NINE TO FIVE: DESIGN FOR CHRONOBIOLOGICAL ASPECTS

OF THE INDOOR ENVIRONMENT

by

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A DISSERTATION

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DISSERTATION ABSTRACT

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Title: Nine to Five: Design for Chronobiological Aspects of the Indoor Environment

We spend more than 90% of our time indoors. In office work environments, occupants are often seated in the same workstation for a prolonged period of time. If they do not receive the recommended quantity and quality of light or access to windows, this will be reflected in their decreased wellbeing, satisfaction, and productivity. This dissertation investigates the metrics, benchmarks, and tools that could test parameters that influence the availability of daylight and access to windows in buildings. It looks at both photopic light (illuminance, lux) for visual task needs as well as melanopic light (equivalent melanopic lux, EML) that triggers alertness levels and affects circadian entrainment for occupant health and wellbeing.

The overarching question asked is whether glazing tints, office floor plates, or office indoor layouts more influential as architectural parameters that enhance or diminish the availability of daylight. To answer this question, fifty office buildings with various forms and interior layouts were simulated in both lighting analyses and isovist software to bridge both lighting design and interior design space syntax fields together. For experimental purposes, the parameters were constrained to limit the variables under

study. The preliminary pilot studies tested the fixed parameters to be used for the lighting simulation conditions for all fifty office buildings: clear glazing, 2 storey height building context, location Portland, OR, climate zone 4C, overcast sky conditions, simulation time 9 am, 12 pm and 3 pm.

The simulation results highlight the impact of a small glazing tint choice that can deteriorate daylighting conditions by up to 82%. The major findings indicate shape factor was the strongest indicator of a building's form for circadian potential. By calculating a building's shape factor and conducting a point isovist analysis to obtain the isovist measures (AP ratio, compactness, and occlusivity) for a specific view, a multiple linear regression model equation was derived to calculate whether the occupant seating position and view meets EML benchmarks.

This research is a response to the need for awareness of the importance of lighting indoor environmental quality and occupant wellbeing by testing and providing quick rules of thumb and accessible simulation methods.

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To my daughter Aliya, whose first real word was ‘light.’

You got the gist of it.

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CHAPTER I: INTRODUCTION

Since buildings are ultimately designed and constructed for human end users, it is critical that they not only satisfy environmental and economic expectations but also meet indoor environment requirements. Indoor environmental parameters that influence occupant well-being include lighting, thermal conditions, air quality, and acoustics. Studies have shown that people spend more than 90% of their time indoors (Frontczak, 2011). This highlights the need to design indoor environments that enhance occupant well-being by creating a connection to the outdoors. More specifically, in the case of work environments, improved indoor conditions can result in increased productivity, worker satisfaction as well as fewer sick leaves. This ties back, once again, to financial gains. Lighting design in office buildings has benefited from contributing positively towards the environment and economy by being energy efficient and cost-effective. However, human-centric approaches and occupant wellbeing considerations need to be acknowledged too.

Most of the light metrics and building standards used by the design industry have been derived from and based on the rods and cones which essentially focus on quantitative and instrumental aspects of light such as: having enough light for task performance, avoiding glare, and visual discomfort, and maximizing energy savings. Though the field has primarily addressed daylight architecturally in terms of these daylight distribution, visual comfort, and energy efficiency metrics, there has been a recent increased interest in the health and well-being components. This is partly due to the recent discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) which are responsible for non-image forming or non-visual functions, both physiological and psychological which include regulating the circadian biological clock and hormones, body temperature, heart rate, vitamin D synthesis, mood, stress, depression, and alertness. These non-visual benefits of daylight that affect well-being are stimulated by a different light action spectrum. Optimal light for vision differs from optical radiation appropriate for non-visual responses (Lucas et al., 2014).

With technological advancements, occupants tend to resort to electric lighting for its instrumental benefits as it offers a controlled electric lighting system with uniform illumination to meet visual task needs. It is constant and predictable, whereas daylight is dynamic and can be unpredictable (Haans, 2014). There are common misconceptions that daylight has only an architectural and aesthetical value, and all other daylight functions can be replaced by electrical lighting solutions. From a physiological standpoint, the literature suggests that melatonin suppression, circadian entrainment, and occupant alertness can be stimulated with electric lighting – provided it replicates daylight's characteristics. Luminous characteristics of both daylight and electric light are determined by its spectrum, color temperature, quantity or intensity, and directionality. Other temporal characteristics of light include timing, duration, and history are factors that are mostly dependent on a building's occupancy patterns which vary from one person to another (Khademagha et al., 2016). Based on critical reviews that address the difficulty of replicating daylight, the feasibility of that is questionable. Other psychological benefits such as views and preferences argue for the implementation of daylighting.

In a study of windowless offices, Ruys (1970) found that 87% of the occupants indicated that they preferred to have windows in their office and that 47.5% of them thought that the lack of windows affected them physically and/or their work. Among the reasons given for being affected were lack of daylight, poor ventilation, desire to know weather conditions, desire to look in the distance for the view, feeling of being cooped up, isolated and claustrophobic, feeling depressed, and tense. It was found that size, office color, lighting level, and the distance to a window had no relationship to the dissatisfaction with the lack of windows. Hence it would seem that the window in its own right performs a unique role, distinct from the provision of light. That unique role may be the ability to be in contact with the external world. In other studies, it has also been found that lighting quality and views influenced occupant's sick leave where occupants seated in workstations with poor lighting quality and poorer views used significantly more sick leaves (Elzeyadi, 2011, Elzeyadi, 2012). This highlights the necessity of creating a physical and visual connection to nature and the outdoors. This can be achieved by means of manipulating the façade's glazing to provide thoughtful window placement and design.

Window placement and design require designers to consider the vertical plane for access to views and light exposure. Traditional office lighting design has focused on light for a paper on a desk, but as we have moved to computers and screens, our lighting needs are also vertical, as well as horizontal. The lighting field has acknowledged that vertical illuminance and view directions are just as, if not more important than horizontal illuminance, to address in building analyses.

As for window glazing type, there are several reasons why designers make the decision to incorporate tinted windows in office buildings. Tinted windows are aesthetically pleasing and create a uniform appearance which is ideal for places of business. Window films create a sense of safety and privacy as they do not allow people to easily look into the building which protects the confidential and discrete nature of some businesses. From a building performance perspective, tinted windows aid in regulating temperature and conserving energy by serving as an insulating film. As the tint deflects light from coming inside, it not only keeps the building cool, but also minimizes glare. However, there is little to no consideration on the impacts of these tints on occupant health and well-being, especially from the perspective of their assessment on spectral influence on circadian transmittance.

To assess human responses to light, it is important to investigate glazing type, the availability of windows influencing the amount of daylight transmittance, occupant's spatial position, view shed, and access to views with which are influenced by the building floorplate and interior layout. Lighting and isovist-based analyses can be used to better understand how occupants experience space and use it.

This research aims to highlight the often-overshadowed components of designing the luminous environment. Prescribing lighting parameters to achieve energy savings guidelines and minimum quantitative requirements is more straightforward than designing the qualitative components of light. Though these methods cover the fundamentals of measuring the circadian potential of a space, based on daylight availability from an architectural standpoint, it is also important to investigate how much exposure occupants receive from that available daylight based on their behavior within building spaces. A successful building should be designed meticulously by paying attention to occupant behavior and expected user patterns in order to maximize the comfort and well-being of all users during all times of the year. Humans should not have to adapt to poorly designed building layouts that deprive them of daylight, instead, buildings should be designed based on human behavior, to maximize the availability of beneficial daylight exposure. This requires designers to pay more attention to isovists and visibility within the indoor building layout to determine if occupants do receive adequate daylight, or whether they do not, despite meeting building performance benchmarks. Creating a human connection to restorative environments can be more challenging. - Despite the uncertainties and complex human physiological and psychological ambiguities, buildings are ultimately designed for people. Thus, designing an indoor environment with an appropriate lighting atmosphere should be a critical design consideration.

1.1. Problem Statements

The lighting design field has recently acknowledged the physiological and psychological impacts of daylight on occupants by developing health-effective metrics, simulation models, field study methods, wearable technology, as well as building standards and benchmarks. Studies need to look at the architectural parameters that influence daylight availability and investigate occupants' physiological and psychological responses to daylight exposure received. This is especially important in the case of office working environments where occupants spend prolonged periods of time at the same workstations, typically from nine to five, where their alertness and wellbeing have an impact on productivity and financial gains. The introduction has outlined several problems to be addressed by the field:

- Building design is often influenced by environmental and economic impacts as set by stakeholders, little consideration is given to occupant user health and wellbeing.
- Most of the light metrics and building standards used by the design industry have been derived from and based on the rods and cones using the photopic action spectrum, the melanopic action spectrum should be incorporated for circadian entrainment assessments.
- There is a heavy reliance on electric lighting; it should be used to supplement daylight when needed, as some physiological and psychological light benefits can only be received from daylight and access to windows.
- Horizontal illuminance is still the primary lighting assessment metric, vertical measures should be included in assessments to avoid over or under designing spaces from an occupant perspective rather than a building performance overview.

- When assessing window design, priority is given to light transmittance performance and light distribution in the space. Lighting analyses are not usually used to investigate occupant access to windows or views from their seated positions.

- Glazing tint decisions are generally influenced by aesthetics, temperature regulation for energy and cost savings as well as minimizing glare. Circadian transmittance and distorting the spectral properties of light for occupant alertness are not considered.

- The spatial composition of office layouts reflects programmatic requirements for adjacency, clustering, isolation, control, supervision, hierarchical stratification, and functional processes. Space syntax methods have not assessed office interiors from access to windows perspective.

1.2. Research Questions

From the previous problem statements, several research questions have been derived:

- Do colored glazing tints create noticeable differences in reduction of visible photopic (T_{vis}) and circadian light transmittance?

- Does a space that meets average horizontal daylight requirement benchmarks (Useful Daylight Illuminance 300 lux – 3,000 lux) necessarily mean seated occupants are receiving sufficient light exposure from their workstations?
- How do different office types perform in terms meeting the 150 – 240 EML WELL Building Standard benchmark for creating an indoor environment with a high circadian potential?
- Which building shape parameters (building form, floorplate type or indoor layout) are more influential in enhancing or diminishing the availability of daylight?
- How can an isovist analysis provide insights on access to windows for daylight availability and views?

1.3. Hypotheses and Expected Outcomes

Three hypotheses inform this research:

- Glazing tints create noticeable differences in both photopic and circadian light transmittance in the perimeter zone, past the perimeter zone the design is ultimately influenced by the building floorplate type and the interior layout.
- The assumptions that meeting horizontal daylight benchmarks (Useful Daylight Illuminance 300 lux – 3,000 lux) to predict average building performance can be

misleading from an occupant workstation perspective facing a cubicle wall where measurements can be much lower.

- There are strong correlations between building design characteristics, isovist components, and daylight availability which can help predict a model.

The expected results of the study are to:

- Describe the ways in which daylight availability and access to window views are influenced by the building context, architectural design parameters, and isovist components.
- Test the feasibility of various simulation tools, benchmarks, and daylight rules of thumb as methods to predict daylight availability and access to windows.
- Provide a model that could predict whether a workstation would meet circadian light benchmarks based on architectural design parameters and isovist components.

1.4. Theoretical Model

This dissertation proposes a theoretical model for conceptualizing the context of human responses from light that is influenced by architectural design and contextual parameters.

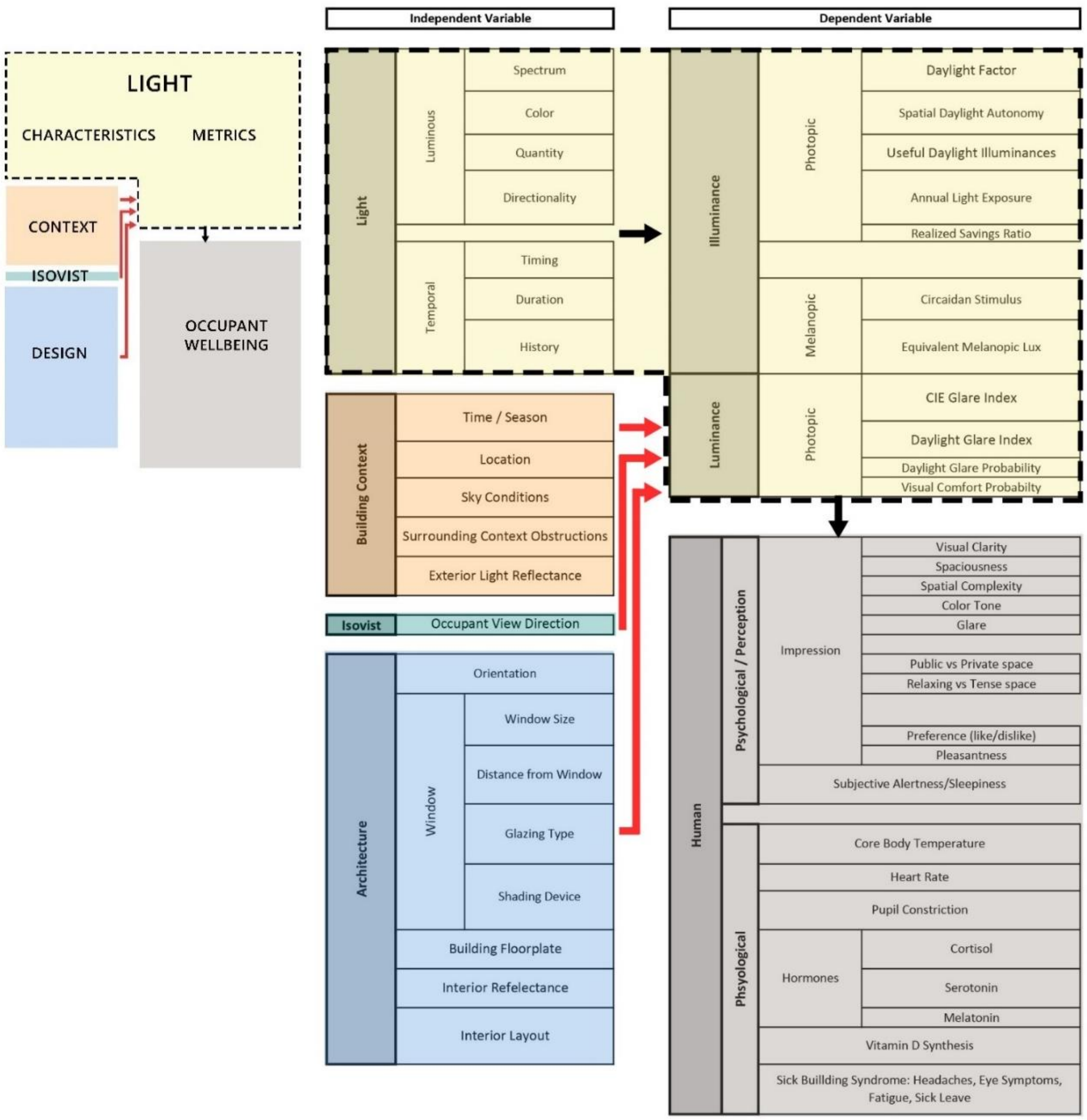


Figure 1 Research topic theoretical framework.

The theoretical model in Figure 1 explains how the research topic is defined. It shows how the building context variables, architectural parameters (orientation, design, building floorplate, interior reflectance, interior layout) as well as occupant isovist view direction interact with light's luminous (spectrum, color, quantity, directionality) and temporal (timing, duration, history) characteristics. These alter light's physical measurements (photopic, melanopic, illuminance and luminance) and in turn affect human responses (psychological, physiological).

1.5. Scope and Limitations

This research took a quantitative methods approach which included collection and processing of data from lighting simulations and isovist analyses. These were performed to study and analyze various architectural parameters within simplified office building models in order to determine their effect upon the photopic and circadian illuminance of a space and access to windows. It should be noted the results that were concluded are relevant to the study's parameters. Several variables were constrained to ensure the results can be meaningfully deduced from the case under assessment within the scope of the study. This includes the building contextual and design parameters: clear glazing, 2 storey height building context, location Portland, OR, climate zone 4C, overcast sky conditions, simulation time 9 am, 12 pm, and 3 pm

While material spectral qualities can play a potentially large role in the quantitative analysis of interior reflectance and circadian light, this was not a targeted parameter being measured in this study. Due to this, simple grayscale materials with reflectance values typical to their location were selected from the ALFA material library for simulation. The study also acknowledges that office buildings will commonly use electric lighting, but it was not evaluated since it is not within the scope of the study. The research aims to investigate baseline building performance under daylight-only conditions. Assessments on electric lighting could be implemented in future studies to evaluate how much electric lighting would be needed to achieve optimum circadian lighting levels that meet recommended benchmarks.

These limitations provide an opportunity for future research to investigate whether the results are consistent under different simulation conditions or to test their impact and extent of change in results.

1.6. Organization of the Dissertation

CHAPTER II LITERATURE REVIEW: Literature review related to physiological and psychological benefits of daylight and views, health metrics and design benchmarks, and architectural parameters that influence daylight availability.

CHAPTER III METHODS: Research methods employed in the study including the research design, building selection, methods comparison, and contextual parameters pilot studies.

CHAPTER IV DAYLIGHT SIMULATION RESULTS: Quantitative analysis of daylight simulations including core and shell, daylight factor, and interior wall descriptive and inferential statistics.

CHAPTER V ISOVIST ANALYSIS RESULTS: Isovist analysis including visibility graphs and multiple regression analysis model comparison.

CHAPTER VI DISCUSSION: Discussion of the results with respect to the questions and hypotheses.

CHAPTER VII CONCLUSION: Conclusion and suggestions for future research.

CHAPTER II: LITERATURE REVIEW

2. Health Benefits of Daylight

Studies have shown that humans have a tendency to prefer natural substances over their synthetic counterparts (Haans, 2014). Whilst some may consider this naturalness bias and biophilic nature of humans as irrational, explanations have been derived to comprehend the instrumental views. These believe that natural substances are functionally superior. On the other hand, ideational views see them as morally superior. People's perceptions base naturalness on the source, transformation, and medium. Thus, occupants tend to perceive daylight as more natural and prefer it over electric lighting. In spite of that, occupants tend to resort to artificial lighting for its instrumental benefits. Electric lighting offers more control for occupants in terms of providing a lighting environment with the requirements needed to meet visual task needs. It also makes light available during the evenings, whereas natural light is dynamic and can be unpredictable. This, by no means, entails that it is acceptable to design deep buildings that function solely on artificial lighting. Similarly, it would be difficult and illogical to justify only using natural light in a building when artificial light is widely available and convenient for some uses

To retort to the postulations by those who do not appreciate lighting's many facets, a wide body of research has investigated the non-instrumental benefits of light. Daylight embodies information about the weather, the time of day, and satisfies other deeply rooted psychological and biological needs. As opposed to electric lighting, there are both visual and non-visual health benefits received from daylight that cannot be replicated (Jennifer A. Veitch, 2000). Though there is a dominance of the eye and vision, and suppression of other senses and biological functions, the non-visual aspects of light and health are critical (Pallasmaa, 2012)

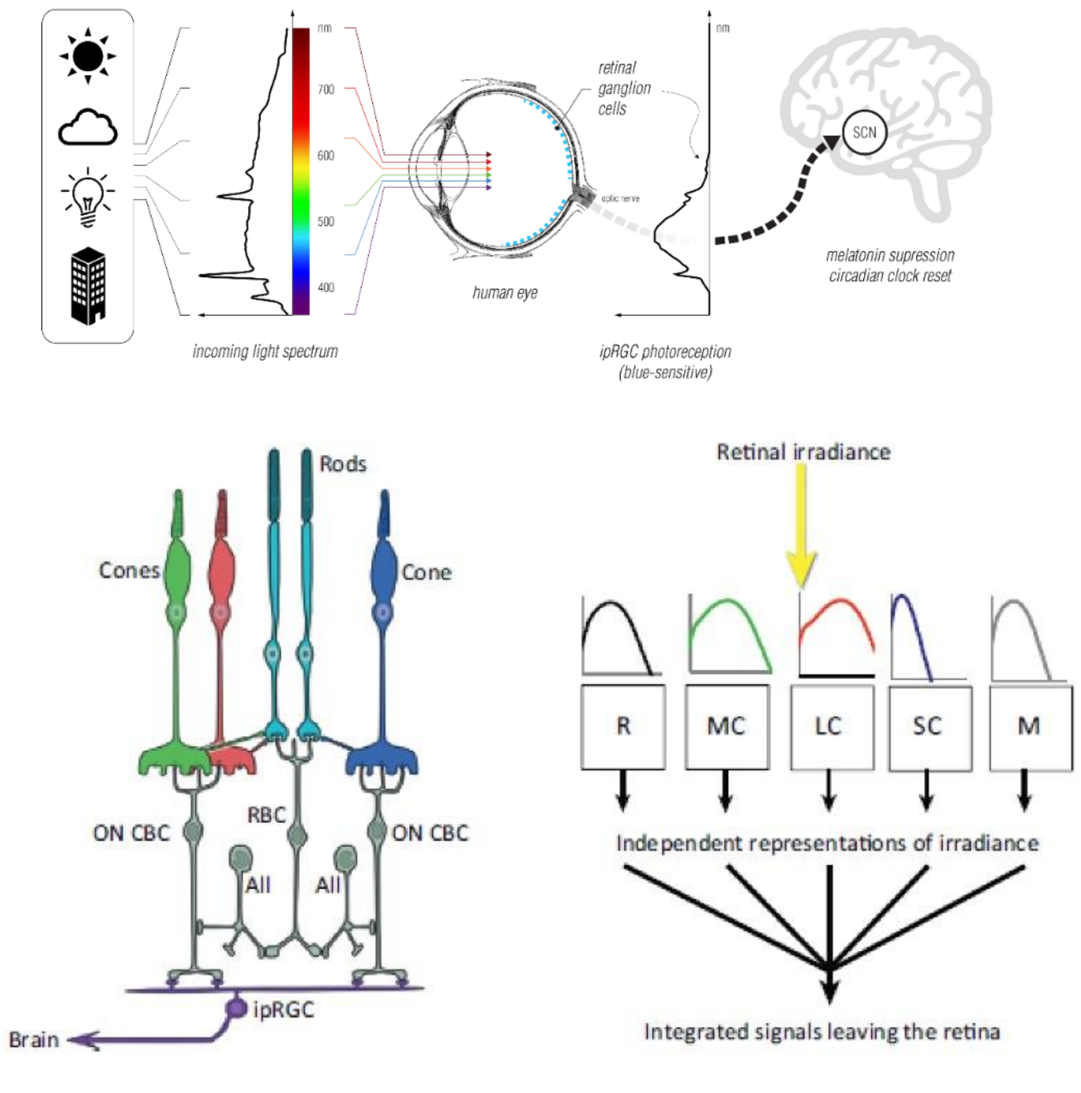


Figure 2 Schematic of retinal circuitry and photoreceptive mechanisms in humans ((Solemma, 2019, Lucas et al., 2014).

Most of the metrics and building standards have been derived from and based on our understanding of the function of the rods and cones in our eyes which essentially focus on quantitative and instrumental aspects of light. Similarly, occupant well-being and human health models have mostly assessed the luminous environment for visual effects of glare (Wallace et al., 1991), flicker (Salinas, 1982), and perceptual health based on the meaning that occupants give lit environments (Kim et al., 2016). These have found that glare and flicker to be one of the main environmental variables to be correlated with the occurrence of headaches, eye symptoms, fatigue, and difficulty concentrating.

But there are still a lot of unexplained aspects about our relationship to light including influencing variables and metrics. Though we are familiar with the rods and cones which are responsible for image forming, not everyone is familiar with intrinsically photosensitive retinal ganglion cells (ipRGCs) which are found at the back of our retina. These are responsible for non-image forming or non-visual functions, both physiological and psychological which include regulating the circadian biological clock and hormones, body temperature, heart rate, vitamin D synthesis, mood, stress, depression, and alertness.

These non-visual benefits of daylight that affect well-being are stimulated by a different light action spectrum. The common measurement of illuminance, photopic lux $V(\lambda)$, describes the spectral sensitivity of one aspect of human cone-based vision which peaks at 555 nm. The spectral sensitivities of non-visual systems peak at 490 nm respectively. Optimal light for vision differs from optical radiation appropriate for non-visual responses (Lucas et al., 2014). Since there has been the recent discovery of ipRGCs, these non-visual components should be taken into consideration and designers should incorporate human biological impacts of light as a design criterion. It is important to investigate how architecture can act as a mediating component between these quantitative instrumental, physiological health effective aspects and the qualitative psychological perception aspects of light to enhance occupant wellbeing. This is especially important in work environments where occupants spend prolonged periods of time in the same space.

2.1. Physiological Responses

Achieving an optimum balance of quantity and quality of light can minimize light-related symptoms of sick building syndrome and help regulate endogenous biological systems (Bluyssen, 2009, Edwards and Torcellini, 2002). Endogenous biological rhythms can be grouped according to their duration: ultradian rhythms (<24 h - pupillary diameter, REM sleep), circadian rhythms (24 h - sleep awake, melatonin, alertness), infradian rhythms (>24 h – menstrual), circannual rhythms (approximately one year - seasonal changes in hormone secretion) (Khademagha et al., 2016). This section expands on primary ultradian and circadian

physiological responses to light as outlined in the literature that fall into two categories: those modified by light reaching the retina and those resulting from light on the skin.

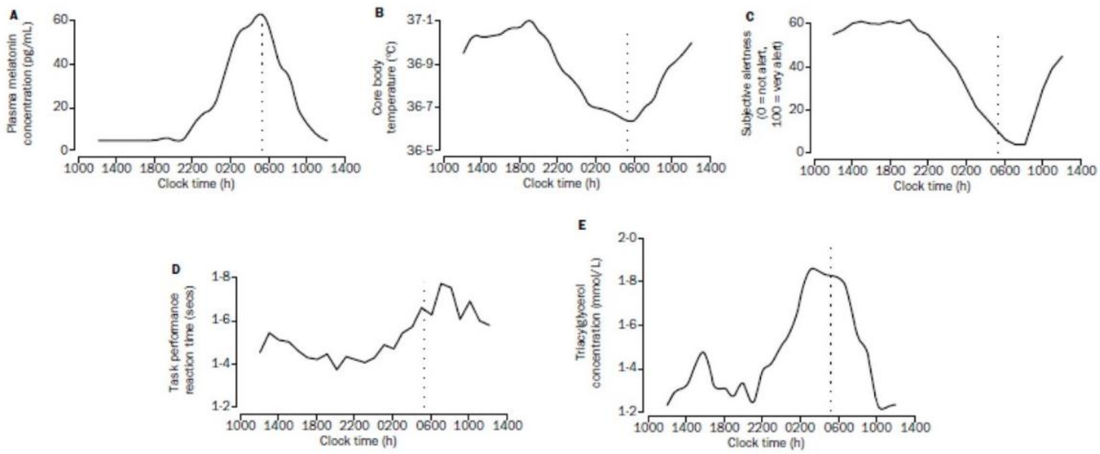


Figure 3 Circadian rhythms of plasma melatonin, core body temperature, subjective alertness, task performance (reaction time, in secs), and triacylglycerol, from human beings held in constant routine conditions (controlled light, posture, activity, and meals) (Rajaratnam and Arendt, 2001).

Based on previous studies, it has become widely acknowledged that the brighter the light, the greater the melatonin suppression - up to a certain point (Mclntyre et al., 1989, Zeitzer et al., 2000). In Lewy et al.'s study (1980), subjects were exposed to bright light during the nighttime melatonin release period. It was noted that melatonin levels began to decrease within 10 to 20 minutes, and within an hour, daytime melatonin levels are reached. Subjects were then placed under dim light, and within 40 minutes melatonin levels were restored to normal nighttime values.

Both body temperature and melatonin release by the pineal gland act as markers of circadian rhythms as they are inversely related. The nocturnal window of melatonin release corresponds to the nocturnal window of lower body temperature. A study conducted by Badia et al (1991) questioned "Will exposure to bright or dim light result in relatively immediate increases or decreases in nighttime body temperature?" Subjects were exposed to alternating bright light (5,000 – 10,000 lux) and dim light (50 lux) conditions in 90-minute blocks. The conclusions affirmed that increases and decreases in light intensity generally resulted in increases and decreases in body temperature.

Other studies went further to investigate the effects of different types of bright and dim light on core body temperature and melatonin levels in humans by modifying the color temperatures of the sources of light. In one study (Morita and Tokura, 1996), subjects were exposed to two kinds of bright light (1,000 lux) with color temperatures of 6,500K and 3,000K. The study findings reported that higher color temperatures resulted in a stronger suppression of the nocturnal drop of core body temperature and nocturnal increase of melatonin secretion.

Whilst earlier studies have focused on lighting intensity and color temperature, more recent studies have investigated light's spectrum on human biological rhythms. It has been demonstrated that monochromatic short-wavelength light is more effective than light at higher wavelengths in suppressing melatonin (Lucas et al., 2014, Brainard et al., 2001, Thapan et al., 2001).

2.2. Psychological Responses

Lighting conditions induce different subjective, multidimensional, psychological responses to the environment. One of the most recognized standardized research procedures (Flynn and Spencer, 1977) breaks down impressions of lighting systems into three main categories: perceptual, behavior setting, and overall preference. The perceptual category includes impressions of visual clarity, spaciousness, spatial complexity, color, and tone. Behavior settings influence occupant's sense of public or private space and whether the space is relaxing or tense. As for the overall preference of the space, occupants' pleasantness ratings are noted. Difficulties arise when these definitions are reviewed. Test participants can be naïve in responding to instructions especially when category definitions can imply different meanings. (Steve Fotios, 2012)

2.2.1. Subjective Alertness/Sleepiness and Productivity

From a physiological standpoint, it has been determined that bright light with blue-enriched spectral power distributions improved occupants' perceived alertness. However, from a psychological standpoint, there is more to consider. Though these conditions tackle issues of sleepiness, other issues such as irritability, concentration, and eye comfort need to be addressed. Results from a longitudinal assessment of a commercial high-performance LEED platinum retrofitted building show strong correlations between improved visual comfort daylight variability and improved employees' productivity and satisfaction (Elzeyadi et al., 2017). This highlights the importance of having a dynamic lighting environment that maintains visual comfort. Providing high illumination at all times is also not practical, especially with electric lighting since it would lead to high energy consumption.

2.2.2. Preference and Biophilia

A common study observation notes that people will tolerate much lower illuminance levels of daylight than artificial light, particularly in diminishing daylight conditions at the end of the day (Baker, 2000). This appeals to our biophilic nature that yearns for a sense of naturalness even in the indoor environment. Building occupants who have a greater connection to nature promoted by sunlight in office environments are noted to have better physical, emotional, and intellectual well-being. Kellert (2012) proposed a conceptual framework that explains the ways people derive benefit from nature. Naturalistic value perceives nature as a source of stimulation, diversity, and detail. Aesthetic value reveals the natural world as a source of beauty and attraction. Optimal sunlight penetration levels that create maximum degrees of relaxation range from 15%-25% of floor area. Sunlight sparkles are generally preferred to large floods when the occupant is sideways to the window (Boubekri et al., 1991) and fractal light patterns of medium to medium-high complexity are perceived to be significantly more visually interesting than other patterns (Abboushi et al., 2019)

In a study of windowless offices, Ruys (1970) found that 87% of the occupants indicated that they preferred to have windows in their office and that 47.5% of them thought that the lack of windows affected them physically and/or their work. Among the reasons given for being affected were: lack of daylight, poor ventilation, desire to know weather conditions, desire to look in the distance for the view, feeling of being cooped up, isolated and claustrophobic, feeling depressed and tense. It was found that size, office color, lighting level, and the distance to a window had no relationship to the dissatisfaction with the lack of windows. Hence it would seem that the window in its own right performs a unique role, distinct from the provision of light. That unique role may be the ability to be in contact with the external world. In other studies, it has also been found that lighting quality and views influenced occupant's sick leave where occupants seated in workstations with poor lighting quality and poorer views used significantly more sick leaves (Elzeyadi, 2011, Elzeyadi, 2012). This highlights the necessity of creating a physical and visual connection to nature and the outdoors. This can be achieved by means of manipulating the façade's glazing to provide thoughtful window placement and design.

2.2.3. Views

In the literature, studies have evaluated window view factor criteria including view distance, the number of view layers, the quality of the landscape/elements, the composition of the view, the view width, the extent of greenery in the view, the presence of water, the weather conditions, gender and age of occupants. Markus (Markus, 1967) argues that the most important characteristic of a view is its horizontal stratification. He divides views into three layers: a layer of the sky, a layer of the city or landscape, and a layer of the ground. Each layer has its own function: the sky is the source of light and keeps occupants in touch with weather, time of day, and year; a view of the landscape or city gives information about the environment on a large scale; a view of the ground gives information about human activities in the immediate vicinity. Other studies confirm the appreciation of the view of the horizon with a margin of ground and sky (Keighley, 1973a, Keighley, 1973b) as well as a balanced composition of natural and urban elements (Tuaycharoen, 2006). In very different cultures all over the world, people tend to like a particular type of landscape or urbanscape. The attributes for a positive evaluation of the aesthetical quality address buildings and trees in terms of age, maintenance/upkeep, moderate complexity, and historical significance. Landscapes vary in coherence, legibility, moderate, complexity, and mystery (Matusiak and Klöckner, 2016). A study conducted in an office building found that office workers with the best possible view, as opposed to no view, performed 10% to 25% better on tests of mental function and memory recall (Heschong, 2003).

Prescribing lighting parameters to achieve energy savings guidelines and minimum quantitative requirements is more straightforward than designing the qualitative components of light. Creating a human connection to restorative environments can be more challenging. Despite the uncertainties and complex human psychological ambiguities, buildings are ultimately designed for people. Thus, designing an indoor environment with an appropriate lighting atmosphere should be a critical design consideration.

2.3. Health Metrics

The common measurement of illuminance, photopic lux V(λ), describes the spectral sensitivity of one aspect of human cone-based vision, these photopic units have limited utility. The spectral sensitivities of the visual and non-visual systems (555 nm and 490 nm, respectively) are different. Thus, illuminance-based photopic lux metrics are not appropriate to evaluate non-visual responses. Researchers and professionals in the field have resorted to developing a set of metrics, simulation, field study methods, and technological tools for new daylight health effective modes of measurements.

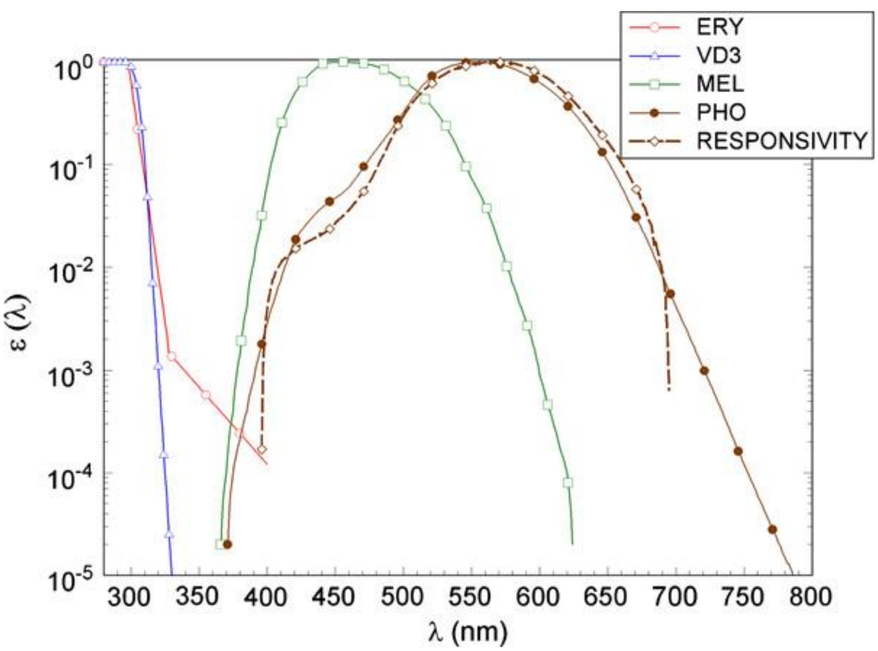


Figure 4 Comparison of the erythemal, vitamin D_3 synthesis, melatonin suppression action spectra, and photopic vision curve. Also shown, the spectral responsivity of the illuminance meter used for the study (Feister et al., 2011).

2.3.1. Equivalent Melanopic Lux (EML)

The biological effects of light on humans are usually translated from light intensity and spectral power distributions to Equivalent Melanopic Lux (EML), a proposed alternate flux density metric that is weighted to the ipRGCs' luminous efficiency function, which peaks at 490 nm and is based on the action spectrum of melanopsin - instead of the cones' photopic luminous efficiency function V(λ), which peaks at 555 nm and is based on the response of foveal, long and middle-wavelength sensitive cones, which is the case with traditional lux (Enezi et al., 2011). This translation is used to understand how much the spectrum of a light source stimulates ipRGCs and affects the circadian system. This results in 1 EML equaling 1 lux under a theoretical equal energy white light. This one-to-one relationship between EML and photopic lux (under equal energy white light) allows for a linear relationship between the units that avoids issues of scaling and allows designers and researchers to work with values that are within a similar range as those used for typical lighting standards (Altenberg Vaz and Inanici, 2020).

While this relationship is useful, it is important to note that there is no simple conversion between lux and EML due to the differences in the spectral range of light these units measure (Lucas et al., 2014). Using this metric by quantifying light in terms of melanopic lux has been deemed to be inaccurate. This is because photometric units have not been established for the circadian luminous efficiency function, the impact on the suprachiasmatic nucleus by different levels of melanopic lux is still unknown, and the fact that basing the metric on melanopsin alone disregards other combined neural channel responses (Mariana Figueiro, 2017). This necessitates the use of tools to simulate and measure circadian light separately from photopic light.

2.3.2. Circadian Stimulus (CS)

The Lighting Research Center at Rensselaer Polytechnic Institute has proposed another metric, known as “the circadian stimulus” for applying circadian light in the built environment (Mariana Figueiro, 2017). It uses irradiance weighted by the spectral sensitivity of every retinal phototransduction mechanism that stimulates the biological clock, as measured by nocturnal melatonin suppression. The metric is derived from a transformation of circadian light into relative units, from 0 to the response saturation of 0.7, and is directly proportional to nocturnal melatonin suppression after one hour of light exposure (0 to 70%). The recommended levels aim for a circadian stimulus greater than 0.3 during the day and less than 0.1 in the evening.

This circadian stimulus metric was developed from several lines of biophysical and retinal neurophysiology interdisciplinary research. It has been validated in several controlled experiments and has been used successfully in a number of real-world applications including nuclear submarines, senior facilities for persons with Alzheimer’s disease, and offices. A circadian stimulus calculator is also made available online for lighting professionals to enable them to convert the photopic illuminance at the eye provided by any light source and level, into the effectiveness of that light for stimulating the human circadian system (Rea and Figueiro, 2016, Rea et al., 2010).

Though the science behind the circadian stimulus metric may be difficult in understanding for designers who have not specialized in lighting, it should not be a reason to adopt the simpler, alternate approaches that either disregard health effective light or are knowingly inaccurate, unreliable, and without validation.

2.3.3. WELL Building Standard

Despite these inaccuracies, the WELL Building Standard adopts EML as the metric to benchmark and assess biologically light and dark spaces in the indoor environment. The WELL Building Standard was launched in October 2014 by The International WELL Building Institute and is administered by The Green Business Certification Inc (Institute, 2019). The standard details the subcategory circadian lighting design in terms of melanopic intensity for work areas, living environments, breakrooms, and learning areas. It aims to support circadian health by setting a minimum threshold for daytime light intensity. Here, we notice the use of melanopic lux as a metric to establish the standard's benchmarks. A minimum of 150 -240 EML is to be achieved for at least four hours (beginning by noon at the latest) at a height of 18 in above the work-plane for all workstations in regularly occupied spaces.

What still needs to be addressed is the basic assumptions this standard implies. Though WELL v2 has made improvements in specifying the time period during the day when the effective lighting must be present – as opposed to v1 which simply states that effective lighting should be present for at least 4 hours per day for every day of the year. It could further benefit from the application of the framework developed by Andersen et al. (2012) which includes a schema to segment the day into three discrete periods of analysis. These are, 6:00-10:00 AM (circadian resetting), 10:00-18:00 (alerting effects of daylight), and 18:00-6:00 (bright light avoidance, dim light only).

The standard still overlooks the complex nature of human behavior – their view direction and how much light exposure is actually received at the eye. In addition, it has been established that the equivalent melanopic lux metric may be not a reliable measure. Other circadian light health metrics, such as circadian stimulus, should be considered or at least incorporated as an alternative benchmark, Though, it is noteworthy that the WELL standard has taken a step further and addressed health effective light in a more rigorous manner.

From a photopic light standpoint, the main points the standard sets are requirements for an average spatial daylight autonomy sDA 300/50% to be achieved for > 75% of floor area. The standard also addresses interior layouts by requiring 70% of all workstations to be within 16-25 ft of transparent envelope glazing, and that at least 75% of all workstations have a direct line of sight to indoor plant(s), water feature(s) and/or nature view(s) or that all workstations are within 33 ft of indoor plant(s), water feature(s) and/or nature view(s). These points best fit the lighting and access to windows scope of the research, though the standard considers indoor plants and water features as views that will be disregarded.

2.3.4. LEED Rating System

The LEED (Leadership in Energy and Environmental Design) rating system is a green building certification program used worldwide (Council, 2019). While this rating system does not specifically focus on occupant health like the WELL Building Standard, it does address similar points. In the daylight category of LEED v4.1, it requires a demonstration through computer modeling that illuminance levels will be between 300 lux and 3,000 lux for 9 a.m. and 3 p.m. Much like WELL, it also requires a spatial daylight autonomy sDA 300/50% for at least 55%, 75%, or 90% of regularly occupied floor area. Its quality views credit aims to give building occupants a connection to the natural outdoor environment by requiring a direct line of sight to the outdoors via vision glazing for 75% of all regularly occupied floor area which is more rigorous than WELL. Views into interior atria may be used to meet up to 30% of the required area.

2.3.5. Lighting Design Benchmarks and Guidelines

Upon reviewing the LEED and WELL benchmarks that are predominantly in use, it is important to instill these requirements in other guidelines to promote design that enhances occupant health and well-being. Some of the other leading green building assessment tools include Building Research Establishment (BRE) Environmental Assessment Method (BREEAM, United Kingdom), Green Building Council of Australia Green Star (GBCA, Australia), Deutsche Gesellschaft für Nachhaltiges Bauen e.V (DGNB, Germany), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), and Korea Green Building Certification (KGBC).

As examples, these rating and certification systems provide frameworks for assessing a building's performance, though they are also generally used as design guides by professionals through prescriptive-based and performance-based evaluations with respect to international and national, regional and local building regulations (Hraska, 2011). Their criteria differentiate each other and are expressed in several ways but fundamentally adopt the same principles.

Though these benchmarks are becoming increasingly acknowledged, the methods to assess buildings are not as well established. There are no unified approaches to quantify the benchmark requirements, and the rating systems often keep guidelines vague. Several rules of thumb and simulation tools are available – some free, some not as accessible to everyone. To encourage designers to design with these benchmarks in mind in the early design stages, an accessible, holistic method that addresses several benchmarks and credit requirements simultaneously would ease the process. This dissertation tests assessment approaches that could be used to check for LEED and WELL credit requirements.

2.4. Architectural Parameters

2.4.1. Window Tints

Architecture plays a major influential role in how much light exposure occupants receive and how they behave inside buildings. On a large exterior scale, light penetrating a building's interior can be predetermined based on the surrounding environment's exterior reflectance. This can be mediated with the building's orientation and façade design by altering window parameters: ratio, size, position, glazing type, and whether shading devices will be allocated.

Architectural design parameters of buildings should respect the cyclical nature of light, the specific spectrum of daylight, and the intensity of light that people are exposed to. Not all daylighting practices have followed the chronobiological fundamentals of daylighting. Daylight apertures and the glazing material allocated should distort the daylight spectrum only minimally. Very few studies have looked at the circadian potential of transmitted light through different glazing types. Although some types of glazing provide a comparable amount of transmitted photopic light, the amount of transmitted circadian light can be very different.

In one study, Hraska (2015) assessed differences between light transmittance T_{vis} and circadian transmittance T_c of several materials. In some cases, the glazing transmittance of light in the non-visual photoreception region can be so small that may disrupt circadian rhythms or cause other health problems for occupants, this was especially evident with tint colors such as bronze which reduce the blue light component of daylight. The study concluded that further research should be undertaken to determine the health and wellbeing benefits associated with spectral filters in daylighting of buildings.

2.4.2. Office Types

On a small interior scale, light penetrating the building's envelope is either enhanced or diminished based on the indoor profile, surface properties, and interior reflectance. Many factors influence the design decisions for an office's interior layout which has led to several typologies each with its own advantages and disadvantages. The spatial composition of layouts reflects programmatic requirements for adjacency, clustering, isolation, control, supervision, hierarchical stratification, and functional processes.

2.4.2.1. Interior Layouts

Some of the most prominent office layout types include cellular office layouts, open office layouts, and mixed/combination office plans. In a cellular office layout, the floor space is divided into individual spaces or cubicles to give employees their own private space and foster autonomous work, improves focus, concentration and ensures privacy. However, these cells consume a lot of space as opposed to other design layouts and hinder communication between employees. In contrast, open office layouts aim for effective communication, transparency, collaboration while promoting employee relationships through non-territorial design which can be more cost-effective. Workstations do not have physical barriers and may be shared by employees. Though this enhances communication, it leads to a noisy and distracting environment. Mixed or combination office layouts incorporate both cellular and open office layouts, creating a versatile design that shares the advantages and disadvantages of both respective layouts together.

2.4.2.2. Floor Plates

To best describe the building forms and geometries I wanted to assess in this study, I had to have clear and quantifiable components I could compare across all building cases. The first one is the shape factor. The shape factor is defined as the ratio between external envelope area and the inner volume of a building and thereby a measure of buildings compactness (A/V). It describes whether a building is internally or externally dominated. A building with high shape factor has a larger envelope area for a given building volume.

The next two measures are the Relative Grid Distance (RGD) and Convex Fragmentation (CF). These are adopted from a dissertation study conducted by Shpuza (2006), where office layouts were evaluated for their effect on circulation integration. In this study, floor plate shapes were described by two proposed concepts: The Relative Grid Distance and Convex Fragmentation.

The Relative Grid Distance (RGD) gauges the compactness of the shape and is calculated by comparing the aggregate of grid distances between all units in the shape to the aggregate of grid distances between all units of a square with the equivalent number of units. The conceptual foundation of this description is derived from the affordance of shapes for given metric distances. Low values of RGD, close to 1, correspond to compact floorplates where little differentiation exists among distances. Greater values of RGD correspond to elongated and broken shapes where distances in the shape are more differentiated.

The Convex Fragmentation (CF) measures the convexity of the shape and is defined based on aggregate changes of directions, according to two main orthogonal axes, between units in a shape, such as the number of boundaries between containing convex spaces crossed to reach from one unit to another. This description was based on the directional changes constituting the primary experience of moving across the circulation system. Low values of CF denote floor plates that approximate convex shapes, while greater values of CF correspond to shapes with wings and holes.

Based on the relative grid distance and convex fragmentation floor plate shape concepts, several categories were derived to best identify buildings with values calculated from these descriptions. Calculations were performed using a Java computer application developed for this purpose.

- *Compact Blocks External Core* (rgd<1.2 and cf<0.5).

It includes floor plates with compact shapes and those with external cores and a few and small internal cores.

- *Bars* (rgd>1.2 and cf<0.5).

It includes floorplates with elongated rectangular shapes and external cores.

- *Deep Space Small Central Core* (rgd<1.2 and cf>0.5).

It includes floorplates with internal cores where dimensions of cores are relatively small in comparison to the depth between core and perimeter. The increase of CF moving vertically along the y-axis is associated with a greater number of internal cores.

- *Shallow Space Large Central Core* (1.2<rgd<1.4 and 0.5<cf<1).

It includes floorplates with ring-like configurations of shapes with large holes, which correspond to large cores in high-rise buildings, central atria, and internal courtyards.

- *Pavilions* (1.2<rgd<1.4 and cf>1)

It includes floorplates with distinct pavilions and floorplates with many large internal cores or atria.

- *Wings* (rgd>1.4 and cf>0.5)

It includes elongated floorplates broken into distinct wings.

This section has outlined various aspects considered in office indoor designs, but the focus of the study is to evaluate these different layouts in terms of daylight distribution and seated occupants’ visual access to windows.

2.5. Conceptual Framework

As a conclusion to the literature review and to narrow down the scope of the study, the conceptual framework (Figure 5) identifies the primary components that will be addressed in this research. Daylight availability is first influenced by its context, this is the first line that dictates how much light enters buildings. The design parameters of a building then play a role in either maximizing or minimizing light transmittance and reflectance into the space's interior. Occupants are then restricted by the interior layout that could diminish isovist views and access to light and views. This all needs to be considered to achieve occupant wellbeing from a light visual and non-visual perspective.

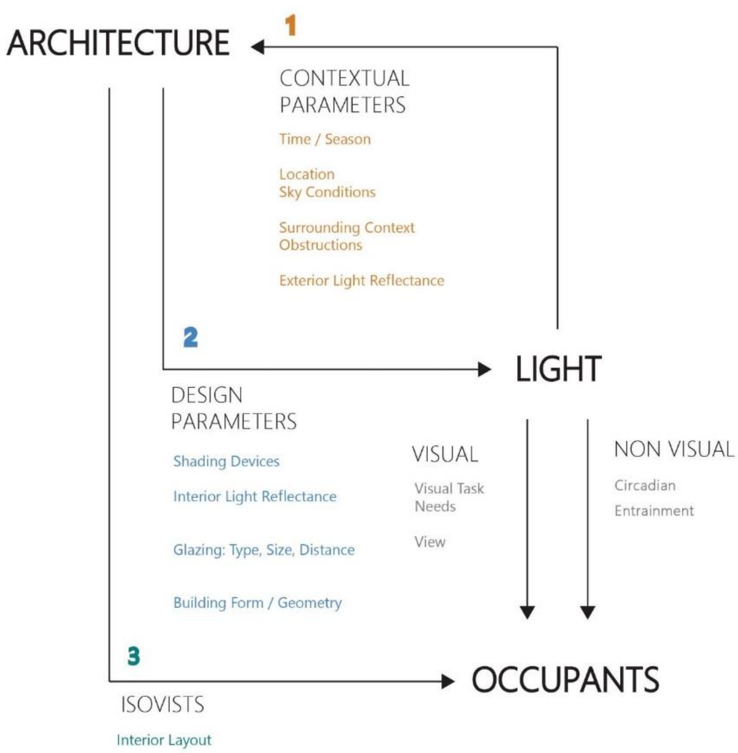


Figure 5 Research topic conceptual framework.

CHAPTER III: METHODS

This dissertation study aims to assess how architectural parameters influence the circadian potential of an office space. This is to justify design decisions for occupant alertness, performance, and wellbeing. As previously outlined, there are various parameters that affect occupants' exposure to daylight at their workstations. To narrow down the scope of the study, the parameters were limited to glazing tint and office typology which encompasses office floorplate and layout.

The focus of the study was to investigate the office spaces in daylight-only conditions as a base that could then be improved with electric lighting design schemes. Assessments on electric lighting could be implemented in future studies to evaluate how much electric lighting would be needed to achieve optimum circadian lighting levels that meet recommended benchmarks. Results from spatial energy loads could further justify design decisions from an energy savings and cost analysis perspective.

3. Research Design

Before carrying out the research, pilot studies were conducted to compare simulation tools and daylight model methods that could potentially be used. Once the method was selected, the research was then broken down into three main stages. The first stage investigated the contextual and design parameters that needed to be constrained for consistent simulation results. The second stage assessed the parameters of interest which include building forms, first as core and shell floorplate types only, then modeled with interior walls and partitions. The last stage built on the interior simulations with an isovist analysis to evaluate interior layouts in-depth and predict a statistical model.

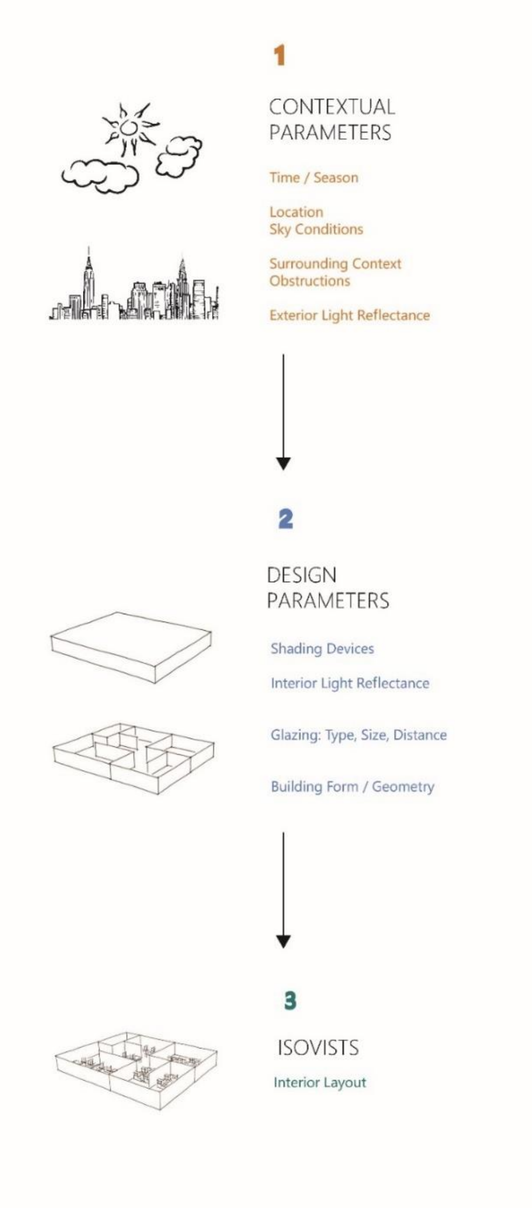


Figure 6 Research design stage.

3.1. Computer Simulation Tools for Circadian Assessments

Less than 12% of designers a use simulation software to assess the impact of circadian light during the design process (Inanici et al., 2015). As methods are becoming increasingly popular and more accessible, research is addressing various lighting design issues with various approaches. Rockcastle et al. (2019) opens a dialog about how view-based vertical metrics may be considered alongside task-based horizontal metrics. With the web-based visualizer OCUVIS the study uses the non-visual Direct Response (nvRD) model (Ámundadóttir, 2016) to predict daily light dose based on cumulative vertical illuminance accounting for the ipRGC spectral effectiveness and Spatial Contrast (mSC) (Rockcastle et al., 2017), which proposes thresholds for determining the impact of daylight composition on ratings of calm or excitement. The simulations results were assigned with a view-based score, subject to seating arrangements which shows that occupant-centric performance is impacted not only by office layout and orientation, but also by seating location and view direction.

Konis similarly previously outlined a procedure using annual, climate-based daylight modeling of eye-level light exposures to analyze and map indoor environments in regard to spatial and seasonal changes in the availability of a circadian-effective daylight stimulus (Konis, 2017, Konis and Selkowitz, 2017). The procedure is currently implemented with a Grasshopper plugin entitled "LARK Spectral Lighting' that analyzes luminance renderings and irradiance data to obtain point-in-time calculations of EML or CS. This is based on the view vector analyzed as it shows the percentage of the year where a stimulus frequency of at least 71 % (5 of 7 days/week) is achieved. It defines an annual Circadian Effective Area (CEA) falling into entrainment quality grade categories. It should be noted that this approach does not account for the modification of the relative spectrum of light by glass or non-neutral internal surfaces. Despite its limitations and inaccuracies, this simulation model has been be used in multiple studies to make relative comparisons between various daylighting strategies during design to understand their circadian potential. It can also identify biologically dark spaces in existing buildings, which require remediation or repurposing.

This approach was used in a study conducted by Amirazar et al. (2018) where one floor plate with no shade based on a real office building located in Charlotte, NC was modeled in order to compare CEA for two time periods: 7:00 AM - 10:00 AM and 10:00 AM - 5:00 PM. The model is analyzed without the presence of electric lighting and only considers daylight as the only source of lighting. Electric lighting cannot be simulated in LARK. The other parameters Konis's method fails to address include exterior context, glazing optics, surface materials and interior design.

Another relatively newer circadian lighting design software "Adaptive Lighting for Alertness" (ALFA), developed by Solemma, deploys spectral calculations that carry out 81-channel renderings. These consider skies using libRadtran, glazing and materials using the international glazing database and is embedded into the Rhinoceros 3d CAD system with the Radiance lighting engine extension. Thus, ALFA will be used as the computer simulation tool for the methods comparison pilot studies.

3.2. Methods Comparison Pilot Study

The aim of this preliminary study was to see which method, a daylight model or a simulation tool, is more applicable to address the research's scope of study and to check if there was a difference in results based on the method approach. Window glazing tints as an architectural parameter were investigated to verify if a difference in circadian and light transmittance will be noted under clear glass, blue, and bronze tints. If there was a difference in absolute result values, was the magnitude of change between the tints the same?

3.2.1. Daylight Model Pilot Study

In this preliminary study, the daylight model approach, like Hraska (2015), was taken. The study employs spot measurements in a scale model of an office building floor (100ft x 60ft x 12ft). A model is ideal to consider detailed refinement of spatial components, to have highly detailed inside views, to study accurately diffuse and direct daylight penetration, and allows for flexibility and ease of use as a kit of parts. Illuminance levels and spectral power distribution measurements were taken every 5ft from 0ft to 30ft on both horizontal plane and vertical plane at the North, East, West, and South cardinal points using a handheld spectroradiometer (Asensetek Lighting Passport accuracy: x, y ︰ ± 0.002, Illuminance ︰ ± 3 %, CCT ︰ ± 2 %). The collected data was interpreted by computing visual comfort and chronobiological light metrics. The computed metrics included: Illuminance Levels (lux), Circadian Stimulus (CS), and Equivalent Melanopic Lux (EML).

Figure 7 Daylight model measurements taken with a handheld spectroradiometer (Asensetek Lighting Passport).

Table 1 Daylight model illuminance, circadian stimulus and equivalent melanopic lux results for clear, blue, and bronze tinted glazing.

		Illuminance (Lux)					Circadian Stimulus (CS)					Equivalent Melanopic Lux (EML)				
	Distance	Horizontal	North	East	South	West	Horizontal	North	East	South	West	Horizontal	North	East	South	West
CLEAR	0ft	12428	-	-	36922	-	0.69	-	-	0.7	-	12206	-	-	37217	-
	5ft	11561	-	30563	32559	20898	0.69	-	0.7	0.7	0.7	11061	-	29501	32751	19714
	10ft	6687	11584	19648	22091	17743	0.68	0.69	0.7	0.7	0.69	6123	10695	19110	22406	16533
	15ft	6337	11100	17332	19558	16276	0.68	0.69	0.69	0.7	0.69	5788	10297	16672	19370	14950
	20ft	6814	10508	15809	18041	14927	0.68	0.69	0.69	0.7	0.69	6323	9793	15028	17551	13572
	25ft	823	9966	14518	16650	13769	0.53	0.69	0.69	0.69	0.69	533	9344	13745	15918	12454
	30ft	2979	9709	13611	15578	12880	0.64	0.69	0.69	0.69	0.69	2473	9170	12882	14741	11601

		Illuminance (Lux)					Circadian Stimulus (CS)					Equivalent Melanopic Lux (EML)				
	Distance	Horizontal	North	East	South	West	Horizontal	North	East	South	West	Horizontal	North	East	South	West
BLUE	0ft	6818	-	-	14640	-	0.68	-	-	0.7	-	5432	-	-	16641	-
	5ft	5953	-	13216	14359	5822	0.67	-	0.69	0.69	0.69	4760	-	14288	15979	6331
	10ft	4934	3347	5339	6486	4798	0.66	0.67	0.68	0.69	0.68	3795	3485	5872	7467	5122
	15ft	4371	3113	4662	5828	4445	0.65	0.67	0.68	0.69	0.68	3248	3258	5020	6601	4677
	20ft	3974	2972	4290	5271	4131	0.64	0.66	0.68	0.68	0.68	2962	3120	4570	5829	4294
	25ft	3932	2902	3943	4842	3769	0.64	0.66	0.67	0.68	0.67	2806	3072	4159	5256	3899
	30ft	3972	2966	3745	4838	3552	0.64	0.66	0.67	0.68	0.67	2873	3178	3945	5180	3643

		Illuminance (Lux)					Circadian Stimulus (CS)					Equivalent Melanopic Lux (EML)				
	Distance	Horizontal	North	East	South	West	Horizontal	North	East	South	West	Horizontal	North	East	South	West
BRONZE	0ft	6914	-	-	21672	-	0.68	-	-	0.69	-	4491	-	-	14611	-
	5ft	5955	-	11583	23548	10070	0.68	-	0.68	0.69	0.68	3845	-	7783	15768	6638
	10ft	5662	4641	7586	11746	7768	0.67	0.64	0.67	0.69	0.67	3709	3058	5038	8213	5123
	15ft	4654	4349	6510	9040	6641	0.67	0.64	0.66	0.68	0.68	3007	2874	4328	6335	4355
	20ft	4250	4057	5956	8137	5978	0.66	0.63	0.66	0.68	0.68	2736	2702	3989	5581	3914
	25ft	4316	3895	5379	7302	5429	0.67	0.63	0.65	0.67	0.65	2659	2604	3550	4967	3572
	30ft	4075	3772	5057	6689	5170	0.66	0.63	0.65	0.67	0.65	2624	2560	3378	4474	3385

OUTDOOR	Time	Illuminance (Lux)	Circadian Stimulus (CS)	Equivalent Melanopic Lux (EML)
	9:27 AM	59855	0.7	59127

3.2.2. Computer Simulation Model Pilot Study

The daylight model study settings were replicated using a computer simulation method to address inaccuracies and other approaches that could be taken for the research. ALFA (Adaptive Lighting for Alertness) is a collaboration between Solemma and sleep experts at the Alertness CRC in Australia. It is a new software that extends the Radiance lighting engine, embedded in Rhino, to conduct simulations in 81 color channels. It accounts for the action of each of the five photoreceptors in the human eye – including the melanopsin-containing cells that help regulate alertness and sleep. The same 100ft x 60ft x 12ft box was modeled in Rhino but with surface materials reflectance from ALFA resources as follows:

- Ceiling: White Painted Room Ceiling _ 82
- Floor: Light Grey Floor Tiles Nonslip _ 42
- Ground: Rock 7 _ 20
- Walls: - Single Pane Clear 6mm_ 88 (for clear scenario) - Double IGU Blue _ 47 (for blue tint scenario) – Double IGU Bronze _ 18 (for bronze tint scenario)

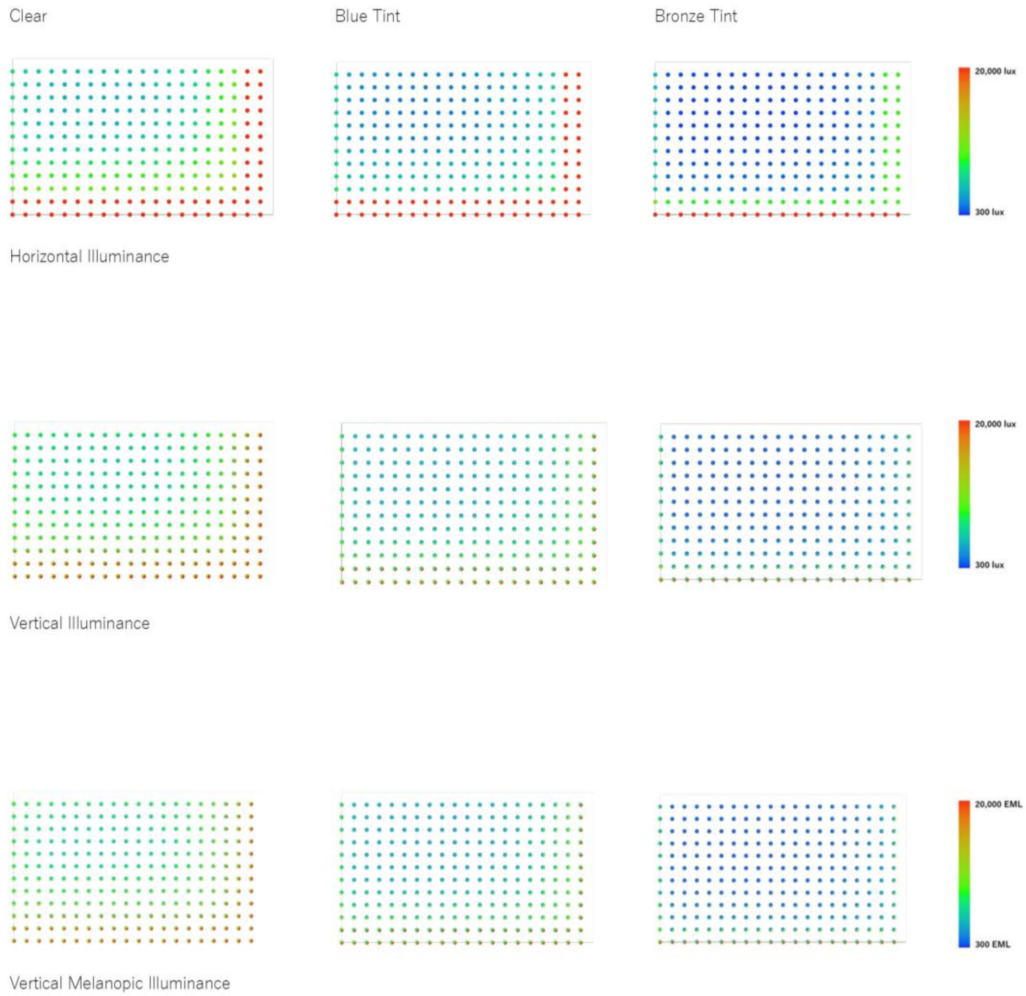


Figure 8 Computer simulation results under clear, blue and bronze tints.

3.2.3. Methods Results Comparison

The daylight model and computer simulation pilot studies were conducted to provide insights on both the effects of glazing tints on light transmittance, the various metrics used as well as method advantages and disadvantages.

There are several advantages to the daylight study model approach. It allows the researcher to use products as they are, available in the market – in this case, different glazing types from companies. It also provides flexibility when constructed as a kit of parts that can accommodate changes of materials for various test scenarios. It can also be claimed that results from these models are most reliable when constructed correctly, as they use real-time sky conditions as opposed to simulated data from weather files.

In this pilot study, this approach faced several complications. It proved to be an inconvenient method even when constructed as a kit of parts. The process of taking morning measurements was time-consuming and only allowed for 3 iterations before running into the afternoon measurements time frame. The outdoor conditions were also harsh, which cut the measurement taking short during the afternoon period. This shortcoming is also elaborated in the fact that measurements can only be taken at specific times of the study, annual overviews require an extensive period of time to conduct. In addition, the spectrometer's dimensions obstructed part of several measurement points at 0ft and 5ft (North, East, and South), these were noted in the data compilation.

Because the effect of light on the non-visual system is cumulative, instantaneous daylight model evaluations are inappropriate due to fundamental characteristics of the light that stimulates the non-visual system over time, namely: quantity, spectrum, timing, duration, and prior light history. ALFA, as a simulation method, has the potential to determine where, when and to what extent circadian entrainment and alertness effects are likely to occur in a space over the year for someone looking in a specific view direction at a specific location.

It can be argued that measurements taken on-site from a field study are more accurate than simulations as simulation models will, without a doubt, fail to accurately replicate the environment or take all aspects of the real-life situation into consideration. Lighting is commonly simulated through tristimulus color space such that spectral information for lights and materials are defined and computed with the RGB data. There are certain discrepancies associated with the simulation of light and materials with the RGB values in comparison to the full spectral data. The discrepancies may hinder the accurate computation of color-dependent lighting metrics, especially the ones that are not dependent on the CIE photopic spectral sensitivity curves, such as the circadian light. In addition, the light source we deliver to interiors through building apertures is not simply a function of the sun and the sky, but incorporates reflections from building materials, foliage, and terrain.

However, the results from the simulations are quicker and will provide more insight into the space's performance during different times of the year as opposed to point-in-time daylight model or field study measurements. In addition, simulation methods are beneficial to test building designs that are in the schematic and design stages as opposed to post-occupancy field study evaluations.

Table 2 Differences in results for clear and bronze tinted glazing for vertical, North orientation measurements at 30ft.

	Clear	Bronze	
Lux	9709	3772	Daylight Model
	5623.93	1419.64	Computer Simulation
EML	9170	2560	Daylight Model
	5706.40	1329.51	Computer Simulation
CS	0.69	0.63	Daylight Model
	0.68	0.59	Computer Simulation

The spectroradiometer used in the daylight model study recorded illuminance levels, circadian stimulus, and equivalent melanopic lux simultaneously, whereas ALFA results do not directly output circadian stimulus. The results' spectral data needs to be converted using the calculator developed by the Lighting Research Center at Rensselaer Polytechnic Institute. In order to determine if the differences in circadian stimulus were noticeable, the greatest change in the daylight model was noted – clear and bronze tints, vertical, North orientation at 30ft (0.69 and 0.63 CS respectively, with a difference of 0.06 CS). The simulations spectral results of this case were then calculated to establish if the magnitude of change would be as minimal. As shown in Table 2, the calculated results indicate that the differences in CS for this same case in the simulation model is 0.09 CS. The recommended levels aim for a circadian stimulus greater than 0.3 during the day. The lowest recorded measurement, 0.63 CS in this study, is well above the recommended benchmark so circadian stimulus results were disregarded as the differences were minimal.

Illuminance levels and equivalent melanopic lux results for the daylight model and ALFA computer simulation model were compiled in Table 3. These were focused on the horizontal plane and vertical, south-facing measurements to show the greatest differences under the clear, blue, and bronze tint scenarios at 5-30ft. The values were plotted in Figure 9 to depict the changes in both the daylight model and computer simulation results as the distance from the window increases. The bar charts represent horizontal illuminance measurements and vertical, south-facing measurements for both illuminance and EML, as EML is only applicable in the vertical plane.

At a glance, the charts plotted in Figure 9 look very similar. This indicates that illuminance levels and equivalent melanopic lux measurements follow the same trends. It is also noted that the vertical, south-facing measurements are always higher than the horizontal measurements which highlight the need to take orientation into consideration as lighting designers may overdesign or under design the design scheme if they base their concept on the horizontal plane only.

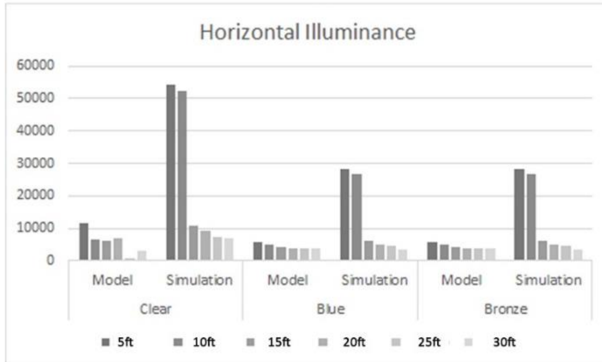
Upon close inspection of the individual glazing performance, the results for the daylight model and simulation model differ. In the simulation model results, clear glazing is clearly followed by blue tint and lastly bronze tint glazing. There is a clear distinction in the charts and table values. In the daylight model results there are some discrepancies where the blue and bronze tints vertical measurements can be higher than clear horizontal measurements. The blue and bronze tint horizontal measurements are also too close to establish strong conclusions. These inconsistencies can be due to inaccuracies from the method which caused timing differences.

What can be derived as a general conclusion from these studies is that clear glazing is best performing in terms of photopic and circadian light transmittance, followed by blue tints and bronze tints. This series of pilot studies have also shown that using a computer simulation model with ALFA is the most suitable method to fulfill the study's objectives of assessing the circadian potential of a space. A computer simulation model will allow for quicker, more reliable results in a shorter time frame.

Table 3 Compilation of daylight model and ALFA simulation results for horizontal and vertical, South facing illuminance levels and equivalent melanopic lux of clear, blue and bronze tinted glazing.

Illuminance (Lux)					
		Horizontal		Vertical, South	
	Distance	Model	Simulation	Model	Simulation
CLEAR	5ft	11561	54401	32559	56544
	10ft	6687	52200	22091	54023
	15ft	6337	10929	19558	15708
	20ft	6814	9333	18041	12475
	25ft	823	7228	16650	11269
	30ft	2979	6790	15578	11002
BLUE	5ft	5953	28328	14359	29089
	10ft	4934	26860	6486	28007
	15ft	4371	6166	5828	8279
	20ft	3974	5046	5271	7054
	25ft	3932	4583	4842	6108
	30ft	3972	3525	4838	5594
BRONZE	5ft	5955	9233	23548	10156
	10ft	5662	8930	11746	9705
	15ft	4654	2417	9040	3386
	20ft	4250	1962	8137	2788
	25ft	4316	1642	7302	2440
	30ft	4075	1467	6689	2094

Equivalent Melanopic Lux (EML)					
		Horizontal		Vertical, South	
	Distance	Model	Simulation	Model	Simulation
CLEAR	5ft	11061	51406	32751	53387
	10ft	6123	48592	22406	50531
	15ft	5788	9933	19370	15255
	20ft	6323	8415	17551	12073
	25ft	533	6563	15918	10814
	30ft	2473	5984	14741	10508
BLUE	5ft	4760	27560	15979	28312
	10ft	3795	25635	7467	27012
	15ft	3248	6179	6601	8485
	20ft	2962	4918	5829	7274
	25ft	2806	4476	5256	6303
	30ft	2873	3407	5180	5732
BRONZE	5ft	3845	8570	15768	9301
	10ft	3709	8102	8213	8857
	15ft	3007	2065	6335	3071
	20ft	2736	1673	5581	2556
	25ft	2659	1371	4967	2231
	30ft	2624	1216	4474	1898



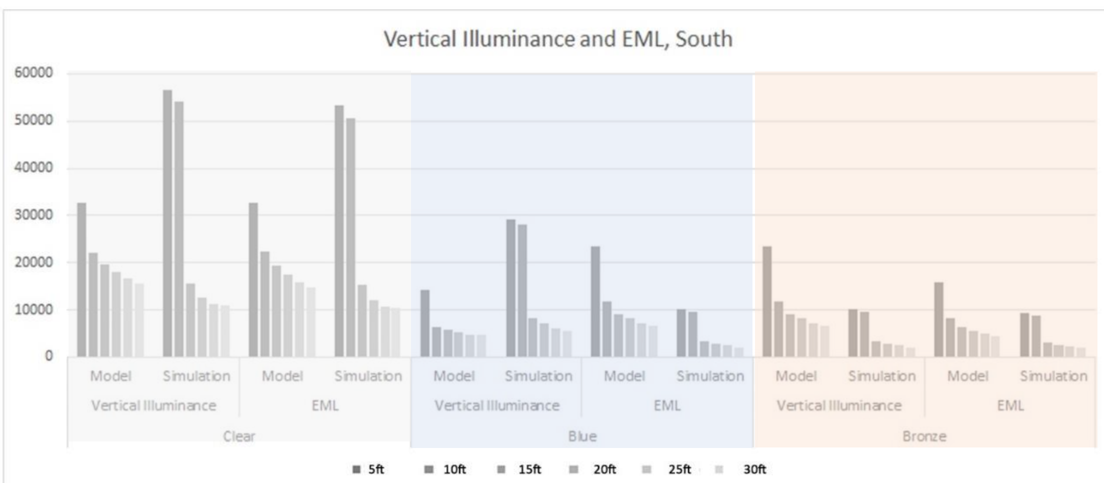


Figure 9 Plotted charts of daylight model and ALFA simulation results for horizontal and vertical, south facing illuminance levels and equivalent melanopic lux of clear, blue and bronze tinted glazing.

3.3. Building Selection

A repository by Shpuza (2006) was used to detail fifty office buildings in various locations to potentially use for the study (Table 4, Figure 10). To determine the predominant interior layout, the percentage of open plan and cellular floor area was calculated. Floor plate types were characterized using Shpuza's proposed concepts: The Relative Grid Distance (RGD) and Convex Fragmentation (CF). For the proposed study, buildings across all six office floor plate type categories will be nominated: compact blocks external core, bars, deep space small central core, shallow space large central core, pavilions, and wings. From the inventory of nominated buildings, cellular, open plan and mixed interior layouts will be selected to establish a diverse list and range of office environments within the parameters of the scope of the study.

Table 4 Building selection repository

#	Name	Architect (Shell - Layout)	Location	Net Floor Area (sq ft)	Cellular % of Floor Area	Open Plan % of Floor Area	Predominant Layout Type	Floor Plate Type
1	3com Corporation	Studios Architecture - Studios Architecture	Santa Clara, CA, USA	38,700	0	32.6	Open Plan	Pavilions
2	Andersen (after move)	Mies van der Rohe - DEGW & SOM	Chicago, IL, USA	31,200	12.9	29.5	Mixed	Deep Space, Small Central Core
3	Andersen (before move)	Unknown - Unknown	Chicago, IL, USA	14,100	43.6	28.5	Mixed	Deep Space, Small Central Core
4	Allen & Overy	The Associated Architects - The Switzer Group	New York, NY, USA	8,300	41.3	10.6	Cellular	Bars
5	Arthur Andersen	Unknown - BDG McColl	London, UK	12,700	0	35.6	Open Plan	Bars
6	Apicorp	DEGW, Ove Arup & Assoc. - DEGW	Al Khober, Saudi Arabia	39,100	30.5	5.5	Cellular	Pavilions
7	Apple Computer Inc.	Unknown - Gensler	Cupertino, CA, USA	48,900	5.2	33.3	Open Plan	Shallow Space, Large Central Core
8	Andersen Consulting	F. Gehry & Milunić - E. Jiřičná Architects	Prague, Czech Republic	4,450	18.7	13.2	Mixed	Deep Space, Small Central Core
9	Buch und Ton	Unknown - The Quickborner Team	Gütersloh, Germany	24,300	0	48.5	Open Plan	Compact Blocks, External Core
10	Chase Manhattan Bank	Carson, Lundin & Shaw - The Switzer Group	New York, NY, USA	38,800	9.7	24.2	Mixed	Compact Blocks, External Core
11	Chiat/Day Advertising	F. Gehry & Associates - F. Gehry & Associates	Venice, CA, USA	18,700	0	30.9	Open Plan	Wings
12	TBWA Chiat/Day	Emery Roth & Sons - Gaetano Pesce	New York, NY, USA	21,500	3	17.3	Open Plan	Deep Space, Small Central Core
13	Citicorp	SOM - SOM	New York, NY, USA	22,800	20.8	33.8	Mixed	Shallow Space, Large Central Core
14	Commerzbank AG	Sir N. Foster & Partners - Sir N. Foster & Partners	Frankfurt, Germany	12,300	67.3	0.5	Cellular	Pavilions
15	Data Firmengruppe	Kauffmann Theilig - Kauffmann Theilig	Gniebel, Germany	12,900	31.3	31.5	Mixed	Pavilions
16	Davis Polk & Wardwell	SOM - Gensler	New York, NY, USA	24,500	44.8	12.2	Mixed	Deep Space, Small Central Core
17	DEGW London Office	Unknown - DEGW	London, UK	14,350	0	21	Open Plan	Deep Space, Small Central Core
18	Discovery Channel Latin Am.	Unknown - Studios Architecture	Miami, FL, USA	21,450	23.5	17.3	Mixed	Shallow Space, Large Central Core
19	DuPont	Unknown - The Quickborner Team	Wilmington, DE, USA	10,200	0	42.7	Open Plan	Compact Blocks, External Core
20	The Equitable	Harrison & Abramovitz & E. Roth - Switzer Group	New York, NY, USA	18,500	10	43.3	Open Plan	Shallow Space, Large Central Core
21	Ford Foundation	Roche/Dinkerloo & Assoc. - Roche/Dinkerloo	New York, NY, USA	11,900	53.2	10.2	Cellular	Wings
22	Ford Motor Co.	Unknown - The Quickborner Team	Cologne, Germany	23,350	0	59.6	Open Plan	Compact Blocks, External Core
23	f/X Networks	Johnson, Fain & Pereira - Fernau & Hartman	Los Angeles, CA, USA	16,550	28.1	21.5	Mixed	Shallow Space, Large Central Core
24	Greenberg Traurig	Emery Roth & Sons, Gropius - Switzer Group	New York, NY, USA	25,800	43.8	9.5	Cellular	Shallow Space, Large Central Core
25	Hoffmann La Roche	The Hillier Group - Gensler	Nutley, NJ, USA	30,000	1.6	32.3	Open Plan	Deep Space, Small Central Core
26	IBM Regional Headquarters	Unknown - The Switzer Group	Cranford, NJ, USA	86,500	0	27.6	Open Plan	Compact Blocks, External Core
27	IBM (UK) Limited	M. Hopkins & Partners - M. Hopkins & Partners	London, UK	35,000	19	18	Mixed	Pavilions
28	IBM Australia	Buchan, Laird & Bawden - Daryl Jackson Intl.	Melbourne, Australia	12,300	31.7	2.9	Cellular	Shallow Space, Large Central Core
29	Interpolis	Abe Bonema - Abe Bonema, Kho le Associates	Tilburg, Holland	4,850	28.8	16.8	Mixed	Compact Blocks, External Core
30	Direct. of Telecom., MPBW	Whitehall Dev. Group - Whitehall Dev. Group	Kew, UK	14,400	0	58.3	Open Plan	Deep Space, Small Central Core
31	Eastman Kodak	Unknown - The Quickborner Team	Rochester, NY, USA	28,300	0	67	Open Plan	Compact Blocks, External Core
32	Lend Lease Interiors	H. Seidler, P.L. Nervi - Bligh Voller, DEGW	Sydney, Australia	8,450	4.5	42.4	Open Plan	Shallow Space, Large Central Core
33	Leo A Daly	Thompson, Ventulett, Stainback - TVS	Atlanta, GA, USA	21,050	0	28.4	Open Plan	Deep Space, Small Central Core
34	Lowe & Partners/SMS	SOM - Sedley Place	New York, NY, USA	20,900	49.5	5.5	Cellular	Shallow Space, Large Central Core
35	McDonald's	Heikkinen Komonen - Heikkinen Komonen	Helsinki, Finland	15,450	6.5	25.5	Open Plan	Deep Space, Small Central Core
36	McDonald's Italia	Atelier Mendini - Atelier Mendini	Milan, Italy	21,500	8.2	19.2	Mixed	Compact Blocks, External Core
37	MGIC	SOM - Warren Platner Associates	Milwaukee, WI, USA	20,150	27.6	13.6	Mixed	Deep Space, Small Central Core
38	Nickelodeon	Kahn & Jacobs, Der Scutt - Fernau Hartman	New York, NY, USA	24,300	8.5	38.5	Open Plan	Deep Space, Small Central Core
39	Olivetti A	DEGW, Studio De Luchi - DEGW, De Luchi	Bari, Italy	5,650	7.9	68.7	Open Plan	Compact Blocks, External Core
40	Olivetti B	DEGW, Studio De Luchi - DEGW, De Luch	Bari, Italy	5,650	4.1	62.9	Open Plan	Compact Blocks, External Core
41	Olivetti C	DEGW, Studio De Luchi - DEGW, De Luch	Bari, Italy	5,650	4.7	73.8	Open Plan	Compact Blocks, External Core
42	Orenstein Koppel	Unknown - The Quickborner Team	Dortmund, Germany	17,500	0	38.8	Open Plan	Deep Space, Small Central Core
43	Sears 40	SOM - SIS/Environetics Inc.	Chicago, IL, USA	44,100	17.1	32.7	Mixed	Deep Space, Small Central Core
44	Sears 70	SOM - The Environments Group	Chicago, IL, USA	23,100	39.7	8.9	Cellular	Deep Space, Small Central Core
45	Steelcase Inc.	WBDC, Inc. - Steelcase	Grand Rapids, MI, USA	20,200	0	38.9	Open Plan	Compact Blocks, External Core
46	British Telec., 5 Longwalk	Sir N. Foster & Partners - Sir N. Foster & Partners	London, UK	54,400	4.8	51.4	Open Plan	Pavilions
47	British Telec., The Square	Arup Associates - Arup Associates, DEGW	London, UK	16,450	5.7	42.5	Open Plan	Deep Space, Small Central Core
48	Vitra International AG	F. Gehry & Associates - F. Gehry & Associates	Basel, Switzerland	10,100	22.7	31.7	Mixed	Bars
49	Weyerhaeuser Company	SOM - Sidney Rodgers & Associates	Tacoma, WA, USA	41,750	0	45	Open Plan	Deep Space, Small Central Core
50	WMA Consulting Engineers	Unknown - Valerio Dewalt Train & Associates	Chicago, IL, USA	17,300	12.1	36.6	Mixed	Compact Blocks, External Core

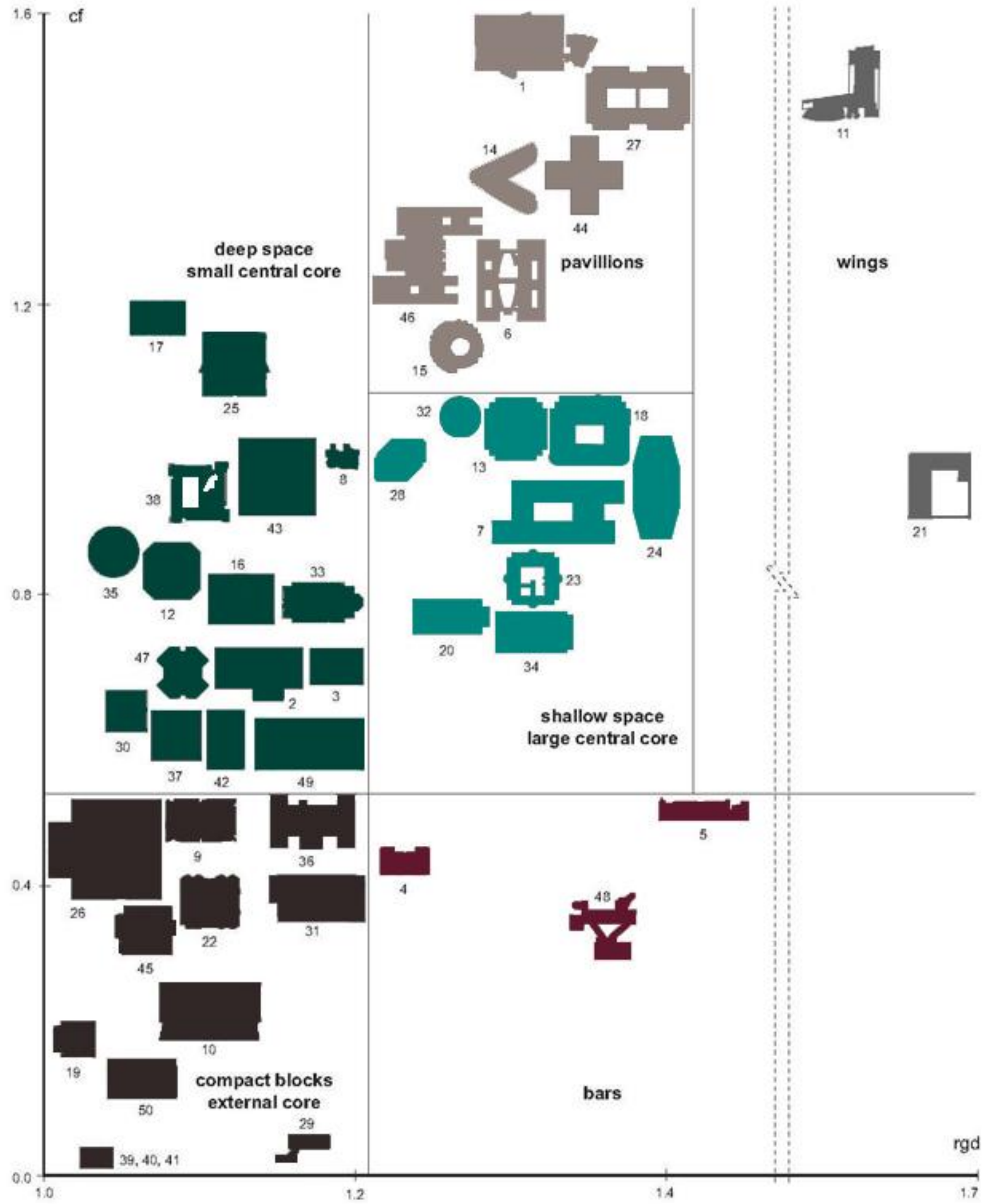


Figure 10 Floor plate and office layout plot of the building repository based on the relative grid distance (rgd) and convex fragmentation (cf). ((Shpuza, 2006) reproduced by Sadiqa Al Awadh)

Floor Plate Types

Compact Blocks External Core (rgd<1.2 and cf<0.5).

It includes floor plates with compact shapes and those with external cores and a few and small internal cores.

Bars (rgd>1.2 and cf<0.5).

It includes floorplates with elongated rectangular shapes and external cores.

Deep Space Small Central Core (rgd<1.2 and cf>0.5).

It includes floorplates with internal cores where dimensions of cores are relatively small in comparison to the depth between core and perimeter. The increase of cf, moving vertically along the y-axis is associated with a greater number of internal cores.

Shallow Space Large Central Core (1.2<rgd<1.4 and 0.5<cf<1).

It includes floorplates with ring-like configurations of shapes with large holes, which correspond to large cores in high-rise buildings, central atria, and internal courtyards.

Pavilions (1.2<rgd<1.4 and cf>1)

It includes floorplates with distinct pavilions and floorplates with many large internal cores or atria.

Wings (rgd>1.4 and cf>0.5)

It includes elongated floorplates broken into distinct wings.

The previous pilot studies have settled that the ALFA computer simulation method is the most appropriate method to be used to fulfill the goals of the scope of the larger study. The following sensitivity studies were performed to establish the simulation conditions to be used for the larger study. The first section covers contextual parameters which include the simulation time/season, location, sky conditions, surrounding context, and building obstructions as well as exterior light reflectance. The second section details the design parameters of the buildings to be simulated, this includes shading devices, interior light reflectance, glazing, and building form/geometry. The last section assesses interior layouts from an isovist and occupant point of view.

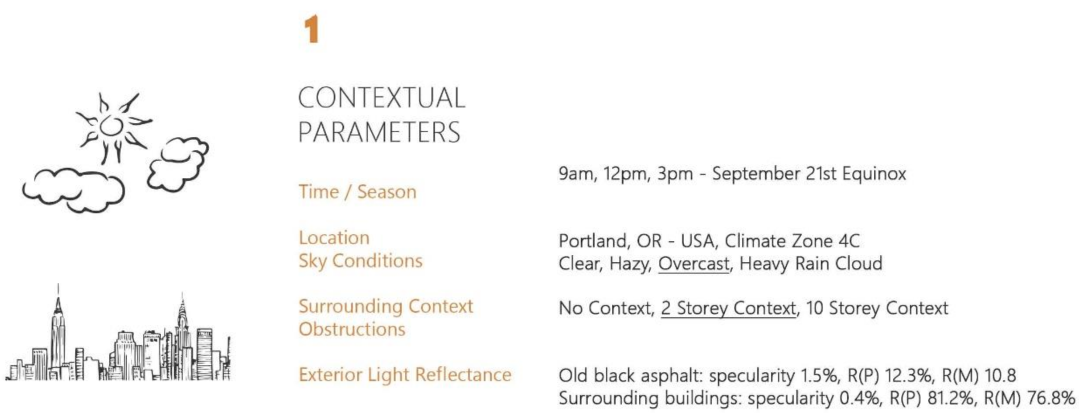


Figure 11 Study settings contextual parameters.

In the following section the contextual parameters were tested and the simulation settings are finalized as follows. For the simulation context, three times are to be assessed: 9 am, 12 pm, and 3 pm on September 21^{st}. The location is set to Portland, Oregon in climate zone 4C with an overcast sky condition. A 2 storey building context is simulated as surrounding obstructions. From the ALFA materials library, the ground reflectance was set to old black asphalt.

3.4. Sky Conditions

Despite the temporal and spatial variation of daylight spectral distribution, daylight simulation platforms most commonly use luminance-based sky models (CIE or all-weather Perez skies) that lack spectral and colorimetric information. LARK and ALFA are the two currently available spectral daylight simulation platforms that use spectral data of skies and materials to produce daylight renderings. While LARK can take measured global spectral sky irradiance as an input, it lacks an atmospheric profile found in ALFA. Without an atmospheric profile, color renditions of the low-angle sun in the sky cannot be depicted. To further justify the use of ALFA simulations, it performs simulations on 81-color channels, whereas LARK is set up to run a maximum of 9-channel simulations. Table 5 summarizes the spectral (LARK and ALFA) and non-spectral (PEREZ) simulation parameters (Balakrishnan and Jakubiec, 2019)

Table 5 Summary of the spectral (LARK and ALFA) and non-spectral (PEREZ) simulation parameters.

Parameters	LARK	ALFA	PEREZ
Sky input	Measured spectral sky irradiance, global solar irradiance, location, time	Pre-computed spectral sky irradiance generated in libRadtran, location, time	Non-spectral and luminance based sky, global solar irradiance, location, time
Sun	Non-spectral, equal energy white source	Spectral sun	Non-spectral, equal energy white source
Atmosphere	N/A	Sky spectra is computed using an AFGL atmospheric profile	N/A
Sky condition	Determined by the global horizontal irradiance input to gendaylit program	Users can choose from overcast, hazy, heavy rain clouds	Determined by the global horizontal irradiance input to gendaylit program
Simulation format	9-channel	81-channel	Standard RGB
Material Input	Spectral material reflectance	Spectral material reflectance	RGB material reflectance

3.4.1. Simulation Pilot Study

The Bertelsmann ‘Buch und Ton’ office space was modeled in Rhino for the simulation and was analyzed using ALFA with varying sky conditions to assess the potential impact of sky conditions as a parameter on daylight availability and the circadian part of the spectrum.

The daytime sky is a powerful driver of circadian biology. Unlike (most) man-made light sources, it varies in color not only by the time of day, but also by direction of view. To simulate it accurately, ALFA deploys spectral calculations using the best-in-class radiative transfer library, libRadtran. This lets ALFA users pull up physically accurate clear, hazy, or overcast skies for any location on Earth.

All moveable obstructions were removed for the simulation, these included partitions, and planters. This was done to investigate the bare and essential floorplan structure as it is. Moveable obstructions can only hinder the floorplan's performance, but it is useful to assess the permanent floorplan. This could help designers establish a strong foundation that would then be modified by the users with moveable obstructions depending on their needs and workspace requirements. How much flexibility they have depends on the preliminary design of the building and the openness of the floorplan. In this case, the building floorplan allows for various workspace configuration.

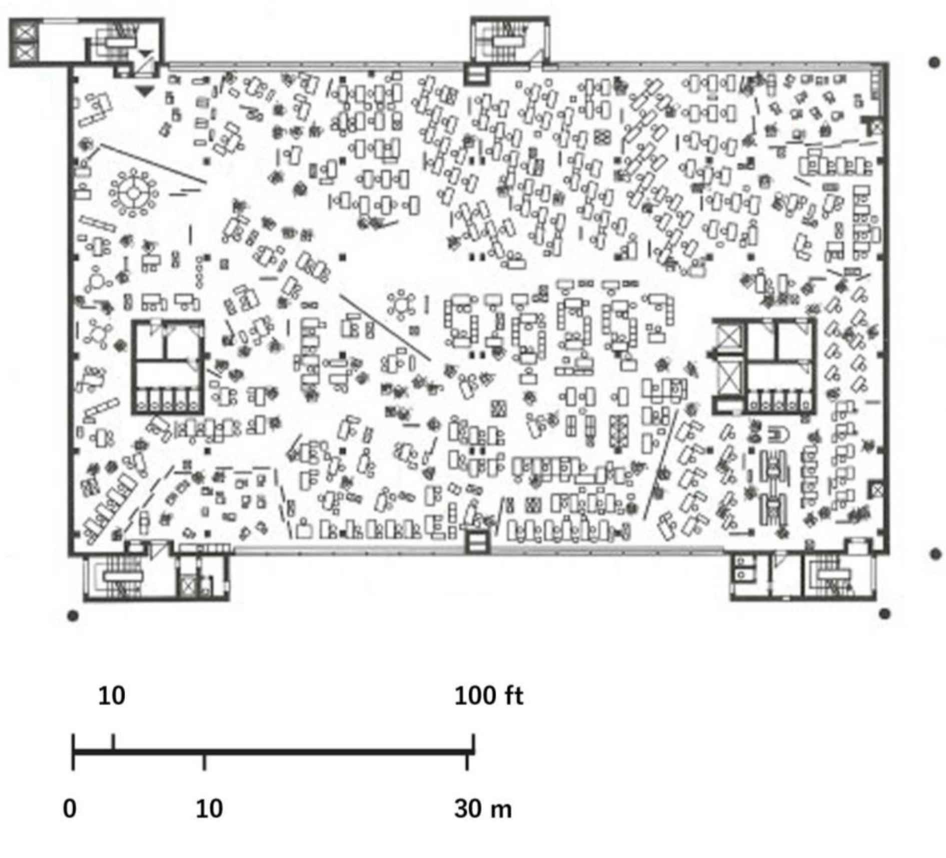


Figure 12 Buch und Ton floorplans (https://publik.tuwien.ac.at/files/PubDat_215835.pdf)

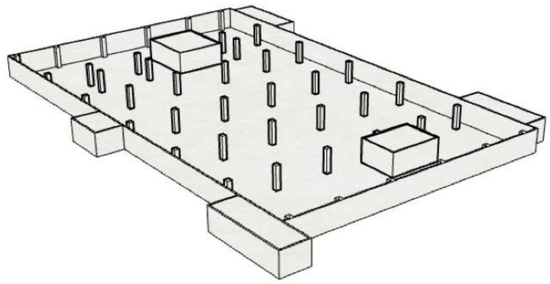


Figure 13 Empty floorplan Rhino 3D model used for the comparison simulations.

Location

Germany, Latitude (N) 51.90, Longitude (E) 8.39, Elevation (m) 22

Sky condition

- clear
- hazy
- overcast
- heavy rain cloud

Ground spectrum – uniform, albedo 0.15

Materials

Walls – white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

Floor – dark grey floor tiles: specularity 1.2%, R(P) 20.1%, R(M) 19.1%, M/P 0.95

Ceiling – white painted corridor ceiling: specularity 0.5%, R(P) 87.2%, R(M) 81.8%, M/P 0.94

Glass - double IGU clear Tvis 78%: R_front(P) 81.2%, R_front(M) 76.8%, R_back(P) 81.2%, R_back(M) 76.8%, T(P) 78.5%, T(M) 77.7%, M/P 0.99

Ground – old black asphalt: specularity 1.5%, R(P) 12.3%, R(M) 10.8%, M/P 0.87

The simulation was run at 9am, 12pm and 3pm for March 21st.

Tables 6-7 and Figure 14 summarize the simulation results. Figure 15-18 visualize the results of the building floorplan.

Table 7 Average Melanopic Lux results for the simulation model under different sky conditions and times of the day

Av. Melanopic Lux (EML)	Time of Day		
Sky Condition	**9:00 AM**	**12:00 PM**	**3:00 PM**
Clear	2624	3426	3621
Hazy	1203	2330	2076
Overcast	685	1501	1060
Heavy Rain Cloud	425	877	655

Table 6 Average illuminance results for the simulation model under different sky conditions and times of the day

Av. Horizontal Illuminance (Lux)	Time of Day		
Sky Condition	**9:00 AM**	**12:00 PM**	**3:00 PM**
Clear	2747	3401	3687
Hazy	1374	2496	2301
Overcast	683	1521	1068
Heavy Rain Cloud	413	869	644

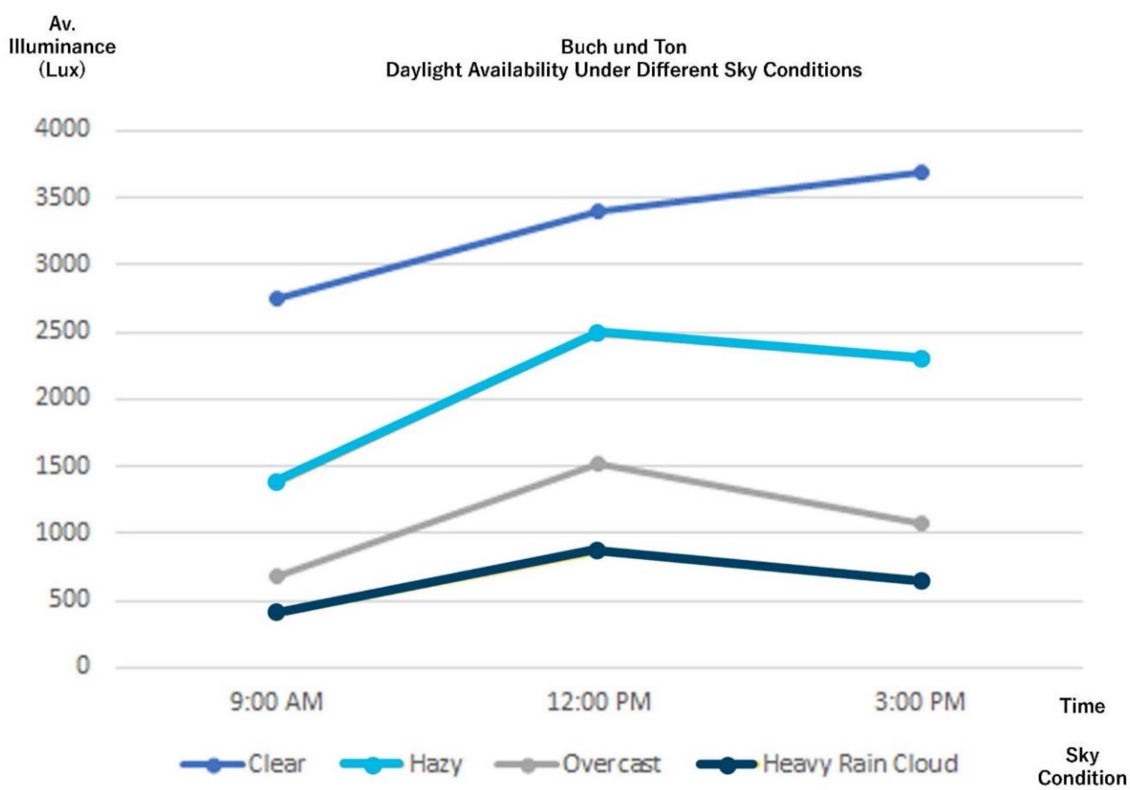


Figure 14 Plot of simulation results.

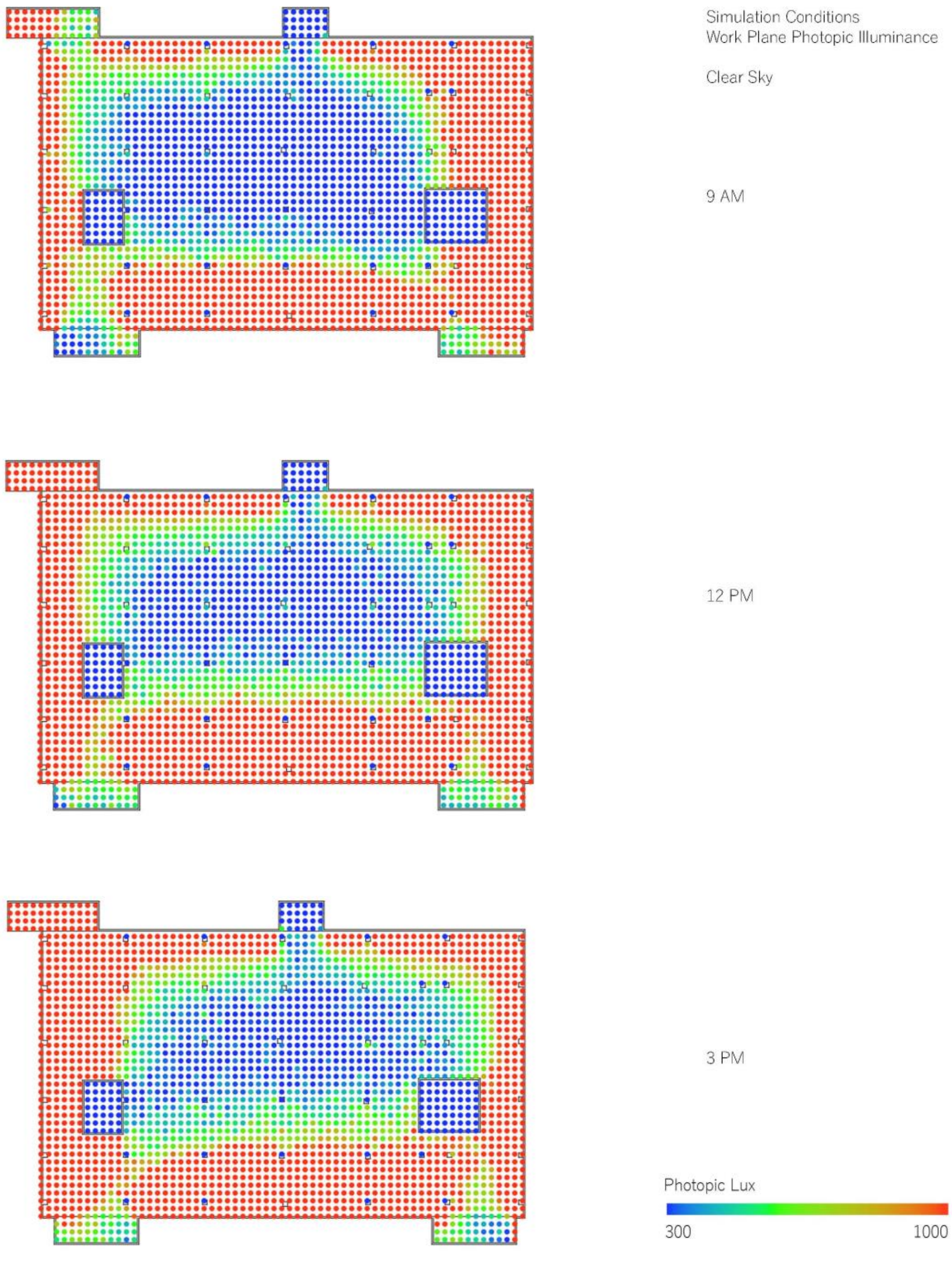


Figure 15 Clear sky conditions illuminance levels

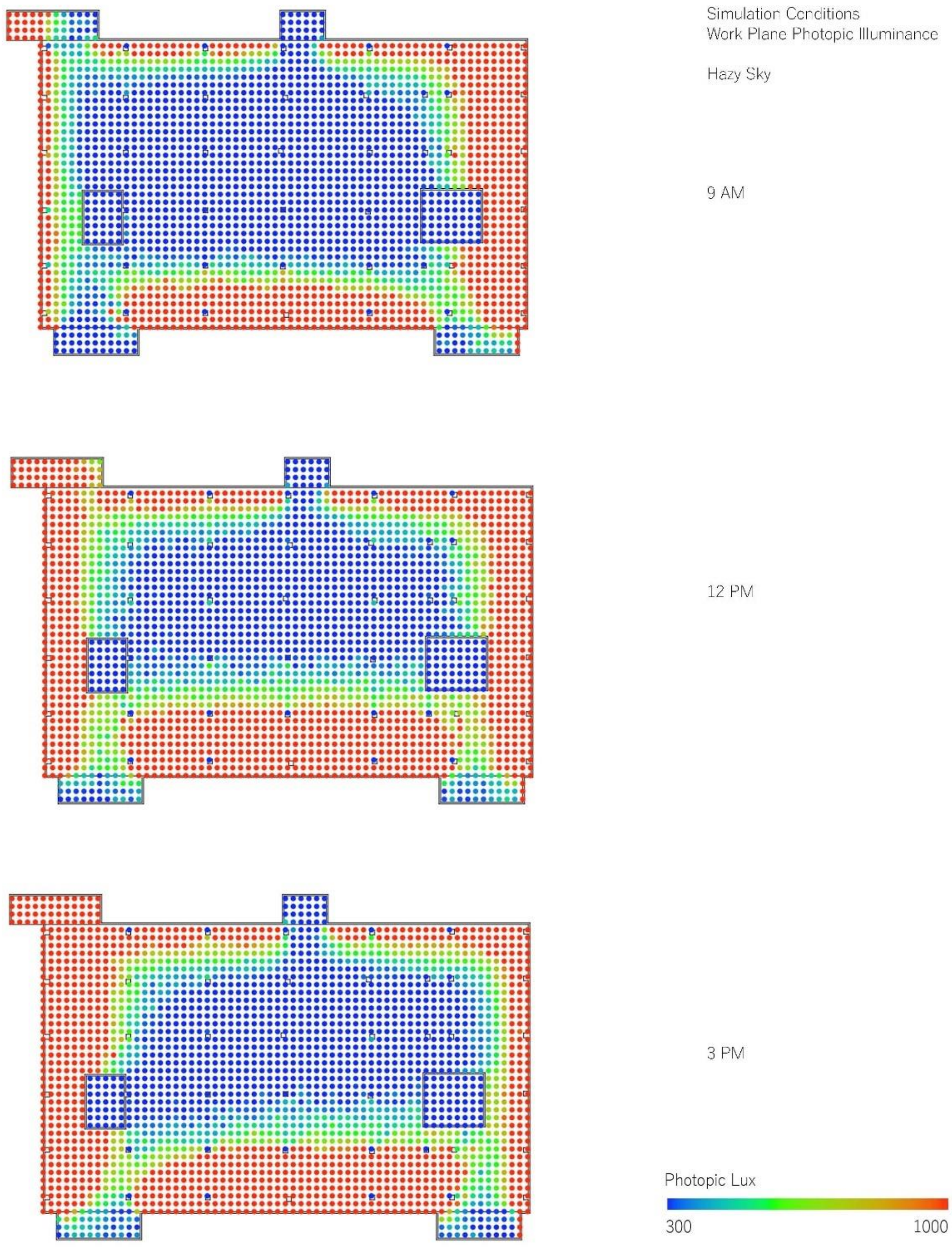


Figure 16 Hazy sky conditions illuminance levels

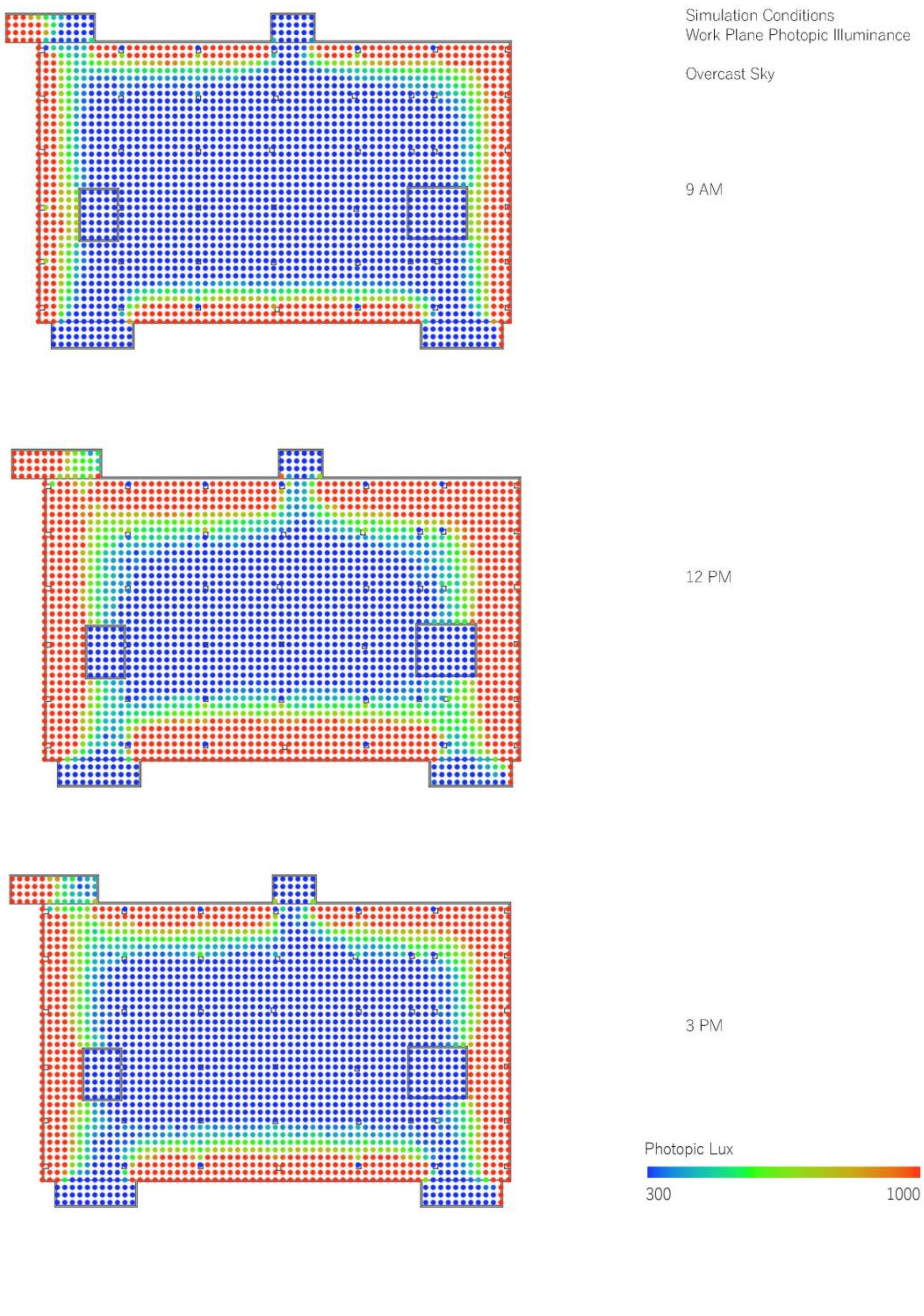


Figure 17 Overcast sky conditions illuminance levels

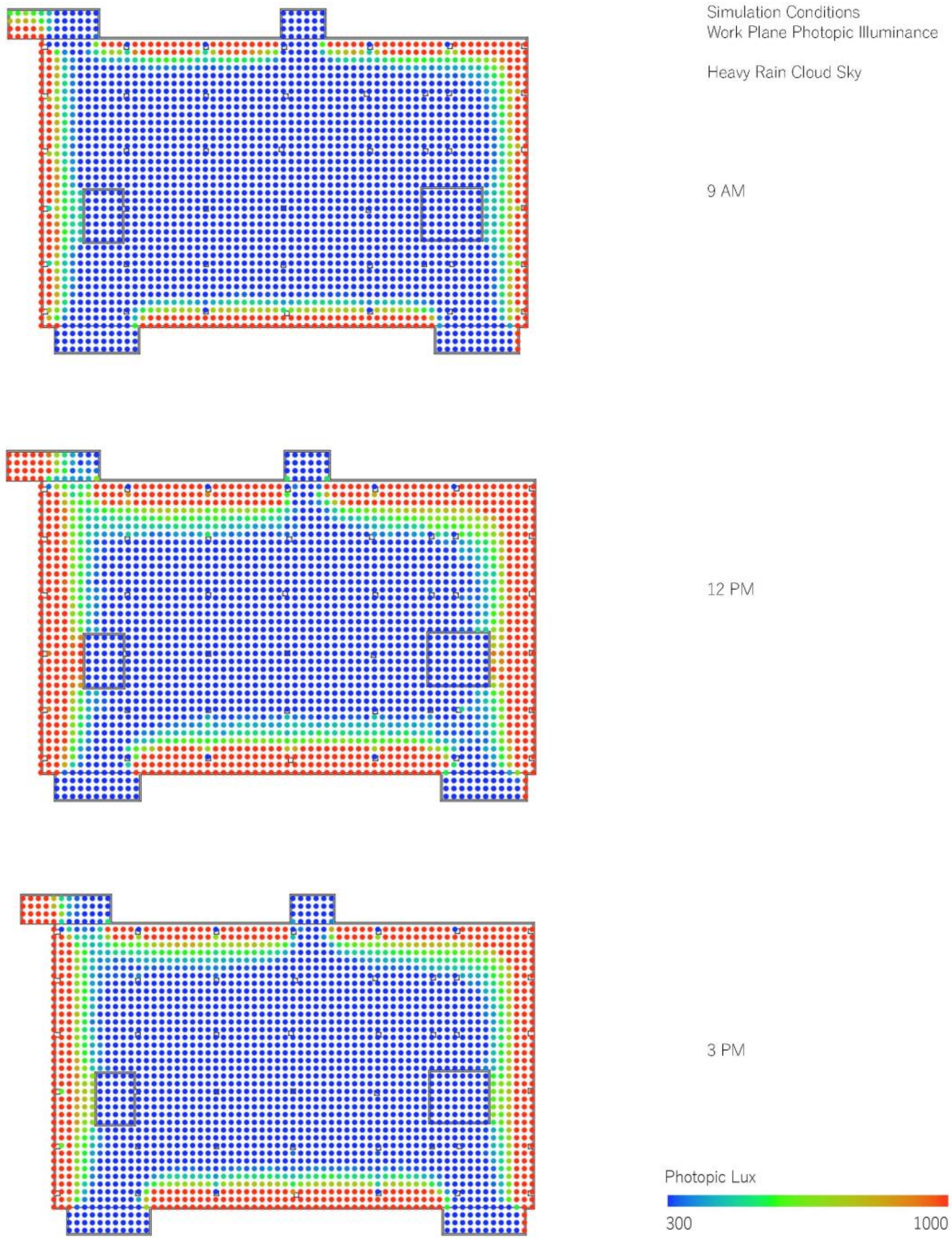


Figure 18 Heavy rain cloud sky conditions illuminance levels

As expected, the results indicate a major drop in illuminance levels and EML from clear skies as the sky conditions deteriorate to hazy, overcast, and heavy rain cloud. Both photopic illuminance and melanopic illuminance followed the same trends and had roughly the same values. The results are both numerically and visually apparent which indicates the ALFA software is sensitive enough to depict changes in the environment.

3.4.2. Climate Zone 4C

ASHRAE climate region definitions are based on heating degree days, average temperatures, and precipitation as follows: hot-humid (2A and 3A), mixed-humid (4A and 3A), hot-dry (3B), mixed-dry (4B), cold (5 and 6), very-cold (7), subarctic (8), and marine (C). A zone C marine climate is defined as a region in which the coldest month mean temperature between 27°F (-3°C) and 65°F (18°C), the warmest month mean of less than 72°F (22°C). At least 4 months with mean temperatures higher than 50°F (10°C) and a dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere (Baechler et al., 2010). Elzeyadi (2017) describes Portland, Oregon in ASHRAE climate zone 4C as a representative of a city in a moderate climate zone in the middle of the range of values for shading impacts on energy and occupants' indoor comfort.

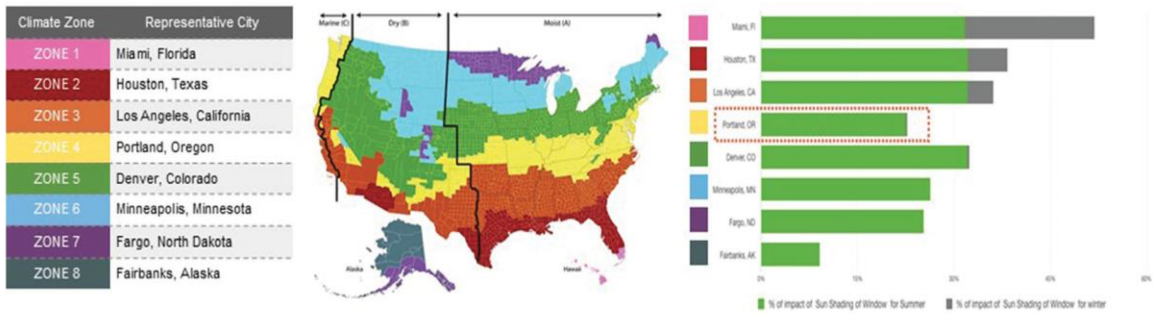


Figure 19 Climate zone city representatives (Elzeyadi, 2017).

Portland, OR Climate Zone 4C

Table 8 METAR Sky conditions (National Weather Service, 2019).

SKC	"Sky clear" = 0 oktas	0-25% cloud cover
FEW	"Few" = 1–2 oktas	26 – 50% cloud cover
SCT	"Scattered" = 3–4 oktas	51 - 69% cloud cover
BKN	"Broken" = 5–7 oktas	70 - 87% cloud cover
OVC	"Overcast" = 8 oktas	88 – 100% cloud cover

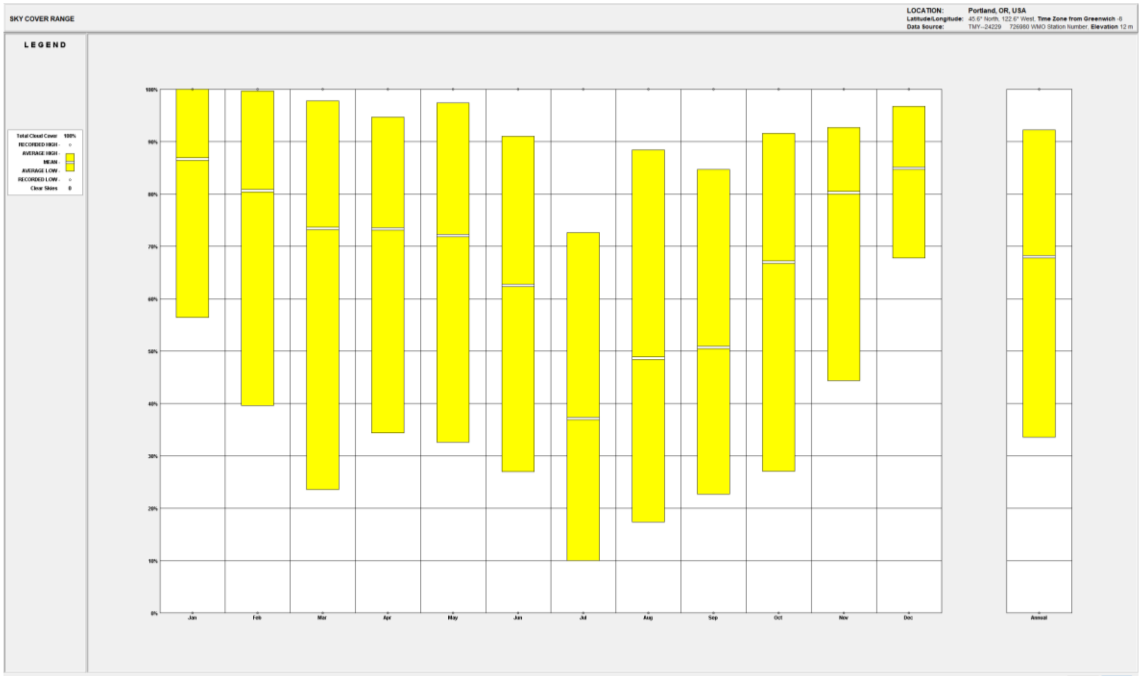
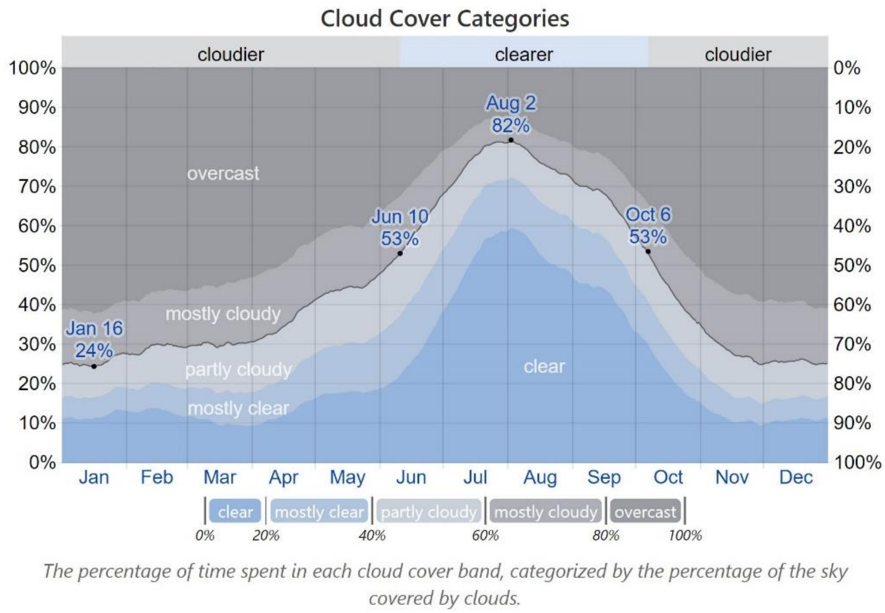


Figure 20 Annual sky cover range (Climate Consultant, 2019).

In Portland, the average percentage of the sky covered by clouds experiences extreme seasonal variation over the course of the year with a 68% cloud coverage as the annual average. The clearer part of the year in Portland begins around June 10 and lasts for 3.9 months, ending around October 6. On August 2, the clearest day of the year, the sky is clear, mostly clear, or partly cloudy 82% of the time, and overcast or mostly cloudy 18% of the time. The cloudier part of the year begins around October 6 and lasts for 8.1 months, ending around June 10. On January 16, the cloudiest day of the year, the sky is overcast or mostly cloudy 76% of the time, and clear, mostly clear, or partly cloudy 24% of the time.



The percentage of time spent in each cloud cover band, categorized by the percentage of the sky covered by clouds.

Figure 21 Portland annual cloud cover (Weather Spark, 2019).

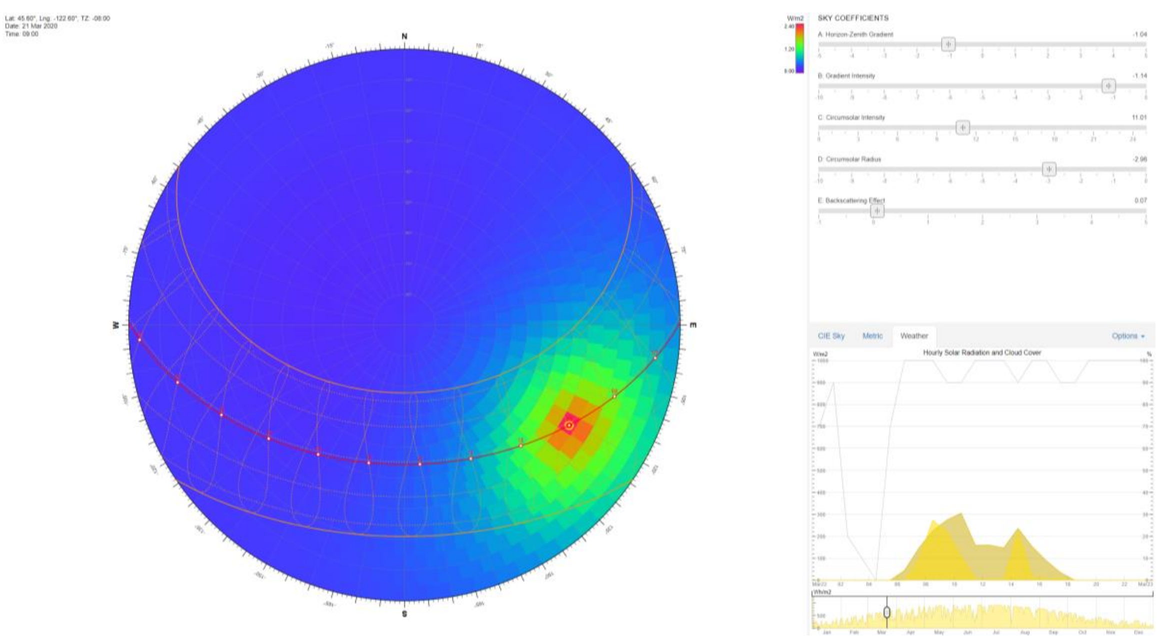


Figure 22 Portland sky coefficients (Climate Consultant, 2019).

3.5. Building Context

The aim of this study is to investigate the effect of a building's context on daylight availability. Surrounding building heights were simulated (0 storey/ no context, 2 storey and 10 storey high) as variables for the simulation.

Location

Portland, OR: Latitude (N) 45.52, Longitude (E) -122.68, Elevation (m) 15

Sky condition – overcast

Time – 9am

Ground spectrum – uniform, albedo 0.15

Materials

Walls – white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

Floor – dark grey floor tiles: specularity 1.2%, R(P) 20.1%, R(M) 19.1%, M/P 0.95

Ceiling – white painted corridor ceiling: specularity 0.5%, R(P) 87.2%, R(M) 81.8%, M/P 0.94

Glass - double IGU clear Tvis 78%: R_front(P) 81.2%, R_front(M) 76.8%, R_back(P) 81.2%, R_back(M) 76.8%, T(P) 78.5%, T(M) 77.7%, M/P 0.99

Ground – old black asphalt: specularity 1.5%, R(P) 12.3%, R(M) 10.8%, M/P 0.87

Surrounding Building Context – white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

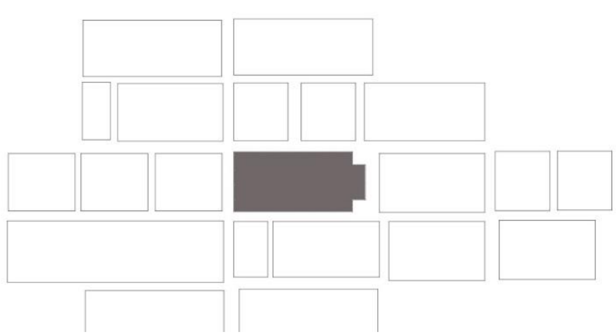


Figure 23 Surrounding building context used for the simulation settings.

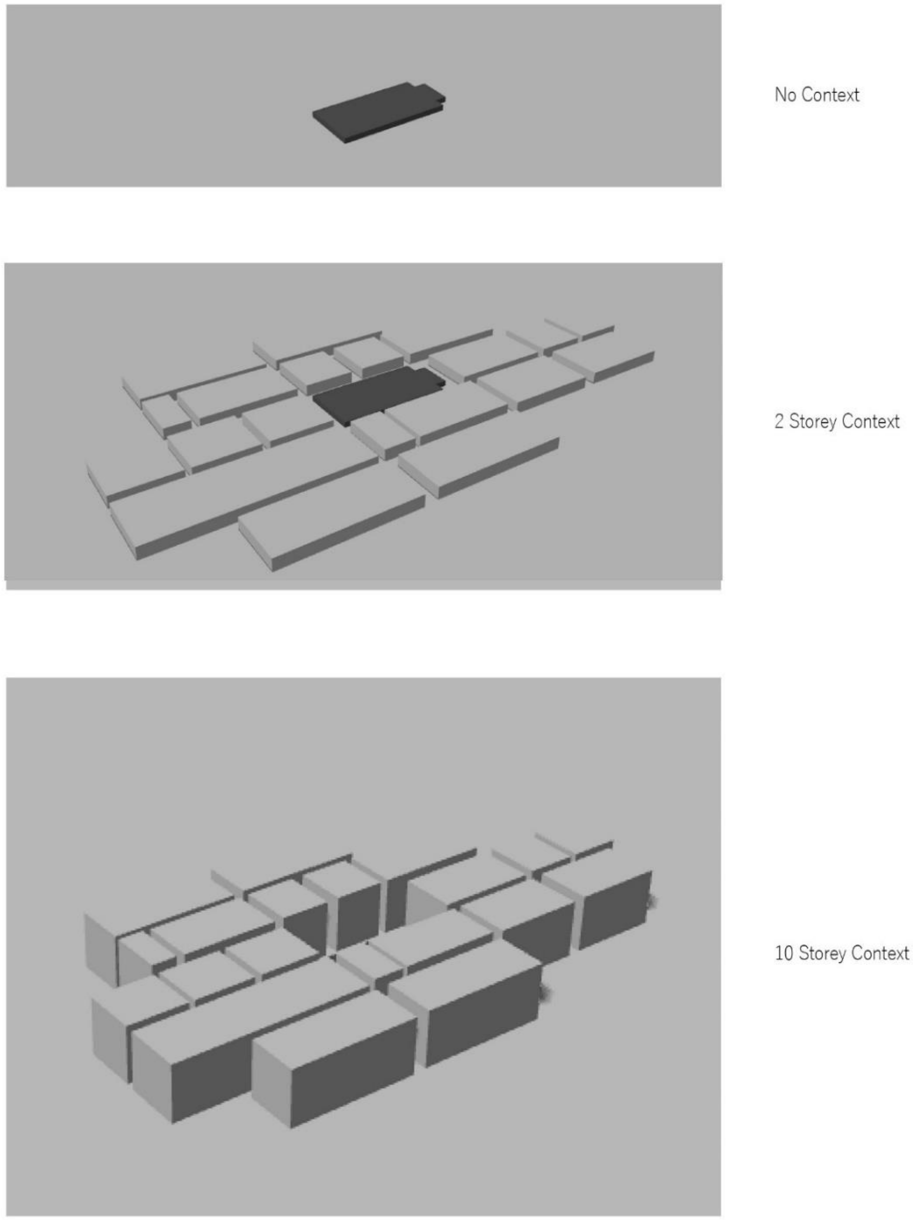


Figure 24 Storey heights simulation variable.

Results from average work plane illuminance are summarized in Table 9 and Figure 25. Figure 26 visually displays illuminance results of the building floorplan under different contextual storey height conditions.

Table 9 Average work plane illuminance simulation results.

	Average Workplane Illuminance (Lux)
No Context	2039
2 Storey Context	1806
10 Storey Context	1041

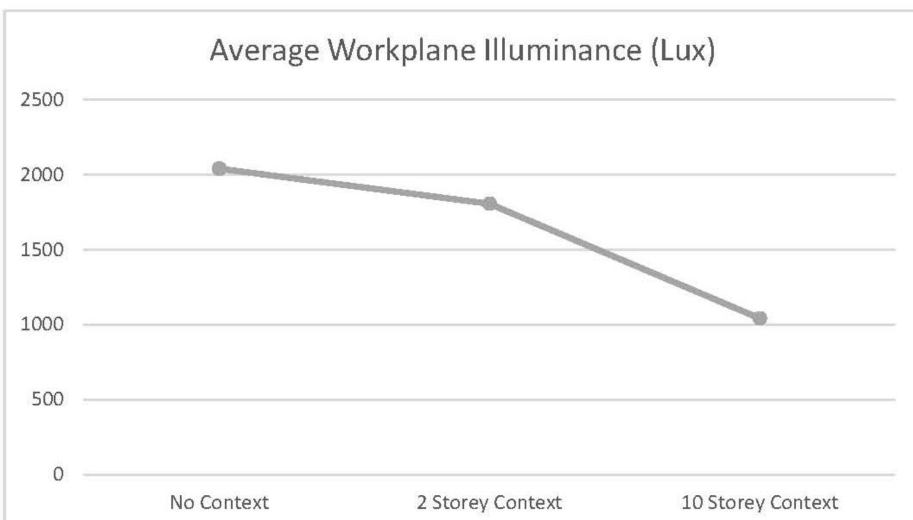


Figure 25 Plot of average work plane illuminance in different context heights.

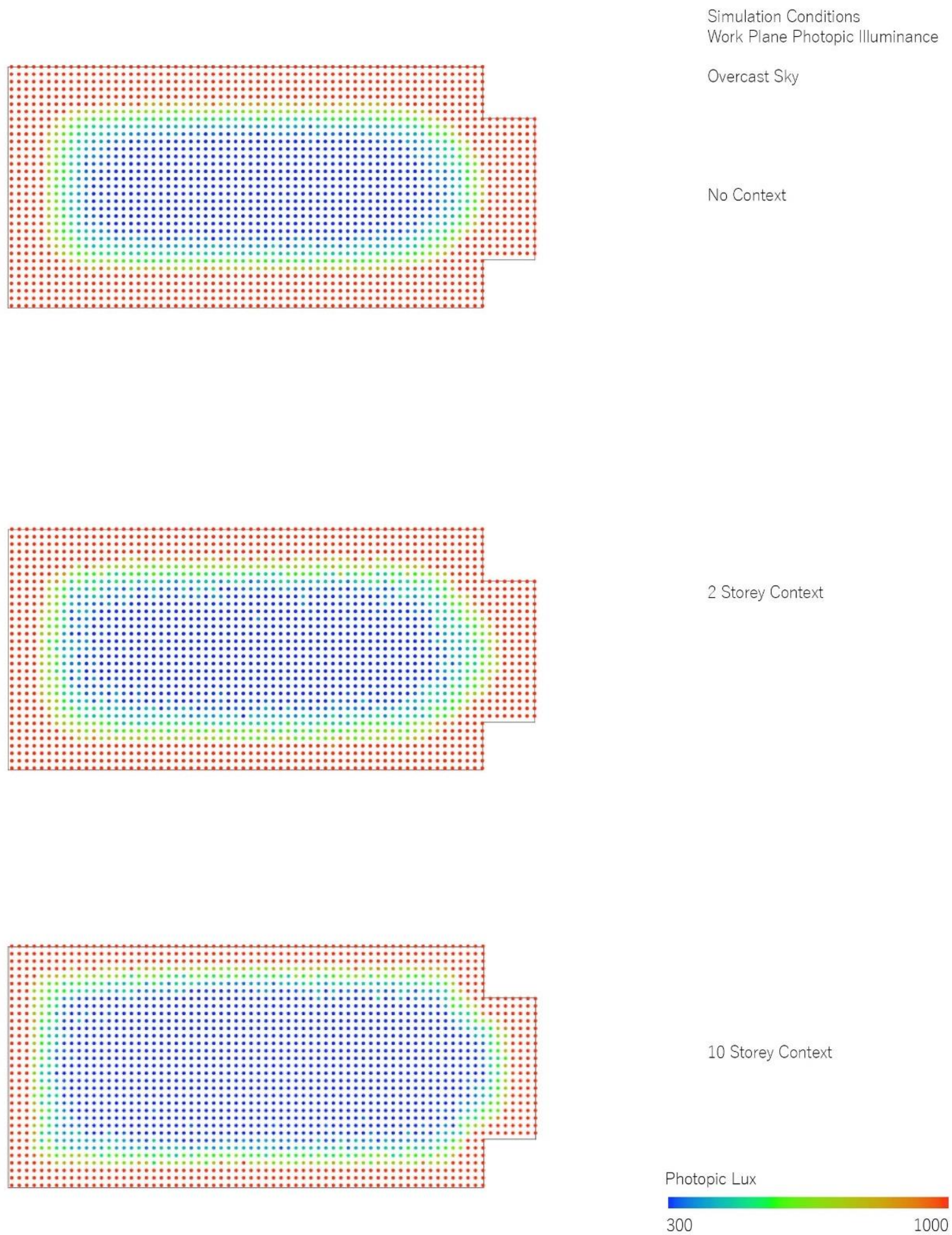


Figure 26 Work plane illuminance in different context heights

The results in Table 1 and Figure 5 clearly indicate a noticeable drop in illuminance levels as the surrounding buildings' height increases.   Figure 26 visualizes how the core receives less light and the perimeter zone diminishes with the increasing context height.

Moving forward in the final dissertation study, including a building context with at least 2 storey building height's surrounding would portray a more realistic setting for the simulation than a stand-alone building. It would also provide more difficult conditions which would urge designers to aim for designing for worst-case scenarios.

In the literature, a study conducted by Strømann-Andersen and Sattrup (2011) analyzed the distribution of solar radiation and daylight in a range of urban canyons reflecting different urban densities and demonstrated how this distribution affects the total energy use for heating, cooling, and artificial lighting on different storeys of low-energy buildings facing the urban canyon. It was found that the geometry of urban canyons has a relative impact on total energy consumption, compared to unobstructed sites, in the range of up to +30% for offices, indicating that urban geometry is a key factor in energy use in buildings. The results presented indicated that energy consumption for artificial light increases in lower levels of buildings due to lower daylight levels. These findings support the conclusions of the pilot study conducted. Their investigation also showed that reflected light makes an important contribution to the energy consumption of buildings and is the greatest fraction of daylight available to housing and offices on the lowest floors in high urban densities.

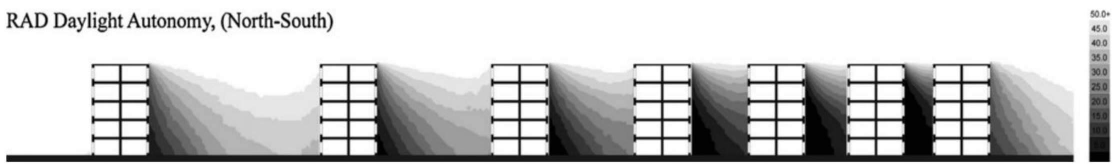


*Figure 27 Annual illuminance > 10,000 lx in street canyon. Calculated in RADIANCE/DAYSIM (working hours 08–17, contour range 0–50% in steps of 5%). Weather data, Copenhagen (*epw). (Strømann-Andersen and Sattrup, 2011).*

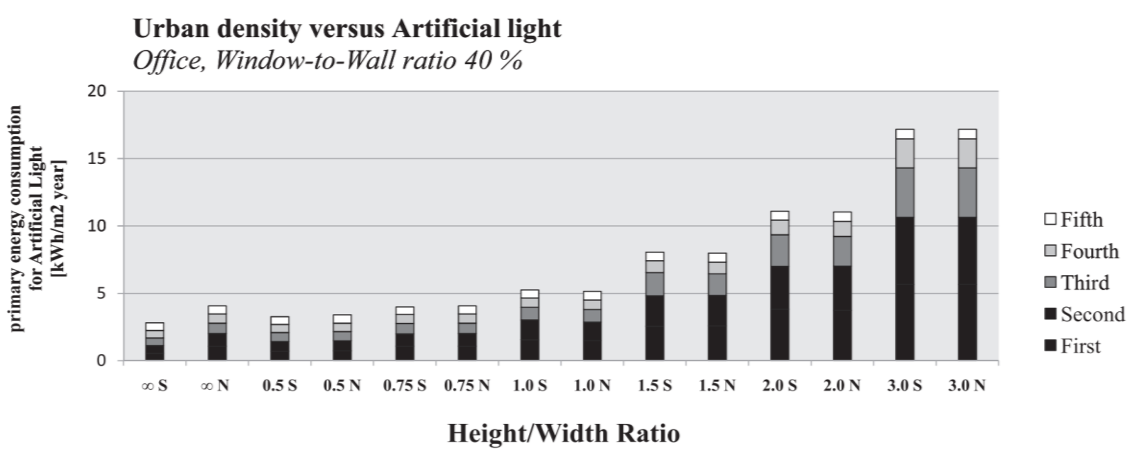


Figure 28 Primary energy consumption for artificial light (kWh/m2/year) for a 5-storey office building (north/south) as a function of urban density (Strømann-Andersen and Sattrup, 2011).

Figure 29 Study settings design parameters.

In the following section the design parameters were tested, and the simulation settings are finalized as follows. No shading devices will be assigned to the windows. For the interior, the following materials were used: white painted room walls, dark grey floor tiles, white painted ceiling. The building is fully glazed with a clear curtain wall.

3.6. Glazing Tint

The aim of this study is to investigate the effect of different glazing tints (clear, blue tint, bronze tint) on daylight availability. Three office buildings with various geometries were simulated with different glazing tints to draw results that confirm a similar trend in their effect on daylight availability. Three buildings were selected for their various geometries. Figure 30 shows the floorplans of the selected buildings for the simulation study

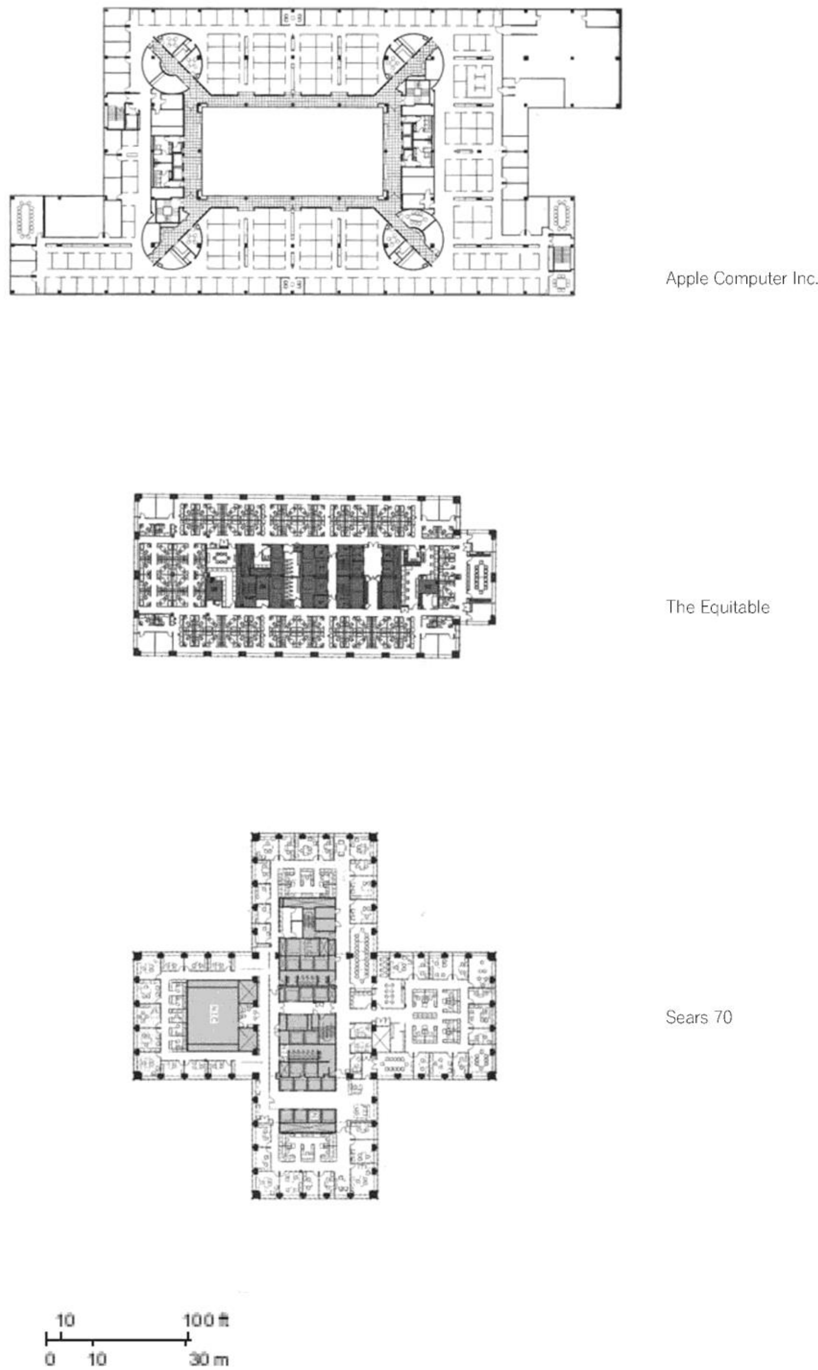


Figure 30 Floorplans of buildings selected for the simulation study.

Location

Portland, OR: Latitude (N) 45.52, Longitude (E) -122.68, Elevation (m) 15

Time – 9am

Sky condition – overcast

Ground spectrum – uniform, albedo 0.15

Materials

Walls – white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

Floor – dark grey floor tiles: specularity 1.2%, R(P) 20.1%, R(M) 19.1%, M/P 0.95

Ceiling – white painted corridor ceiling: specularity 0.5%, R(P) 87.2%, R(M) 81.8%, M/P 0.94

Glass - double IGU clear Tvis 78%: R_front(P) 81.2%, R_front(M) 76.8%, R_back(P) 81.2%, R_back(M) 76.8%, T(P) 78.5%, T(M) 77.7%, M/P 0.99

- double IGU blue Tvis 47%: R_front(P) 17.1%, R_front(M) 20.0%, R_back(P) 10.9%, R_back(M) 10.5%, T(P) 46.7%, T(M) 50.9%, M/P 1.09
- double IGU bronze Tvis 18%: R_front(P) 9.8%, R_front(M) 8.9%, R_back(P) 19.5%, R_back(M) 23.4%, T(P) 18.4%, T(M) 17.2%, M/P 0.93

Ground – old black asphalt: specularity 1.5%, R(P) 12.3%, R(M) 10.8%, M/P 0.87

Table 10 and Figure 31 summarize the average work plane illuminance results for all three buildings. Figures 32-34 visualize the illuminance levels for each building with the varying glazing tints.

Table 10 Summary of average work plane illuminance results.

Avg. Workplanne Illuminance (Lux)	Clear Glazing	Blue Tint	Bronze Tint
Apple Computer Inc.	5518	3079	1007
The Equitable	2028	1440	875
Sears 70	5626	3537	1484

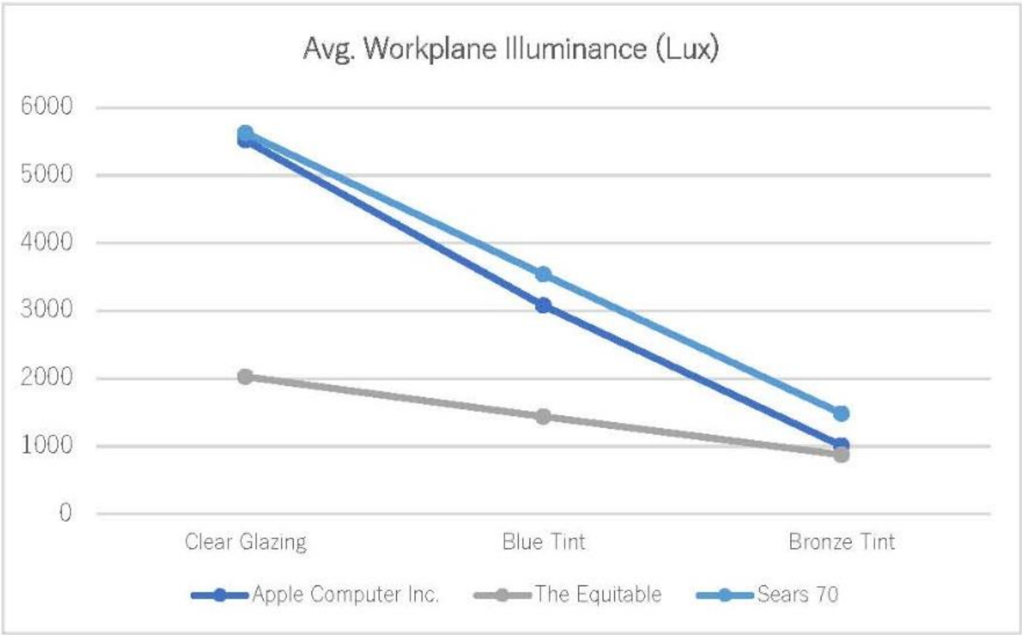


Figure 31 Plot of average work plane illuminance results.

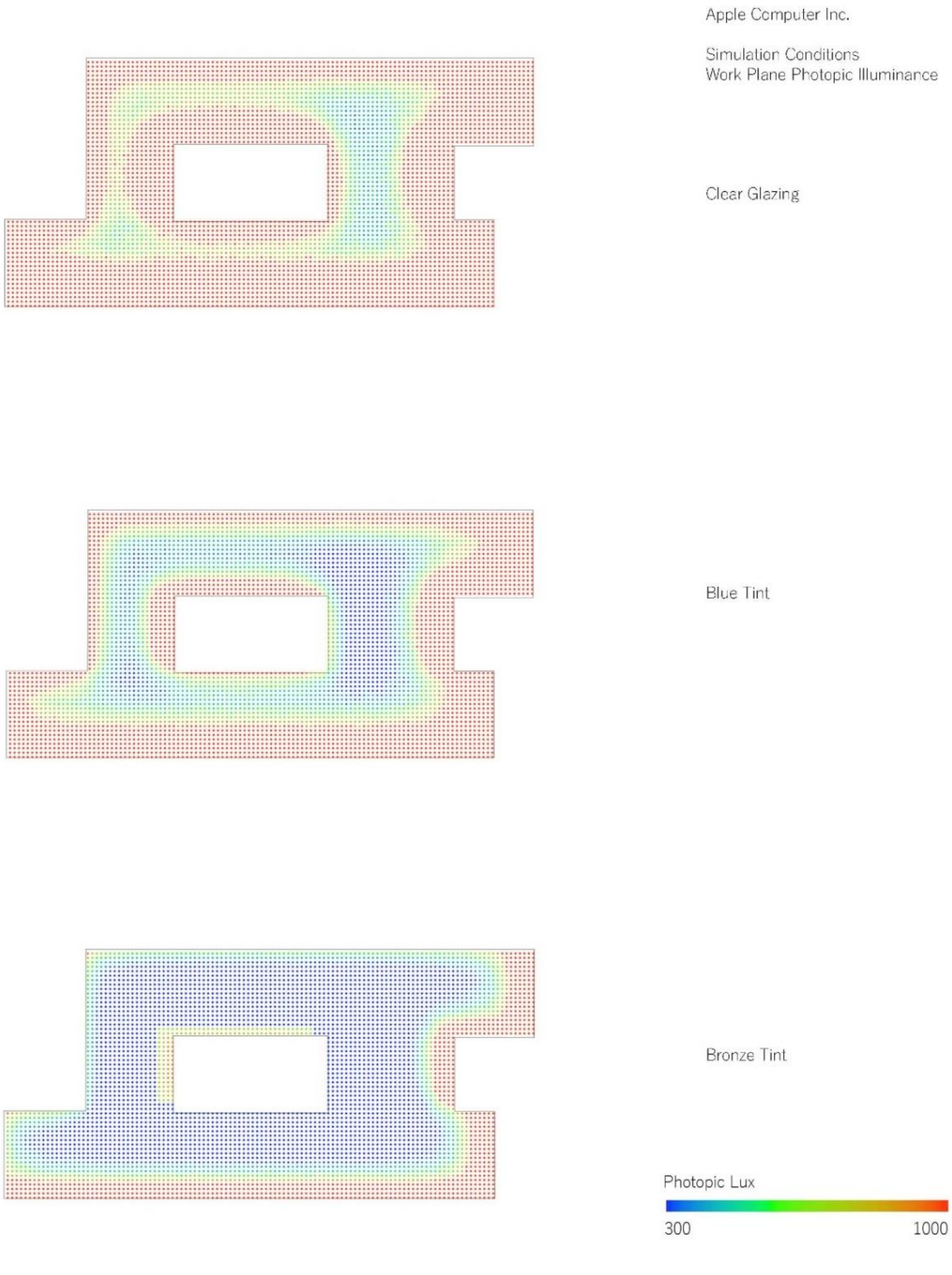


Figure 32 Apple Computer Inc. work plane illuminance in varying glazing tints

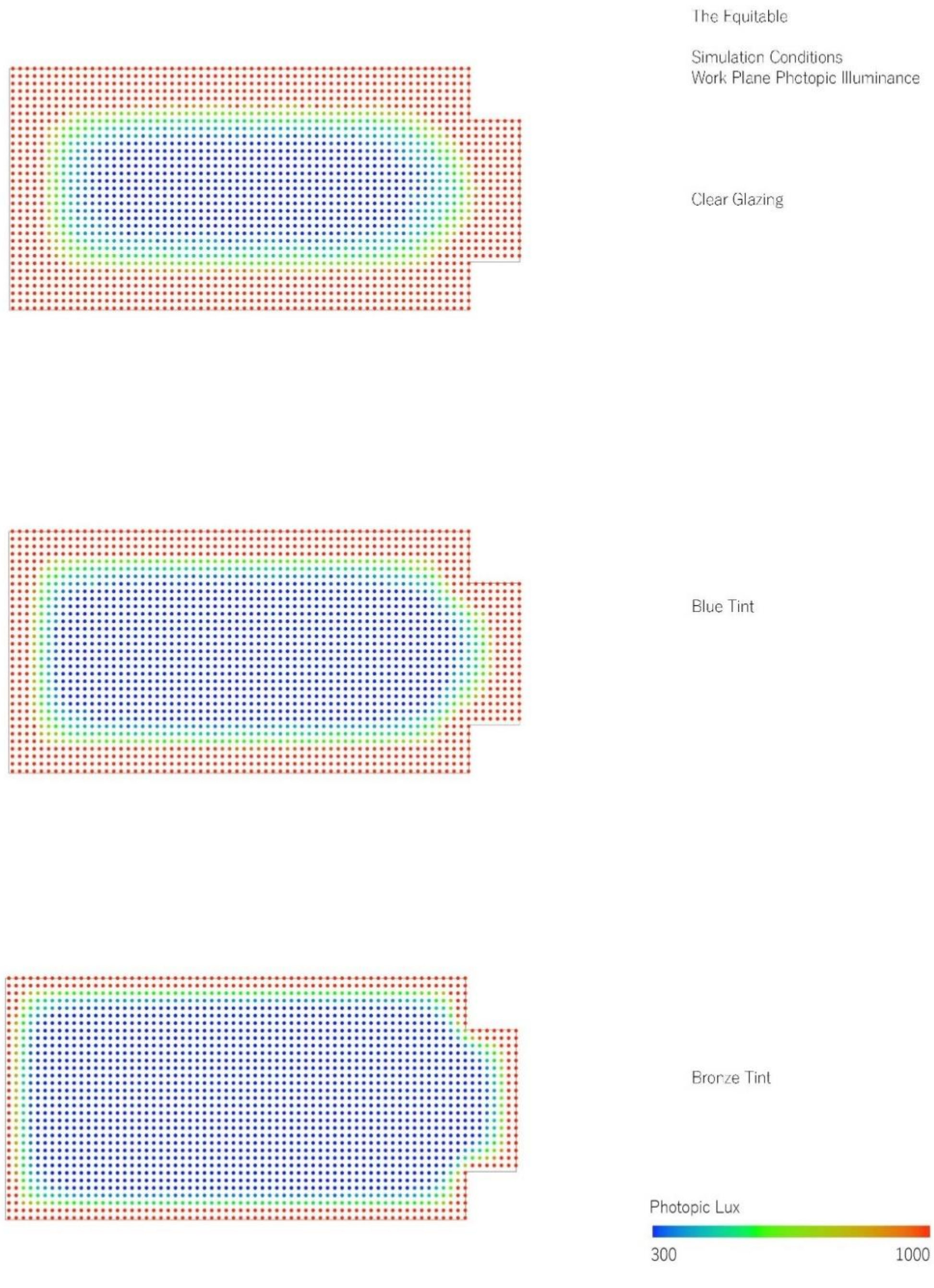


Figure 33 The Equitable work plane illuminance in varying glazing tints

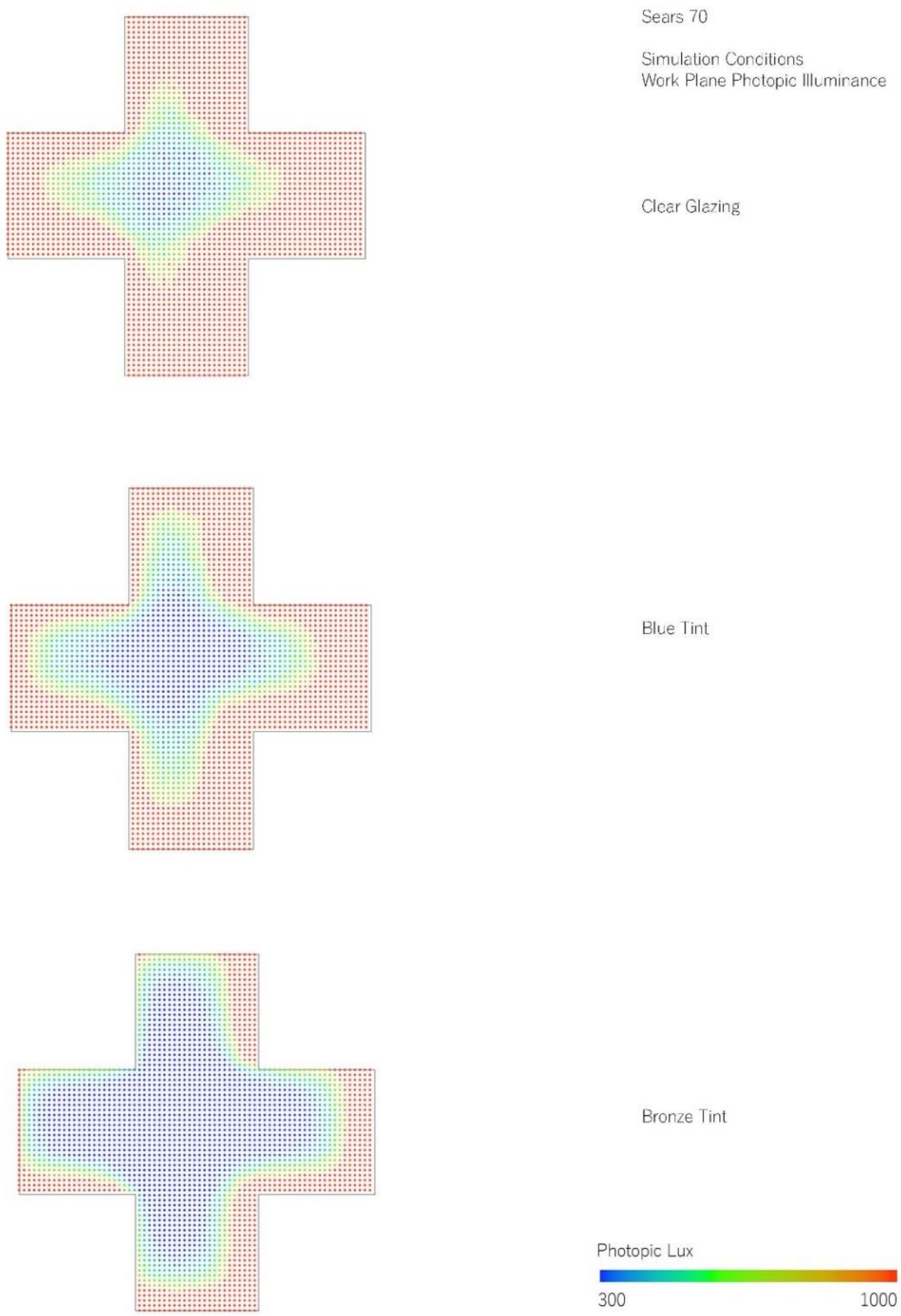


Figure 34 Sears 70 work plane illuminance in varying glazing tints

From the results, it can be concluded that clear glazing allows the most daylight in, followed by blue tints and lastly bronze tints. All three buildings followed the same trend, but with different deltas depending on their geometries and atrium allocation.

As previously mentioned, from the literature a study conducted by Hraska (2015) assessed differences between light transmittance t_v and circadian transmittance t_c of several materials using a daylight model. In some cases, the glazing transmittance of light in the non-visual photoreception region can be so small that may disrupt circadian rhythms or cause other health problems for occupants, this was especially evident with tint colors such as bronze which reduce the blue light component of daylight. This was also evident in the pilot study results.

Table 11 Ratios between photopic illuminance values and circadian stimulus values measured in the modified room and simultaneously in the reference room (Hraska, 2015).

Spectral filter	Ratio of spectral filters influence on photopic illuminance (R_{PI}) and circadian stimulus (R_{CS}) levels		
	R_{PI}	R_{CS}	R_{CS}/R_{PI}
UV filter – AMBER	0.74	0.39	0.53
Antelio blue 6 mm	0.79	1.00	1.27
Yellow color curtain	0.18	0.11	0.61
Red color curtain	0.11	0.08	0.73
Green color curtain	0.11	0.08	0.73
Planibel green 6 mm	0.51	0.55	1.08
Planibel bronze 6 mm	0.29	0.25	0.86
Yellow foil	0.67	0.72	1.07
Green foil	0.40	0.39	0.98

3.7. Daylight Simulation Study Settings

To assess human responses to light, it is important to investigate glazing type, the availability of windows influencing the amount of daylight transmittance, occupant's spatial position, viewshed, and access to views with which are influenced by the building floorplate and interior layout. Lighting and isovist-based analysis can be used to better understand how occupants experience space and use it. These pilot studies have provided a visual overview of the floorplan performance. Overlaying it with an isovist analysis will help determine which areas are being used the most and which zones should or do not need to meet certain benchmarks with or without the help of supplemental electric lighting. For an in-depth assessment, a quantitative and statistical analysis is warranted. Case studies of buildings will investigate the relationships between the shape factor and relative grid distance variables and daylight availability. A cross-case synthesis will aggregate the findings across the series of individual building studies to assess the success or failure of design principles.

- Time frame 9 – 3 pm for WELL building standard recommendations.
- Benchmarks for photopic illuminance 300 – 3,000 lux (useful daylight illuminance)
- Benchmarks for melanopic illuminance 200 EML (WELL) - At 75% or more of workstations, at least 200 equivalent melanopic lux is present, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the

view of the occupant). This light level may incorporate daylight and is present for at least the hours between 9:00 AM and 1:00 PM for every day of the year.

- Shape Factor x Relative Grid Distance x Convex Fragmentation x Percentage in the benchmark range

3.8. Isovist Pilot Study

An isovist is a constructed planar two-dimensional polygon that represents the totality of all visible and potentially visible space from a specific location, usually at eye level. Defining spatial components of the environment by means of isovists will allow for the prediction of trends, optima, and limits on a variety of possible spatial behaviors and perceptions in a given environment. In order to quantify a whole configuration, more than a single isovist is required. The interplay of isovists explains how we experience a space, and how we use it.

One of the earliest methods of depicting isovists, formulated by Benedikt (1979), is with 'isovist fields' which record a single isovist property for all locations in a configuration by using contours to plot the way those features vary through space. The packing of the contours shows how quickly the isovist property is changing. With this method, internal visual relationships between locations within the isovist are ignored and it proved to be difficult to interpret useful results from these measures (Turner et al., 2001). Since then, other methods to represent 2D and 3D isovists have been developed.

The proposed dissertation area of study refers to the importance of window availability on the amount of daylight, occupant's spatial position, viewshed, and access to views within the building interior. Thus, from a seated occupant's view, the area and perimeter local measures are important to determine the visibility of windows and access to daylight. From an architectural standpoint, drift will identify regions from which space can be surveyed with a minimum of head-turning which will help assess a zone's performance in terms of how much vertical illuminance can be received by occupants facing specific directions.

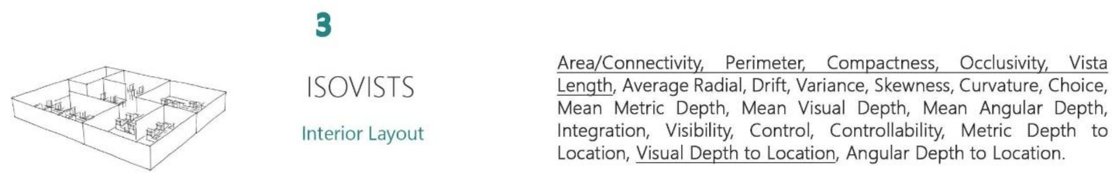


Figure 35 Study settings isovist parameters

There are two prominent computer simulation software tools used for isovist analyses 'Isovist' and 'depthmapX'. The measures and fields generated by Isovist have been developed from the isovist literature based on Benedikt as well as from space syntax literature based on the work of Bill Hillier and Julienne Hanson. The two works of literature overlap, conceptually and in application. Isovist work tends to focus on the building interiors, and on human social and aesthetic experience and perception, whilst depthmapX space syntax tends to focus on the city, behavior, and configurative aspects of space.

The Isovist 2.3 software computer simulation tool's key isovist field measures have been shown to correlate with equivalent measures produced by depthmapX methods, but are calculated in a fraction of the time, for a higher number of data points. A study demonstrating the correlation of Isovist Mean Visual Depth against depthmapX Mean Visual Depth is outlined in Table 4 (isovists.org, 2017). Comparing Isovist_2.0 Connectivity to depthmapX Connectivity gives an R value of 0.99 (Rsq = 0.98). Comparing Isovist_2.0 Mean Visual Depth to depthmapX Visual Mean Depth gives an R value of 0.95 (Rsq = 0.90).

Table 12 Isovist and depthmapX results comparison (isovists.org, 2017).

	No. data points	Time to calculation / scan consistency	
		Connectivity (Cv)	Visual Mean Depth/ Mean Visual Depth
DepthMapX	58,650	32 seconds	Cv + 4hrs, 16 minutes
Isovist_2.0	1,550,751	43 seconds	Cv + 3 minutes, 35 seconds

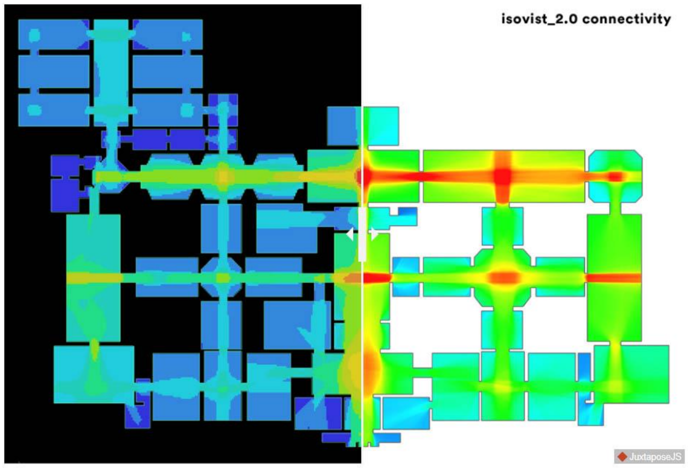


Figure 36 Visual comparison of the Isovist_2.0 Connectivity scan to the DepthMapX Visual Mean Depth map (isovists.org, 2017)

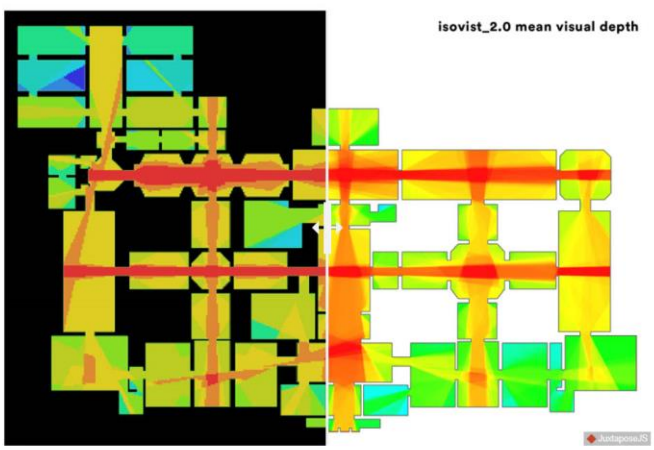


Figure 37 Visual comparison of the Isovist_2.0 Mean Visual Depth scan to the DepthMapX Visual Mean Depth map (isovists.org, 2017).

The purpose of the pilot study is to compare and contrast the usability and results of the two prominent software programs used in the space syntax field (DepthmapX and Isovist_2.3.9) in relation to the scope of the study. It assesses an office space from an occupant perspective through isovist analyses

Building Name / Client: Bertelsmann Verlag, Buch und Ton
Location: Güttersloh, Germany
Year: 1961
Architects: Quickborner
Floor Area (sq ft): Gross 27,000 / Net 24,300

Figure 38 Buch und Ton exterior shot (Source: https://www.die-glocke.de/lokalnachrichten/kreisguetersloh/guetersloh/Bertelsmann-waechst-mit-Digitalgeschaeft-251ca08c-1e74-4003-91e8-a5a436428246-ds)

The Bertelsmann ‘Buch und Ton’ office space is housed in the converted top floor of an existing warehouse for books and records on the company site and was roughly half the size of a football pitch. This office space was selected for this study for its pioneering landscaping layout, ‘Bürolandschaft’ (office landscape). The Bürolandschaft concept was driven by the designers’ ambition (1) to create an office space as a flexible and adaptable instrument for corporations by conceptualizing space that is easy to arrange to new formations of work processes, and (2) to design a workplace as an all-embracing environment for living: an environment that, due to anticipated automation of administrative work, would dismiss people into an everlasting leisure time (Rumpfhuber, 2011). The pioneering landscaping layout consists of clusters of open-plan workstations that are mostly arranged according to a rectilinear grid parallel to the perimeter. However, the circulation among these clusters has an organic configuration with primary circulation linking core to one another and secondary one creating rings around each team cluster. It consists of four external cores attached to the 205x123 ft floorplate, while two internal ones are positioned 18 ft from the perimeter. The ceiling was fitted with suspended aluminum rectilinear panels; Lighting was provided by fluorescent tubes glowing in ‘White de Luxe’. Each of the panels’ illumination levels was separately controlled.

Figure 39 Buch und Ton interior shots (https://www.buerolandschaft.net/en/landscapes/detail/buch-und-ton/)

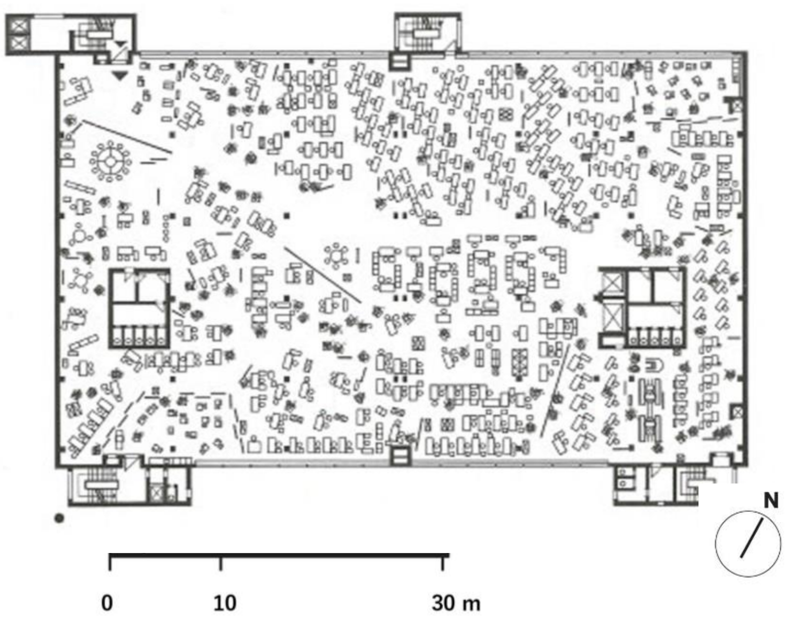


Figure 40 Buch und Ton floorplans (https://publik.tuwien.ac.at/files/PubDat_215835.pdf).

For this study's purposes, the floorplan has been simplified to take partitions and planters into account as obstructions. The workstations have been eliminated from any calculations, but were left as annotations to indicate seating position orientations.

3.8.1. Isovist Software

The isovist analysis in this software allows basic visual analysis using 'point isovists', 'region isovists', or 'isovist agents'. A 'point isovist', as used in this study, is set by the user moving the cursor or clicking at a point of interest, it identifies the space in plan that falls within the isovist from any given location. The isovist menu controls the parameters of isovist sweep (angle of view cone), direction (heading that the isovist is 'looking' in), far rim (how far the isovist can 'see'), near rim (an internal horizon that sets the nearest visible edges of the isovist).

The software produces twenty-one different field measures, ten are 'local' isovist measures that relate to occupant experience within space; Area (or Connectivity), Perimeter, Compactness, Occlusivity, Vista Length, Average Radial, Drift, Variance, Skewness and Curvature. Five are 'global' Space Syntax-type measures that characterize configurational relations across a plan as a whole; Choice, Mean Metric Depth, Mean Visual Depth, Mean Angular Depth, and Integration (HH). The remaining six measures are 'semi-local' or relational measures that span between local and global information; Visibility, Control, Controllability, Metric Depth to Location, Visual Depth to Location, and Angular Depth to Location. To help assess when a field analysis is ‘complete'. Local isovist measures tend to be statistically stable after 3-5 local cycles, and global space syntax measures after 200+ global cycles.

Figure 41 portrays sample visible point isovists with their corresponding values. For a general overview, the plan is scanned as a 2D form to display the visual analyses of isovist area, perimeter, drift, visibility, control, and controllability (figures 42-43). As the scale bar indicates, areas in red depict a high value of the respective measure, areas in blue depict lower values of the measure that is being examined. To elaborate on isovist area and drift, the values of the measures for all the points in the plan were averaged in table 13. These measures are especially important in this pilot study because they give an indication of daylight accessibility and penetration in a building which is relevant to the investigative goal of the bigger study.

Table 13 Average area and drift attribute summary.

av. Area	av. Drift
341.5081	9.34186

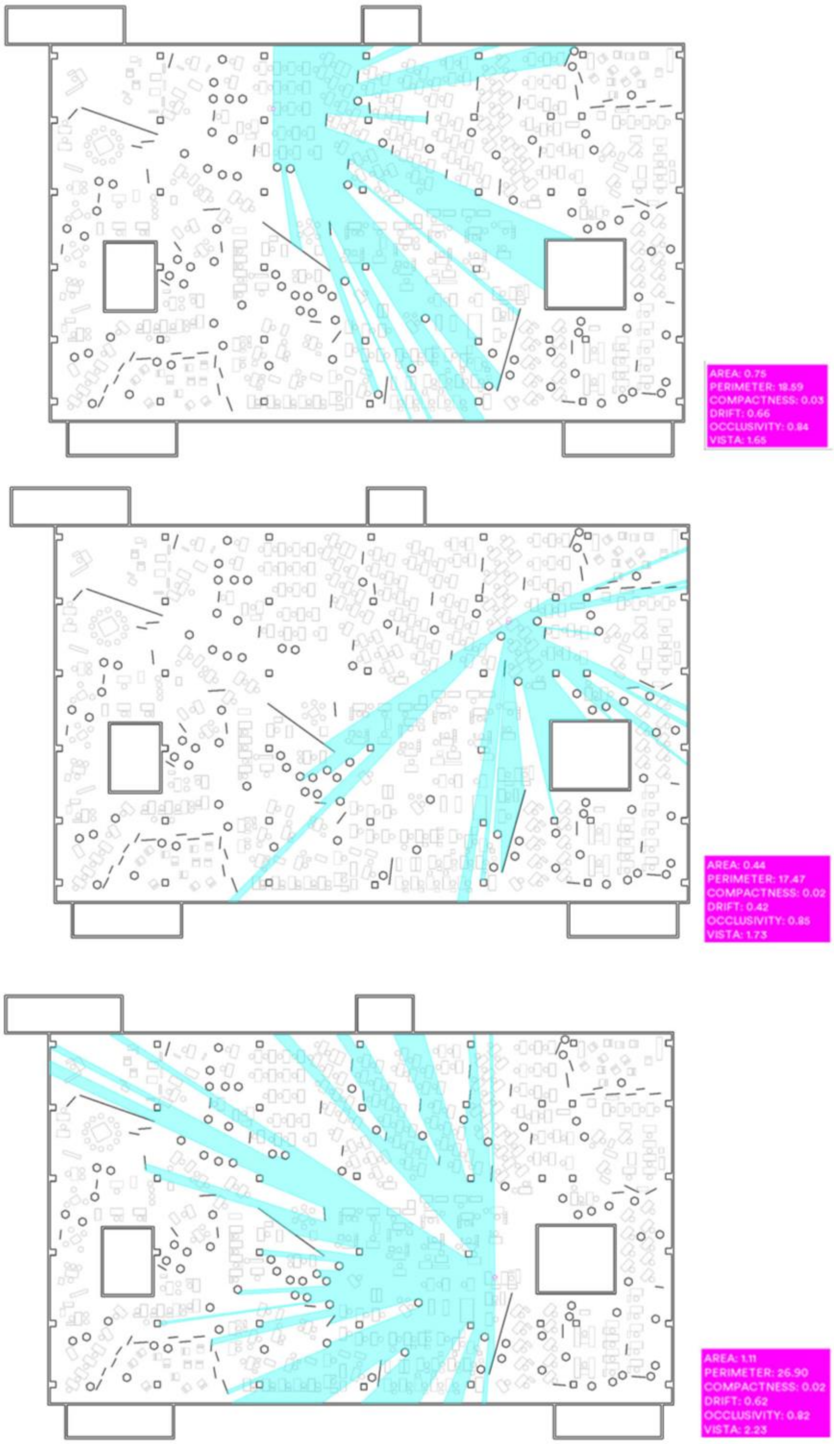


Figure 41 Buch und Ton point isovist analysis.

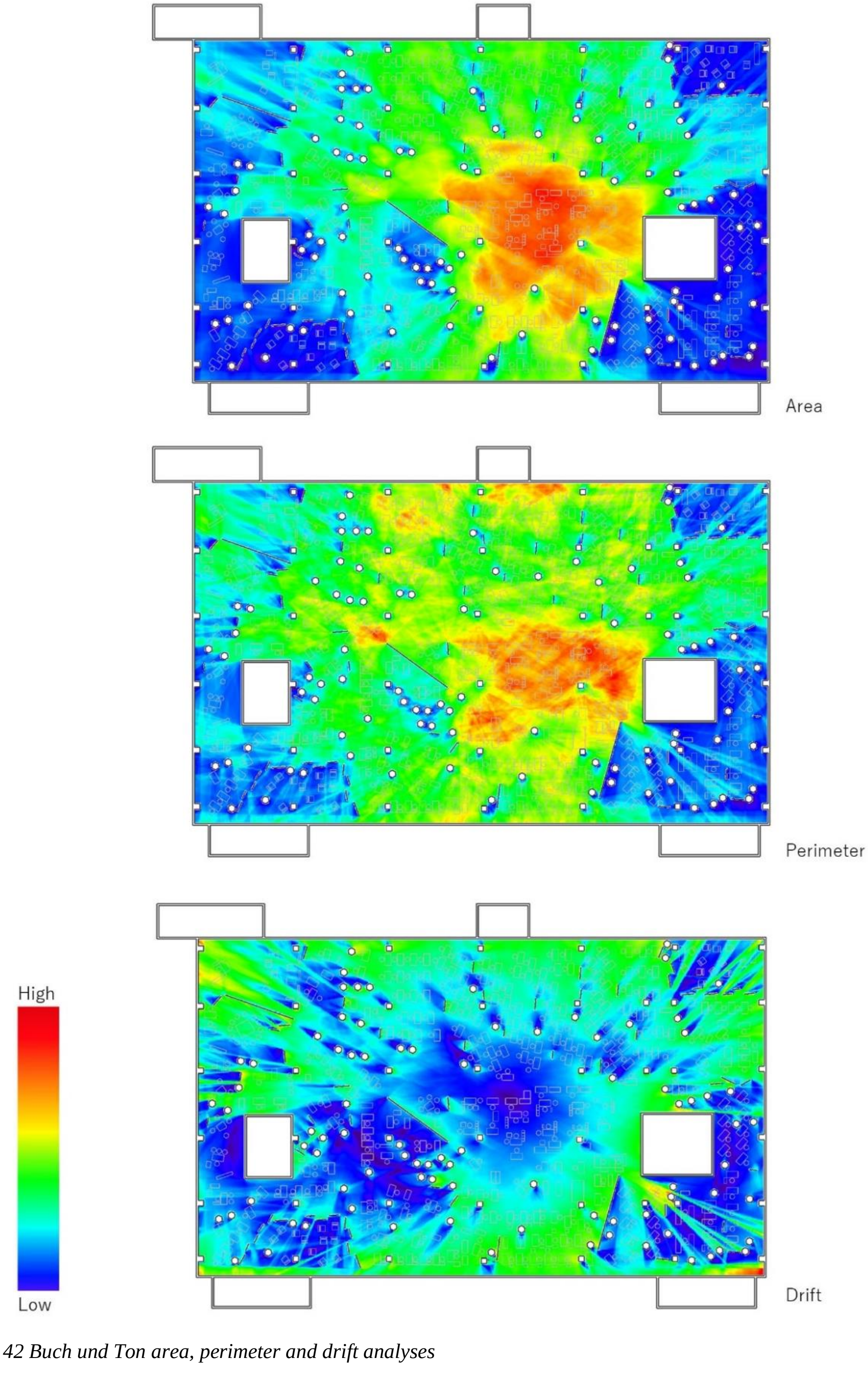


Figure 42 Buch und Ton area, perimeter and drift analyses

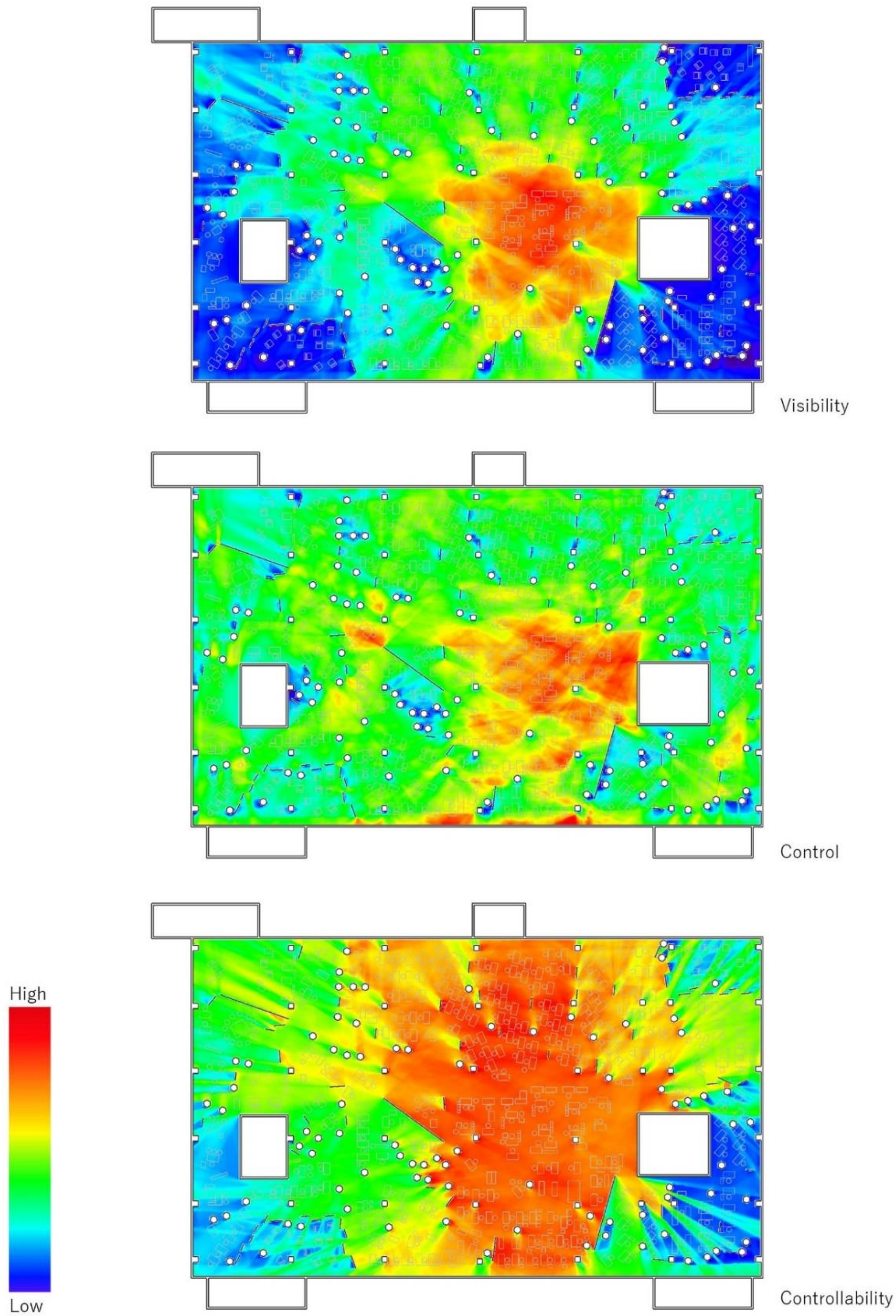


Figure 43 Buch und Ton visibility, control and controllability analyses.

3.8.2. depthmapX Software

depthmapX is an open-source and multi-platform spatial analysis software for spatial networks of different scales. The software was originally developed by Alasdair Turner from the Space Syntax group as DepthMap, now open-source and available as depthmapX. depthmapX works at a variety of scales from buildings and small urban areas to whole cities or states. At each scale, the aim of the software is to produce a map of spatial elements and connect them via relationship to create a graph analysis of the resulting network.

At the building scale, depthMapX can be used to assess the visual accessibility of a place by producing point isovists. These are the core elements behind Visibility Graph Analysis (VGA), a graph of intervisible points, which may then be analyzed using various graph measures: connectivity, isovist area, compactness, drift angle, drift magnitude, isovist max radial, isovist min radial, occlusivity, perimeter, point first moment, point second moment, visual clustering coefficient, control, controllability, entropy, integration (HH, P value, Tekl), visual mean depth, visual node count, and visual relativized entropy.

For this pilot study, isovist area, perimeter, and drift magnitude were addressed to match the analysis conducted in the Isovist program (figure 44).

Table 14 depthmapX attribute summary

Attribute	Minimum	Average	Maximum
Connectivity	28	4645.42	10174
Point First Moment	57.2019	69944.2	165842
Point Second Moment	101.34	1.4524e+006	4.2395e+006
Visual Clustering Coefficient	0.320702	0.0116685	0.796611
Visual Control	0.247618	0.0232218	1.27467
Visual Controllability	0.0247193	0.00289337	0.205245
Visual Entropy	0.416603	0.0221234	1.19519
Visual Integration [HH]	7.98167	0.339499	14.9893
Visual Integration [P-value]	0.667926	0.0284101	1.25435
Visual Integration [Tekl]	0.895327	0.02582	0.952656
Visual Mean Depth	1.79674	0.0547958	2.49625
Visual Node Count	23606	653	23606
Visual Relativised Entropy	2.46905	0.0743818	3.0497

Attribute	Minimum	Average	Maximum
Connectivity	78	4607.36	10065
Isovist Area	7.30138	416.386	907.075
Isovist Compactness	0.00451805	0.0166694	0.541873
Isovist Drift Angle	0.0217439	182.225	359.989
Isovist Drift Magnitude	0.0769496	9.28228	26.64
Isovist Max Radial	4.13226	42.9844	70.486
Isovist Min Radial	6.95643e-006	1.24855	5.84167
Isovist Occlusivity	7.08533	526.087	1041.5
Isovist Perimeter	14.9006	608.564	1181.64
Point First Moment	146.31	69039	163107
Point Second Moment	292.14	1.42632e+006	4.17273e+006

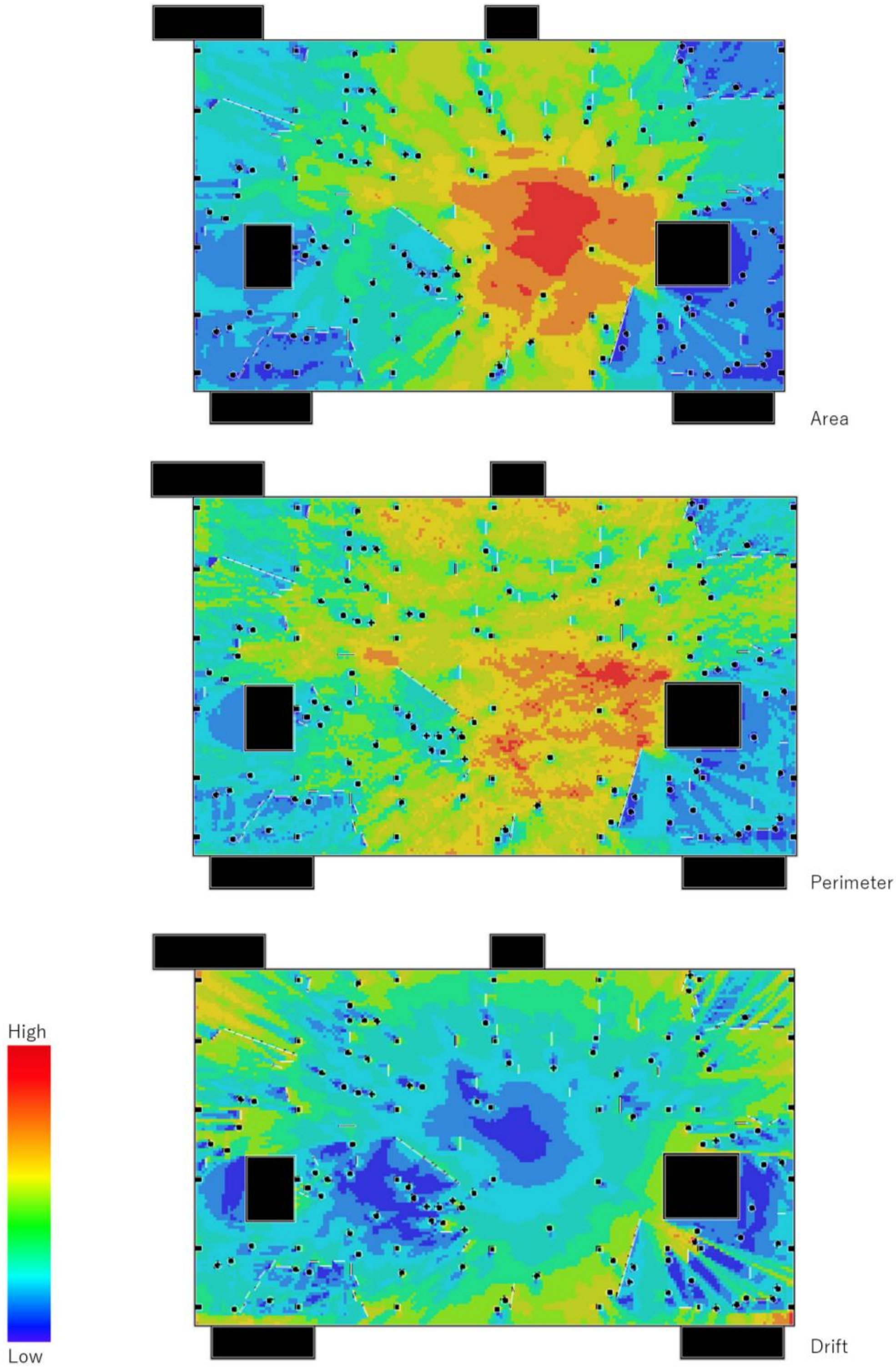


Figure 44 Buch und Ton area, perimeter and drift analyses

Though you can set the isovist field of view (quarter 90, third 120, half 180, full 360), the point isovist analysis in depthmapX does not indicate the direction of view (figure 45). The point also has to be set before the view is generated, whereas in the Isovist software the view is generated as you move the cursor across the floorplan. The annotations layer also needs to be removed so that it is not included in the calculations.

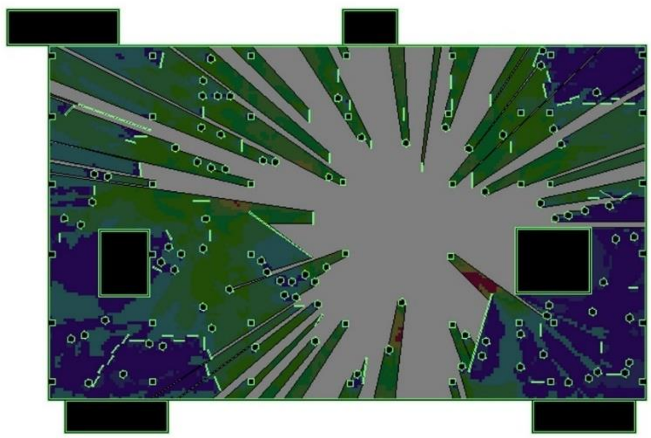


Figure 45 Buch und Ton point isovist analysis

3.8.3. Software Comparison

The results from both the Isovist and depthmapX visibility graph analyses are visually identical. These help explore spatial layout advantages and pitfalls. To address these in detail, a quantitative analysis is required. It would be misleading to use isovist properties' averages, since some areas and orientations of the floorplan are used more frequently and are critical to occupant workstations, whereas other areas may perform poorly but are simply circulation spaces. Therefore, for future studies, it would be more insightful to investigate different zones in the floorplan and be selective for any data analyses. Moving forward, the Isovist software will be used since it produces the same results as the more traditional depthmapX software, but in a significantly shorter period of time and is easier to navigate through.

CHAPTER IV: DAYLIGHT SIMULATION RESULTS

Location

Portland, OR: Latitude (N) 45.52, Longitude (E) -122.68, Elevation (m) 15

Sky condition – overcast

Time – 9am, 12pm, 3pm

Ground spectrum – uniform, albedo 0.15

Materials

Walls – white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

Floor – dark grey floor tiles: specularity 1.2%, R(P) 20.1%, R(M) 19.1%, M/P 0.95

Ceiling – white painted corridor ceiling: specularity 0.5%, R(P) 87.2%, R(M) 81.8%, M/P 0.94

Glass - double IGU clear Tvis 78%: R_front(P) 81.2%, R_front(M) 76.8%, R_back(P) 81.2%, R_back(M) 76.8%, T(P) 78.5%, T(M) 77.7%, M/P 0.99

Ground – old black asphalt: specularity 1.5%, R(P) 12.3%, R(M) 10.8%, M/P 0.87

Surrounding Building Context – 2 storey, white painted room walls: specularity 0.4%, R(P) 81.2%, R(M) 76.8%, M/P 0.95

4. Core and Shell Simulations

Three simulations were run for each of the fifty buildings for the various times of the day: 9 am, 12 pm, and 3 pm. Data extracted from the daylight simulations include average horizontal illuminance, average vertical illuminance, percentage of sensors below 300 lux, percentage of sensors above 3,000 lux for both horizontal and vertical planes, average vertical EML, and percentage of sensors below 200 EML. The floorplans for the building daylight simulations can be found in Appendix A: Core and Shell Simulations.

The boxplots in Figure 46 summarize the results of all fifty buildings at three different times of the day. The benchmark requirements were adopted from the LEED rating system and WELL Building Standard and have been highlighted on the charts. Data points outside the red highlighted region do not meet the benchmarks. For average horizontal illuminance, the Useful Daylight Illuminance range is from 300-3,000 lux. This was also used for vertical illuminance. To test the Spatial daylight autonomy requirements for at least 75% of regularly occupied floor area to be in that range, only 25% of sensors could be below 300 lux or above 3,000 lux. Hence, the 0-25% range was highlighted as the data points that meet the benchmarks. Even though there are no current guidelines for the percentage of occupied floor area EML benchmarks need to meet, this research adopts the same illuminance guidelines. For average vertical EML, the benchmark was set at 200 EML as a midpoint between the 150-240 EML standard requirement. There is no known maximum threshold.

The boxplots indicate that meeting the horizontal benchmarks appears to be more difficult than the vertical. More data points are found outside the highlighted horizontal benchmark regions in the charts. This may be due to the fact that the vertical sensor point measurements were taken at a higher eye level plane and there are no obstructions in these core and shell simulations facing the building envelope. The horizontal sensor point measurements were taken at a lower desk level plane where less light would be available. The results follow the same trend that indicates 12 pm has the highest levels of daylight illumination followed by 3 pm and lastly 9 am. Tables 15-17 show the results for each individual building.

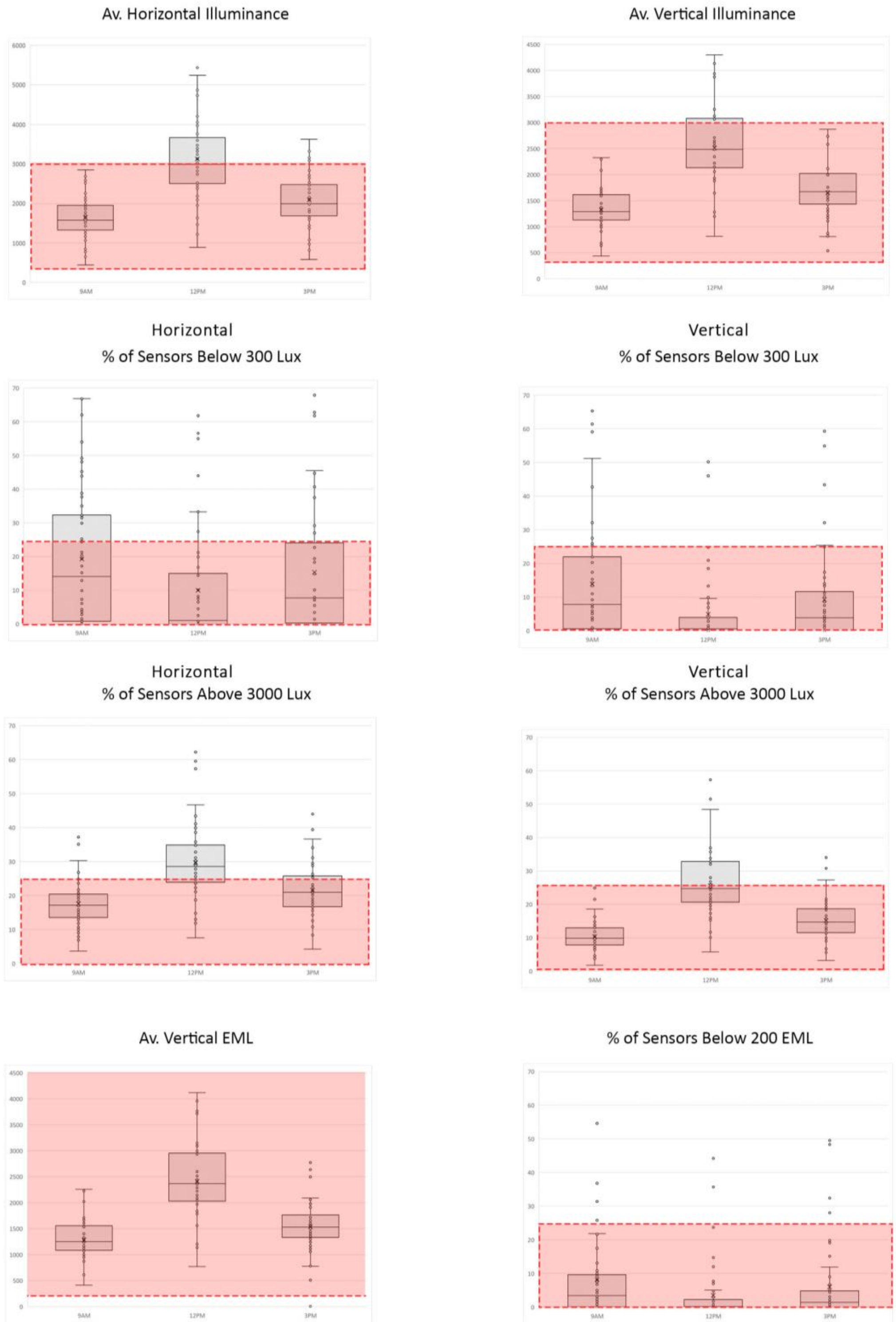


Figure 46 Boxplots of building compilation results.

Table 15 9am Building compilation results.

#	Name	Relative Grid Distance (RGD)	Convex Fragmentation (CF)	Shape Factor (SF)	Horizontal: Av. Horizontal Illuminance	Horizontal: % of Sensors Below 300 Lux (Horizontal)	Horizontal: % of Sensors Above 3000 Lux (Horizontal)	Vertical: Av. Vertical Illuminance	Vertical: % of Sensors Below 300 Lux (Vertical)	Vertical: % of Sensors Above 3000 Lux (Vertical)	Vertical: Av. Vertical EML	Vertical: % of Sensors Below 200 EML
1	3com Corporation	1.335	1.534	0.75	1432	35	16.2	1199	27.5	10.5	1170	21.6
2	Andersen (after move)	1.157	0.706	0.73	1753	12.9	17.6	1390	9.7	10.3	1288	4.3
3	Andersen (before move)	1.173	0.657	0.77	2027	0	20.3	1593	0.5	11.9	1535	0.1
4	Allen & Overy	1.221	0.440	0.81	1336	3.6	10.7	1174	3.7	5.7	1121	1.2
5	Arthur Andersen	1.424	0.525	0.82	2256	0.2	21.6	1767	0.3	16.3	1710	0
6	Apicorp	1.292	1.276	1.12	2190	1.5	26.8	1638	0.5	13.8	1604	0.1
7	Apple Computer Inc.	1.289	0.975	0.80	1705	15.7	17	1351	7.2	10.2	1317	3.4
8	Andersen Consulting	1.189	0.968	0.86	2846	0	35.1	2325	0	24.9	2260	0
9	Bach und Tre	1.060	0.458	0.76	1115	38.8	11.8	991	21.9	5.4	953	7.5
10	Chase Manhattan Bank	1.104	0.307	0.73	452	62	3.7	434	65.3	1.8	414	54.5
11	Chiat/Day Advertising	1.513	1.529	0.86	2073	1.3	23.9	1647	0.4	14.8	1611	0
12	TBWA Chiat/Day	1.132	0.802	0.74	1285	29.4	14.2	1115	15.3	7.7	1072	8.2
13	Citicorp	1.280	1.007	0.72	1478	25.2	14	1145	14.2	8.5	1111	5.2
14	Commerzbank AG	1.327	1.345	0.81	1778	7.3	23.3	1449	5.1	11.8	1403	3.7
15	Data Firmengruppe	1.248	1.176	0.79	1983	0	20.8	1689	0	13	1635	0
16	Davis Polk & Wardwell	1.177	0.755	0.74	1167	37.7	8.3	908	22.3	4.6	872	9.5
17	DEGW London Office	1.087	1.130	0.78	1550	30.5	15.9	1135	22.2	8.5	1087	10
18	Discovery Channel Latin Am.	1.343	1.087	0.76	1516	19.4	15.2	1198	5.9	7.9	1162	1.6
19	DuPont	1.010	0.189	0.79	1768	32.7	18.2	1258	25.2	10.8	1212	17.5
20	The Equitable	1.259	0.783	0.76	1591	7.5	15.9	1253	3.9	8.9	1204	0.6
21	Ford Foundation	1.575	0.944	0.88	1823	6.1	18.7	1378	7.4	9.8	1328	4.2
22	Ford Motor Co.	1.061	0.413	0.75	1250	43.9	14.3	1107	25.9	9.1	1070	13.7
23	f/X Networks	1.271	0.912	0.88	1913	0	21.7	1625	0.9	14.3	1577	0
24	Greenberg Traurig	1.338	0.932	0.74	1317	2.8	13.4	1132	8.3	7.9	1085	2.2
25	Hoffmann La Roche	1.125	1.057	0.73	1340	31.5	14.9	1187	17.4	8.6	1150	10.8
26	IBM Regional Headquarters	1.019	0.436	0.71	660	66.3	6.9	648	51.2	3.6	624	35.8
27	IBM (U.K) Limited	1.365	1.477	0.80	2140	0	24	1706	0	13	1664	0
28	IBM Australia	1.216	0.984	0.77	1469	6.4	12.4	1148	7	5.6	1093	2.3
29	Interpolis	1.167	0.000	0.92	2579	0	37.2	2295	0	21.5	2227	0
30	Direct. of Telecom., MP3W	1.075	0.607	0.77	1548	15.2	18.4	1368	7.9	10.9	1312	3.3
31	Eastman Kodak	1.167	0.399	0.74	848	66.9	9	637	61.4	4.8	611	54.6
32	Lend Lease Interiors	1.270	1.030	0.84	1944	0	19.9	1609	0	13	1549	0
33	Leo A Daly	1.202	0.804	0.76	1568	9.9	17.1	1290	9.2	9.9	1243	3.7
34	Lowe & Partners/SMS	1.280	0.748	0.75	1527	7.4	17.2	1283	3.8	9.7	1231	5
35	McDonald's	1.122	0.856	0.72	1611	4.3	18.8	1400	3.4	10.9	1348	0.8
36	McDonald's Italia	1.159	0.505	0.78	1067	32.2	9.9	1038	20.3	5.4	1004	3.1
37	MGIC	1.104	0.586	0.76	1723	20.4	19.2	1311	11	10.5	1263	3.4
38	Nickelodeon	1.160	0.549	0.95	1705	0	19.1	1392	1.1	10.7	1339	0.1
39	Olivetti A	1.031	0.000	0.83	2515	0.8	24.8	1735	0	15	1667	0
40	Olivetti B	1.031	0.000	0.83	2515	0.8	24.8	1735	0	15	1667	0
41	Olivetti C	1.031	0.000	0.83	2515	0.8	24.8	1735	0	15	1667	0
42	Orenstein Koppel	1.117	0.534	0.76	1853	21.3	15.4	1331	13.4	8.8	1285	6.7
43	Sears 40	1.178	0.917	0.72	782	54	7.8	681	42.7	3.8	647	31.4
44	Sears 70	1.351	1.450	0.76	1505	17.2	14.6	1187	14.5	7.1	1141	9.2
45	Steelcase Inc.	1.046	0.406	0.76	1324	45.2	12.1	1048	28	3.1	1014	13.1
46	British Telec., 5 Longwalk	1.231	1.249	0.77	1575	25.5	18.2	1291	15.4	9.9	1260	7.9
47	British Telec., The Square	1.094	0.681	0.77	1513	24.4	17.5	1313	3.2	10.7	1265	0.5
48	Vitra International AG	1.367	0.356	0.93	2591	0	30.3	2082	0.1	18.6	2023	0.1
49	Weyerhaeuser Company	1.136	0.584	0.73	1447	49.7	15.1	1038	58.1	8.1	1003	25.8
50	WMA Consulting Engineers	1.046	0.129	0.75	1103	48.1	12.9	929	32.1	7	893	21.8

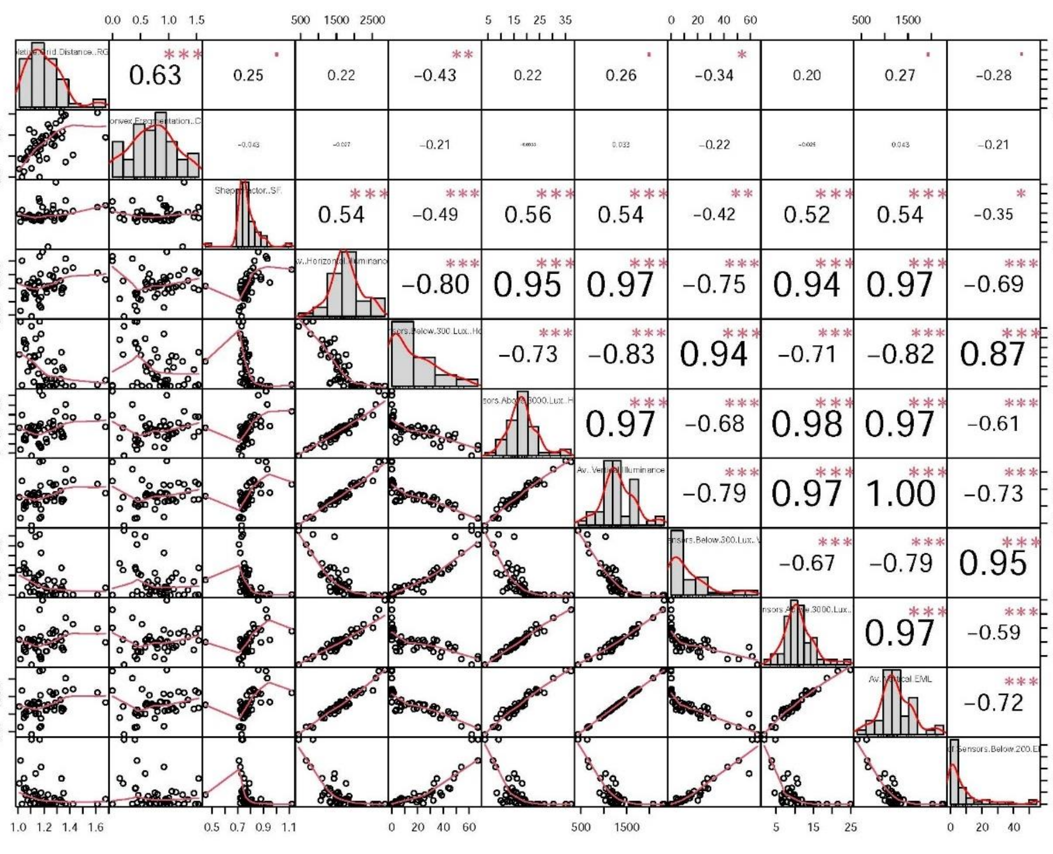


Figure 47 9am correlation analysis.

Table 16 12pm Building compilation results.

#	Name	Relative Grid Distance (RGD)	Convex Fragmentation (CF)	Shape Factor (SF)	Horizontal: Av. Horizontal Illuminance	Horizontal: % of Sensors Below 300 Lux (Horizontal)	Horizontal: % of Sensors Above 3000 Lux (Horizontal)	Vertical: Av. Vertical Illuminance	Vertical: % of Sensors Below 300 Lux (Vertical)	Vertical: % of Sensors Above 3000 Lux (Vertical)	Vertical: Av. Vertical EML	Vertical: % of Sensors Below 200 EML
1	3com Corporation	1.335	1.534	0.75	2735	21.5	27.1	2148	18.5	21.6	2072	14.7
2	Andersen (after move)	1.157	0.706	0.73	3322	2.5	28.4	2486	2	24.3	2381	1
3	Andersen (before move)	1.173	0.657	0.77	3807	0	32.8	3088	0	34.2	3717	0
4	Allen & Overy	1.221	0.440	0.81	2448	0	24	2221	0	20.7	2096	0
5	Arthur Andersen	1.424	0.325	0.82	4207	0	38.6	3937	0	33.1	3763	0
6	Apicorp	1.292	1.276	1.12	4049	0	46.7	3066	0	35.7	2966	0
7	Apple Computer Inc.	1.289	0.975	0.80	3235	4.5	29.5	2497	1.3	24.8	2400	0.7
8	Andersen Consulting	1.189	0.968	0.86	5439	0	62.2	4135	0	51.5	3959	0
9	Buch und Ton	1.060	0.458	0.76	2185	19.9	21.1	1879	1.6	17.3	1785	0.7
10	Chase Manhattan Bank	1.104	0.207	0.73	883	61.8	7.5	837	46	5.8	769	35.7
11	Chiat/Day Advertising	1.613	1.529	0.86	3972	0	39.9	3100	0	34.2	2996	0
12	TBWA Chiat/Day	1.132	0.802	0.74	2451	6.5	25.1	2151	3.3	20.7	2043	2.3
13	Citicorp	1.280	1.007	0.72	2737	0.2	21.3	2067	1.5	17.6	1979	0.3
14	Commerzbank AG	1.377	1.345	0.81	3318	3.1	33.1	2709	2.9	26.4	2599	2
15	Data Firmengruppe	1.246	1.176	0.79	3757	0	41.1	3077	0	32.8	2951	0
16	Davis Polk & Wardwell	1.177	0.755	0.74	2201	7.5	15	1645	3.8	11.7	1559	1.3
17	DEGW London Office	1.087	1.130	0.78	3042	21.2	28.9	2251	2	22	2130	0.6
18	Discovery Channel Latin Am.	1.343	1.087	0.76	2823	0.8	25.7	2358	0.5	21.8	2265	0.2
19	DuPont	1.010	0.189	0.79	3240	16.8	30.7	2504	9.6	26.9	2385	7
20	The Equitable	1.259	0.783	0.78	3030	0.1	25.8	2345	0.1	21.2	2224	0.1
21	Ford Foundation	1.675	0.944	0.88	3391	3.1	30.2	2547	2.8	24.9	2425	2.2
22	Ford Motor Co.	1.061	0.413	0.75	2378	27.4	23.5	3063	8.2	21	1971	3
23	I/X Networks	1.271	0.912	0.88	3597	0	35.2	3124	0	33.8	2995	0
24	Greenberg Traurig	1.338	0.932	0.74	2476	0.5	24	2219	0.2	20.9	2101	0
25	Hoffmann La Roche	1.125	1.057	0.73	2544	10.6	27	2168	7	22.2	2078	5
26	IBM Regional Headquarters	1.019	0.436	0.71	1224	55	11.9	1213	24.8	10.2	1156	12
27	IBM (UK) Limited	1.305	1.477	0.80	4027	0	43.4	3262	0	36.9	3144	0
28	IBM Australia	1.216	0.984	0.77	2755	1	22.3	2220	0.3	19.6	2089	0.1
29	Interpolis	1.167	0.000	0.92	5240	0	59.5	4297	0	57.3	4116	0
30	Direct. of Telecom., MPBW	1.075	0.007	0.77	3125	3	31.1	2580	0.5	28.4	2444	0.1
31	Eastman Kodak	1.167	0.399	0.74	1640	56.6	14.8	1197	50.2	11.9	1136	44.2
32	Lend Lease Interiors	1.270	1.030	0.84	3630	0	34.8	3085	0	32	2936	0
33	Leo A Daly	1.202	0.804	0.76	2941	0.1	28.8	2508	0.8	25.5	2380	0.2
34	Lowe & Partners/SMS	1.280	0.748	0.75	2933	0.2	26.9	2483	0.1	24.7	2354	0.1
35	McDonald's	1.172	0.856	0.77	2914	1.1	29.1	2645	0.2	26.8	2515	0.1
36	McDonald's Italia	1.150	0.505	0.78	2008	10.1	19	1929	0.8	15	1839	0.1
37	MGIC	1.104	0.386	0.76	3266	0.9	30.6	2515	0.3	25.9	2391	0
38	Nickelodeon	1.180	0.849	0.93	3179	0	29.9	2669	0	28	2534	0
39	Olivetti A	1.031	0.000	0.83	4734	0	35.8	3253	0	33.1	3091	0
40	Olivetti B	1.031	0.000	0.83	4734	0	35.8	3253	0	33.1	3091	0
41	Olivetti C	1.031	0.000	0.83	4734	0	35.8	3253	0	33.1	3091	0
42	Drenstein Koppel	1.117	0.634	0.76	3478	6.8	28.1	2601	2.1	25.2	2485	0.7
43	Sears 40	1.178	0.917	0.72	1475	33.3	13	1279	20.9	10.1	1201	23.7
44	Sears 70	1.351	1.450	0.76	2845	8.2	25.6	2252	6.9	20.5	2147	4.7
45	Steelcase Inc.	1.046	0.406	0.76	2521	21.8	21.6	2057	0.7	18.6	1973	0.2
46	British Telec., Stongwalk	1.231	1.249	0.77	2854	14.4	31.3	2376	4.3	25.5	2268	1.7
47	British Telec., The Square	1.094	0.681	0.77	2825	0.6	27.8	2343	0	23	2233	0
48	Vitra International AG	1.367	0.356	0.93	4874	0	57.3	3875	0	48.4	3717	0
49	Weyerhaeuser Company	1.136	0.384	0.73	2744	33.3	24.7	2086	9.9	21.2	1992	3.6
50	WMA Consulting Engineers	1.046	0.129	0.75	1959	44	18.7	1667	13.3	15.3	1582	7.7

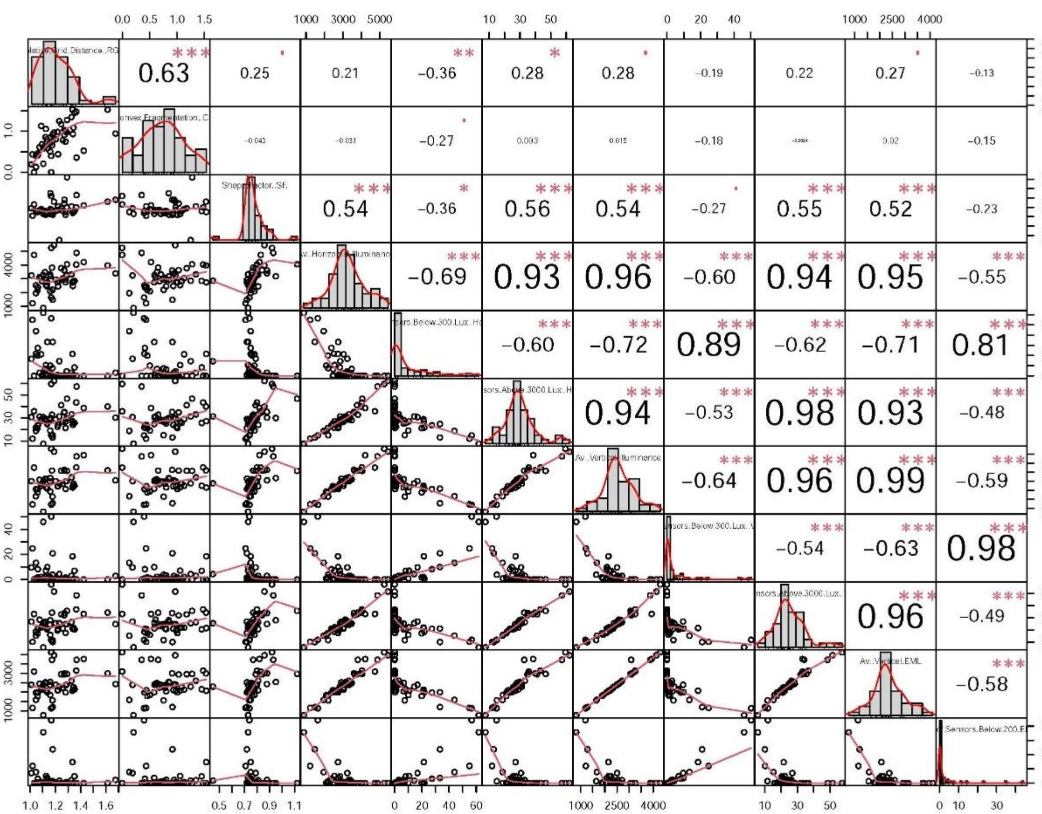


Figure 48 12pm correlation analysis.

Table 17 3pm Building compilation results.

#	Name	Relative Grid Distance (RGD)	Convex Fragmentation (CF)	Shape Factor (SF)	Horizontal			Vertical				
					Av. Horizontal Illuminance	% of Sensors Below 300 Lux (Horizontal)	% of Sensors Above 3000 Lux (Horizontal)	Av. Vertical Illuminance	% of Sensors Below 300 Lux (Vertical)	% of Sensors Above 3000 Lux (Vertical)	Av. Vertical EML	% of Sensors Below 200 EML
1	3com Corporation	1.335	1.534	0.75	1782	28.6	20.1	1441	24.9	14.1	1400	18.8
2	Andersen (after move)	1.157	0.706	0.73	2172	7.9	19.7	1692	5.4	14.8	1630	2.2
3	Andersen (before move)	1.173	0.657	0.77	2540	0	26.3	1994	0	18.3	1913	0
4	Allen & Overy	1.221	0.440	0.81	1702	0.4	16.6	1479	1.3	10.2	1357	0.2
5	Arthur Andersen	1.424	0.525	0.82	2830	0	31.1	2026	0	20.0	1947	0
6	Apicorp	1.292	1.276	1.12	2715	0.2	34.1	2029	0.2	20.1	1978	0.1
7	Apple Computer Inc.	1.289	0.975	0.80	2133	10.4	21.2	1589	4.6	14.9	1637	2
8	Andersen Consulting	1.180	0.968	0.86	3619	0	44	2872	0	34	2773	0
9	Buch und Ton	1.050	0.458	0.75	1445	37.9	15.6	1251	10.6	10.3	1206	2.6
10	Chase Manhattan Bank	1.104	0.207	0.73	585	67.9	4.3	537	59.3	3.2	509	48.5
11	Chiat/Day Advertising	1.613	1.529	0.85	2640	0	29.5	2115	0	21.6	2059	0
12	TBWA Chiat/Day	1.132	0.802	0.74	1671	18.3	18.1	1439	10.1	12.3	1375	4.6
13	Citicorp	1.280	1.007	0.72	1834	10.1	15.6	1463	6.1	11.6	1411	1.5
14	Commerzbank AG	1.327	1.345	0.81	2207	5.5	22.6	1756	4.3	15.9	1695	3.5
15	Data Firmengruppe	1.245	1.176	0.79	2487	0	28.8	2131	0	19.2	2.55	0
16	Davis Polk & Wardwell	1.177	0.755	0.74	1445	29.2	10.9	1159	11.1	6.7	1116	4.4
17	DEGW London Office	1.087	1.130	0.78	1980	22.7	19.1	1439	14	13	1369	5.1
18	Discovery Channel Latin Am.	1.343	1.087	0.76	1873	7.7	18.6	1558	1.7	12.9	1503	0.7
19	DuPont	1.010	0.189	0.79	2181	27	23	1573	17.4	15.1	1506	11.9
20	The Equitable	1.259	0.783	0.75	1995	1.5	18.3	1551	1	12.4	1483	0.7
21	Ford Foundation	1.675	0.944	0.83	2207	3.9	22.4	1687	4.5	13.4	1617	3.2
22	Ford Motor Co.	1.051	0.413	0.75	1588	37.5	17.5	1374	15.8	12.8	1327	5.7
23	GX Networks	1.271	0.912	0.83	2374	0	25.6	2019	0	19.6	1948	0
24	Greenberg Traurig	1.338	0.932	0.74	1651	5.5	16.9	1461	2.3	11.8	1395	0.4
25	Hoffmann La Roche	1.125	1.057	0.73	1675	23.1	18.9	1451	13.6	13.5	1410	9
26	IBM Regional Headquarters	1.019	0.436	0.71	816	61.9	8.4	810	43.4	5.9	776	28
27	IBM (UK) Limited	1.365	1.477	0.80	2667	0	31.2	2153	0	21.3	2089	0
28	IBM Australia	1.216	0.984	0.77	1938	3.4	14.8	1438	2.8	9.9	1362	1
29	Interpolis	1.167	0.000	0.92	3326	0	39.4	2736	0	30.8	2637	0
30	Direct. of Telecom., MPBW	1.075	0.507	0.77	2089	10.3	25.3	1599	4.7	16.1	1620	1.7
31	Eastman Kodak	1.157	0.399	0.74	1081	62.8	10.8	819	54.9	7.3	781	48.3
32	Lend Lease Interiors	1.270	1.030	0.84	2464	0	25.3	2021	0	18.5	1336	0
33	Leo A Daly	1.202	0.804	0.75	2024	1.4	21.3	1571	3.5	15.3	1601	0.9
34	Lowe & Partners/SMS	1.280	0.748	0.75	1990	1.8	21.5	1575	0.6	15.1	1600	0.1
35	McDonald's	1.122	0.856	0.72	1988	7.7	21.9	1594	2.8	15.4	1625	0.4
36	McDonald's Italia	1.159	0.505	0.78	1371	23.1	12.6	1222	5.9	9	1172	1.4
37	MGIC	1.104	0.586	0.75	2161	10.1	21.9	1577	2.7	17	1677	0.7
38	Nickelodeon	1.160	0.849	0.95	2103	0	22.8	1796	0.1	16.6	1718	0
39	Olivetti A	1.031	0.000	0.83	3156	0.3	29	2150	0	21	2058	0
40	Olivetti B	1.031	0.000	0.83	3156	0.3	29	2150	0	21	2058	0
41	Olivetti C	1.031	0.000	0.83	3156	0.3	29	2150	0	21	2058	0
42	Orenstein Koppel	1.117	0.634	0.76	2275	19.4	20.4	1572	8.6	14.6	1607	3.6
43	Sears 40	1.178	0.917	0.72	974	45.5	8.9	871	32.1	5.6	823	32.4
44	Sears 70	1.351	1.450	0.75	1879	14.9	16.8	1509	10.2	11.3	1445	6.9
45	Steelcase Inc.	1.046	0.406	0.76	1661	40.7	16.1	1344	13.3	11.4	1298	4.5
46	British Telec., 3 Longwalk	1.231	1.249	0.77	1976	19.9	23.2	1706	7.5	15.7	1656	3.1
47	British Telec., The Square	1.094	0.681	0.77	1869	7.1	20.8	1514	1.2	14.7	1550	0.1
48	Vitra International AG	1.367	0.356	0.93	3085	0	36.6	2582	0	27.3	2499	0
49	Weyerhaeuser Company	1.135	0.584	0.73	1801	45	17.8	1289	32.2	12.3	1239	19.1
50	WMA Consulting Engineers	1.046	0.129	0.75	1292	44.7	14.3	1109	25.4	9.6	1059	15.1

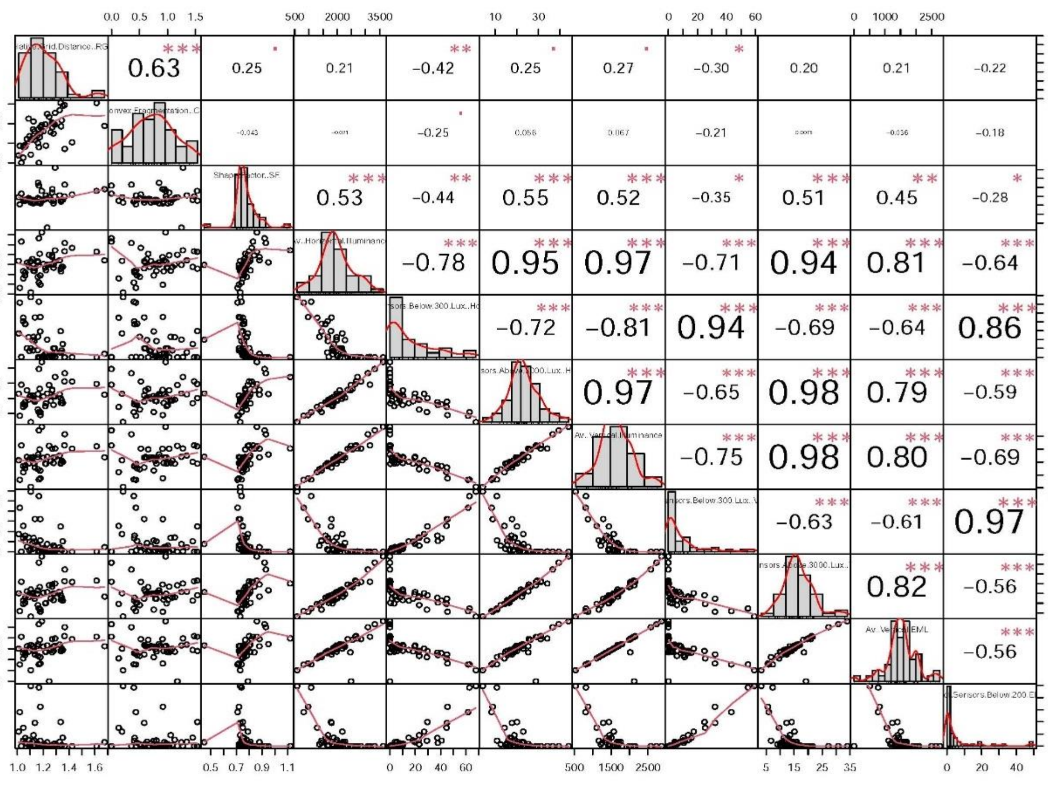


Figure 49 3pm correlation analysis.

A correlation matrix is used to investigate the dependence between multiple variables at the same time. The result is a table containing the correlation coefficients between each variable and the others. Three matrices (figure 47-49) for each time of the day were produced to see if there is a correlation between the daylight simulation measures and the building geometry measures. This was done for relative grid distance (RGD), convex fragmentation (CF), and shape factor (SF). The distribution of each variable is shown on the diagonal. On the bottom of the diagonal, the bivariate scatter plots with a fitted line are displayed. On the top of the diagonal, the value of the correlation and the significance level as stars are displayed. Each significance level is associated to a symbol: p-values (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols (“***”, “**”, “*”, “.”, " “).

There are several findings that can be extracted from these matrices. The first is that there is a strong positive relationship between both of Shpuza’s proposed RGD and CF measures. However, they do not have a correlation with the shape factor measure. The shape factor measure is also evidently the measure that best explains daylight availability. The higher the shape factor, the higher the average horizontal, vertical photopic, and melanopic illuminance and percentage of sensors meeting benchmarks. This implies that buildings do not necessarily have to be compact or have many atriums to achieve high daylighting levels, they just need to have a high shape factor or envelope area.

It is also noted that average horizontal illuminance and average vertical illuminance have a very high correlation. Similarly, average vertical photopic illuminance has a strong, positive relationship with average vertical EML. Meeting the vertical photopic lighting benchmarks would most likely meet the melanopic benchmarks too.

Figure 50 plots the correlation between average horizontal illuminance and shape factor. Figure 51 plots the correlation between average vertical EML and shape factor. Both follow the same trends. The buildings have been color-coded corresponding to their floor plate type categories. It can be seen that pavilions and buildings with wings are higher on the shape factor and daylight availability scale. Bars and buildings with shallow spaces and large central cores are found in the middle. Compact blocks with external cores are on the lower end. Deep spaces with small central cores are spread across the charts.

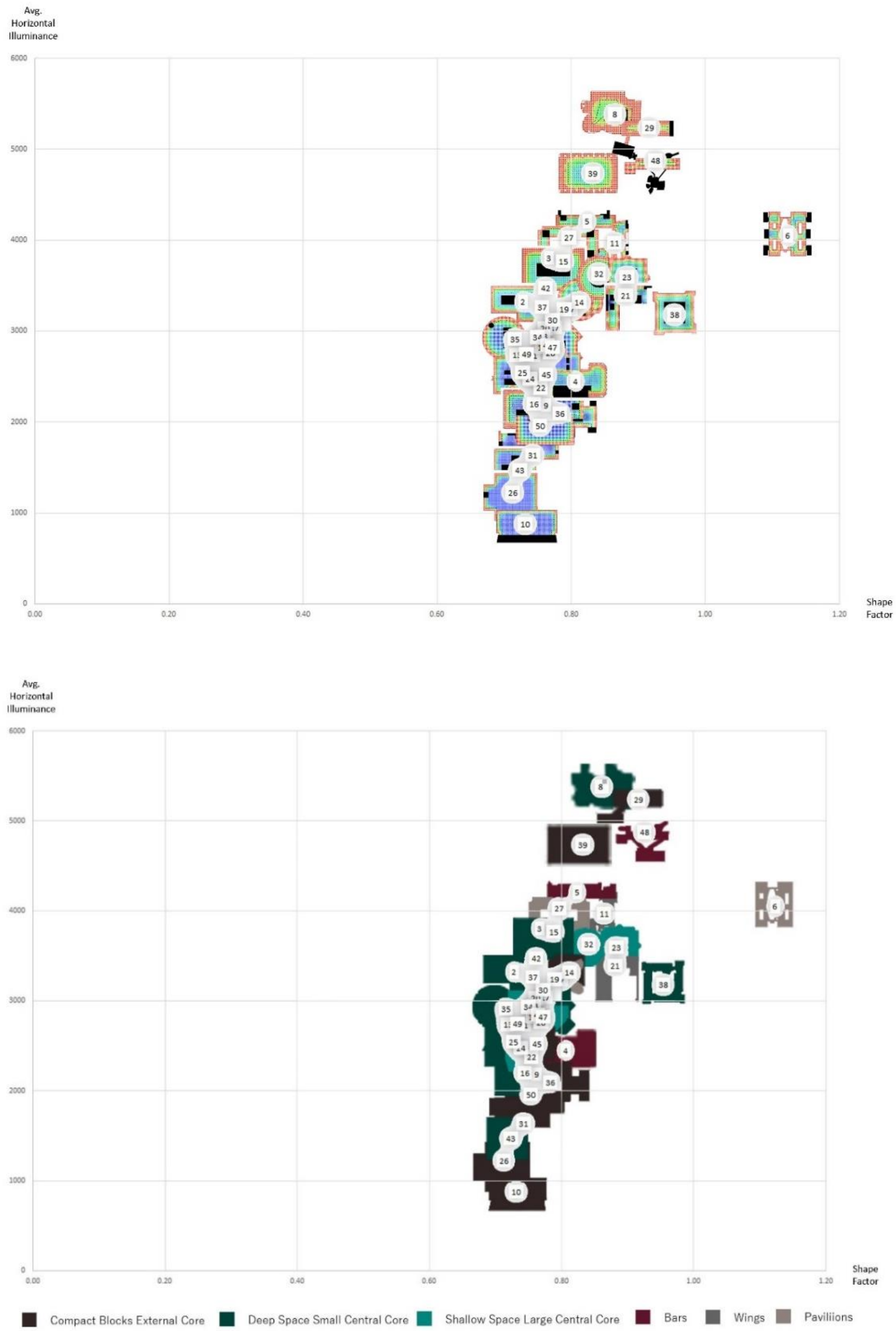
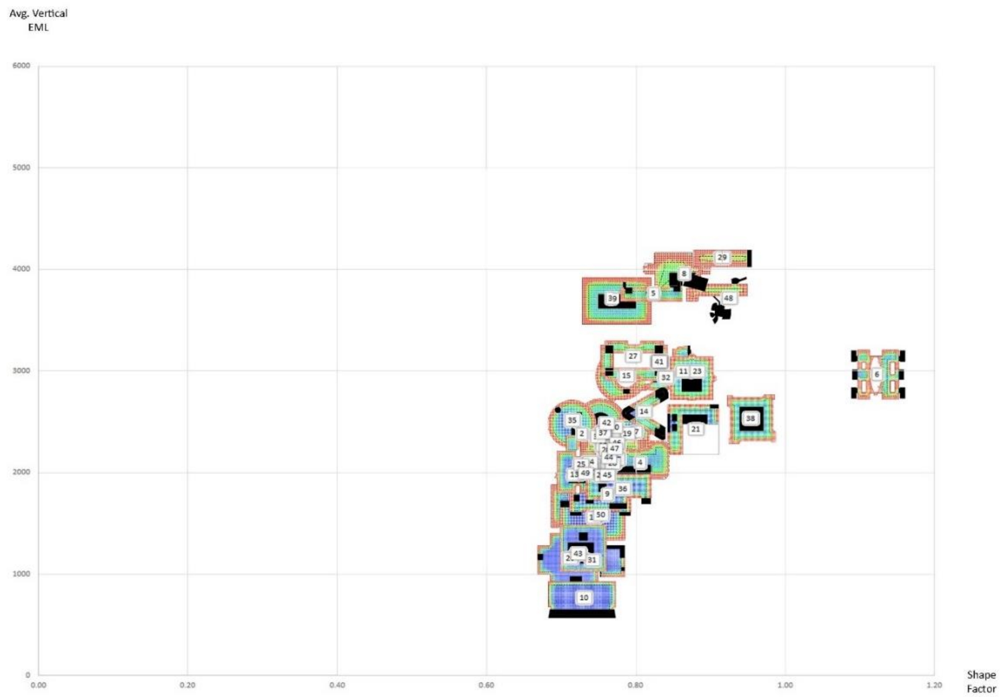


Figure 50 Average Horizontal Illuminance x Shape Factor correlation plots.



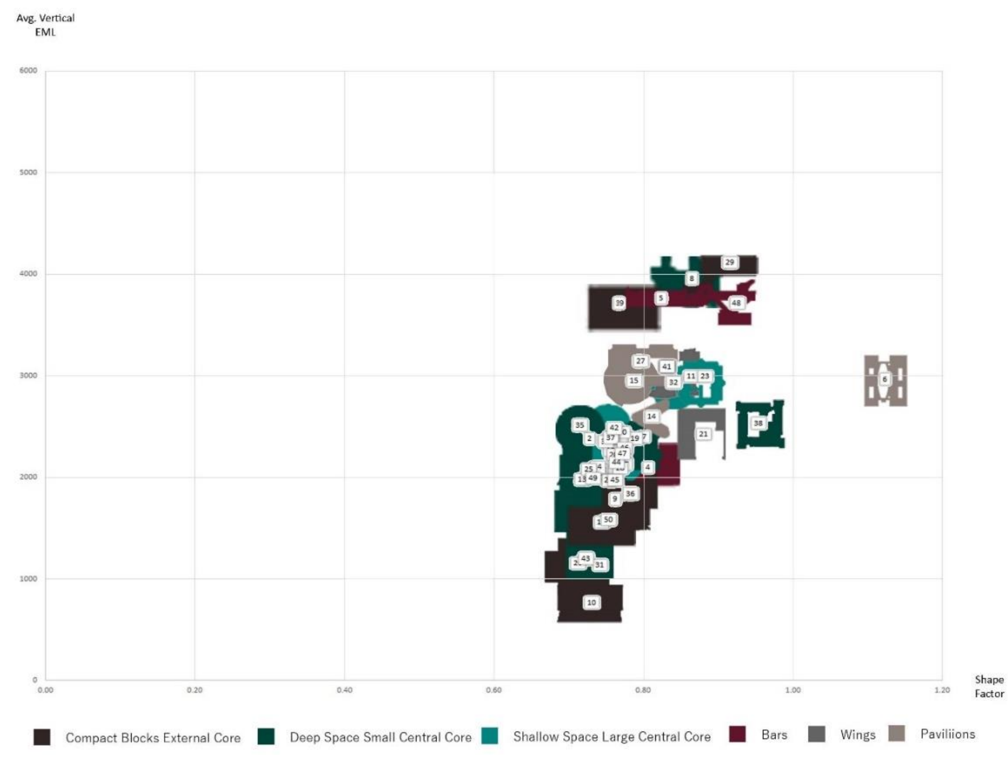


Figure 51 Average Vertical EML x Shape Factor correlation plots.

4.1. Daylight Factor

What primarily started as a means to assess the daylight conditions needed to provide minimally adequate daylight levels in Europe resulted in the development of one of the earliest metrics for daylight performance. The Daylight Factor (DF) is the ratio of internal illuminance at a point in a building to the unshaded, unobstructed, external horizontal illuminance under standard CIE overcast sky conditions - expressed as a percentage (Moon, 1942). An average DF of 2% across a given space is usually required for it to be considered sufficiently daylit.

Because the measurement is made on an overcast day where there is no sun and in which luminance is rotationally symmetrical about the vertical axis, the measurement is independent of climate, time of day, or orientation of the window due to the symmetry of the sky (Mardaljevic et al., 2009). This metric, which was not developed with the intention to accurately assess daylight performance, does not account for different sky conditions and is not sensitive to building orientation, geographic location, or sun position. To address the shortcomings of this overly simplified metric, more complex hourly daylight metrics were developed and adopted. However, the daylight factor is still traditionally used by lighting designers as a quick rule of thumb with a simple calculation:

Equation 1

$$DF_{av} = 0.2 \text{ x window area / floor area}$$

To assess the viability of the rule of thumb calculation as a quick method, its results were compared to computer-simulated results. The equation and simulation daylight factors are noted in table 18. The differences between the results of the two methods were further investigated. For six buildings, the difference between the results was higher than a daylight factor of 5: building 5 Arthur Andersen, building 21 Ford Foundation, building 29 Interpolis, building 38 Nickelodeon, building 39-41 Olivetti A, B, C, and building 48 Vitra International AG.

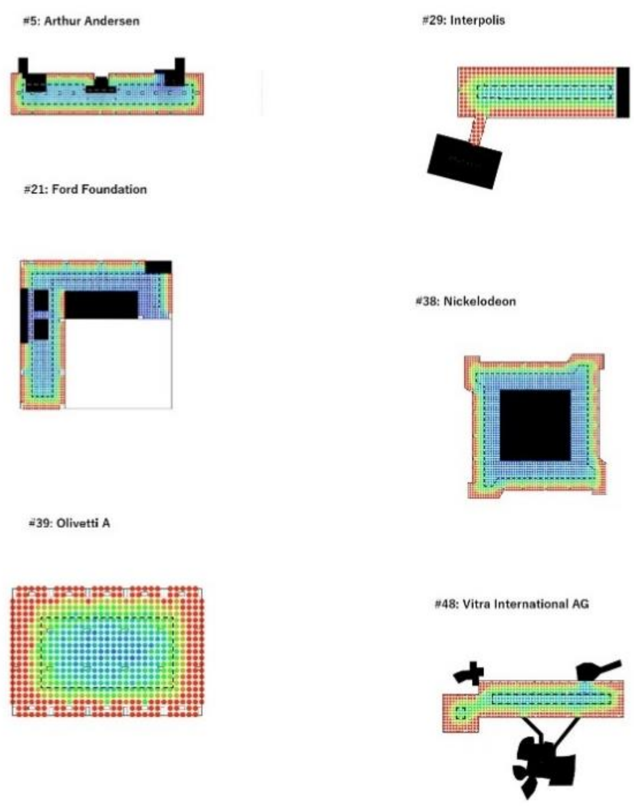


Figure 52 Buildings with highest daylight factor differences.

Table 18 Daylight factor equation and simulation differences.

#	Name	Relative Grid Distance (RGD)	Convex Fragmentation (CF)	Shape Factor (SF)	Daylight Factor (Equation)	Daylight Factor (Simulation)	Difference
1	3com Corporation	1.34	1.53	0.75	4%	5	0
2	Andersen (after move)	1.16	0.71	0.73	5%	3	1
3	Andersen (before move)	1.17	0.66	0.77	6%	4	2
4	Allen & Overy	1.22	0.44	0.81	8%	4	4
5	Arthur Andersen	1.42	0.53	0.82	10%	5	5
6	Apicorp	1.29	1.28	1.12	9%	7	2
7	Apple Computer Inc.	1.29	0.98	0.80	6%	4	2
8	Andersen Consulting	1.19	0.97	0.86	11%	10	2
9	Buch und Ton	1.06	0.46	0.76	6%	3	3
10	Chase Manhattan Bank	1.10	0.21	0.73	4%	1	3
11	Chiat/Day Advertising	1.61	1.53	0.86	10%	7	3
12	TBWA Chiat/Day	1.13	0.80	0.74	4%	4	0
13	Citicorp	1.28	1.01	0.72	5%	3	2
14	Commerzbank AG	1.33	1.35	0.81	9%	6	3
15	Data Firmengruppe	1.25	1.18	0.79	8%	6	2
16	Davis Polk & Wardwell	1.18	0.76	0.74	5%	2	3
17	DEGW London Office	1.09	1.13	0.78	7%	3	4
18	Discovery Channel Latin Am.	1.34	1.09	0.76	5%	4	2
19	DuPont	1.01	0.19	0.79	7%	3	4
20	The Equitable	1.26	0.78	0.76	6%	3	3
21	Ford Foundation	1.68	0.94	0.88	13%	3	10
22	Ford Motor Co.	1.06	0.41	0.75	5%	4	1
23	f/X Networks	1.27	0.91	0.88	11%	6	4
24	Greenberg Traurig	1.34	0.93	0.74	4%	4	0
25	Hoffmann La Roche	1.13	1.06	0.73	5%	5	0
26	IBM Regional Headquarters	1.02	0.44	0.71	3%	2	1
27	IBM (UK) Limited	1.37	1.48	0.80	8%	7	1
28	IBM Australia	1.22	0.98	0.77	6%	4	2
29	Interpolis	1.17	0.00	0.92	15%	10	6
30	Direct. of Telecom., MPBW	1.08	0.61	0.77	6%	4	3
31	Eastman Kodak	1.17	0.40	0.74	5%	1	3
32	Lend Lease Interiors	1.27	1.03	0.84	7%	6	1
33	Leo A Daly	1.20	0.80	0.76	6%	5	1
34	Lowe & Partners/SMS	1.28	0.75	0.75	5%	5	0
35	McDonald's	1.12	0.86	0.72	5%	5	1
36	McDonald's Italia	1.16	0.51	0.78	7%	3	4
37	MGIC	1.10	0.59	0.76	5%	3	3
38	Nickelodeon	1.16	0.85	0.95	11%	5	7
39	Olivetti A	1.03	0.00	0.83	10%	3	7
40	Olivetti B	1.03	0.00	0.83	10%	3	7
41	Olivetti C	1.03	0.00	0.83	10%	3	7
42	Orenstein Koppel	1.12	0.63	0.76	6%	3	3
43	Sears 40	1.18	0.92	0.72	3%	1	2
44	Sears 70	1.35	1.45	0.76	6%	4	2
45	Steelcase Inc.	1.05	0.41	0.76	6%	3	3
46	British Telec., 5 Longwalk	1.23	1.25	0.77	7%	5	2
47	British Telec., The Square	1.09	0.68	0.77	6%	5	2
48	Vitra International AG	1.37	0.36	0.93	14%	8	7
49	Weyerhaeuser Company	1.14	0.58	0.73	4%	2	2
50	WMA Consulting Engineers	1.05	0.13	0.75	5%	2	3

Upon inspection of the buildings in figure 52, it is difficult to determine what they have in common to create high inaccuracies and large differences between the methods. The correlation matrix (figure 53) helps in interpreting relationships between building form and daylight factor results. It can be seen that the higher the shape factor, the higher the daylight factor in both equation and simulation methods. Though both methods have a strong relationship with each other, it is noted that the daylight factor equation has a high correlation with the differences whereas the simulation method does not. This means that the equation will most likely overestimate the daylight factor. In addition, the correlation matrix shows that the higher the shape factor, the higher the difference. This reinforces the findings from Table 18. The six buildings with the difference between the results higher than a daylight factor of 5 were indeed on the higher end of the shape factor scale.

Based on these findings, it can be concluded that the daylight factor equation may be used as a quick rule of thumb in cases of buildings with low shape factors. In cases with high shape factor buildings, the equation will most likely overestimate the daylight factor so it would be best to use a computer simulation to minimize any inaccuracies.

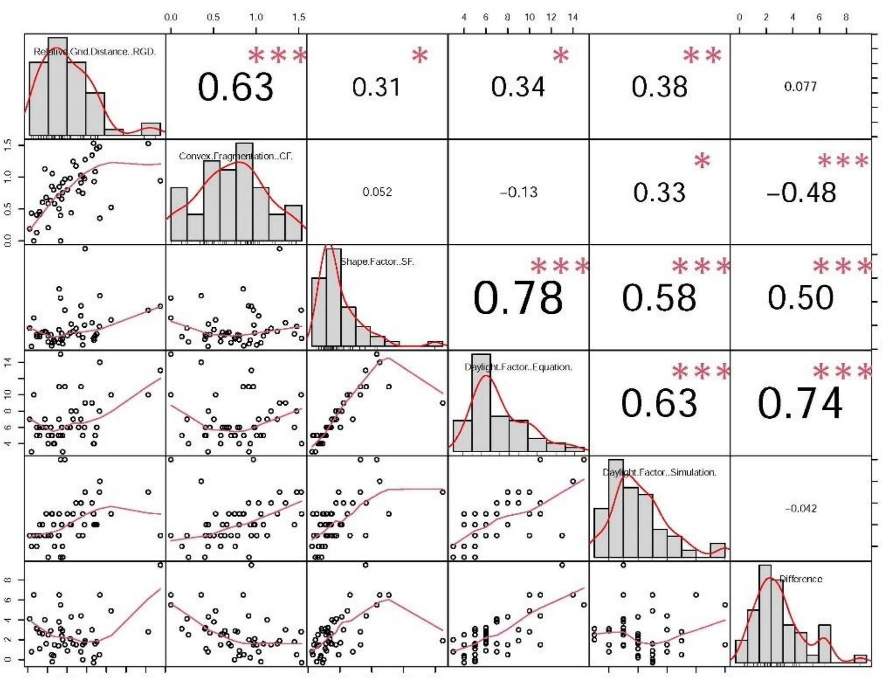


Figure 53 Daylight factor correlation analysis.

4.2. Interior Walls Simulations

The previous simulations investigated building form and geometry as floorplate layouts and their impact on daylight availability. For the second run of simulations, interior walls and partitions were included in the building computer models. This was to address the impact of interior layouts on daylight availability. Six buildings, one from each of the floorplate categories, were selected as a smaller sample for the more detailed interior analyses that follow: Building 5: Arthur Andersen – bar, building 6: Apicorp – pavilion, building 11: Chiat/Day Advertising – wings, building 16: Davis Polk & Wardwell - deep space, small central core, building 26: IBM Regional Headquarters - compact blocks, external core, building 32: Lend Lease Interiors - shallow space, large central core.

Table 19 summarizes the results for the three different times of the day. Table 20 for core and shell and interior walls converts the percentage of sensors of each building to areas (m^2) meeting and not meeting the benchmarks from the building total area. Figure 54 plots the area not meeting the 300 Lux and 200 EML benchmarks for each of the six buildings at 9 am, 12 pm, and 3 pm. The first grey bar shows the total building area. The lighter colored bars indicate the underlit areas for core and shell followed by the darker colored bars that show an increase in underlit areas for simulations with interior walls. This highlights the change and deterioration of daylighting conditions as a building model progresses in the design stages from core and shell to including interior walls. The core and shell and interior walls daylight floorplan simulations comparison side by side can be found in Appendix B: Interior Walls Simulations.

Table 19 Building sensor percentage data compilation.

Building		Horizontal: Av. Horizontal Illuminance	Horizontal: % of Sensors Below 300 Lux (Horizontal)	Horizontal: % of Sensors Above 3000 Lux (Horizontal)	Vertical: Av. Vertical Illuminance	Vertical: % of Sensors Below 300 Lux (Vertical)	Vertical: % of Sensors Above 3000 Lux (Vertical)	Vertical: Av. Vertical EML	Vertical: % of Sensors Below 200 EML
5	Arthur Andersen	2237	5.6	25.3	1642	5.1	16	1581	4.1
6	Apicorp	1883	29.8	26.2	1275	32.3	13	1233	27.9
11	Chiat/Day Advertising	1874	39.3	26.2	1378	37	15.3	1342	31.7
16	Davis Polk & Wardwell	1032	50	8.3	645	53.7	4.3	615	50.4
26	IBM Regional Headquarters	556	73.4	6.5	467	72.1	3.9	447	68.4
32	Lend Lease Interiors	1908	3.9	19.8	1559	3.5	13.1	1492	3

9AM

Building		Horizontal: Av. Horizontal Illuminance	Horizontal: % of Sensors Below 300 Lux (Horizontal)	Horizontal: % of Sensors Above 3000 Lux (Horizontal)	Vertical: Av. Vertical Illuminance	Vertical: % of Sensors Below 300 Lux (Vertical)	Vertical: % of Sensors Above 3000 Lux (Vertical)	Vertical: Av. Vertical EML	Vertical: % of Sensors Below 200 EML
5	Arthur Andersen	4211	3.7	43.6	3085	3.8	33.5	2938	3.7
6	Apicorp	3526	22.8	39.9	2482	23.2	31.2	2374	21.5
11	Chiat/Day Advertising	3548	28.1	38	2570	26.5	32.1	2474	22.2
16	Davis Polk & Wardwell	1922	48	15.2	1207	48.6	10.3	1137	48
26	IBM Regional Headquarters	1021	67.3	10.1	877	62.9	9	829	59.1
32	Lend Lease Interiors	3609	2.8	35.4	2856	2.6	30.8	2703	2.5

12PM

Building		Horizontal: Av. Horizontal Illuminance	Horizontal: % of Sensors Below 300 Lux (Horizontal)	Horizontal: % of Sensors Above 3000 Lux (Horizontal)	Vertical: Av. Vertical Illuminance	Vertical: % of Sensors Below 300 Lux (Vertical)	Vertical: % of Sensors Above 3000 Lux (Vertical)	Vertical: Av. Vertical EML	Vertical: % of Sensors Below 200 EML
5	Arthur Andersen	2811	3.9	32.2	2026	4.3	21.6	1942	3.7
6	Apicorp	2418	26.4	31	1639	28	20.2	1577	24.8
11	Chiat/Day Advertising	2350	34.8	31.2	1757	32.4	22.7	1703	27.8
16	Davis Polk & Wardwell	1270	48.9	10.1	819	50.9	6.6	777	49.1
26	IBM Regional Headquarters	710	70.7	7.9	597	67.7	5.6	568	63.9
32	Lend Lease Interiors	2378	3	24.6	1962	3	19.1	1872	2.7

3PM

Table 20 Building area data compilation.

Core and Shell

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	0.2	2.96	0	0.00
6	Apicorp	3083	3032	12128	1.5	46.25	0.1	3.08
11	Chiat/Day Advertising	2098	1812	7248	1.3	27.27	0	0.00
16	Davis Polk & Wardwell	2718	2228	8912	37.7	1024.69	9.5	258.21
26	IBM Regional Headquarters	8204	7731	30924	66.8	5480.27	36.8	3019.07
32	Lend Lease Interiors	1007	891	3564	0	0.00	0	0.00

9am

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	0.0	0.00	0	0.00
6	Apicorp	3083	3032	12128	0.0	0.00	0	0.00
11	Chiat/Day Advertising	2098	1812	7248	0.0	0.00	0	0.00
16	Davis Polk & Wardwell	2718	2228	8912	7.5	203.85	1.3	35.33
26	IBM Regional Headquarters	8204	7731	30924	55.0	4512.20	12	984.48
32	Lend Lease Interiors	1007	891	3564	0.0	0.00	0	0.00

12pm

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	0	0.00	0	0.00
6	Apicorp	3083	3032	12128	0.2	6.17	0.1	3.08
11	Chiat/Day Advertising	2098	1812	7248	0	0.00	0	0.00
16	Davis Polk & Wardwell	2718	2228	8912	29.2	793.66	4.4	119.59
26	IBM Regional Headquarters	8204	7731	30924	61.8	5070.07	28	2297.12
32	Lend Lease Interiors	1007	891	3564	0	0.00	0	0.00

3pm

Interior Walls

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	5.6	82.77	4.1	60.60
6	Apicorp	3083	3032	12128	29.8	918.73	27.9	860.16
11	Chiat/Day Advertising	2098	1812	7248	39.3	824.51	31.7	665.07
16	Davis Polk & Wardwell	2718	2228	8912	50	1359.00	50.4	1369.87
26	IBM Regional Headquarters	8204	7731	30924	73.4	6021.74	68.4	5611.54
32	Lend Lease Interiors	1007	891	3564	3.9	39.27	3	30.21

9am

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	3.7	54.69	3.7	54.69
6	Apicorp	3083	3032	12128	22.8	702.92	21.5	662.85
11	Chiat/Day Advertising	2098	1812	7248	28.1	589.54	22.2	465.76
16	Davis Polk & Wardwell	2718	2228	8912	48.0	1304.64	48	1304.64
26	IBM Regional Headquarters	8204	7731	30924	67.3	5521.29	59.1	4848.56
32	Lend Lease Interiors	1007	891	3564	2.8	28.20	2.5	25.18

12pm

Building		Total Area m^2	Total Horizontal Sensors	Total Vertical Sensors	% of Sensors Below 300 Lux (Horizontal)	Area Below 300 Lux (Horizontal) m^2	% of Sensors Below 200 EML	Area Below 200 EML (Vertical) m^2
5	Arthur Andersen	1478	1259	5036	3.9	57.64	3.7	54.69
6	Apicorp	3083	3032	12128	26.4	813.91	24.8	764.58
11	Chiat/Day Advertising	2098	1812	7248	34.8	730.10	27.8	583.24
16	Davis Polk & Wardwell	2718	2228	8912	48.9	1329.10	49.1	1334.54
26	IBM Regional Headquarters	8204	7731	30924	70.7	5800.23	63.9	5242.36
32	Lend Lease Interiors	1007	891	3564	3	30.21	2.7	27.19

3pm

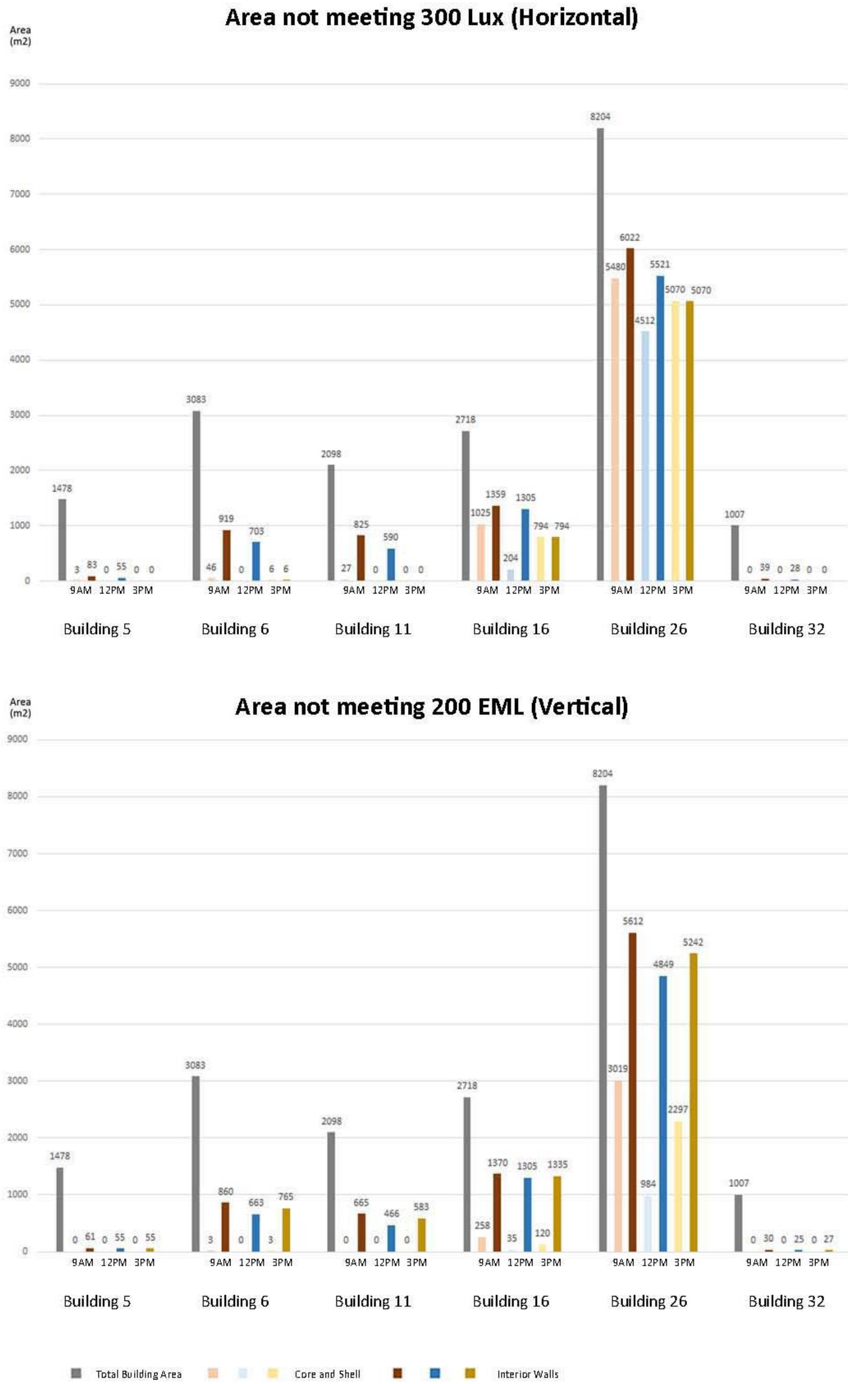


Figure 54 Total building areas, core and shell, and interior wall areas not meeting benchmarks.

CHAPTER V: ISOVIST ANALYSIS RESULTS

The six buildings that were simulated for the Stage 2 design phase with the interior walls were selected for the Stage 3 isovist analysis to better understand how these interior walls influence workstation layouts. The measures extracted from the Isovist software analysis that are related to the scope of the study are defined as follows (isovists.org, 2017):

- Area: expresses the area of all space visible from a subject point in the plan. It represents the number of other subject points that a location is directly connected to.

- Perimeter: expresses the length of the edge of all space visible from a location. It represents the geometric isovist perimeter at a location.

- Compactness: expresses the shape property (relative to a circle) of all space visible from a location. In an isovist field, compactness identifies the regions of plan in which an observer's spatial experience is contiguously consistent.

- Drift: expresses the distance from a subject point to the center of gravity of its isovist. It identifies the inherent flow within a series of spaces. High Drift identifies regions from which space can be surveyed with a minimum of head-turning.

- Occlusivity: represents how previously unseen space may be revealed during movement. Occlusivity fields show moments of dramatic visual change as a user passes between spaces.

- Vista: expresses the longest single view available at each location. Vista Length values identify regions of high axial view.

- Visibility: expresses how often any given subject point is seen from a defined sample region. In isovist terminology, it represents how often a space falls within an isovist generated from within said region.

Another important measure that was computed from the data collected is the A/P ratio. This ratio is calculated by dividing the isovist area by the isovist perimeter. If the ratio drops below 1, then the perimeter value exceeds the area value. This indicates a narrow isovist spike. When the ratio is lower than 0.5 then the visual flow is extremely spiky. The A/P ratio has various applications including explaining patterns of crime (Nubani, 2006). For this study’s purposes, the ratio is used to indicate visual obstructions that could diminish vertical illuminance transmitted through windows.

5. Isovist Analysis Results

To be consistent across all buildings, 30% of the total number of workstations were used as sample point isovist locations. The point isovist visual analysis sweep was set to 179 degrees to best depict occupants' cone of vision in stationary positions at their workstations. For visual purposes, in the point isovist diagrams both the accessible (dark blue) and visible (light blue) isovist cones of vision were overlayed to differentiate what can be seen through the window (light blue) and within the building (dark blue). Accessible point isovists are restricted to just inside the building. The software includes the area through the windows when visible point isovists are selected. For the numerical data, only the visible point isovists were used to easily identify which points have window access (thus a much larger isovist area). By triggering the 'extended visibility' option for the area heat map, it depicts the area through the windows too – which is what is used for the numerical data.

For a general analysis, the visual analysis sweep was set to 360 degrees for all heat maps. This provides an overview from all locations and all view directions within the building. Additionally, the drift heat map was overlayed with flow vectors which draw a series of vector lines that indicate the direction and magnitude of the field results at locations throughout the space.

It should be noted that in some buildings there are wall partitions that are only 1.3m high. These are high enough to block visual connections but allow daylight transmittance over them. The other interior walls are 3m from floor to ceiling, these do not allow visual connections or daylight through. The Isovist software does not differentiate between interior partitions and wall heights as it works two-dimensionally. For the study's purposes, the isovist analysis remains unaffected since in both partitions and walls cases visual connections are blocked. The daylight simulations address the differences in heights and are visually indicated in the 9 am worst case horizontal illuminance isolux plans.

To check each building's performance, the LEED and WELL credit requirements were benchmarked against the isovist results as follows:

- 75% of all workstations have a direct line of sight to the outdoors, up to 30% may be used as views into interior atria.
- 70% of all workstations to be within 16 ft of the envelope glazing.

These benchmarks were used across the 30% of the total number of workstations which were used as sample point isovist locations.

5.1. Building 5 - Arthur Andersen

The Arthur Andersen building has a bar floor plate type. With a 0% cellular floor area and a 35.6% open plan floor area, its predominant layout is open plan. The floorplate is distinctly elongated having a length of 270 ft and a depth of 54 ft. Three separate cores adjacent to the rear wall create four bays of spaces while leaving a continuous space with the width of a column bay along the front wall. A café at the entrance from the elevator extends in two sides with informal meeting spaces. The main curving circulation is developed along the front wall dividing the collaborative workplace from the open-plan concentrated workstations.

The isovist analysis shows that 42 out of 50 workstations have direct views to the outdoors. At 84%, these account for more than the 75% required benchmark, which means the building samples meet the benchmarks. The plans also show that out of 28 out of 50 workstations are within 16 ft of the envelope glazing. At 56%, the 70% benchmark requirements are not met.

The building's floor plate type enables light to penetrate deep into the building, past the perimeter zone. This allows workstations to receive sufficient light even if they are not within 16 ft of the envelope glazing as benchmarks require. Since 84% of the workstations sample points still manage to have direct views to the outdoors, this proves that the open-plan interior layout can remediate having workstations further away from the envelope and achieve sufficient daylight as well as access to views.

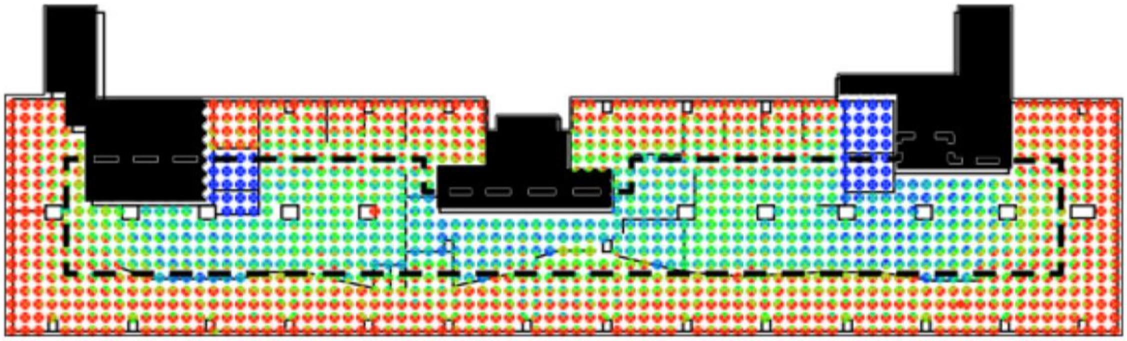


Figure 55 Building 5 horizontal illuminance

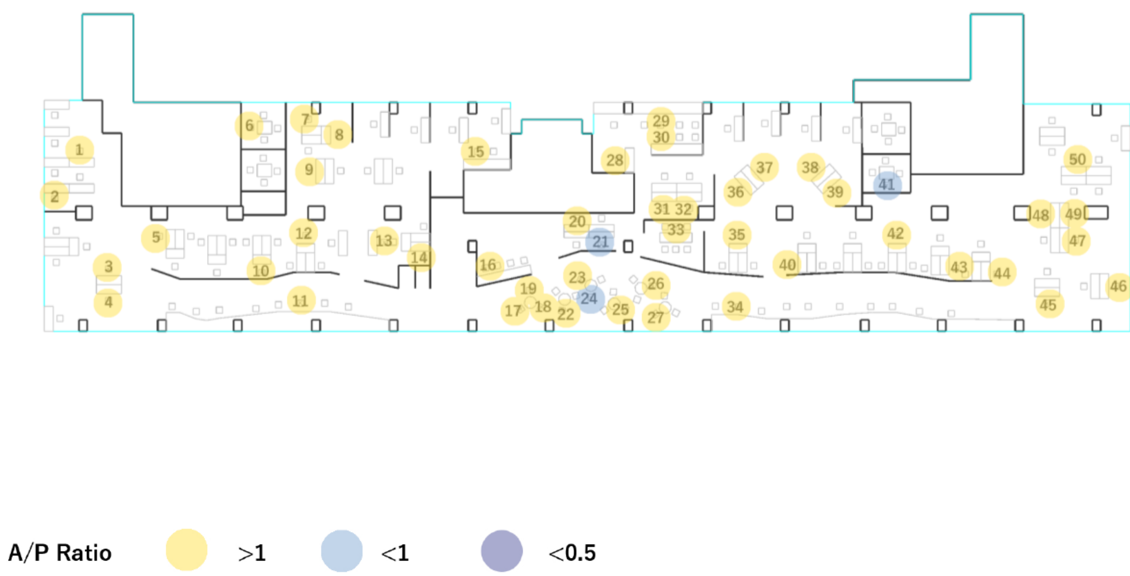


Figure 56 Building 5 A/P ratio

Table 21 Building 5 data points

Point	Area	Perimeter	Area / Perimeter	Compactness	Drift	Occlusivity	Vista
1	1493.78	421.28	3.55	0.11	31.96	0.63	83.88
2	1575.84	183.86	8.57	0.59	27.83	0.22	66.02
3	4059.29	1024.06	3.96	0.05	39.05	0.69	104.81
4	941.54	476.92	1.97	0.05	17.83	0.34	107.79
5	98.91	54.60	1.81	0.42	10.14	0.08	21.25
6	2912.16	236.79	12.30	0.65	49.65	0.35	89.07
7	487.50	201.55	2.42	0.15	43.87	0.60	79.40
8	1186.77	302.71	3.92	0.16	37.01	0.50	65.39
9	1435.98	520.30	2.76	0.07	38.74	0.63	80.51
10	1316.04	563.76	2.33	0.05	36.14	0.68	96.14
11	3715.38	885.93	4.19	0.06	31.12	0.55	92.45
12	579.03	430.46	1.35	0.04	20.17	0.68	83.07
13	1961.26	744.98	2.63	0.04	24.63	0.62	74.58
14	1236.06	572.82	2.16	0.05	41.35	0.64	77.16
15	50.86	45.49	1.12	0.31	8.07	0.18	15.53
16	246.96	225.29	1.10	0.06	39.20	0.43	78.23
17	1157.29	606.83	1.91	0.04	39.41	0.55	76.97
18	1490.67	424.60	3.51	0.10	38.12	0.47	67.39
19	4353.91	1079.63	4.03	0.05	29.38	0.58	74.85
20	710.30	330.49	2.15	0.08	36.80	0.72	69.62
21	62.72	88.68	0.71	0.10	3.00	0.31	17.23
22	359.69	304.45	1.18	0.05	34.95	0.46	73.78
23	3328.89	721.97	4.61	0.08	35.46	0.61	71.13
24	278.48	447.40	0.62	0.02	1.85	0.36	71.21
25	2275.32	526.76	4.32	0.10	36.19	0.47	81.05
26	2671.59	732.98	3.64	0.06	37.87	0.60	75.64
27	1394.59	427.82	3.26	0.10	36.94	0.41	68.35
28	1907.03	368.97	5.17	0.18	42.87	0.54	69.94
29	4758.11	426.23	11.16	0.33	35.98	0.54	75.63
30	18.36	23.22	0.79	0.43	2.25	0.06	6.20
31	1058.09	460.82	2.30	0.06	47.72	0.81	77.02
32	1307.45	330.30	3.96	0.15	41.49	0.75	78.76
33	598.46	480.35	1.25	0.03	16.55	0.60	74.20
34	4017.81	762.33	5.27	0.09	31.36	0.49	81.91
35	897.49	263.64	3.40	0.16	35.81	0.48	60.43
36	1881.82	577.34	3.26	0.07	41.65	0.74	74.39
37	421.89	313.53	1.35	0.05	37.97	0.67	69.95
38	483.46	195.88	2.47	0.16	45.45	0.68	77.29
39	1473.06	537.38	2.74	0.06	45.10	0.74	85.06
40	1143.31	504.18	2.27	0.06	34.34	0.54	76.09
41	9.14	12.33	0.74	0.76	1.24	0.00	3.09
42	488.71	167.84	2.91	0.22	25.81	0.22	46.84
43	118.33	95.48	1.24	0.16	10.78	0.20	24.51
44	1932.96	460.45	4.20	0.11	42.40	0.56	88.12
45	1906.75	661.63	2.88	0.05	27.35	0.38	106.42
46	3522.68	1206.86	2.92	0.03	46.79	0.56	111.53
47	3361.05	838.33	4.01	0.06	36.50	0.55	99.87
48	2656.97	471.91	5.63	0.15	14.52	0.39	64.67
49	2745.03	594.05	4.62	0.10	29.88	0.46	91.48
50	2300.50	460.75	4.99	0.14	34.45	0.55	85.86

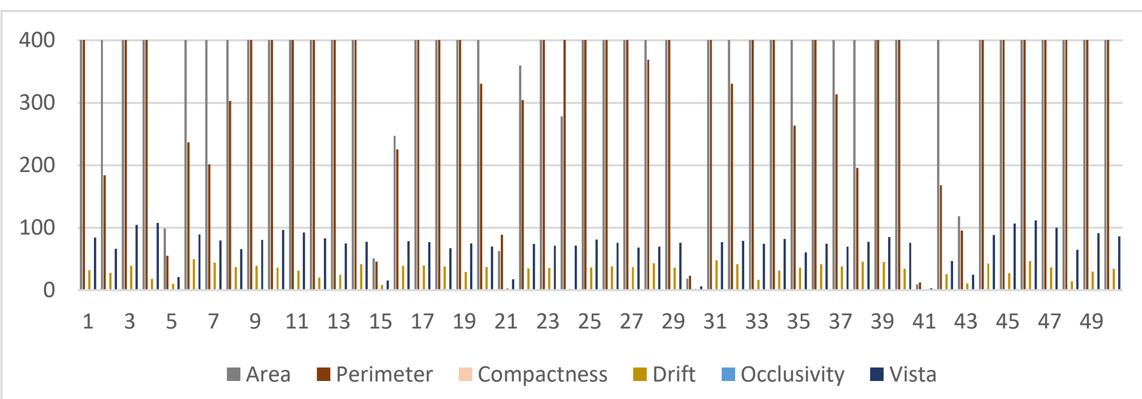


Figure 57 Building 5 plotted isovist point measures.

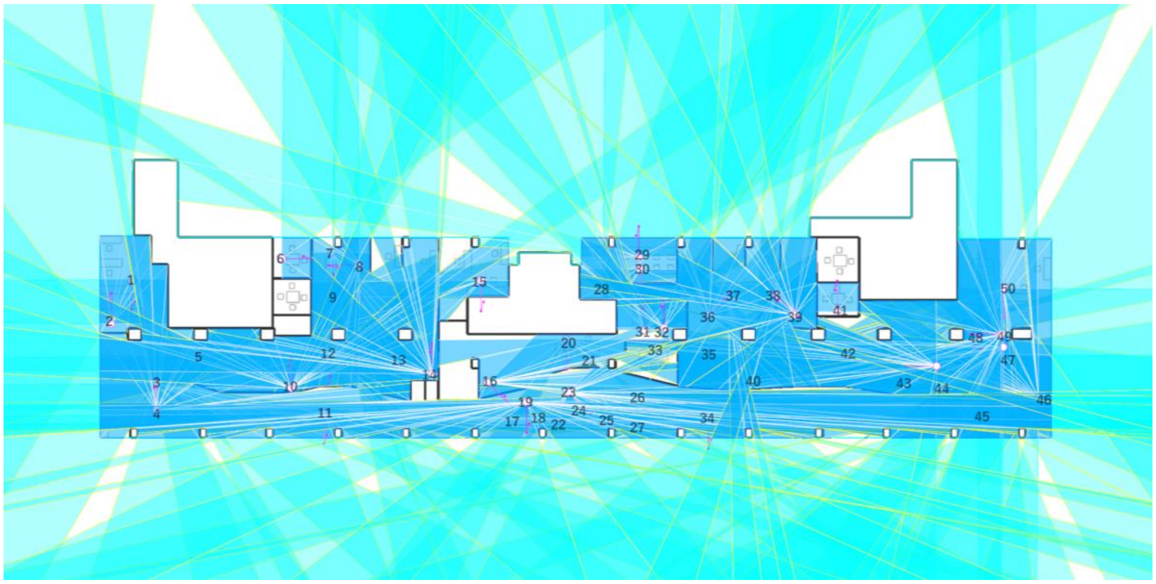


Figure 58 Building 5 point isovist diagram

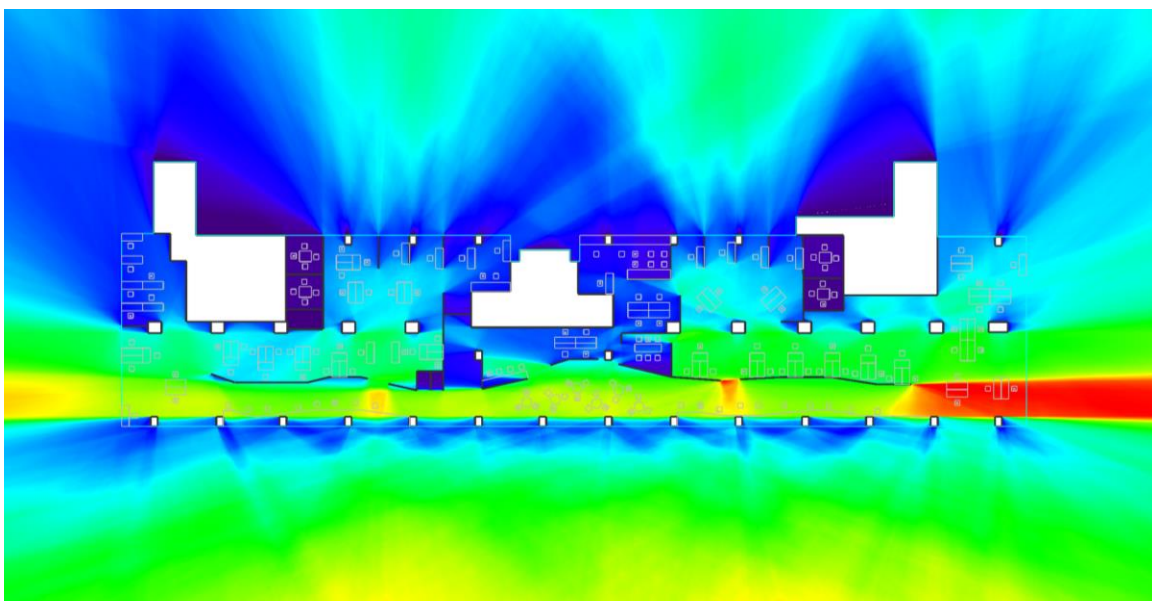


Figure 59 Building 5 area extended visibility

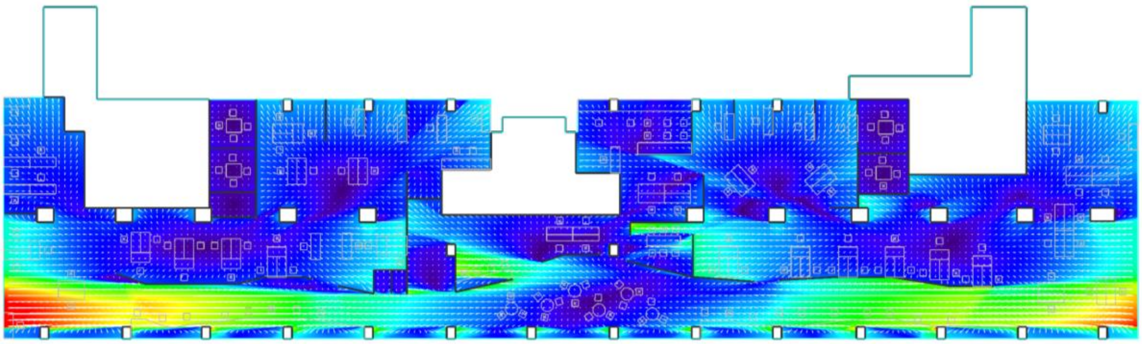


Figure 60 Building 5 drift flow overlay

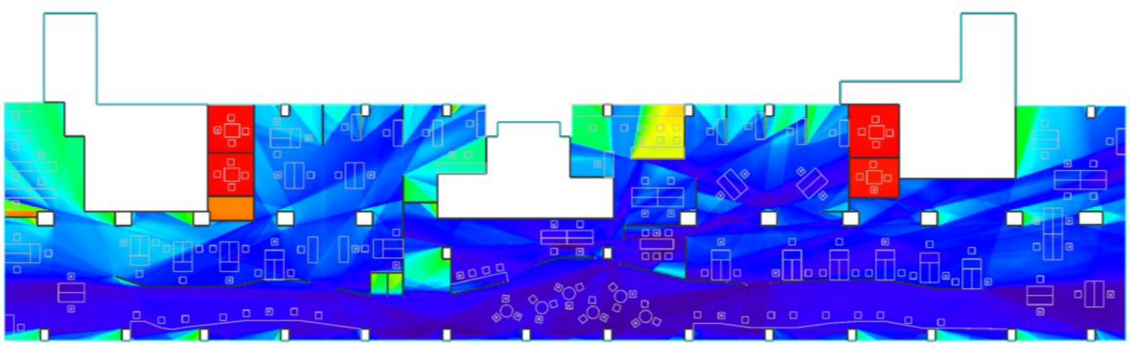


Figure 61 Building 5 compactness

5.2. Building 6 - Apicorp

The Apicorp building has a pavilion floor plate type. With a 30.5% cellular floor area and a 5.5% open plan floor area, its predominant layout is cellular. The plan is organized in two pavilions separated by a central atrium. The design approach to incorporate atria in deep buildings helps sustain daylight levels, especially in this building's case, since the cores and cellular offices along the building envelope create a buffer and do not allow daylight through. Each pavilion is developed around four smaller atria. The atria still do not effectively provide access to outdoor views. However, internal atria are a better alternative to no views. They allow space to be surveyed easily through glazing rather than solid walls or partitions as seen with the drift flow overlays (Figure 67). Three external cores are located on the outer sides of the pavilions for solar shielding. The layout is mostly cellular and is organized based on a clear circulation grid with corridors running across the floorplate between external staircases.

The isovist analysis shows that 13 out of 48 workstations have direct views to the outdoors and 22 more have views into the internal atria. At 27%, these account for less than the 75% required outdoors views, and the 46% internal atria views exceed the 30% internal view maximum, which means the building samples do not meet the benchmarks with an adjusted 57% total. The plans also show that out of 17 out of 48 workstations are within 16 ft of the envelope glazing. At 35%, the 70% benchmark requirements are not met.

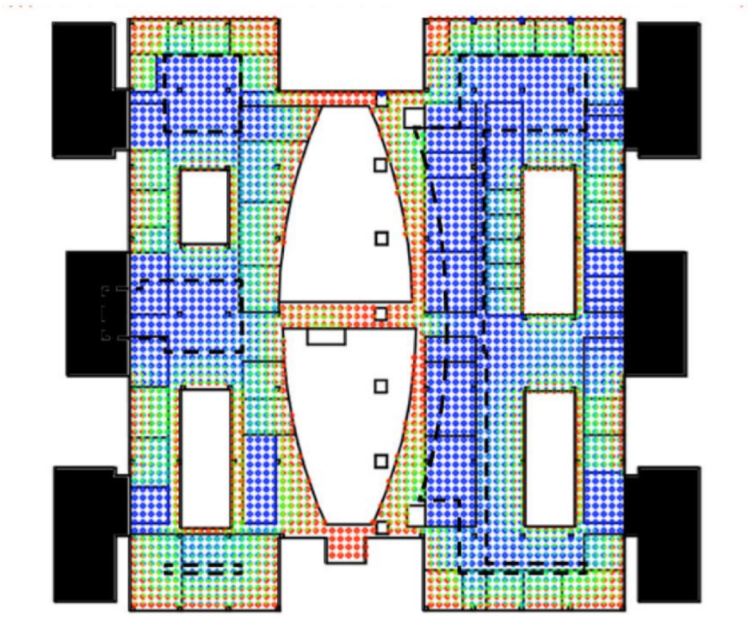


Figure 63 Building 6 horizontal illuminance.

Figure 62 Building 6 A/P ratio.

Table 22 Building 6 data points

Point	Area	Perimeter	Area / Perimeter	Compactness	Drift	Occlusivity	Vista
1	293.77	182.71	1.61	0.11	20.78	0.24	49.52
2	2045.66	428.13	4.78	0.14	29.68	0.48	73.92
3	319.23	88.02	3.63	0.52	20.57	0.26	33.78
4	410.67	279.53	1.47	0.07	26.75	0.29	57.02
5	409.50	271.63	1.51	0.07	25.34	0.23	53.03
6	95.94	57.09	1.68	0.37	5.49	0.12	12.18
7	588.48	356.19	1.65	0.06	26.73	0.49	90.35
8	772.55	269.66	2.86	0.13	33.09	0.43	64.61
9	9.85	18.09	0.54	0.38	2.78	0.00	6.75
10	655.27	284.03	2.31	0.10	32.96	0.44	70.65
11	29.89	22.11	1.35	0.77	3.48	0.00	7.37
12	201.82	114.48	1.76	0.19	11.59	0.19	24.72
13	416.90	245.70	1.70	0.09	12.19	0.27	51.28
14	461.37	263.14	1.75	0.08	17.49	0.27	40.32
15	253.20	177.49	1.43	0.10	14.13	0.44	34.23
16	148.58	102.26	1.45	0.18	8.29	0.34	20.68
17	626.73	119.60	5.24	0.55	25.05	0.46	41.84
18	412.59	103.11	4.00	0.49	20.01	0.20	34.79
19	372.07	338.44	1.10	0.04	22.68	0.40	92.86
20	558.96	341.06	1.64	0.06	26.97	0.44	94.71
21	122.81	218.70	0.56	0.03	4.72	0.34	39.41
22	144.93	81.37	1.78	0.28	22.07	0.33	35.12
23	20.54	19.07	1.08	0.71	2.07	0.00	5.10
24	418.49	287.00	1.46	0.06	20.12	0.37	57.70
25	134.89	81.23	1.66	0.26	5.36	0.17	13.55
26	329.08	249.13	1.32	0.07	18.80	0.41	51.95
27	162.17	86.78	1.87	0.27	2.71	0.04	22.01
28	204.24	108.34	1.89	0.22	9.08	0.23	19.95
29	380.32	249.24	1.53	0.08	17.20	0.29	53.31
30	408.82	223.11	1.83	0.10	8.54	0.27	49.89
31	247.75	108.26	2.29	0.27	8.89	0.20	21.19
32	339.09	143.75	2.36	0.21	13.58	0.27	29.16
33	338.38	213.70	1.58	0.09	13.27	0.32	29.67
34	313.70	158.31	1.98	0.16	14.45	0.23	29.68
35	342.44	176.92	1.94	0.14	17.91	0.13	40.87
36	780.38	127.70	6.11	0.60	27.23	0.39	46.92
37	94.98	59.82	1.59	0.33	6.05	0.41	16.40
38	112.29	63.20	1.78	0.35	7.87	0.16	19.59
39	383.39	225.71	1.70	0.09	27.08	0.24	53.04
40	115.45	82.86	1.39	0.21	5.88	0.23	16.47
41	423.07	265.45	1.59	0.08	27.76	0.27	54.66
42	113.40	79.24	1.43	0.23	5.28	0.25	15.83
43	12.92	14.61	0.88	0.76	2.20	0.00	4.72
44	287.53	237.32	1.21	0.06	10.94	0.25	34.54
45	326.37	369.23	0.88	0.03	13.70	0.26	61.42
46	574.21	390.94	1.47	0.05	22.23	0.25	61.54
47	151.31	212.31	0.71	0.04	18.51	0.16	61.31
48	1681.19	194.34	8.65	0.56	35.34	0.35	77.59

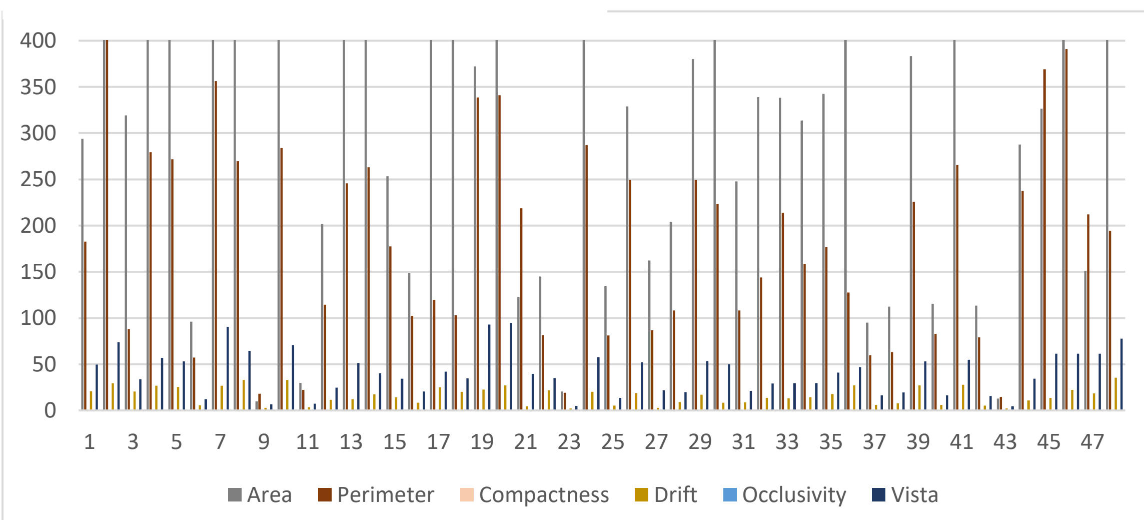


Figure 64 Building 6 plotted isovist point measures.

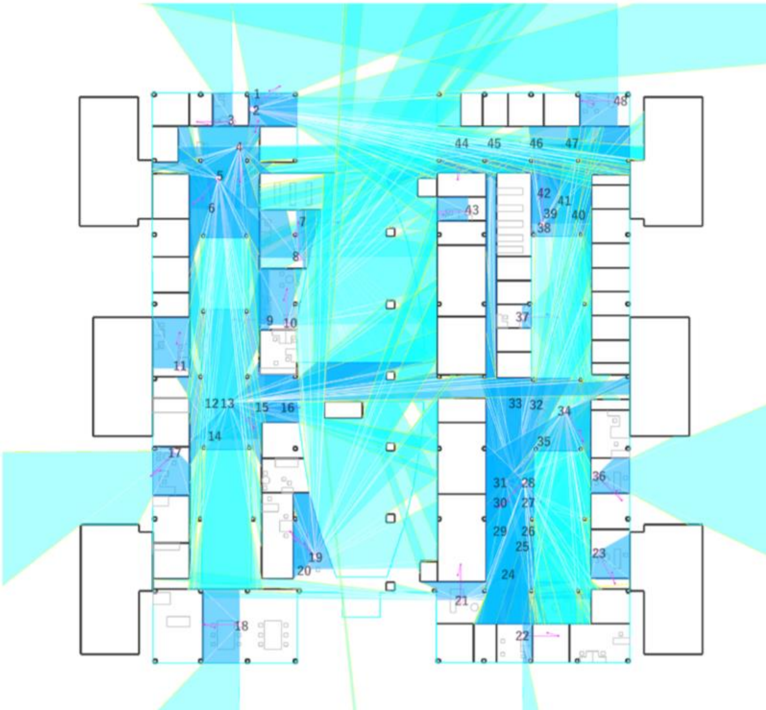


Figure 65Building 6 point isovist diagram.

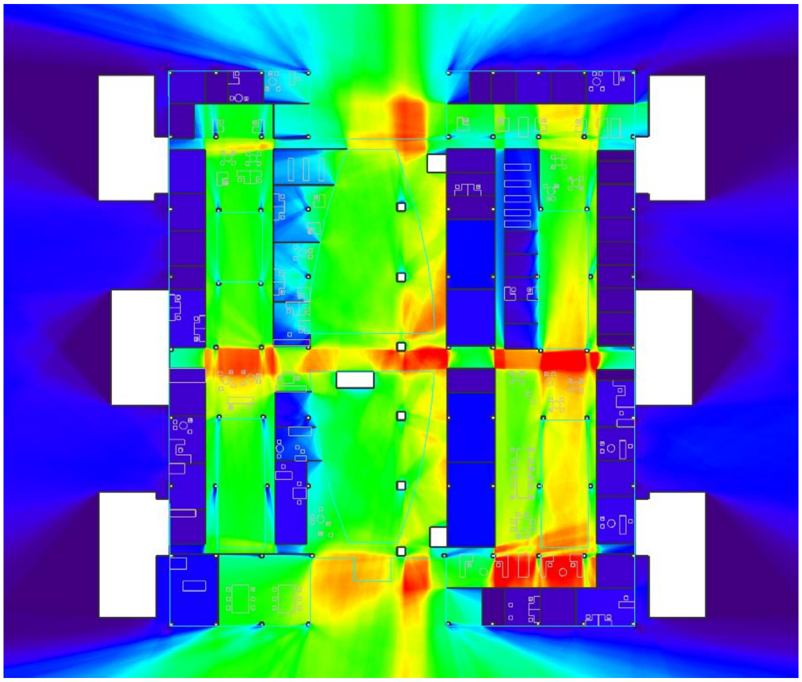


Figure 66 Building 6 area extended visibility.

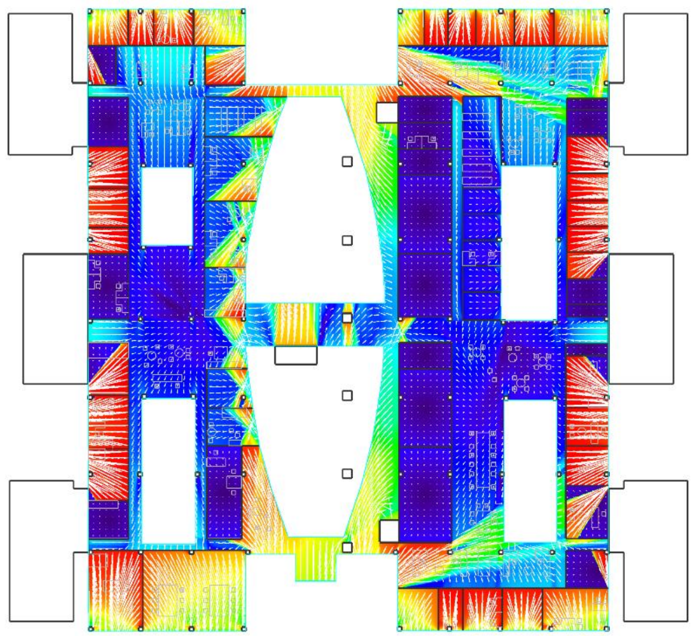


Figure 68 Building 6 drift flow overlay.

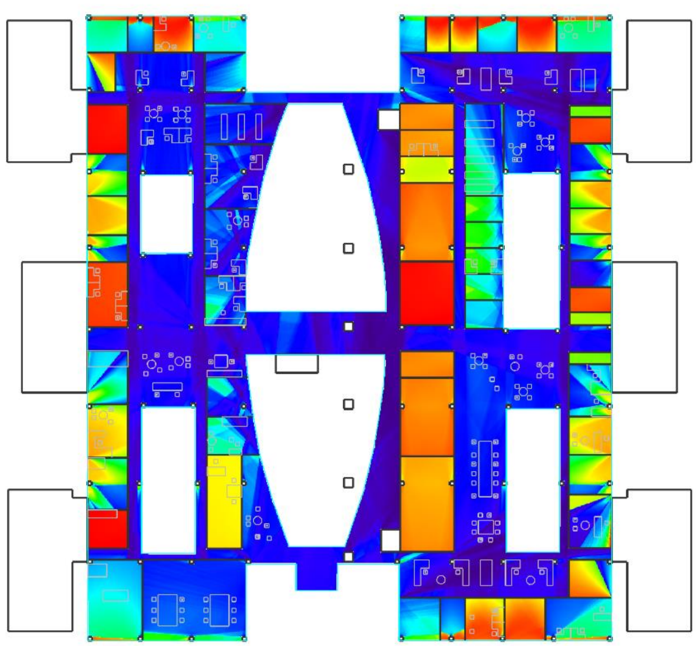


Figure 67 Building 6 compactness.

5.3. Building 11 - Chiat/Day Advertising

The Chiat/Day Advertising building has a wings floor plate type. With a 0% cellular floor area and a 30.9% open plan floor area, its predominant layout is open plan. The L-shaped plot has dictated the shape of the floorplate, while the sculptural entrance and the three atria have affected a rather indented perimeter. Despite having many atria and an open plan, the visual flow is very disrupted in this building. This can be seen in the plan (Figure 69) which indicates very low A/P ratios, most below 0.5. The core, despite small in size, joins the perimeter and segregates a narrow zone of the floorplate behind it. The cubicles contradict the openness of the plan. Though the cubicle height permits daylight, seated occupants' views are blocked by the partitions. Pairs of workstations are arranged to form groups of 2x3 and 2x2 in a grid layout. The disrupted visual flow is also partly due to the wings floor plate type which breaks the plan into two smaller separated areas, rather than one open connected space. The primary circulation consists of two parallel corridors at the periphery of each wing, whereby two of them connect to form an L-shape spine.

The isovist analysis shows that 10 out of 40 workstations have direct views to the outdoors and 3 more have views into the internal atria. At 25%, these account for less than the 75% required outdoors views, and the 1% internal atria views does not exceed the 30% internal view maximum, which means the building samples do not meet the benchmarks with an adjusted 26% total. The plans also show that out of 22 out of 40 workstations are within 16 ft of the envelope glazing. At 55%, the 70% benchmark requirements are not met.

Figure 69 Building 11 horizontal illuminance.

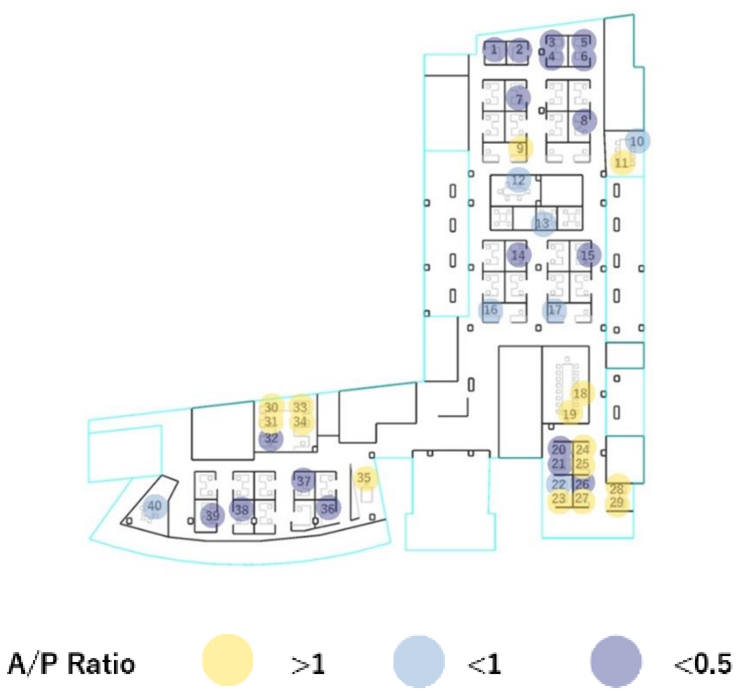


Figure 70 Building 11 A/P ratio..

Table 23 Building 11 data points.

Point	Area	Perimeter	Area / Perimeter	ompactnes	Drift	Occlusivity	Vista
1	3.33	8.29	0.40	0.61	0.65	0.00	1.90
2	4.27	9.14	0.47	0.64	0.79	0.00	2.17
3	2.83	7.49	0.38	0.63	0.85	0.00	2.16
4	5.18	18.61	0.28	0.19	0.74	0.15	5.82
5	1.64	6.51	0.25	0.49	0.75	0.00	2.11
6	3.08	11.00	0.28	0.32	0.82	0.11	2.35
7	3.86	18.13	0.21	0.15	0.50	0.17	5.72
8	1.66	6.53	0.25	0.49	0.89	0.00	2.25
9	191.42	181.99	1.05	0.07	52.92	0.80	85.04
10	69.83	108.47	0.64	0.07	9.44	0.17	24.07
11	1372.50	262.11	5.24	0.25	22.01	0.49	59.87
12	16.96	17.87	0.95	0.67	1.44	0.00	4.37
13	5.19	9.36	0.55	0.74	0.99	0.00	2.57
14	6.44	19.68	0.33	0.21	1.10	0.11	5.95
15	29.56	76.65	0.39	0.06	18.57	0.74	34.15
16	15.97	25.91	0.62	0.30	3.59	0.25	8.94
17	19.75	27.06	0.73	0.32	3.79	0.21	9.13
18	38.60	26.84	1.44	0.67	2.31	0.00	7.00
19	51.49	29.44	1.75	0.75	4.53	0.00	9.54
20	5.83	12.65	0.46	0.46	1.18	0.11	3.85
21	1267.50	188.44	6.73	0.45	36.87	0.40	69.75
22	99.37	100.94	0.98	0.12	15.14	0.14	37.89
23	1418.61	197.34	7.19	0.46	37.48	0.34	72.47
24	135.88	94.23	1.44	0.19	26.21	0.71	43.16
25	63.94	60.75	1.05	0.22	16.28	0.69	26.36
26	5.84	12.50	0.47	0.47	1.80	0.14	4.25
27	306.21	79.92	3.83	0.60	15.82	0.26	28.10
28	84.94	75.80	1.12	0.19	14.89	0.33	27.29
29	2021.85	220.98	9.15	0.52	28.91	0.31	76.16
30	3924.51	372.79	10.53	0.35	38.84	0.27	77.82
31	24.99	21.99	1.14	0.65	2.44	0.00	6.34
32	8.76	17.77	0.49	0.35	1.65	0.00	5.60
33	4187.70	327.96	12.77	0.49	38.18	0.28	75.96
34	23.84	21.68	1.10	0.64	2.78	0.00	6.87
35	965.76	149.42	6.46	0.54	28.12	0.30	52.39
36	2.55	7.07	0.36	0.64	0.73	0.00	2.07
37	1.42	6.18	0.23	0.47	0.54	0.00	1.82
38	1.93	6.58	0.29	0.56	0.61	0.00	1.91
39	10.20	23.38	0.44	0.23	1.60	0.19	5.47
40	13.81	16.75	0.82	0.62	1.51	0.00	4.05

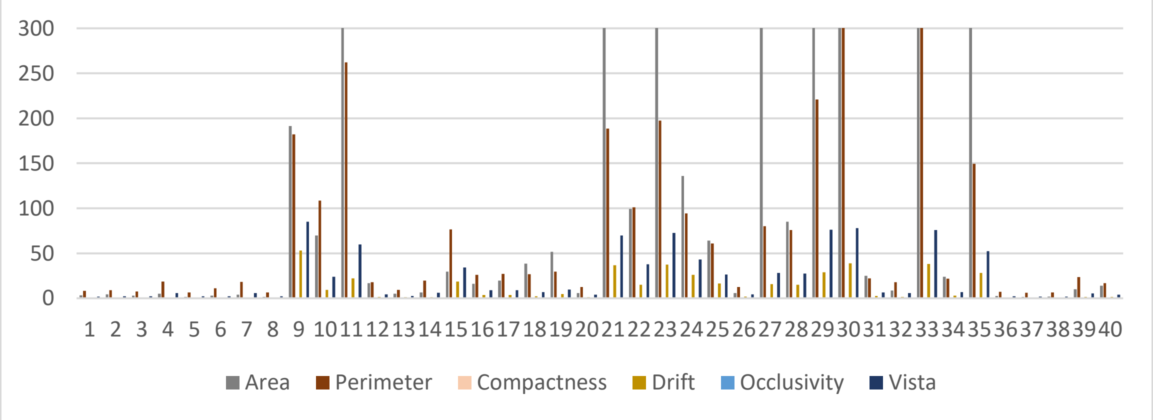


Figure 71Building 11 plotted isovist point measures.

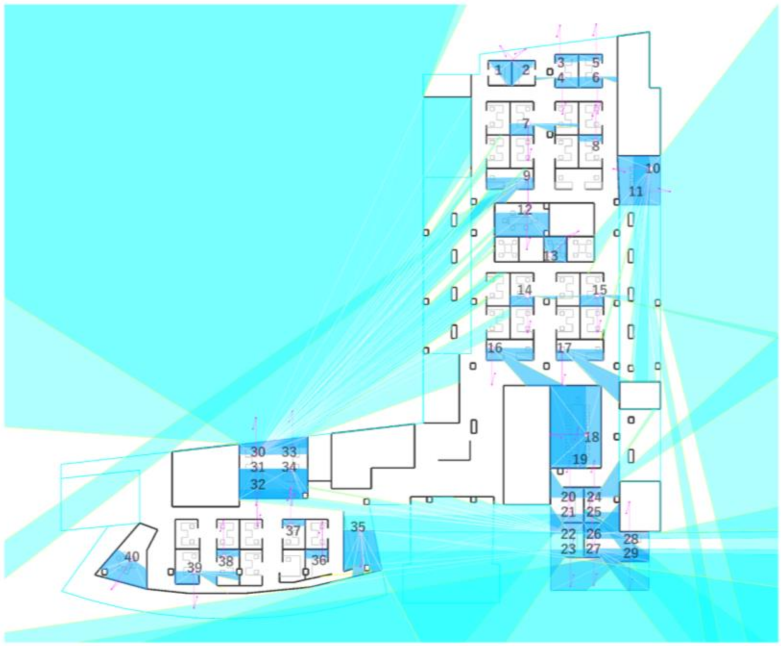


Figure 72 Building 11 point isovist diagram.

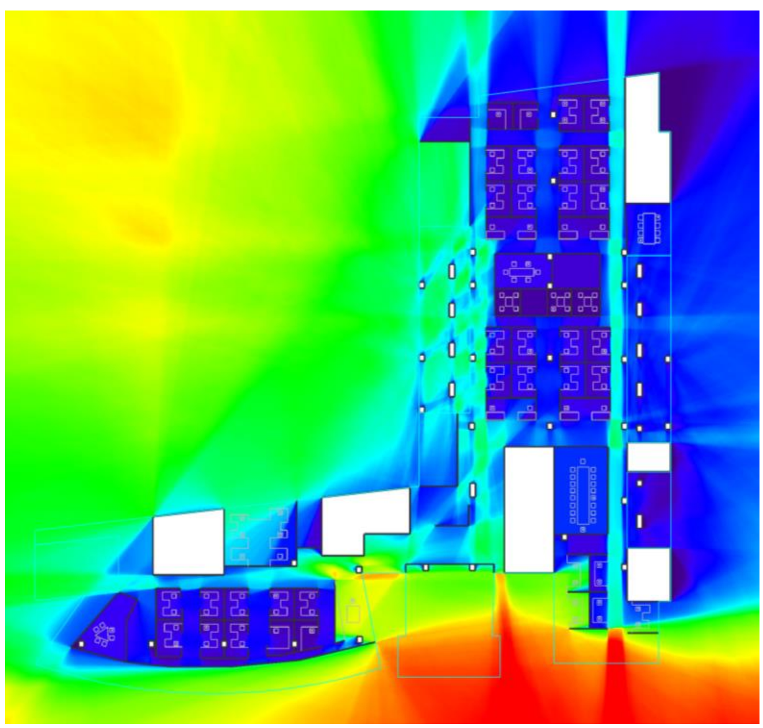


Figure 73 Building 11 area extended visibility.

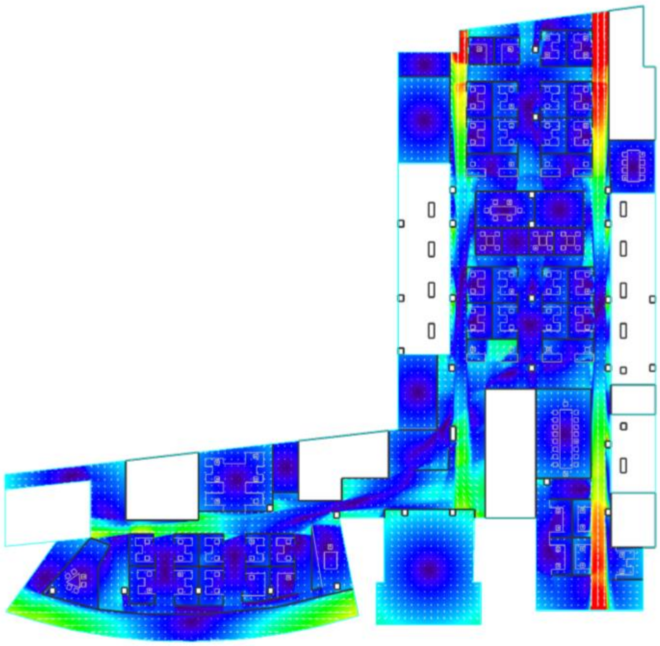


Figure 74 Building 11 drift flow overlay

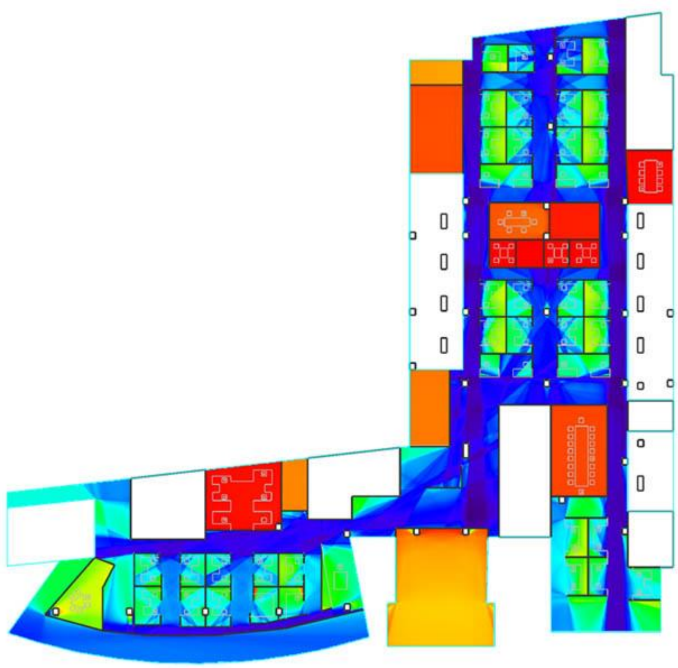


Figure 75 Building 11 compactness.

5.4. Building 16 - Davis Polk & Wardwell

The Davis Polk & Wardwell building has a deep space, small central core floor plate type. With a 44.8% cellular floor area and a 12.2% open plan floor area, its predominant layout is mixed. The rectangular 200x150 ft floorplate has a column-free 52 ft deep usable space developed around a centrally positioned core. This building strategically places the core and services centrally, deep into the plan where there is no daylight.

An unobstructed racetrack circulation is located next to the cellular offices of the associates which occupy the entire perimeter. The compactness plan (Figure 82) clearly highlights the perimeter cellular offices which receive maximum daylight and views in orange and the circulation hallways in blue. Secretarial open-plan workstations, highlighted in green, and meeting rooms are arranged into clusters near the core creating a secondary circulation broken into smaller segments. In contrast to the commanding vistas of the primary circulation, the secondary one affords only partial views.

The isovist analysis shows that 31 out of 65 workstations have direct views to the outdoors. At 48%, these account for less than the 75% required benchmark, which means the building samples do not meet the benchmarks. The plans also show that out of 39 out of 65 workstations are within 16 ft of the envelope glazing. At 60%, the 70% benchmark requirements are not met.

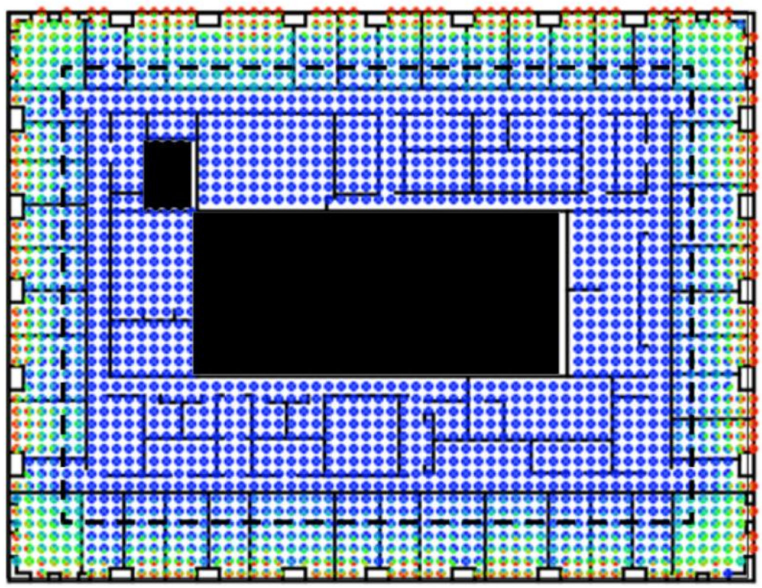


Figure 76 Building 16 horizontal illuminance.

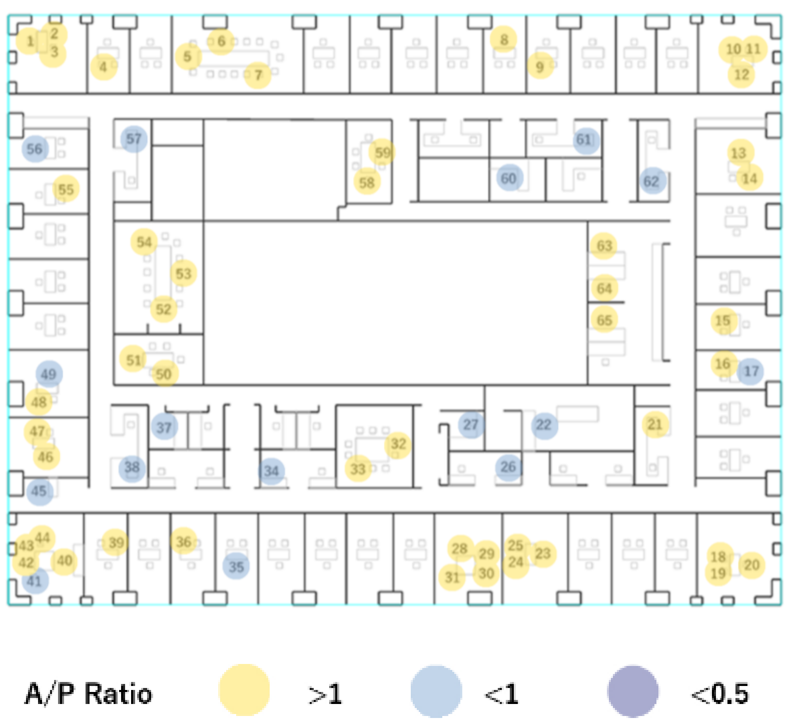


Figure 77 Building 16 A/P ratio.

Table 24 Building 16 data points.

Point	Area	Perimeter	Area / Perimeter	Compactness	Drift	Occlusivity	Vista
1	404.49	226.16	1.79	0.10	24.54	0.64	62.79
2	414.34	205.69	2.01	0.12	12.48	0.67	41.82
3	356.86	183.65	1.94	0.13	13.19	0.65	36.20
4	218.00	83.70	2.60	0.39	20.11	0.57	35.09
5	688.70	222.82	3.09	0.17	27.64	0.53	60.33
6	53.19	32.07	1.66	0.65	2.71	0.00	8.45
7	789.07	188.54	4.19	0.28	22.25	0.52	42.32
8	17.39	16.78	1.04	0.78	2.35	0.00	5.08
9	382.63	98.24	3.89	0.50	23.04	0.56	38.51
10	189.29	133.75	1.42	0.13	18.30	0.52	36.52
11	201.85	138.71	1.46	0.13	19.80	0.55	38.74
12	448.95	247.96	1.81	0.09	17.60	0.60	45.25
13	351.31	97.08	3.62	0.47	19.59	0.29	36.81
14	297.97	86.73	3.44	0.50	15.70	0.21	27.37
15	258.29	81.81	3.16	0.48	19.11	0.51	31.34
16	247.46	79.59	3.11	0.49	18.74	0.52	30.41
17	13.83	14.92	0.93	0.78	2.04	0.00	4.43
18	358.94	180.33	1.99	0.14	13.64	0.60	33.85
19	389.47	193.87	2.01	0.13	13.77	0.63	38.28
20	369.29	188.08	1.96	0.13	24.94	0.57	52.06
21	33.60	31.55	1.06	0.42	2.91	0.13	8.87
22	12.26	18.89	0.65	0.43	1.70	0.12	5.66
23	530.52	116.87	4.54	0.49	25.10	0.29	44.50
24	419.67	104.95	4.00	0.48	20.90	0.24	34.99
25	468.13	107.29	4.36	0.51	22.16	0.22	37.47
26	18.27	25.42	0.72	0.36	2.96	0.15	7.57
27	7.13	10.78	0.66	0.77	1.16	0.00	2.79
28	438.26	172.45	2.54	0.19	23.98	0.66	40.36
29	445.46	206.51	2.16	0.13	24.21	0.58	44.02
30	434.23	117.16	3.71	0.40	26.02	0.61	45.40
31	36.23	24.11	1.50	0.78	2.94	0.01	7.10
32	34.96	24.04	1.45	0.76	2.47	0.00	6.17
33	35.65	24.00	1.49	0.78	2.93	0.00	7.00
34	14.81	25.34	0.58	0.29	2.98	0.17	7.75
35	15.11	15.56	0.97	0.78	2.07	0.00	4.57
36	346.25	96.92	3.57	0.46	23.09	0.54	39.68
37	5.34	9.76	0.55	0.70	0.92	0.00	2.58
38	37.88	45.58	0.83	0.23	3.35	0.21	13.77
39	171.88	78.99	2.18	0.35	19.23	0.54	33.36
40	177.50	86.93	2.04	0.30	20.51	0.32	36.14
41	207.52	231.88	0.89	0.05	24.06	0.81	60.24
42	408.10	200.50	2.04	0.13	24.90	0.58	55.27
43	429.05	224.10	1.91	0.11	20.75	0.60	49.98
44	411.96	246.72	1.67	0.09	18.31	0.61	44.51
45	177.45	185.41	0.96	0.06	40.55	0.28	86.48
46	389.94	99.68	3.91	0.49	19.46	0.29	37.11
47	350.90	92.00	3.81	0.52	15.61	0.23	28.48
48	209.51	93.93	2.23	0.30	21.24	0.63	38.34
49	71.92	73.80	0.97	0.17	13.03	0.29	27.74
50	25.15	21.93	1.15	0.66	1.92	0.00	5.86
51	25.04	20.18	1.24	0.77	2.88	0.00	6.17
52	60.23	31.01	1.94	0.79	3.92	0.00	8.82
53	51.79	33.36	1.55	0.58	2.72	0.01	7.54
54	65.56	36.04	1.82	0.63	4.04	0.01	9.56
55	252.24	79.70	3.16	0.50	18.20	0.50	30.58
56	15.15	15.68	0.97	0.77	2.20	0.00	4.77
57	19.45	26.53	0.73	0.35	2.74	0.13	7.24
58	20.28	18.17	1.12	0.77	2.61	0.00	5.62
59	22.61	20.67	1.09	0.66	1.75	0.00	5.40
60	12.01	13.92	0.86	0.78	1.63	0.00	3.86
61	16.03	25.26	0.63	0.32	2.88	0.16	7.28
62	20.12	30.63	0.66	0.27	3.04	0.19	9.27
63	49.21	45.95	1.07	0.29	5.40	0.18	18.49
64	41.05	31.57	1.30	0.52	3.70	0.07	10.85
65	40.39	31.14	1.30	0.52	3.69	0.07	10.68

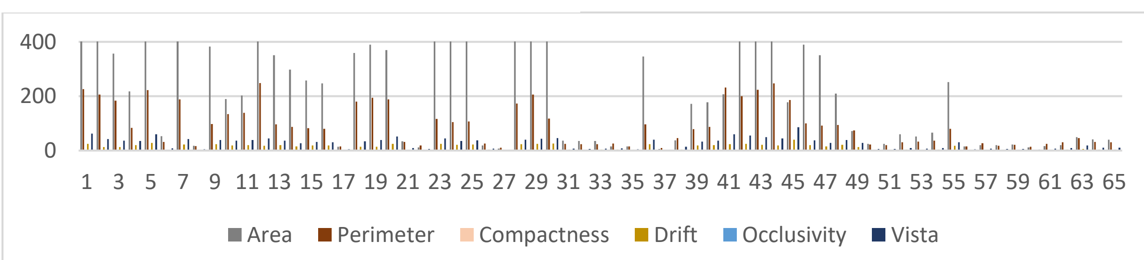


Figure 78 Building 16 plotted isovist point measures.

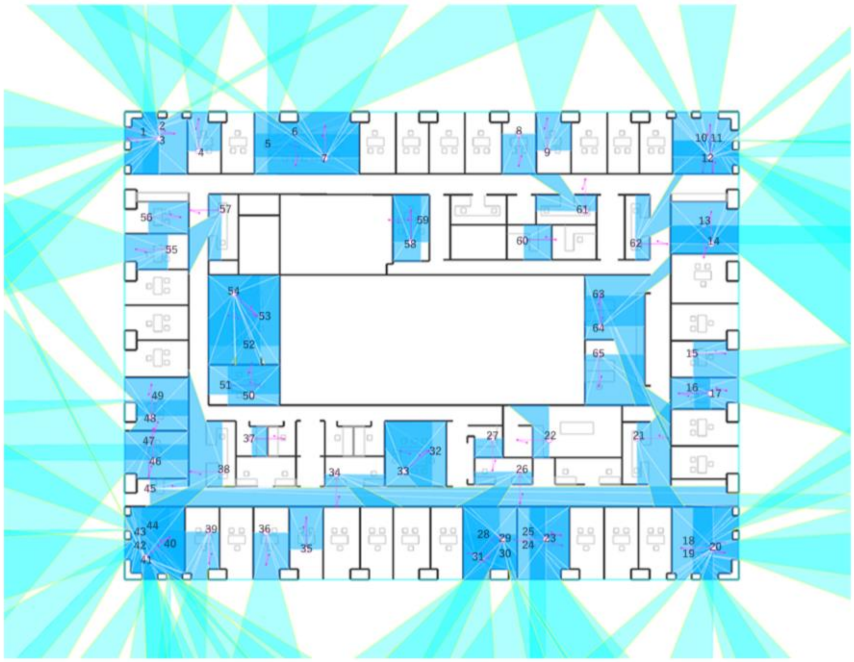


Figure 79 Building 16 point isovist diagram.

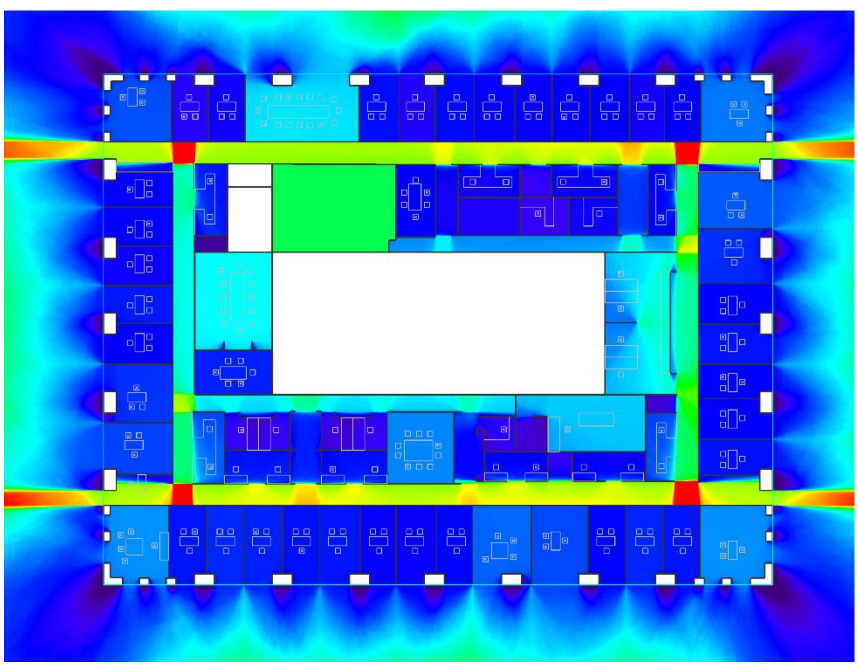


Figure 80 Building 16 area extended visibility.

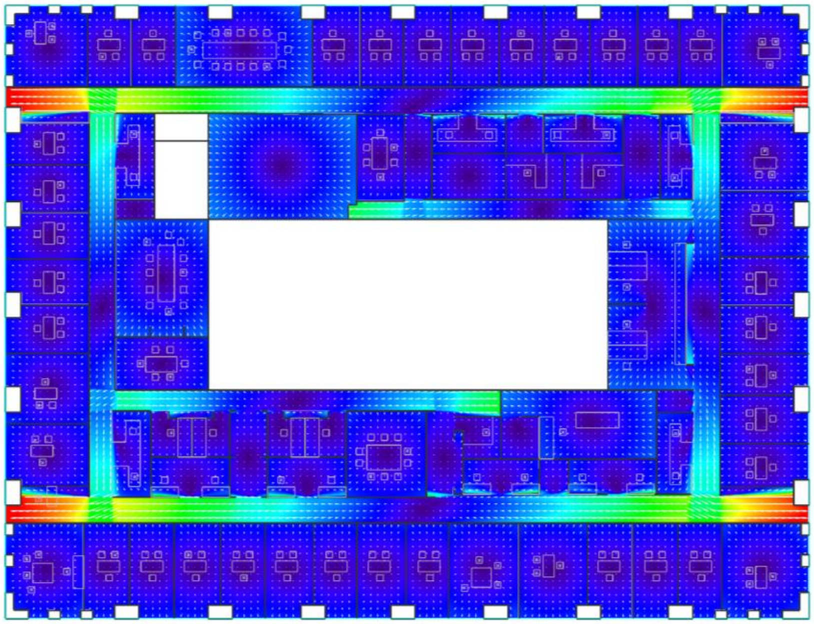


Figure 81 Building 16 drift flow overlay.

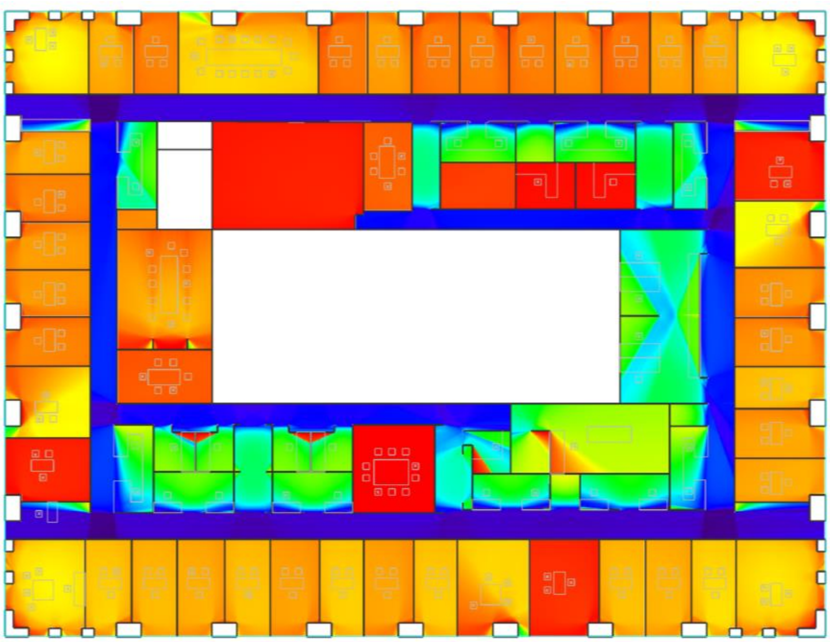


Figure 82 Building 16 compactness.

5.5. Building 26 - IBM Regional Headquarters

The Arthur Andersen building has a compact block, external core floor plate type. With a 0% cellular floor area and a 27.6% open plan floor area, its predominant layout is open plan. The large one-story-high industrial shed is laid out according to a strict orthogonal grid that separates well-defined functional zones. Primary circulation corridors have a greater width. For almost three-quarters of the floor, open-plan cubicles are grouped into 5x2, 4x2, and 3x2. These receive no daylight or access to views.

Conference rooms, cafeterias, and supporting spaces in the other quarter of the plan interrupt several parts of the rectilinear circulation grid. These are found mostly along the building envelope where some daylight is permitted into the perimeter zone. These zones have no partitions and are also less congested which allow occupants to survey the space with unobstructed views. A clear distinction can be seen in Figure 88 between the purple office spaces which denote low drift values and the red supporting spaces which denote high drift.

The isovist analysis shows that 58 out of 148 workstations have direct views to the outdoors. At 57%, these account for less than the 75% required benchmark, which means the building samples do not meet the benchmarks. The plans also show that out of 35 out of 148 workstations are within 16 ft of the envelope glazing. At 24%, the 70% benchmark requirements are not met.

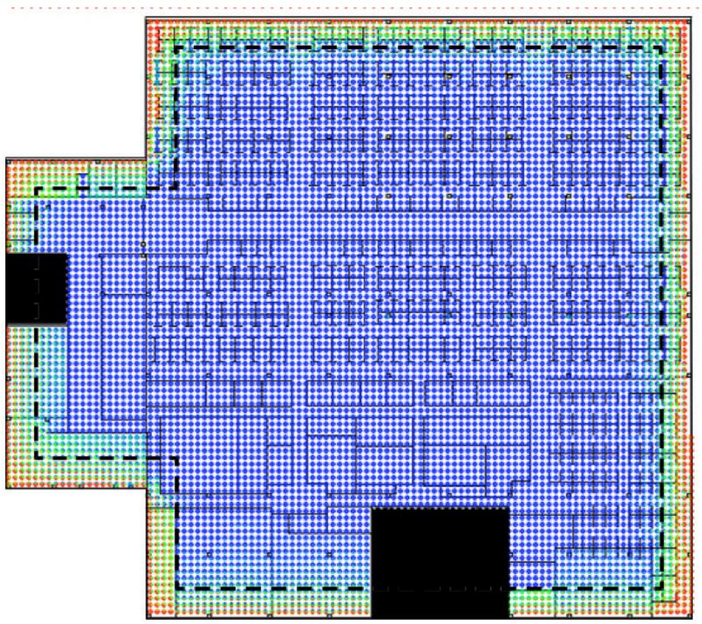


Figure 83 Building 26 horizontal illuminance.

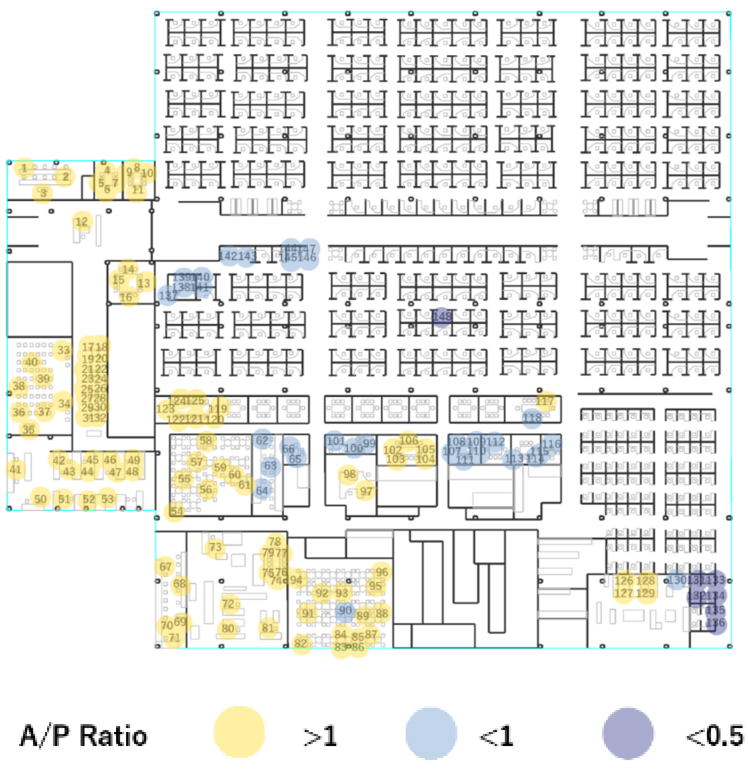


Figure 84 Building 26 A/P ratio.

Table 25 Building 26 data points

Point	Area	Perimeter	Area / Perimeter	Compactness	Drift	Occlusivity	Vista
1	1395.65	188.69	7.40	0.49	32.09	0.31	68.44
2	382.16	114.49	3.34	0.37	28.59	0.28	48.17
3	2412.72	546.84	4.41	0.10	28.86	0.53	82.64
4	16.24	16.12	1.01	0.79	2.12	0.00	4.73
5	425.75	255.22	1.67	0.08	38.58	0.60	70.50
6	1090.42	358.51	3.04	0.11	37.73	0.65	69.68
7	805.21	236.25	3.41	0.18	34.02	0.53	58.78
8	17.71	16.82	1.05	0.79	2.16	0.00	4.97
9	469.00	248.42	1.89	0.10	36.90	0.36	64.96
10	1385.45	170.33	8.13	0.60	33.31	0.25	59.35
11	1046.62	259.01	4.04	0.20	36.80	0.53	64.87
12	588.11	340.60	1.73	0.06	26.76	0.54	49.72
13	25.97	20.56	1.26	0.77	2.27	0.00	5.39
14	30.31	22.25	1.36	0.77	2.38	0.00	5.70
15	29.93	22.05	1.36	0.77	2.74	0.00	6.43
16	29.55	22.25	1.33	0.75	2.67	0.00	6.29
17	66.29	38.68	1.71	0.56	6.98	0.01	14.18
18	69.65	39.47	1.76	0.56	6.77	0.01	14.43
19	111.01	59.38	1.87	0.40	11.45	0.11	21.95
20	115.67	58.53	1.98	0.42	11.08	0.10	22.26
21	54.38	33.14	1.64	0.62	5.69	0.01	11.70
22	57.63	34.64	1.66	0.60	5.41	0.01	11.88
23	121.50	65.97	1.84	0.35	12.58	0.09	24.44
24	125.58	62.47	2.01	0.40	12.46	0.09	24.84
25	39.55	28.36	1.39	0.62	4.21	0.02	8.83
26	43.02	28.15	1.53	0.68	4.19	0.02	9.25
27	133.19	70.84	1.88	0.33	13.90	0.08	27.19
28	139.63	69.27	2.02	0.37	13.45	0.08	27.47
29	28.92	23.52	1.23	0.66	2.93	0.03	6.87
30	30.52	23.03	1.33	0.72	3.03	0.03	6.90
31	144.49	70.90	2.04	0.36	15.08	0.06	29.65
32	150.82	74.12	2.03	0.34	14.68	0.07	29.98
33	1305.80	239.53	5.45	0.29	28.40	0.51	53.61
34	1475.23	249.08	5.92	0.30	29.06	0.51	58.33
35	1700.18	310.79	5.47	0.22	32.32	0.49	74.40
36	1532.85	314.85	4.87	0.19	30.87	0.54	75.79
37	1344.19	257.68	5.22	0.25	31.51	0.46	65.03
38	1652.68	193.12	8.56	0.56	31.11	0.28	67.90
39	926.21	146.25	6.33	0.54	28.94	0.27	53.28
40	714.55	134.39	5.32	0.50	27.45	0.29	48.45
41	2822.44	349.65	8.07	0.29	21.71	0.40	75.92
42	1817.99	355.36	5.12	0.18	24.56	0.48	57.17
43	1171.53	367.12	3.19	0.11	39.29	0.48	80.21
44	1981.01	341.15	5.81	0.21	25.48	0.57	56.60
45	1080.34	318.06	3.40	0.13	41.66	0.35	76.32
46	1897.36	420.57	4.51	0.13	28.79	0.51	60.63
47	529.96	316.30	1.68	0.07	37.59	0.54	70.64
48	2022.04	526.76	3.84	0.09	28.64	0.57	59.96
49	414.15	369.81	1.12	0.04	40.84	0.55	69.92
50	2916.62	494.40	5.90	0.15	31.94	0.44	86.59
51	1982.54	357.45	5.55	0.19	22.59	0.48	61.82
52	1240.75	307.68	4.03	0.16	37.90	0.35	74.94
53	2169.61	437.60	4.96	0.14	24.55	0.50	58.90
54	122.24	43.57	2.81	0.81	6.89	0.00	14.68
55	36.67	29.65	1.24	0.52	3.79	0.00	10.04
56	55.21	33.84	1.63	0.61	3.52	0.00	9.89
57	33.89	29.44	1.15	0.49	1.95	0.00	7.91
58	114.10	42.03	2.71	0.81	5.51	0.00	12.38
59	36.35	29.50	1.23	0.52	1.99	0.00	6.86
60	84.66	39.35	2.15	0.69	4.28	0.00	10.39
61	115.08	42.07	2.74	0.82	5.80	0.00	12.77
62	18.09	25.45	0.71	0.35	4.96	0.00	10.62
63	18.17	25.43	0.71	0.35	1.76	0.00	7.31
64	18.76	25.54	0.73	0.36	2.27	0.00	7.86
65	12.21	13.96	0.87	0.79	1.73	0.00	3.90
66	10.50	13.34	0.79	0.74	1.29	0.00	3.35
67	2450.11	721.13	3.40	0.06	28.21	0.57	74.17
68	132.34	117.74	1.12	0.12	29.67	0.28	49.57
69	1757.11	490.03	3.59	0.09	40.94	0.44	83.71
70	2971.15	614.29	4.84	0.10	30.16	0.46	85.44
71	1969.35	282.75	6.96	0.31	22.16	0.44	60.49
72	2092.69	284.46	7.36	0.32	30.22	0.52	67.06
73	374.63	125.86	2.98	0.30	32.01	0.21	53.72
74	87.87	40.22	2.18	0.68	6.31	0.00	13.88
75	275.91	130.53	2.11	0.20	31.66	0.27	53.86
76	1221.09	258.79	4.72	0.23	30.08	0.54	54.72
77	1101.92	249.16	4.42	0.22	32.29	0.34	55.85
78	1203.76	285.27	4.22	0.19	33.52	0.41	56.79
79	226.93	127.72	1.78	0.17	33.58	0.26	56.63
80	2887.12	326.61	8.84	0.34	28.88	0.52	78.20
81	2140.99	299.93	7.14	0.30	25.71	0.54	55.67
82	1673.07	237.61	7.04	0.37	39.79	0.30	79.49
83	155.38	60.56	2.57	0.53	6.43	0.12	16.45
84	2056.19	319.08	6.44	0.25	28.62	0.45	68.93
85	2281.81	316.67	7.21	0.29	25.32	0.43	66.70
86	152.75	59.53	2.57	0.54	7.05	0.18	17.22
87	1900.45	193.60	9.82	0.64	27.77	0.26	56.00
88	2097.50	319.66	6.56	0.26	30.40	0.54	66.80
89	2164.71	295.28	7.33	0.31	28.33	0.41	58.52
90	123.68	159.45	0.78	0.06	7.72	0.29	59.70
91	1780.57	185.59	9.59	0.65	30.37	0.45	59.23
92	53.59	39.08	1.37	0.44	2.75	0.11	9.11
93	62.39	48.15	1.30	0.34	2.35	0.11	10.40
94	88.24	60.78	1.45	0.30	6.49	0.10	14.74
95	1735.56	272.08	6.38	0.29	33.23	0.53	61.30
96	1598.61	287.62	5.56	0.24	34.44	0.52	62.99
97	45.30	27.17	1.67	0.77	3.48	0.00	8.13
98	34.87	27.01	1.29	0.60	2.30	0.00	6.64
99	14.97	16.69	0.90	0.68	2.88	0.00	5.92
100	14.03	17.99	0.78	0.54	1.49	0.00	4.92
101	16.69	18.17	0.92	0.63	2.99	0.00	6.41
102	26.02	20.85	1.25	0.75	3.16	0.00	6.64
103	24.17	22.19	1.09	0.62	1.92	0.00	6.10
104	23.96	22.13	1.08	0.61	2.39	0.00	6.64
105	26.77	21.19	1.26	0.75	3.24	0.00	6.84
106	25.84	22.60	1.14	0.64	1.71	0.00	5.63
107	12.44	14.25	0.87	0.77	1.55	0.00	3.73
108	12.93	14.63	0.88	0.76	1.59	0.00	4.04
109	12.54	14.45	0.87	0.75	1.73	0.00	4.26
110	14.80	15.40	0.96	0.78	1.83	0.00	4.19
111	13.10	14.70	0.89	0.76	1.52	0.00	3.79
112	12.51	14.28	0.88	0.77	1.55	0.00	3.81
113	11.83	13.89	0.85	0.77	1.62	0.00	3.97
114	12.73	14.35	0.89	0.78	1.84	0.00	4.31
115	7.88	12.01	0.66	0.69	1.02	0.00	3.00
116	6.62	10.30	0.64	0.78	1.24	0.00	2.88
117	22.83	21.24	1.07	0.64	2.61	0.00	6.67
118	20.21	20.54	0.98	0.60	1.35	0.00	4.78
119	28.59	22.87	1.25	0.69	3.89	0.00	8.02
120	25.22	23.01	1.10	0.60	3.10	0.00	7.62
121	25.10	22.98	1.09	0.60	1.79	0.00	5.99
122	25.66	23.09	1.11	0.60	1.83	0.00	6.10
123	24.07	20.43	1.18	0.72	3.29	0.00	6.86
124	25.26	23.01	1.10	0.60	2.15	0.00	6.55
125	25.28	23.01	1.10	0.60	1.53	0.00	5.50
126	593.77	179.79	3.30	0.23	24.50	0.33	44.65
127	615.95	178.56	3.45	0.24	23.02	0.33	42.90
128	369.27	168.08	2.20	0.16	23.62	0.39	42.28
129	435.83	168.62	2.58	0.19	22.94	0.38	42.07
130	84.07	86.37	0.97	0.14	24.96	0.26	40.79
131	1.59	5.24	0.30	0.73	0.54	0.00	1.34
132	1.59	5.24	0.30	0.73	0.54	0.00	1.34
133	1.59	5.24	0.30	0.73	0.54	0.00	1.34
134	1.59	5.24	0.30	0.73	0.54	0.00	1.34
135	1.59	5.24	0.30	0.73	0.54	0.00	1.34
136	1.59	5.24	0.30	0.73	0.54	0.00	1.34
137	10.33	13.12	0.79	0.75	1.34	0.00	3.53
138	5.77	11.08	0.52	0.59	0.83	0.00	2.48
139	10.06	13.01	0.77	0.75	1.59	0.00	3.70
140	12.75	21.61	0.59	0.34	2.16	0.00	4.68
141	9.99	13.01	0.77	0.74	1.79	0.00	3.81
142	15.41	28.68	0.54	0.24	3.09	0.16	8.58
143	22.47	36.63	0.61	0.21	4.60	0.20	13.04
144	157.82	254.52	0.62	0.03	28.65	0.57	95.29
145	76.30	107.88	0.71	0.08	8.34	0.30	28.95
146	35.79	69.15	0.52	0.09	3.22	0.34	13.29
147	104.40	105.61	0.99	0.12	14.79	0.30	39.63
148	2.13	6.58	0.32	0.62	0.53	0.00	1.50

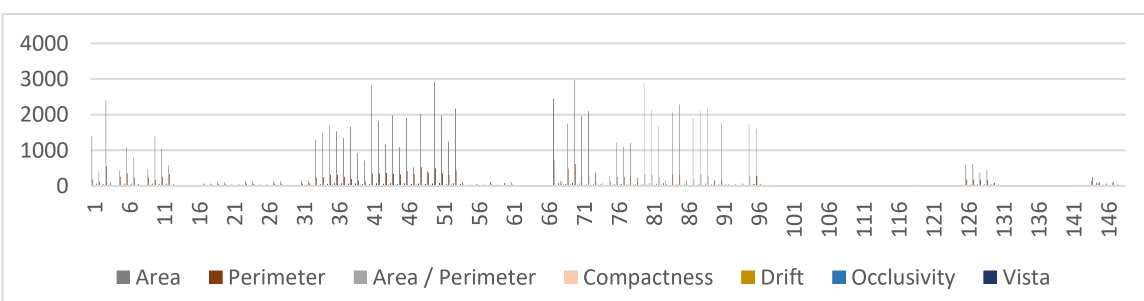


Figure 85 Building 26 plotted isovist point measures.

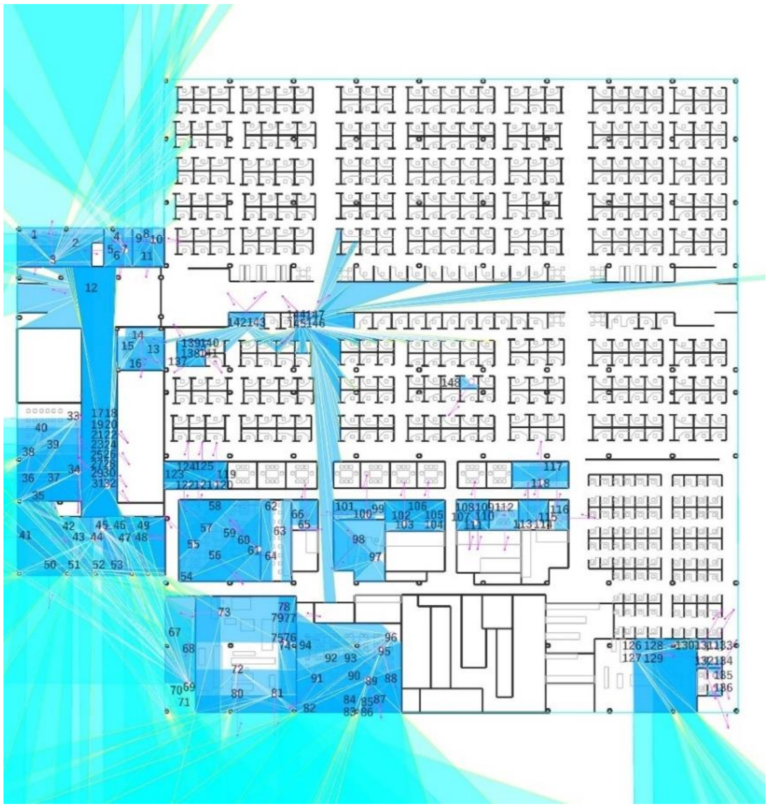


Figure 86 Building 26 point isovist diagram

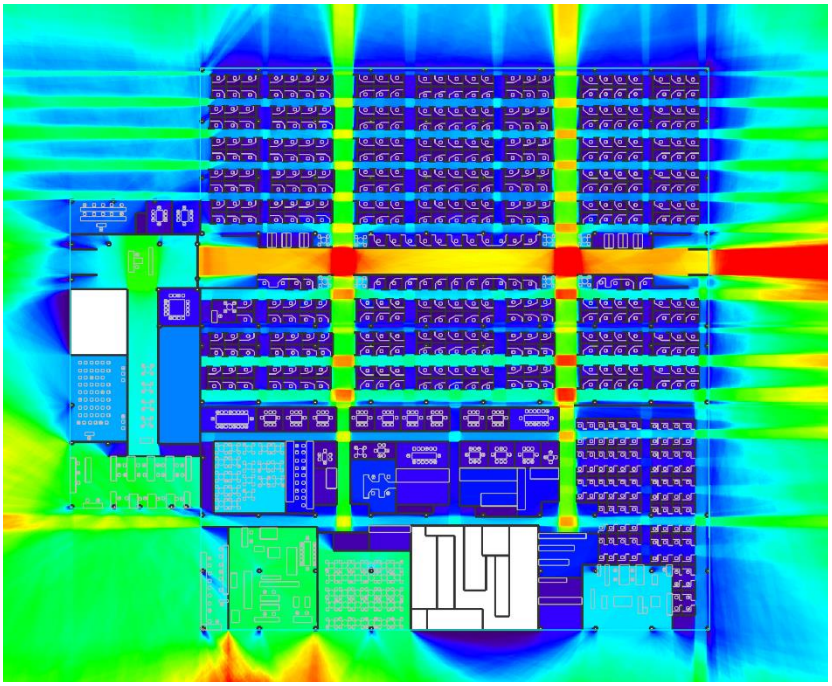


Figure 87 Building 26 area extended visibility.

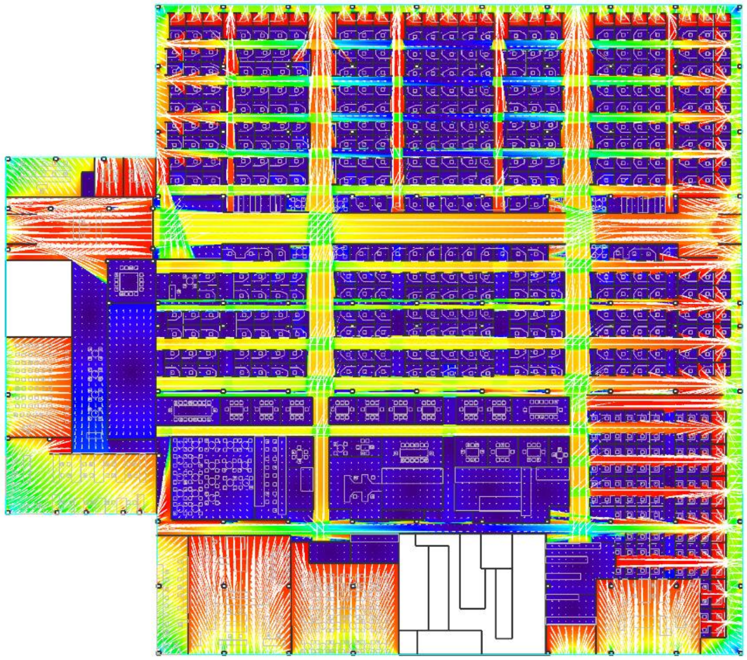


Figure 89 Building 26 drift flow overlay.

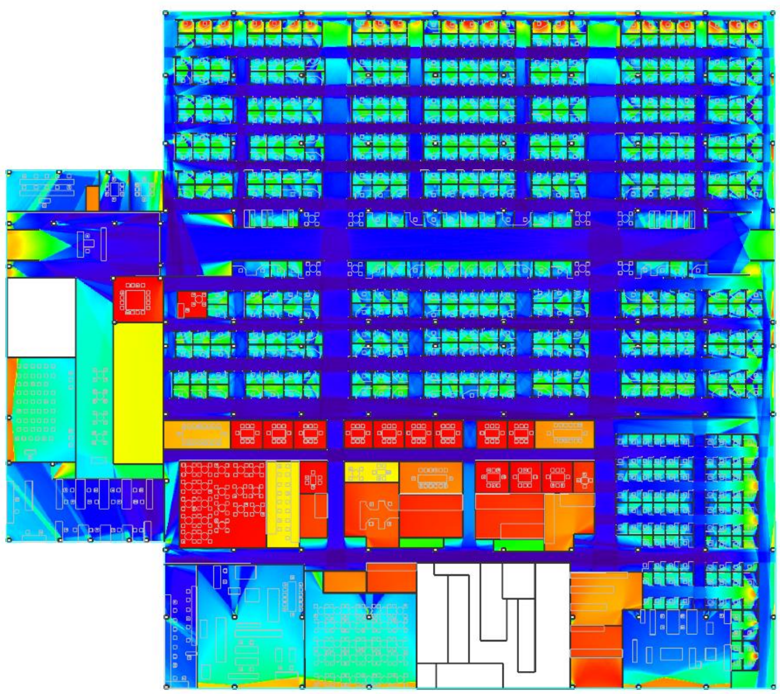


Figure 88 Building 26 compactness.

5.6. Building 32 - Lend Lease Interiors

The Lend Lease Interiors building has a shallow space, large central core floor plate type. With a 4.5% cellular floor area and a 42.4% open plan floor area, its predominant layout is open plan. The usable space has a donut shape of 39’6” and 9’6” radii. Three main corridors pass tangent to the core and connect to each other at the location of three meeting spaces. With only one closed meeting room, low partitions, and a shallow, round geometry, daylight levels are high even past the perimeter zone.

The den layout, placed perpendicular to each corridor, contains open plan workstations grouped into bays with filing cabinets and meeting desks in the middle. To maximize the use of the round space, workstations are rotated in directions that do not necessarily have views within the field of vision as seen with the point isovist analysis. However, with minimum head tilting the space can be surveyed as it has high drift in most locations. The exceptions are the meeting areas with seats at round tables that have their backs to the building envelope.

The isovist analysis shows that 27 out of 41 workstations have direct views to the outdoors. At 66%, these account for less than the 75% required benchmark, which means the building samples do not meet the benchmarks. However, the plans also show that out of 30 out of 41 workstations are within 16 ft of the envelope glazing. At 73%, the 70% benchmark requirements are met.

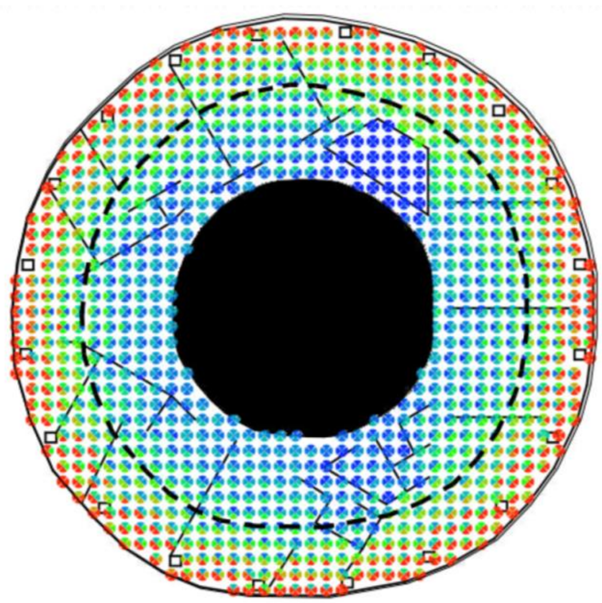


Figure 90 Building 32 horizontal illuminance.

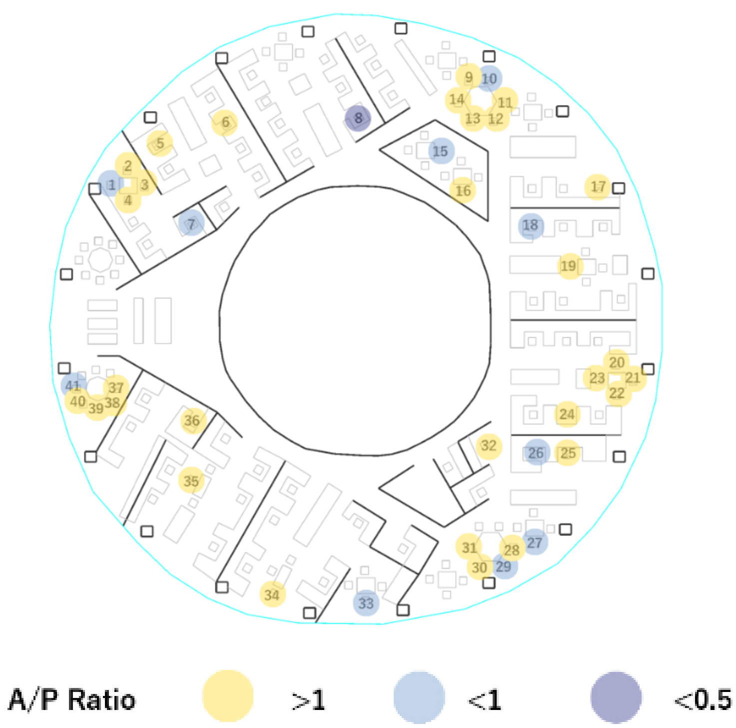


Figure 91 Building 32 A/P ratio.

Table 26 Building 32 data points.

Point	Area	Perimeter	Area / Perimeter	Compactness	Drift	Occlusivity	Vista
1	61.04	68.76	0.89	0.16	8.30	0.28	23.92
2	92.62	63.57	1.46	0.29	9.76	0.28	21.26
3	215.25	71.80	3.00	0.52	11.25	0.39	20.01
4	202.17	72.74	2.78	0.48	12.02	0.43	22.43
5	109.28	62.86	1.74	0.35	10.45	0.50	18.13
6	100.45	61.91	1.62	0.33	11.67	0.00	20.32
7	17.17	20.62	0.83	0.51	3.17	0.19	7.05
8	20.74	53.43	0.39	0.09	4.91	0.44	21.43
9	423.65	281.07	1.51	0.07	9.65	0.45	47.69
10	355.03	365.42	0.97	0.03	10.13	0.41	48.63
11	333.55	267.51	1.25	0.06	13.38	0.33	47.16
12	510.66	177.49	2.88	0.20	12.22	0.39	32.78
13	677.75	268.37	2.53	0.12	8.85	0.43	31.10
14	473.18	209.89	2.25	0.13	12.63	0.45	33.01
15	9.46	13.59	0.70	0.64	1.38	0.00	4.03
16	18.67	17.91	1.04	0.73	2.29	0.00	5.75
17	94.96	68.14	1.39	0.26	12.93	0.56	24.21
18	51.24	61.67	0.83	0.17	12.81	0.23	22.74
19	326.63	112.83	2.89	0.32	12.23	0.46	24.07
20	294.67	123.42	2.39	0.24	10.87	0.38	26.06
21	96.02	93.08	1.03	0.14	5.69	0.21	26.65
22	263.53	128.49	2.05	0.20	11.69	0.40	29.55
23	410.86	125.30	3.28	0.33	10.36	0.48	25.74
24	74.72	66.46	1.12	0.21	11.10	0.23	20.53
25	74.71	64.29	1.16	0.23	11.24	0.49	22.56
26	53.04	64.32	0.82	0.16	11.45	0.25	23.50
27	169.03	192.81	0.88	0.06	11.69	0.52	33.19
28	229.12	219.60	1.04	0.06	9.83	0.36	48.44
29	191.40	266.98	0.72	0.03	12.53	0.43	49.29
30	383.82	300.47	1.28	0.05	10.18	0.54	48.75
31	443.28	208.96	2.12	0.13	12.48	0.47	33.07
32	156.48	67.55	2.32	0.43	15.13	0.48	24.50
33	27.10	30.57	0.89	0.36	4.18	0.27	10.60
34	66.87	39.00	1.71	0.55	4.89	0.06	11.87
35	192.57	77.45	2.49	0.40	11.75	0.17	24.52
36	181.94	140.10	1.30	0.12	13.42	0.59	25.74
37	400.89	124.07	3.23	0.33	10.76	0.51	26.47
38	390.28	173.75	2.25	0.16	11.39	0.50	31.04
39	344.07	175.89	1.96	0.14	14.88	0.50	35.00
40	259.85	186.57	1.39	0.09	15.35	0.51	35.73
41	112.59	137.64	0.82	0.07	2.61	0.28	35.17

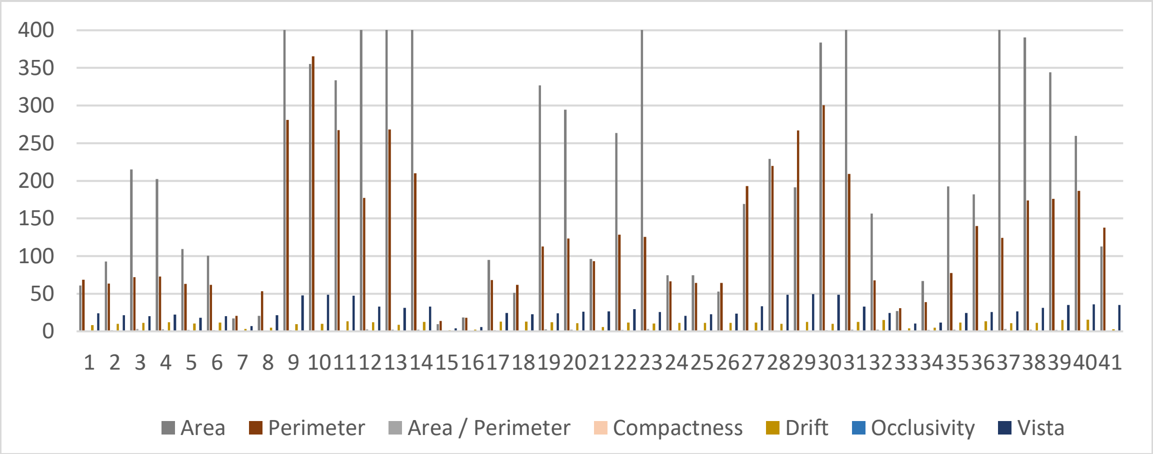


Figure 92 Building 32 plotted isovist point measures.

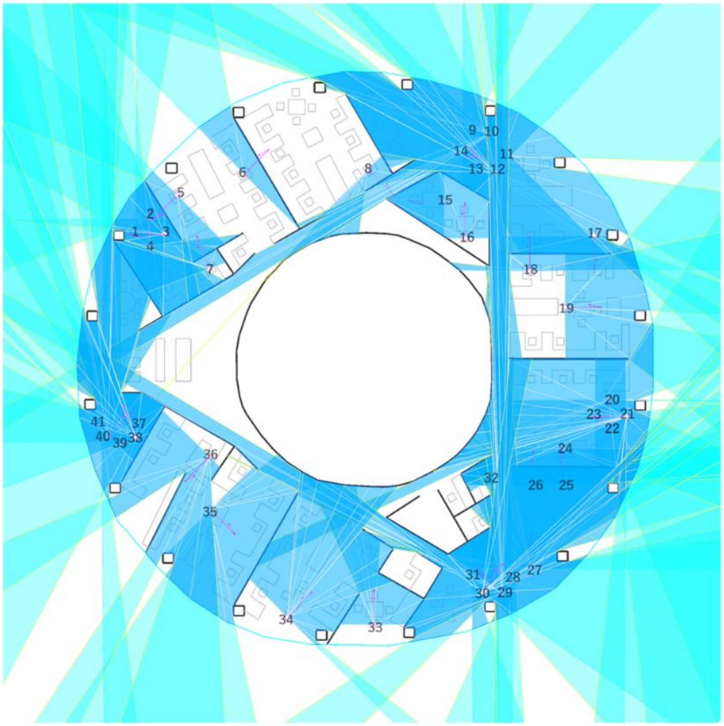


Figure 94 Building 32 point isovist diagram.

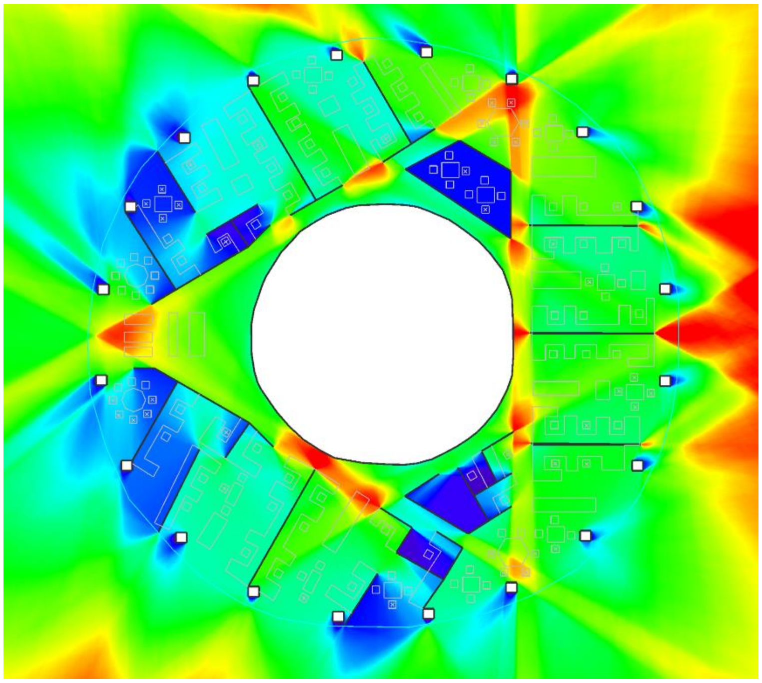


Figure 93 Building 32 area extended visibility.

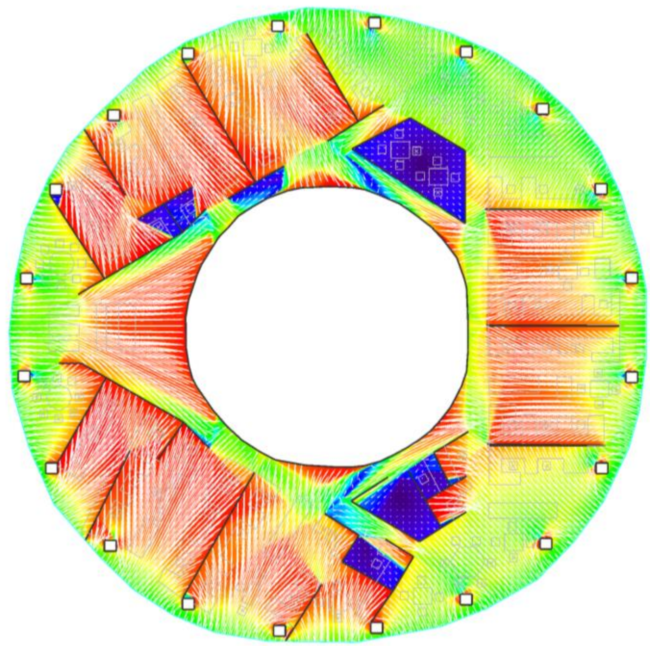


Figure 95 Building 32 drift flow overlay.

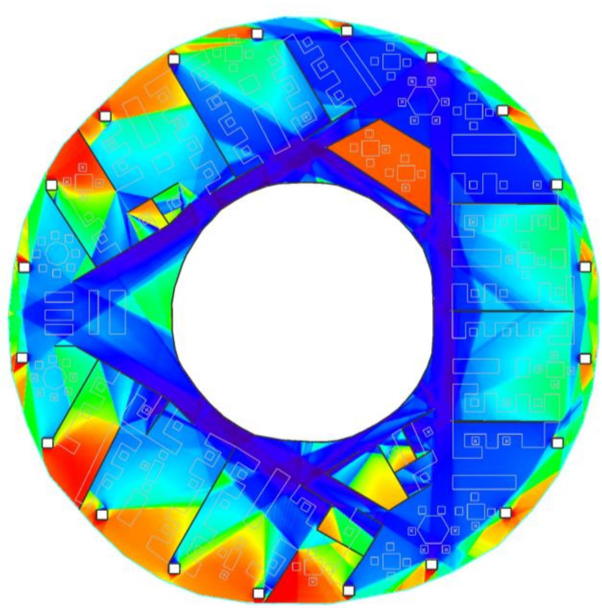


Figure 96 Building 32 compactness.

5.7. Visual Depth to Location

A ‘visual step’ is taken whenever a path passes across the threshold of all space visible from the start of the previous visible step. This can be used to assess the visual accessibility of a daylight source. The lower the step depth, the more accessible the location is visually. It can potentially warrant and maximize the potential of a window or atrium location in the early design stages. Figure 97 shows an example of this measure at an atrium location in building 11. The results indicate a step depth maximum of 5, minimum 1, and average 3.

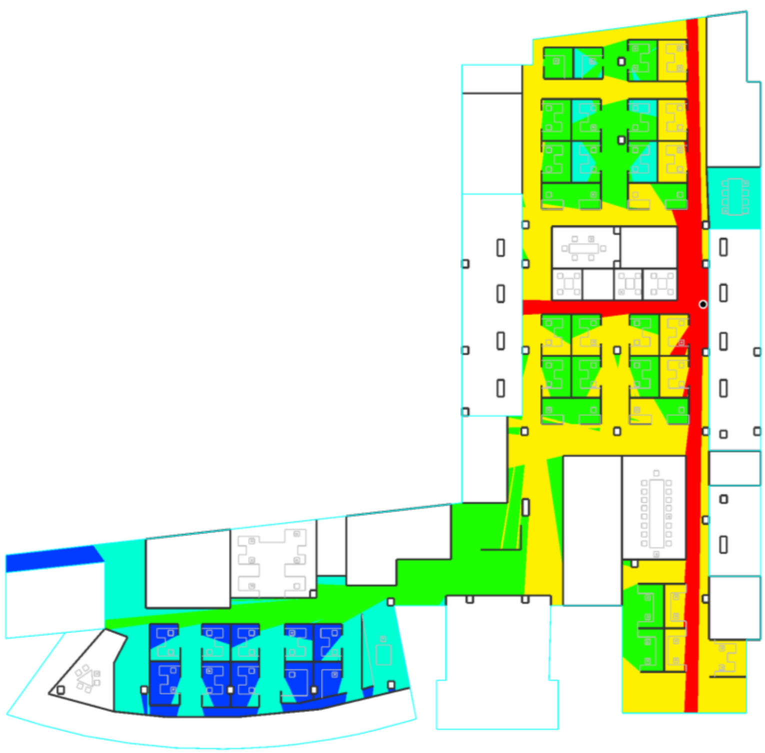


Figure 97 Building 11 visual step depth to location.

5.8. Statistical Analyses

The point isovist analysis provided insights on specific workstations and zones within each building. This would be useful when working on the later design and interior furnishing stages or to remediate buildings for post-occupancy evaluations. To test the importance of analyzing individual point isovists rather than the general building for an overview, the average isovist measures for each building were analyzed. This was done by exporting the results from the Isovist software with fields for all point coordinates within the analysis area, and every value, for every scan measure, at each point. The measures were then individually averaged.

A correlation analysis would also help investigate relationships between building form, daylight performance, and isovist measures as averages. This would either reinforce the concept that averages are not sufficient to explain trends across various parameters or prove that averages can be used as quick general overviews. Table 27 summarizes the building form parameters (convex fragmentation, relative grid distance, shape factor), daylight performance measures at 12 pm (average horizontal illuminance, average vertical equivalent melanopic lux), and isovist measures (area, perimeter, compactness, drift, occlusivity, vista).

Table 27 Building form, daylight and isovist measures correlation measures.

Building		Form			Daylight		Isovist					
		CF	RGD	SF	Avg. Horizontal Illuminance	Avg. Vertical EML	Area	Perimeter	Compactness	Drift	Occlusivity	Vista
5	Arthur Andersen	0.53	1.42	0.82	4211.00	2938.00	9216.21	569.77	0.41	43.37	2.56	88.05
6	Apicorp	1.28	1.29	1.12	3526.00	2374.00	4552.60	439.57	0.27	41.08	3.72	84.23
11	Chiat/Day Advertising	1.53	1.61	0.86	3548.00	2474.00	4828.22	299.19	0.37	38.95	3.26	70.34
16	Davis Polk & Wardwell	0.76	1.18	0.74	1922.00	1137.00	1915.99	158.38	7485.03	20.91	1.76	51.76
26	IBM Regional Headquarters	0.44	1.02	0.71	1021.00	829.00	13011.06	859.15	5.81	57.49	25.55	107.30
32	Lend Lease Interiors	1.03	1.27	0.84	3609.00	2703.00	1238.61	212.04	0.21	16.65	1.97	37.24

Figure 98 plots the distribution of each variable as shown on the diagonal. On the bottom of the diagonal, the bivariate scatter plots with a fitted line are displayed. On the top of the diagonal, the value of the correlation and the significance level as stars are displayed. Each significance level is associated to a symbol: p-values (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols (“***”, “**”, “*”, “.”, " “).

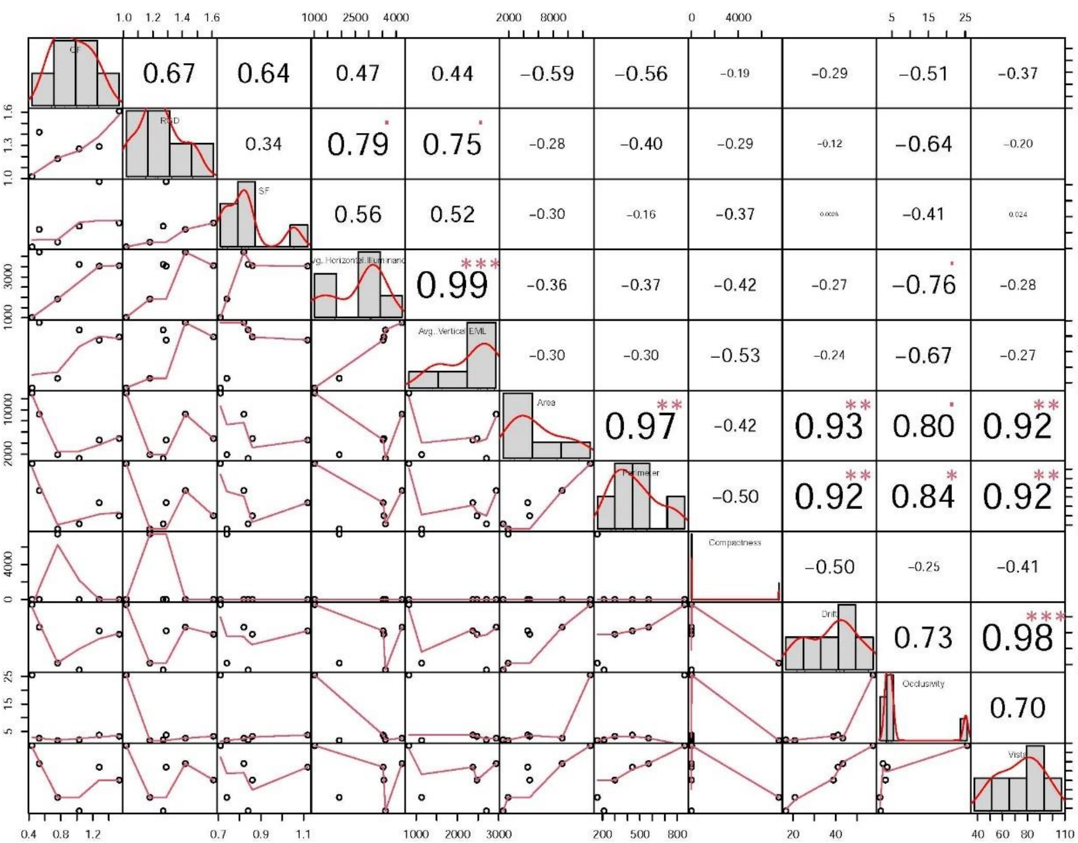


Figure 98 Building form, daylight and isovist measures correlation matrix.

Several results can be drawn from the correlation analysis. The first findings are between the isovist measures. Area and perimeter seem to explain most of the other measures with very positive and statistically significant results, with the exception of compactness. The higher the isovist area, the higher the isovist perimeter, drift, occlusivity and vista.

The most important finding is that there is no correlation between isovist measure averages and daylight measure averages or building form parameters. This indicates that isovist measure averages can explain trends between each other as numerical data but cannot be applied to explaining buildings. When comparing the heatmaps with the isolux daylight plans, there is a clear relationship between individual points within the plans. This proves that though there is a relationship that can be visually depicted in building plans, numerical averages cannot be used as indicators to explain building performance. Plans and diagrams are more reliable alternatives that assign a color-coded value to each corresponding point. For detailed numerical occupant workstation assessments, point isovist analyses should be conducted. The main takeaways from using isovist analyses as a tool to assess access to daylight and views are as follows:

- Isovist areas plotted on a bar chart can easily identify workstations that have access to windows. This could be used to calculate the percentage of workstations with window access.

- Overlaying a daylighting analysis and an isovist area analysis can identify workstations that receive sufficient daylight over the partitions but do not have access to window views.
- Drift flow vectors overlay can help assess the openness of a design and occupants' ease of surveying the unobstructed space to receive sufficient vertical light.
- An isovist compactness heat map can easily identify open cubicle and closed office work areas.
- Visual depth to location can be used to assess the visual accessibility of a daylight source. This could be used to warrant and maximize the potential of a window or atrium location.
- Isovist measure averages but cannot be applied to explaining buildings. For detailed numerical occupant workstation assessments, point isovist analyses should be conducted.

5.8.1. Correlation Analysis

To elaborate on the previous average data correlation analysis, another correlation analysis was computed. Since it was established that correlating averaged data across the entire building floorplan did not produce positive results, this time the correlation was for the individual point isovist locations for each building (30% of total workstations). Each location point was computed against its corresponding EML category (1 – 'No' for below the 200 EML benchmark, 2 – 'Yes' for above the 200 EML benchmark). This would identify any relationships between the isovist measures and meeting EML benchmarks.

The matrix in figure 99 below summarizes the results of all the points across all six buildings which shows that EML can be explained by the isovist measures. This may not be sensitive enough as it is a compilation of six different building geometries and layouts. To identify any trends figures 100-105 show correlation matrices for the individual buildings.

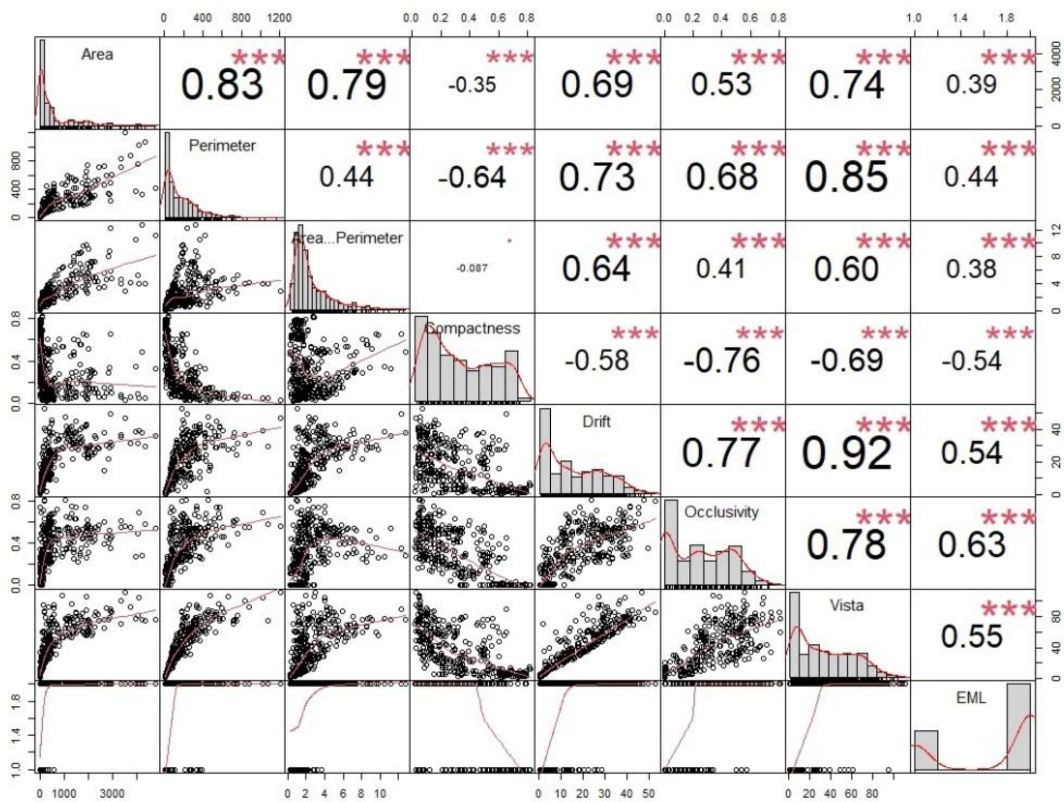


Figure 99 Total building isovist and EML correlation analysis.

Building 5

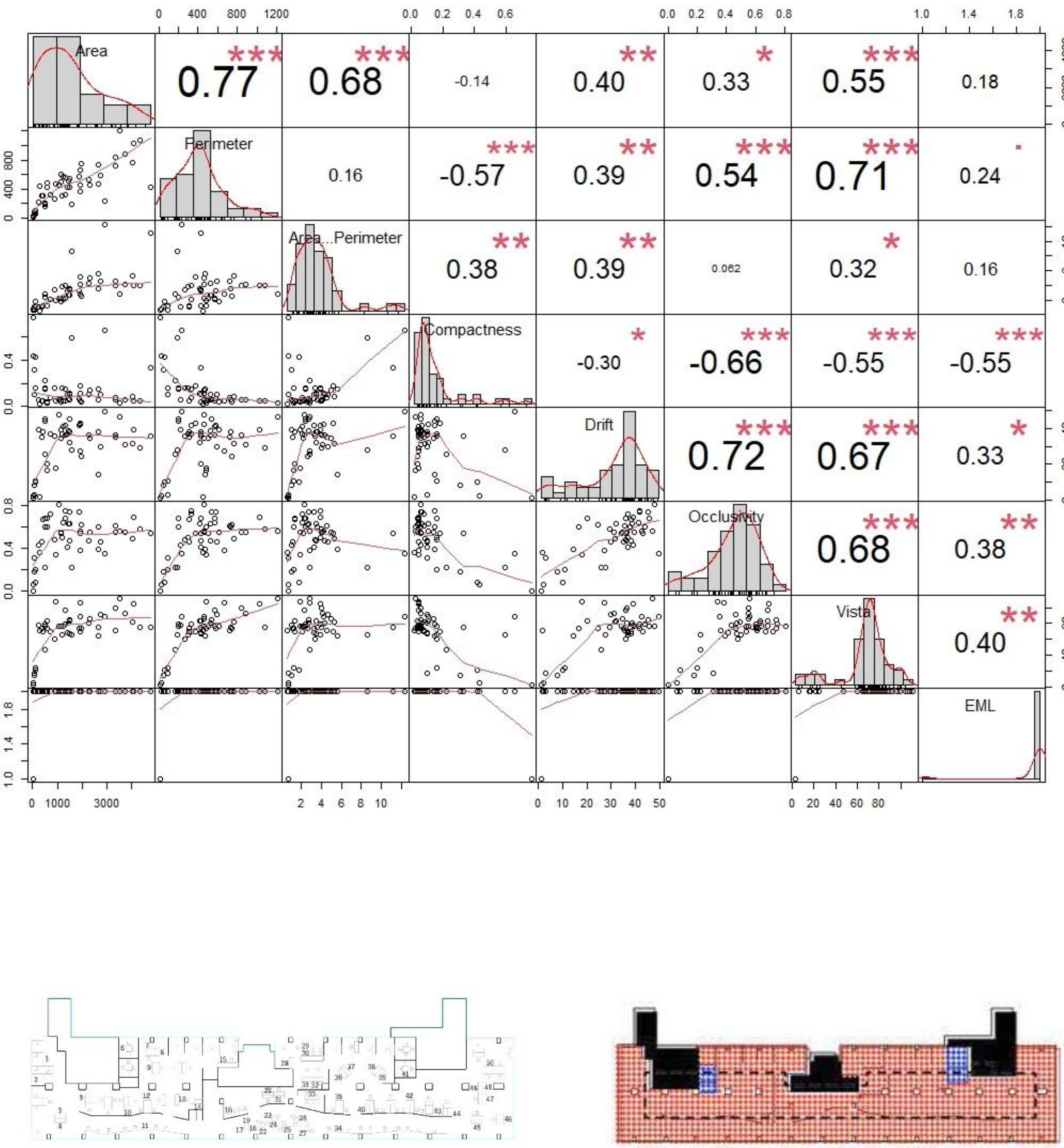


Figure 100 Individual Building 5 isovist and EML correlation analysis.

Building 6

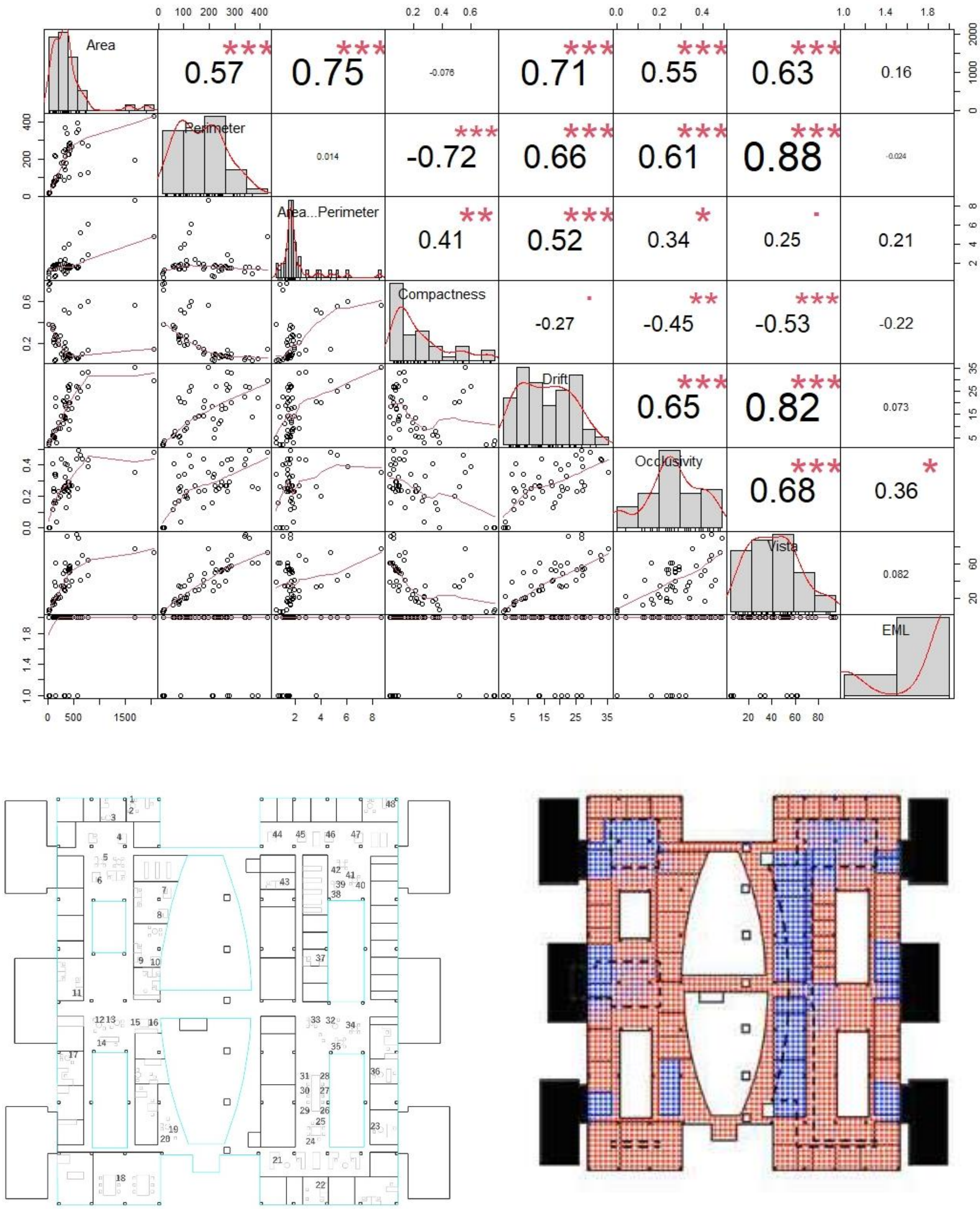


Figure 101 Individual Building 6 isovist and EML correlation analysis.

Building 11

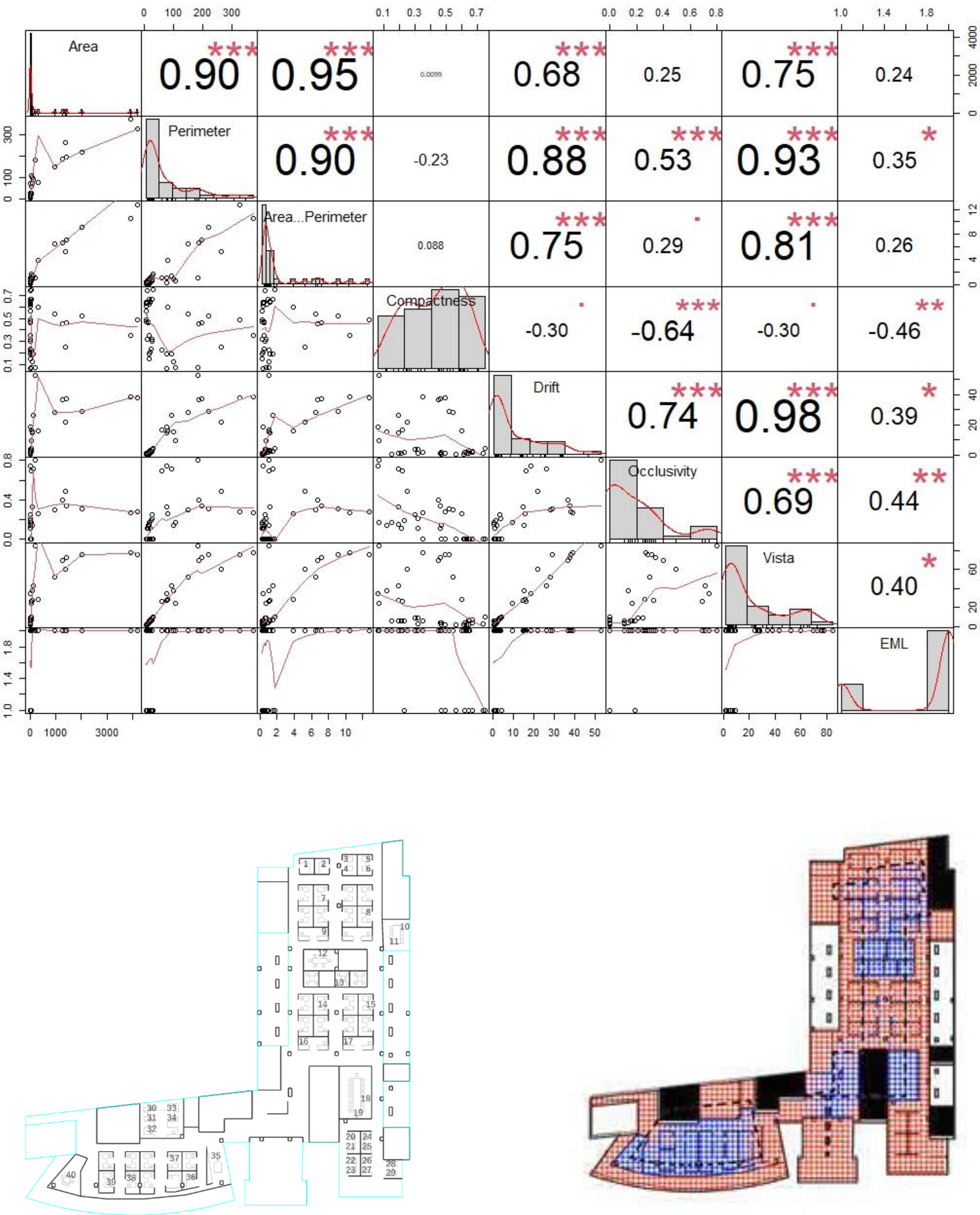
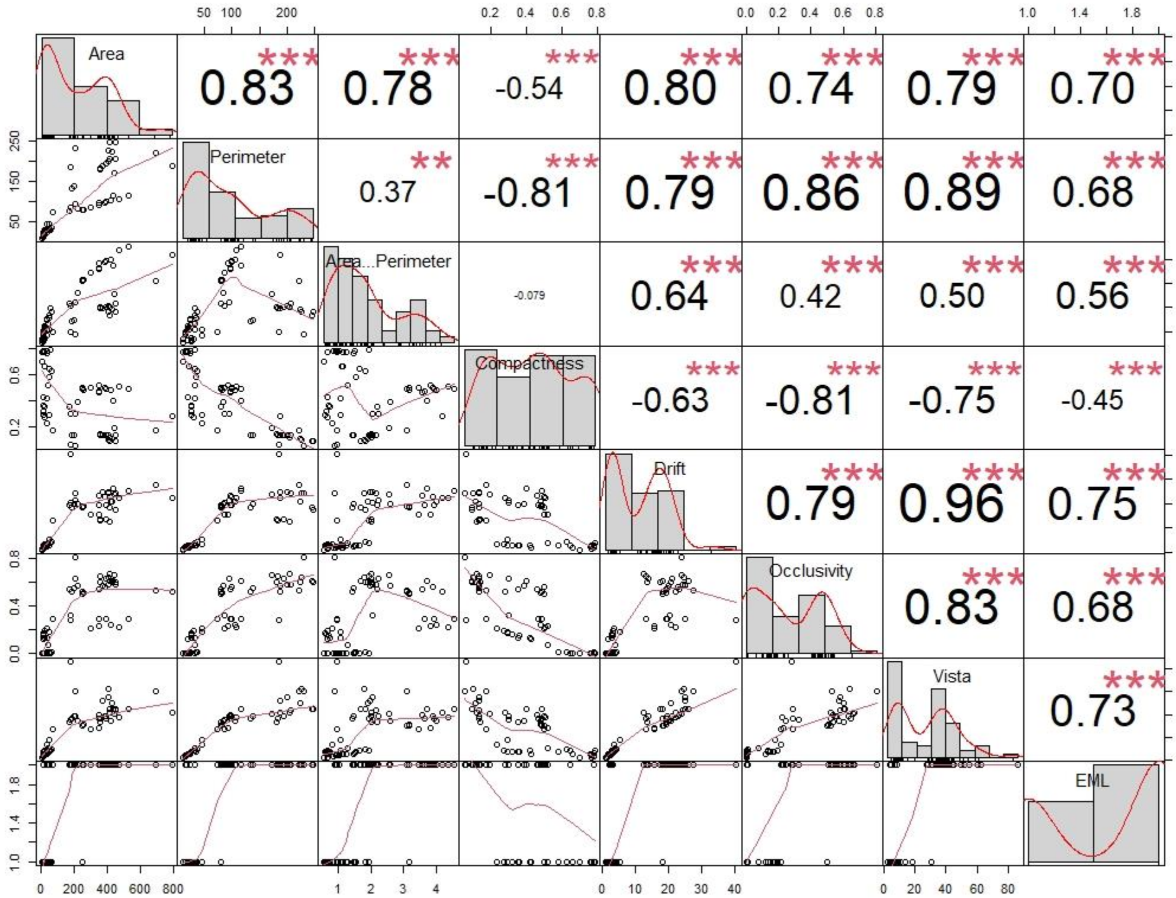
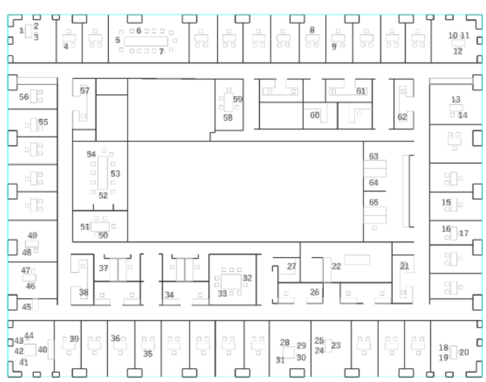


Figure 102 Individual Building 11 isovist and EML correlation analysis.

Building 16





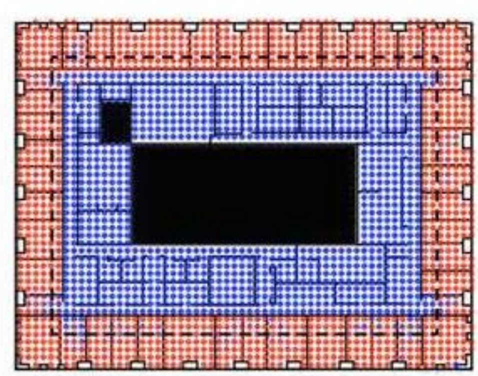


Figure 103 Individual Building 16 isovist and EML correlation analysis.

Building 26

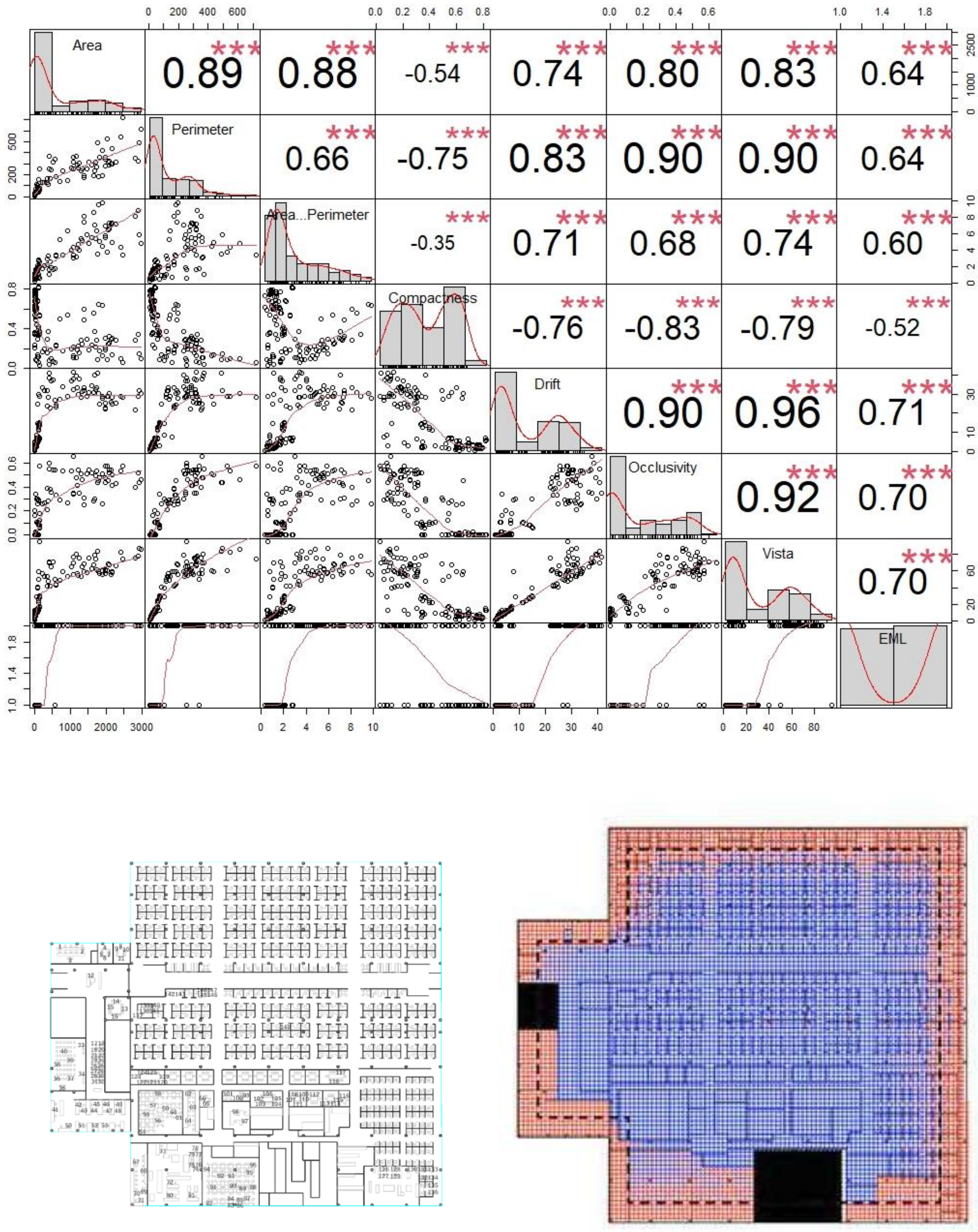
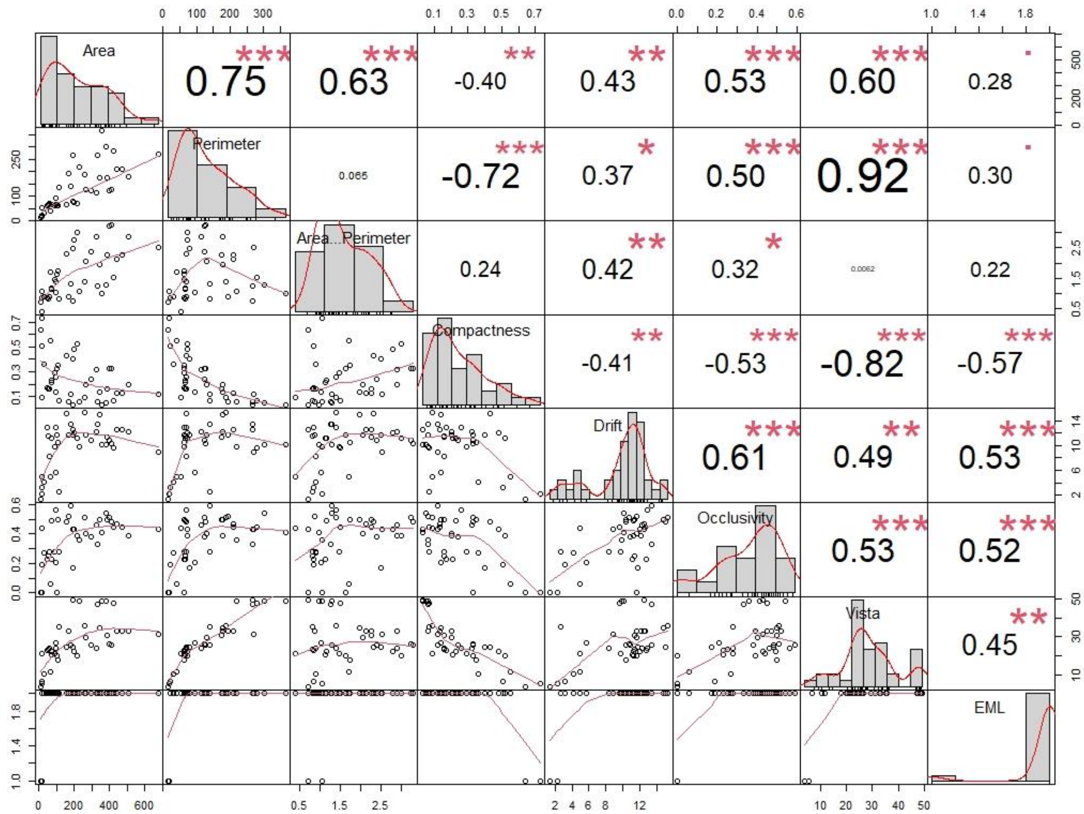
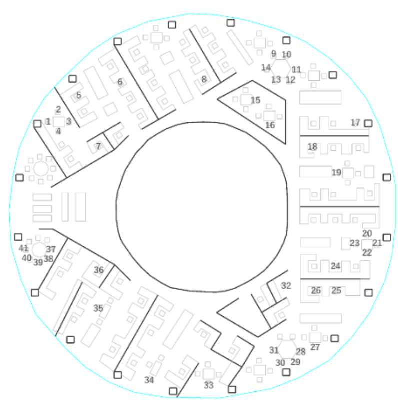


Figure 104 Individual Building 26 isovist and EML correlation analysis.

Building 32





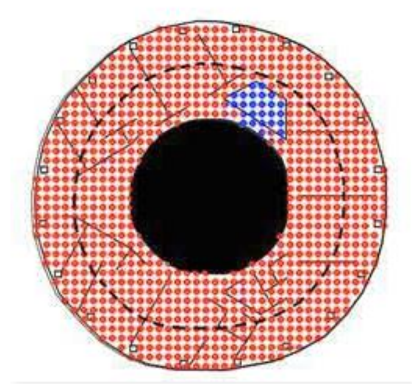


Figure 105 Individual Building 32 isovist and EML correlation analysis.

Upon inspecting the matrix results for the individual buildings, it can be seen that the correlation between the isovist measures and EML differs from case to case. This indicates that the building form and layout play a role in strengthening or weakening and explaining the relationship between the isovist variables and meeting daylighting benchmarks. All isovist measures of building 16 and 26 which are deep and have no atriums have a strong relationship with EML. Buildings 5 and 32 are shallower thus only compactness, occlusivity and vista explain EML availability. In building 32’s case, drift also has a positive but relatively weaker relationship as it has a round geometry. Buildings 6 and 11 have multiple atriums which have weakened relationships to only compactness and occlusivity. Figure 106 summarizes the findings that indicate compactness and occlusivity are the strongest isovist indicators across all buildings.

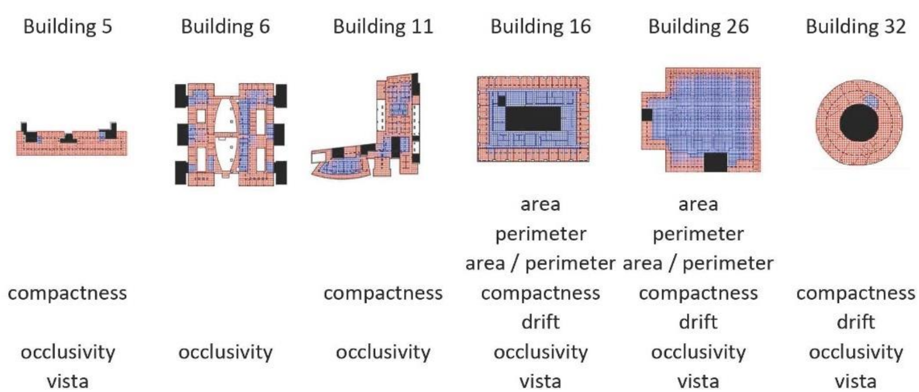


Figure 106 Six building isovist component correlation comparison.

5.8.2. Multiple Regression Analysis

Multiple linear regression is an extension of simple linear regression used to predict an outcome variable on the basis of multiple distinct predictor variables. With the building geometry and isovist measure predictor variables, the prediction of EML is expressed by the following equation:

Equation 2

EML = b0 + b1*Shape Factor + b2*Area + b3*Area/Perimeter + b4*Compactness + b6*Drift + b7*Occlusivity + b8*Vista

The first step in interpreting the multiple regression analysis is to examine the F-statistic and the associated p-value, at the bottom of the model summary.

Table 28 Isovist component multiple regression model.

```
                    Estimate  Std. Error t value         Pr(>|t|)    
(Intercept)       1.13443800  0.15880042   7.144 0.00000000000459 ***
Shape.Factor      0.50518566  0.14446421   3.497         0.000526 ***
Area             -0.00006119  0.00003987  -1.535         0.125701    
Area...Perimeter  0.07424495  0.01604419   4.628 0.00000506842239 ***
Compactness      -0.48869945  0.14088627  -3.469         0.000582 ***
Drift             0.00122290  0.00360248   0.339         0.734449    
Occlusivity       0.82564277  0.14909228   5.538 0.00000005690636 ***
Vista            -0.00192367  0.00197014  -0.976         0.329476    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3394 on 384 degrees of freedom
Multiple R-squared:  0.4712,	Adjusted R-squared:  0.4615 
F-statistic: 48.87 on 7 and 384 DF,  p-value: < 0.00000000000000022
```

In the table above, it can be seen that p-value of the F-statistic is < 2.2e-16, which is highly significant. This means that, at least, one of the predictor variables is significantly related to the outcome variable. To see which predictor variables are significant, the coefficients table is examined to show the estimate of regression beta coefficients, that is whether the beta coefficient of the predictor is significantly different from zero, and the associated t-statistic p-values.

It can be seen that changing in shape factor, AP ratio, compactness, and occlusivity are significantly associated with changes in EML while changes in area, drift, and vista are not significantly associated with EML. As these variables are not significant, it is possible to remove them from the model:

Table 29 Adjust multiple regression model.

```
     Min       1Q   Median       3Q      Max 
-0.94287 -0.23180 -0.00105  0.17480  0.80606 

Coefficients:
                Estimate Std. Error t value        Pr(>|t|)    
(Intercept)      1.04404    0.15335   6.808 0.0000000000378 ***
Shape.Factor     0.53508    0.14299   3.742         0.00021 ***
Area...Perimeter  0.04672    0.00958   4.876 0.0000015815256 ***
Compactness     -0.33428    0.12120  -2.758         0.00609 ** 
Occlusivity      0.79943    0.13686   5.841 0.0000000109982 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3407 on 387 degrees of freedom
Multiple R-squared:  0.463,	Adjusted R-squared:  0.4575 
F-statistic: 83.42 on 4 and 387 DF,  p-value: < 0.00000000000000022
```

Equation 3

EML = 1.04 + 0.53*Shape Factor + 0.05*AP Ratio – 0.33*Compactness + 0.8*Occlusivity

The confidence interval of the model coefficient is extracted as follows:

Table 30 Model confidence intervals.

```
                       2.5 %      97.5 %
(Intercept)       0.74254869  1.34554065
Shape.Factor      0.25394703  0.81620629
Area...Perimeter  0.02787989  0.06555176
Compactness      -0.57257639 -0.09597523
Occlusivity       0.53034612  1.06851553
```

The error rate is estimated by dividing the residual standard error by the mean outcome variable. In this multiple regression, the RSE is 0.3407 corresponding to a 20% error rate.

5.8.3. Model Comparison

The table below summarizes model accuracy assessments by examining the residual standard error (RSE), error rate percentage, the adjusted R2 by taking into account the number of predictor variables, the F statistic, and p-value for each model.

Table 31Model comparison.

Model	RSE	Percentage Error	Adjusted R2	F Statistic	p Value
Shape Factor x EML Linear Regression	0.45	27%	0.045	19.85	0
Area x EML Linear Regression	0.43	25%	0.15	70.32	0
All Variable Multipe Regression	0.34	20%	0.46	48.87	0
Selected Variable Multiple Regression	0.34	20%	0.46	83.42	0

The table indicates that the final multiple regression model with selected variables provides the most accurate results:

Equation 3

EML = 1.04 + 0.53*Shape Factor + 0.05*AP Ratio – 0.33*Compactness + 0.8*Occlusivity

This model is reinforced by the individual building correlations that indicated compactness and occlusivity as the strongest isovist indicators across all buildings (figure). By calculating a building's shape factor and conducting a point isovist analysis to obtain the isovist measures (AP ratio, compactness, and occlusivity) for a specific view, the equation can be used to calculate the EML rounded to one significant figure. If it is 1, then the view does not meet the 200 EML benchmark, if the value is 2, then the view meets the EML benchmark. This can be applied to cases that match the study's limitations and conditions.

CHAPTER VI: DISCUSSION

This research has aimed to address and answer several questions regarding lighting design within indoor environments. It has been argued that building design is often influenced by environmental and economic impacts as set by stakeholders, hence the research highlights the importance of lighting design considerations from the perspective of enhancing occupant user health and wellbeing. Though there is a heavy reliance on electric lighting to achieve benchmark requirements, the literature review outlined physiological and psychological light benefits that can only be received from daylight and access to windows. Through computer simulations, this research has identified methods to assess both access windows for both daylight and views.

It is commonly known that horizontal illuminance is still the primary lighting assessment metric. This research aimed to investigate whether this is appropriate and if a space that meets horizontal daylight requirement benchmarks necessarily means seated occupants are receiving sufficient light exposure from their workstations. By simulating fifty office buildings and running several correlation analyses, it was concluded that as an average, horizontal and vertical illuminance were highly correlated. Similarly, there was a strong relationship between vertical illuminance and vertical equivalent melanopic lux, implying that meeting the vertical photopic lighting benchmarks would most likely meet the melanopic benchmarks too.

It should be noted the results that were concluded are relevant to the study's parameters. Several variables were constrained to ensure the results can be meaningfully deduced from the case being studied. The simulations were conducted in Portland, Oregon climate zone 4C, under overcast sky conditions, with a 2 storey building context, clear curtain wall glazing, and neutral white and gray interiors. These limitations provide an opportunity for future research to investigate whether the results are consistent under different simulation conditions or to test their impact and extent of change in results.

In the earlier stages of the research, a pilot study investigated glazing tints as a variable before the parameter was constrained as clear glazing for the final computer simulations. Glazing tint decisions are generally influenced by aesthetics, temperature regulation for energy and cost savings as well as minimizing glare. Circadian transmittance and distorting the spectral properties of light for occupant alertness are not considered. The pilot study aimed to answer whether colored glazing tints create noticeable differences in circadian light transmittance by simulating three buildings with clear, blue, and bronze tints. The results across all three buildings followed the same trend, it can be concluded that clear glazing allows the most daylight in, followed by blue tints and lastly bronze tints.

The research also addressed office types' performance in terms of creating an indoor environment with high circadian potential. The shape factor measure is evidently the measure that best explains daylight availability. The higher the shape factor, the higher the average horizontal, vertical photopic, and melanopic illuminance and percentage of sensors meeting benchmarks. This implies that buildings do not necessarily have to be compact or have many atriums to achieve high daylighting levels, they just need to have a high shape factor or envelope area. It can be seen that pavilions and buildings with wings are higher on the shape factor and daylight availability scale. Bars and buildings with shallow spaces and large central cores are found in the middle. Compact blocks with external cores are on the lower end. Deep spaces with small central cores are spread across the charts.

The overarching question to be answered is: Are glazing tints, office floor plates, or office indoor layouts more influential as architectural parameters that enhance or diminish the availability of daylight? Tables 32-34 compile the results of average horizontal illuminance from the studies conducted in this research. This is done across several cases to show a range of percentage differences in the results by modifying the variables under study. It can be seen that by changing clear glazing to blue tints the average horizontal illuminance can drop by up to 44%, and by changing it to a bronze tint conditions can deteriorate by up to 82%. Table 34 groups the fifty core and shell buildings by their floor plate type and ranks them in order with the highest shape factor at the top of each list. The highest and lowest shape factors for each floor plate type were compared respectively. Percentage differences range from as little as a 7% drop to a 55% increase. The interior wall results in table 33 state 16% as the largest drop in average horizontal illuminance.

This provides an overview of daylight availability determining factors. It highlights the impact of a small glazing type choice compared to a larger building form design decision. It should not be underestimated and be carefully considered as the easily most influential. The cases compared in this research provide a small sample under specific simulation conditions. Interior walls and building forms may result in larger differences depending on their design and study conditions.

Table 32 Glazing tints differences comparison.

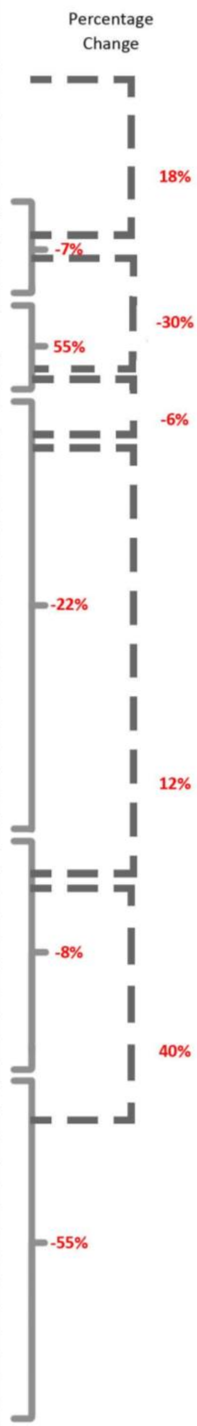
Building	Clear Glazing	Percentage Change	Blue Tint	Percentage Change	Bronze Tint	Percentage Change
Apple Computer Inc.	5518	-44%	3079	-67%	1007	-82%
The Equitable	2028	-29%	1440	-39%	875	-57%
Sears 70	5626	-37%	3537	-58%	1484	-74%

Table 33 Core and shell, interior walls differences comparison.

Building	Core and Shell	Interior Walls	Percentage Change
Arthur Andersen	2256	2237	-1%
Apicorp	2190	1883	-14%
Chiat/Day Advertising	2073	1874	-10%
Davis Polk & Wardwell	1167	1032	-12%
IBM Regional Headquarters	660	556	-16%
Lend Lease Interiors	1944	1908	-2%

Table 34 Floor plate type and shape factor differences comparison.

Building	Floor Plate Type	Shape Factor (SF)	Av. Horizontal Illuminance
Apicorp	Pavillions	1.12	2190
Commerzbank AG	Pavillions	0.81	1778
IBM (UK) Limited	Pavillions	0.80	2140
Data Firmengruppe	Pavillions	0.79	1983
British Telec., 5 Longwalk	Pavillions	0.77	1575
3com Corporation	Pavillions	0.75	1432
Vitra International AG	Bars	0.93	2591
Arthur Andersen	Bars	0.82	2256
Allen & Overy	Bars	0.81	1336
Ford Foundation	Wings	0.88	1823
Chiat/Day Advertising	Wings	0.86	2073
Nickelodeon	Deep Space, Small Central Core	0.95	1705
Andersen Consulting	Deep Space, Small Central Core	0.86	2846
DEGW London Office	Deep Space, Small Central Core	0.78	1550
Direct. of Telecom., MPBW	Deep Space, Small Central Core	0.77	1648
British Telec., The Square	Deep Space, Small Central Core	0.77	1513
Andersen (before move)	Deep Space, Small Central Core	0.77	2027
Sears 70	Deep Space, Small Central Core	0.76	1505
Orenstein Koppel	Deep Space, Small Central Core	0.76	1853
Leo A Daly	Deep Space, Small Central Core	0.76	1568
MGIC	Deep Space, Small Central Core	0.76	1723
Davis Polk & Wardwell	Deep Space, Small Central Core	0.74	1167
TBWA Chiat/Day	Deep Space, Small Central Core	0.74	1285
Andersen (after move)	Deep Space, Small Central Core	0.73	1753
Weyerhaeuser Company	Deep Space, Small Central Core	0.73	1447
Hoffmann La Roche	Deep Space, Small Central Core	0.73	1340
Sears 40	Deep Space, Small Central Core	0.72	782
McDonald's	Deep Space, Small Central Core	0.72	1611
f/X Networks	Shallow Space, Large Central Core	0.88	1913
Lend Lease Interiors	Shallow Space, Large Central Core	0.84	1944
Apple Computer Inc.	Shallow Space, Large Central Core	0.80	1705
IBM Australia	Shallow Space, Large Central Core	0.77	1469
The Equitable	Shallow Space, Large Central Core	0.76	1591
Discovery Channel Latin Am.	Shallow Space, Large Central Core	0.76	1516
Lowe & Partners/SMS	Shallow Space, Large Central Core	0.75	1527
Greenberg Traurig	Shallow Space, Large Central Core	0.74	1317
Citicorp	Shallow Space, Large Central Core	0.72	1478
Interpolis	Compact Blocks, External Core	0.92	2679
Olivetti A	Compact Blocks, External Core	0.83	2515
Olivetti B	Compact Blocks, External Core	0.83	2515
Olivetti C	Compact Blocks, External Core	0.83	2515
DuPont	Compact Blocks, External Core	0.79	1768
McDonald's Italia	Compact Blocks, External Core	0.78	1067
Buch und Ton	Compact Blocks, External Core	0.76	1115
Steelcase Inc.	Compact Blocks, External Core	0.76	1324
Ford Motor Co.	Compact Blocks, External Core	0.75	1250
WMA Consulting Engineers	Compact Blocks, External Core	0.75	1103
Eastman Kodak	Compact Blocks, External Core	0.74	848
Chase Manhattan Bank	Compact Blocks, External Core	0.73	452
IBM Regional Headquarters	Compact Blocks, External Core	0.71	660



CHAPTER VII: CONCLUSION

Lighting analyses do not necessarily investigate vertical illuminance and occupant access to windows and daylight from their seated positions, priority is given to light transmittance performance and light distribution in the space. Similarly, space syntax methods have not assessed office interiors from an access to windows perspective. Investigations on the spatial composition of office layouts reflect programmatic requirements for adjacency, clustering, isolation, control, supervision, hierarchical stratification, and functional processes. This research bridges both lighting design and space syntax fields together to provide a process of assessing building daylight performance. This novel method allows designers from both lighting and interior design fields to understand the considerations to be taken during the design stages and brings awareness to influencing design parameters.

Isovist areas plotted on a bar chart can easily identify workstations that have access to windows. This could be used to calculate the percentage of workstations with window access. Overlaying a daylighting analysis and an isovist area analysis can identify workstations that receive sufficient daylight over the partitions but do not have access to window views. Drift flow vectors overlay can help assess the openness of a design and occupants' ease of surveying the unobstructed space to receive sufficient vertical light. An isovist compactness heat map can easily identify open cubicle and closed office work areas. Visual depth to location can be used to assess the visual accessibility of a daylight source. This could be used to warrant and maximize the potential of a window or atrium location.

Several conclusions were drawn from the isovist analyses that investigated the sample floorplate types and interior layouts. In the cases where cores were centrally located in the plans, daylight reached deeper into the buildings, and it provided more potential for workstations to be placed along the envelope to maximize views. In some cases, the perimeter was used for closed cellular offices, these blocked any views and do not permit daylight past the perimeter zone. This could be compromised by either designing lower partitions instead of solid walls or allocating atria that would provide supplemental daylight and allow users to survey the space with internal views for the workstations found deeper into the plan. Open-plan offices with clustered workstations have higher drift and lower A/P ratios, whereas open-plan cubicle offices create spaces with high occlusivity and, smaller vistas, and obstructed lines of sight.

In the end, the design decisions need to be balanced out to enhance occupant wellbeing but also meet requirements for privacy and space allocation based on the culture of the office to prioritize the zones that would be used most. However, some recommendations can be made that clear glazing is the best option for light transmittance, cores should be centralized and surrounded by the closed cellular offices so that they do not block the building envelope. To ensure these receive daylight, atria can be allocated as buffers between these single offices and open plan workstations along the perimeter. Increasing the building's shape factor would be ideal.

The research also concludes that by calculating a building's shape factor and conducting a point isovist analysis to obtain the isovist measures (AP ratio, compactness, and occlusivity) for a specific view, the following multiple linear regression model equation can be used to calculate the EML rounded to one significant figure. If it is 1, then the view does not meet the 200 EML benchmark, if the value is 2, then the view meets the EML benchmark.

Equation 3

EML = 1.04 + 0.53*Shape Factor + 0.05*AP Ratio – 0.33*Compactness + 0.8*Occlusivity

This equation can be applied to cases that match the study's limitations and conditions to provide quick insights on benchmark requirements. Similarly, the daylight factor equation may be used as a quick rule of thumb, but as tested in this research and compared to computer simulation results, the higher the shape factor of the building, the higher the equation inaccuracies. To fully evaluate a building's performance, the simulation conditions should be replicated as closely as possible to best achieve reliable results.

Using ALFA would produce the same result and arguably more accurately, but using the equation is a free alternative. ALFA is not available for free, so some designers might not have access to it. It also requires a 3D model which is more time consuming. The Isovist software is free, and only requires a simple 2D floorplan that could easily be imported. This approach not only gives results for predicted EML, but also checks on other windows and views credit requirements. The aim is to have an accessible and holistic approach that would tackle more than one issue simultaneously.

To simplify the equation even more, each isovist property can be given a range to help designers visualize and estimate what is required to meet the EML benchmark without running an isovist computer simulation. As a first attempt and to introduce a potential direction future studies could investigate, this section will estimate compactness ranges. In an isovist field compactness identifies the regions of plan in which an observer's spatial experience is contiguously consistent. The values range from 0 to 1. Low values of compactness indicate very narrow and long isovists which explains why the equation subtracts compactness values as it has a negative correlation with EML. To predict a high EML in the equation, a compactness value between 0.1 and 0.3 is recommended. Recommendations can be made for all the isovist properties in this equation so that designers can visually assess and predict whether a workstation would meet the EML benchmark with the study's conditions.

For a step further, future studies could conduct surveys to test designers' awareness of the indoor environmental quality of case studies. By recording lighting levels from building simulations and asking designers to predict them, it would provide insight into the level of responsiveness in the design field. If designers fail to predict building performance and access to daylight and windows, this would further justify the importance of this research and the need for quick rules of thumb and accessible simulation methods to aid designers. For a better understanding of occupant wellbeing in the built environment, issues of glare and visual comfort, which were not within the scope of this study, could either be simulated or conducted in a field study to provide a more comprehensive outlook.

Designing human-centric environments is still a relatively new concept and not usually the driving force in building design. Though this research has aimed to shed light on its importance and provide accessible methods for these considerations, it must still be accepted that stakeholders need more incentive than daylight design for occupant wellbeing. It is generally believed that effective daylighting design will lead to reductions in electric lighting consumption which leads to a reduction in overall building energy consumption.

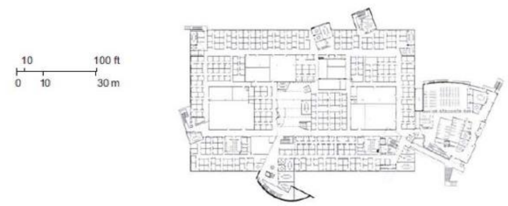
In order to meet circadian lighting benchmark requirements at workstations for all times of the year a more comprehensive analysis is required. A simulation study conducted by Safranek et al. (2020) estimates a 15% to 100% increase in annual energy usage depending on the duration of occupied hours to ensure the circadian metric recommendations are met. Additional luminaires or luminaires with a higher lumen output would have to be installed as solutions to meet the requirements which increase the connected electrical load and potentially negate other energy saving efforts. Hence, future studies can address the key issue of the potential to save energy through daylighting design that still focuses on occupant wellbeing. With the use of the ratio of predicted to realised energy savings, defined as the ‘realised savings ratio’ or RSR, it can supplement and justify design decisions that would also allow access to daylight and windows.

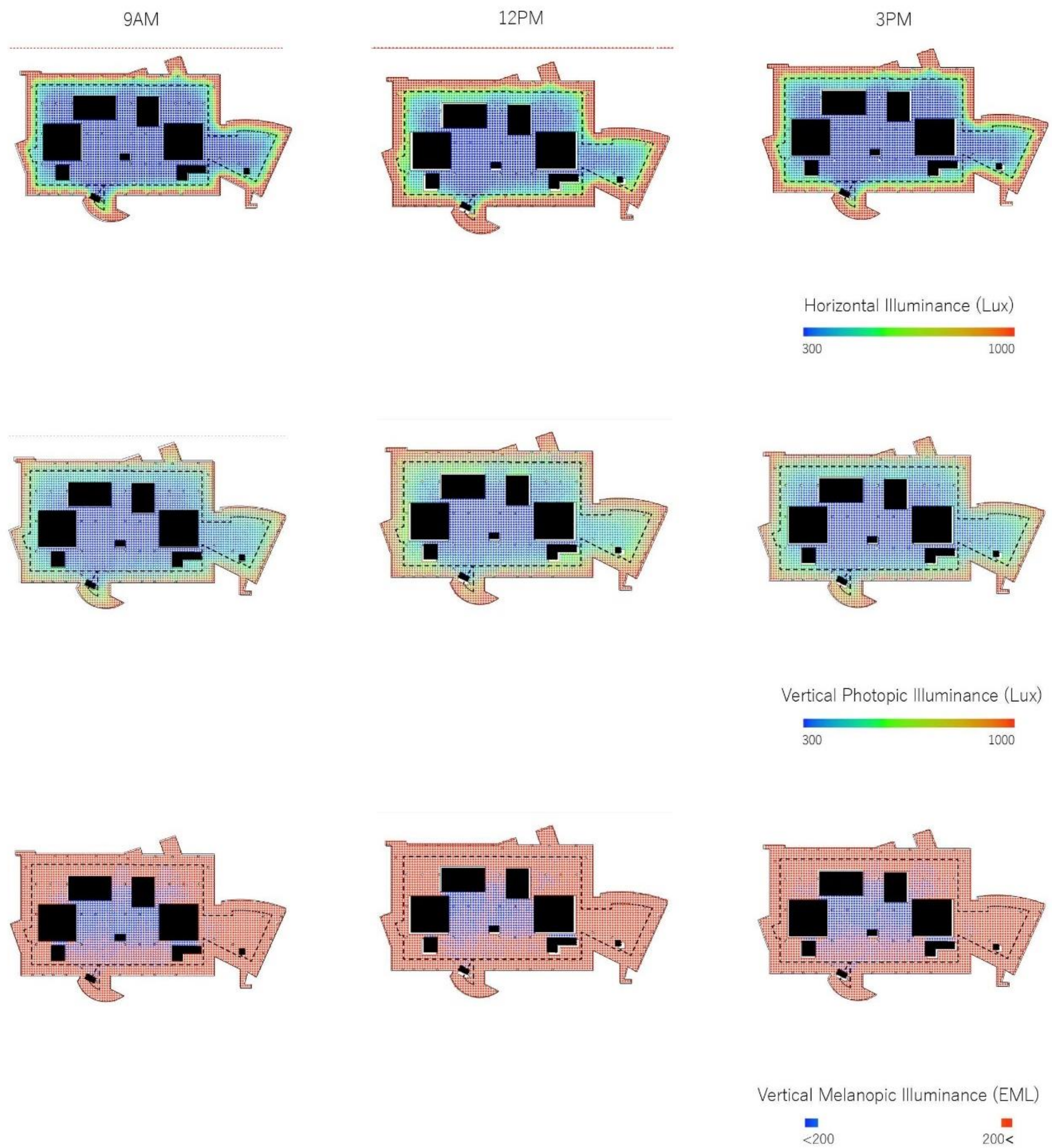
In cases where the buildings do not have a fully glazed curtain wall, such as those simulated in this research, daylight transmittance and access to windows will be greatly affected by the various window sizes. This could be incorporated in future models. As this research has not included electric lighting, it would also be beneficial to simulate and predict the performance of buildings as they would occur with electric lighting and address areas that do not receive sufficient daylight with the change of window to wall ratio and need supplemental electric lighting.

There are countless variables that influence daylight availability. Some can be simulated and others that are yet to be comprehended but are estimated to the best of our abilities. There are also many aspects about our physiological and psychological relationships to daylight and the outdoors that are not fully understood. What we know should at least be considered in building design. In the end, buildings are designed by humans for humans.

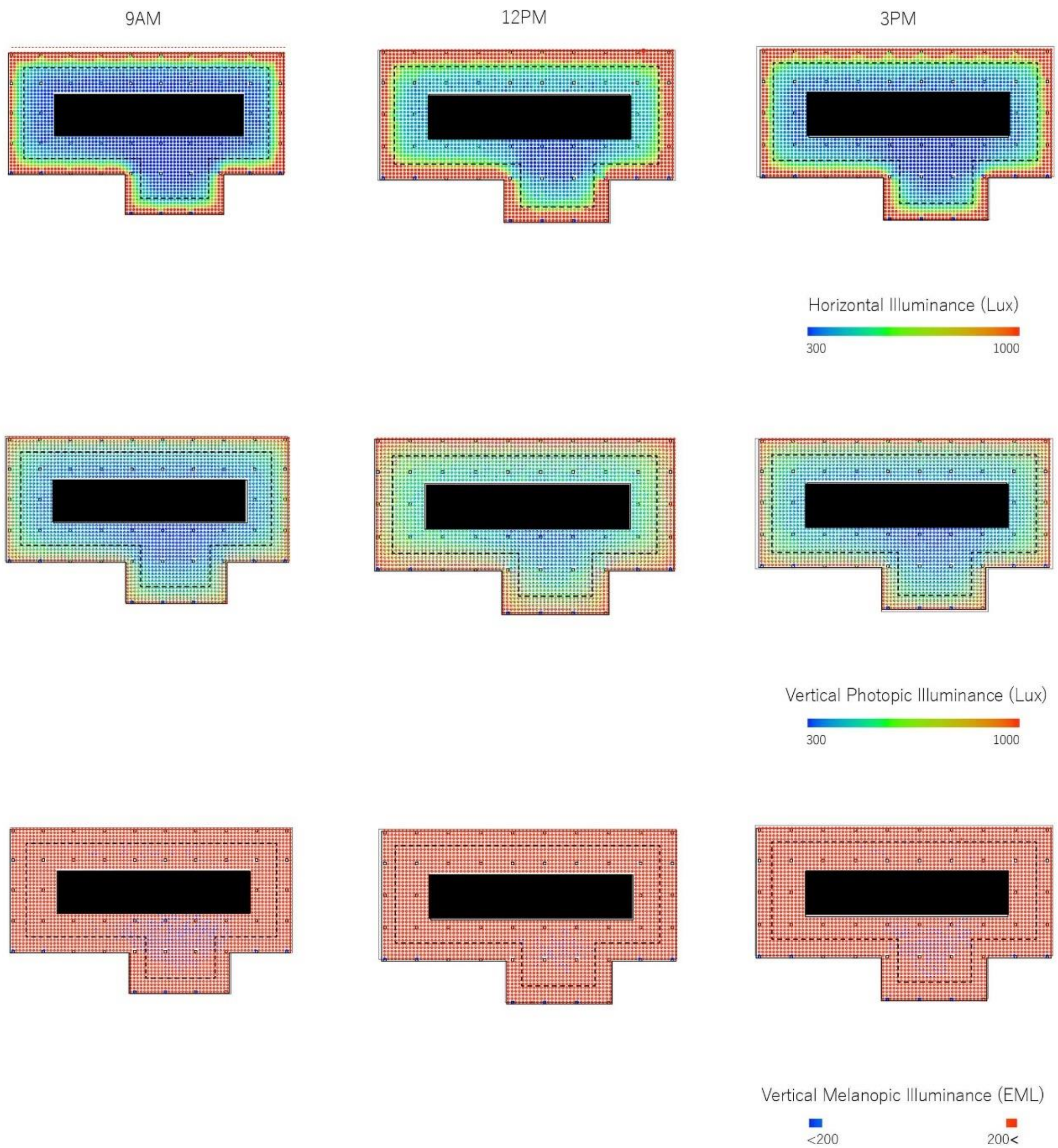
APPENDIX A - CORE AND SHELL SIMULATIONS

#1 3com Corporation

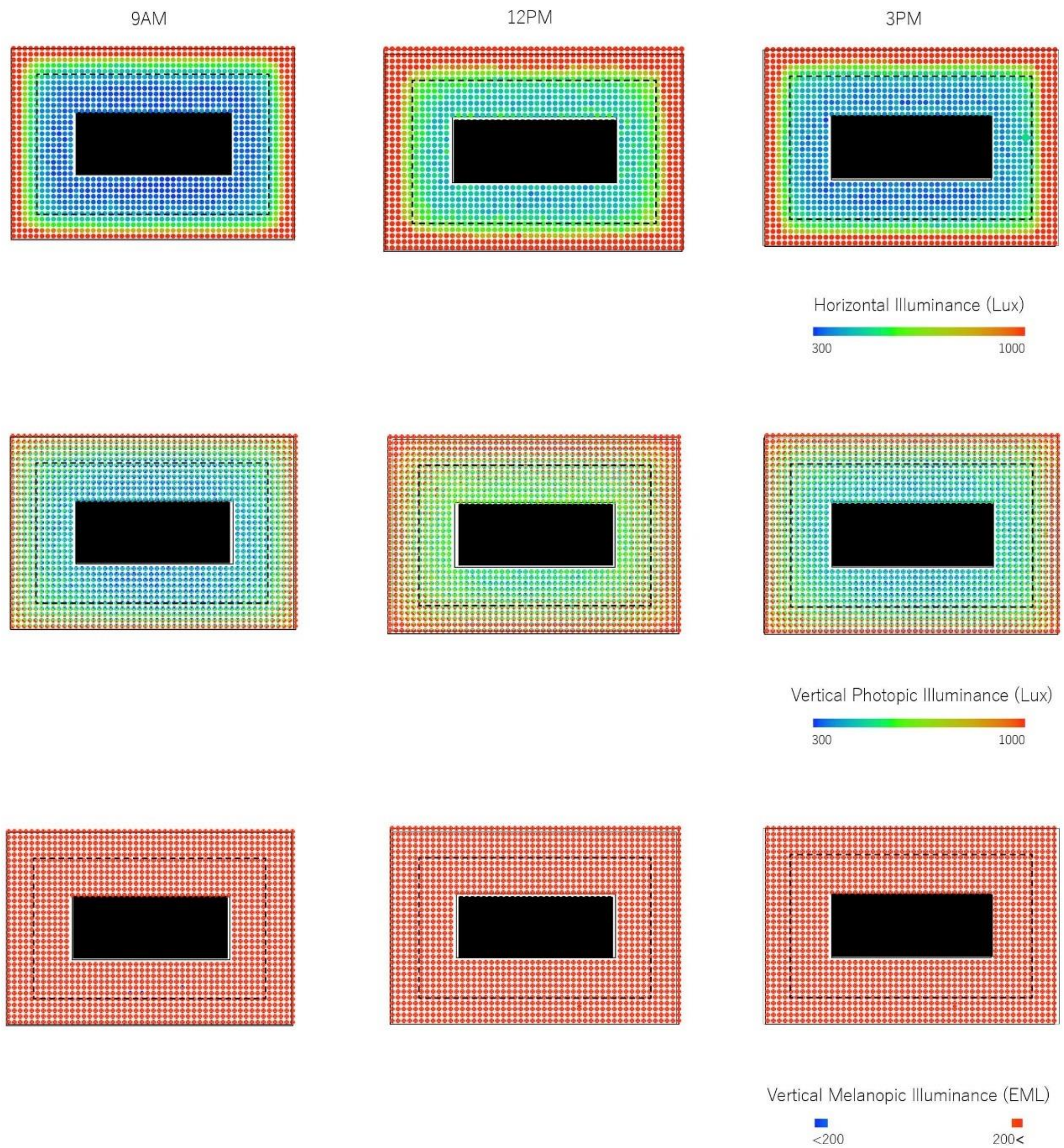




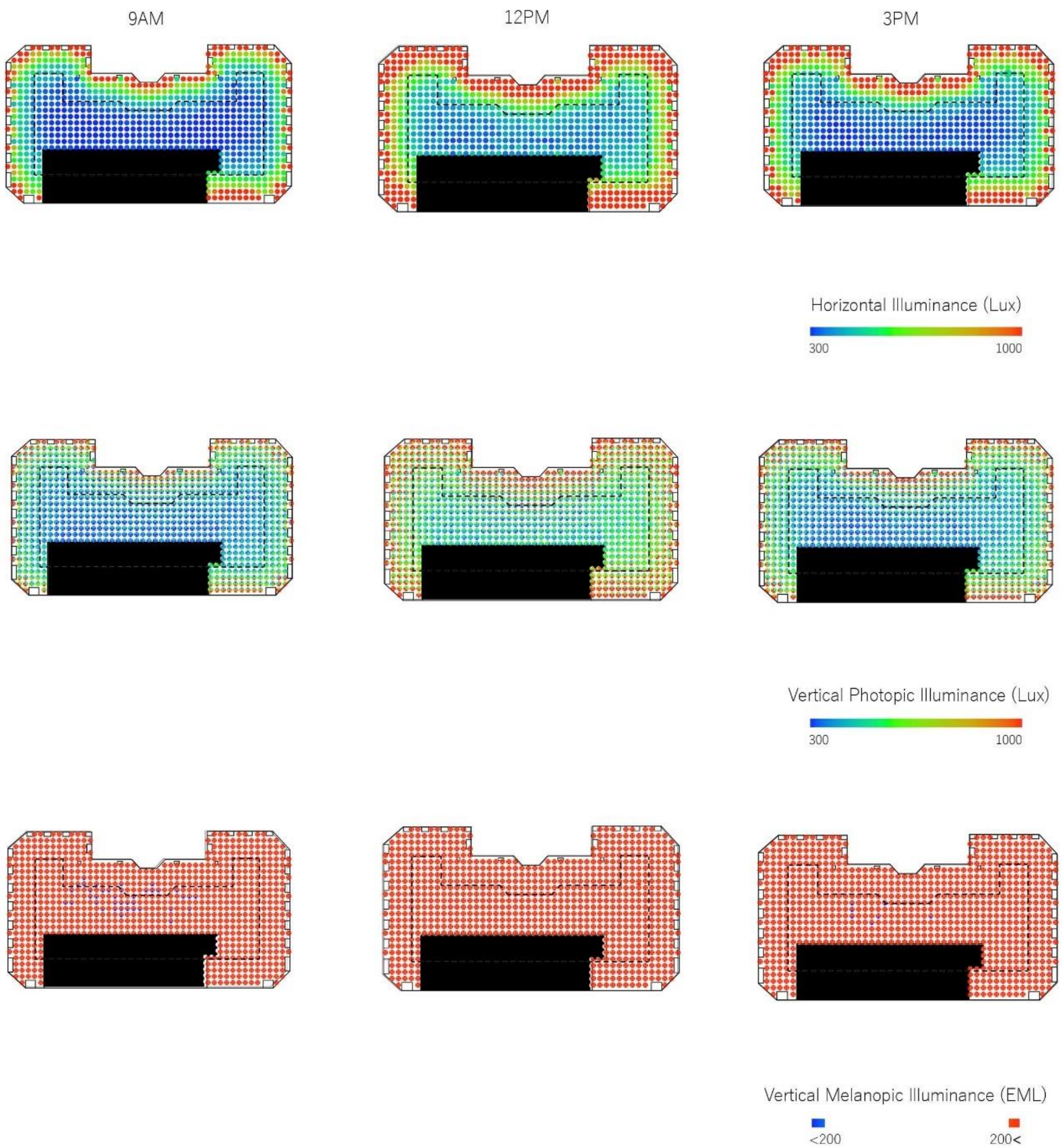
#2: Andersen (after move)



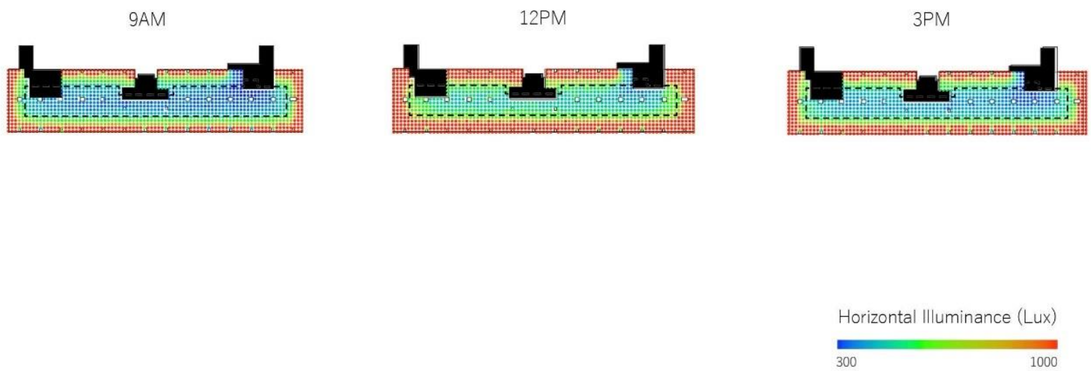
#3: Andersen (before move)

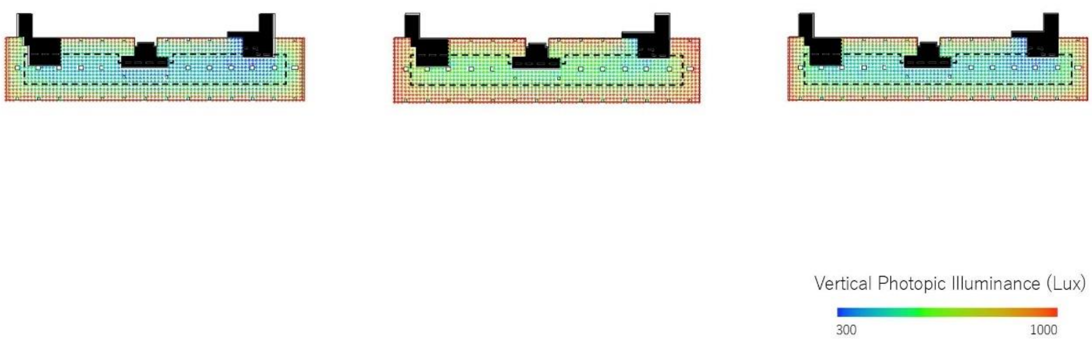


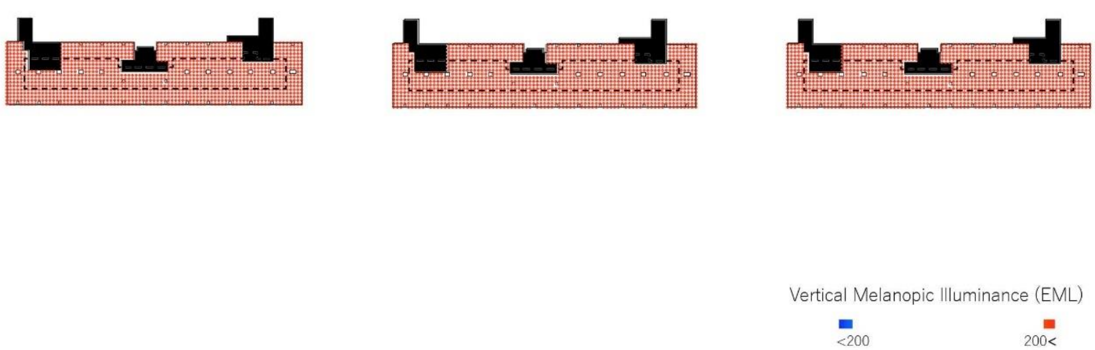
#4: Allen & Overy



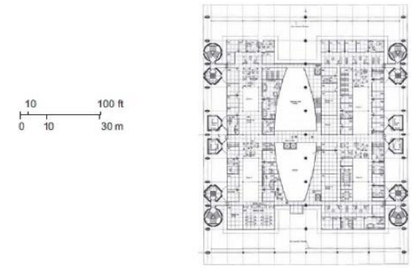
#5: Arthur Andersen







#6: Apicorp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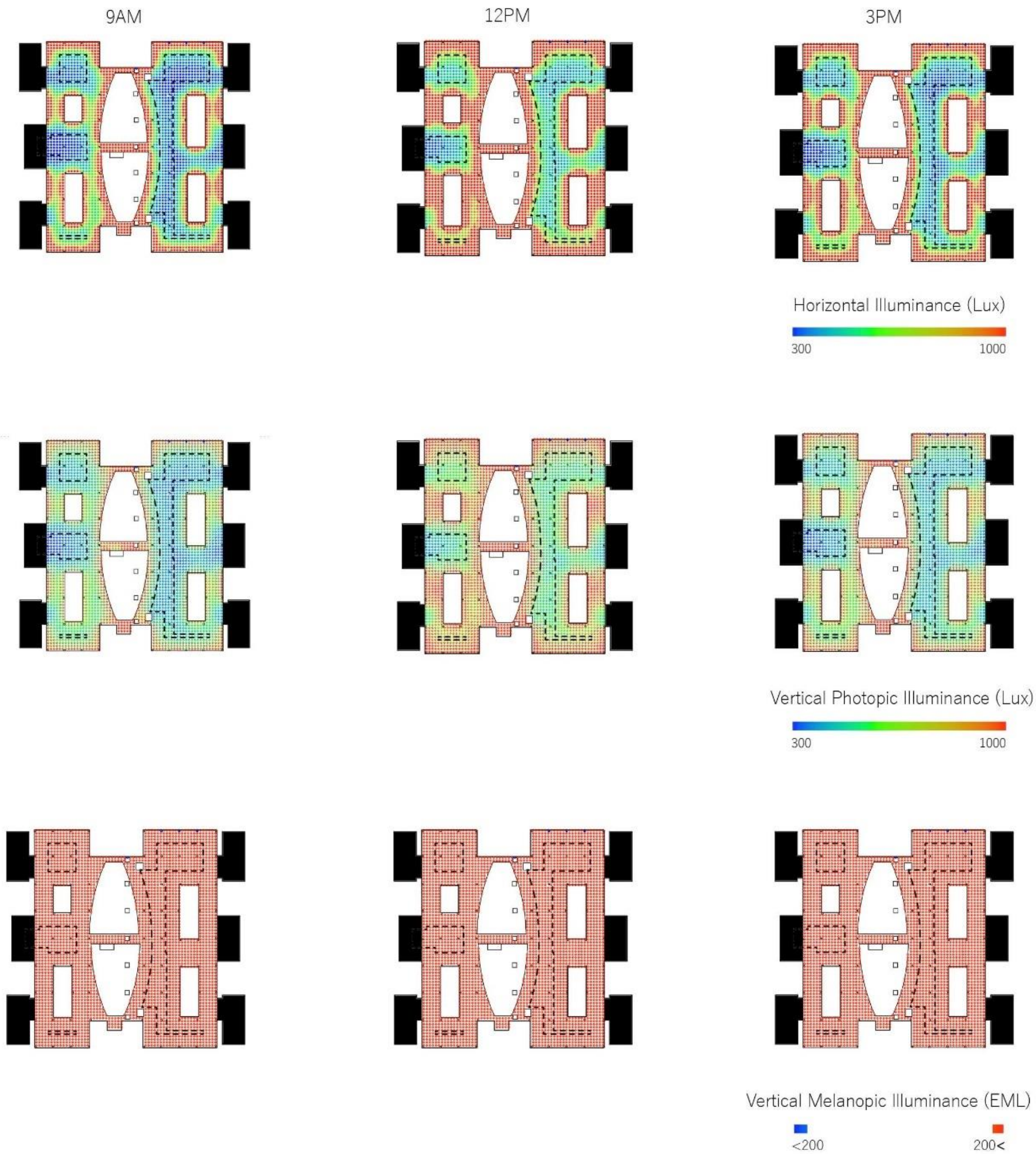
9AM
12PM
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Horizontal Illuminance (Lux)
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Vertical Photopic Illuminance (Lux)
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Vertical Melanopic Illuminance (EML)
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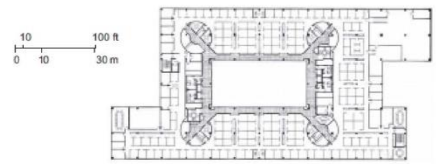
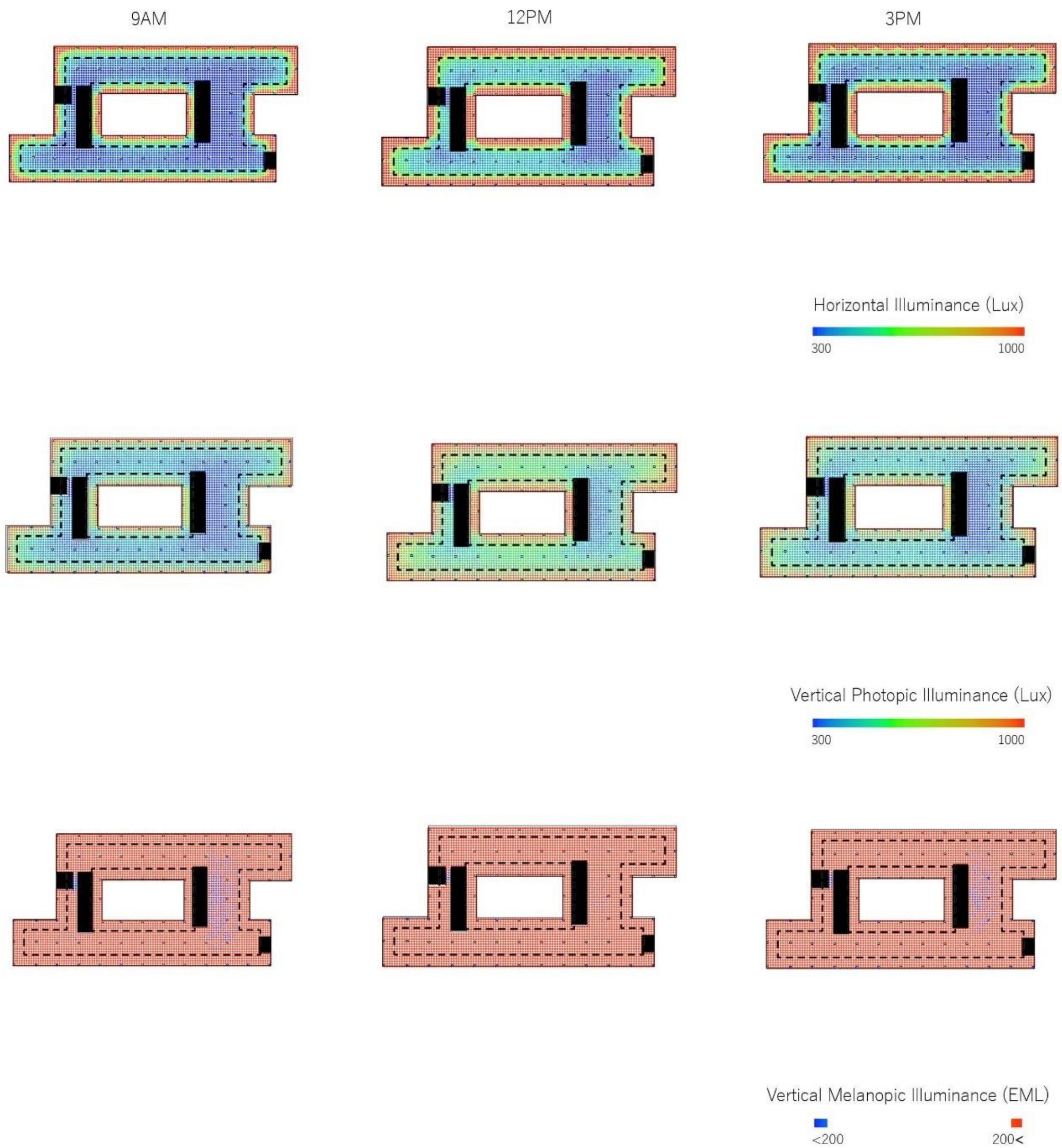
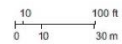
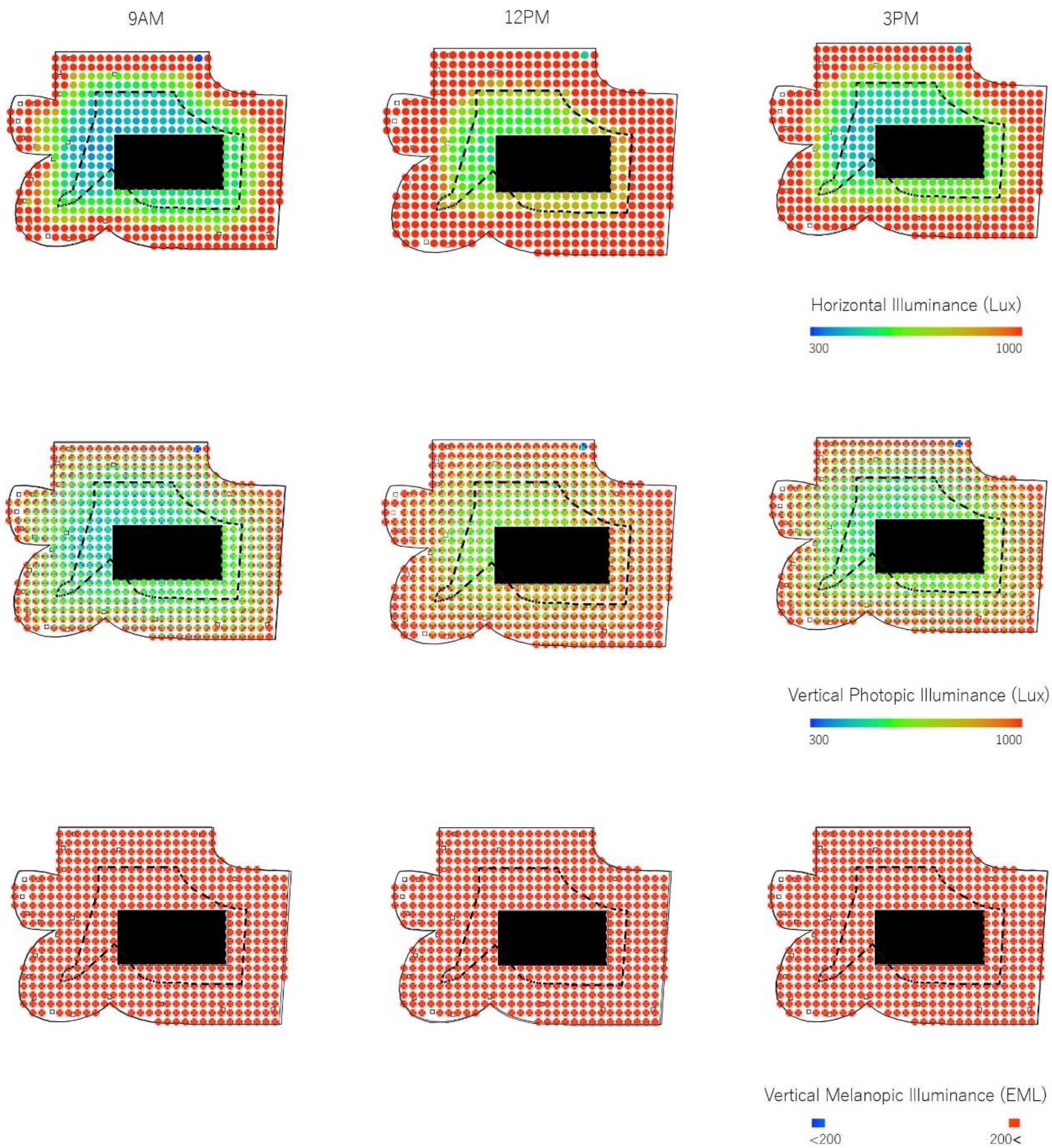
#7: Apple Computer Inc.





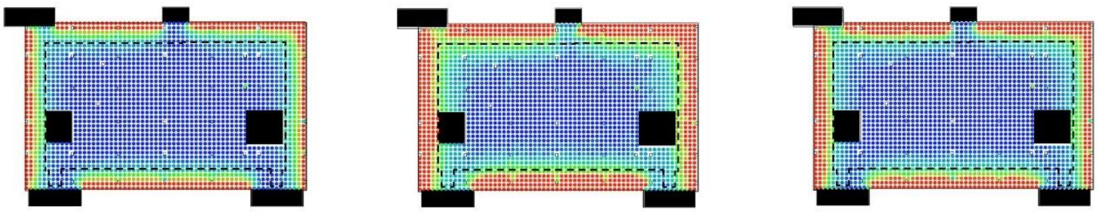
#8: Andersen Consulting





#9: Buch und Ton

9AM 12PM 3PM



Horizontal Illuminance (Lux)

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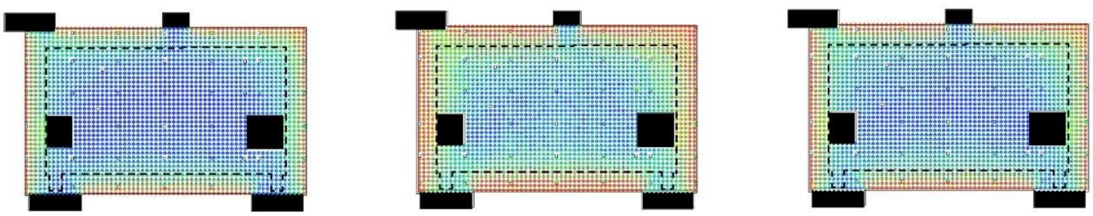

Vertical Photopic Illuminance (Lux)

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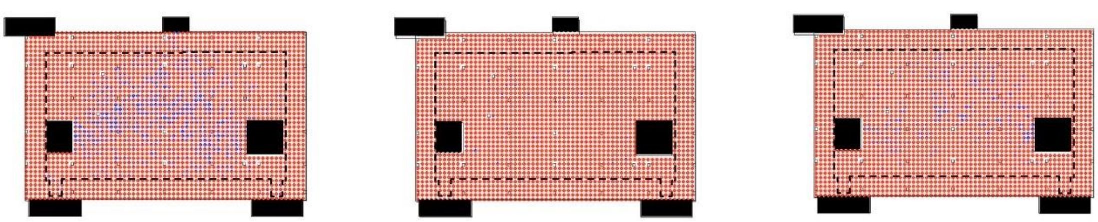

Vertical Melanopic Illuminance (EML)

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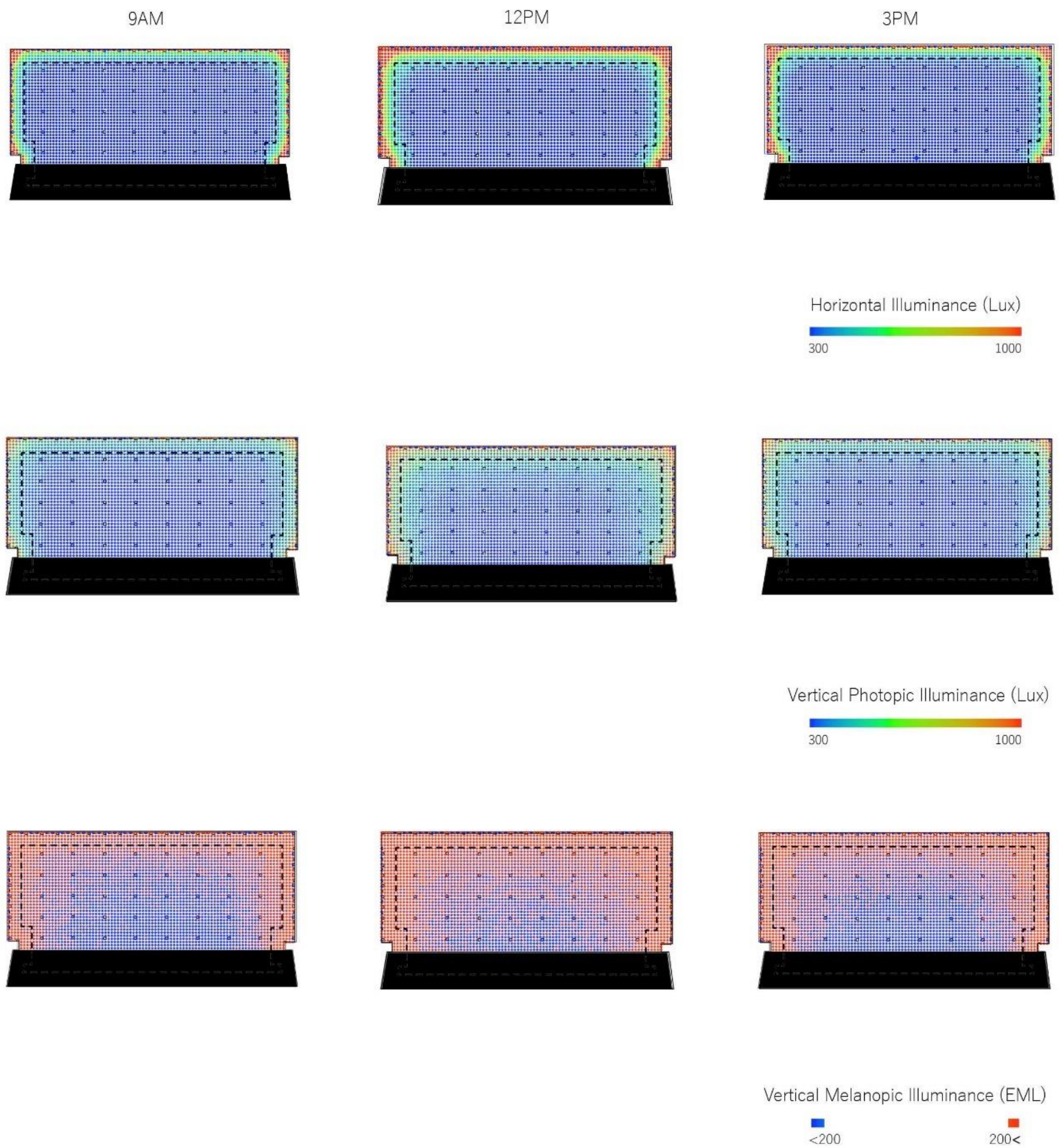
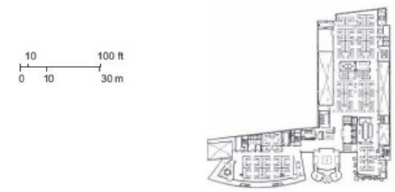
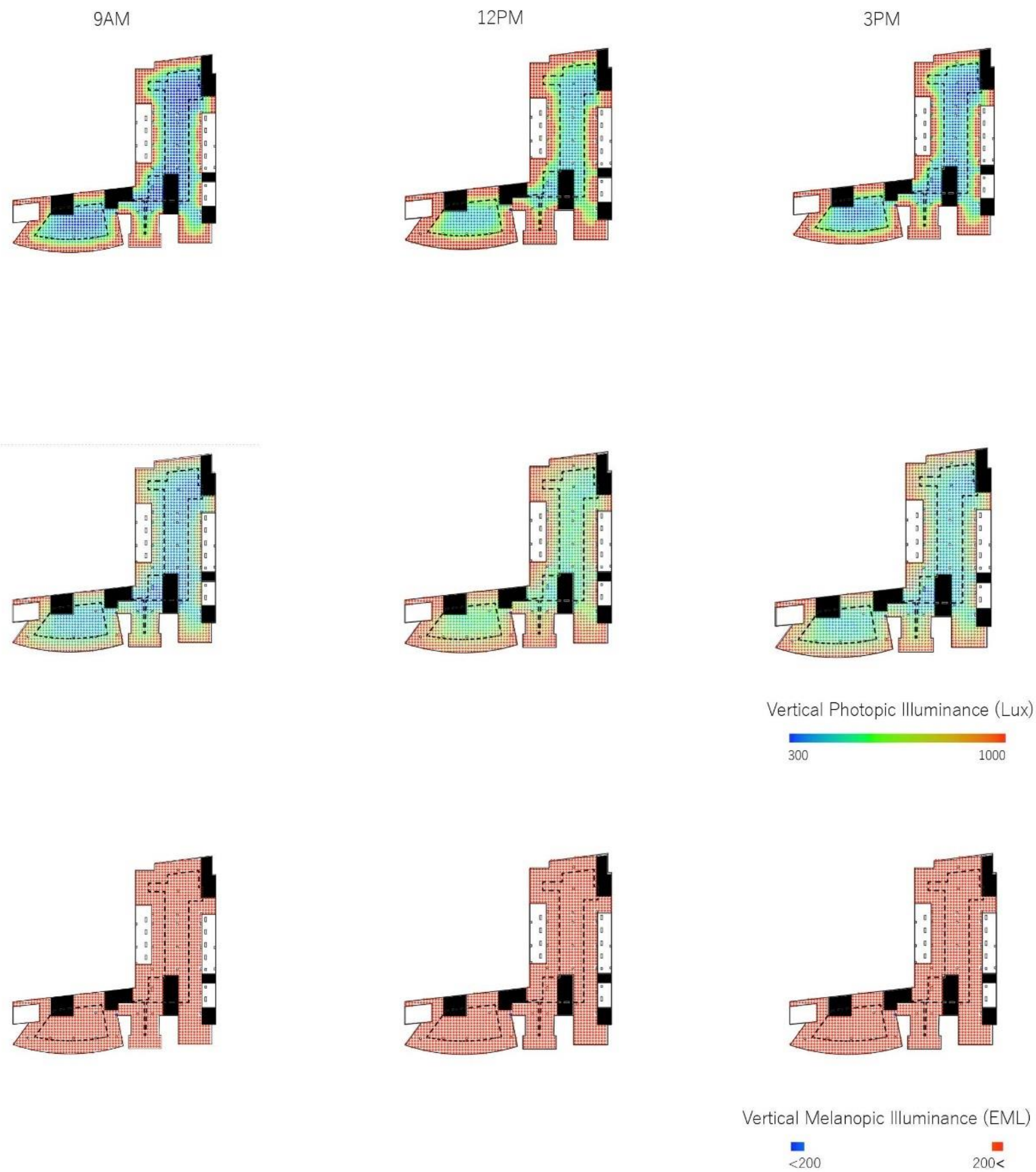
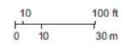


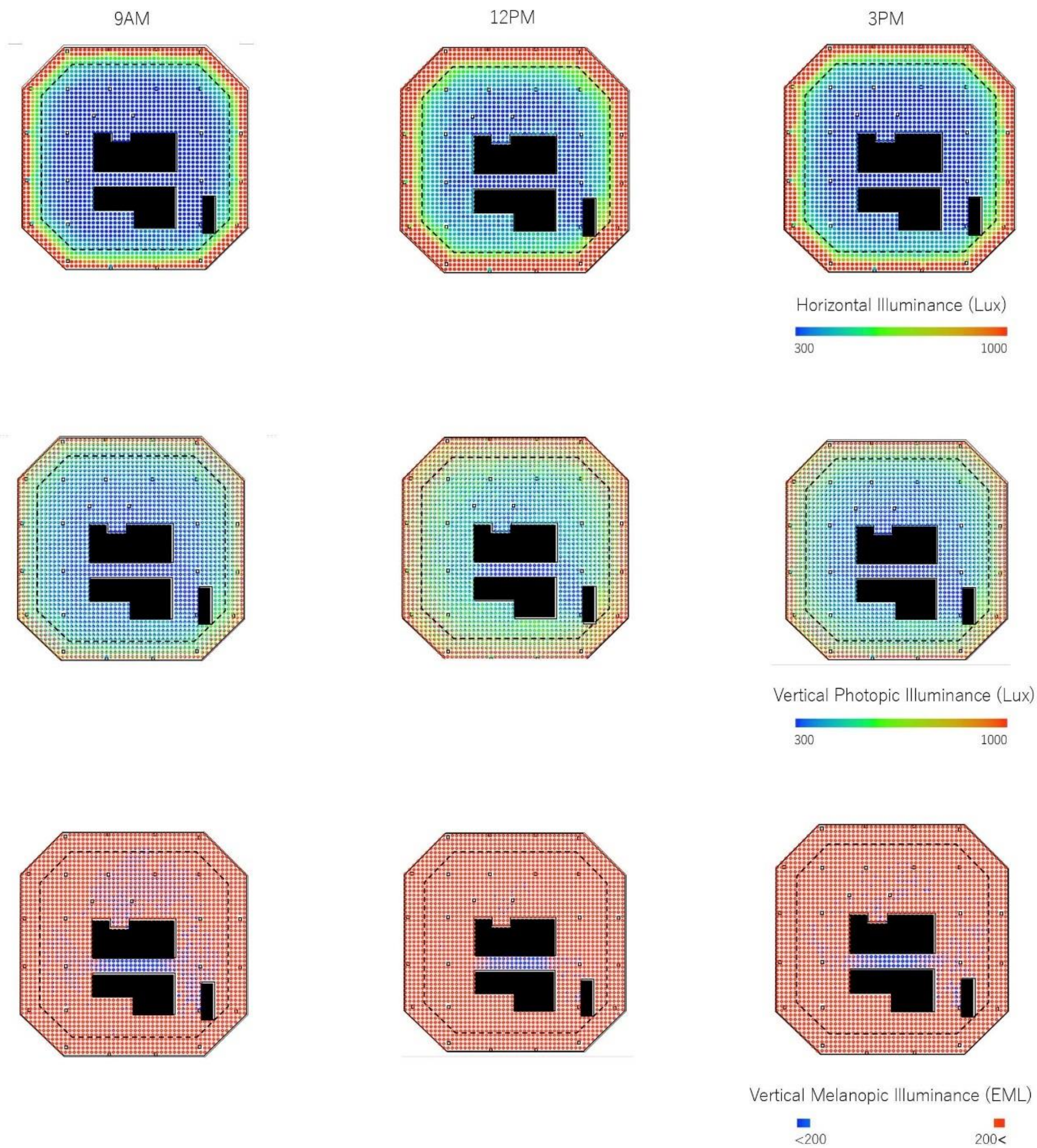
#11: Chiat/Day Advertising





#12: TBWA Chiat/Day





#13: Citicorp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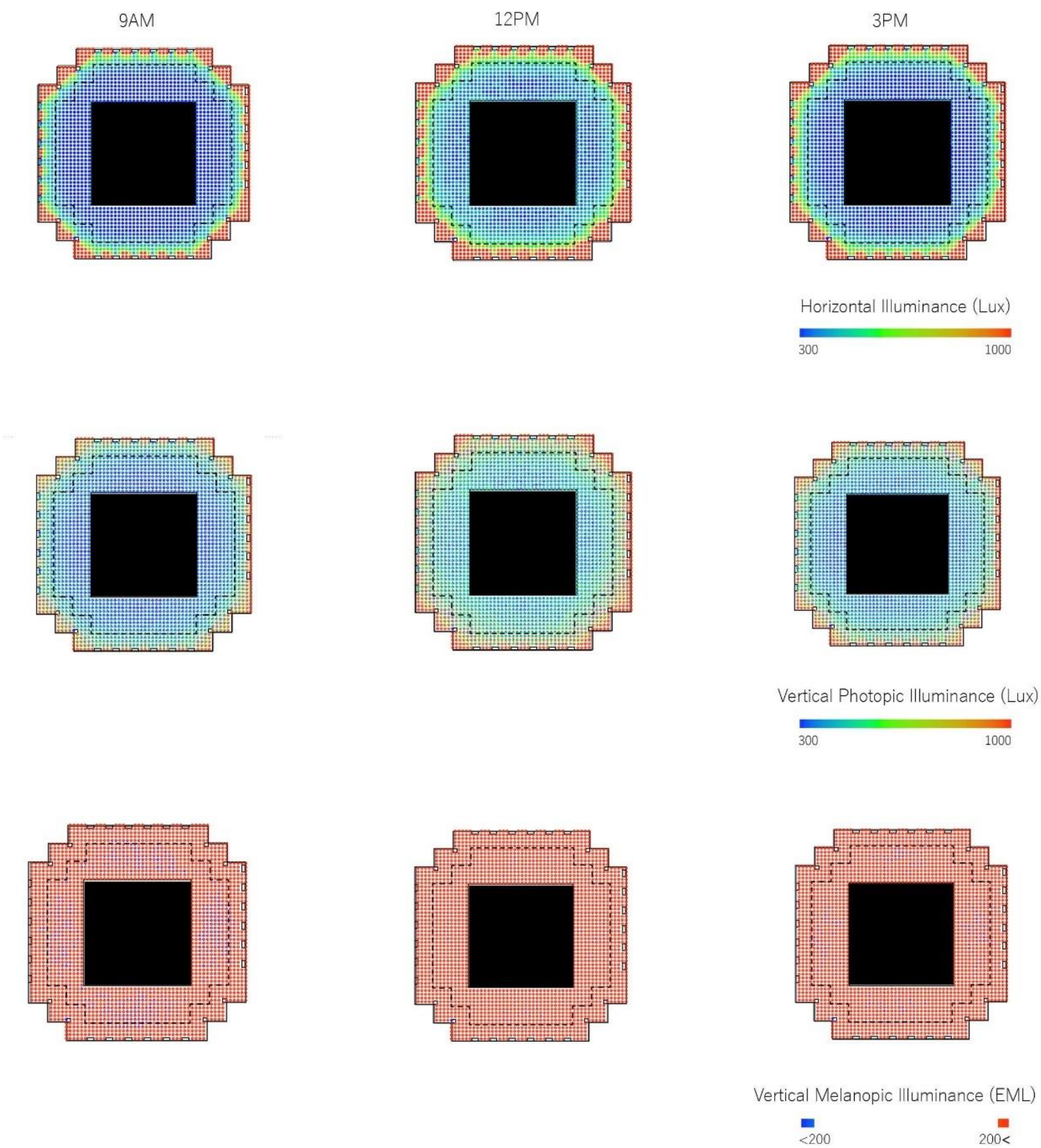
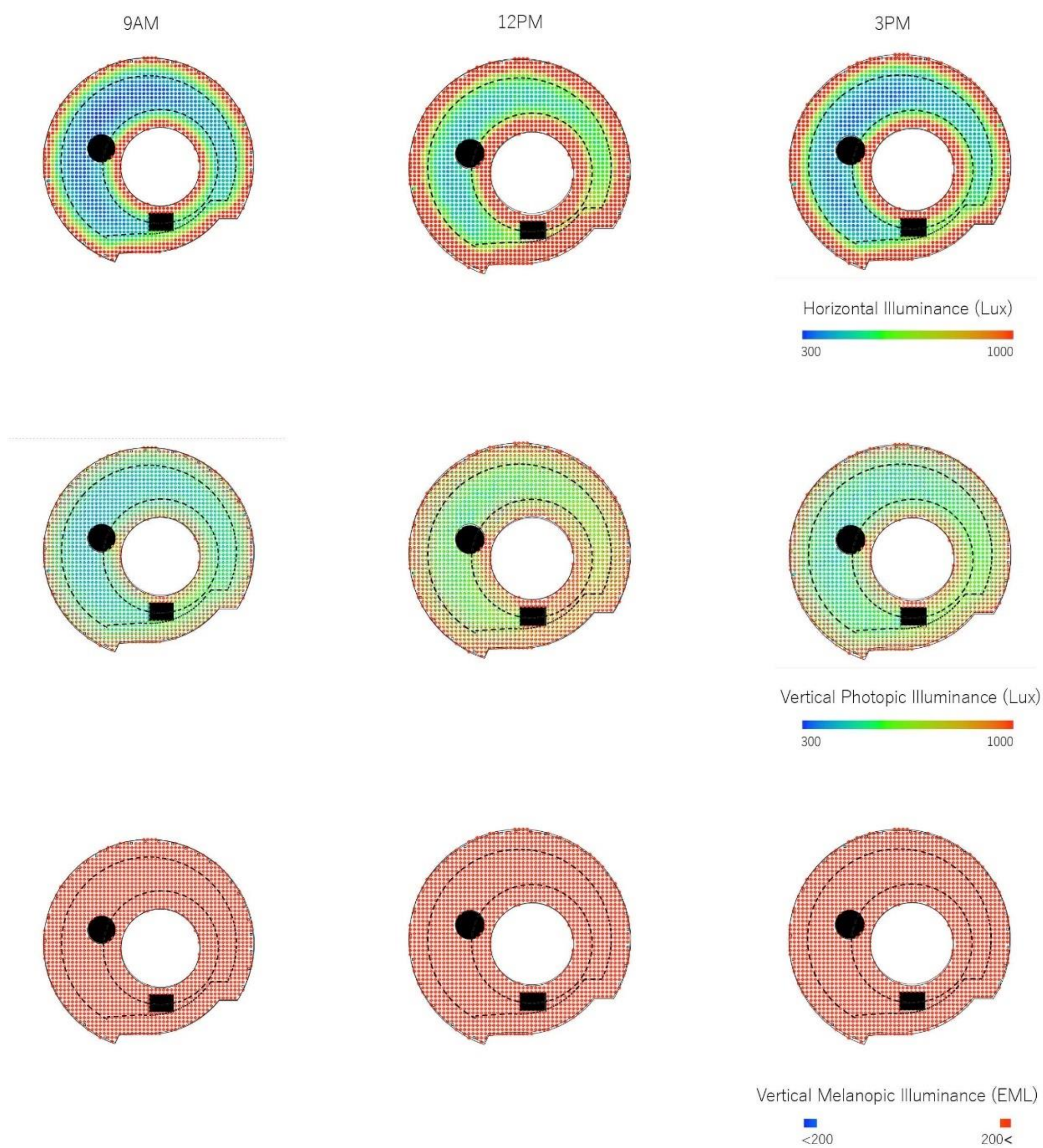
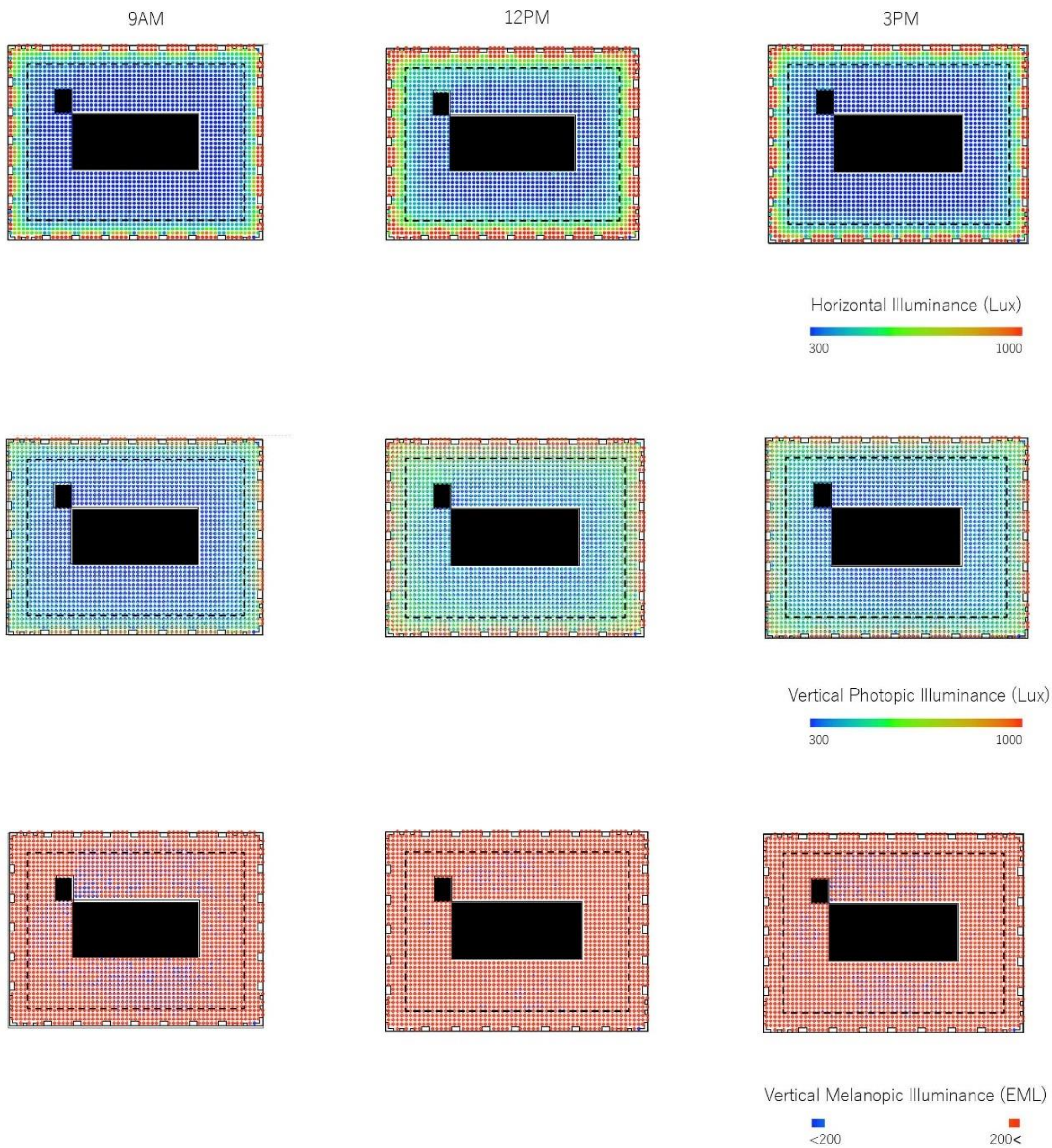
30 m


9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

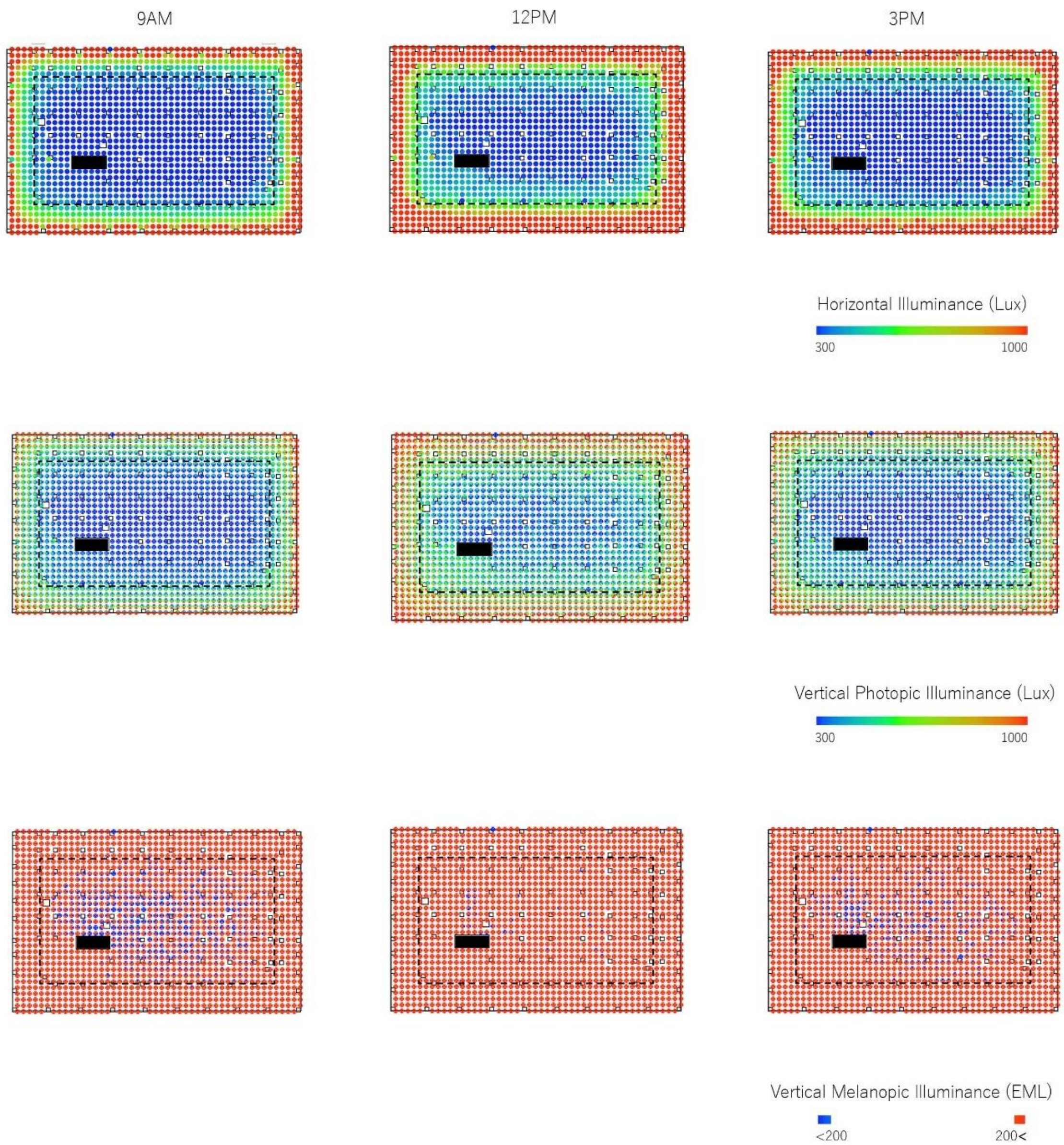
#15: Data Firmengruppe



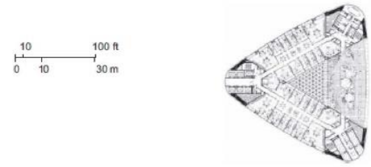
#16: Davis Polk & Wardwell



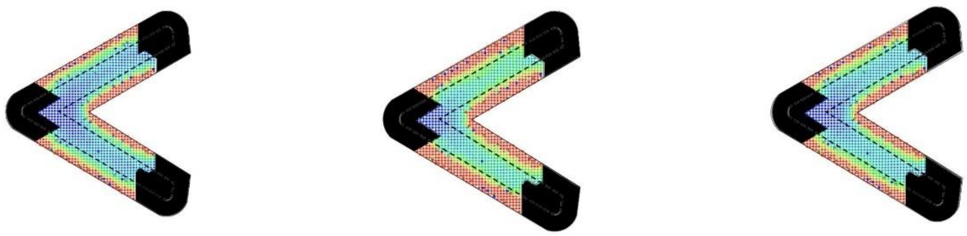
#17: DEGW London Office



#14: Commerzbank AG

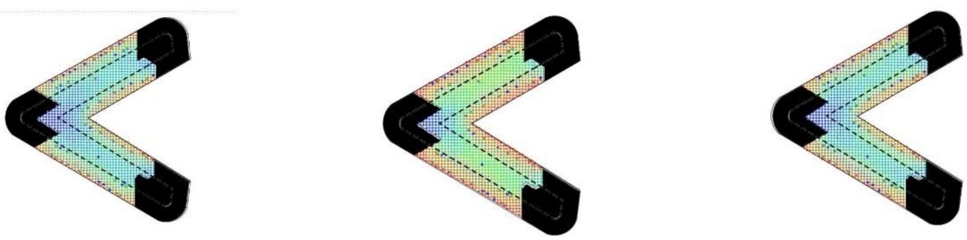


9AM | 12PM | 3PM



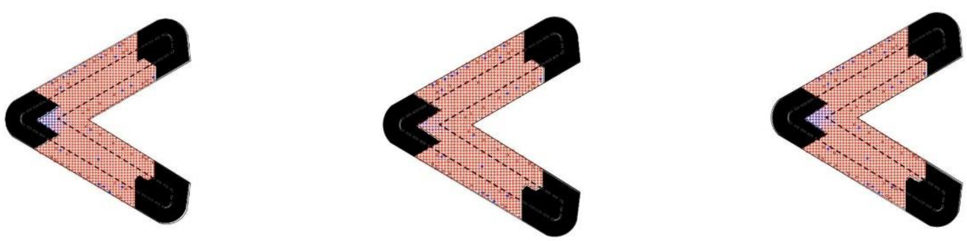
Horizontal Illuminance (Lux)

300 — 1000



Vertical Photopic Illuminance (Lux)

300 — 1000



Vertical Melanopic Illuminance (EML)

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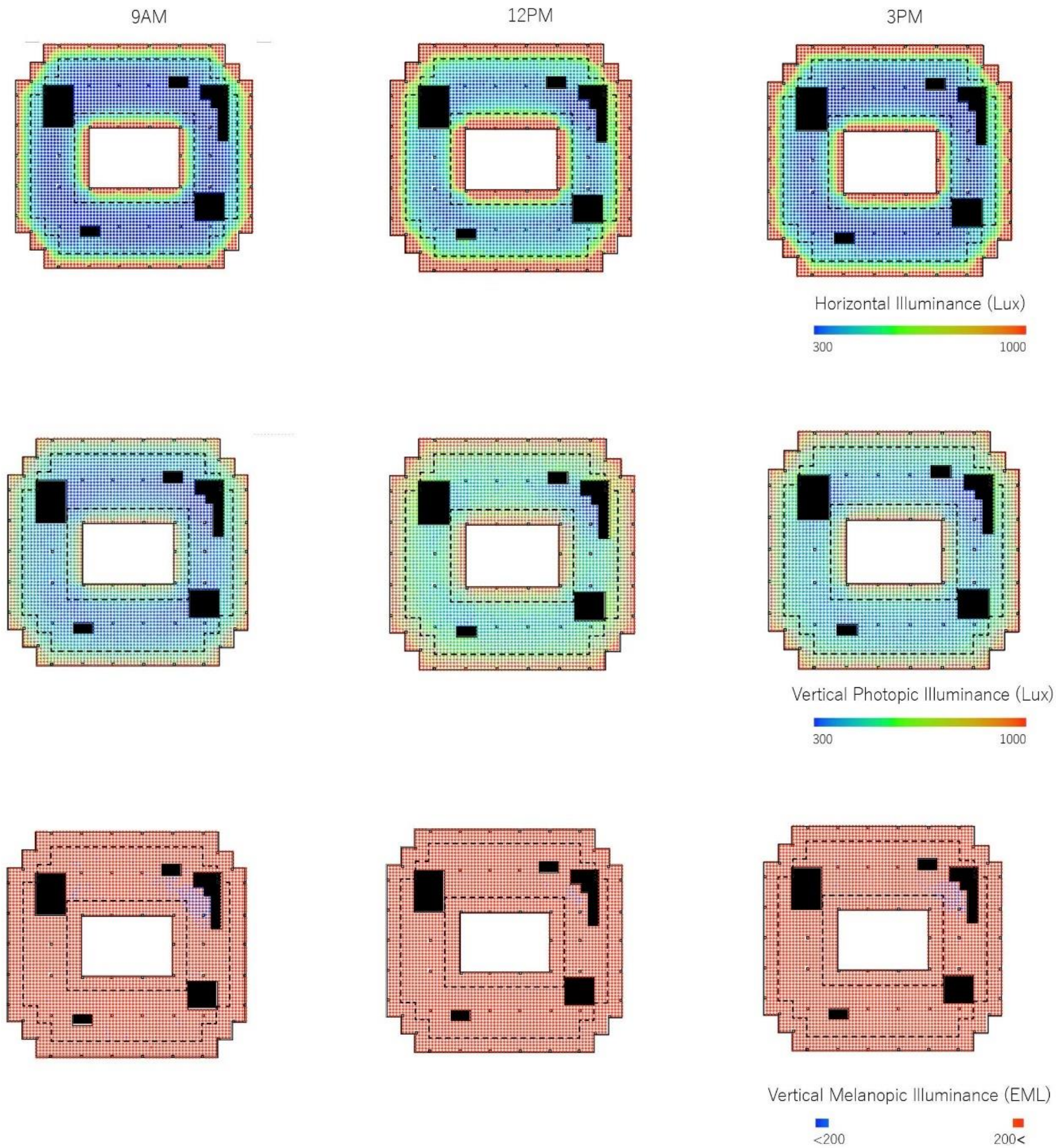
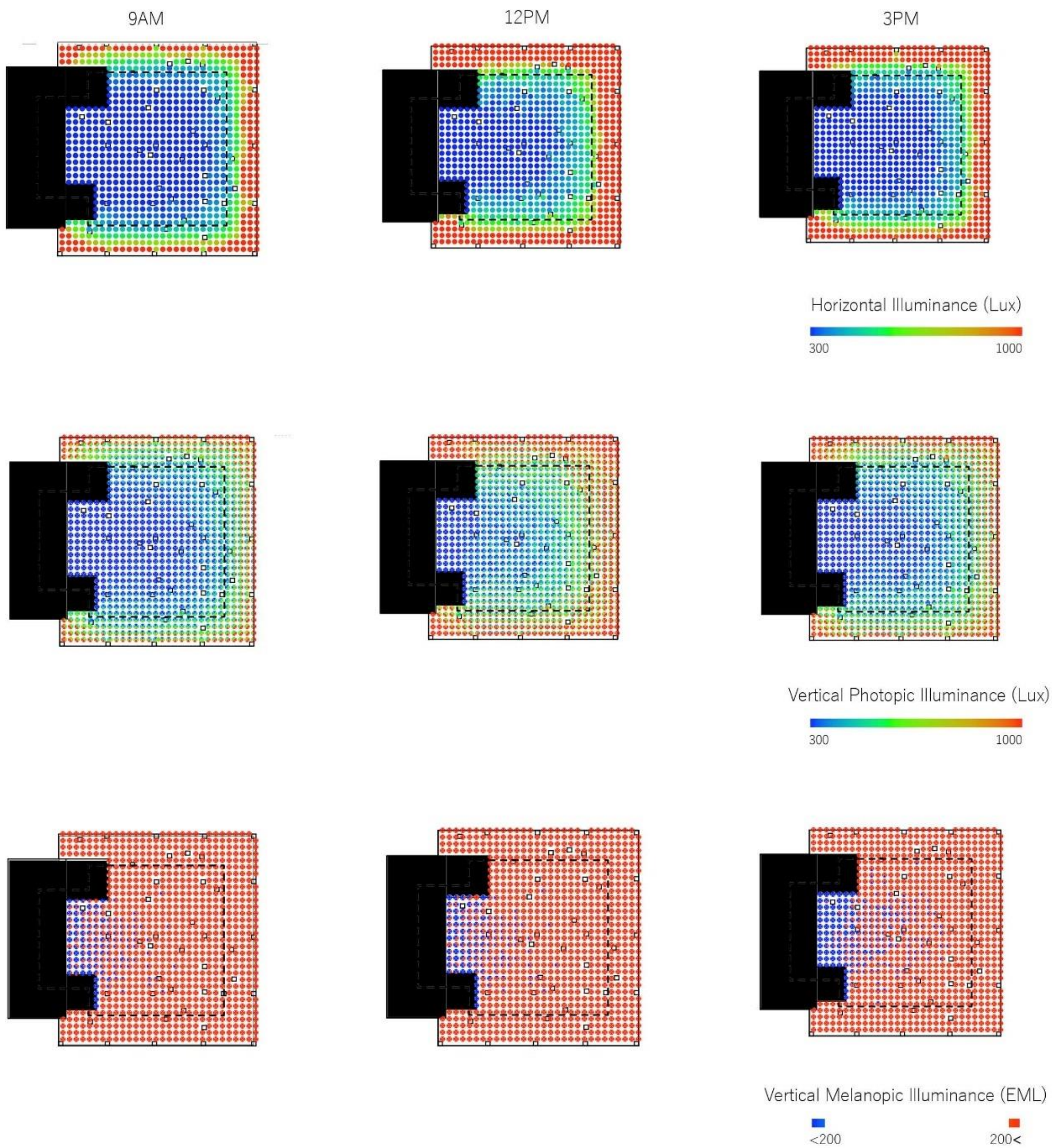
#18: Discovery Channel Latin Am.



#19: DuPont


10
100 ft
0
10
30 m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3PM
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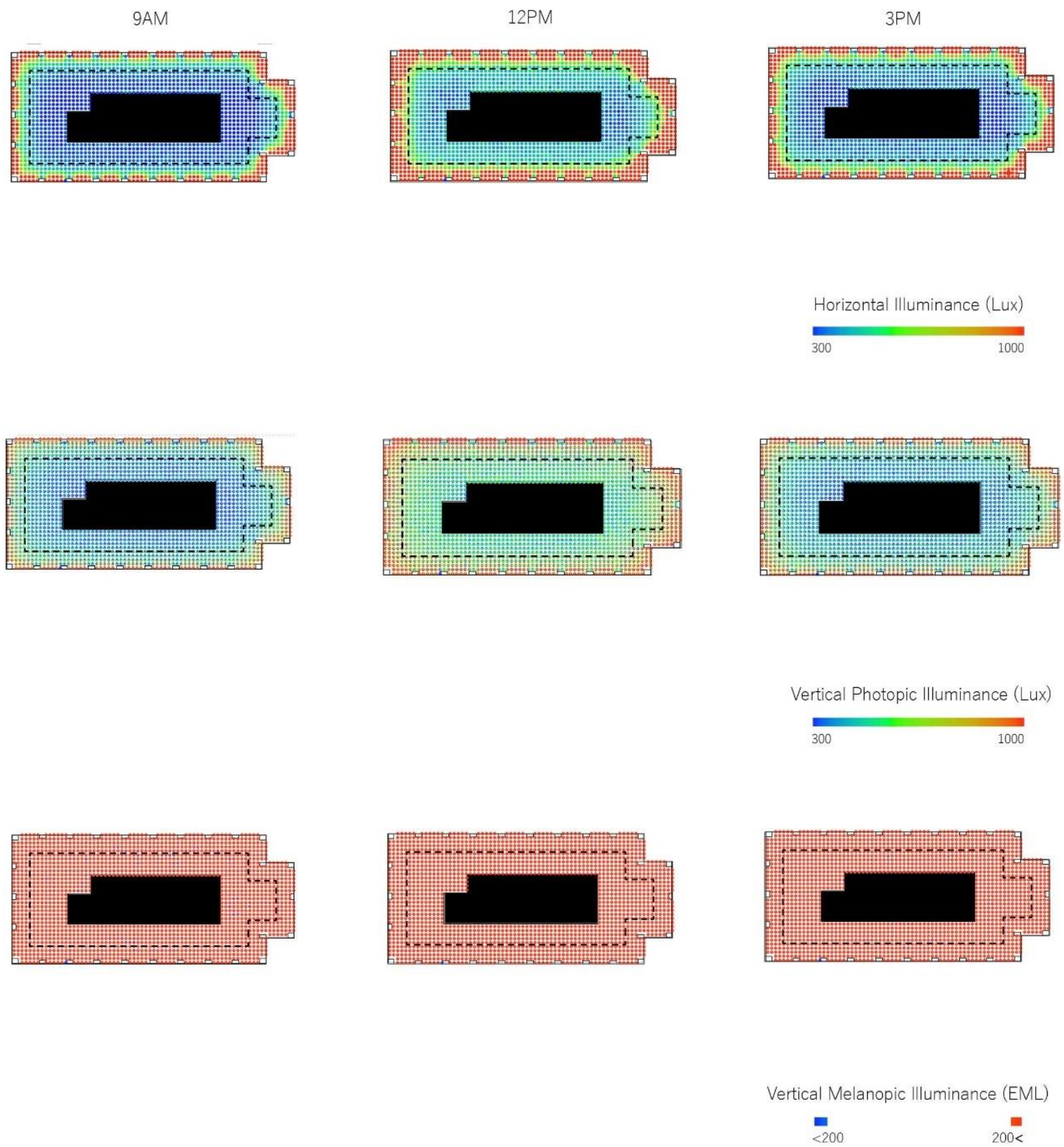
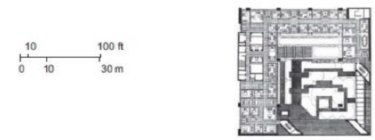
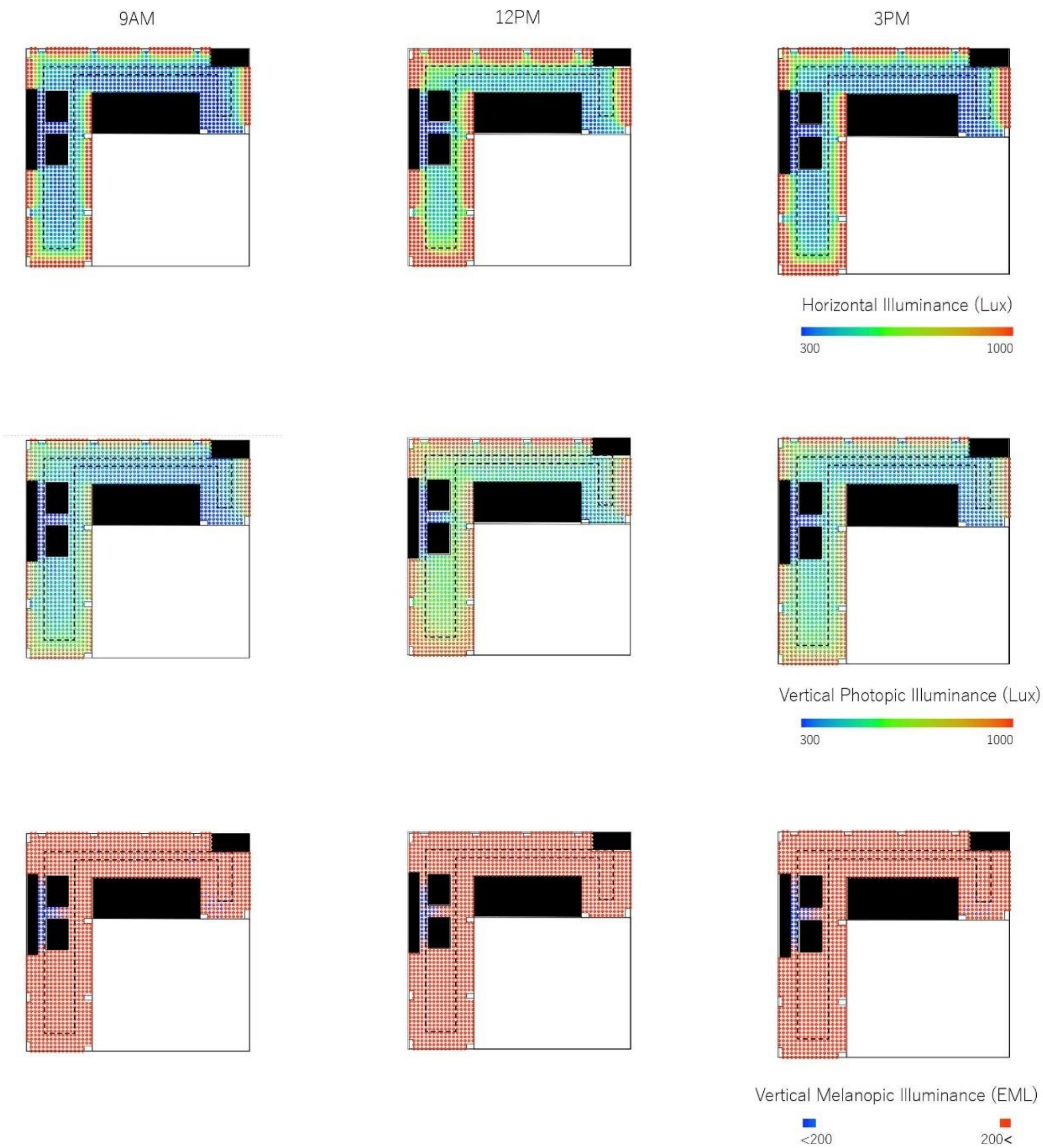
1000
Vertical Melanopic Illuminance (EML)
<200
200<

#20: The Equitable

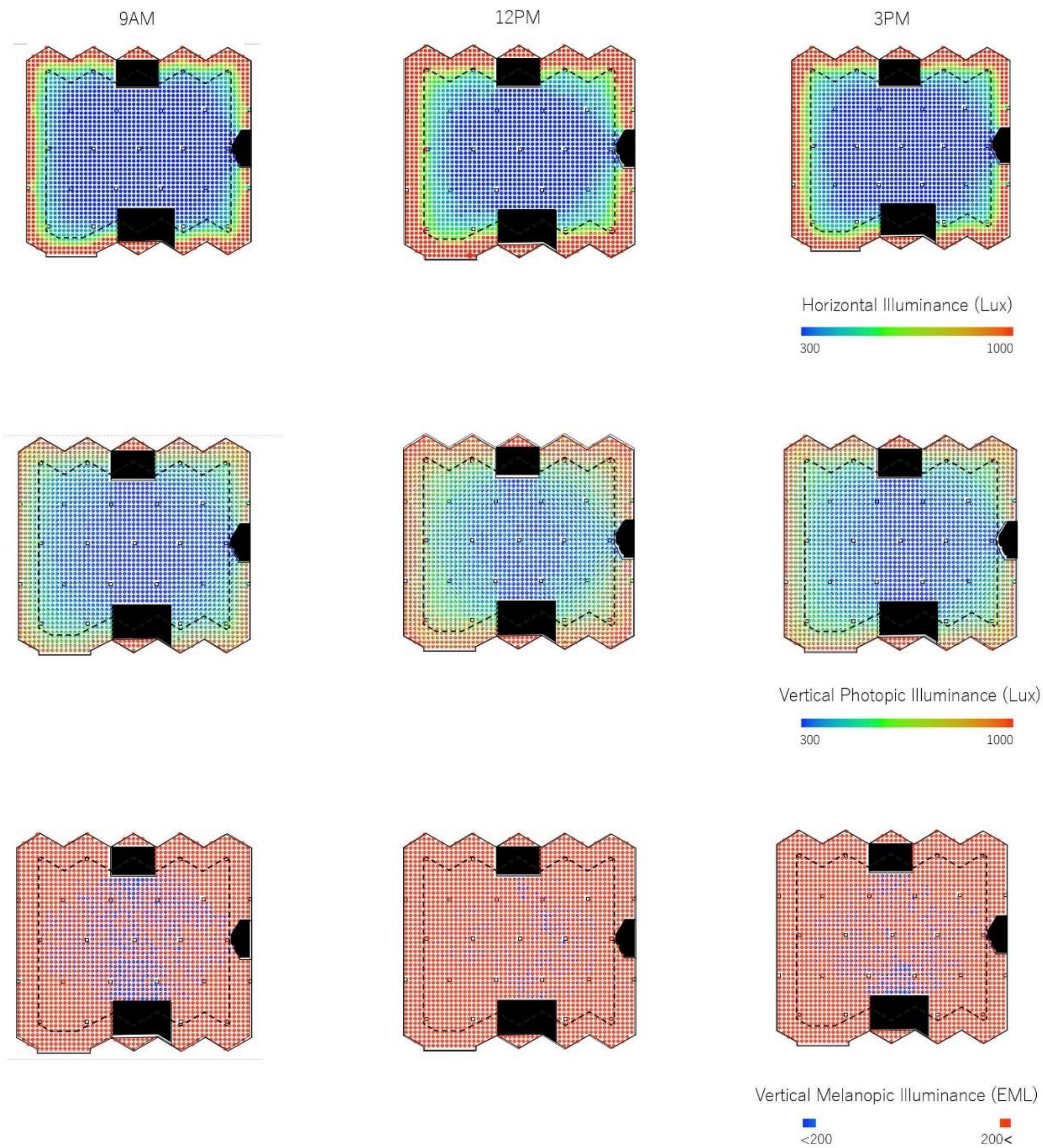


#21: Ford Foundation





#22: Ford Motor Co.



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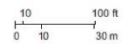
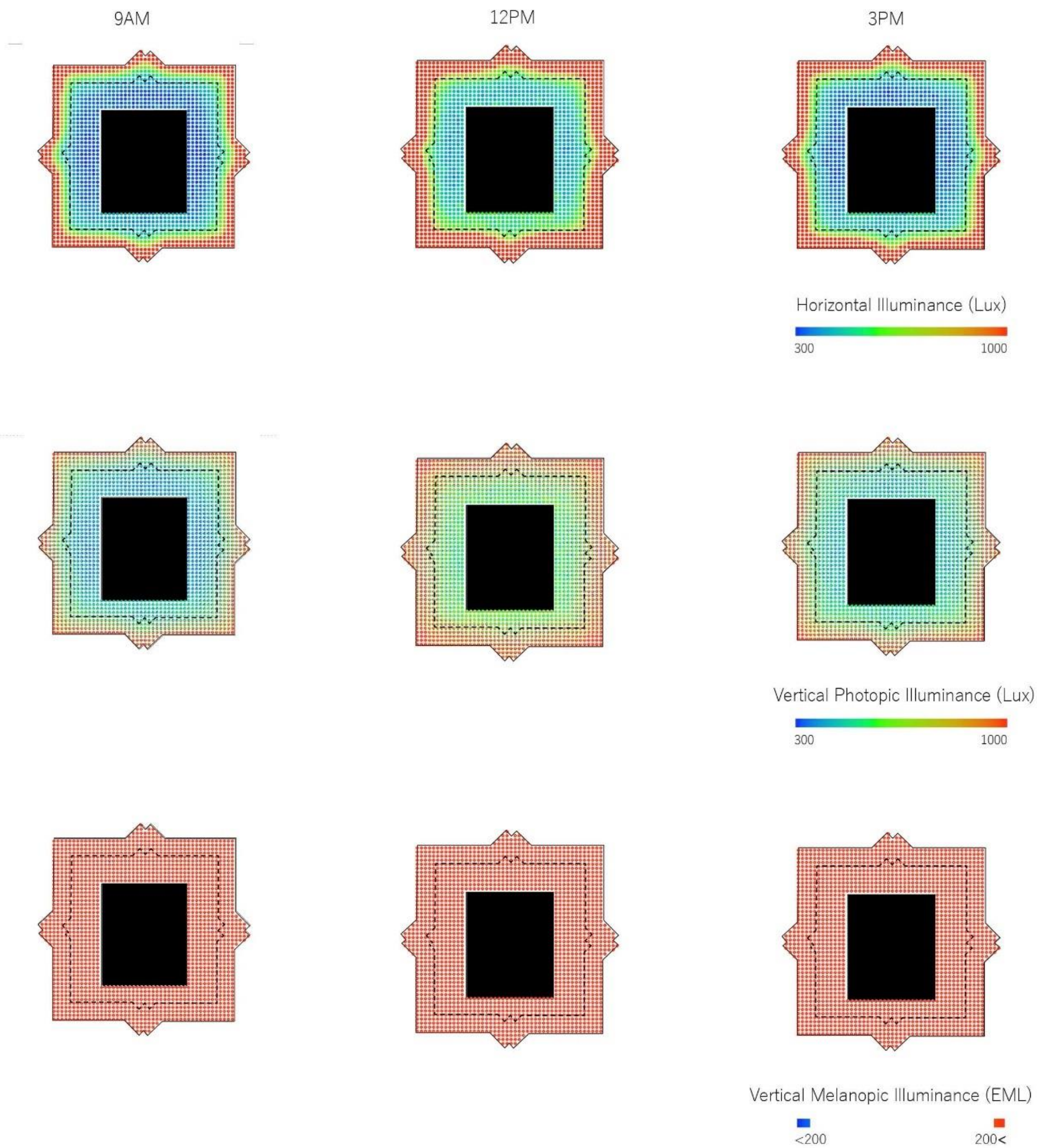
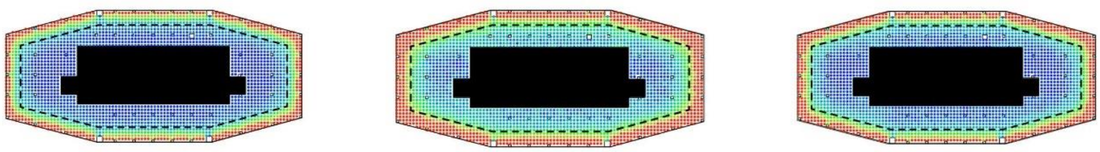




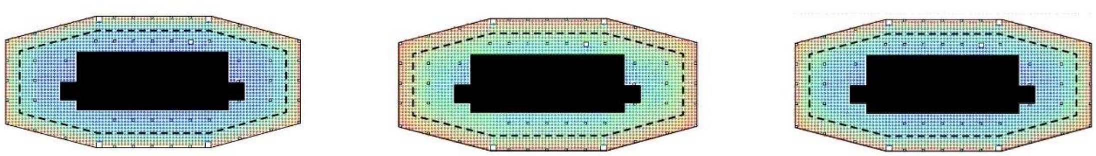
#24: Greenberg Traurig

9AM | 12PM | 3PM



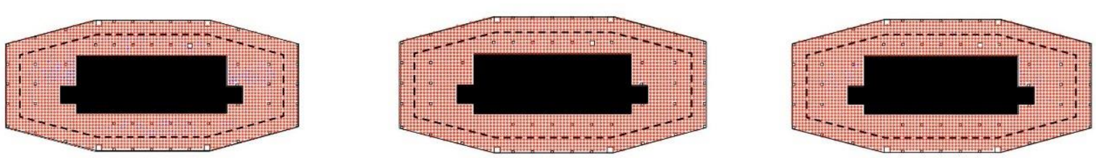
Horizontal Illuminance (Lux)

300 — 1000



Vertical Photopic Illuminance (Lux)

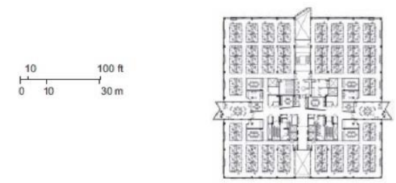
300 — 1000

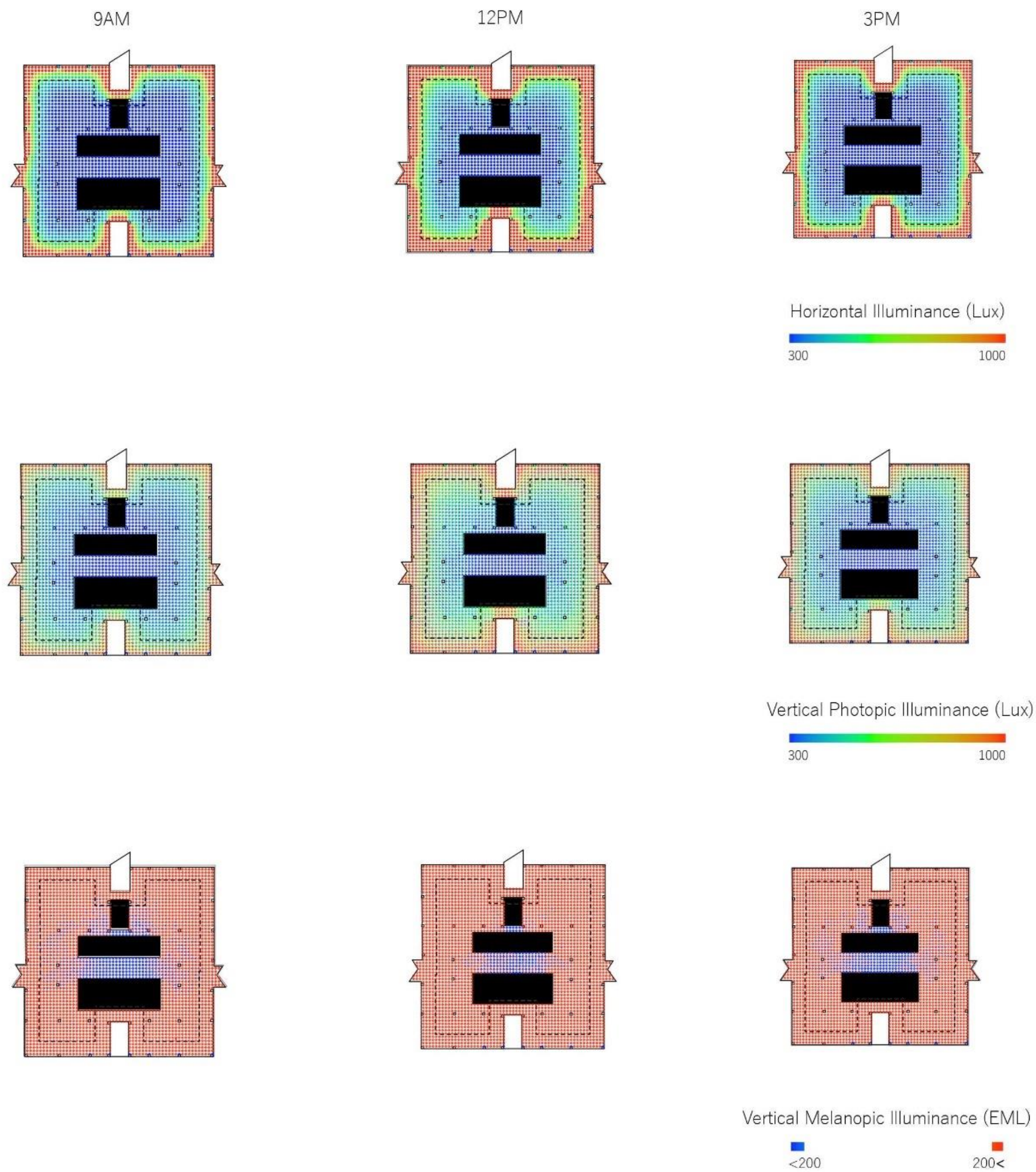


Vertical Melanopic Illuminance (EML)

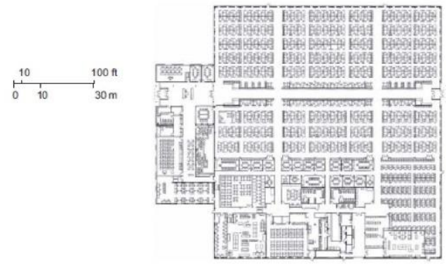
<200 — 200<

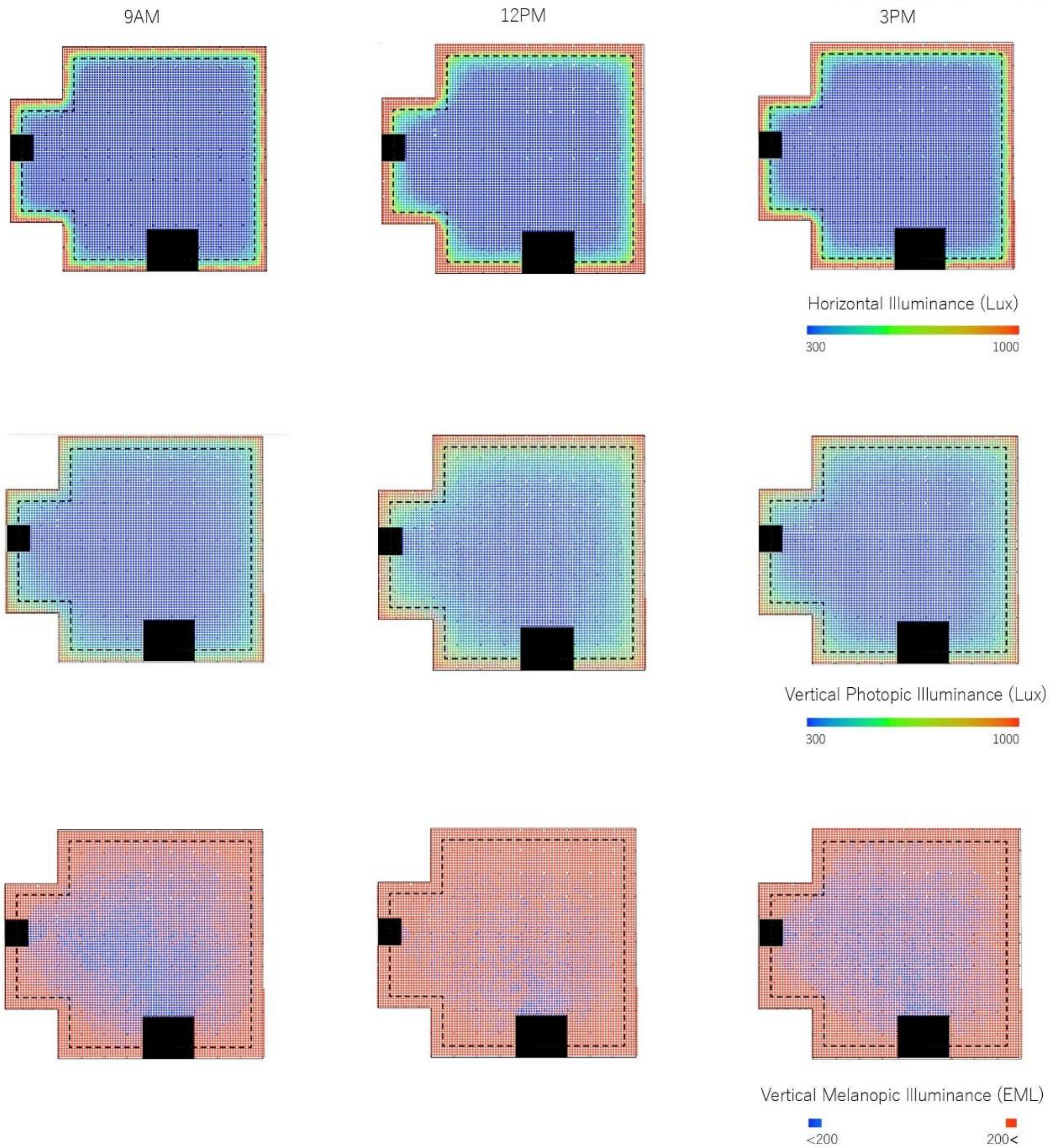
#25: Hoffmann La Roche



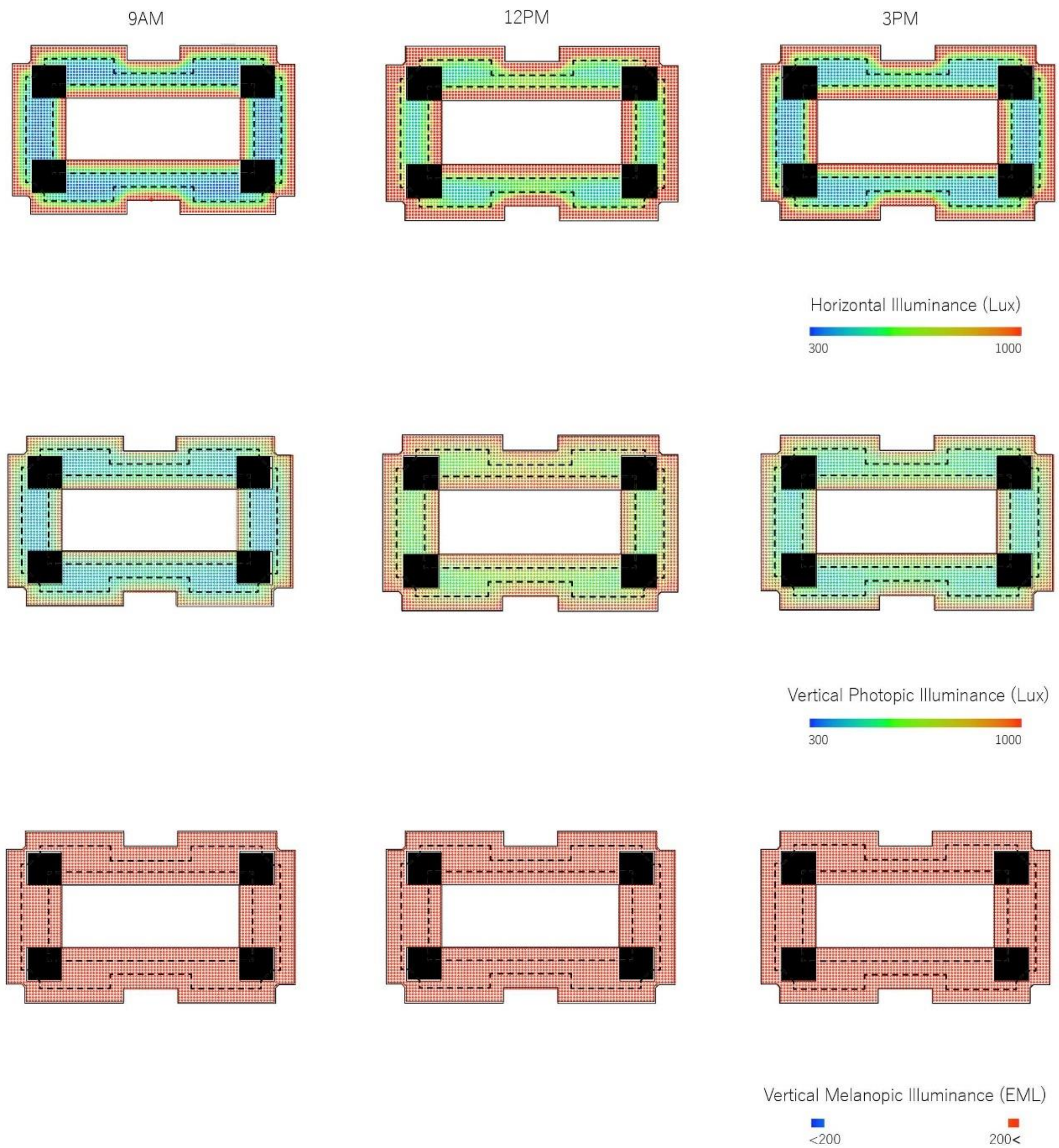


#26: IBM Regional Headquarters

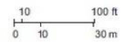


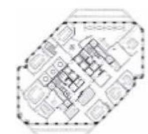


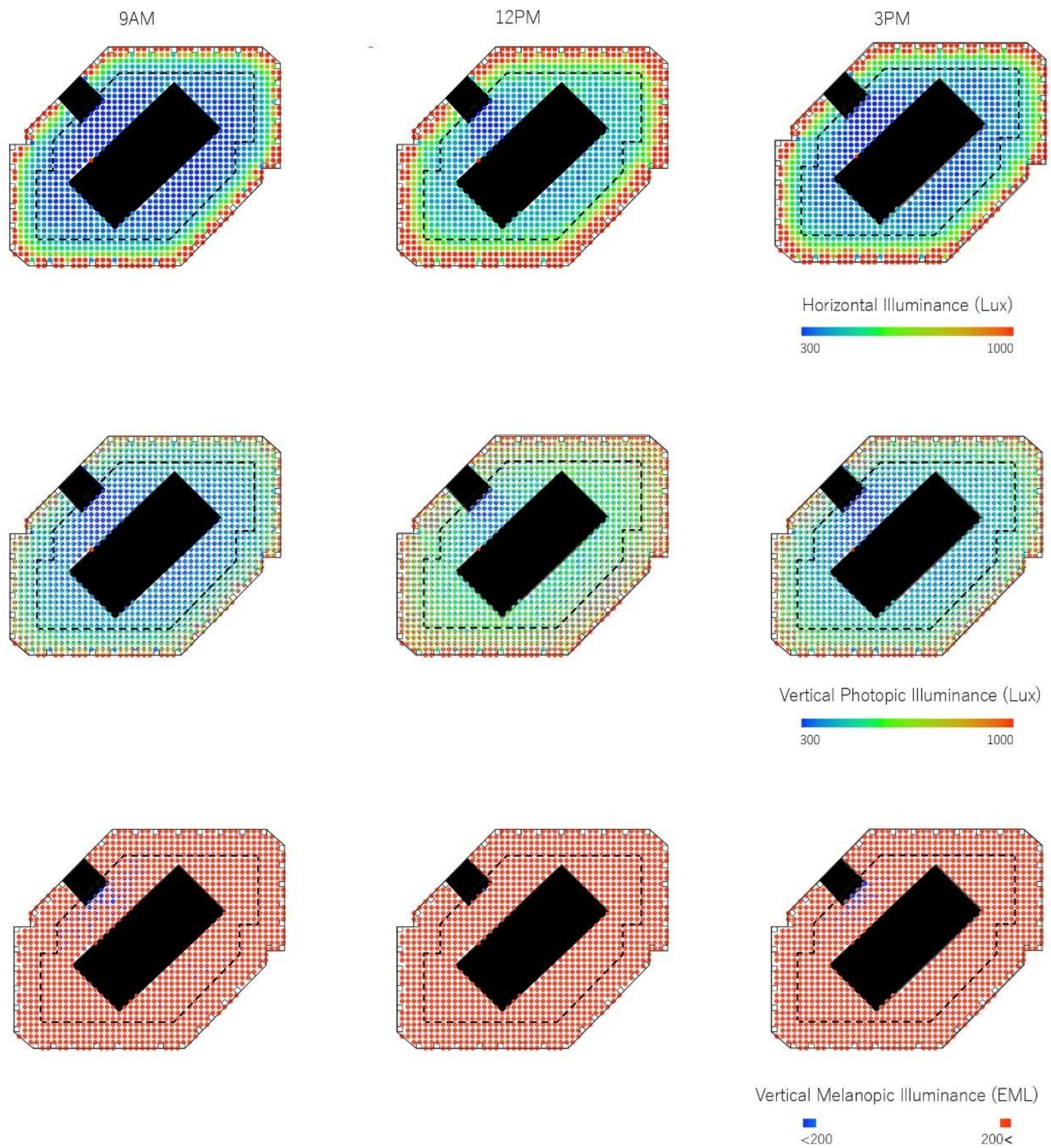
#27: IBM (UK) Limited



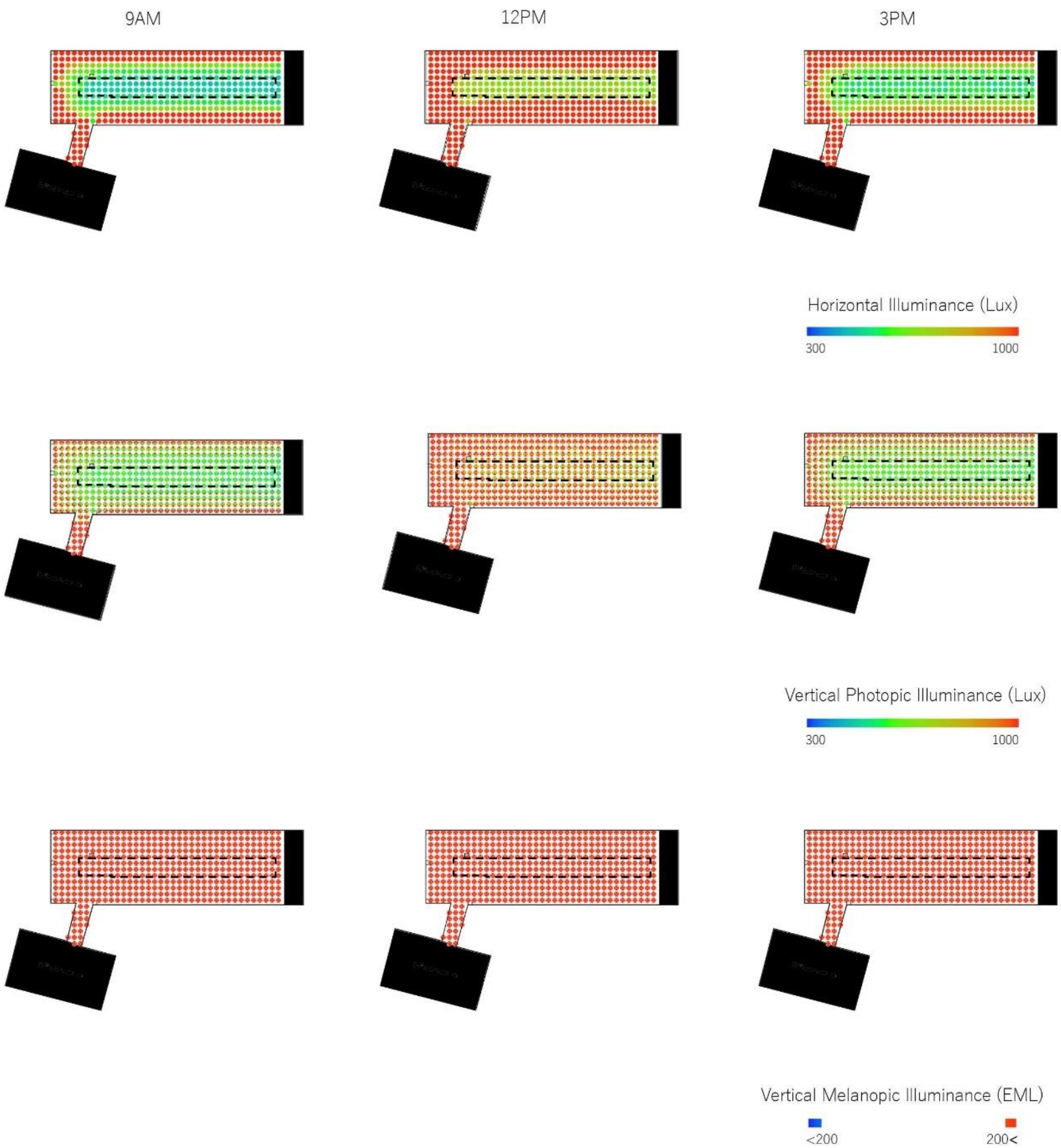
#28: IBM Australia



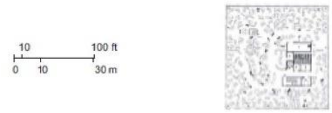


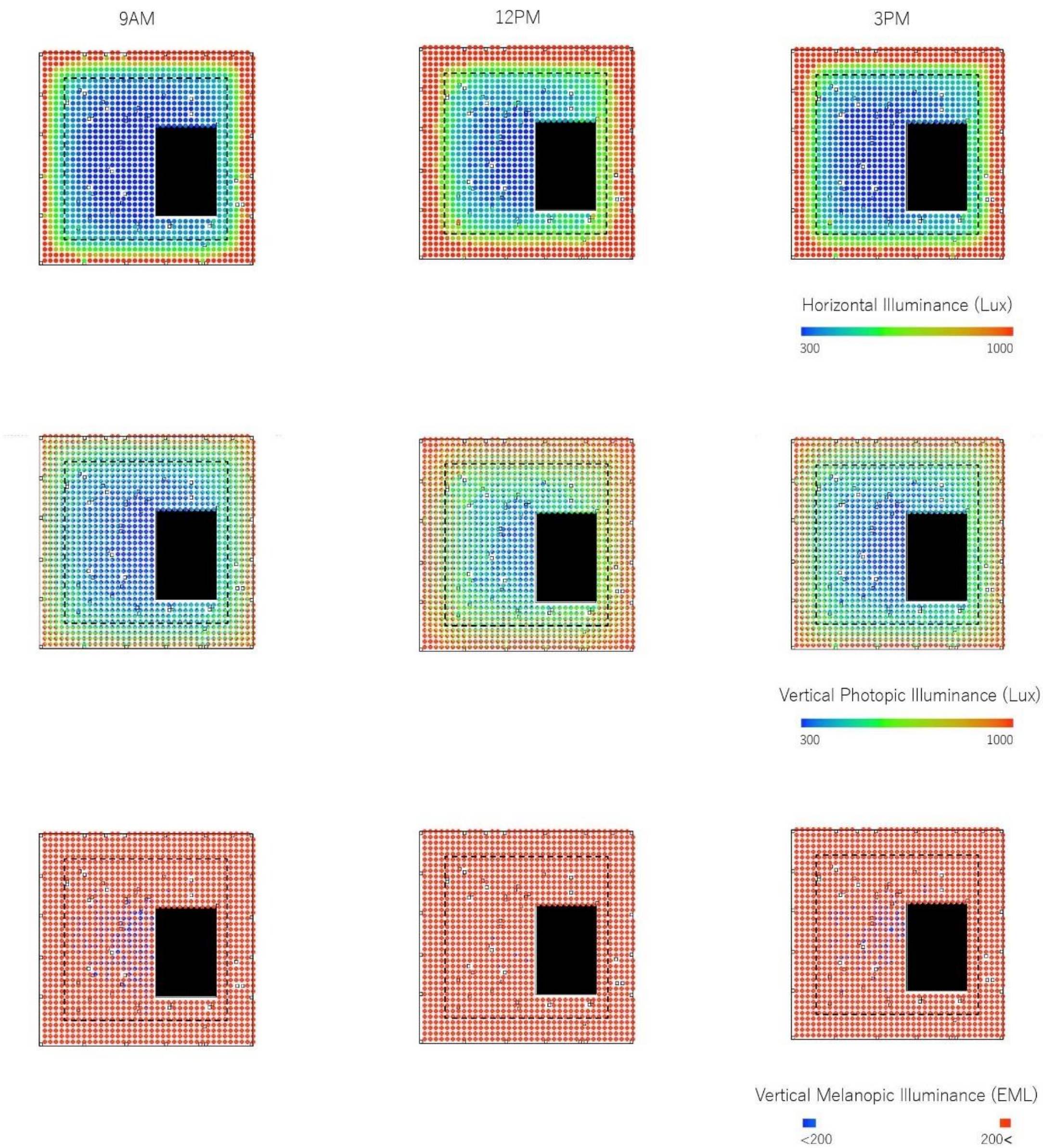


#29: Interpolis



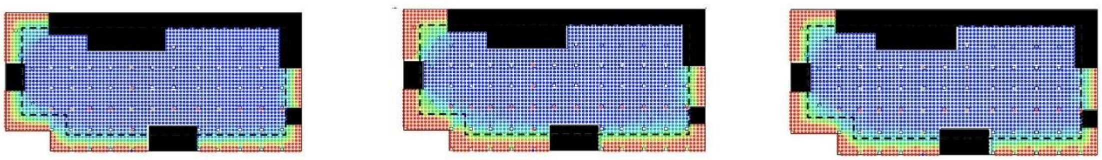
#30: Direct. of Telecom., MPBW





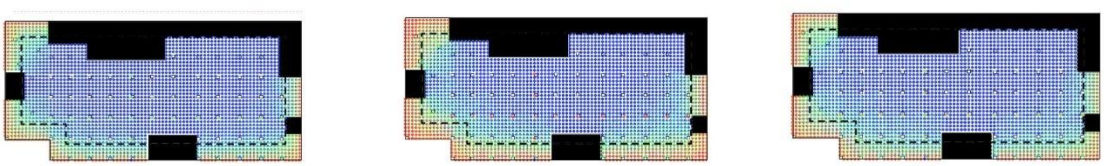
#31: Eastman Kodak

9AM | 12PM | 3PM



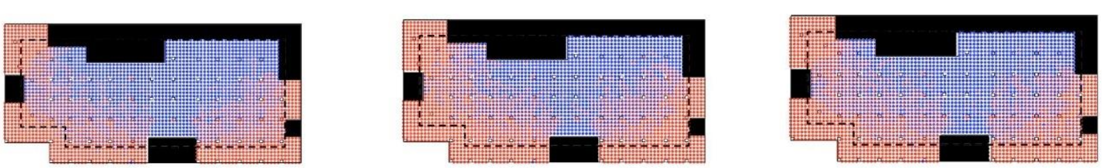
Horizontal Illuminance (Lux)

300 1000



Vertical Photopic Illuminance (Lux)

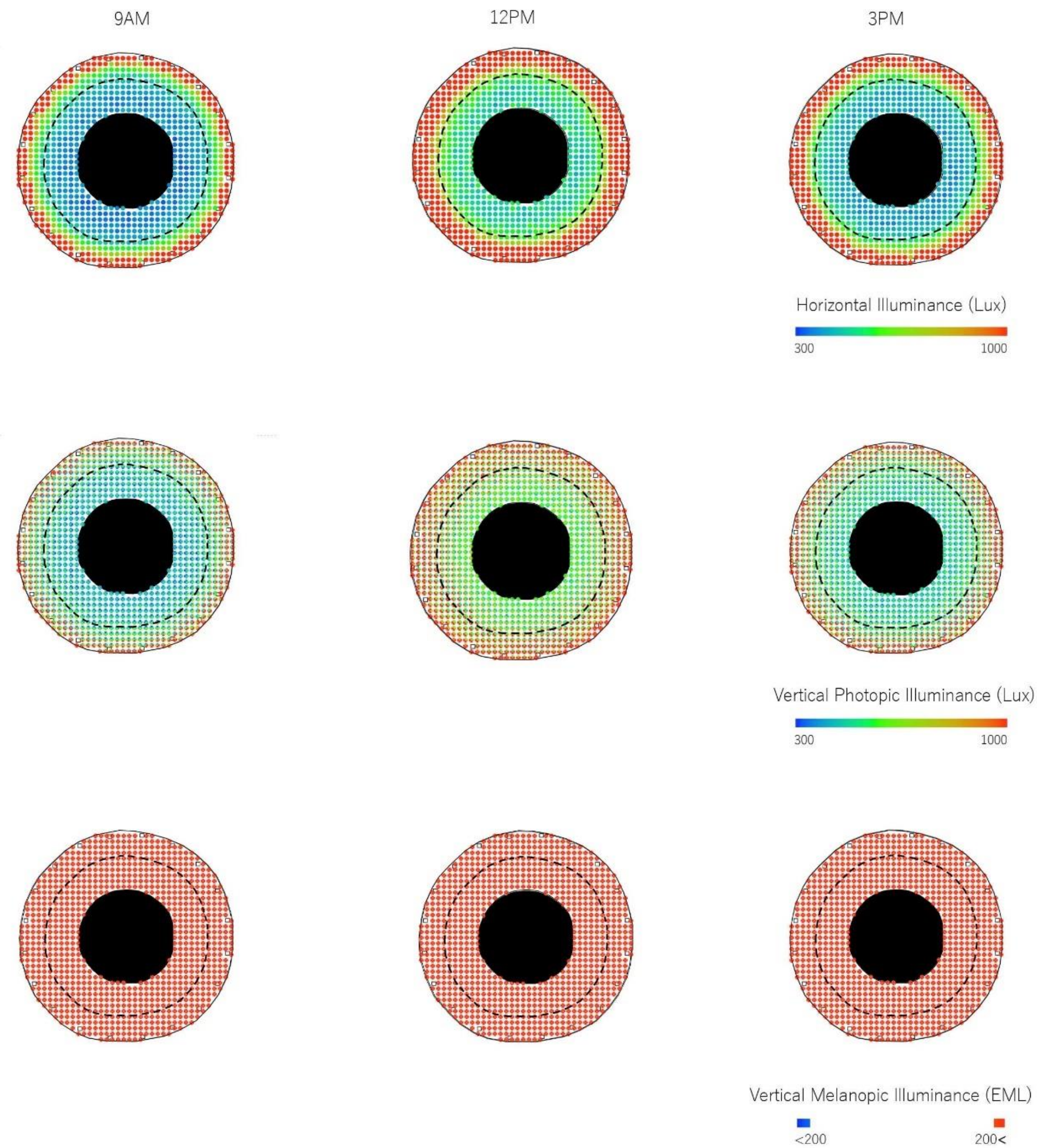
300 1000



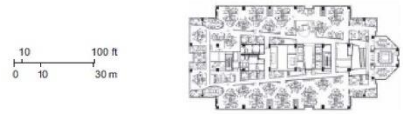
Vertical Melanopic Illuminance (EML)

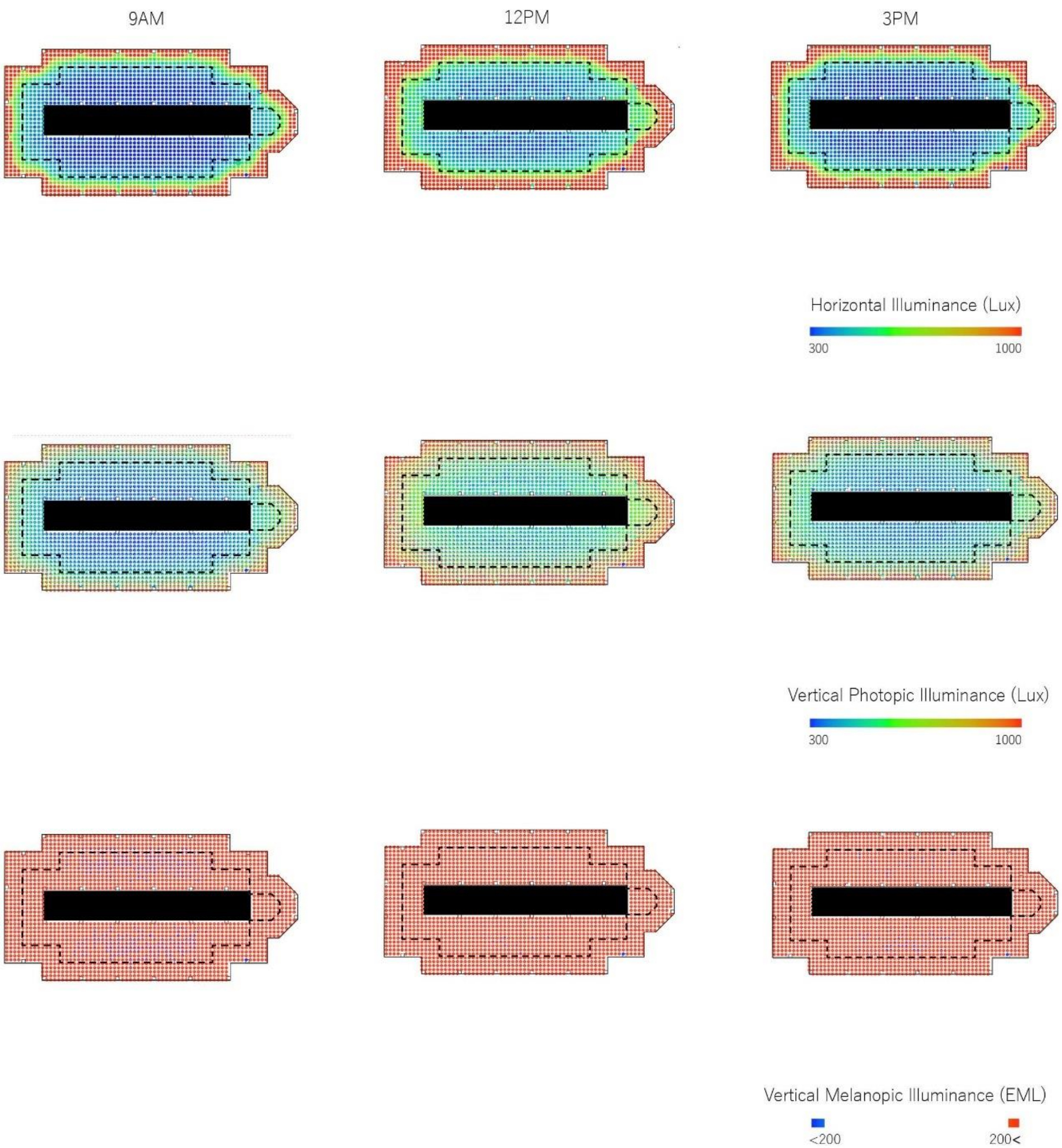
<200 200<

#32: Lend Lease Interiors



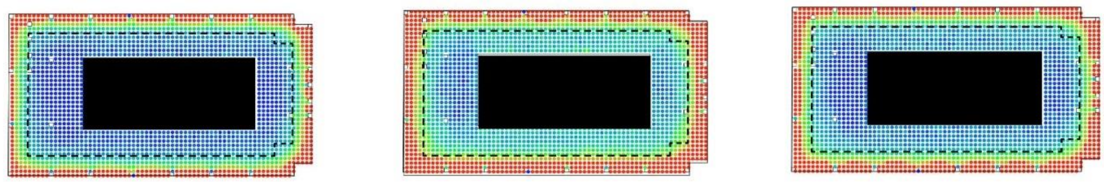
#33: Leo A Daly


10
100 ft
0 10
30 m


9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

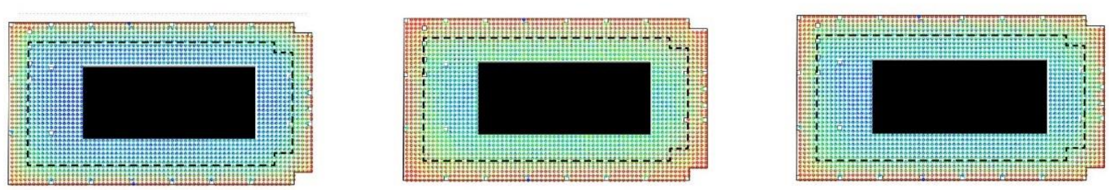
#34: Lowe & Partners/SMS

9AM 12PM 3PM



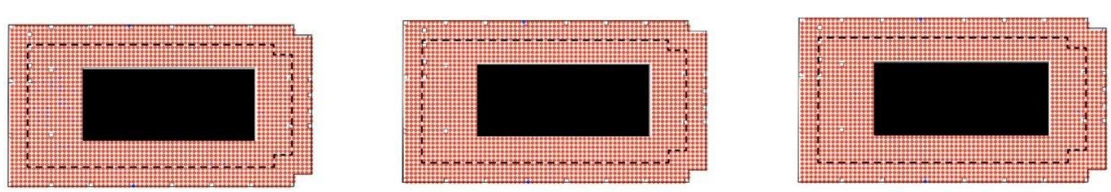
Horizontal Illuminance (Lux)

300 1000



Vertical Photopic Illuminance (Lux)

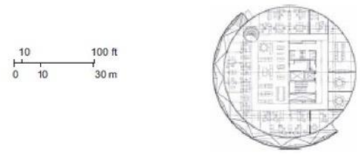
300 1000

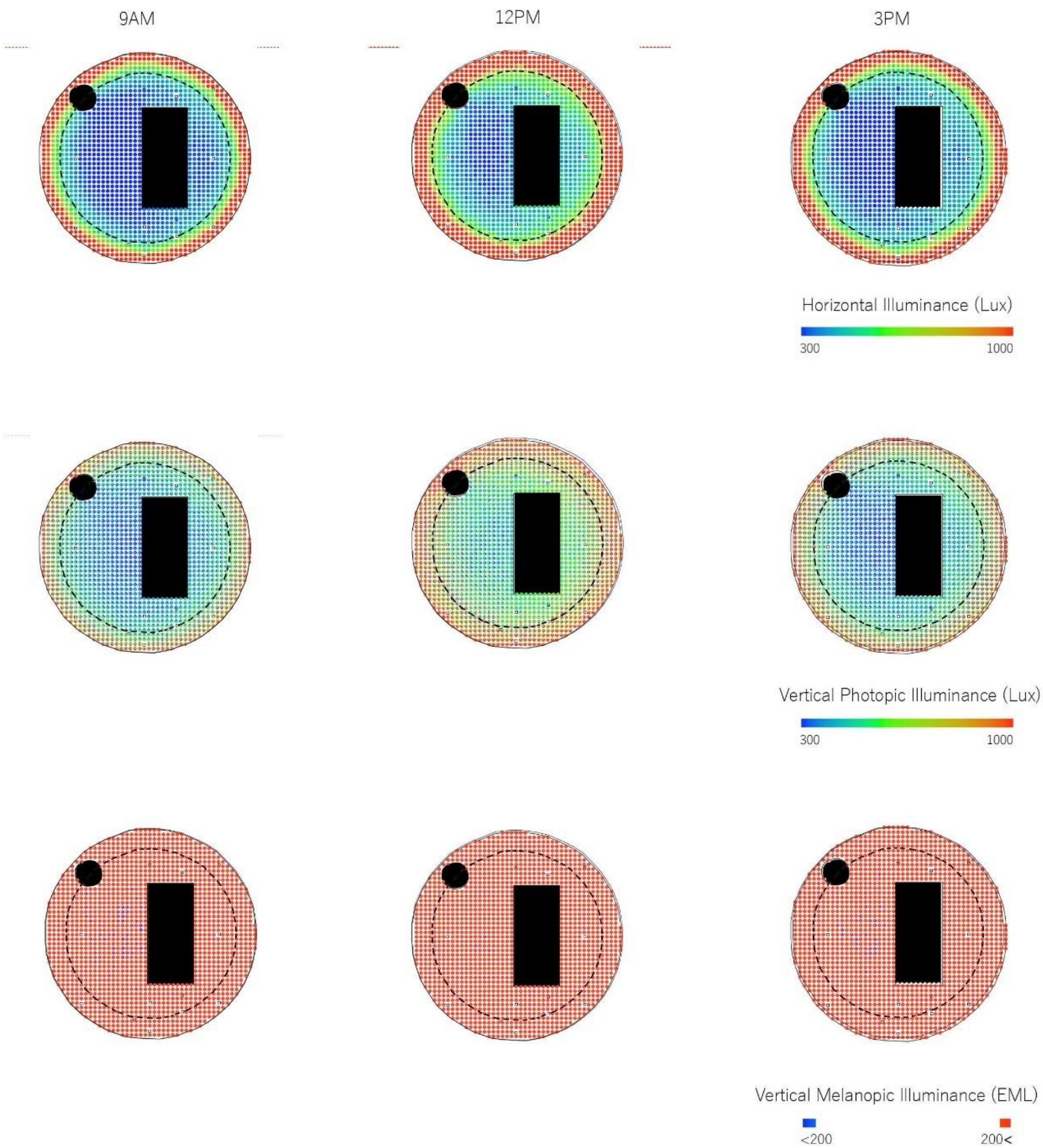


Vertical Melanopic Illuminance (EML)

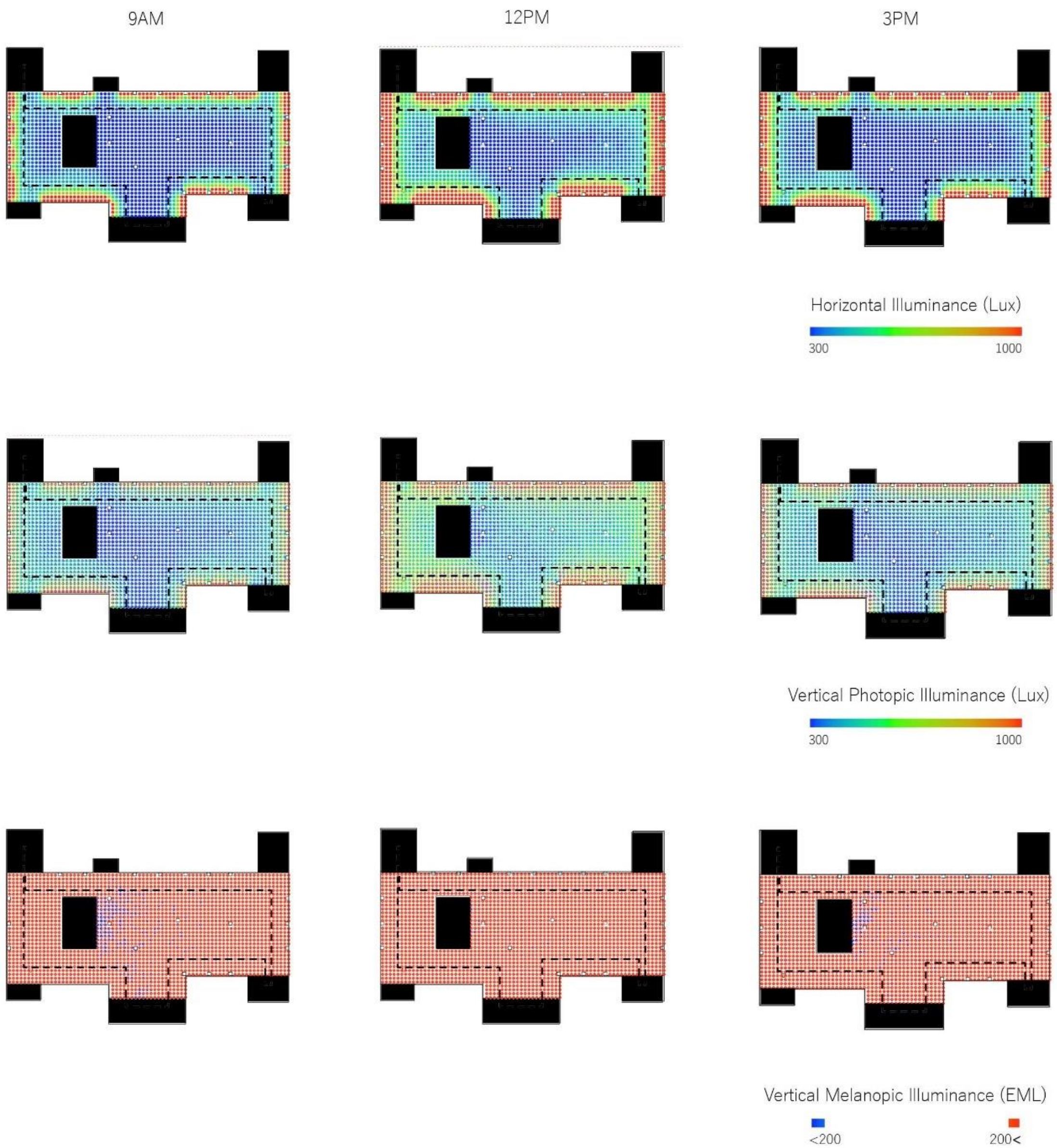
<200 200<

#35: McDonald's

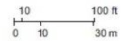


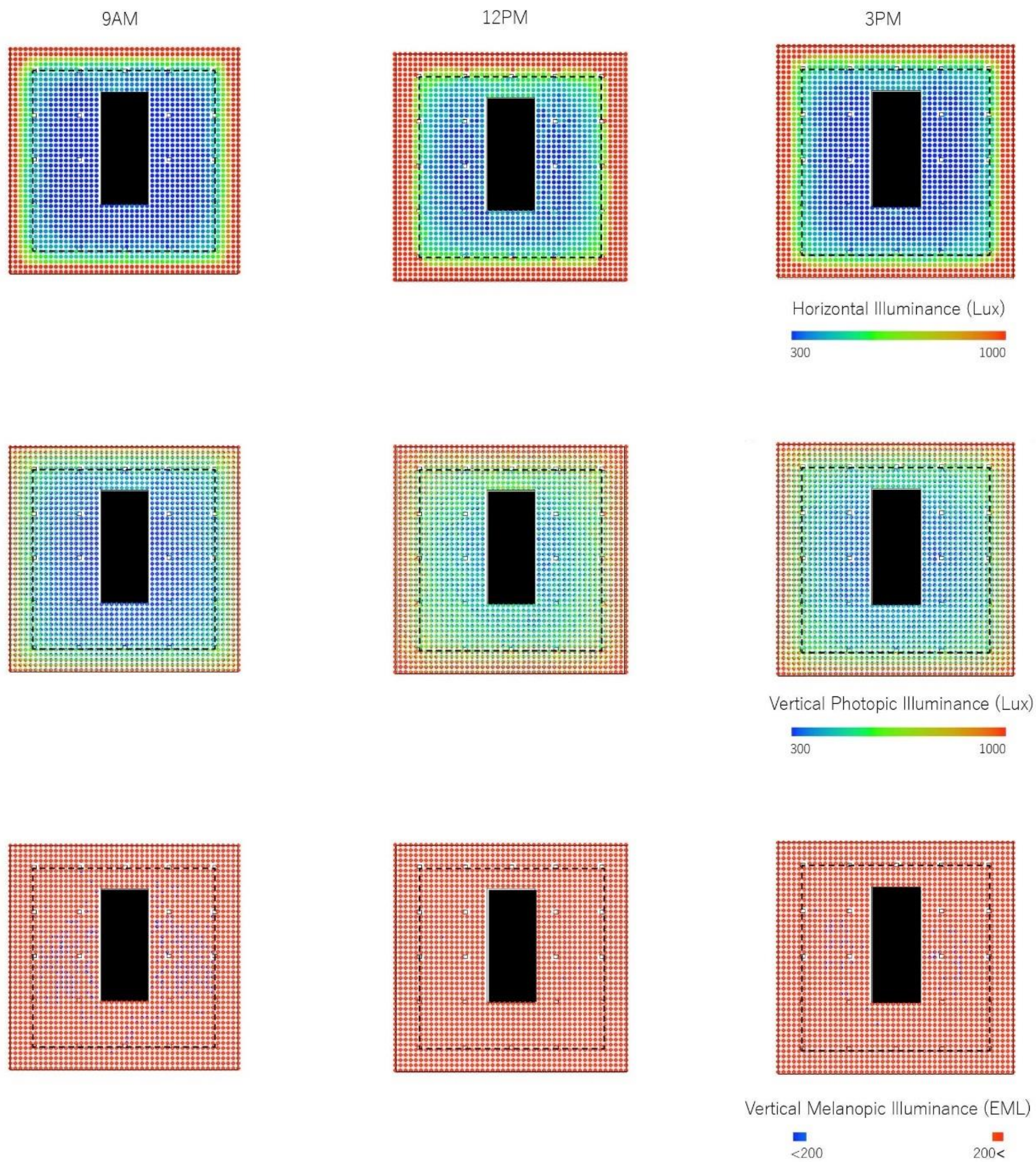


#36: McDonald's Italia

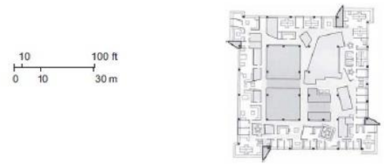


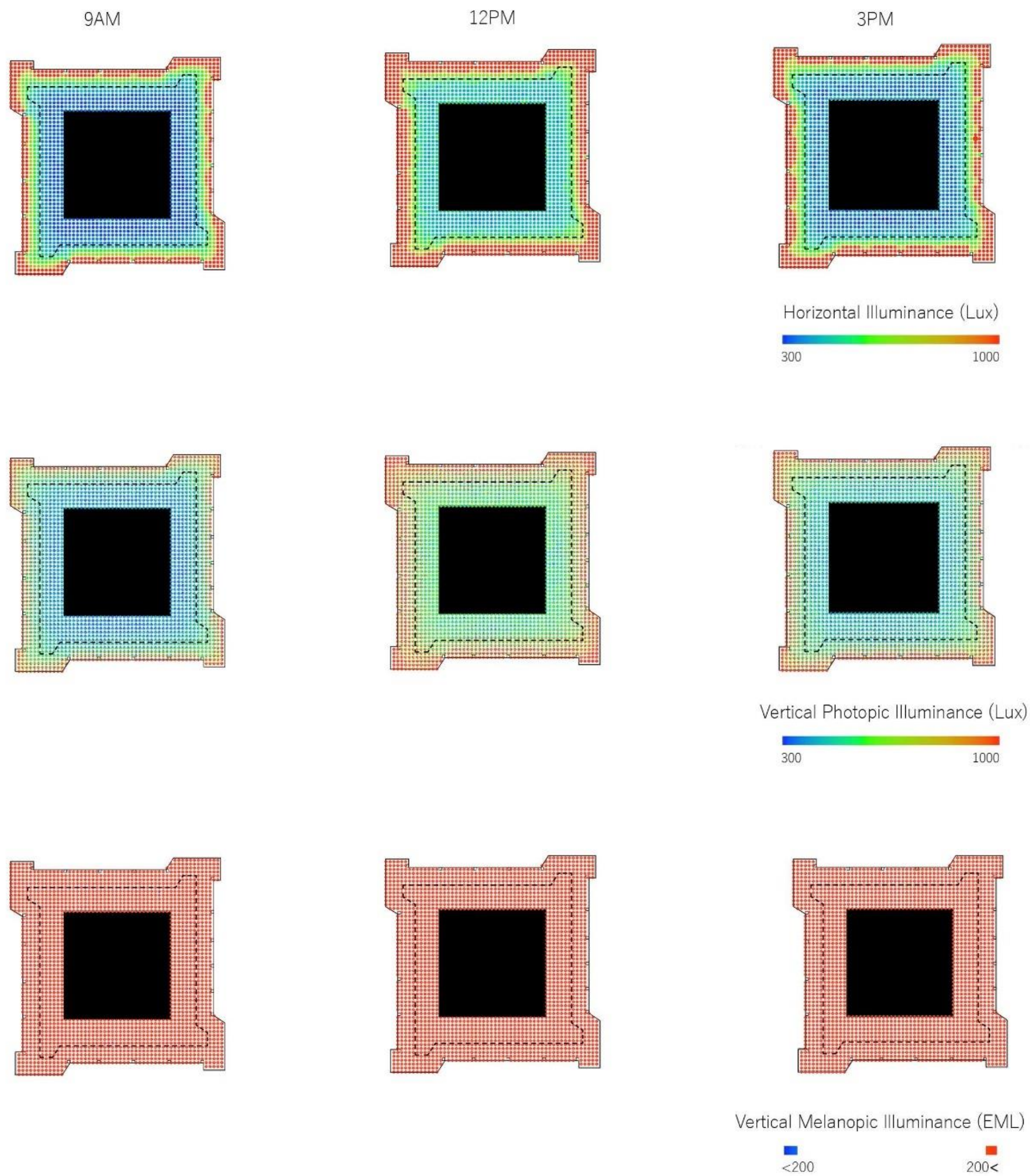
#37: MGIC


10
100 ft
0
10
30 m

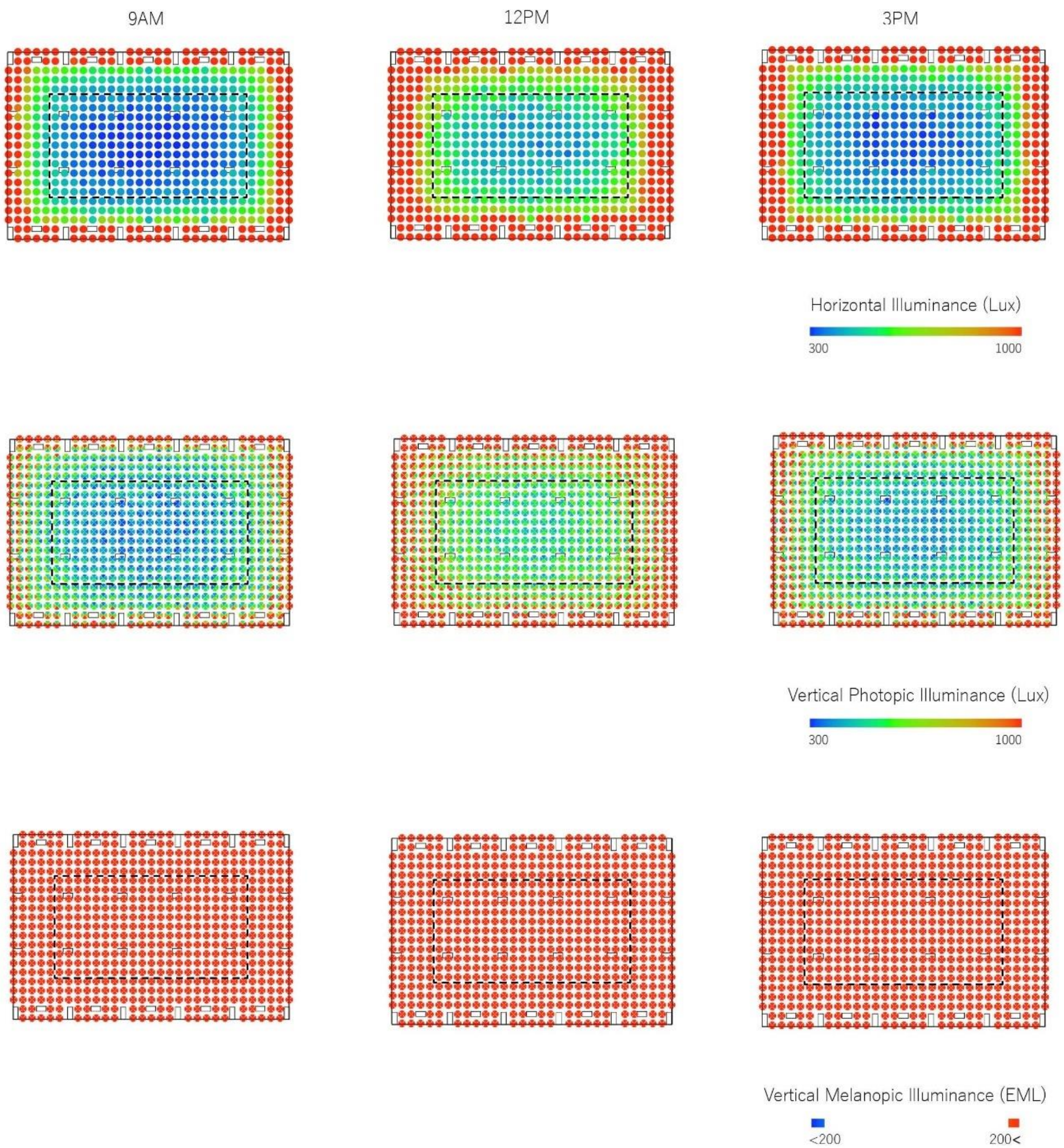

9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

#38: Nickelodeon

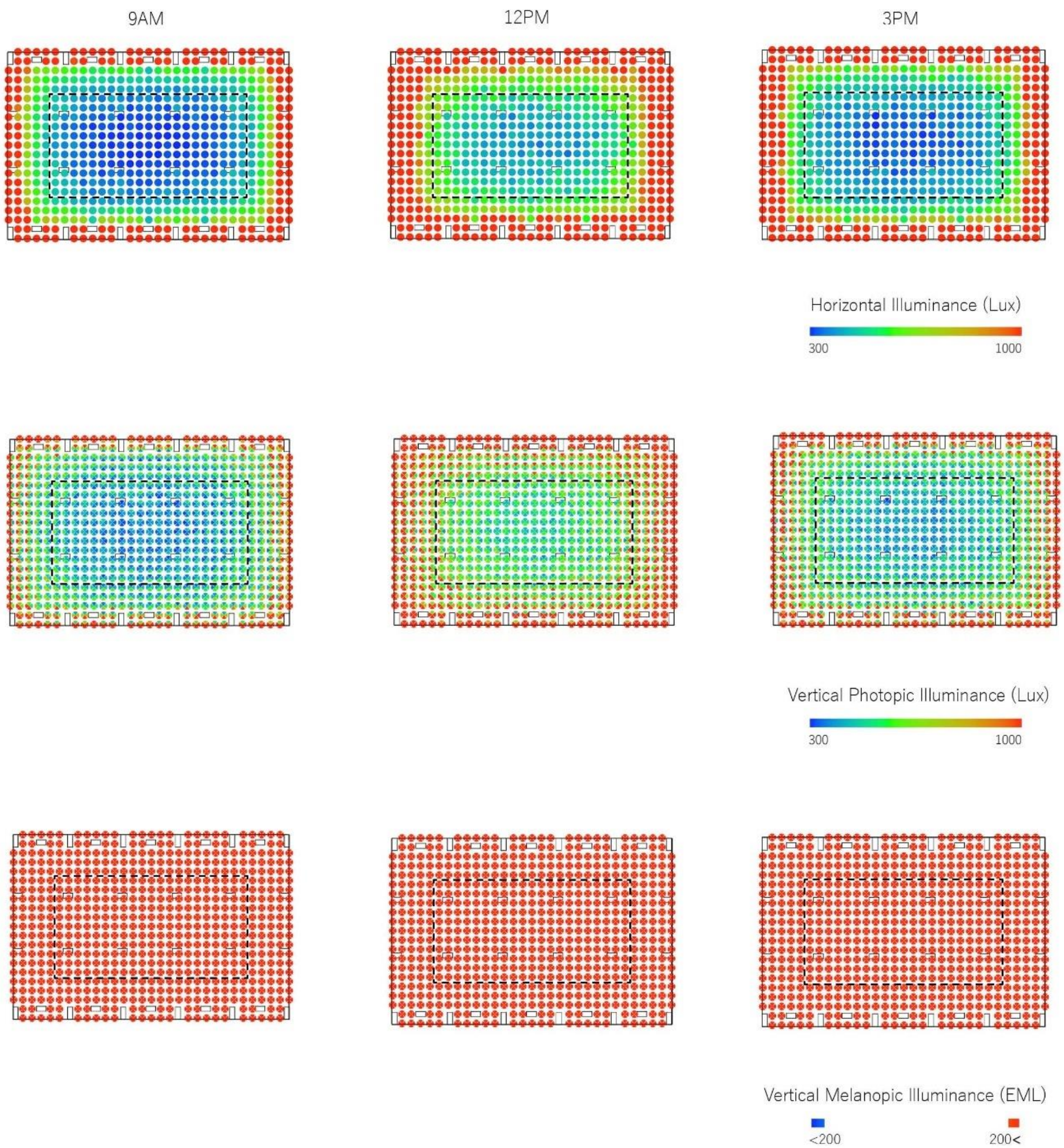




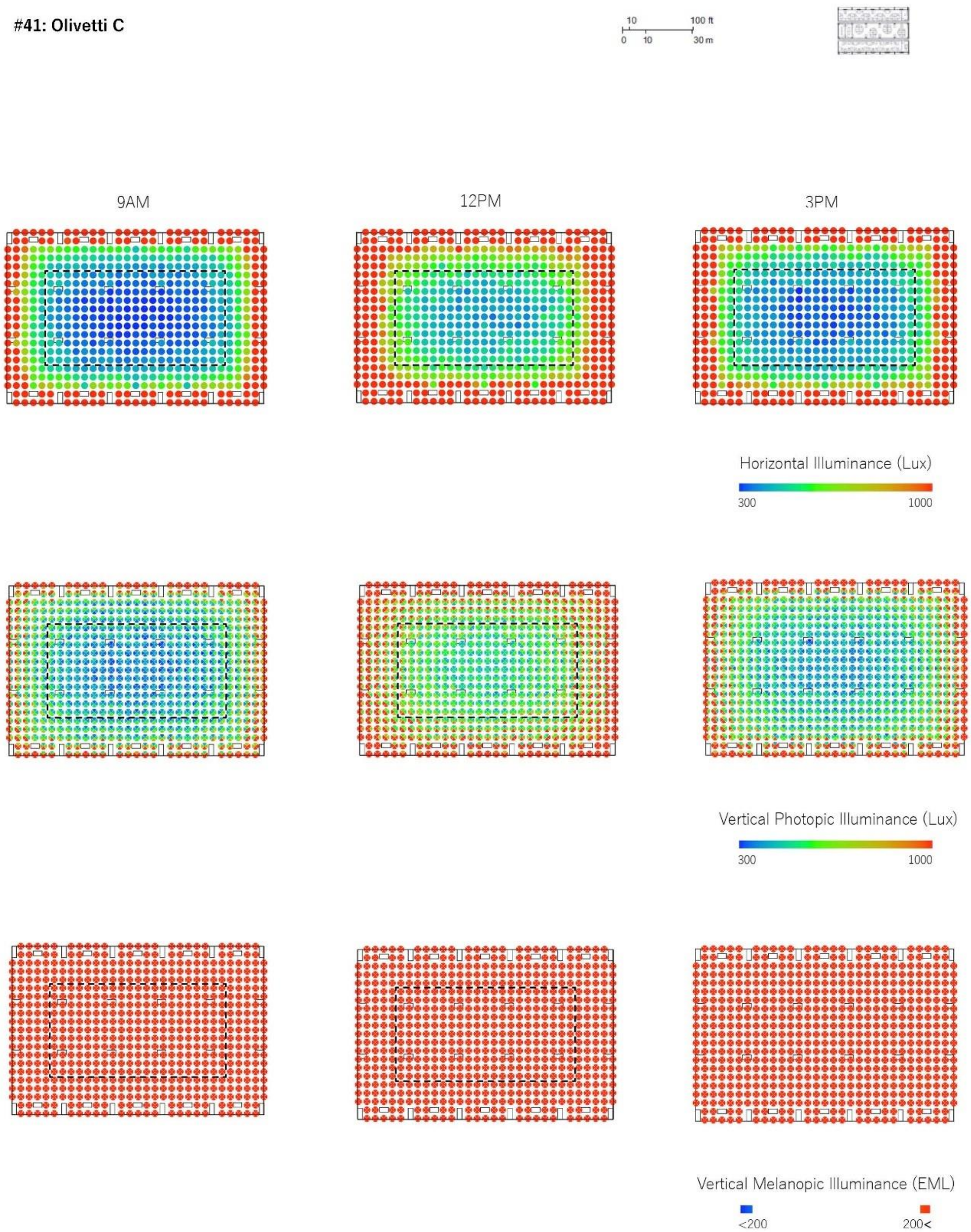
#39: Olivetti A



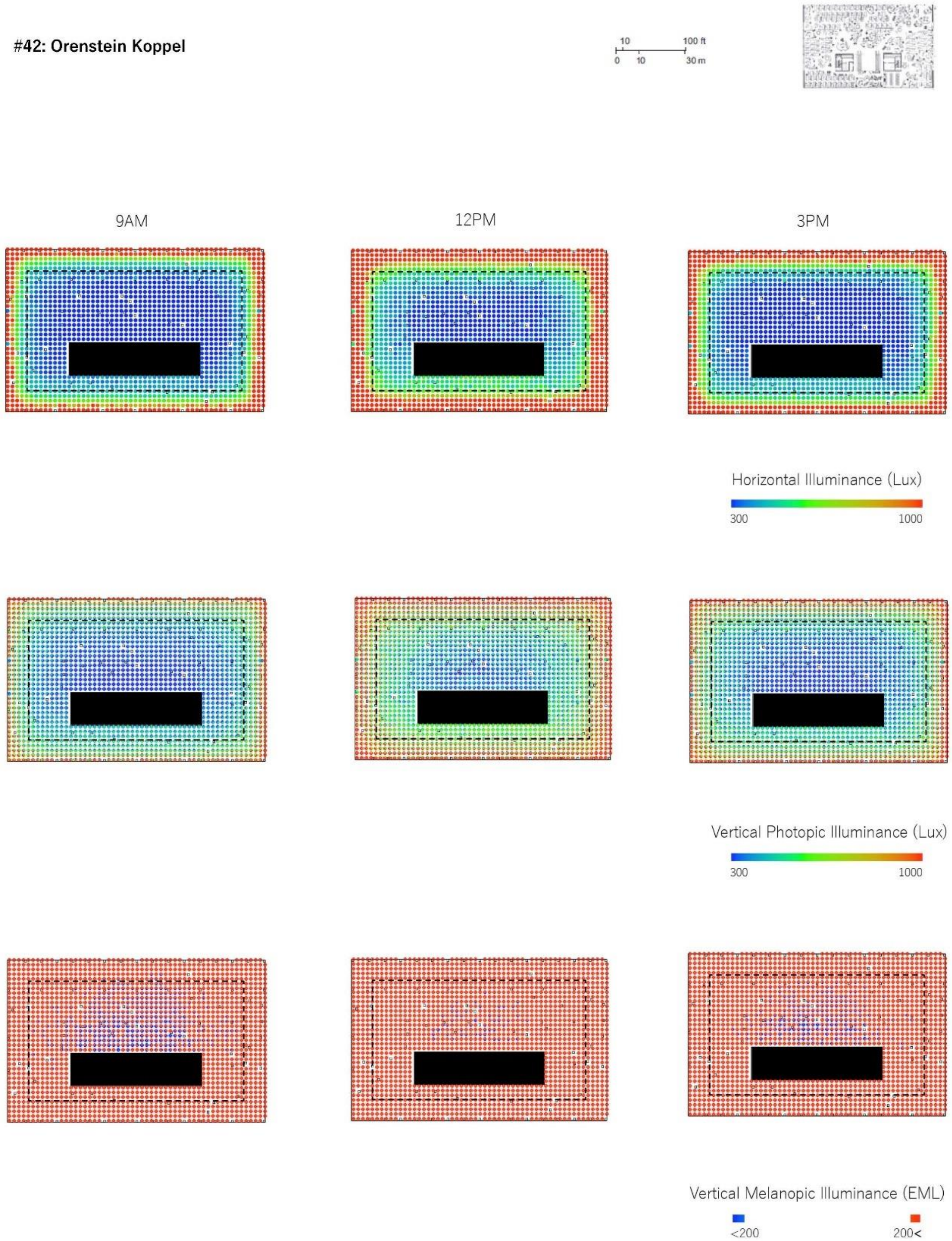
#40: Olivetti B



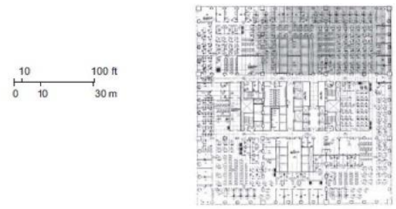
#41: Olivetti C



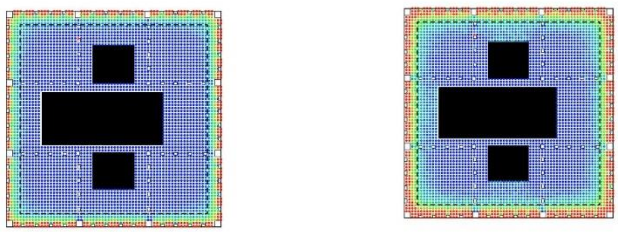
#42: Orenstein Koppel



#43: Sears 40

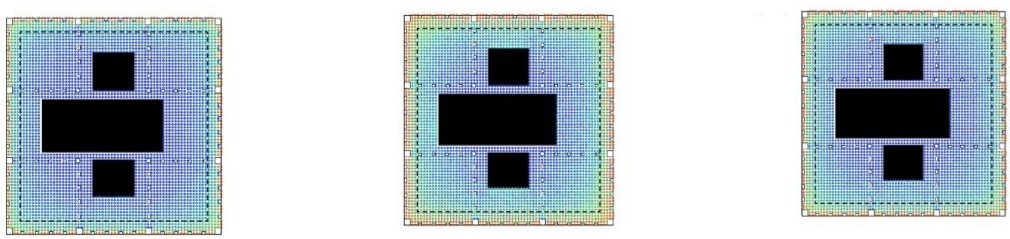


9AM 12PM 3PM



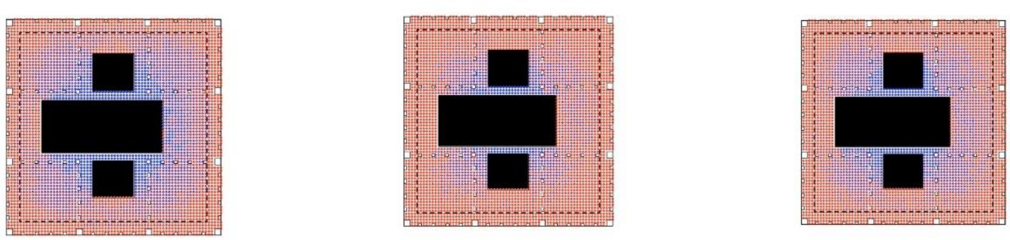
Horizontal Illuminance (Lux)

300 1000



Vertical Photopic Illuminance (Lux)

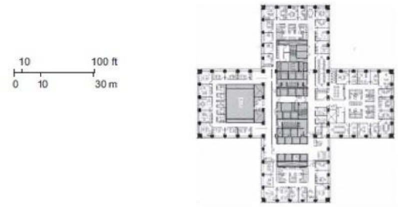
300 1000

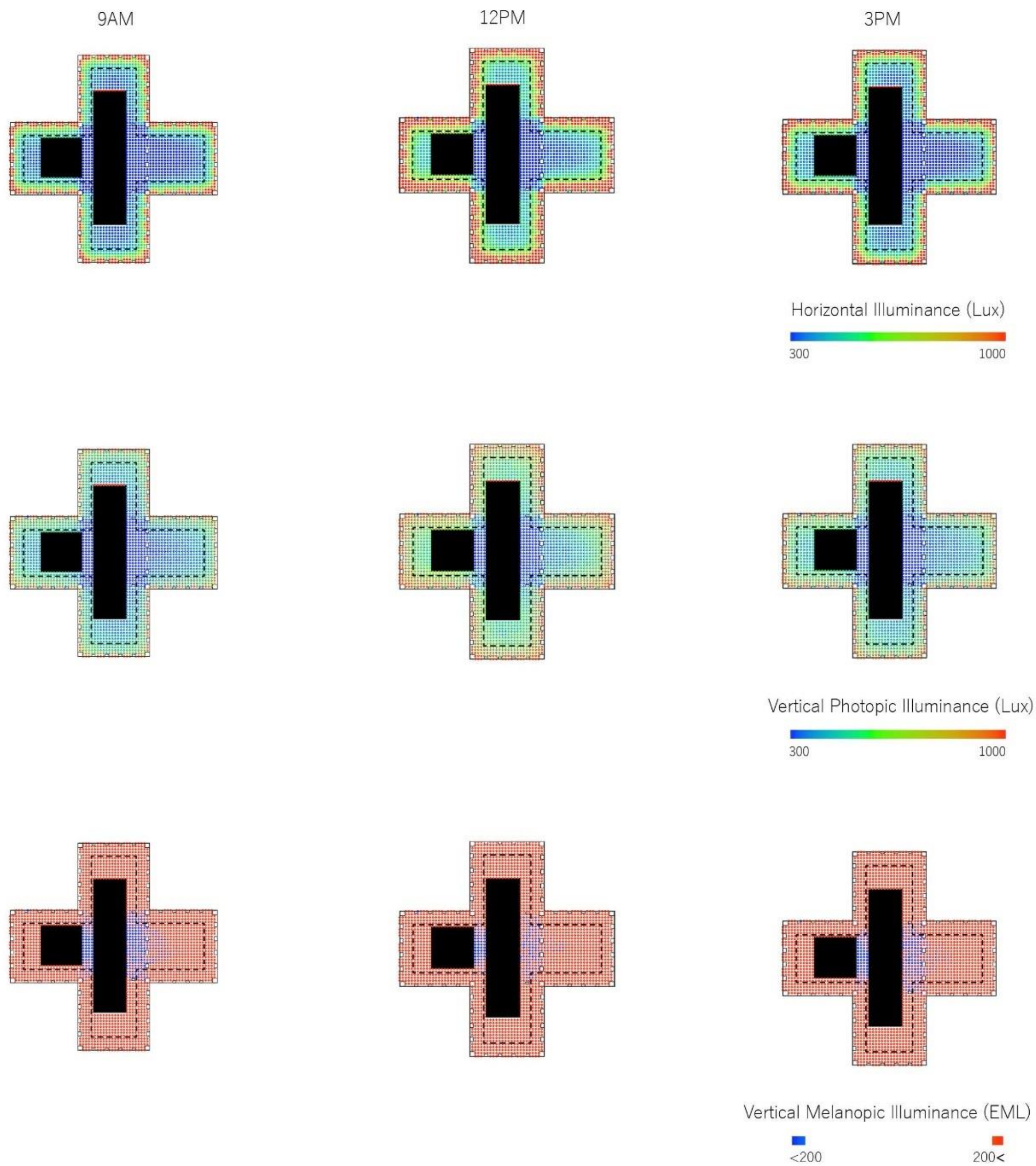


Vertical Melanopic Illuminance (EML)

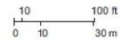
<200 200<

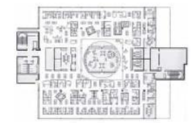
#44: Sears 70

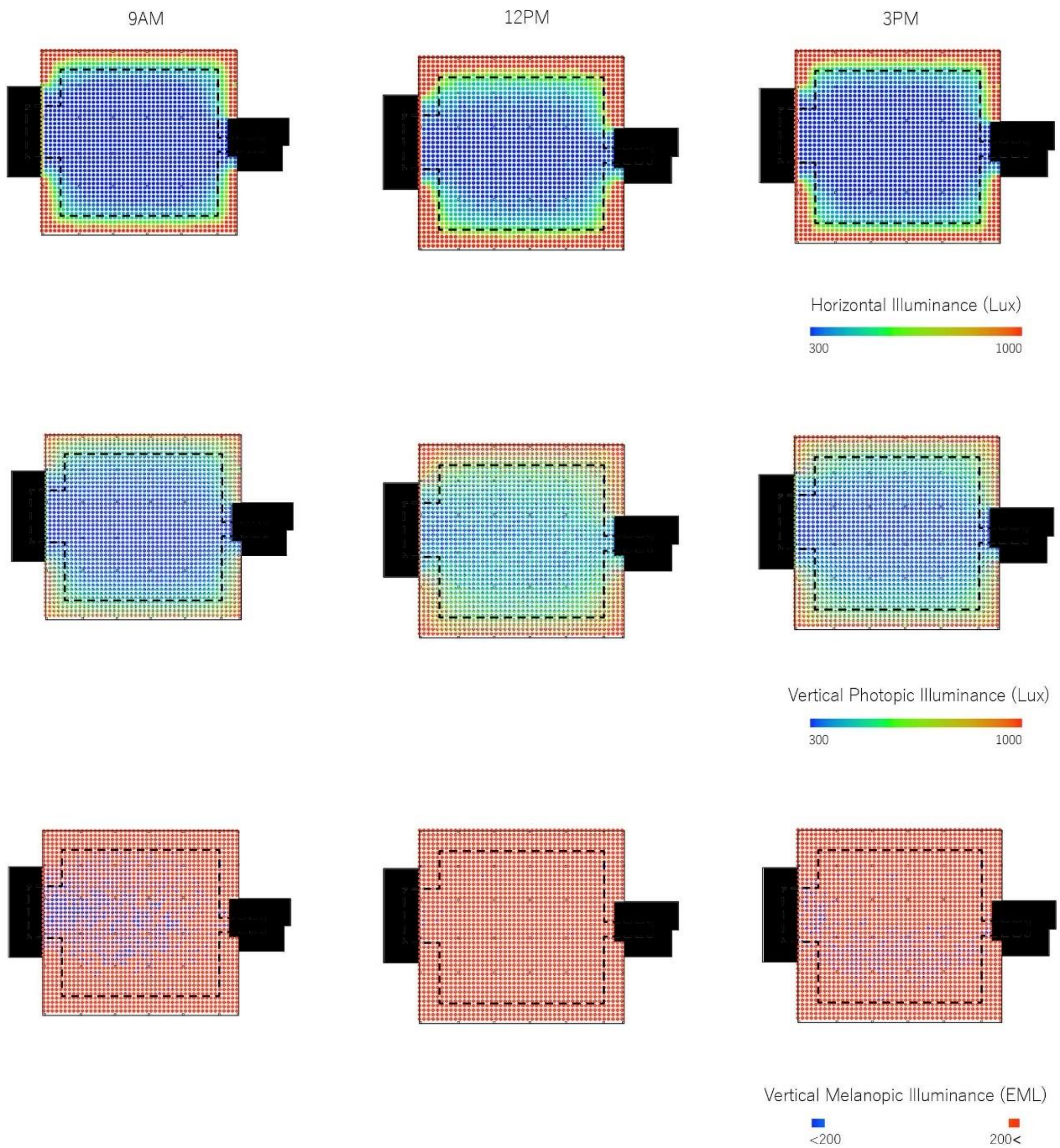

10
100 ft
0
10
30 m


9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

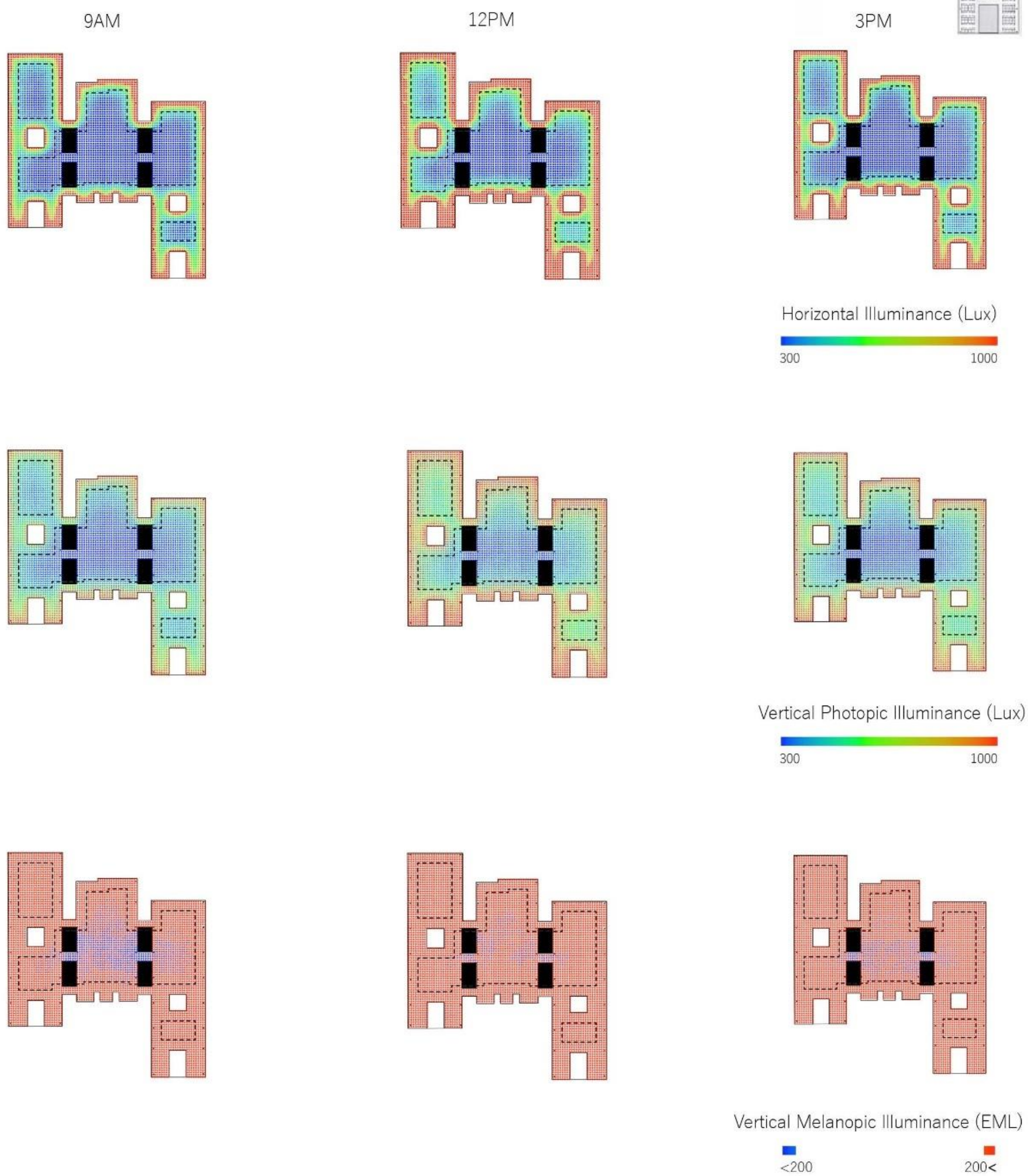
#45: Steelcase Inc.



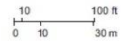


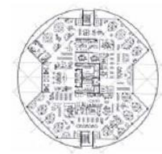


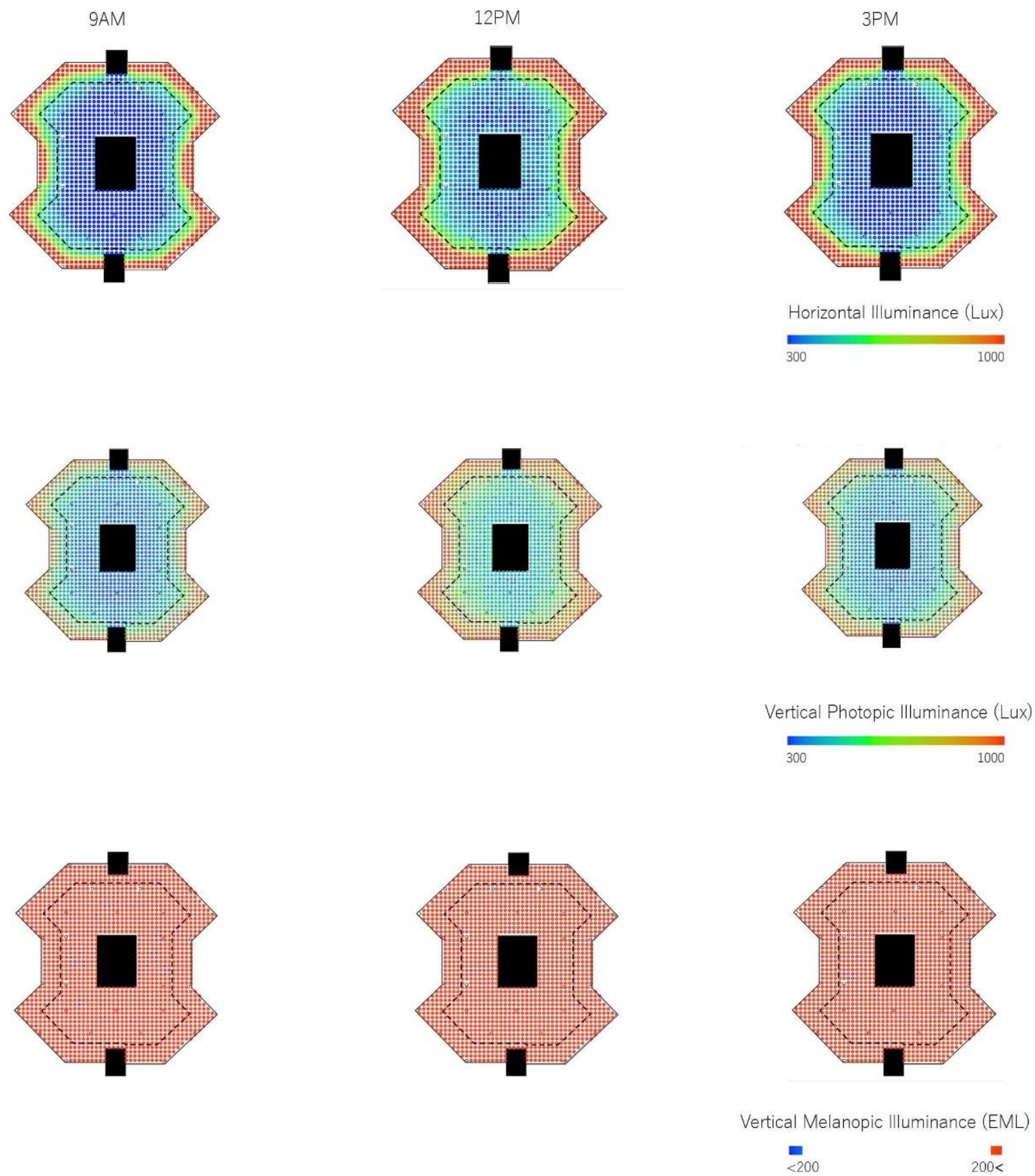
#46: British Telec., 5 Longwalk



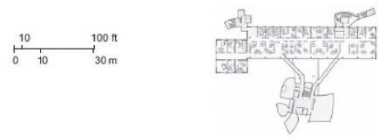
#47: British Telec., The Square

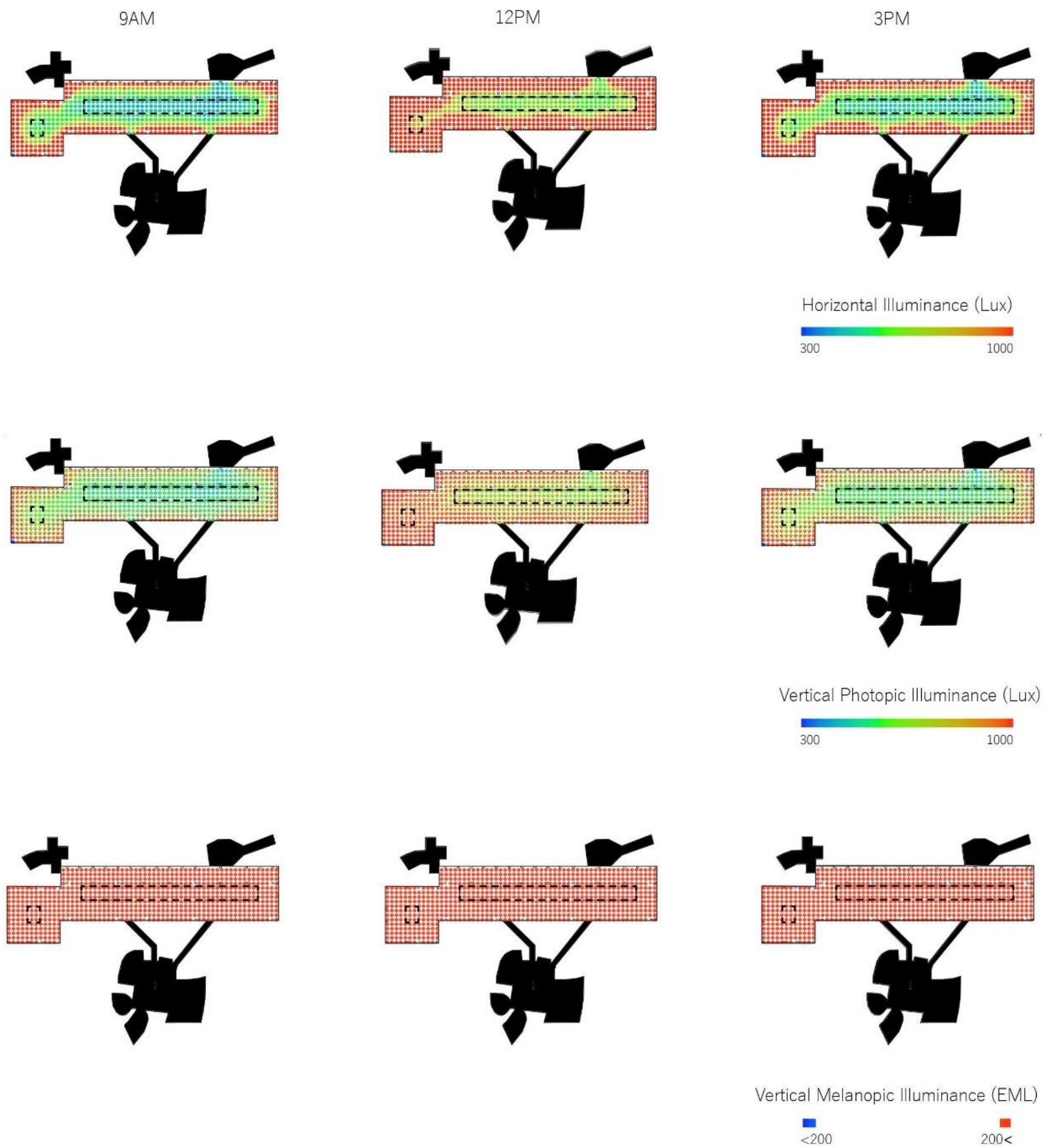




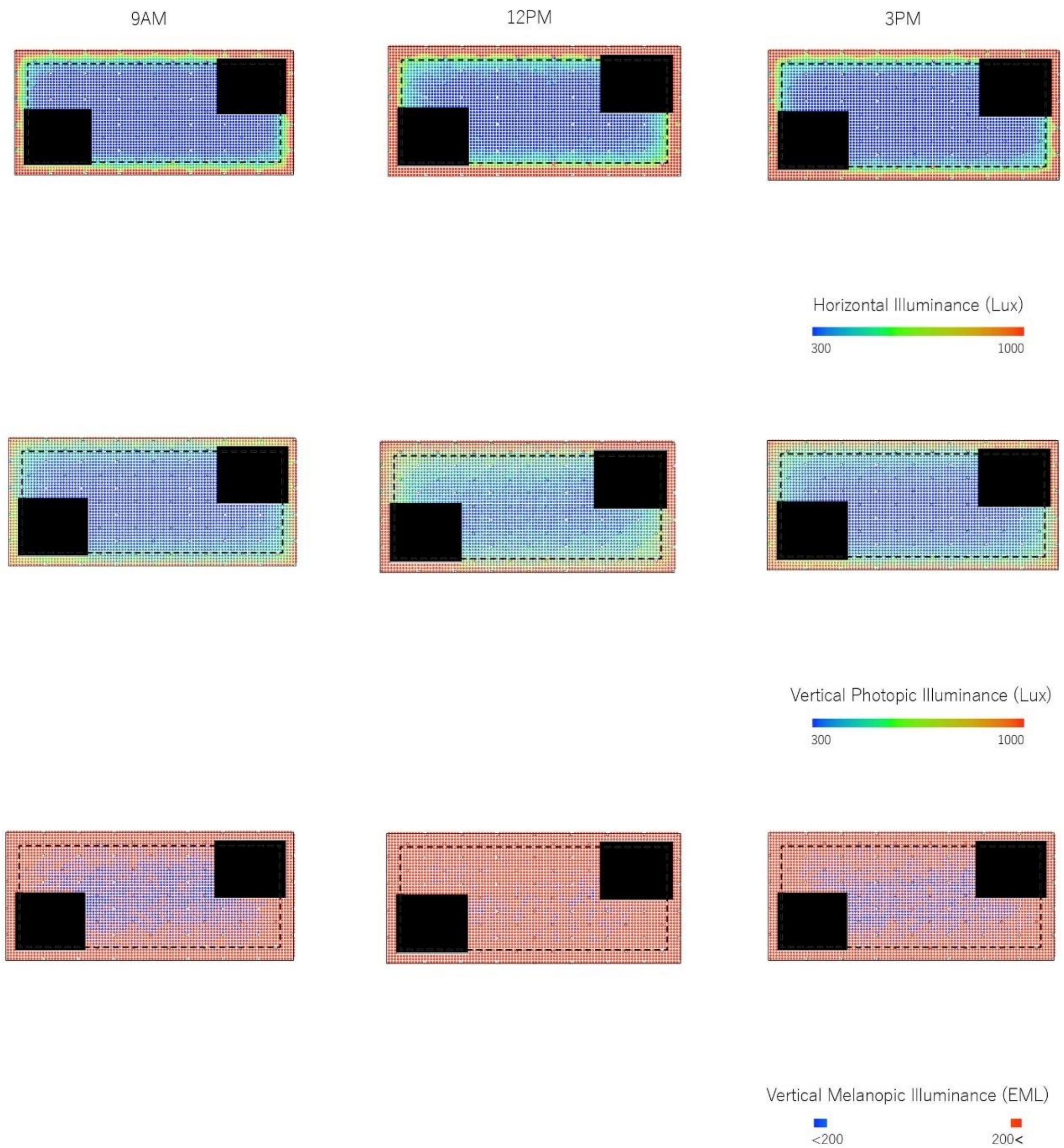


#48: Vitra International AG

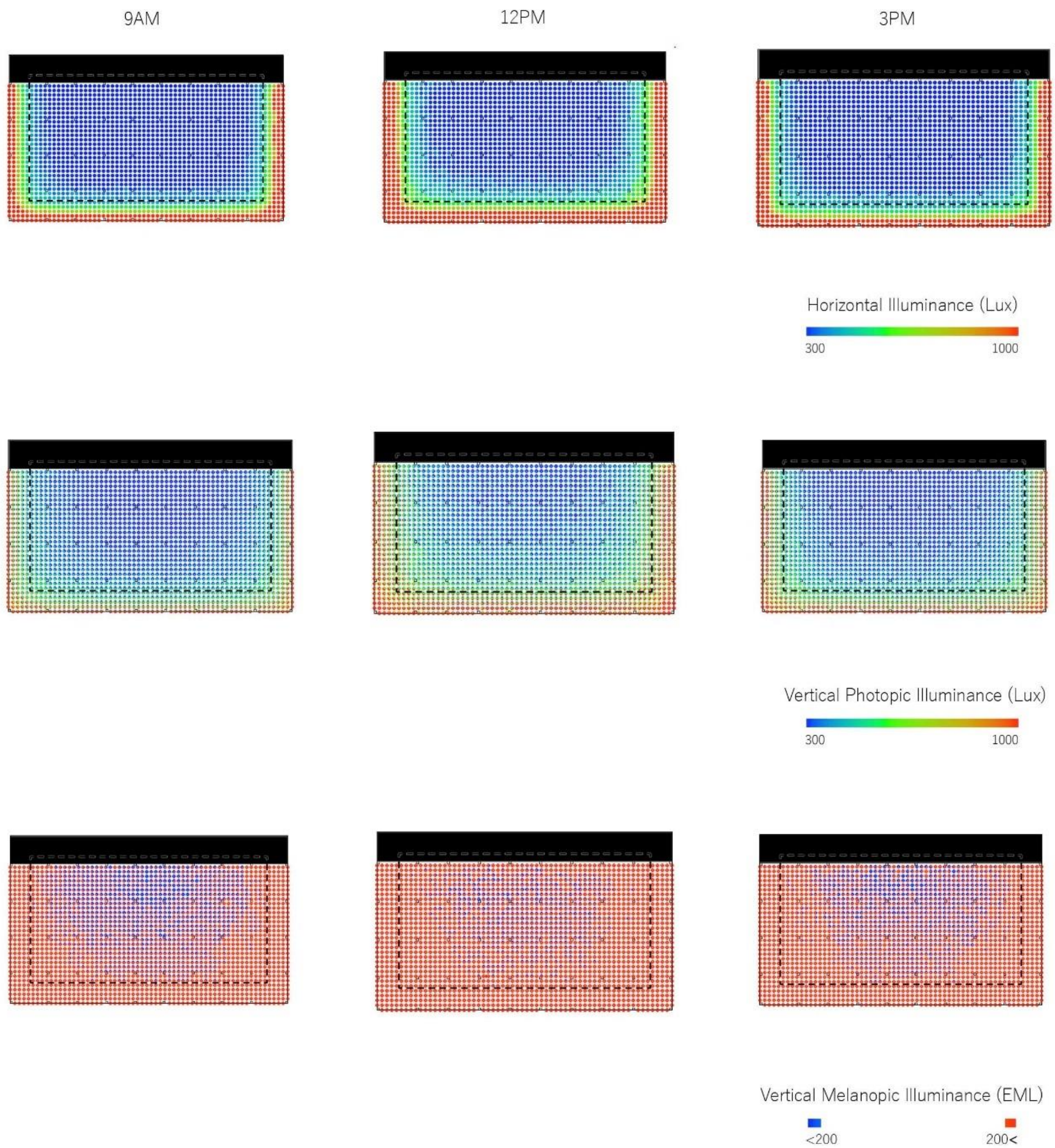




49: Weyerhaeuser Company

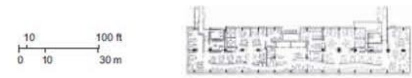


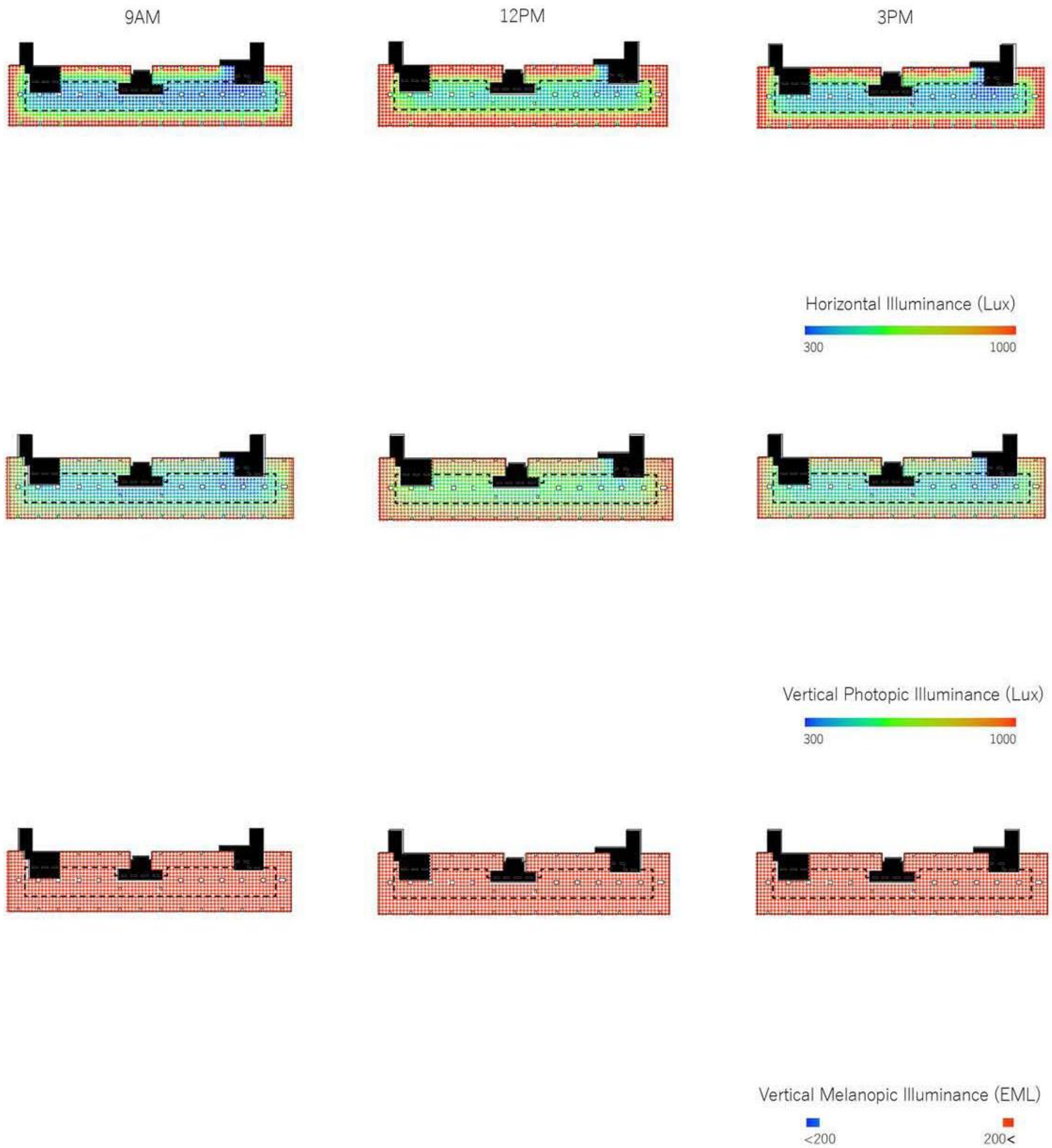
#50: WMA Consulting Engineers



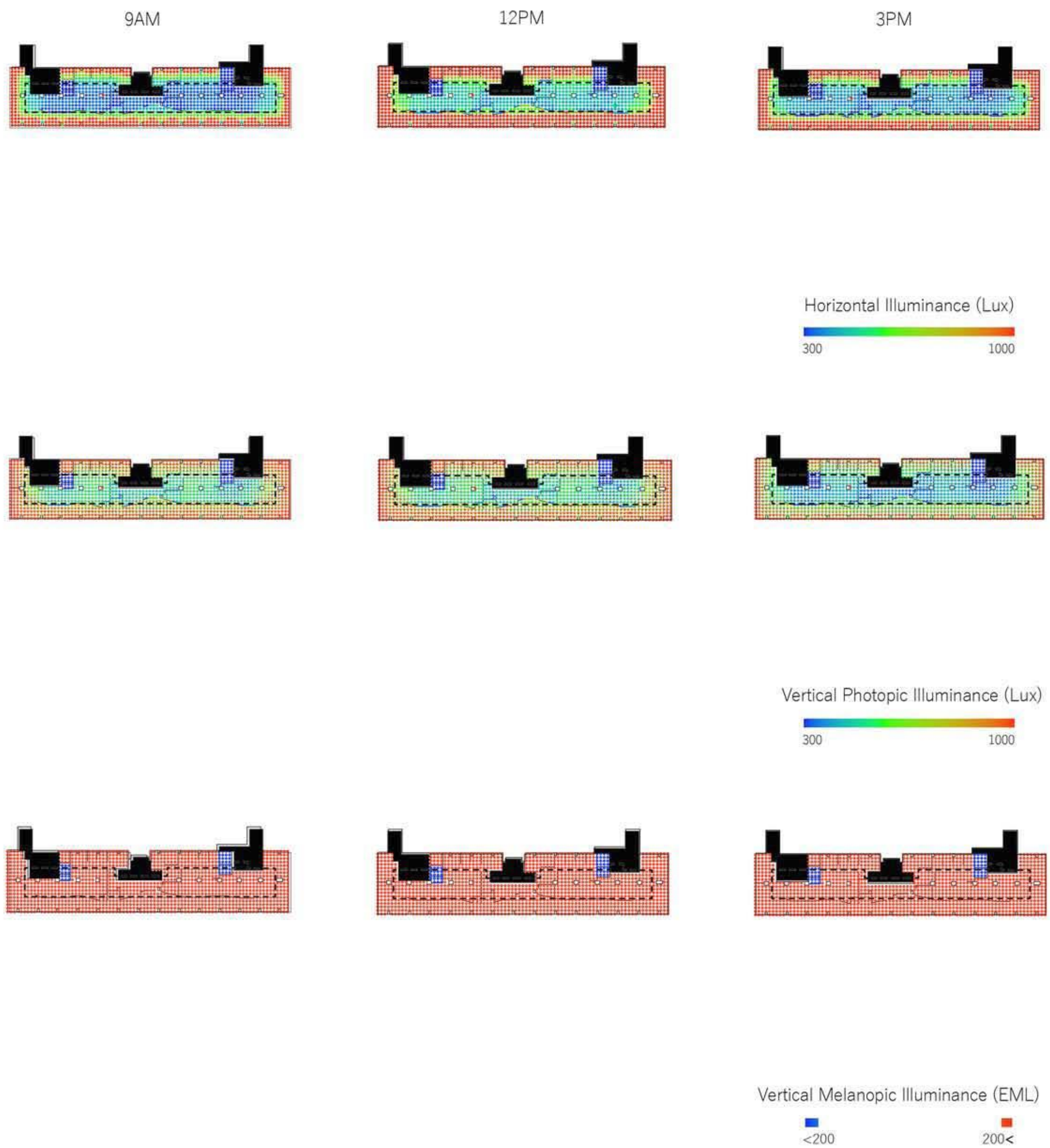
APPENDIX B – INTERIOR WALLS SIMULATIONS

#5: Arthur Andersen



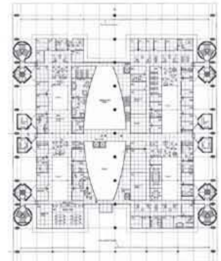


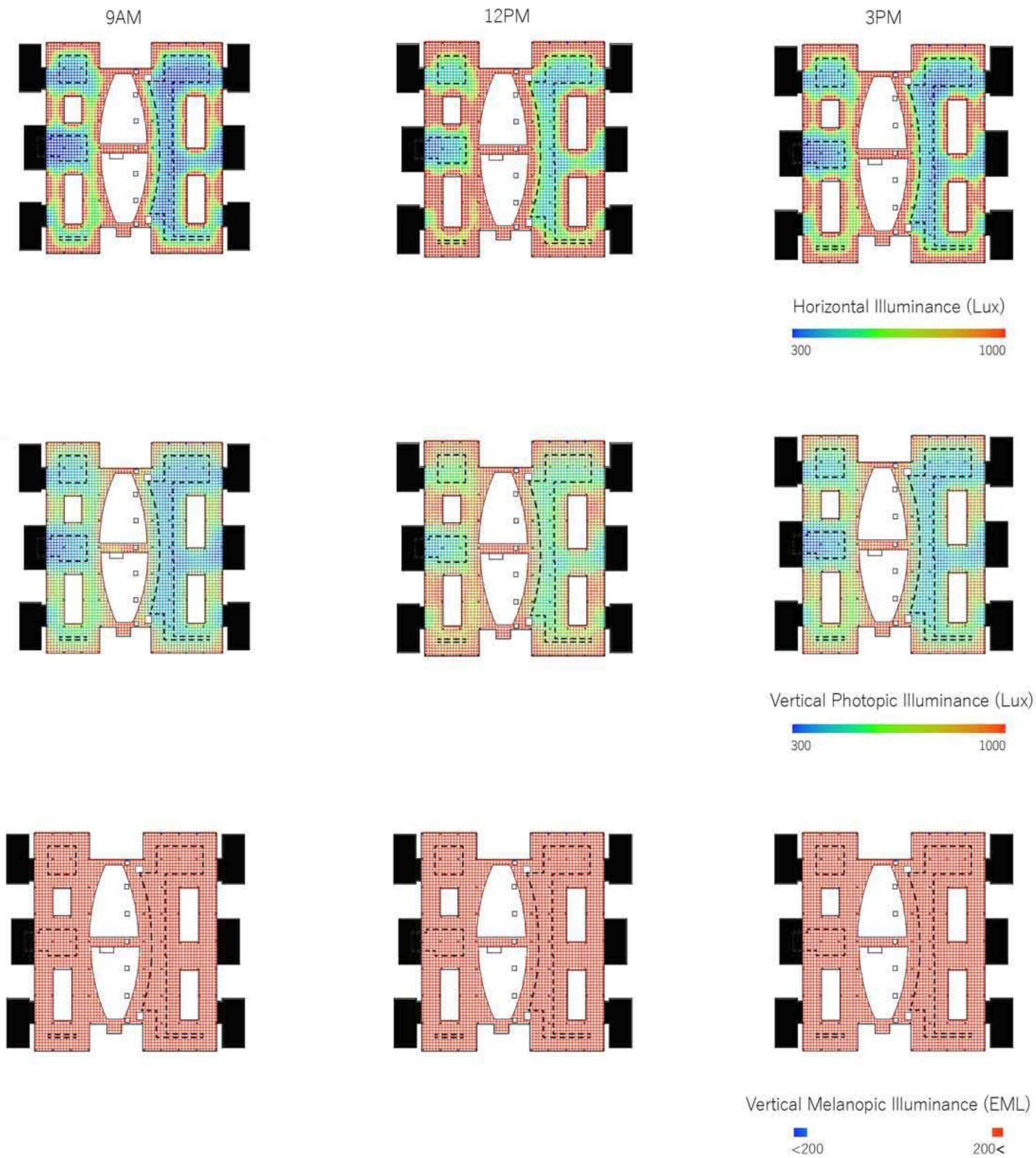
#5: Arthur Andersen



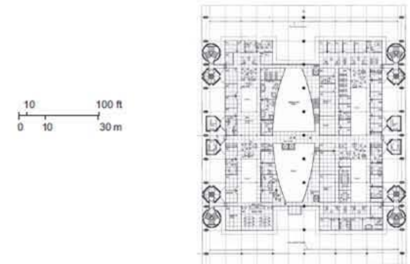
#6: Apicorp

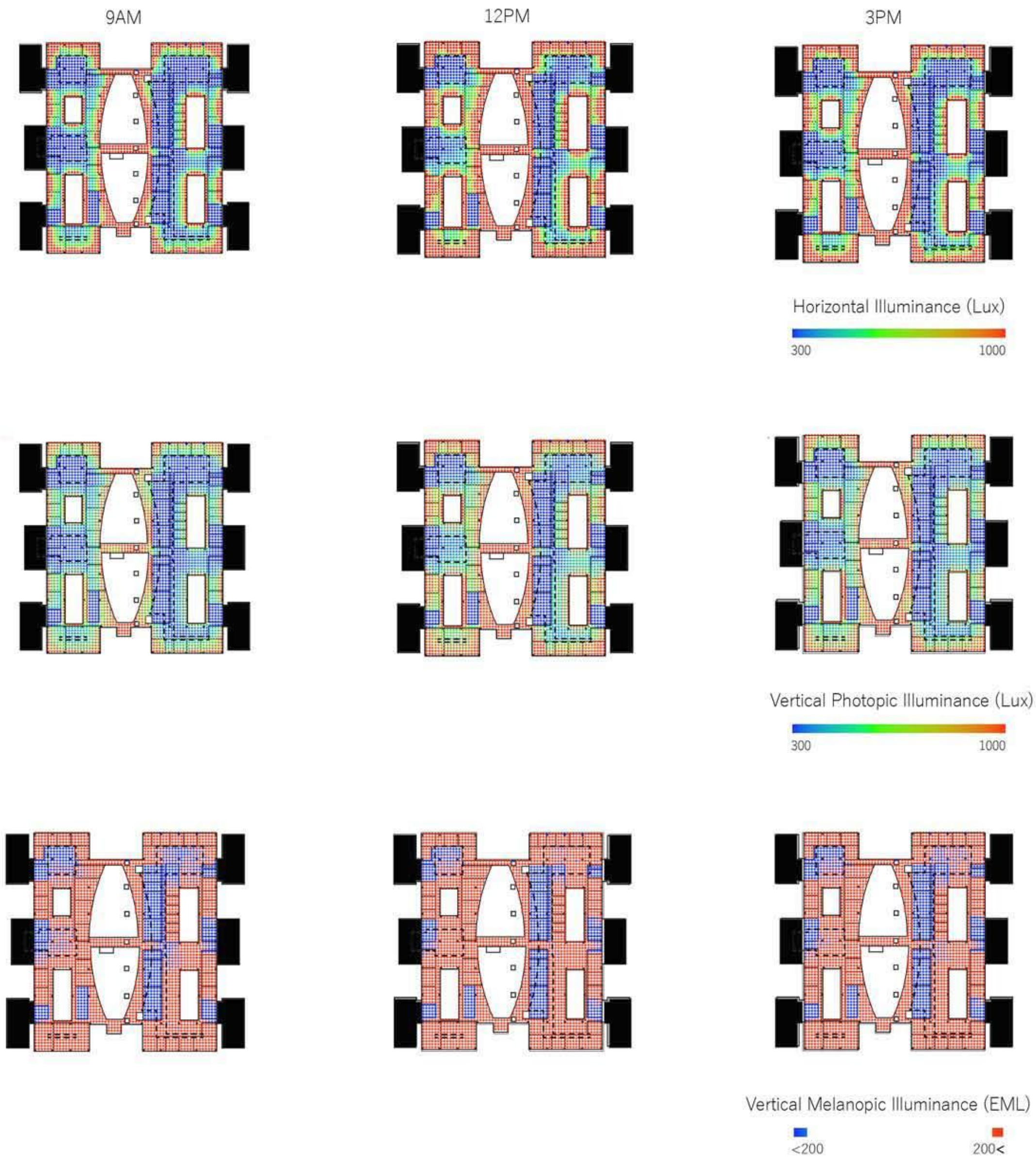

10
100 ft
0
10
30 m



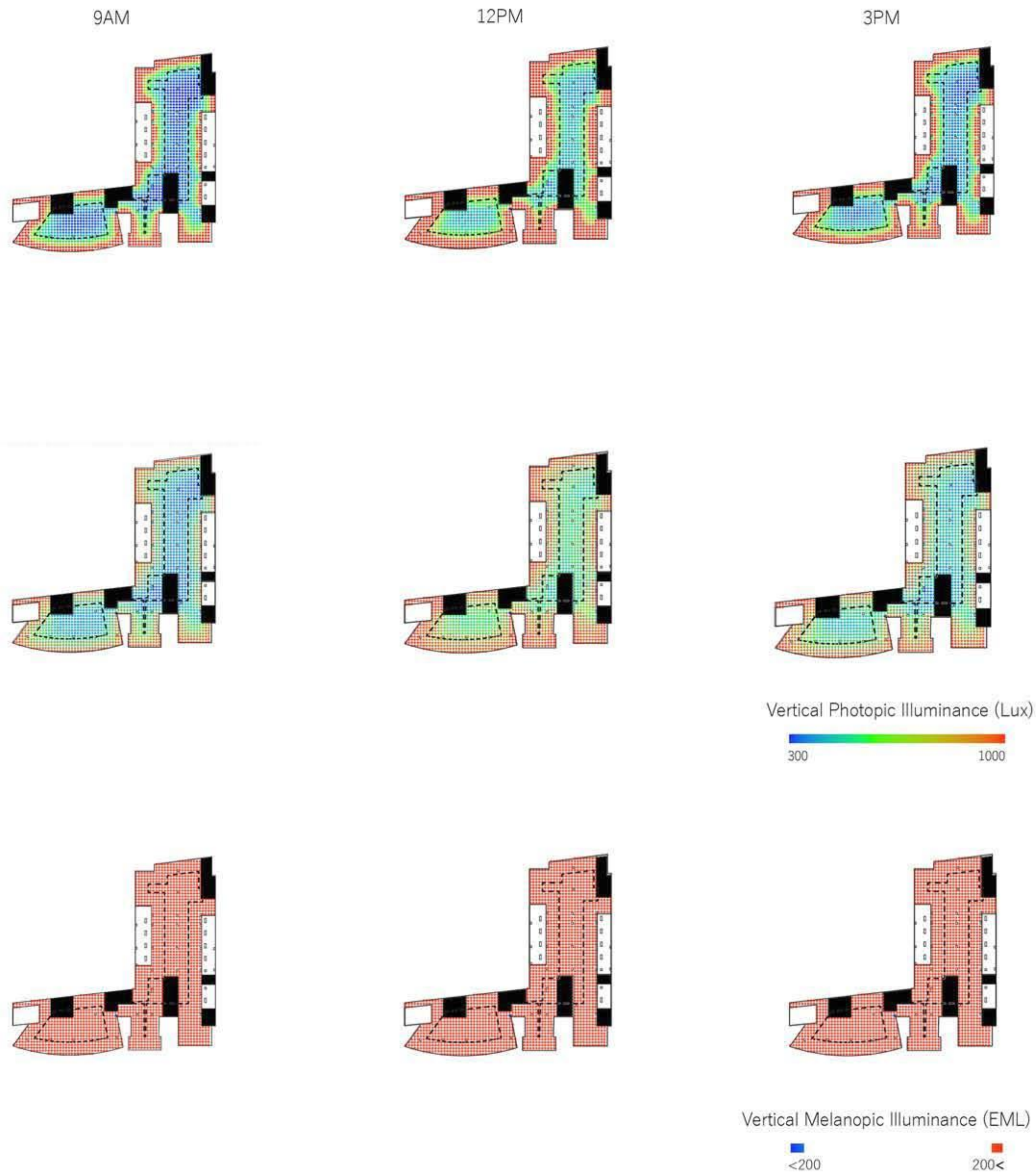

9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

#6: Apicorp

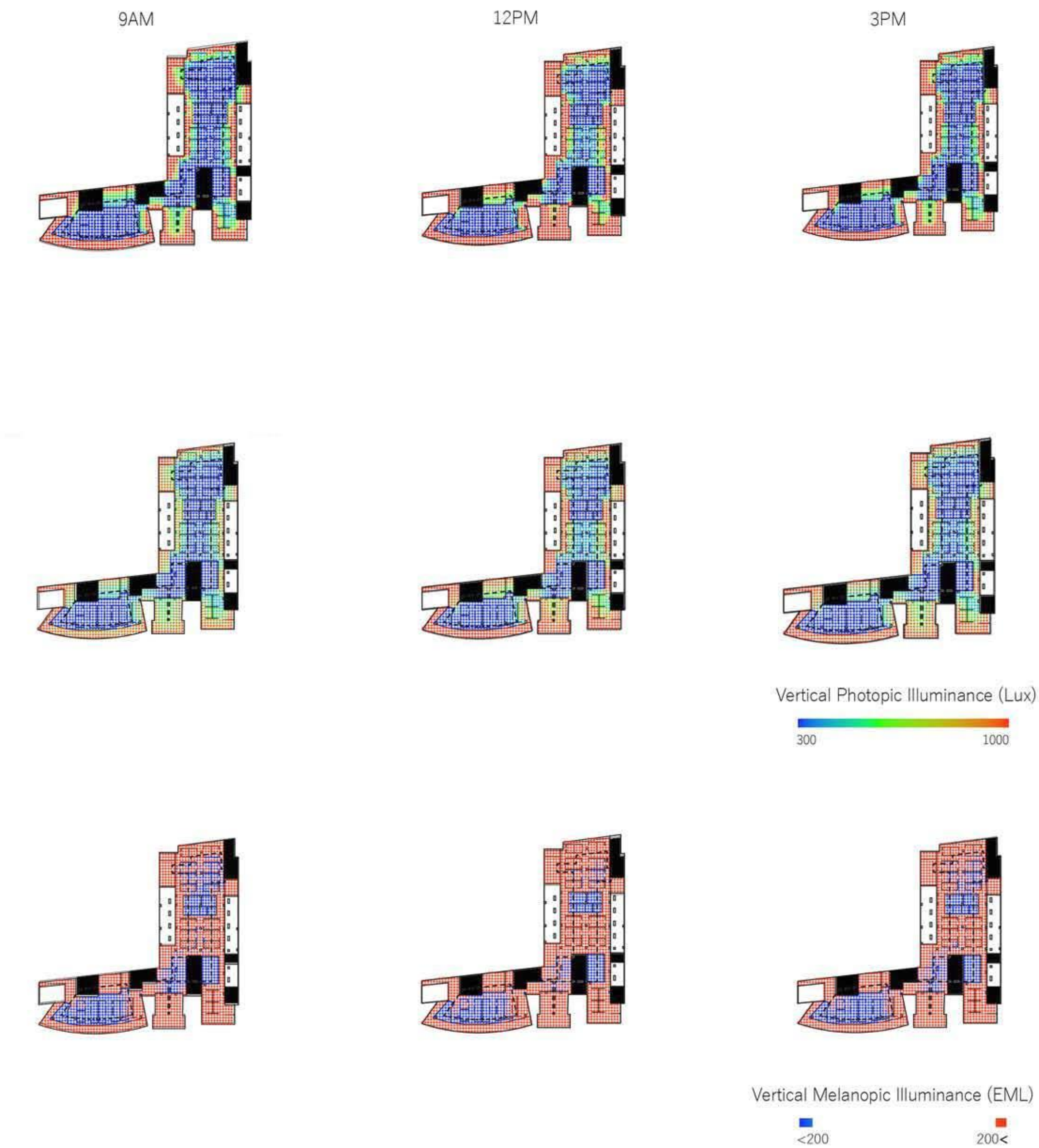

10 100 ft
0 10 30 m


9AM
12PM
3PM
Horizontal Illuminance (Lux)
300
1000
Vertical Photopic Illuminance (Lux)
300
1000
Vertical Melanopic Illuminance (EML)
<200
200<

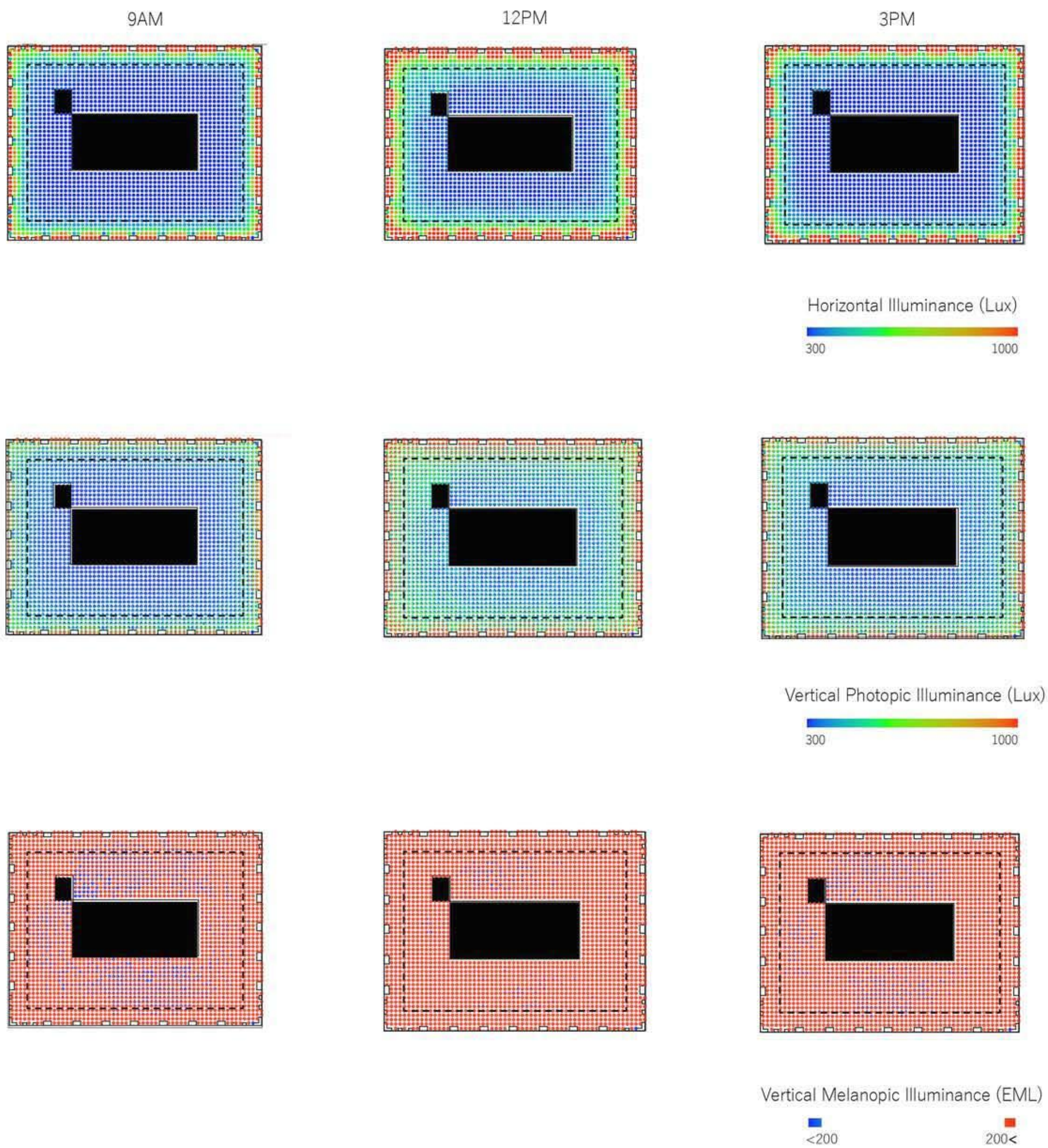
#11: Chiat/Day Advertising



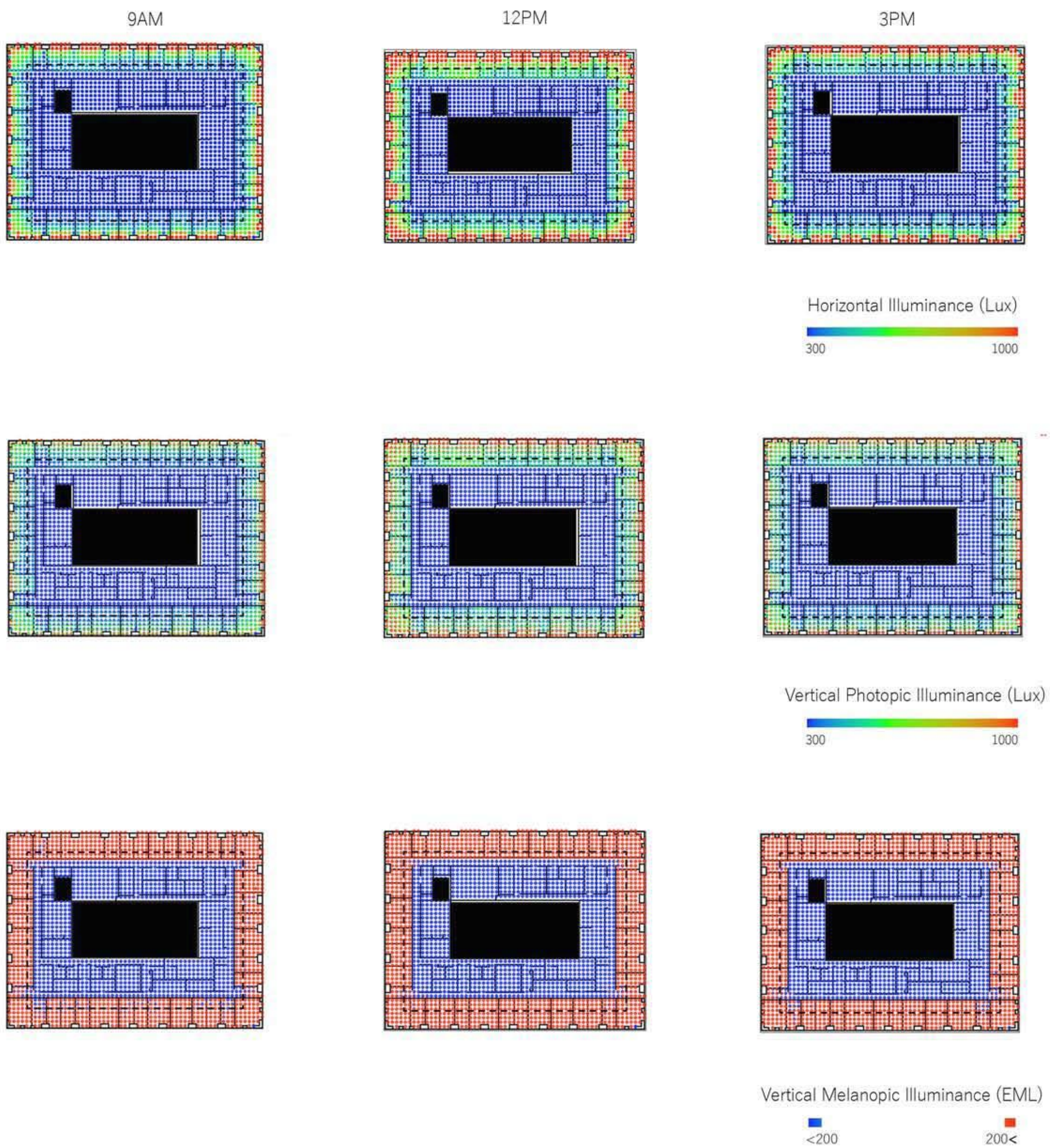
#11: Chiat/Day Advertising



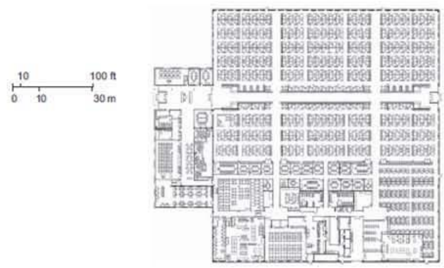
#16: Davis Polk & Wardwell

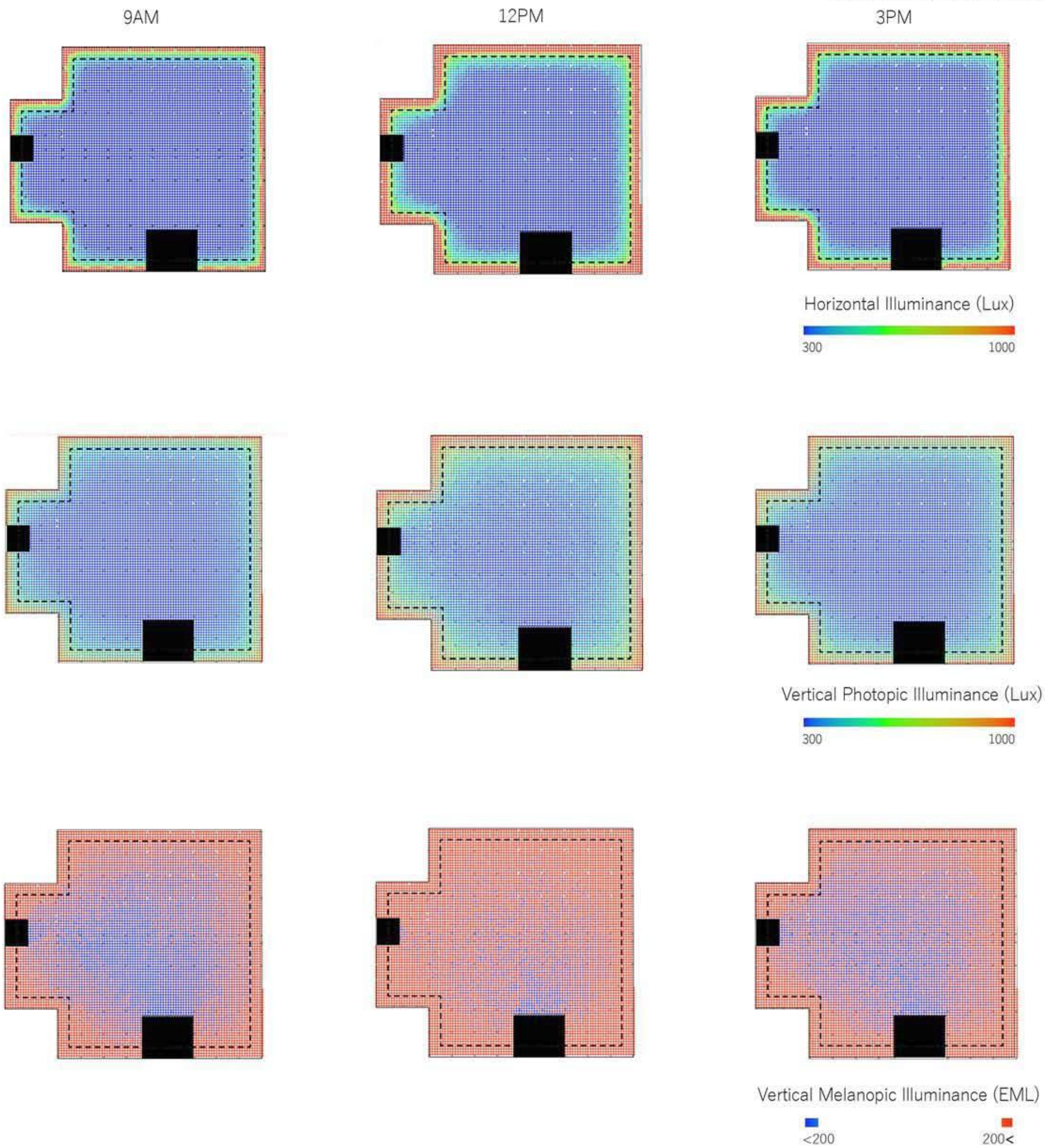


#16: Davis Polk & Wardwell

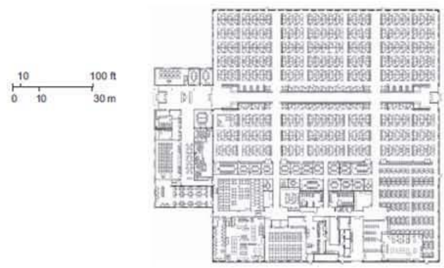


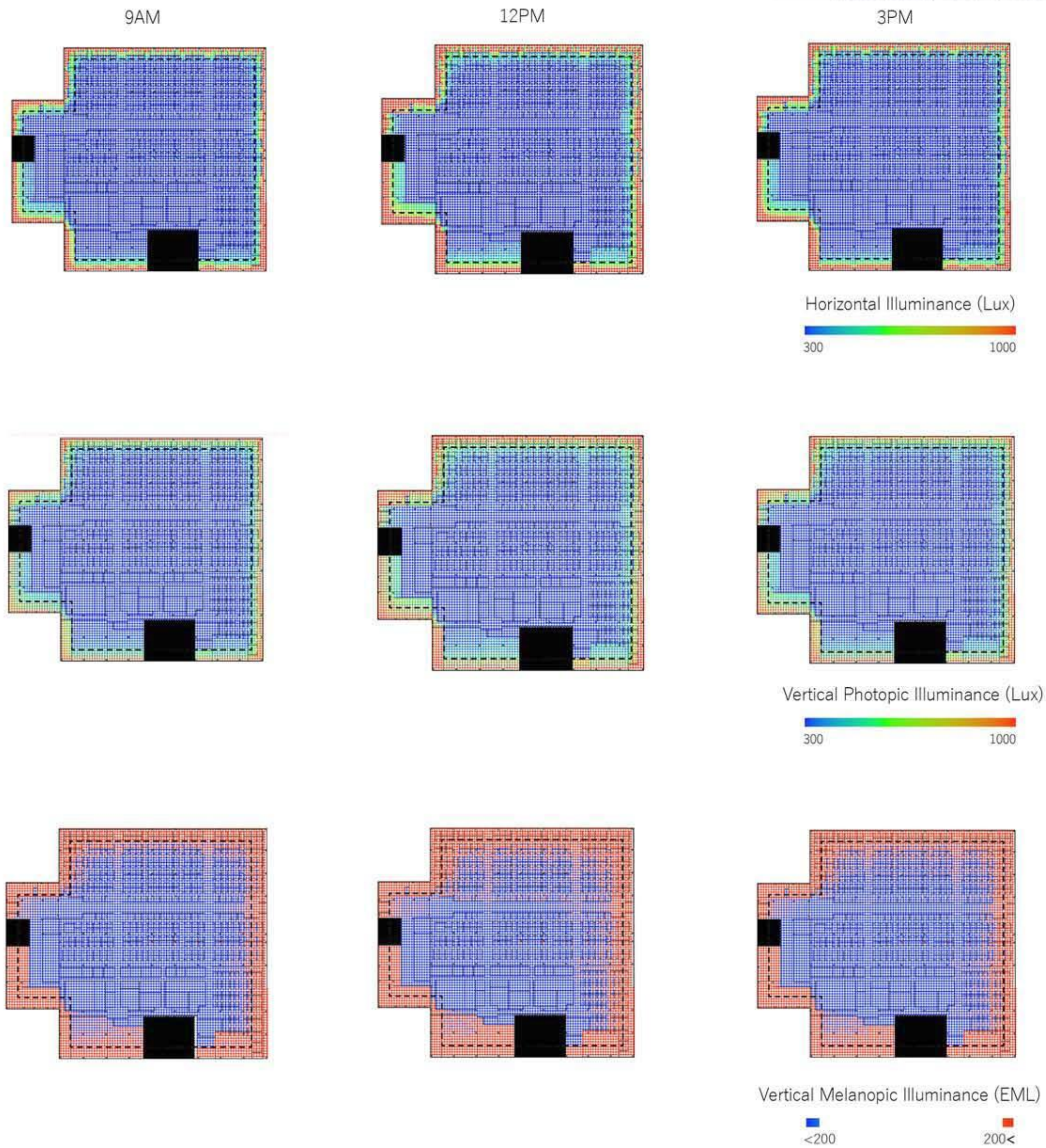
#26: IBM Regional Headquarters



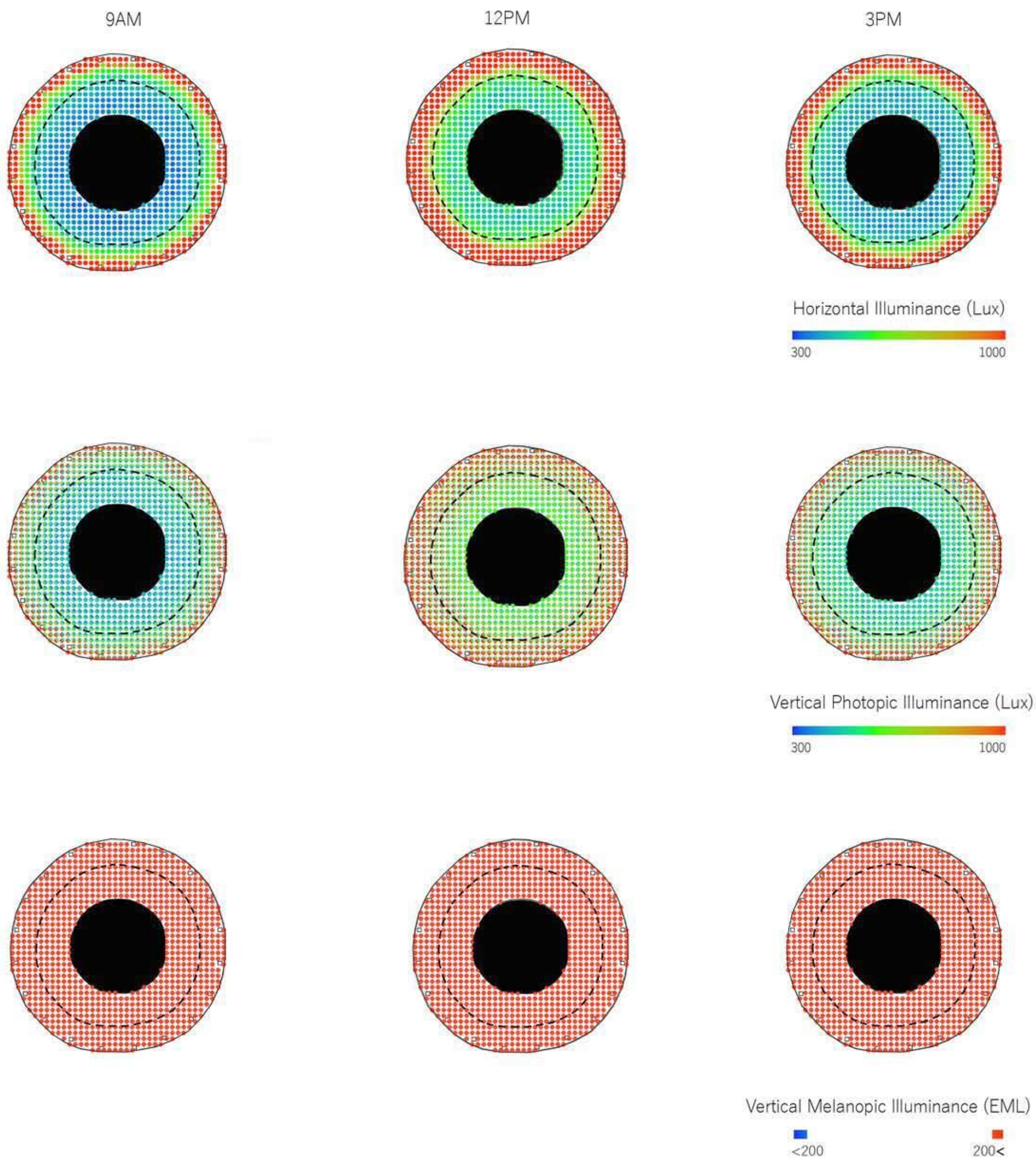


#26: IBM Regional Headquarters

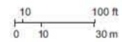


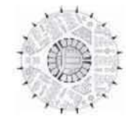


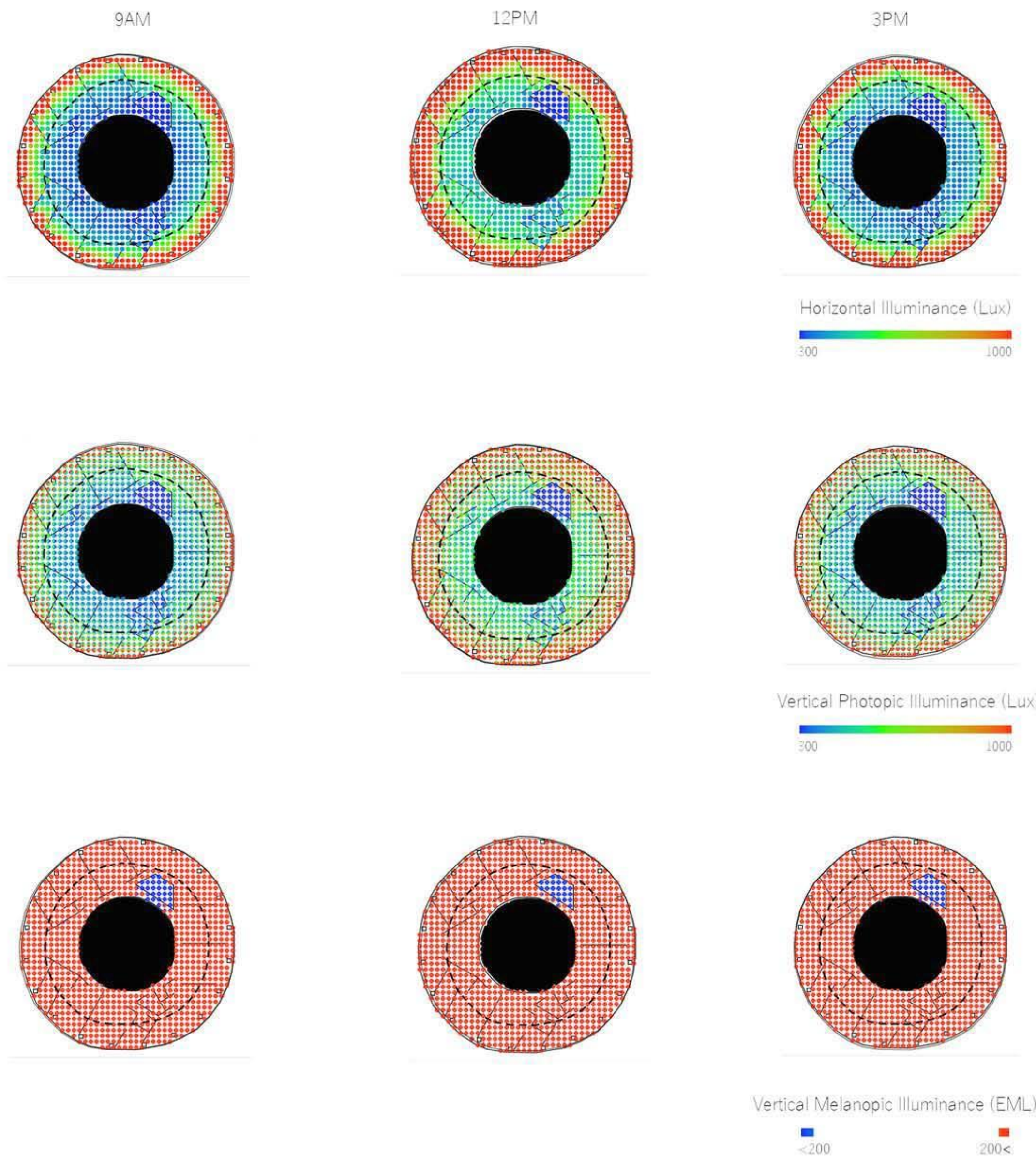
#32: Lend Lease Interiors



#32: Lend Lease Interiors







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