: Exploring Human-Centric Lighting." *Lighting Research & Technology*., vol. 48, no. 2, 2016, pp. 101–101

Chapter 6: Conclusions

I started this thesis based on the assumption that the Pennsylvania Academy of the Fine Arts has lost its authenticity of daylight environment in the Gallery 10, due to its contextual change over time. Through the simulation results, I have observed a remarkable quantitative change of light intensity in the interior space. Since the simulated space, Gallery 10, has the most complex daylight environment among the galleries in PAFA, if the methodology expands to the other galleries, the results would be easier to analyze than that of Gallery 10.

Daylight—the intensity and the color temperature (K)—changes throughout the day and affects the tone of the space as well as the viewer's mood. The mood of the space is not measurable but is critically related to the authenticity of the historic building. However, light intensity, which needs to be transformed into the measurable form, can be simulated to observe the change in daylight quality from the past and the present. Considering all the factors related to the daylight environment at Gallery 10, it is recommended that artificial lights be installed in order to restore the daylight environment of the interior space. The restoration process can be done manually but utilizing high-technology such as Human Centric Lighting at historic buildings like the PAFA could automate the restoration process.

Based on the simulation that I performed, further research on soiling effects on the skylights in other galleries, or the assessment of the performance of the shutters on the skylight should be researched. Also, to address the sustainability issue of historic skylights, restoration methods such as reducing heat gain, UV radiation control, and installing Low-

E glass, can be utilized when the glass material on the skylights of the galleries in the PAFA are replaced.

Authenticity, or originality of historic buildings, is not limited to the materiality or craftsmanship. Lighting and many other environmental factors—including temperature, humidity, ventilation, and acoustic features—are also important affecting factors in the authentic space. It will become more important to restore these factors to their original conditions as visitors' appreciation of historic buildings takes a big share of the historic preservation field.

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The Pennsylvania Academy of the Fine Arts Archive

Record Group 6: Buildings 6-B 118 North Broad Street (Furness-Hewitt Building)

Correspondence with Architects and Suppliers, 1871–76 (1 box). The original architects'

drawings for the building are part of the museum collection. The Archives houses full-size

negatives and mylars of these drawings, used at various times for large reproductions. Other records in the Archives include.

Correspondence re: Repairs and Alterations, 1877–1971 (1 box)

Renovation Drawings, 1940–60 (1 oversize drawer), 1976 (1 large tube)

Architect's Prospectus for the Restoration, 1973 (1 volume)

Correspondence re: Renovations, 1974–75 (3 boxes in the general office files of Richard J. Boyle)

Photographs, 1876– (2 linear feet of folders and 1 oversize drawer)

Photography of the building is extensive and includes images of the interior, exterior, and details of all areas. Photographs taken before the major restoration of 1974–75, as well as those taken during the project, are segregated. Also see museum and school photographs in ″Special-Format Museum Records"

Appendix (Figures)
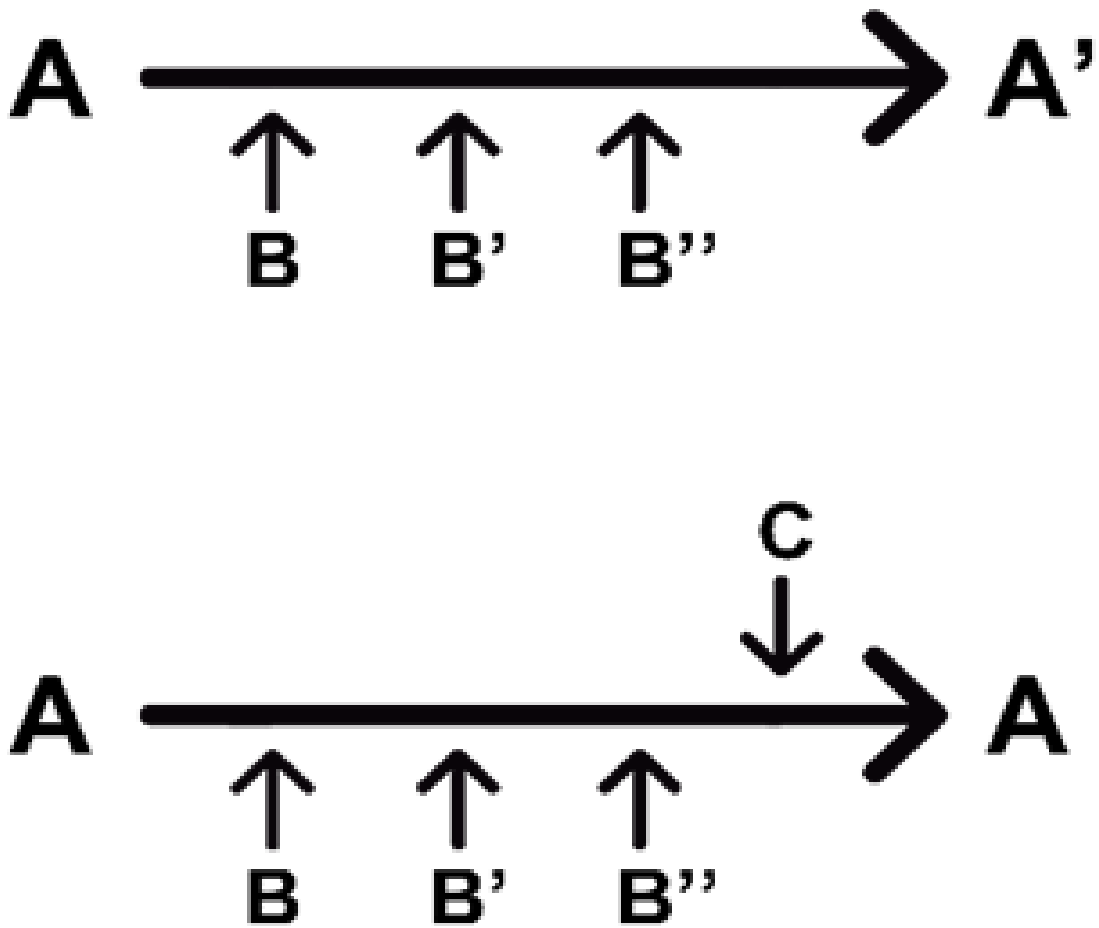
Figure 1 Key diagram showing the concept of the research (Pae, 2019)

Fig. 9 - Correlated colour temperature (°K), of several electric light and daylight sources
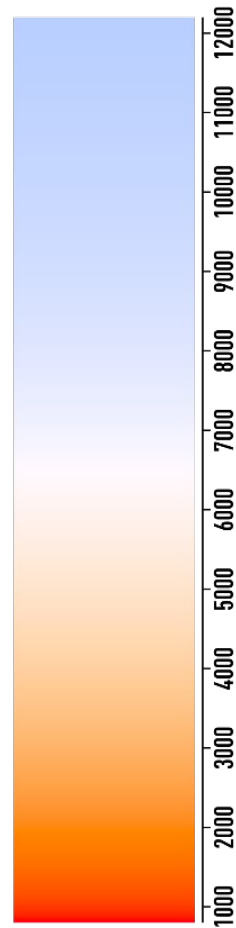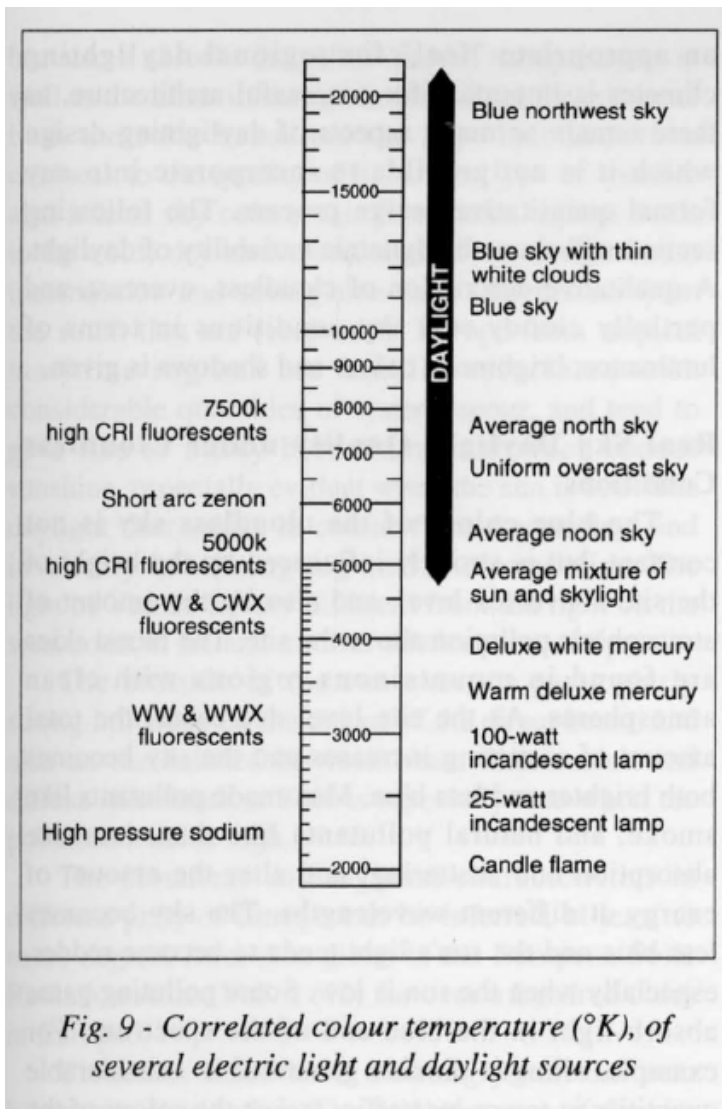
Figure 2 Approximate color temperatures of common illuminants (Architect's Handbook of Energy Practice- Daylighting)

Figure 3 Noon at the Arctic Circle on each month of the year (Susan Ubbelohde)
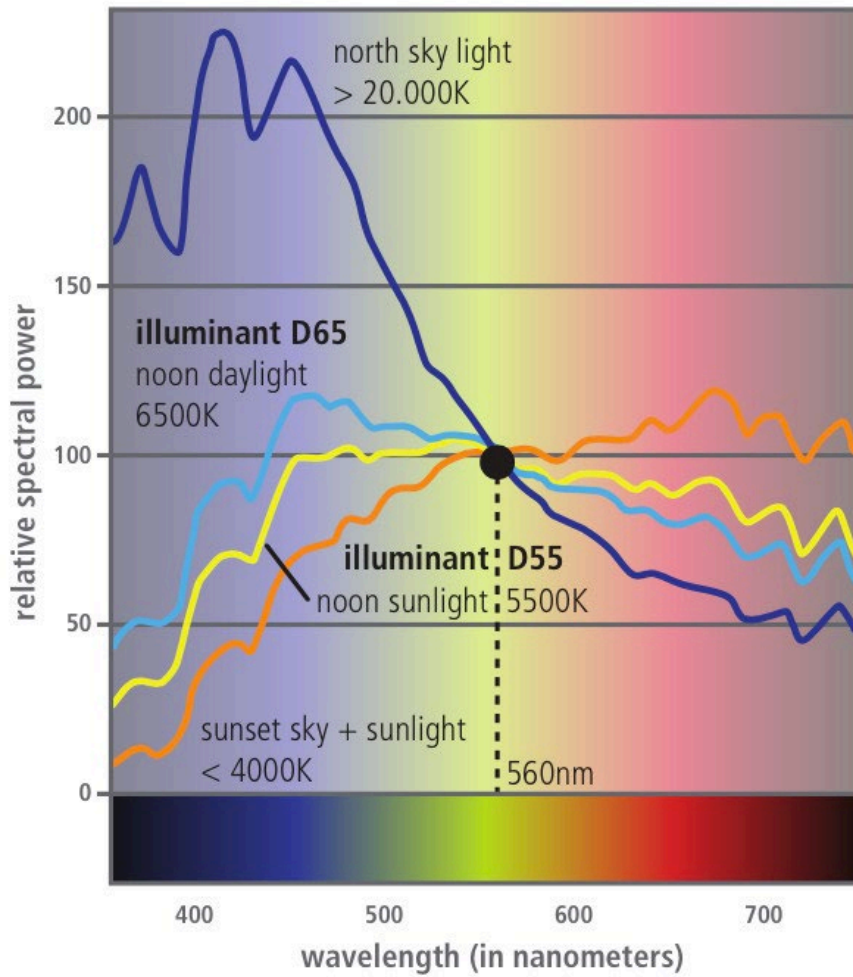
Figure 4 Spectral variations in natural light (www.ledrise.eu)
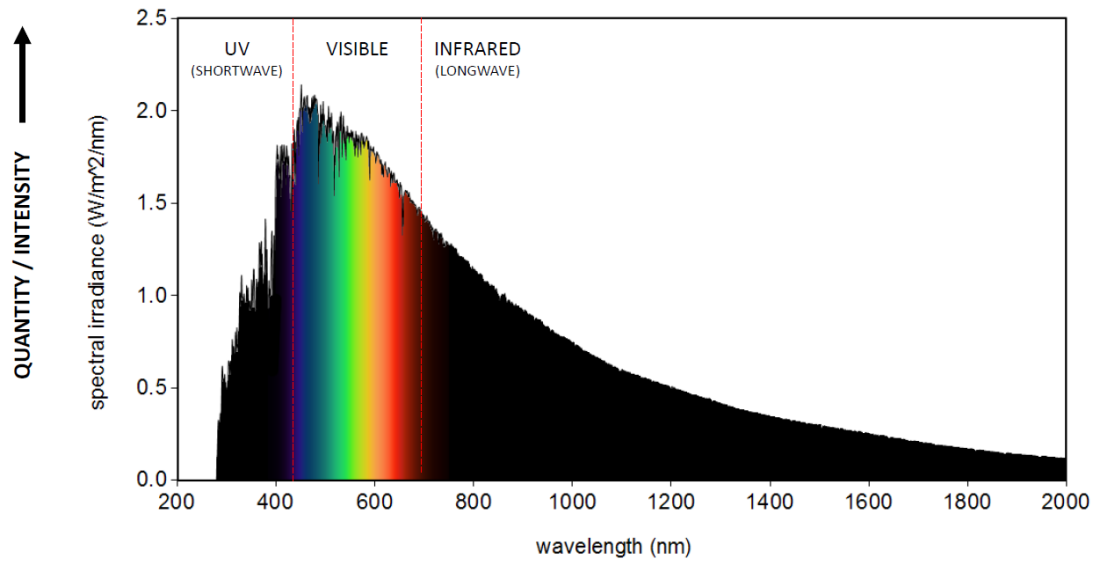
Figure 5 Solar light spectrum (Daylighting Handbook)
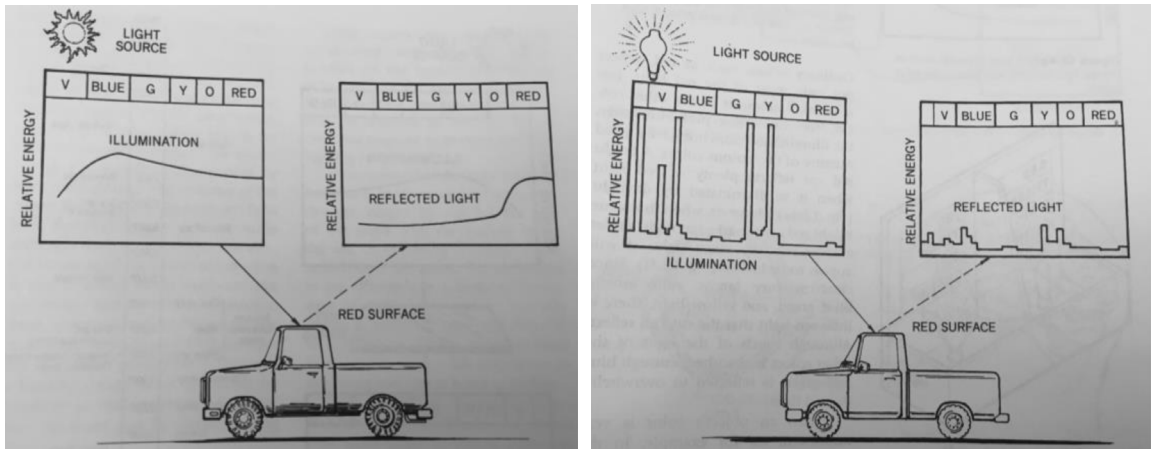
Figure 6 Color difference due to the light source (IES Llighting Handbook)
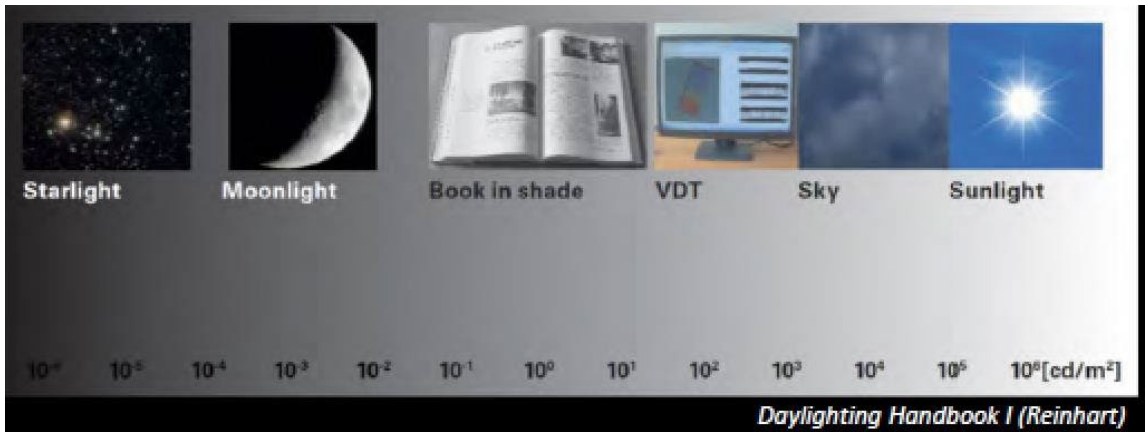
Figure 7 Capability of Human Vision (Daylighting Handbook)
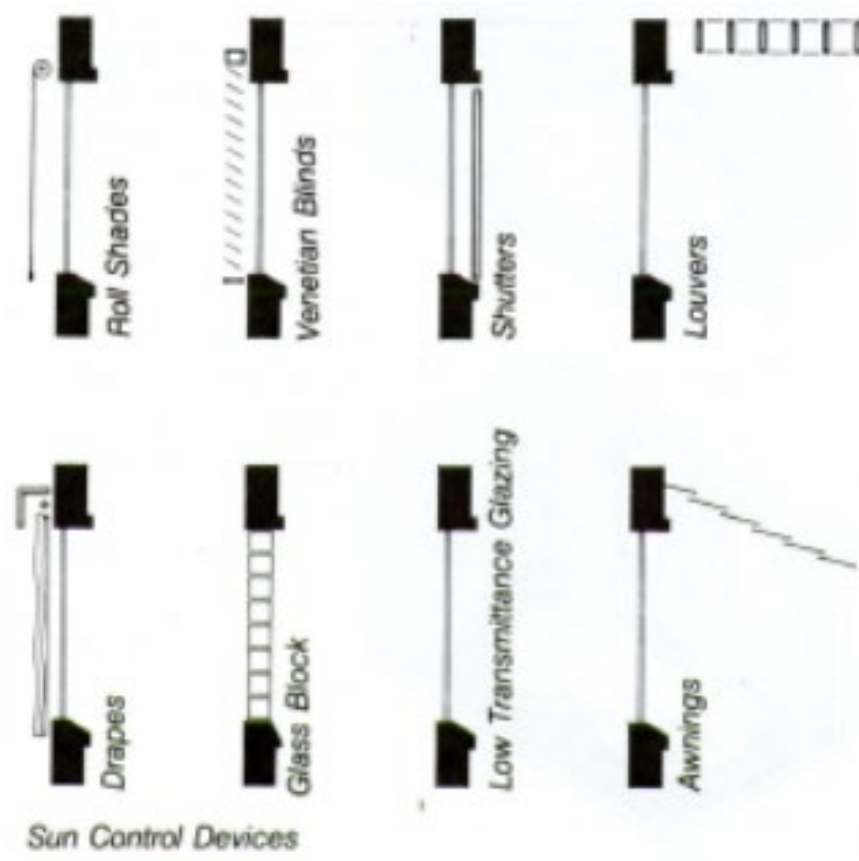
Figure 8 Sun Control Devices (AIA Daylighting)

Sawtooth Roof

Clerestory
Effective Proportions for Sawtooth Roofs and Clerestories

Large Skylights (3/4H in diameter)
Effective Proportion for Skylights
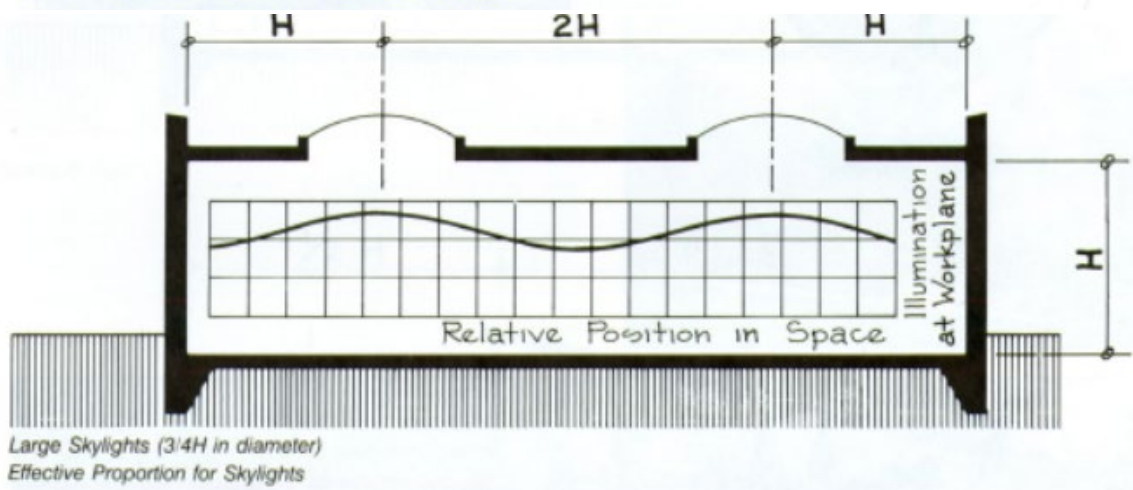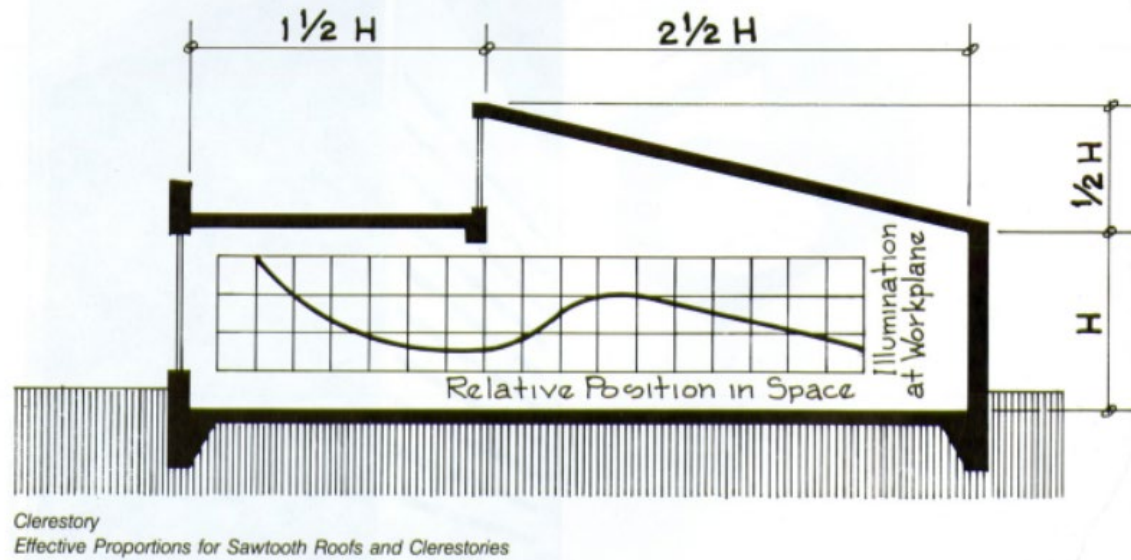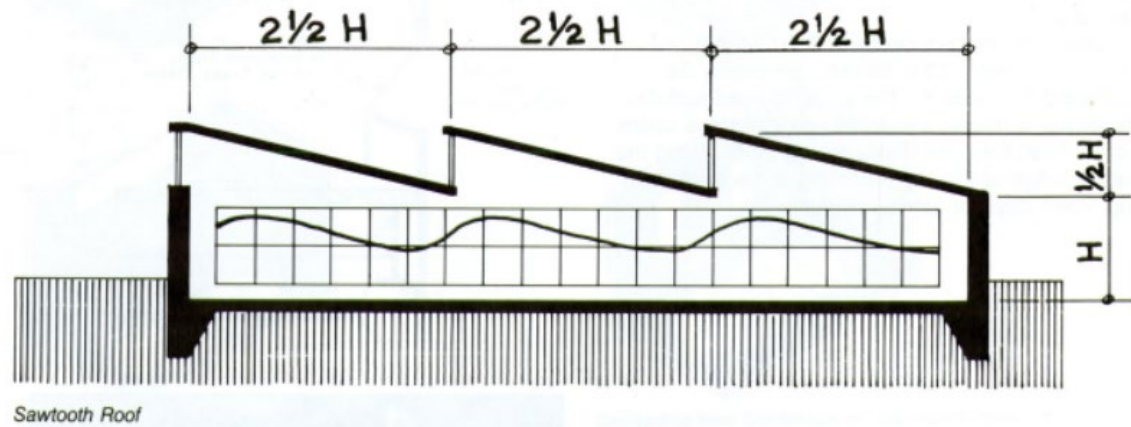
Figure 9 Daylight Designs (AIA Daylighting)

43
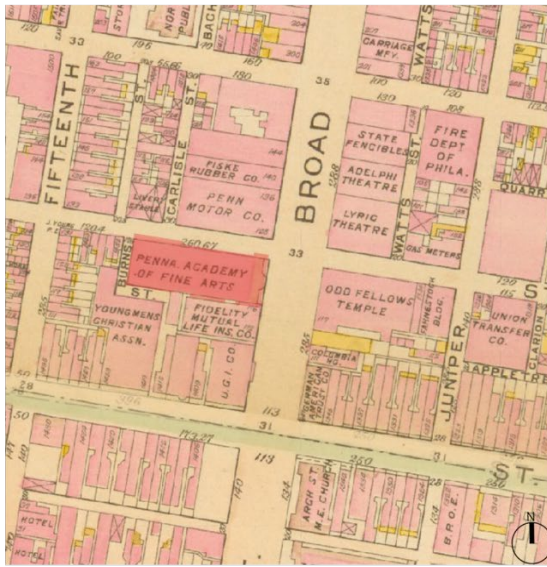
1910 PHILADELPHIA ATLAS
G.W. Bromley
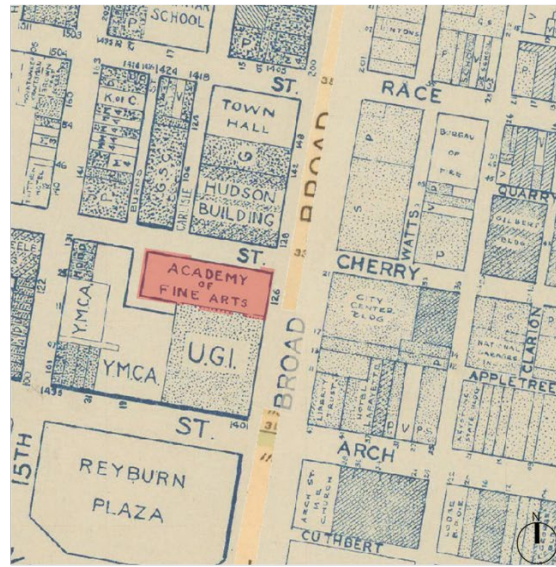
1942 LAND USE MAPS
Works Progress Administration

1875 PHILADELPHIA ATLAS
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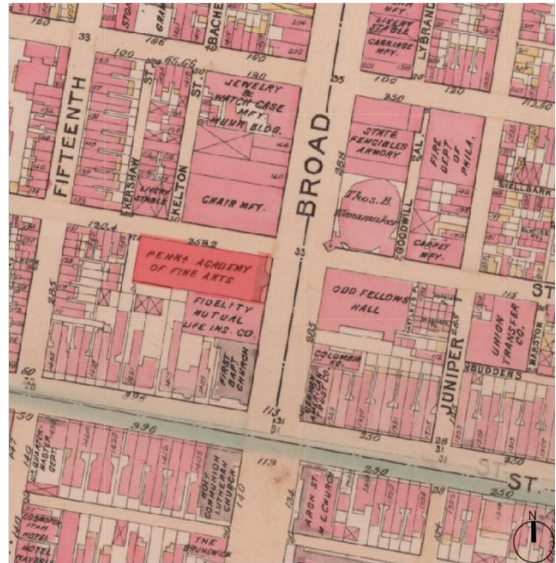
1895 PHILADELPHIA ATLAS
G. W. Bromley

Figure 10 Historic maps showing context change (Phila Geo History Map)
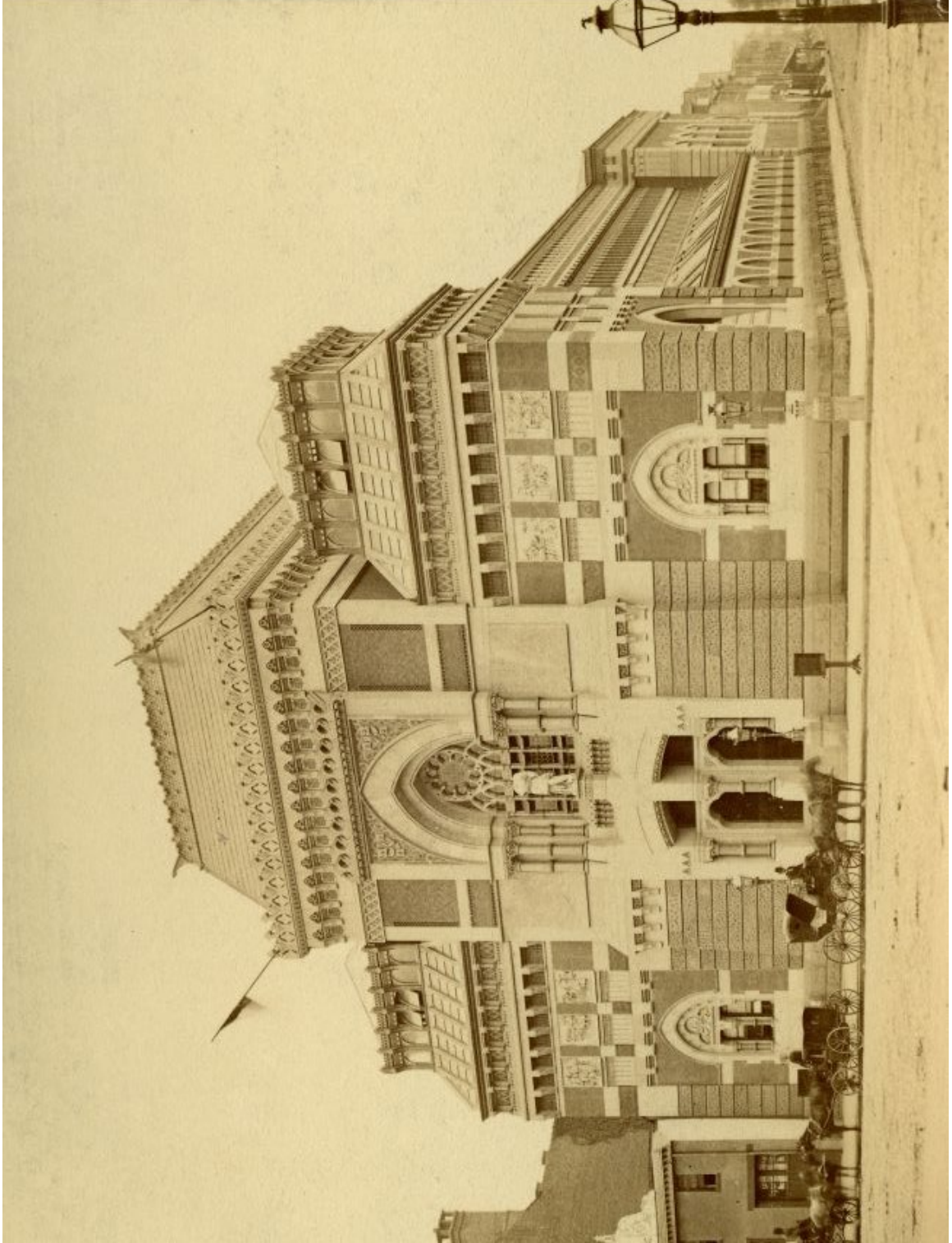
Figure 11 Pennsylvania Academy of the Fine Arts (Gutekunst, 1876)

Figure 12 Broad and Cherry Streets (City Archives, 1926)

Figure 13 Pennsylvania Academy of the Fine Arts (Pae, 2019)

Figure 14 Current Context of PAFA (Google map, 2019)

Figure 15 The Current Context of Pennsylvania Academy of the Fine Arts
(Institutes of Energy and the Environment in Penn State University, 2019)

48

Figure 16 Detail of the skylight structure (North side of the museum) (Harris Davis Photography 1973)

Figure 17 Detail of the skylight structure (North side of the museum) (Harris Davis Photography 1973)

Figure 18 Detail of the skylight structure (view of skylight frame from the gallery)
(Harris Davis Photography 1973)

Figure 19 Detail of the skylight structure above the gallery space (Harris Davis Photography 1973)

Figure 202 Detail of the skylight structure above the central hallway (Harris Davis Photography 1973)
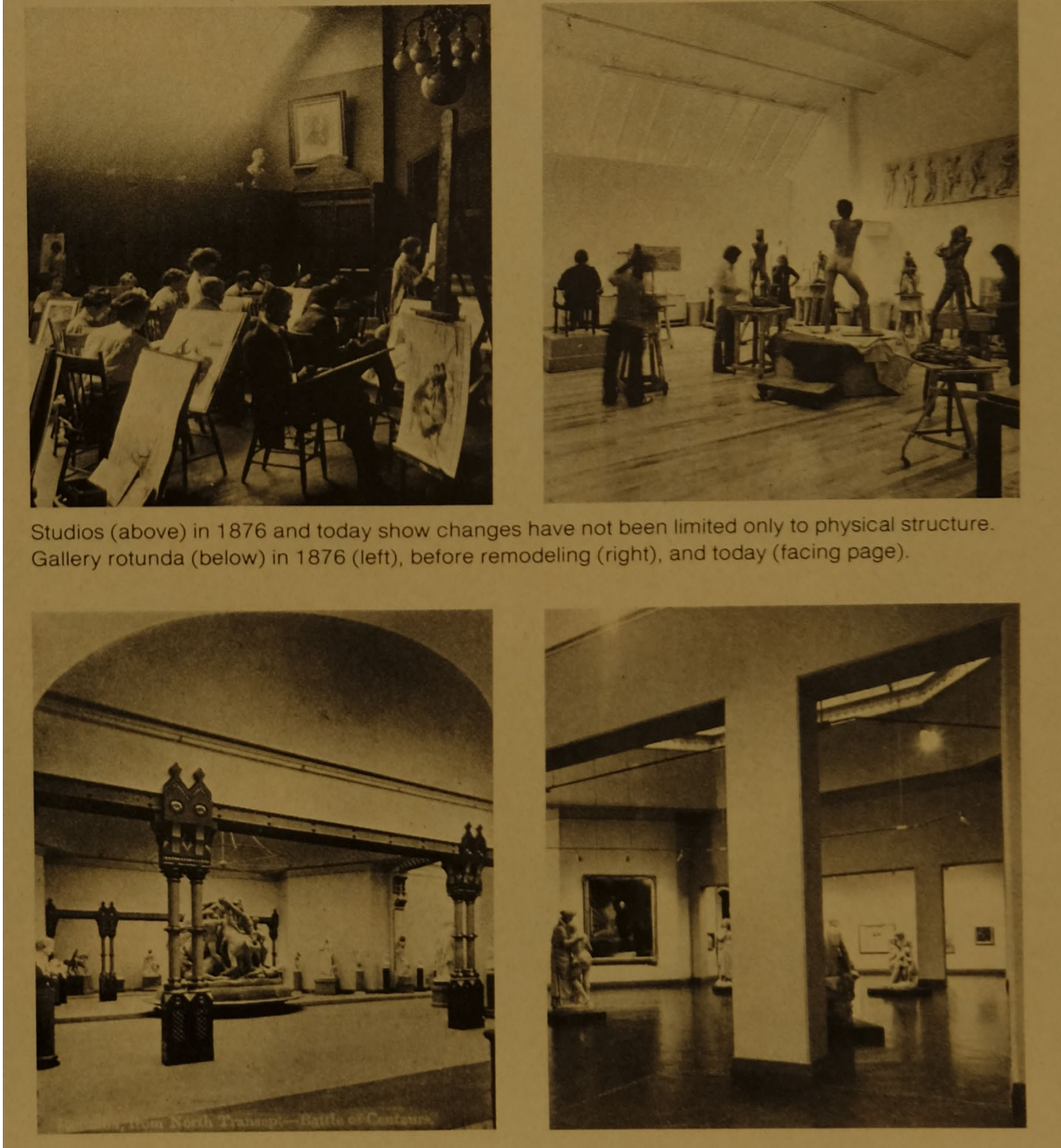
Studios (above) in 1876 and today show changes have not been limited only to physical structure. Gallery rotunda (below) in 1876 (left), before remodeling (right), and today (facing page).

Figure 21 Architectural Treasure Is Restored (Form & Function magazine, 1976)

Figure 22 1884 Ads for The Phoenix Iron Co. (historicbridges.org)

Figure 23 Benj. H. Shoemaker, Importer and Manufacturer of Window Glass, Bill of Sale in 1868 (Free Library of Philadelphia)

Figure 24 Ads for Thackara, Buck & Co. in 1876 (Ephemera collection, Historic New England)
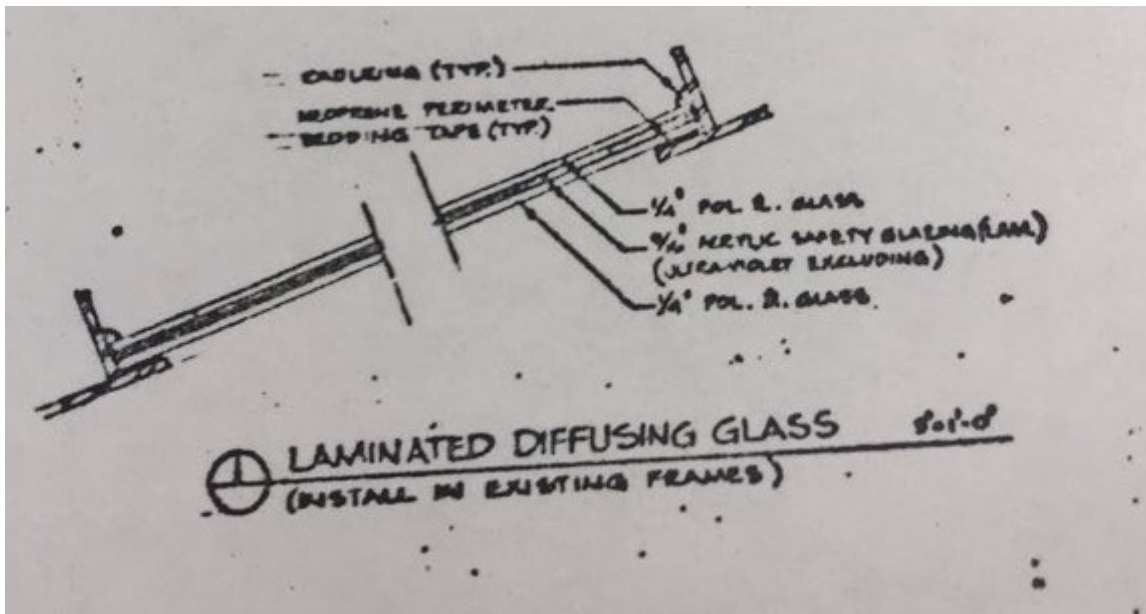
Figure 25 Detail description of Diffusing glass for the Skylight (PAFA Archive)

Figure 26 Gas jets on the Hallway (Gutekunst, 1876)
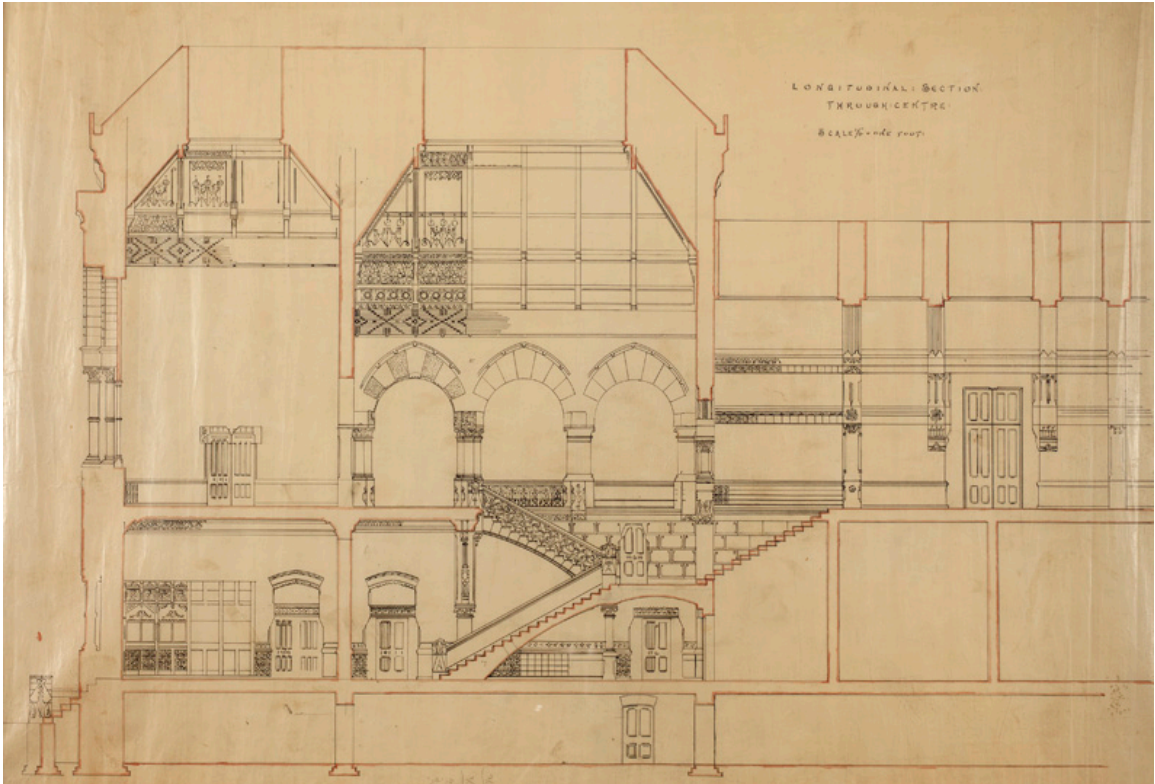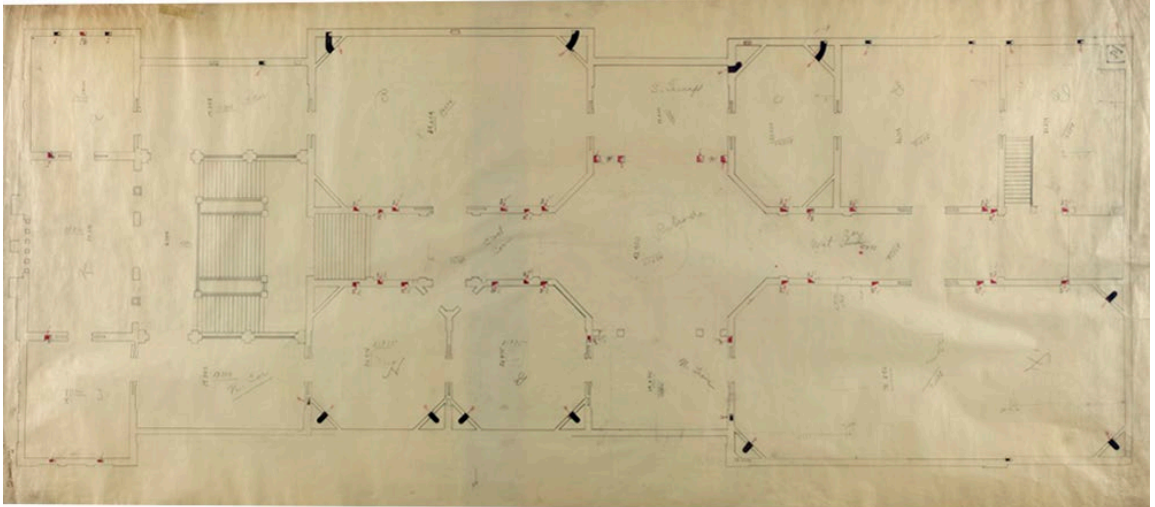
Figure 27 Historic W-E Section Drawing (PAFA Archive)
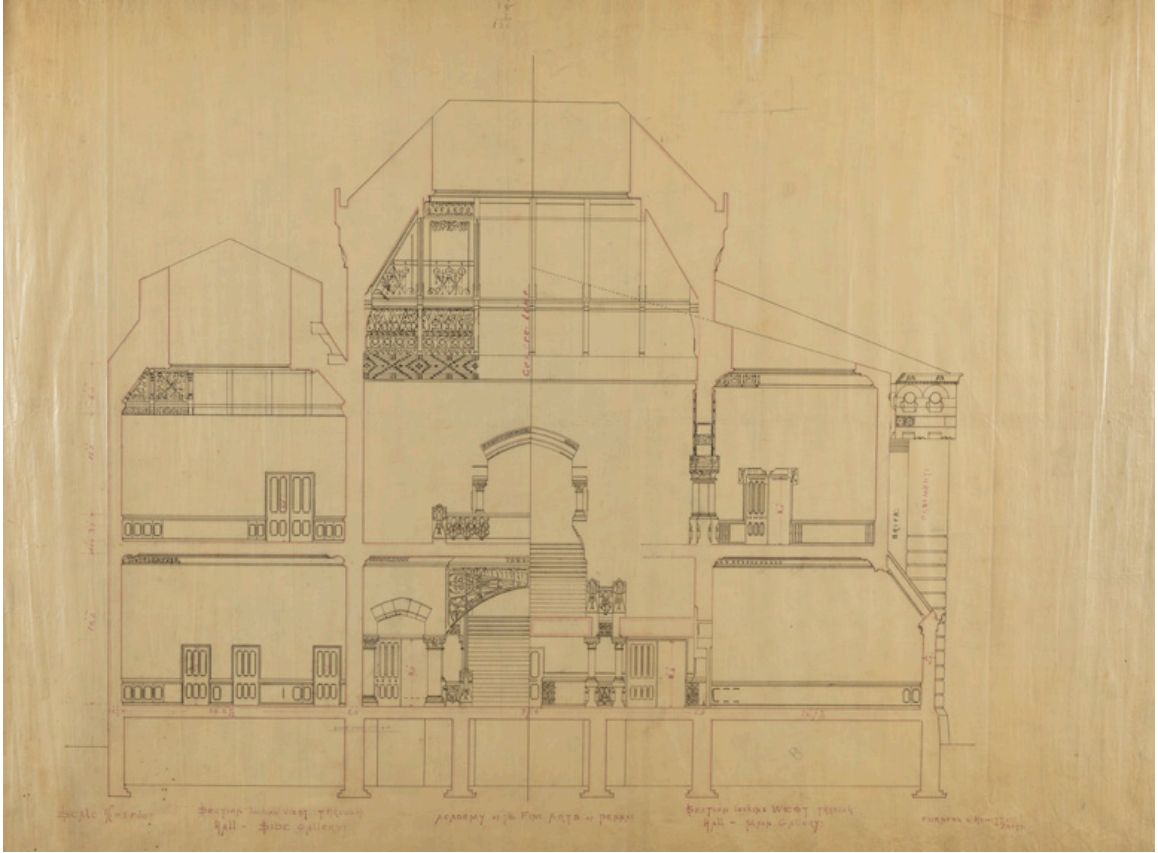

Figure 28 Historic Plan Drawing (PAFA Archive)

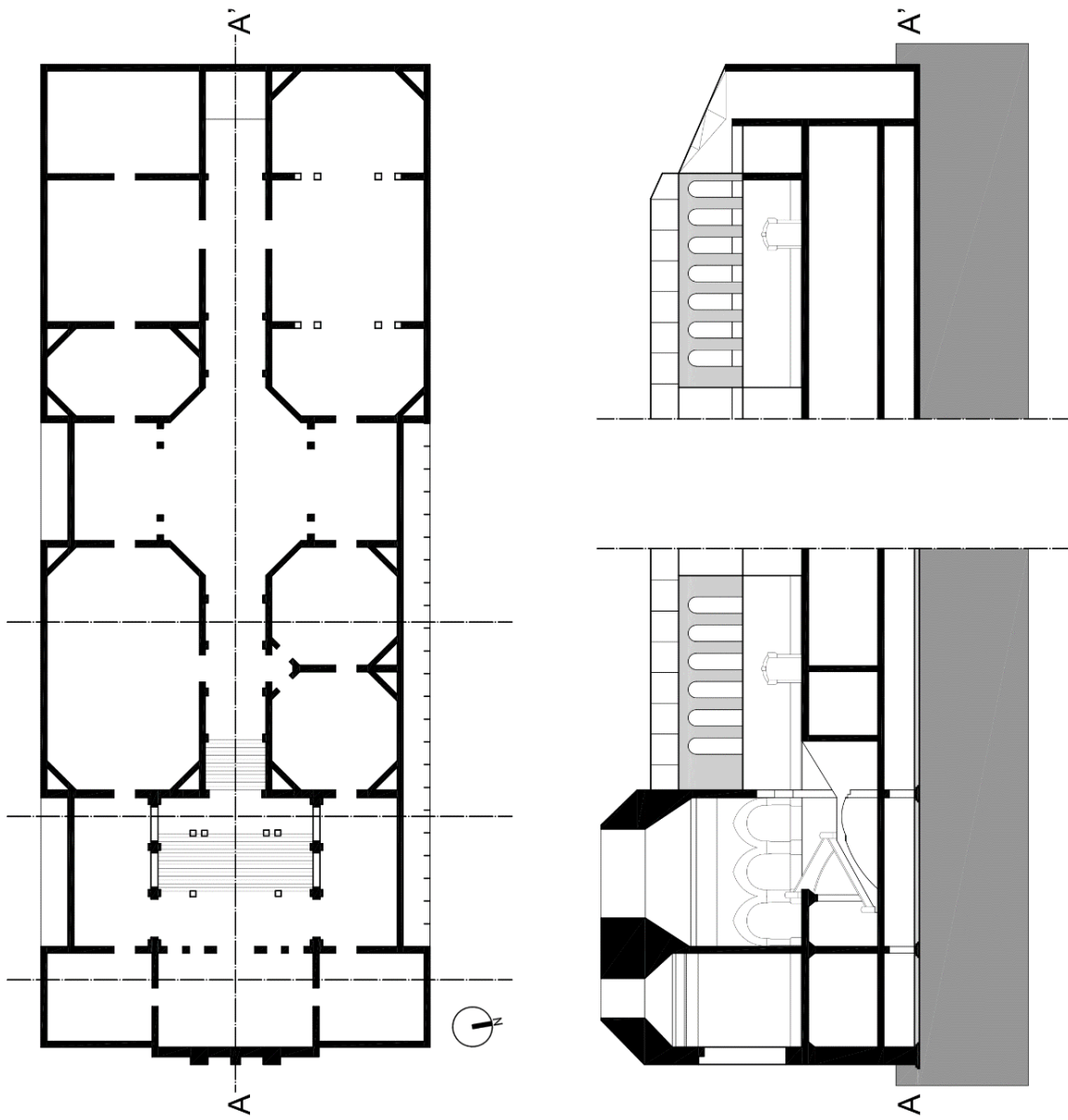Figure 29 Historic N-S Section Drawing (PAFA Archive)
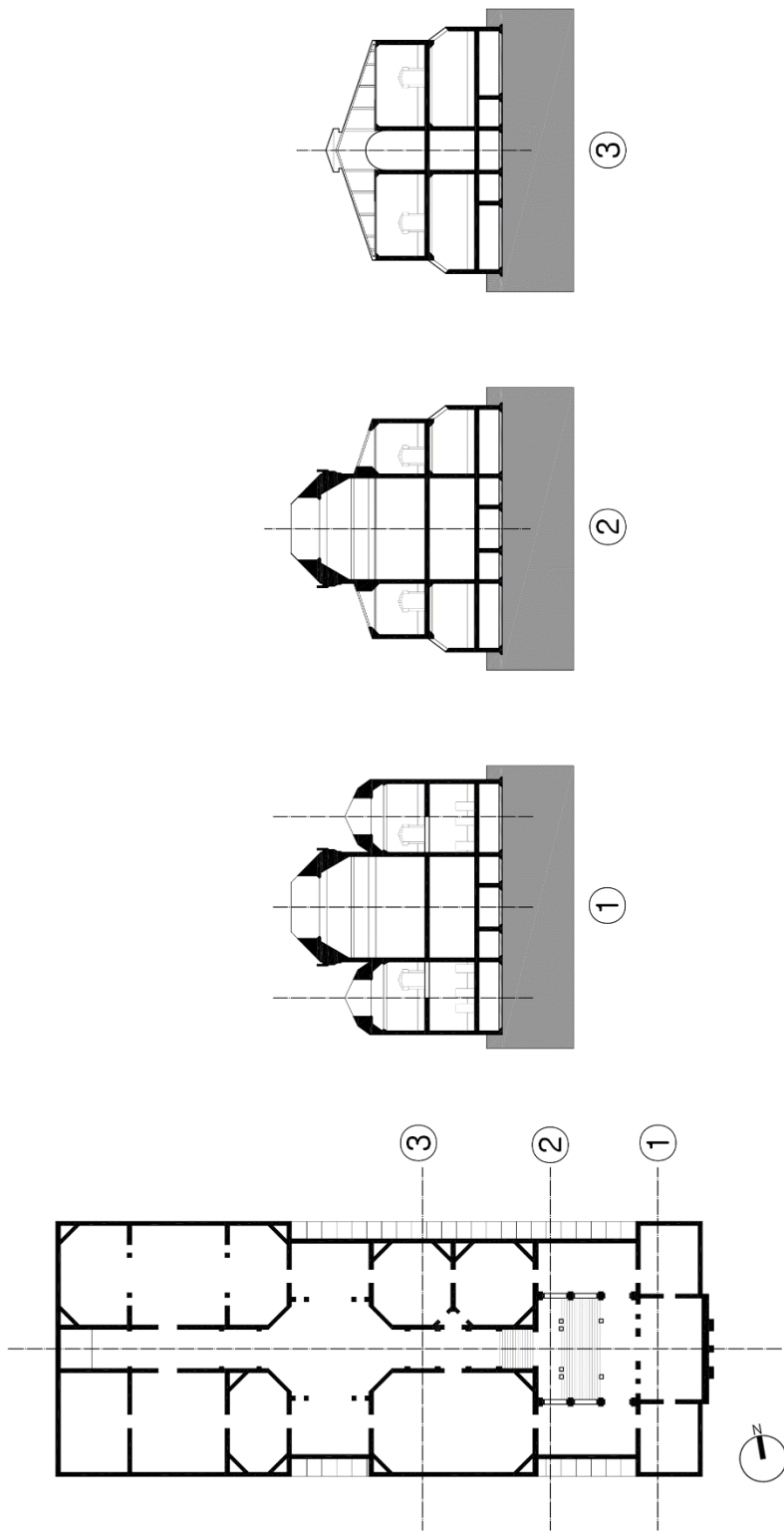
Figure 30 W-E Section (Pae,2019)
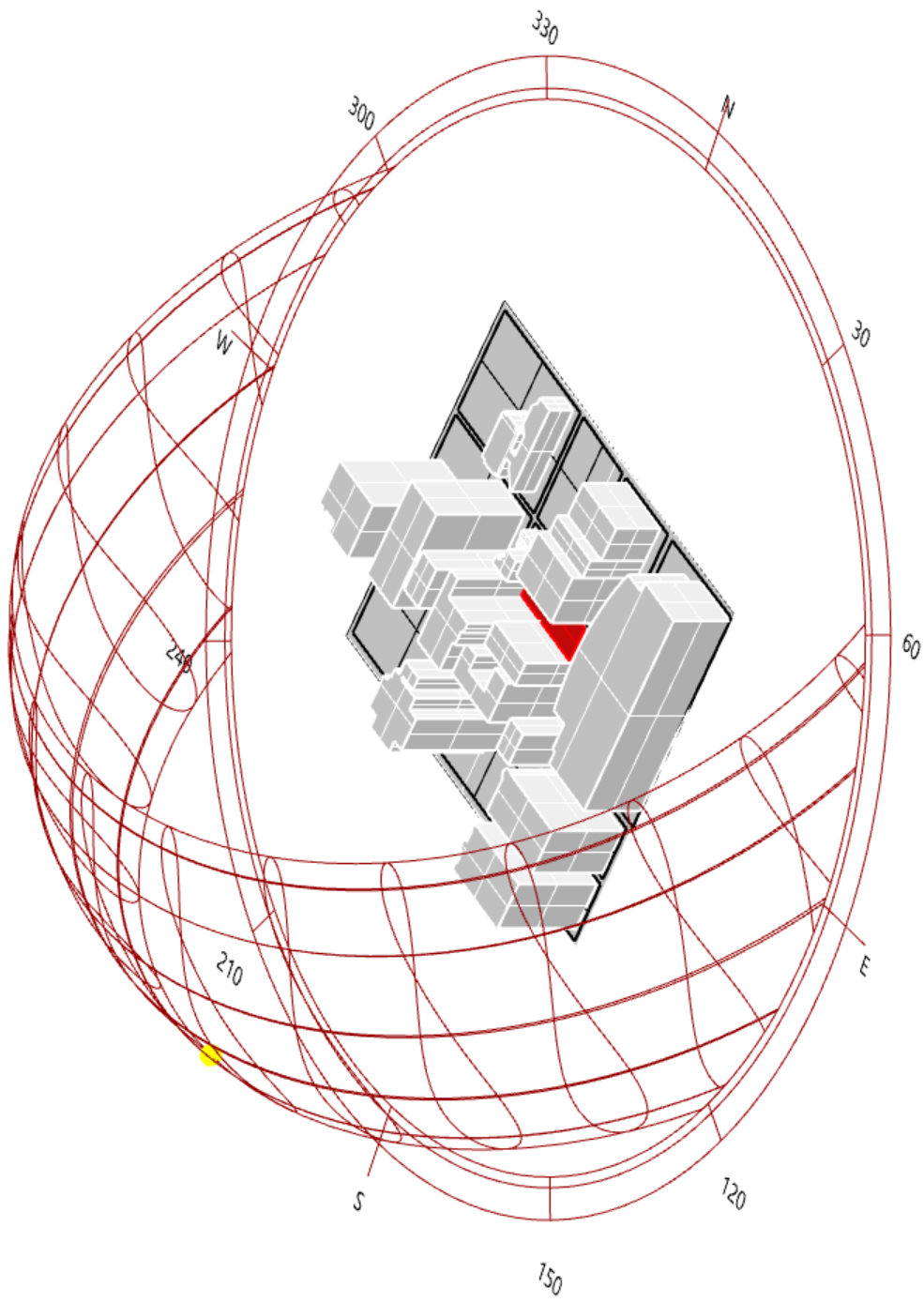
Figure 31 N-S Sections (Pae, 2019)

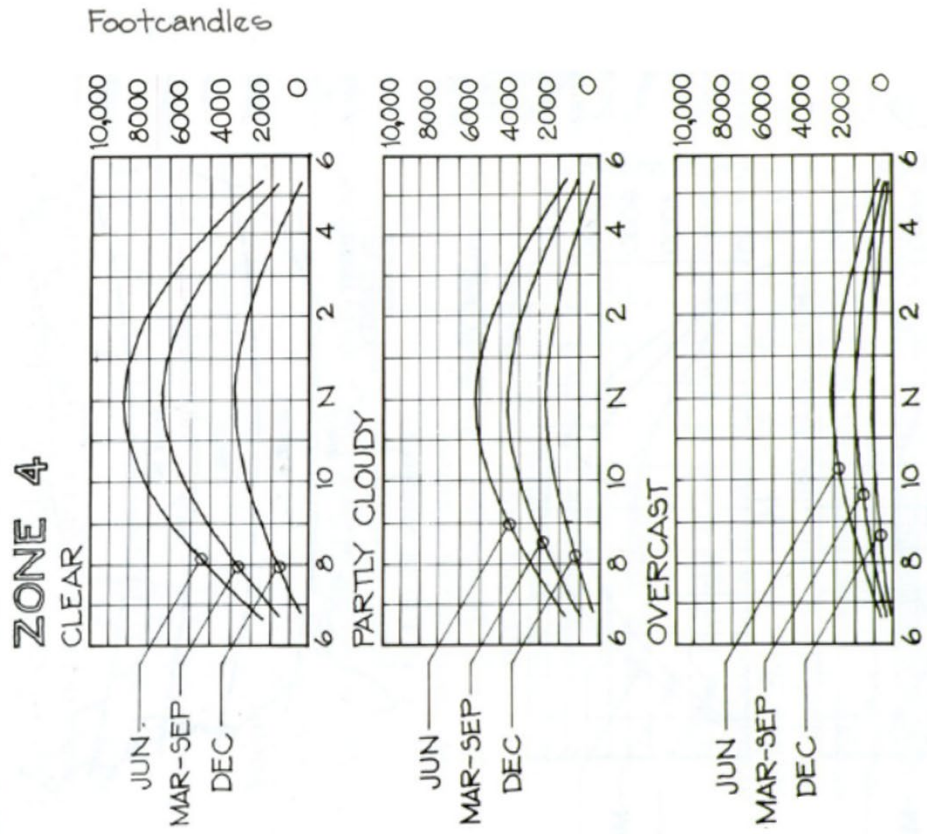Figure 32 Context Modeling; PAFA in red (Pae, 2019)

Figure 33 Light Intensity Zones in US & Yearly Light Intensity in Philadelphia
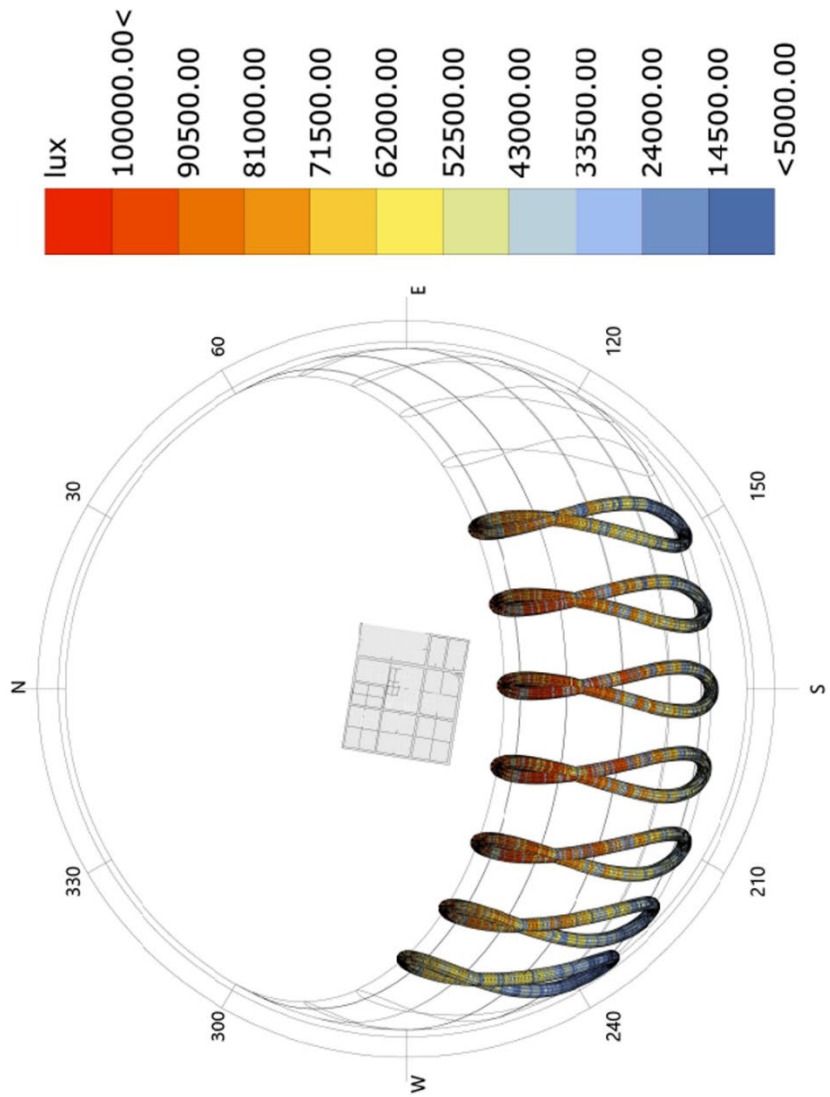(Architect's Handbook of Energy Practice- Daylighting)

Figure 34 Sun path and Global Illuminance in Philadelphia (Yearly) (Pae, 2019)
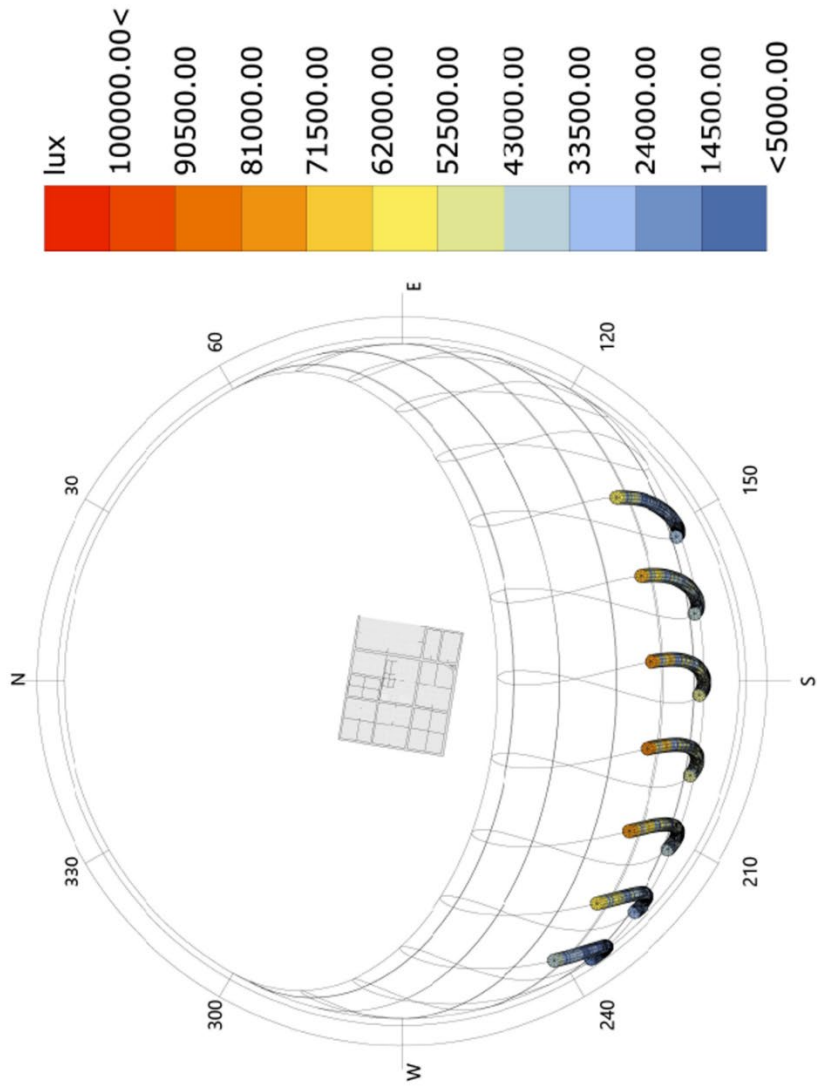
Figure 35 Sun path and Global Illuminance in Philadelphia (Dec to Feb) (Pae, 2019)

65
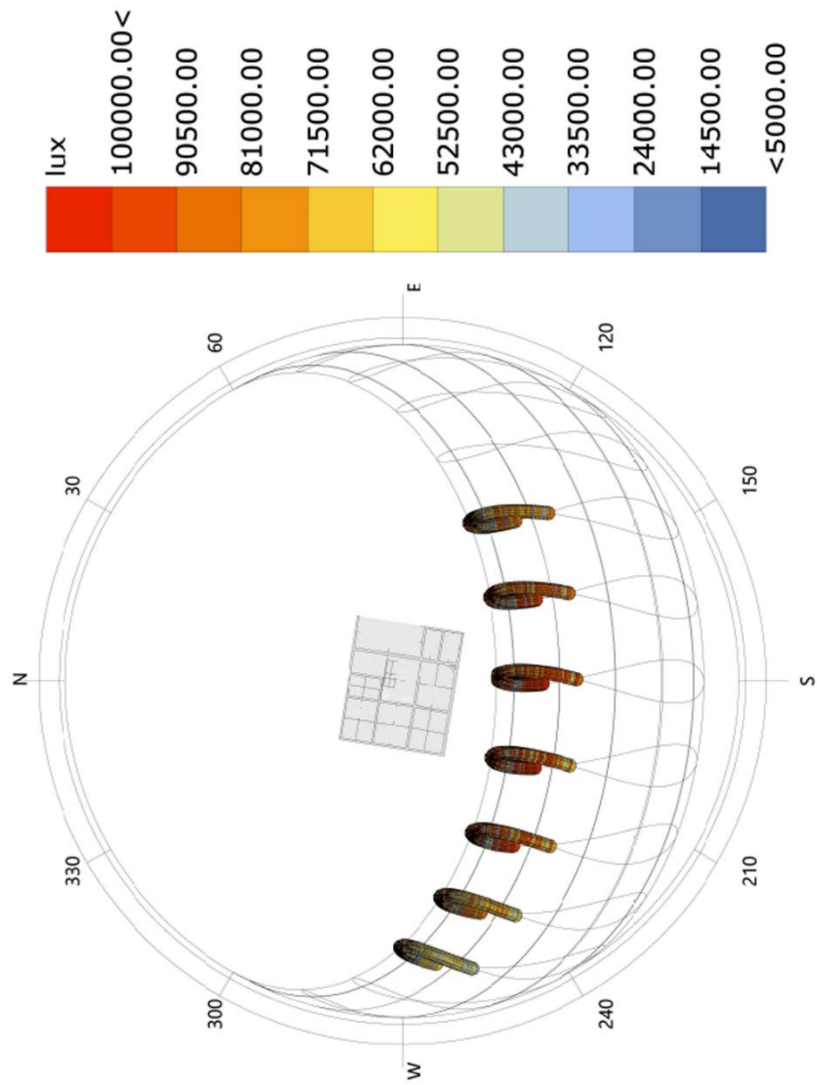
Figure 36 Sun path and Global Illuminance in Philadelphia (May to Aug) (Pae, 2019)
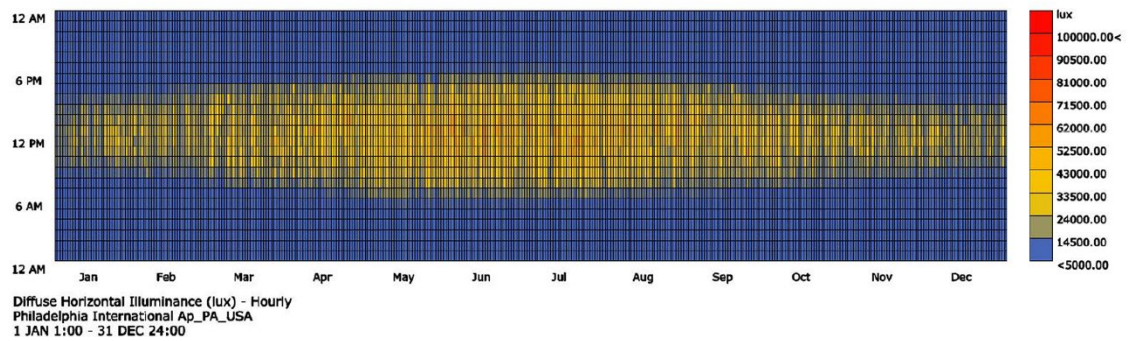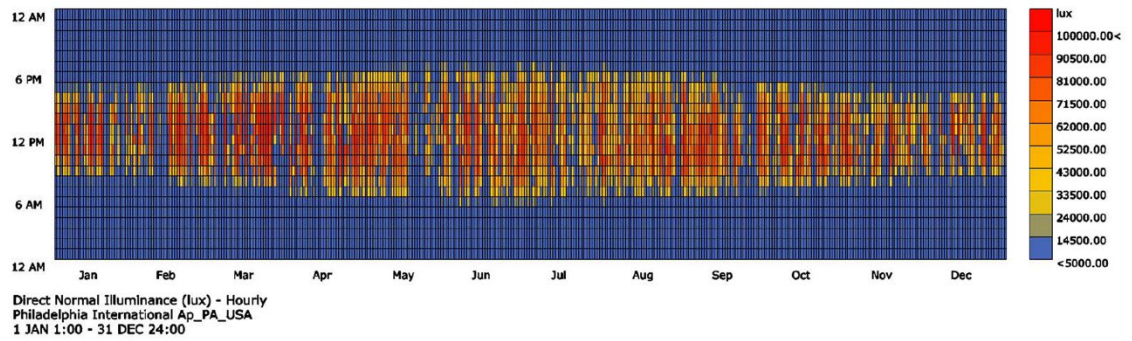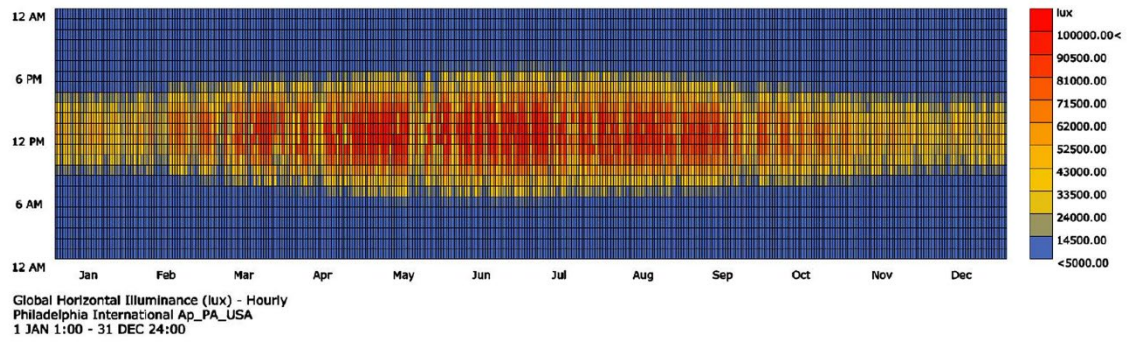
Figure 37 Yearly Illuminance Data in Philadelphia (Pae, 2019)

67

JAN 15, 10AM

JAN 15, 11AM

JAN 15, 12PM

JAN 15, 1PM

JAN 15, 2PM

JAN 15, 3PM

JAN 15, 4PM

NO SUNLIGHT
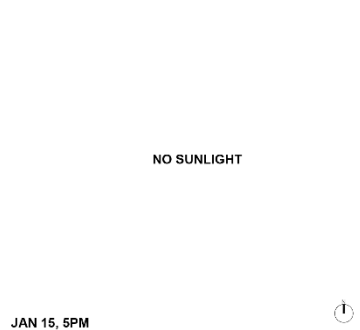
JAN 15, 5PM

Figure 38 Shade Simulation (Jan 15) (Pae, 2019)

68

JUN 15, 10AM

JUN 15, 11AM

JUN 15, 12PM
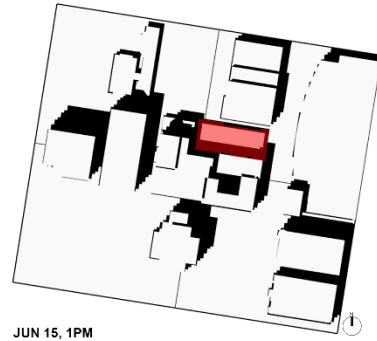
JUN 15, 1PM
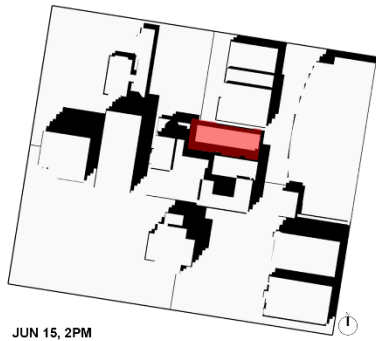
JUN 15, 2PM

JUN 15, 3PM

JUN 15, 4PM

JUN 15, 5PM

Figure 39 Shade Simulation (Jun 15) (Pae, 2019)
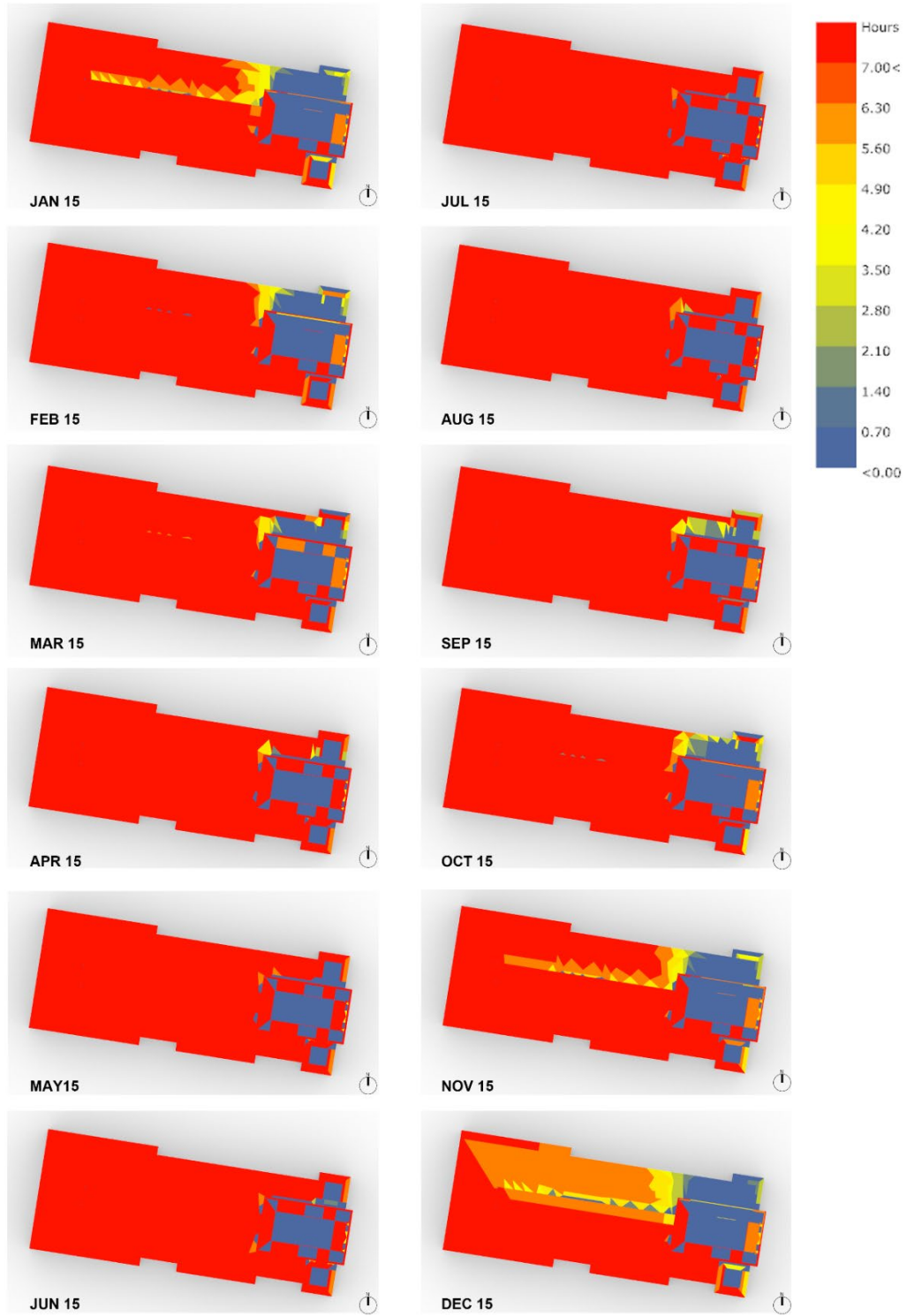
Sunlight Hours Analysis (10AM-5PM) in 1876

Figure 40 Sunlight Hours Analysis in 1876 (Pae, 2019)

70

Figure 41 Sunlight Hours Analysis in 2019 (Pae, 2019)
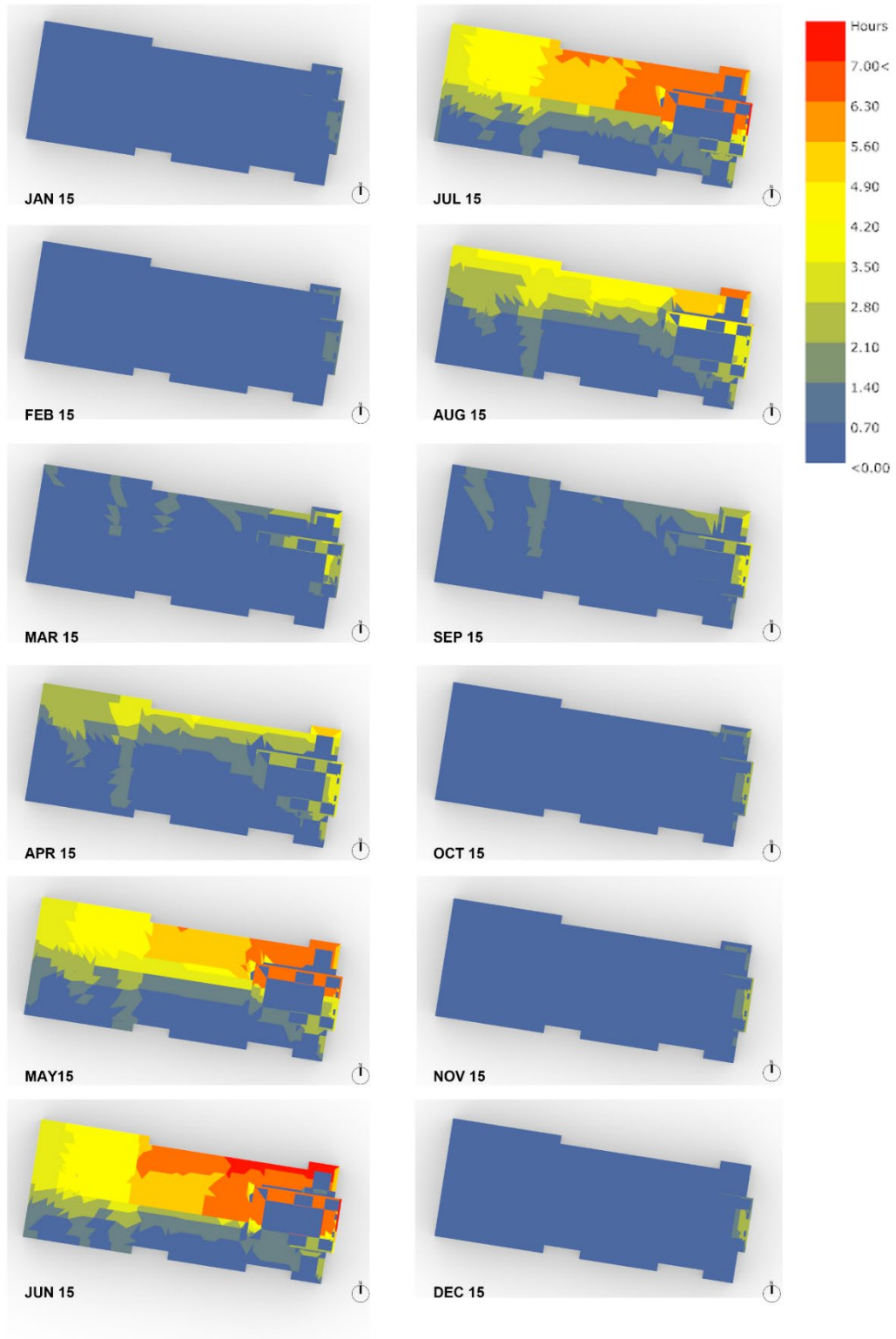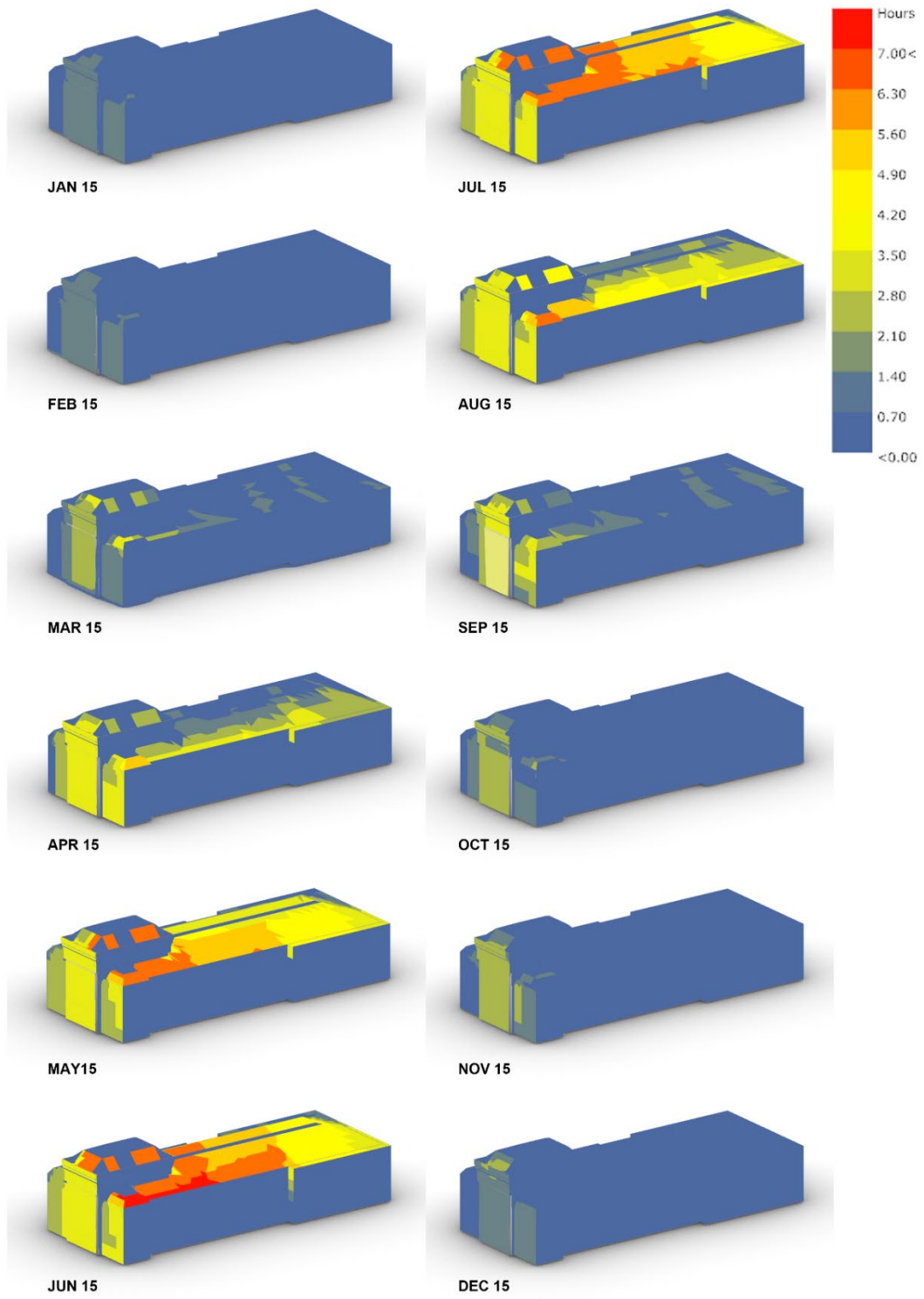
Sunlight Hours Analysis (10AM-5PM) in 2019

Figure 42 Sunlight Hours Analysis in 2019 (Perspective view) (Pae, 2019)

72

Figure 43 Shutters on the skylights on each gallery (Pae, 2019)
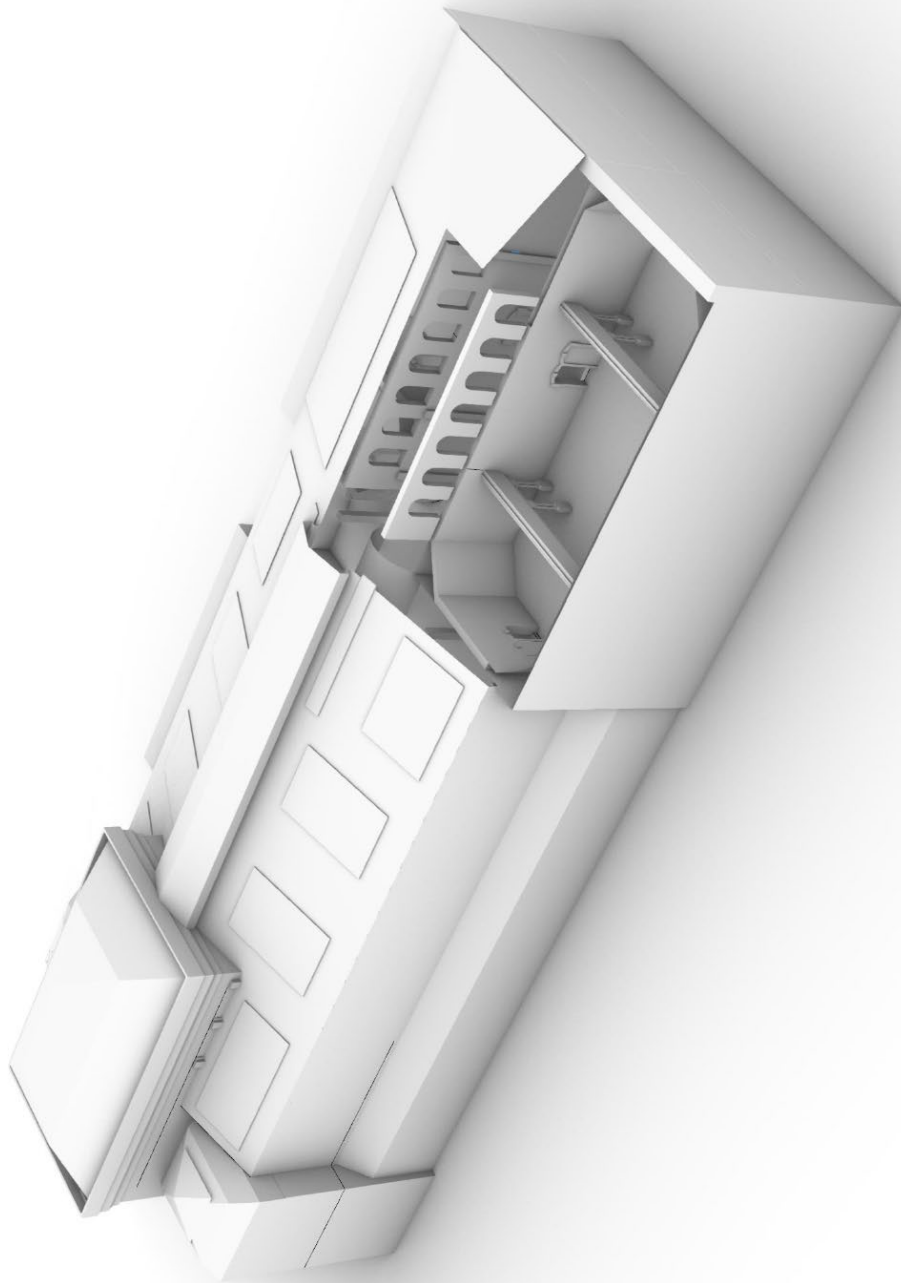
Figure 44 3D modeling of PAFA (Pae, 2019)

Central Rooflight

Side Rooflight and Roof

Attic (Masonry Arch)

Ceiling and Skylight

Gallery Interior
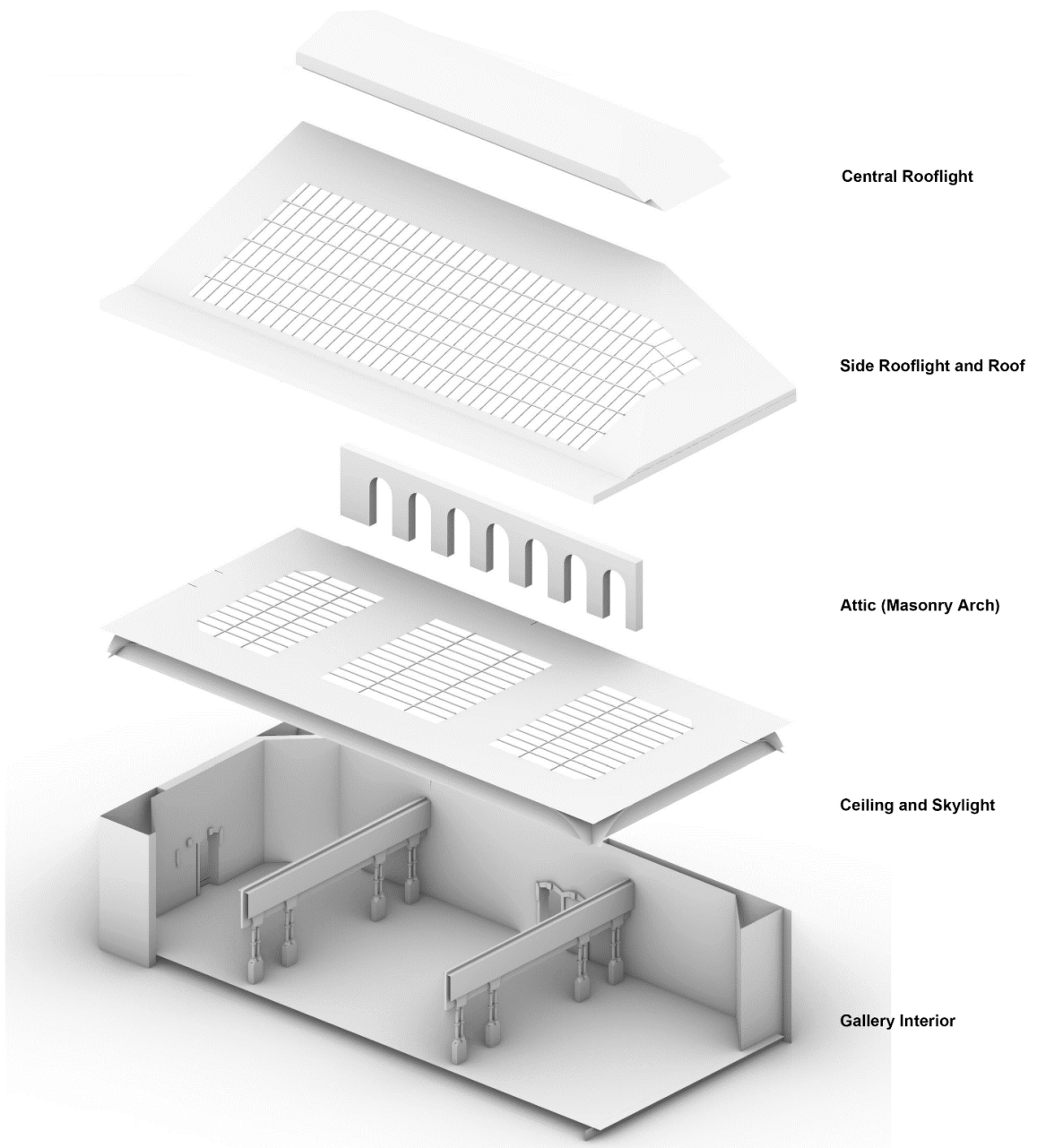
Figure 45 Structure diagram of the gallery (Pae, 2019)
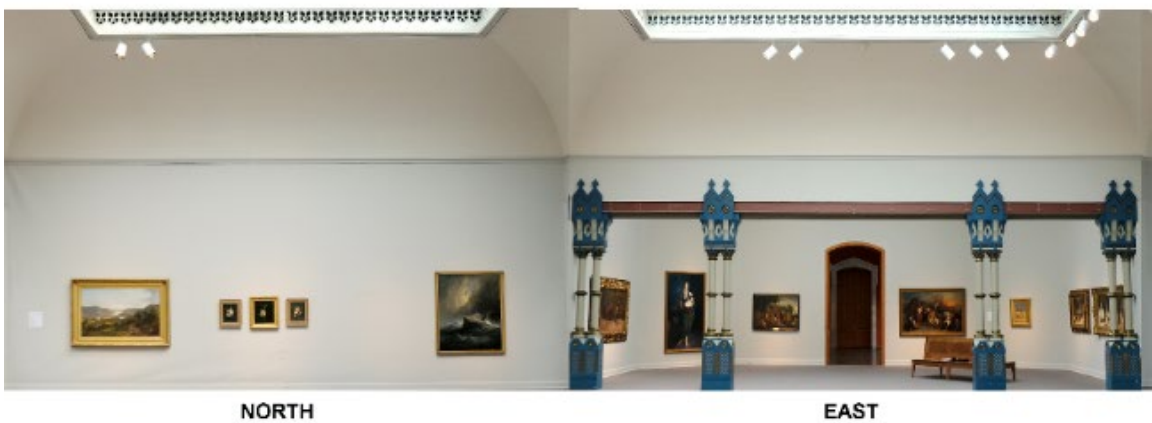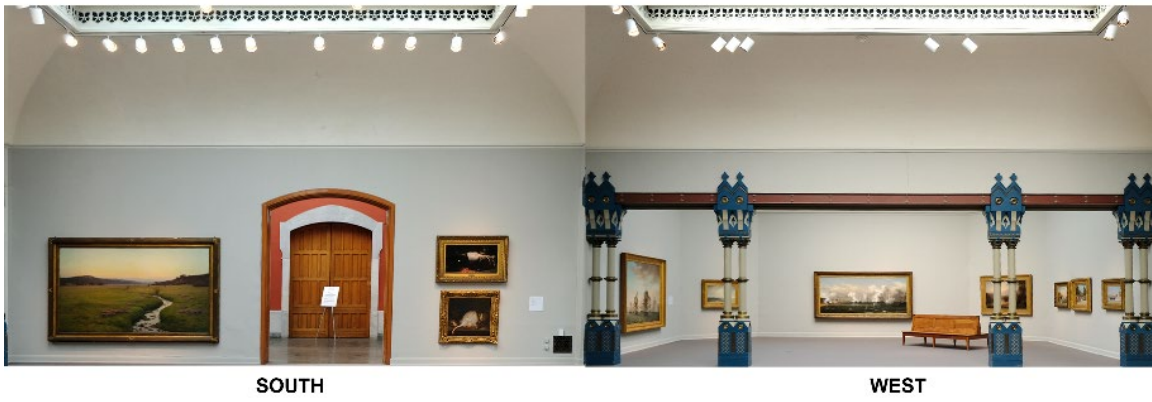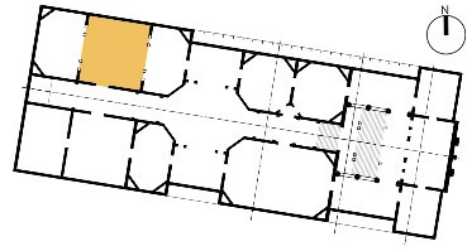
Figure 46 Rectified photograph of the gallery 10 (Pae, 2019)

WALL   FLOOR   COLUMNS
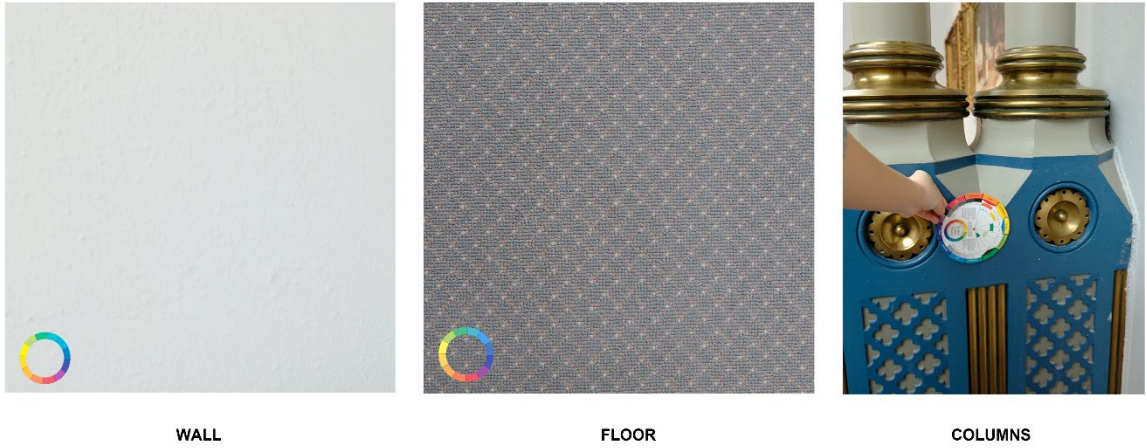
Figure 47 Detailed photo with color reference card (Pae, 2019)

Figure 48 Photo of the skylight and spotlights on the gallery 10 (Pae, 2019)
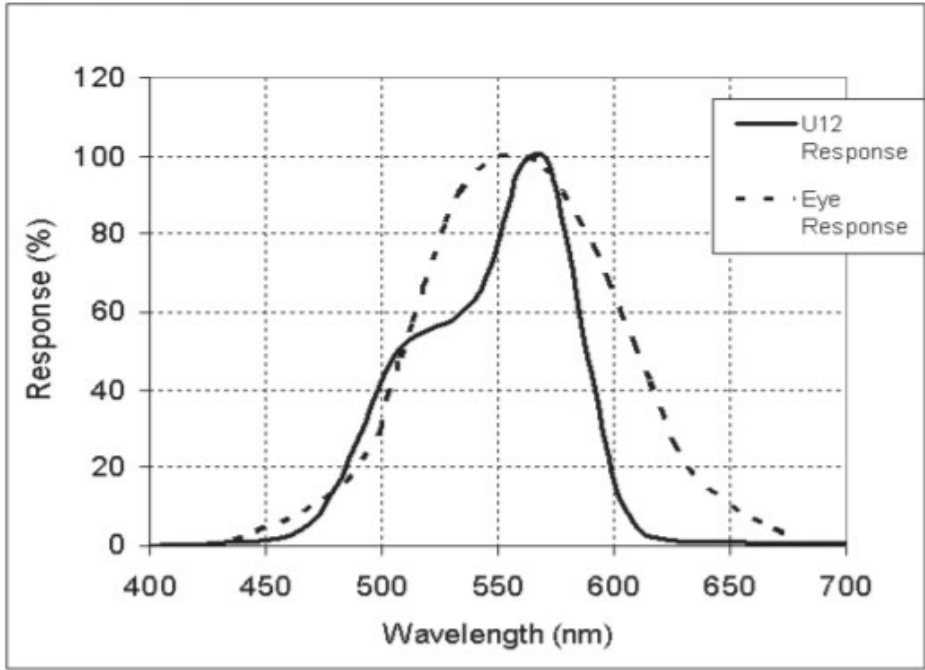
Figure 49 Response ratio of the light meter by the wavelength (HOBO U12 Manual)
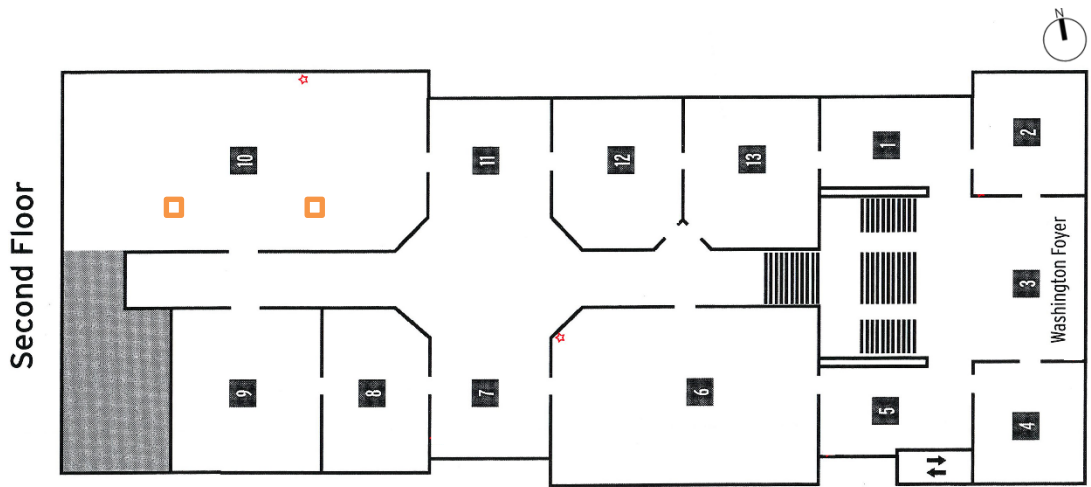
Figure 50 Installed location of the light loggers at gallery 10 (Pae, 2019)

Figure 51 Photos of the installed location of the light loggers at gallery 10 (Pae, 2019)
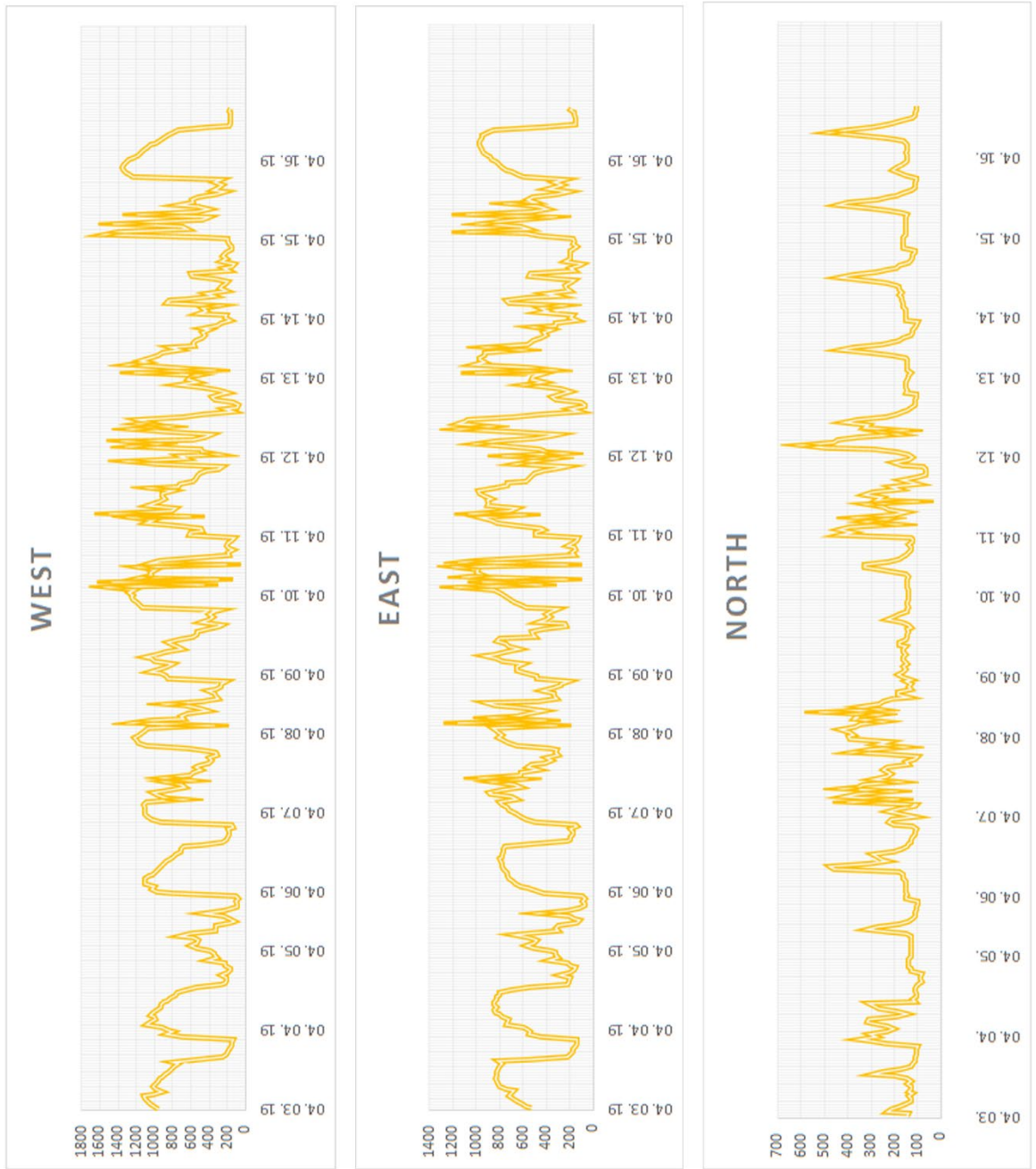
Figure 52 Illuminance data graph from Apr 3rd to Apr16th (Pae, 2019)
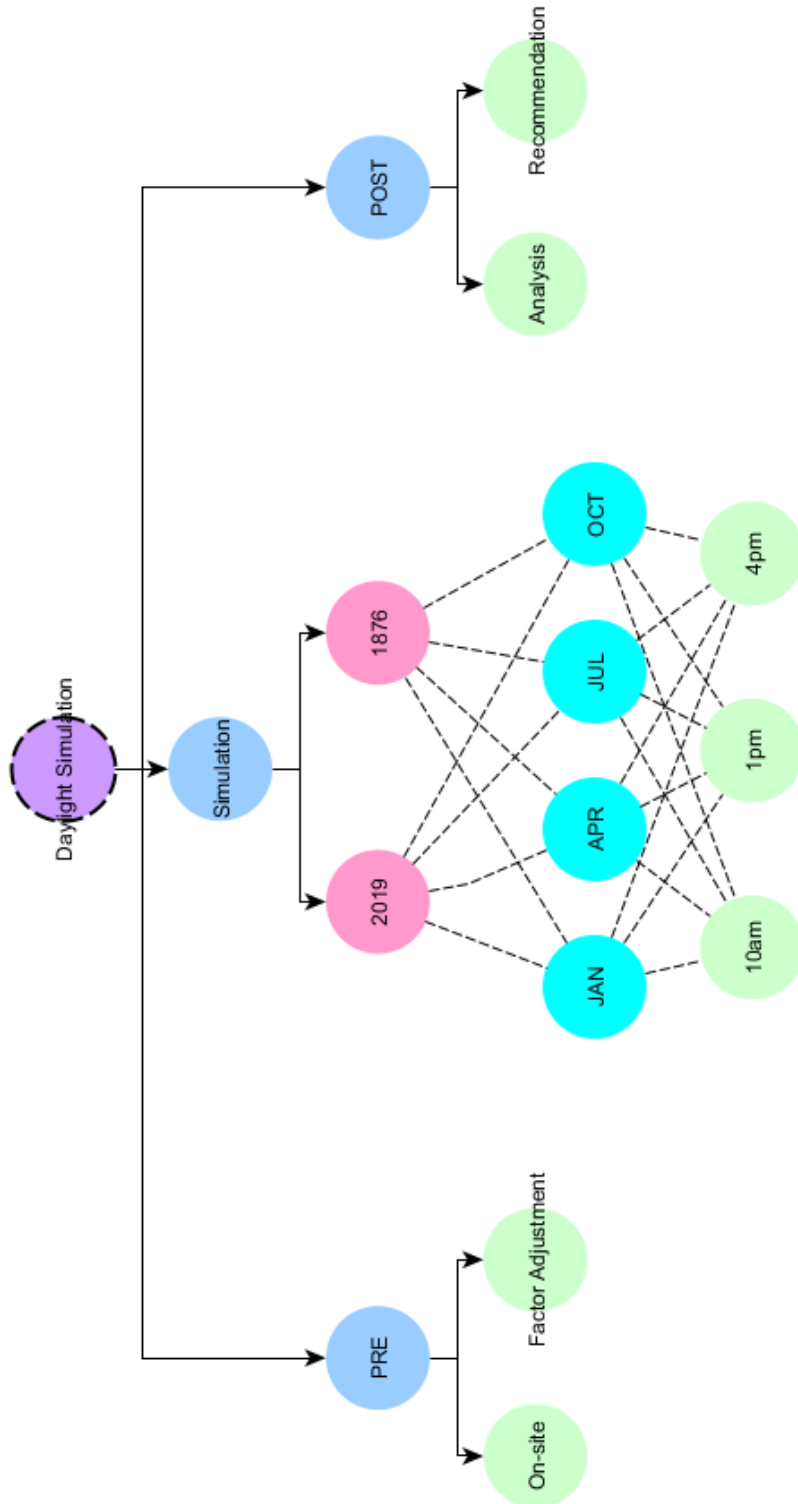
Figure 53 Methodology Diagram (Pae, 2019)

JAN 15, 10AM

JAN 15, 1PM

2019 CONTEXT

JAN 15, 4PM
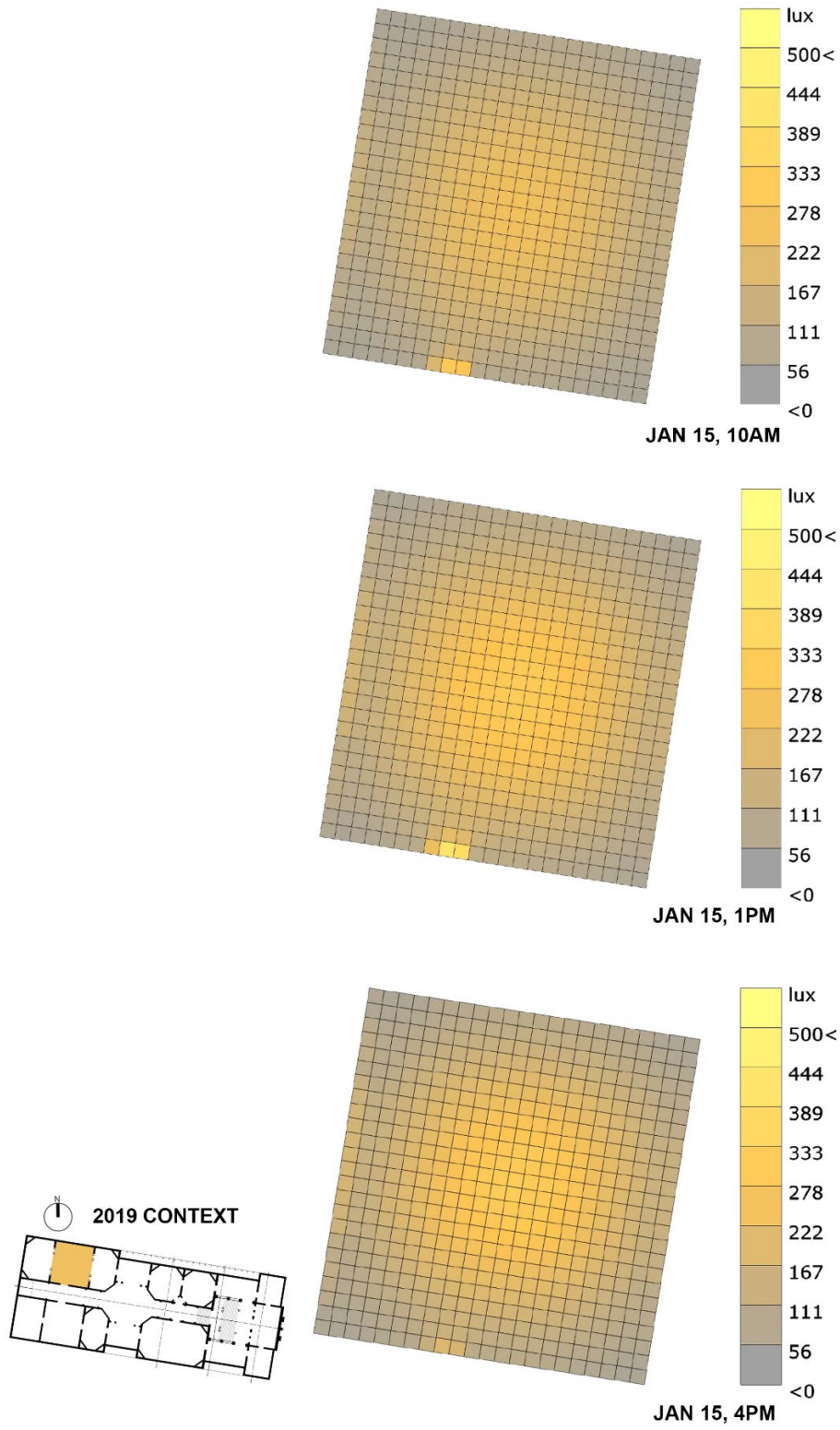
Figure 54 Current illuminance simulation results on Jan 15th (Pae, 2019)
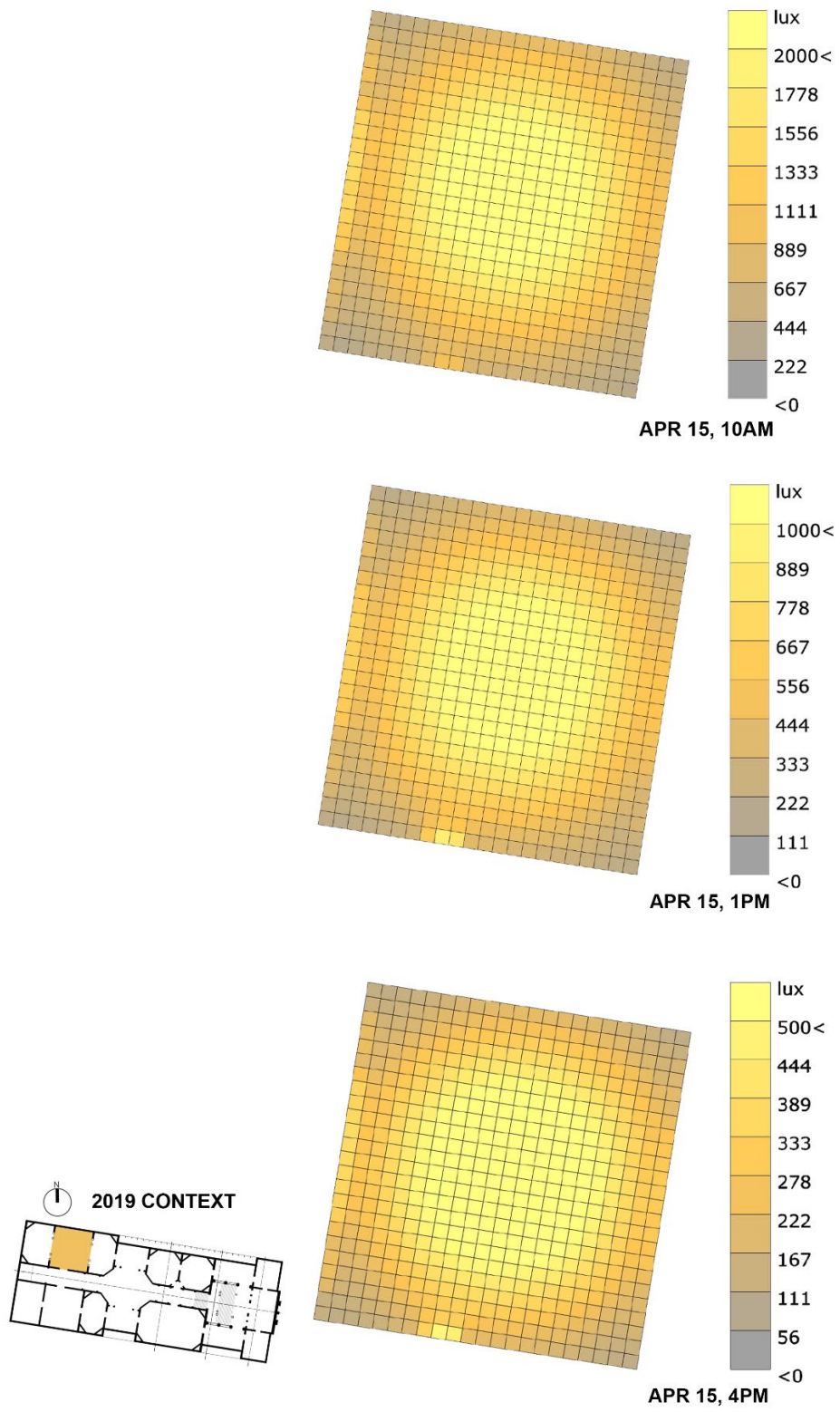
Figure 55 Current illuminance simulation results on Apr 15th (Pae, 2019)

lux
2000<
1778
1556
1333
1111
889
667
444
222
<0

JUL 15, 10AM

lux
5000<
4444
3889
3333
2778
2222
1667
1111
556
<0

JUL 15, 1PM

N **2019 CONTEXT**

lux
500<
444
389
333
278
222
167
111
56
<0

JUL 15, 4PM
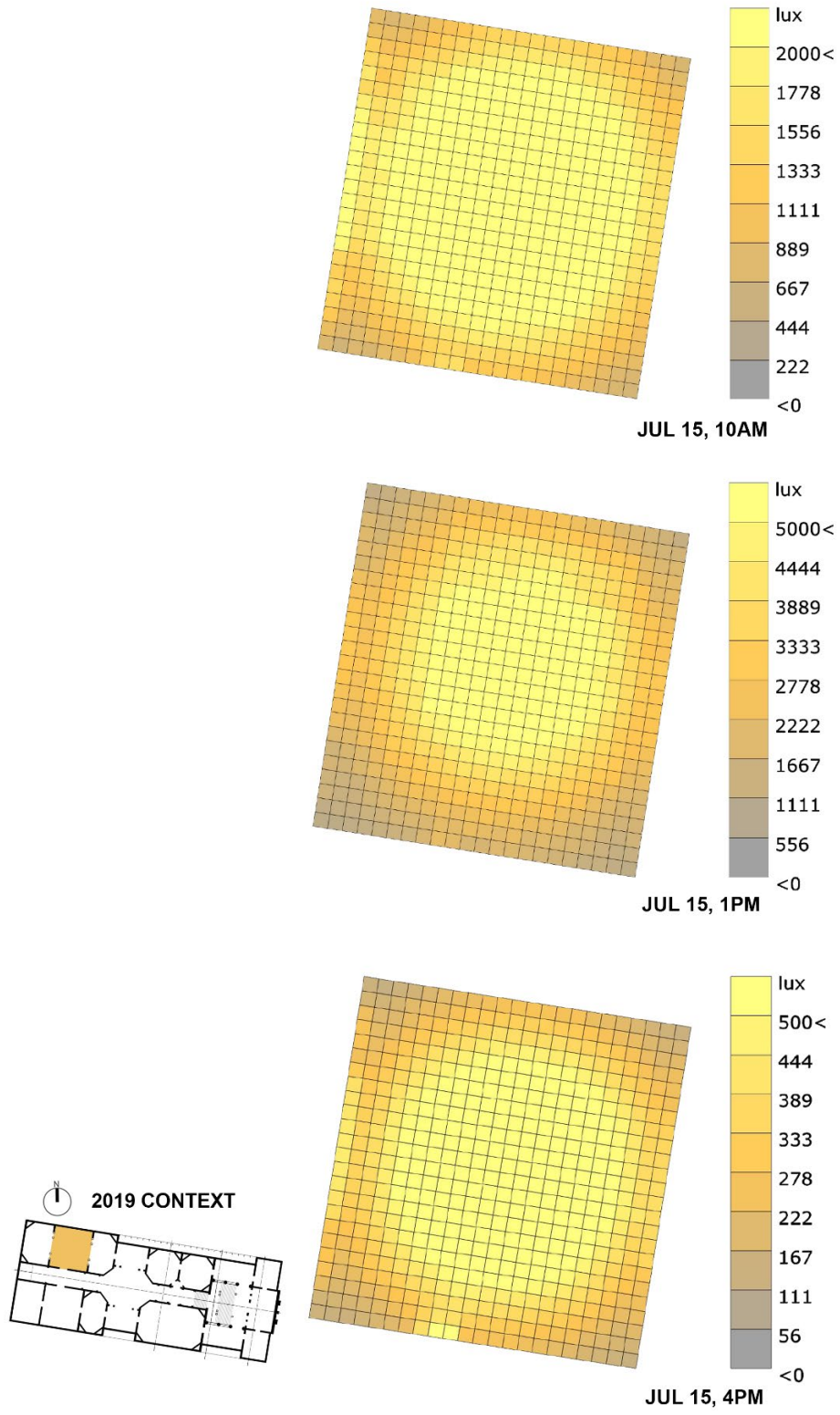
Figure 56 Current illuminance simulation results on Jul 15th (Pae, 2019)
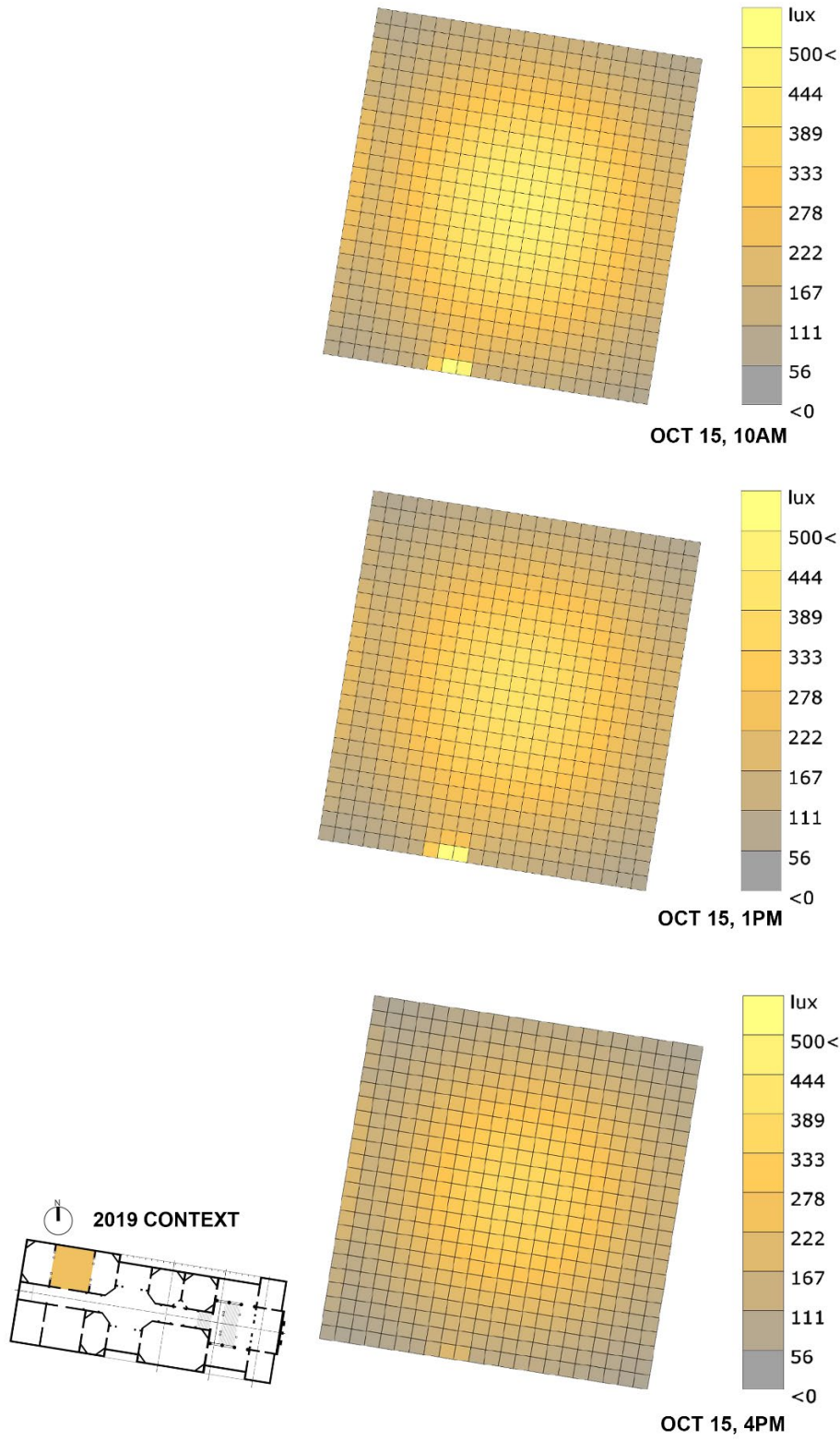
Figure 57 Current illuminance simulation results on Oct 15th (Pae, 2019)
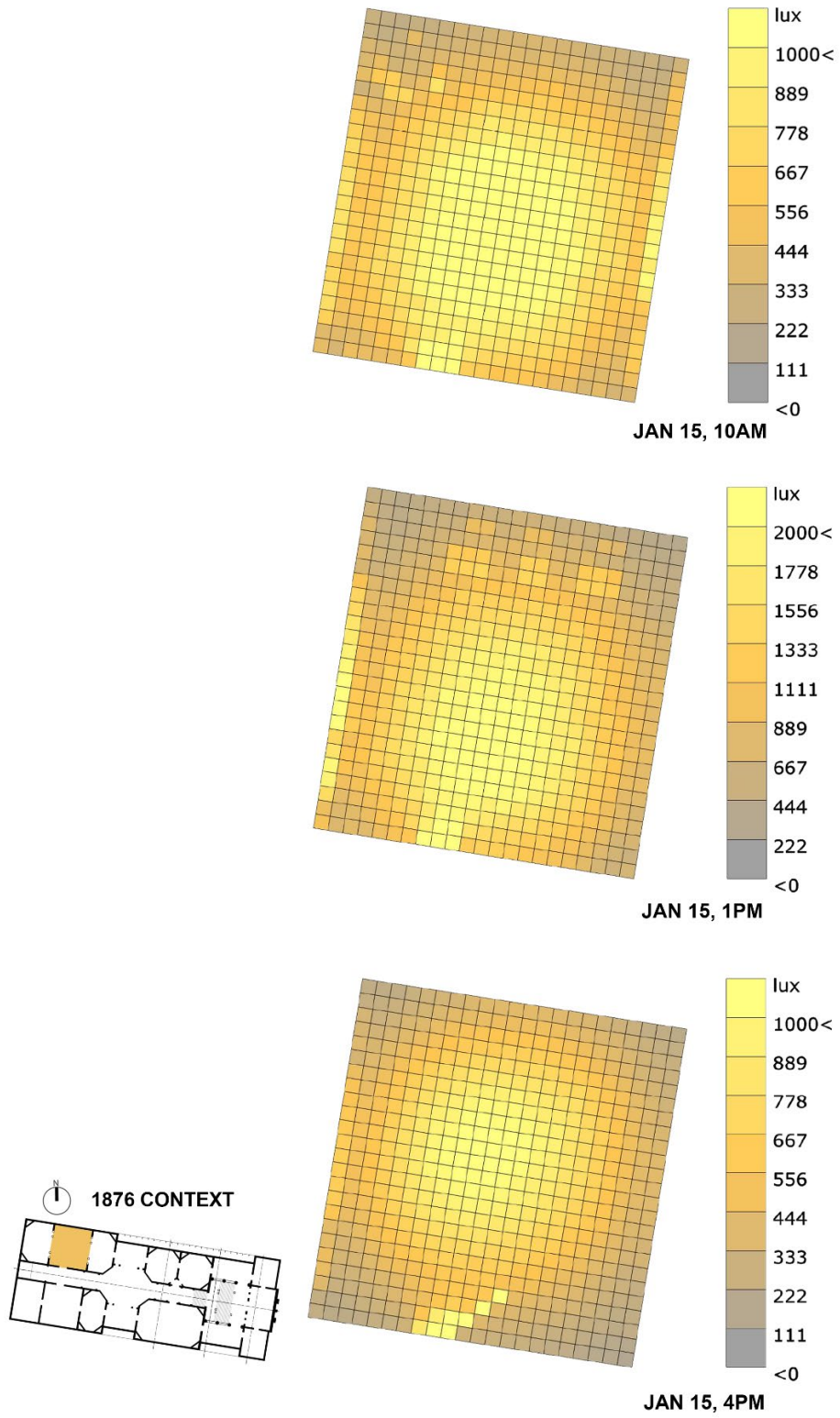
Figure 58 Historic illuminance simulation results on Jan 15th (Pae, 2019)
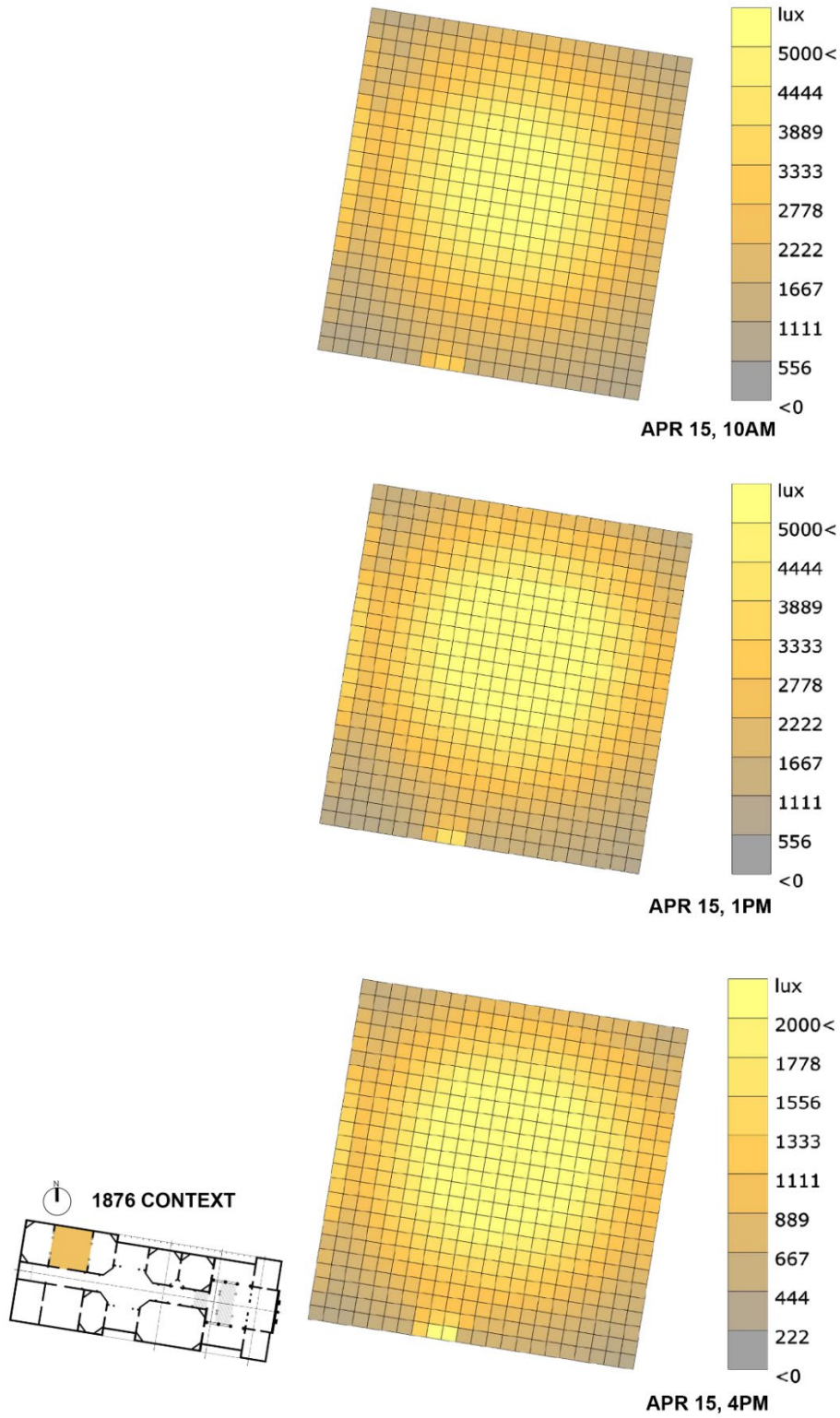
Figure 59 Historic illuminance simulation results on Apr 15th (Pae, 2019)
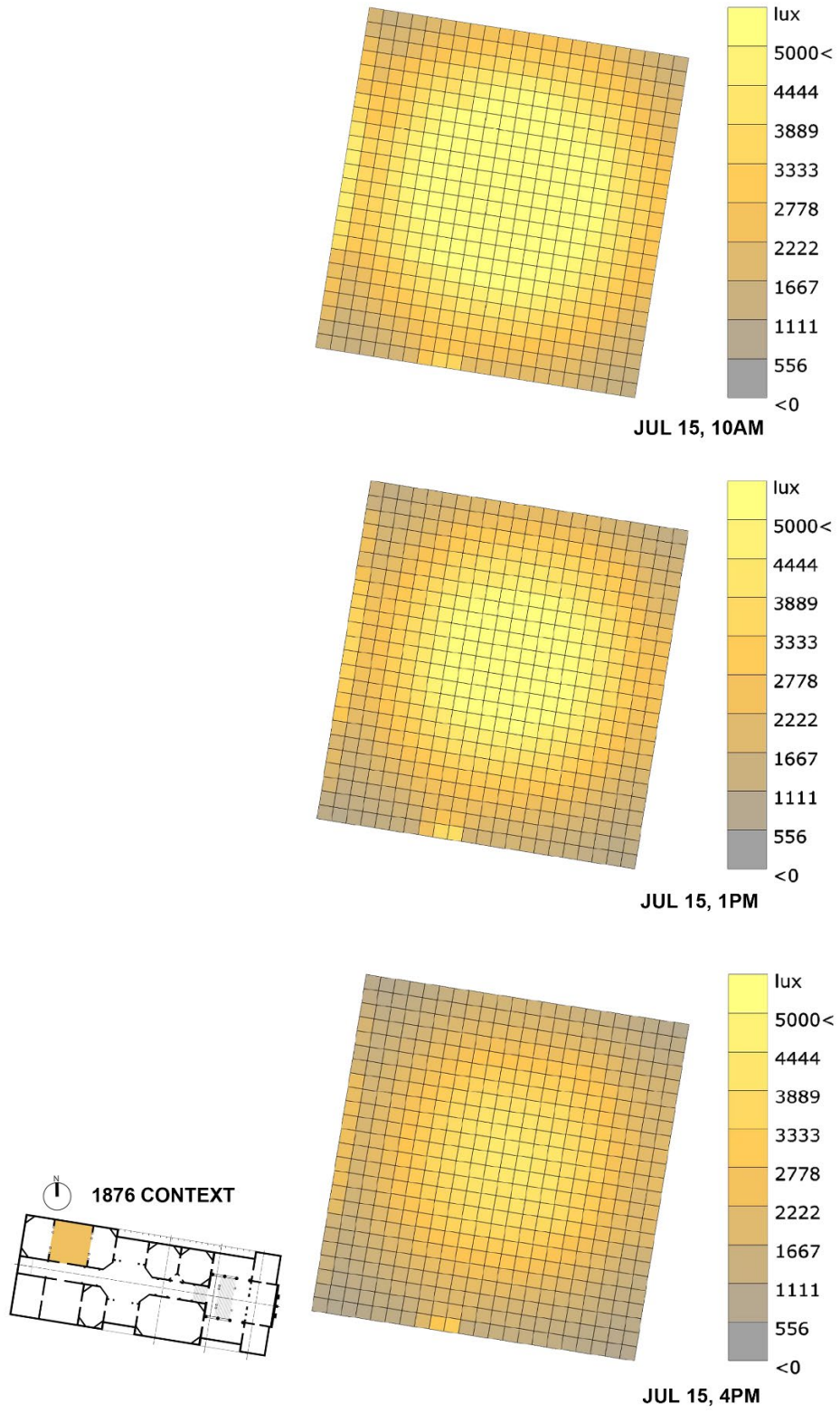
Figure 60 Historic illuminance simulation results on Jul 15th (Pae, 2019)

OCT 15, 10AM

OCT 15, 1PM

1876 CONTEXT

OCT 15, 4PM
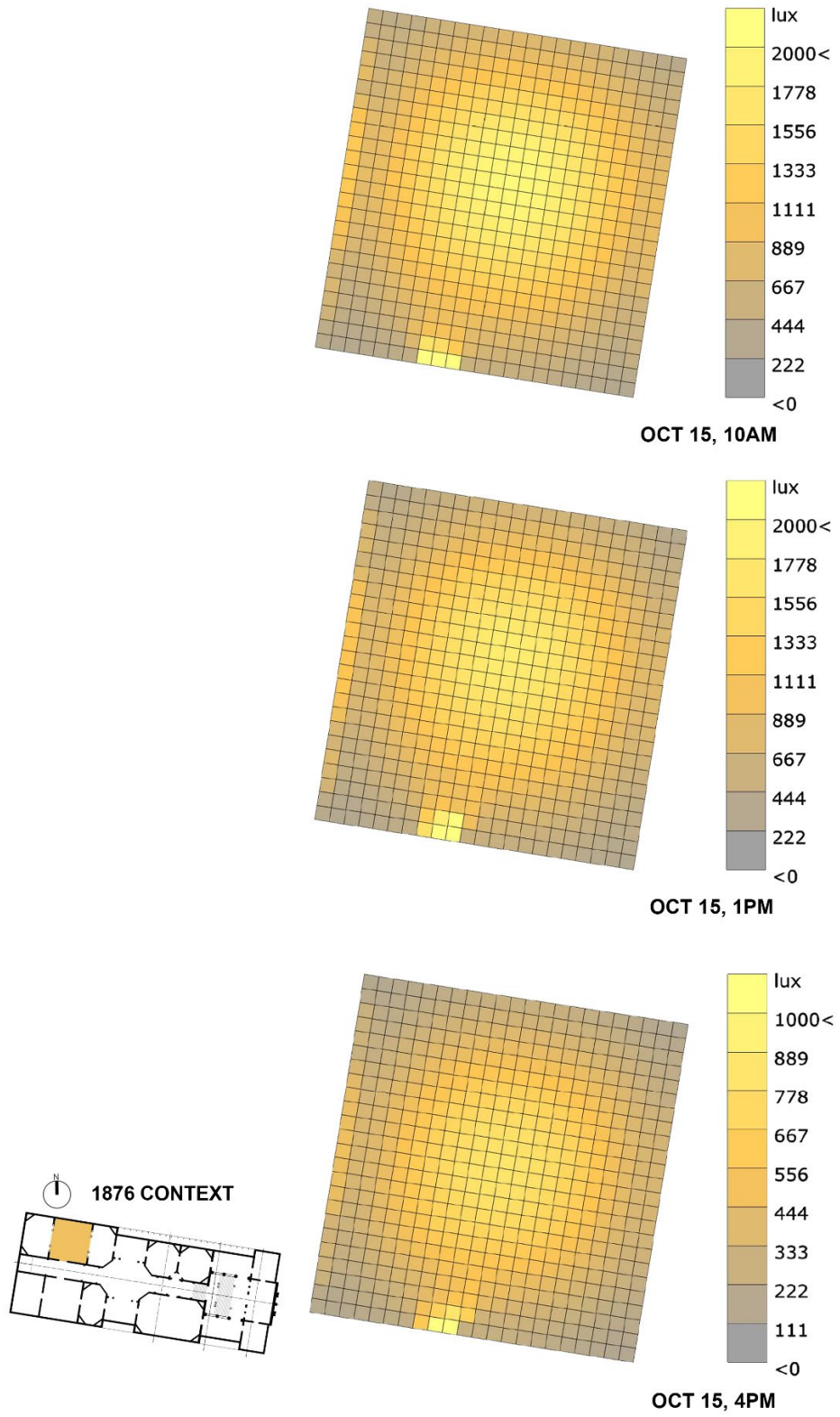
Figure 61 Historic illuminance simulation results on Oct 15th (Pae, 2019)
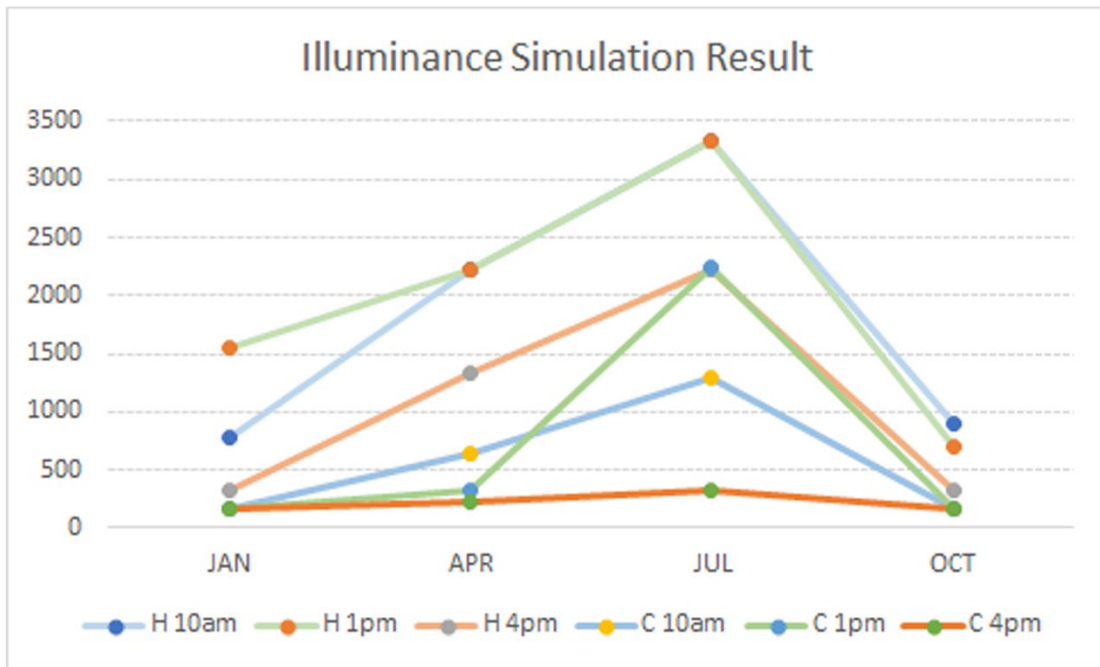
Figure 62 Historic illuminance simulation results on Oct 15th (Pae, 2019)
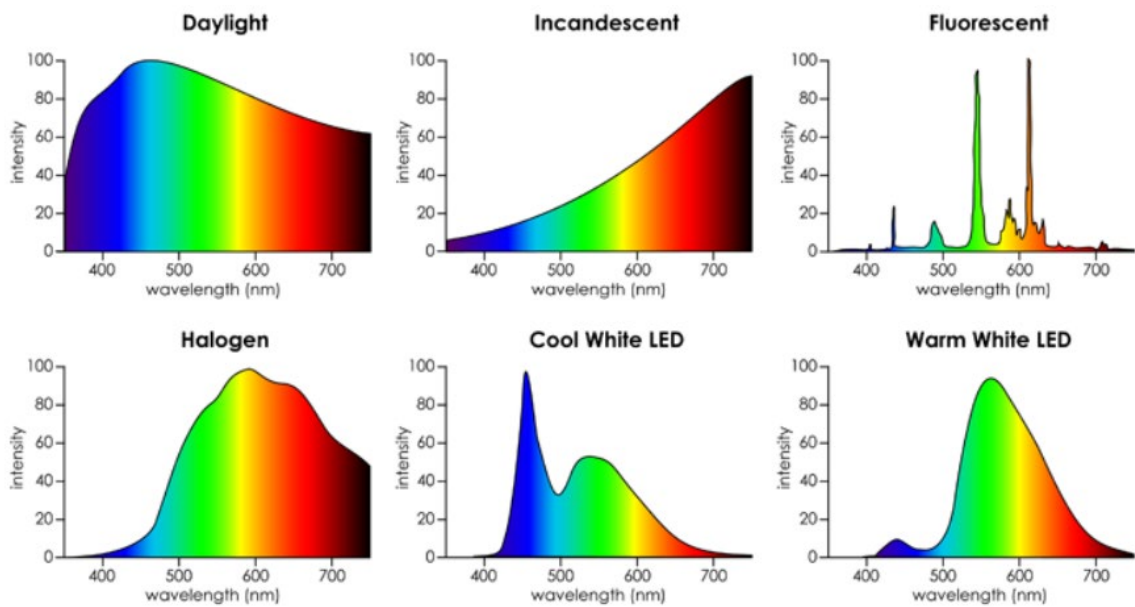
Figure 63 comparison of various light sources

Appendix (Tables)

Condition	Illumination	
	(ftcd)	(lux)
Sunlight	10000	107527
Full Daylight	1000	10752
Overcast Day	100	1075
Very Dark Day	10	107
Twilight	1	10.8
Deep twilight	.1	1.08
Full Moon	.01	.108
Quarter Moon	.001	.0108
Starlight	.0001	.0011
Overcast Night	.00001	.0001

Table 1 Common Light Levels Outdoors from Natural Sources

Levels of Susceptibility to Light Damage & Types of Materials	Recommended Levels of Illuminance
Category 1: Most Susceptible e.g. textiles, cotton, wool, silk and other natural fibers, most paper-based materials, watercolors, fugitive photographic images, most organic-based natural history specimens, fugitive dyes, watercolors, some minerals.	50 lux
Category 2: Susceptible e.g. high quality paper with light stable inks such as carbon black, modern black and white gelatin silver photographs, textiles with stable dyes.	100 lux
Category 3: Moderately Susceptible e.g., oil and tempera paintings, bone, ivory, wood finishes, leather, some plastics.	200 lux
Category 4: Least Susceptible e.g. metal, stone, glass, ceramic, most minerals and inorganic natural history specimens.	Dependent upon exhibition situation

Table 2 Recommendation of the light level for collections of artifacts (http://www.conservation-wiki.com/wiki/Light)

Details	Adjustments
Benchmark value, reasonable visibility for young viewer:	50 lux
For dark surfaces:	Up to 3 times the lux
For low contrast details:	Up to 3 times the lux
For very fine details or complex time-limited task:	Up to 3 times the lux
For older viewers:	Up to 3 times the lux
A combination of the above factors: multiply the factors; therefore, up to $3 \times 3 \times 3 \times 3 \times 50$ lux, for a total of up to ~4,000 lux for an old person looking for subtle patterns in fine detail in a dark object.	

Table 3 Adjustments to provide equal visibility of details (Michalski, 1997)

DATE	TIME	West	East	North
04. 03. 19	AM 10: 00	958	531.7	145.31279
04. 03. 19	AM 10: 15	1005.4	571.6	137.77805
04. 03. 19	AM 10: 30	1044.1	611.4	232.50047
04. 03. 19	AM 10: 45	1076.4	650.1	216.3546
04. 03. 19	AM 11: 00	1100.1	690	177.60452
04. 03. 19	AM 11: 15	1115.1	721.2	153.92392
04. 03. 19	AM 11: 30	1020.4	706.1	130.24332
04. 03. 19	AM 11: 45	918.2	682.4	130.24332
04. 03. 19	PM 12: 00	989.2	752.4	137.77805
04. 03. 19	PM 12: 15	1020.4	799.8	122.70858
04. 03. 19	PM 12: 30	989.2	815.9	137.77805
04. 03. 19	PM 12: 45	965.5	823.4	130.24332
04. 03. 19	PM 01: 00	950.5	839.6	130.24332
04. 03. 19	PM 01: 15	918.2	832.1	145.31279
04. 03. 19	PM 01: 30	887	832.1	130.24332
04. 03. 19	PM 01: 45	847.1	823.4	145.31279
04. 03. 19	PM 02: 00	815.9	815.9	201.28512
04. 03. 19	PM 02: 15	784.7	808.4	296.00754
04. 03. 19	PM 02: 30	744.9	784.7	248.64633
04. 03. 19	PM 02: 45	792.2	815.9	168.99339
04. 03. 19	PM 03: 00	540.4	547.9	130.24332
04. 03. 19	PM 03: 15	256.2	225	122.70858
04. 03. 19	PM 03: 30	208.8	192.7	114.09745
04. 03. 19	PM 03: 45	192.7	177.6	114.09745
04. 03. 19	PM 04: 00	177.6	169	114.09745
04. 03. 19	PM 04: 15	161.5	153.9	106.56271
04. 03. 19	PM 04: 30	153.9	145.3	106.56271
04. 03. 19	PM 04: 45	153.9	145.3	106.56271
04. 03. 19	PM 05: 00	145.3	137.8	99.027976
04. 04. 19	AM 10: 00	697.5	445.6	240.0352
04. 04. 19	AM 10: 15	879.4	555.4	303.54227
04. 04. 19	AM 10: 30	799.8	540.4	350.90348
04. 04. 19	AM 10: 45	855.7	579.1	279.86167
04. 04. 19	AM 11: 00	910.6	602.8	303.54227
04. 04. 19	AM 11: 15	1091.5	744.9	232.50047
04. 04. 19	AM 11: 30	1044.1	737.3	201.28512
04. 04. 19	AM 11: 45	989.2	728.7	232.50047
04. 04. 19	PM 12: 00	1005.4	776.1	296.00754
04. 04. 19	PM 12: 15	1052.7	808.4	319.68814
04. 04. 19	PM 12: 30	1020.4	839.6	311.07701
04. 04. 19	PM 12: 45	981.7	847.1	192.674
04. 04. 19	PM 01: 00	934.3	832.1	145.31279
04. 04. 19	PM 01: 15	934.3	855.7	192.674
04. 04. 19	PM 01: 30	903.1	847.1	263.71581
04. 04. 19	PM 01: 45	855.7	832.1	287.39641
04. 04. 19	PM 02: 00	823.4	823.4	311.07701
04. 04. 19	PM 02: 15	776.1	799.8	114.09745
04. 04. 19	PM 02: 30	752.4	799.8	122.70858
04. 04. 19	PM 02: 45	658.8	697.5	106.56271
04. 04. 19	PM 03: 00	531.7	540.4	106.56271
04. 04. 19	PM 03: 15	263.7	225	114.09745
04. 04. 19	PM 03: 30	225	208.8	114.09745
04. 04. 19	PM 03: 45	216.4	208.8	106.56271
04. 04. 19	PM 04: 00	208.8	201.3	99.027976
04. 04. 19	PM 04: 15	272.3	287.4	82.88211
04. 04. 19	PM 04: 30	192.7	192.7	90.416848
04. 04. 19	PM 04: 45	169	161.5	90.416848
04. 04. 19	PM 05: 00	161.5	153.9	82.88211
04. 05. 19	AM 10: 00	232.5	201.3	130.24332
04. 05. 19	AM 10: 15	232.5	216.4	130.24332
04. 05. 19	AM 10: 30	414.4	382.1	137.77805
04. 05. 19	AM 10: 45	319.7	303.5	137.77805
04. 05. 19	AM 11: 00	343.4	327.2	137.77805
04. 05. 19	AM 11: 15	343.4	319.7	137.77805
04. 05. 19	AM 11: 30	382.1	358.4	130.24332
04. 05. 19	AM 11: 45	540.4	508.1	130.24332
04. 05. 19	PM 12: 00	611.4	571.6	130.24332
04. 05. 19	PM 12: 15	540.4	508.1	130.24332
04. 05. 19	PM 12: 30	524.2	484.4	130.24332
04. 05. 19	PM 12: 45	571.6	555.4	130.24332
04. 05. 19	PM 01: 00	721.2	673.8	130.24332

DATE	TIME	West	East	North
04. 05. 19	PM 01: 15	602.8	564	130.24332
04. 05. 19	PM 01: 30	327.2	303.5	130.24332
04. 05. 19	PM 01: 45	334.8	319.7	153.92392
04. 05. 19	PM 02: 00	327.2	303.5	216.3546
04. 05. 19	PM 02: 15	161.5	137.8	319.68814
04. 05. 19	PM 02: 30	130.2	114.1	272.32693
04. 05. 19	PM 02: 45	177.6	161.5	177.60452
04. 05. 19	PM 03: 00	240	208.8	137.77805
04. 05. 19	PM 03: 15	460.7	460.7	122.70858
04. 05. 19	PM 03: 30	240	225	114.09745
04. 05. 19	PM 03: 45	137.8	122.7	114.09745
04. 05. 19	PM 04: 00	90.4	75.3	114.09745
04. 05. 19	PM 04: 15	90.4	75.3	106.56271
04. 05. 19	PM 04: 30	106.6	90.4	106.56271
04. 05. 19	PM 04: 45	82.9	66.7	99.027976
04. 05. 19	PM 05: 00	114.1	99	99.027976
04. 06. 19	AM 10: 00	792.2	429.5	153.92392
04. 06. 19	AM 10: 15	973.1	493	153.92392
04. 06. 19	AM 10: 30	1036.6	564	145.31279
04. 06. 19	AM 10: 45	1005.4	626.5	153.92392
04. 06. 19	AM 11: 00	1107.6	666.3	153.92392
04. 06. 19	AM 11: 15	1100.1	690	153.92392
04. 06. 19	AM 11: 30	1100.1	721.2	153.92392
04. 06. 19	AM 11: 45	1067.8	737.3	153.92392
04. 06. 19	PM 12: 00	1012.9	737.3	161.45866
04. 06. 19	PM 12: 15	989.2	752.4	161.45866
04. 06. 19	PM 12: 30	958	768.5	161.45866
04. 06. 19	PM 12: 45	934.3	784.7	177.60452
04. 06. 19	PM 01: 00	903.1	784.7	460.69537
04. 06. 19	PM 01: 15	870.8	792.2	476.84123
04. 06. 19	PM 01: 30	847.1	799.8	311.07701
04. 06. 19	PM 01: 45	799.8	776.1	232.50047
04. 06. 19	PM 02: 00	776.1	784.7	256.18107
04. 06. 19	PM 02: 15	706.1	768.5	272.32693
04. 06. 19	PM 02: 30	706.1	768.5	296.00754
04. 06. 19	PM 02: 45	682.4	761	201.28512
04. 06. 19	PM 03: 00	476.8	493	168.99339
04. 06. 19	PM 03: 15	248.6	216.4	145.31279
04. 06. 19	PM 03: 30	208.8	201.3	137.77805
04. 06. 19	PM 03: 45	201.3	201.3	130.24332
04. 06. 19	PM 04: 00	185.1	177.6	130.24332
04. 06. 19	PM 04: 15	177.6	177.6	122.70858
04. 06. 19	PM 04: 30	201.3	192.7	114.09745
04. 06. 19	PM 04: 45	145.3	145.3	114.09745
04. 06. 19	PM 05: 00	153.9	153.9	106.56271
04. 07. 19	AM 10: 00	934.3	493	122.70858
04. 07. 19	AM 10: 15	1029	571.6	201.28512
04. 07. 19	AM 10: 30	1083.9	618.9	224.96573
04. 07. 19	AM 10: 45	1100.1	658.8	216.3546
04. 07. 19	AM 11: 00	1100.1	697.5	114.09745
04. 07. 19	AM 11: 15	1100.1	728.7	168.99339
04. 07. 19	AM 11: 30	1107.6	737.3	224.96573
04. 07. 19	AM 11: 45	1115.1	784.7	177.60452
04. 07. 19	PM 12: 00	1091.5	808.4	114.09745
04. 07. 19	PM 12: 15	697.5	650.1	106.56271
04. 07. 19	PM 12: 30	879.4	697.5	374.58408
04. 07. 19	PM 12: 45	965.5	879.4	208.81986
04. 07. 19	PM 01: 00	1012.9	894.5	414.41055
04. 07. 19	PM 01: 15	823.4	784.7	358.43822
04. 07. 19	PM 01: 30	666.3	618.9	216.3546
04. 07. 19	PM 01: 45	713.7	682.4	414.41055
04. 07. 19	PM 02: 00	870.8	855.7	358.43822
04. 07. 19	PM 02: 15	611.4	618.9	334.75761
04. 07. 19	PM 02: 30	887	934.3	185.13926
04. 07. 19	PM 02: 45	611.4	618.9	287.39641
04. 07. 19	PM 03: 00	579.1	618.9	232.50047
04. 07. 19	PM 03: 15	484.4	476.8	216.3546
04. 07. 19	PM 03: 30	555.4	564	240.0352
04. 07. 19	PM 03: 45	516.7	524.2	248.64633
04. 07. 19	PM 04: 00	405.8	414.4	232.50047
04. 07. 19	PM 04: 15	374.6	358.4	137.77805
04. 07. 19	PM 04: 30	398.3	398.3	153.92392

Date	Time				Date	Time			
04.07.19	PM 04:45	319.7	303.5	114.09745	04.10.19	PM 01:00	1171.1	1067.8	145.31279
04.07.19	PM 05:00	334.8	327.2	99.027976	04.10.19	PM 01:15	1029	941.8	137.77805
04.08.19	AM 10:00	414.4	311.1	256.18107	04.10.19	PM 01:30	1044.1	997.8	153.92392
04.08.19	AM 10:15	635.1	367.1	382.11882	04.10.19	PM 01:45	989.2	989.2	185.13926
04.08.19	AM 10:30	1091.5	658.8	311.07701	04.10.19	PM 02:00	1171.1	1155	256.18107
04.08.19	AM 10:45	1178.7	721.2	161.45866	04.10.19	PM 02:15	287.4	279.9	327.22288
04.08.19	AM 11:00	1202.3	768.5	272.32693	04.10.19	PM 02:30	1052.7	1107.6	327.22288
04.08.19	AM 11:15	1226	815.9	224.96573	04.10.19	PM 02:45	950.5	1005.4	224.96573
04.08.19	AM 11:30	1162.5	776.1	390.72995	04.10.19	PM 03:00	564	564	177.60452
04.08.19	AM 11:45	1147.4	815.9	398.26469	04.10.19	PM 03:15	185.1	161.5	161.45866
04.08.19	PM 12:00	1100.1	823.4	374.58408	04.10.19	PM 03:30	201.3	185.1	153.92392
04.08.19	PM 12:15	1083.9	863.3	390.72995	04.10.19	PM 03:45	145.3	153.9	137.77805
04.08.19	PM 12:30	414.4	367.1	429.48003	04.10.19	PM 04:00	177.6	161.5	130.24332
04.08.19	PM 12:45	1242.2	1100.1	367.04935	04.10.19	PM 04:15	208.8	216.4	130.24332
04.08.19	PM 01:00	1029	460.7	343.36874	04.10.19	PM 04:30	201.3	177.6	137.77805
04.08.19	PM 01:15	682.4	855.7	256.18107	04.10.19	PM 04:45	153.9	137.8	122.70858
04.08.19	PM 01:30	713.7	650.1	374.58408	04.10.19	PM 05:00	130.2	130.2	122.70858
04.08.19	PM 01:45	642.6	547.9	367.04935	04.11.19	AM 10:00	626.5	493	130.24332
04.08.19	PM 02:00	421.9	421.9	279.86167	04.11.19	AM 10:15	602.8	493	429.48003
04.08.19	PM 02:15	524.2	587.7	492.9871	04.11.19	AM 10:30	469.3	429.5	382.11882
04.08.19	PM 02:30	666.3	839.6	263.71581	04.11.19	AM 10:45	484.4	445.6	437.01476
04.08.19	PM 02:45	855.7	918.2	343.36874	04.11.19	AM 11:00	752.4	658.8	390.72995
04.08.19	PM 03:00	469.3	476.8	263.71581	04.11.19	AM 11:15	1091.5	832.1	192.674
04.08.19	PM 03:15	303.5	311.1	248.64633	04.11.19	AM 11:30	1012.9	870.8	319.68814
04.08.19	PM 03:30	327.2	334.8	208.81986	04.11.19	AM 11:45	1233.5	965.5	240.0352
04.08.19	PM 03:45	350.9	334.8	137.77805	04.11.19	PM 12:00	682.4	635.1	358.43822
04.08.19	PM 04:00	414.4	437	185.13926	04.11.19	PM 12:15	1423	1012.9	201.28512
04.08.19	PM 04:15	334.8	350.9	185.13926	04.11.19	PM 12:30	815.9	713.7	153.92392
04.08.19	PM 04:30	272.3	272.3	130.24332	04.11.19	PM 12:45	776.1	650.1	224.96573
04.08.19	PM 04:45	272.3	279.9	137.77805	04.11.19	PM 01:00	1076.4	910.6	248.64633
04.08.19	PM 05:00	208.8	208.8	130.24332	04.11.19	PM 01:15	989.2	894.5	319.68814
04.09.19	AM 10:00	855.7	484.4	153.92392	04.11.19	PM 01:30	941.8	910.6	122.70858
04.09.19	AM 10:15	879.4	484.4	130.24332	04.11.19	PM 01:45	887	870.8	279.86167
04.09.19	AM 10:30	926.8	571.6	161.45866	04.11.19	PM 02:00	910.6	934.3	256.18107
04.09.19	AM 10:45	1052.7	658.8	185.13926	04.11.19	PM 02:15	918.2	981.7	327.22288
04.09.19	AM 11:00	941.8	650.1	161.45866	04.11.19	PM 02:30	799.8	989.2	296.00754
04.09.19	AM 11:15	855.7	650.1	153.92392	04.11.19	PM 02:45	1036.6	847.1	177.60452
04.09.19	AM 11:30	792.2	602.8	161.45866	04.11.19	PM 03:00	744.9	737.3	216.3546
04.09.19	AM 11:45	1005.4	784.7	145.31279	04.11.19	PM 03:15	721.2	737.3	99.027976
04.09.19	PM 12:00	1036.6	832.1	153.92392	04.11.19	PM 03:30	579.1	579.1	122.70858
04.09.19	PM 12:15	1100.1	926.8	161.45866	04.11.19	PM 03:45	547.9	547.9	168.99339
04.09.19	PM 12:30	981.7	839.6	161.45866	04.11.19	PM 04:00	540.4	531.7	106.56271
04.09.19	PM 12:45	879.4	752.4	153.92392	04.11.19	PM 04:15	500.5	508.1	66.736245
04.09.19	PM 01:00	697.5	635.1	161.45866	04.11.19	PM 04:30	429.5	429.5	66.736245
04.09.19	PM 01:15	752.4	728.7	161.45866	04.11.19	PM 04:45	296	287.4	66.736245
04.09.19	PM 01:30	823.4	744.9	153.92392	04.11.19	PM 05:00	256.2	232.5	75.347373
04.09.19	PM 01:45	855.7	832.1	177.60452	04.12.19	AM 10:00	973.1	650.1	168.99339
04.09.19	PM 02:00	737.3	808.4	177.60452	04.12.19	AM 10:15	1280.9	524.2	201.28512
04.09.19	PM 02:15	571.6	500.5	153.92392	04.12.19	AM 10:30	658.8	343.4	137.77805
04.09.19	PM 02:30	540.4	516.7	145.31279	04.12.19	AM 10:45	721.2	728.7	122.70858
04.09.19	PM 02:45	540.4	524.2	145.31279	04.12.19	AM 11:00	296	263.7	137.77805
04.09.19	PM 03:00	414.4	421.9	137.77805	04.12.19	AM 11:15	469.3	405.8	192.674
04.09.19	PM 03:15	287.4	232.5	145.31279	04.12.19	AM 11:30	484.4	460.7	287.39641
04.09.19	PM 03:30	256.2	248.6	130.24332	04.12.19	AM 11:45	1257.2	728.7	492.9871
04.09.19	PM 03:45	493	476.8	137.77805	04.12.19	PM 12:00	973.1	997.8	595.24425
04.09.19	PM 04:00	398.3	398.3	168.99339	04.12.19	PM 12:15	1304.6	839.6	460.69537
04.09.19	PM 04:15	358.4	367.1	232.50047	04.12.19	PM 12:30	571.6	508.1	445.62589
04.09.19	PM 04:30	398.3	405.8	201.28512	04.12.19	PM 12:45	445.6	358.4	350.90348
04.09.19	PM 04:45	350.9	358.4	177.60452	04.12.19	PM 01:00	367.1	303.5	185.13926
04.09.19	PM 05:00	287.4	296	145.31279	04.12.19	PM 01:15	855.7	697.5	256.18107
04.10.19	AM 10:00	1131.3	579.1	145.31279	04.12.19	PM 01:30	1233.5	1131.3	168.99339
04.10.19	AM 10:15	1171.1	626.5	137.77805	04.12.19	PM 01:45	863.3	894.5	327.22288
04.10.19	AM 10:30	1202.3	673.8	145.31279	04.12.19	PM 02:00	1162.5	1155	311.07701
04.10.19	AM 10:45	1233.5	713.7	145.31279	04.12.19	PM 02:15	1060.3	1091.5	414.41055
04.10.19	AM 11:00	1249.7	752.4	137.77805	04.12.19	PM 02:30	1178.7	1083.9	358.43822
04.10.19	AM 11:15	1242.2	784.7	137.77805	04.12.19	PM 02:45	682.4	682.4	240.0352
04.10.19	AM 11:30	1289.5	832.1	137.77805	04.12.19	PM 03:00	476.8	445.6	192.674
04.10.19	AM 11:45	1218.5	847.1	137.77805	04.12.19	PM 03:15	137.8	114.1	161.45866
04.10.19	PM 12:00	1486.5	1131.3	137.77805	04.12.19	PM 03:30	225	201.3	145.31279
04.10.19	PM 12:15	540.4	500.5	145.31279	04.12.19	PM 03:45	99	75.3	130.24332
04.10.19	PM 12:30	1406.8	894.5	145.31279	04.12.19	PM 04:00	75.3	66.7	114.09745
04.10.19	PM 12:45	374.6	272.3	145.31279	04.12.19	PM 04:15	137.8	106.6	114.09745

Date	Time			
04. 12. 19	PM 04:30	343.4	327.2	114.09745
04. 12. 19	PM 04:45	367.1	358.4	106.56271
04. 12. 19	PM 05:00	272.3	272.3	106.56271
04. 13. 19	AM 10:00	201.3	192.7	153.92392
04. 13. 19	AM 10:15	296	272.3	145.31279
04. 13. 19	AM 10:30	476.8	367.1	153.92392
04. 13. 19	AM 10:45	737.3	587.7	153.92392
04. 13. 19	AM 11:00	540.4	421.9	153.92392
04. 13. 19	AM 11:15	635.1	531.7	145.31279
04. 13. 19	AM 11:30	602.8	516.7	137.77805
04. 13. 19	AM 11:45	531.7	437	137.77805
04. 13. 19	PM 12:00	1147.4	958	130.24332
04. 13. 19	PM 12:15	398.3	358.4	145.31279
04. 13. 19	PM 12:30	815.9	564	145.31279
04. 13. 19	PM 12:45	1289.5	1020.4	145.31279
04. 13. 19	PM 01:00	1091.5	926.8	145.31279
04. 13. 19	PM 01:15	1155	973.1	145.31279
04. 13. 19	PM 01:30	1052.7	973.1	153.92392
04. 13. 19	PM 01:45	958	934.3	216.3546
04. 13. 19	PM 02:00	918.2	934.3	311.07701
04. 13. 19	PM 02:15	721.2	618.9	429.48003
04. 13. 19	PM 02:30	823.4	903.1	374.58408
04. 13. 19	PM 02:45	564	564	256.18107
04. 13. 19	PM 03:00	579.1	531.7	201.28512
04. 13. 19	PM 03:15	547.9	516.7	177.60452
04. 13. 19	PM 03:30	476.8	445.6	161.45866
04. 13. 19	PM 03:45	445.6	405.8	130.24332
04. 13. 19	PM 04:00	476.8	421.9	122.70858
04. 13. 19	PM 04:15	405.8	358.4	122.70858
04. 13. 19	PM 04:30	476.8	508.1	114.09745
04. 13. 19	PM 04:45	319.7	319.7	106.56271
04. 13. 19	PM 05:00	272.3	319.7	99.027976
04. 14. 19	AM 10:00	161.5	145.3	153.92392
04. 14. 19	AM 10:15	232.5	192.7	153.92392
04. 14. 19	AM 10:30	208.8	177.6	153.92392
04. 14. 19	AM 10:45	516.7	453.2	153.92392
04. 14. 19	AM 11:00	437	390.7	153.92392
04. 14. 19	AM 11:15	476.8	445.6	161.45866
04. 14. 19	AM 11:30	303.5	279.9	161.45866
04. 14. 19	AM 11:45	879.4	721.2	161.45866
04. 14. 19	PM 12:00	839.6	752.4	168.99339
04. 14. 19	PM 12:15	635.1	564	168.99339
04. 14. 19	PM 12:30	350.9	303.5	177.60452
04. 14. 19	PM 12:45	429.5	398.3	168.99339
04. 14. 19	PM 01:00	216.4	192.7	177.60452
04. 14. 19	PM 01:15	287.4	232.5	177.60452
04. 14. 19	PM 01:30	256.2	248.6	192.674
04. 14. 19	PM 01:45	225	201.3	240.0352
04. 14. 19	PM 02:00	192.7	161.5	334.75761
04. 14. 19	PM 02:15	343.4	311.1	437.01476
04. 14. 19	PM 02:30	595.2	547.9	382.11882
04. 14. 19	PM 02:45	602.8	540.4	279.86167
04. 14. 19	PM 03:00	185.1	161.5	224.96573
04. 14. 19	PM 03:15	240	192.7	192.674
04. 14. 19	PM 03:30	153.9	114.1	177.60452
04. 14. 19	PM 03:45	122.7	99	137.77805
04. 14. 19	PM 04:00	263.7	248.6	130.24332
04. 14. 19	PM 04:15	208.8	192.7	122.70858
04. 14. 19	PM 04:30	256.2	192.7	122.70858
04. 14. 19	PM 04:45	225	192.7	114.09745
04. 14. 19	PM 05:00	216.4	192.7	114.09745
04. 15. 19	AM 10:00	153.9	169	161.45866
04. 15. 19	AM 10:15	153.9	137.8	161.45866
04. 15. 19	AM 10:30	185.1	169	161.45866
04. 15. 19	AM 10:45	192.7	161.5	161.45866
04. 15. 19	AM 11:00	201.3	177.6	161.45866
04. 15. 19	AM 11:15	469.3	445.6	153.92392
04. 15. 19	AM 11:30	1541.4	579.1	153.92392
04. 15. 19	AM 11:45	1399.3	1029	153.92392
04. 15. 19	PM 12:00	642.6	555.4	153.92392
04. 15. 19	PM 12:15	690	626.5	153.92392
04. 15. 19	PM 12:30	1391.8	950.5	153.92392
04. 15. 19	PM 12:45	839.6	776.1	153.92392
04. 15. 19	PM 01:00	469.3	484.4	153.92392
04. 15. 19	PM 01:15	398.3	367.1	145.31279
04. 15. 19	PM 01:30	1115.1	1029	161.45866
04. 15. 19	PM 01:45	540.4	524.2	232.50047
04. 15. 19	PM 02:00	398.3	390.7	327.22288
04. 15. 19	PM 02:15	540.4	476.8	445.62589
04. 15. 19	PM 02:30	737.3	713.7	398.26469
04. 15. 19	PM 02:45	571.6	500.5	272.32693
04. 15. 19	PM 03:00	595.2	564	224.96573
04. 15. 19	PM 03:15	516.7	516.7	192.674
04. 15. 19	PM 03:30	334.8	311.1	161.45866
04. 15. 19	PM 03:45	225	208.8	130.24332
04. 15. 19	PM 04:00	358.4	390.7	114.09745
04. 15. 19	PM 04:15	303.5	296	114.09745
04. 15. 19	PM 04:30	256.2	263.7	114.09745
04. 15. 19	PM 04:45	350.9	334.8	106.56271
04. 15. 19	PM 05:00	272.3	240	106.56271
04. 16. 19	AM 10:00	1242.2	602.8	153.92392
04. 16. 19	AM 10:15	1289.5	658.8	177.60452
04. 16. 19	AM 10:30	1312.1	697.5	208.81986
04. 16. 19	AM 10:45	1344.4	752.4	192.674
04. 16. 19	AM 11:00	1352	784.7	168.99339
04. 16. 19	AM 11:15	1335.8	808.4	153.92392
04. 16. 19	AM 11:30	1312.1	832.1	145.31279
04. 16. 19	AM 11:45	1289.5	870.8	145.31279
04. 16. 19	PM 12:00	1233.5	887	145.31279
04. 16. 19	PM 12:15	1186.2	910.6	153.92392
04. 16. 19	PM 12:30	1155	941.8	145.31279
04. 16. 19	PM 12:45	1123.8	950.5	145.31279
04. 16. 19	PM 01:00	1083.9	965.5	145.31279
04. 16. 19	PM 01:15	1044.1	973.1	153.92392
04. 16. 19	PM 01:30	989.2	973.1	161.45866
04. 16. 19	PM 01:45	950.5	965.5	240.0352
04. 16. 19	PM 02:00	903.1	958	350.90348
04. 16. 19	PM 02:15	863.3	958	476.84123
04. 16. 19	PM 02:30	799.8	910.6	405.79942
04. 16. 19	PM 02:45	737.3	855.7	296.00754
04. 16. 19	PM 03:00	421.9	453.2	232.50047
04. 16. 19	PM 03:15	185.1	153.9	208.81986
04. 16. 19	PM 03:30	161.5	153.9	168.99339
04. 16. 19	PM 03:45	161.5	153.9	122.70858
04. 16. 19	PM 04:00	161.5	153.9	114.09745
04. 16. 19	PM 04:15	161.5	161.5	114.09745
04. 16. 19	PM 04:30	161.5	161.5	106.56271
04. 16. 19	PM 04:45	177.6	192.7	106.56271
04. 16. 19	PM 05:00	161.5	185.1	106.56271

Table 4 Illuminance Data from the Data Loggers

	H 10AM	C 10AM	Difference
JAN	780	160	620
APR	2220	650	1570
JUL	3330	1300	2030
OCT	890	160	730

	H 1PM	C 1PM	Difference
JAN	1550	160	1390
APR	2220	330	1890
JUL	3330	2050	1280
OCT	1300	160	1140

	H 4PM	C 4PM	Difference
JAN	330	160	170
APR	1330	220	1110
JUL	2220	330	1890
OCT	330	160	170

Table 5 Simulation Results

Index

A

B

C

D

E

F

98